SIGNAL PHASE AND TIMING (SPaT) APPLICATIONS, COMMUNICATIONS REQUIREMENTS, COMMUNICATIONS TECHNOLOGY POTENTIAL SOLUTIONS, ISSUES AND RECOMMENDATIONS

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Final Report — April 3, 2012

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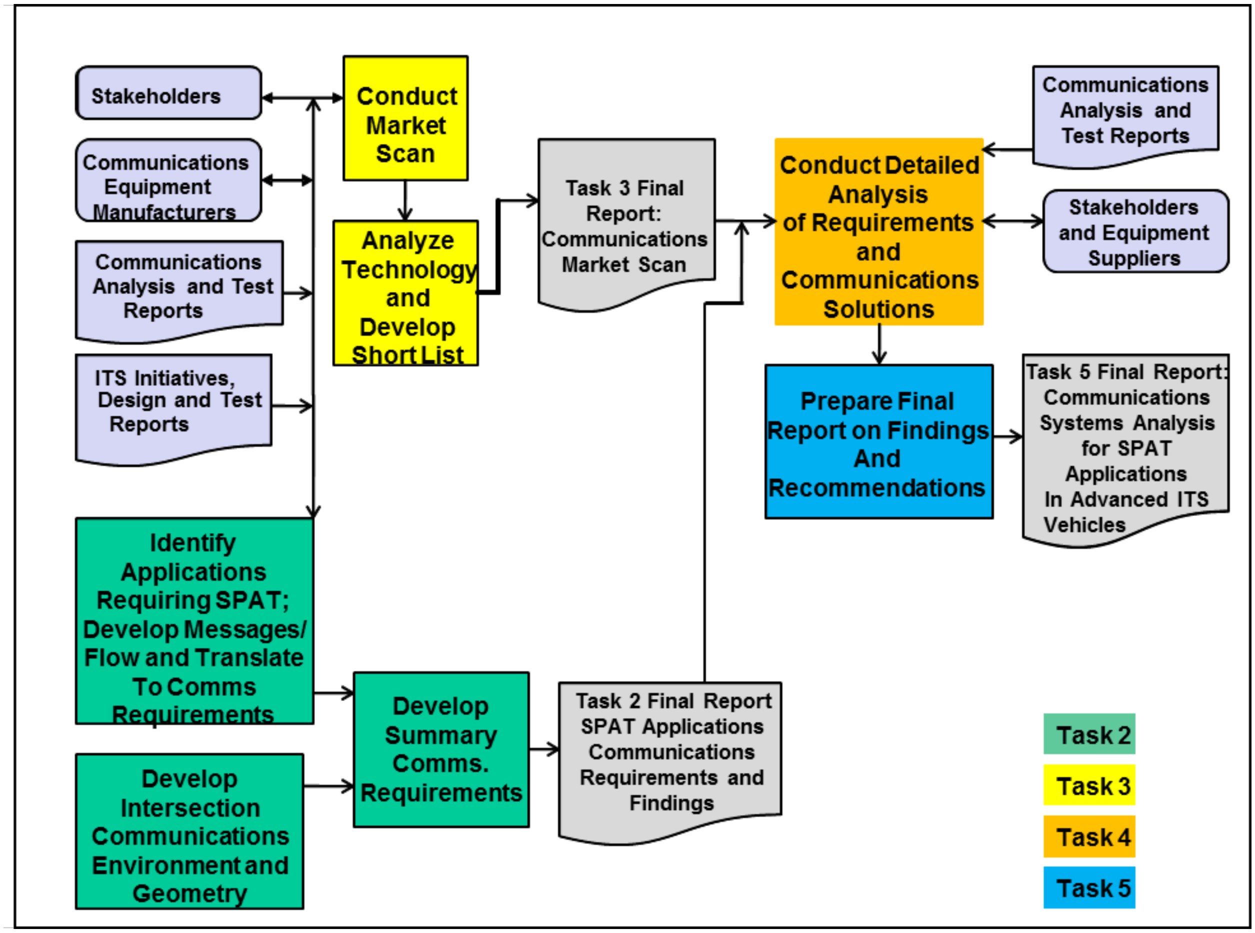
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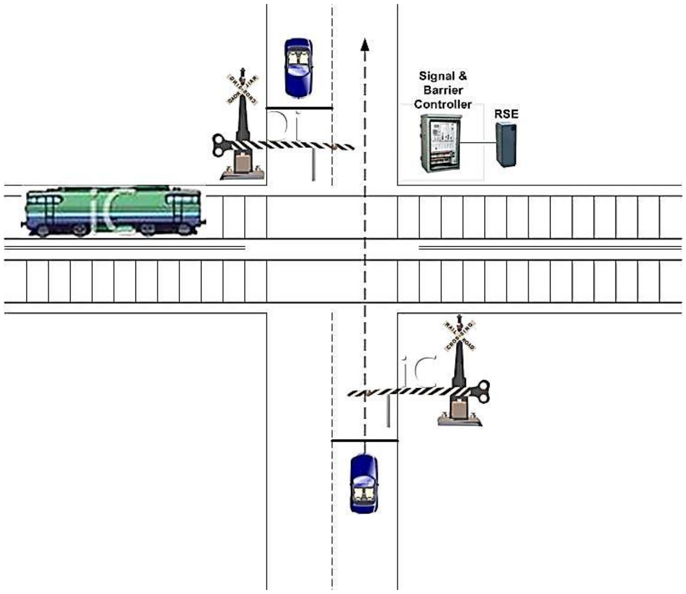
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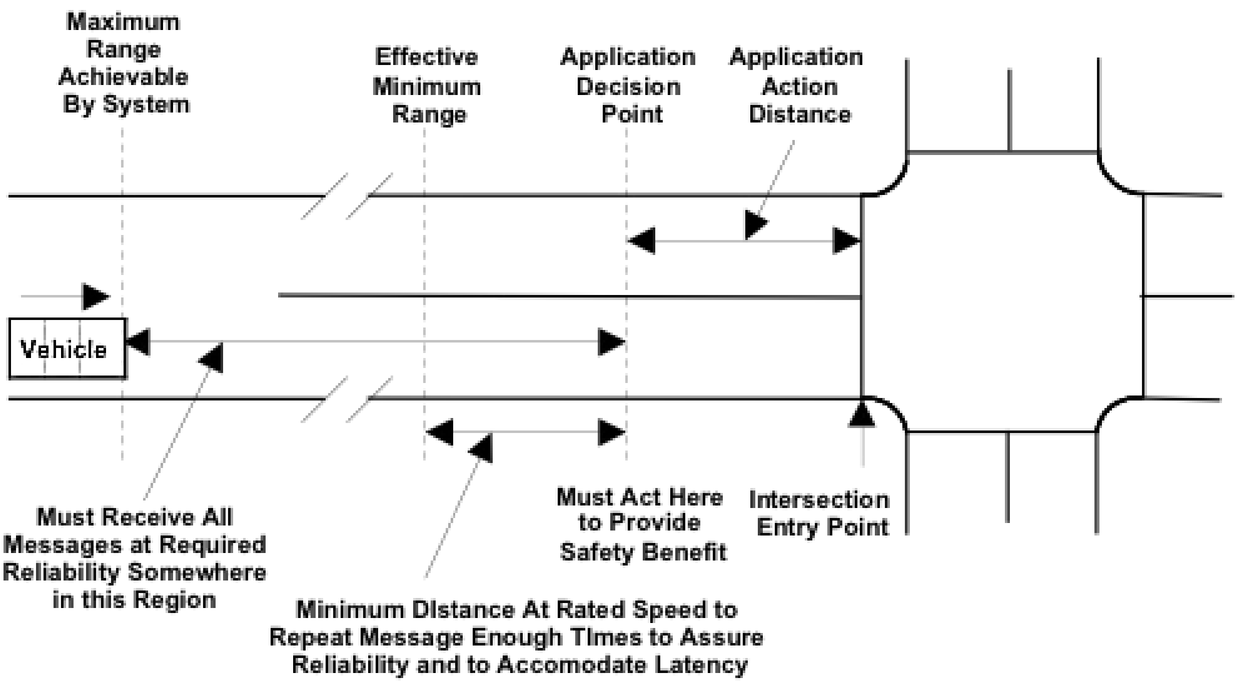
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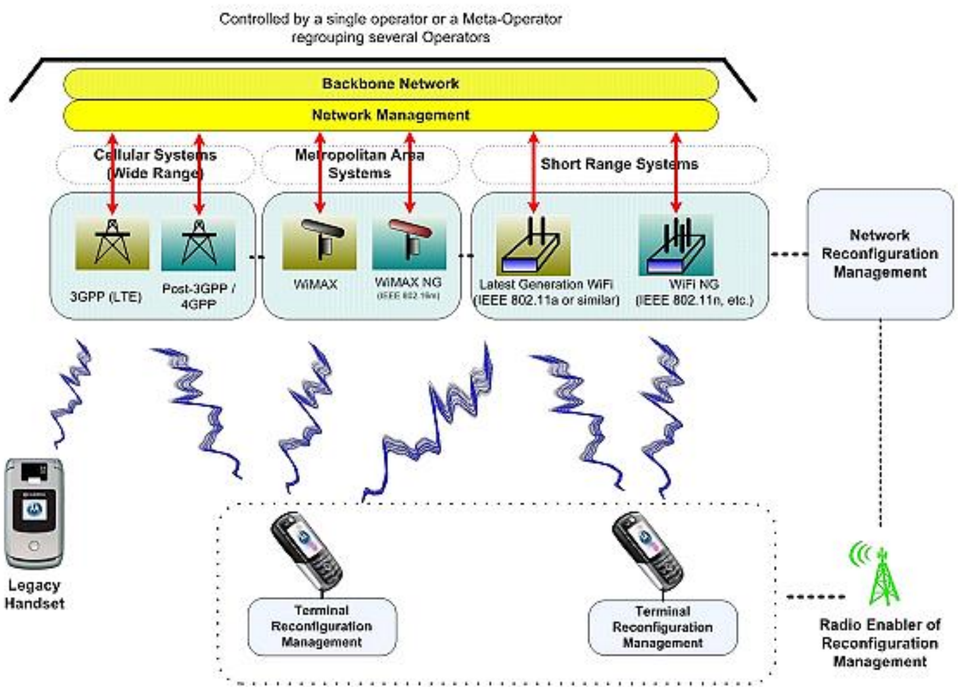
Minimum Distance At Rated Speed to Repeat Message Enough Times to Assure Reliability and to Accomodate Latency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Executive Summary

Communication Systems Analysis for SPaT Applications in Advanced ITS Systems Final Report

This report addresses communications to support safety applications specifically aimed at improving safety for mobile entities (vehicles, pedestrians, bicycles etc.) at signalized intersections. Collectively these applications are referred to as Signal Phase and Timing (SPaT) applications based on the (SPaT) messages used to convey the state of the signals at the intersection. SPaT applications support not only safety, but also support enhanced mobility and improved traffic flow (reduced congestion) caused by reduced incidents at intersections. Reduced congestion further has a positive impact on the environment by reducing fuel consumption.

The major components associated with SPaT applications are:

Roadside equipment (RSE) associated with the intersection, including: The traffic signal controller, traffic sensors, safety applications processor(s), communications equipment and GPS time reference equipment.

On-board Equipment (OBE) associated with mobile entities using the intersection, including: mobile communications transceivers, positioning sensors, time references, and applications processors. In some applications the OBE includes interfaces to other vehicle systems via a network interface (typically the Controller Area Network (CAN) bus).

The current signal phase and timing information is transmitted via the RSE communications devices from the traffic signal controller to OBE communications devices within communications range of the RSE. The SPaT message informs the applications that are addressed in this report.

This research project addresses:

Analyzing and defining applications requiring signal phase and timing (SPaT) information;

Defining and analyzing message content and flow associated with SPaT applications;

Defining the radio frequency (RF) environment, distances and roadway/intersection geometries in which the SPaT related communications between infrastructure and vehicles must reliably operate;

Developing communications related specifications to be matched with communications technology solutions;

Conducting a market scan of existing and emerging communications technologies, identifying candidates for meeting SPaT related communications requirements and documenting the results;

Correlating communications technology and associated, available products with requirements, identifying the best candidates for meeting requirements;

Analyzing maintenance and operations processes related to supporting the communications solutions and document findings;

Identifying any technical issues and providing recommendations relating to SPaT communications solutions.

The project consisted of five tasks:

1. Develop Project Work Plan;
2. Define Applications requiring SPaT messages and document in a Technical Memorandum (Ref: ARINC, "Task 2 Technical Memorandum; Applications Requiring SPaT Messages" [1]); Analyze Communications messages associated with applications and develop communications requirements, including radio frequency environment; (Ref: ARINC, Task 2 Report: "Interim Technical Report on SPaT Application, Characterization of the RF Environment and Communications Requirements [2]);
3. Conduct market scan of communications technology and associated products and specifications (Ref: ARINC, Task 3 Report: "Interim Technical Report Communications Technology Market Scan", [3]);

4. Analyze communications technology complying with SPaT communications requirements and identify operations and maintenance (O&M) considerations; (Ref: ARINC, "Technical Memorandum: Maintenance and Operations Considerations for Vehicle OBE and Infrastructure RSE Communications Equipment" [4];
5. Prepare Final Report on SPaT communications requirements, technology solutions, issues and recommendations.

This project used the IEEE Std. 802.11p Dedicated Short Range Communications (DSRC), IEEE Std. 1609 series, and SAE J2735 message standards as a baseline; however, requirements developed from the message content and flow analysis are generic and are compared with other candidate technology solutions. Issues found with current SAE J2735 messages are identified and discussed in the Task 2 report.

This project limited analysis to vehicle-to-infrastructure (V2I) communications and only considered vehicle-to-vehicle (V2V) communications as it may be part of SPaT message sequencing or impact reliable SPaT applications communications. The scope of this project precluded use of RF modeling which is recommended to fully characterize and understand the impact of the RF environment and improvements gained by use of advanced communications technology, especially as related to antenna design. Also precluded is consideration of technology and associated communications solutions that require a continuing fee for communications service.

Figure ES-1 illustrates the basic critical distances and times associated with SPaT related applications. The SPaT message representing the current signal phase and timing must be received by an approaching vehicle prior to it reaching the stopping sight distance (as defined in the American Association of State Highway and Transportation Officials (AASHTO) "Green Book- A Policy on Geometric Design of Highways and Streets, 6th Edition" [5]). This project considered both private, commercial fleet and jurisdictional fleet vehicles as illustrated in Figure ES-2. Also addressed in this project were signalized, at grade rail crossings as illustrated in Figure ES-3.

National ITS Architecture was used, including the Traffic Management Center (TMC) connection to intersection traffic controllers and related sensors via a communications network (referred to in this report as the ITS Communications Network), facilitating monitoring and management of traffic control devices to support traffic flow.

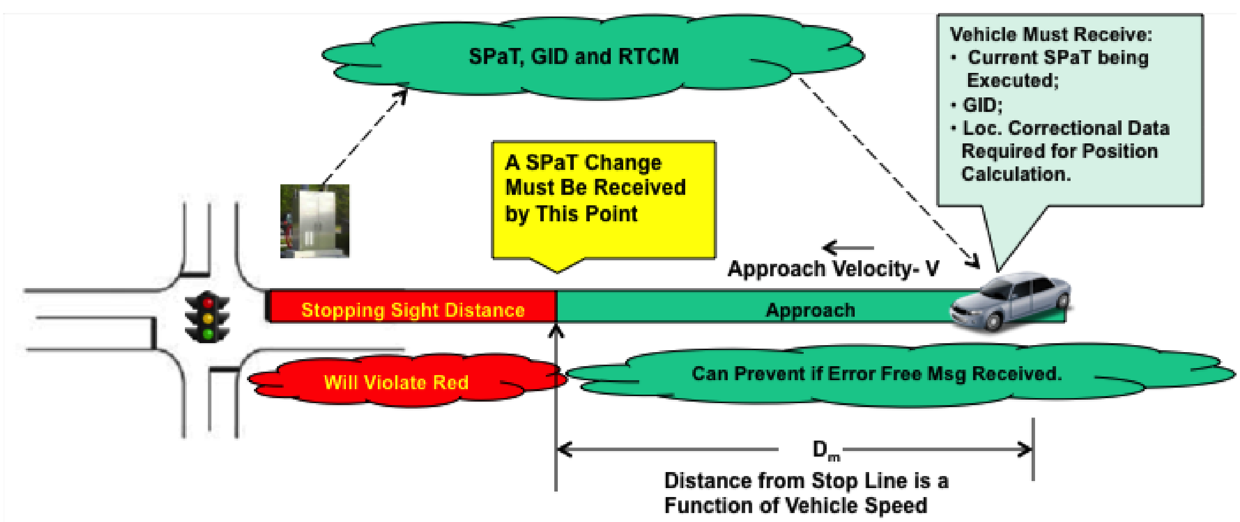


Figure ES-1. Basic Geometry and Timing Considerations Related to SPaT
Source: ARINC April 2012

In system diagrams the Traffic Management Center (TMC) is shown connected to intersection traffic controllers and related sensors via a communications network (referred to in this report as the ITS Communications Network), facilitating monitoring and management of traffic control devices to support traffic flow. The TMC and jurisdictional engineering play a major role in design of signalized intersections and associated modifications to the intersection. National ITS architecture identifies the regional Traveler Information Center (also called Information Service Provider) as having responsibility for distributing near real time safety information to travelers and vehicle navigation/route guidance systems. This project recommends additional analysis related to roles and responsibility for developing GIDs, responsively developing changes to GIDs necessitated by both permanent and temporary changes to the intersection, and providing management and quality oversight assuring that GIDs and other safety related data used by vehicles approaching an intersection are accurate and represents current configuration and conditions. For the purpose of this report, the traveler information center supported by the TMC is shown distributing digital information to vehicles via a mobile, wireless communications link as shown in Figure ES-4; further study and analysis may designate other information flow paths. This report addresses wireless communications options for distributing GIDs, which includes GID receipt via the communications network linking the RSE to the TMC, with the RSE communicating the GID to vehicles approaching the intersection.

A wireless, mobile communications link between the infrastructure and vehicle is needed to support SPaT communications requirements. Figure ES-1 illustrates the SPaT communications from the traffic controller via SPaT applications processor to roadside equipment (RSE) communications linking the infrastructure to vehicle onboard equipment (OBE). SPaT messages themselves are generally time critical, especially since the SPaT status may change from one transmission to the next (such as associated with traffic signal emergency preemption). However, some SPaT related communications is not time critical. For example, the geometric intersection description (GID) can be transmitted infrequently and may be carried via other communications links.

Figure ES-3 shows the intersection configuration to support a specialized version of SPaT application to support at grade rail crossings.

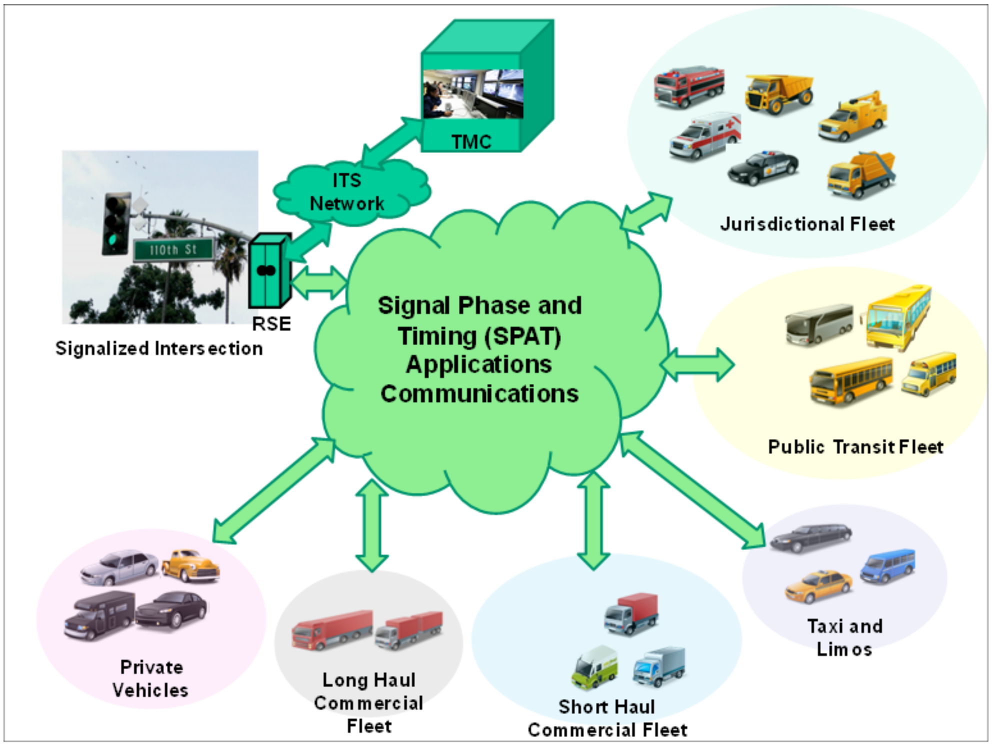


Figure ES-2. Communications Considerations Associated with SPaT Applications
Source: ARINC April 2012

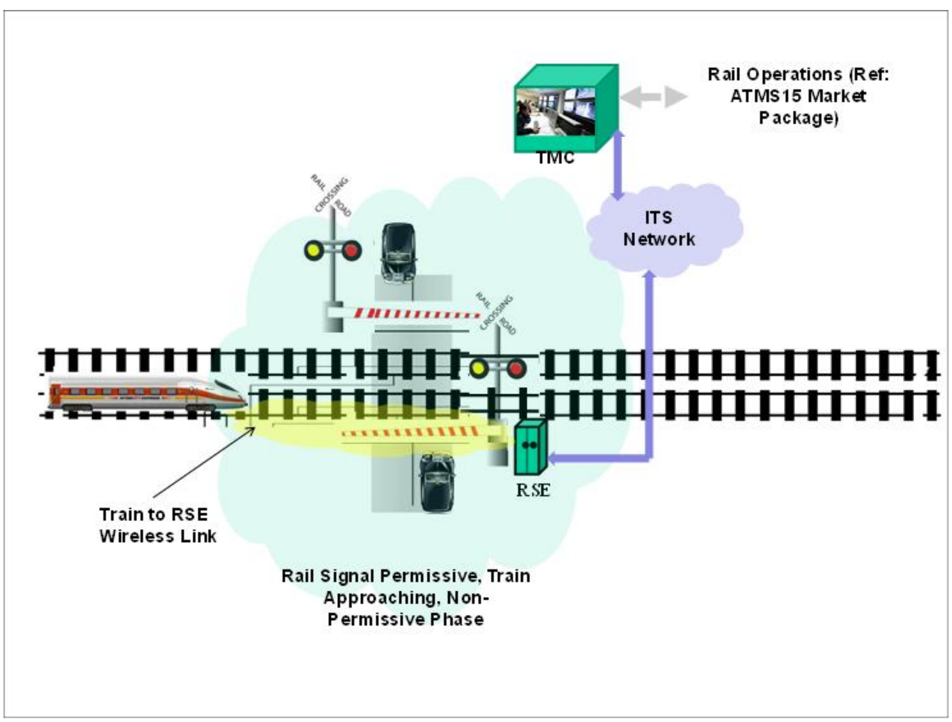


Figure ES-3. Communications Associated with a Signalized Rail Crossing
Source: ARINC April 2012

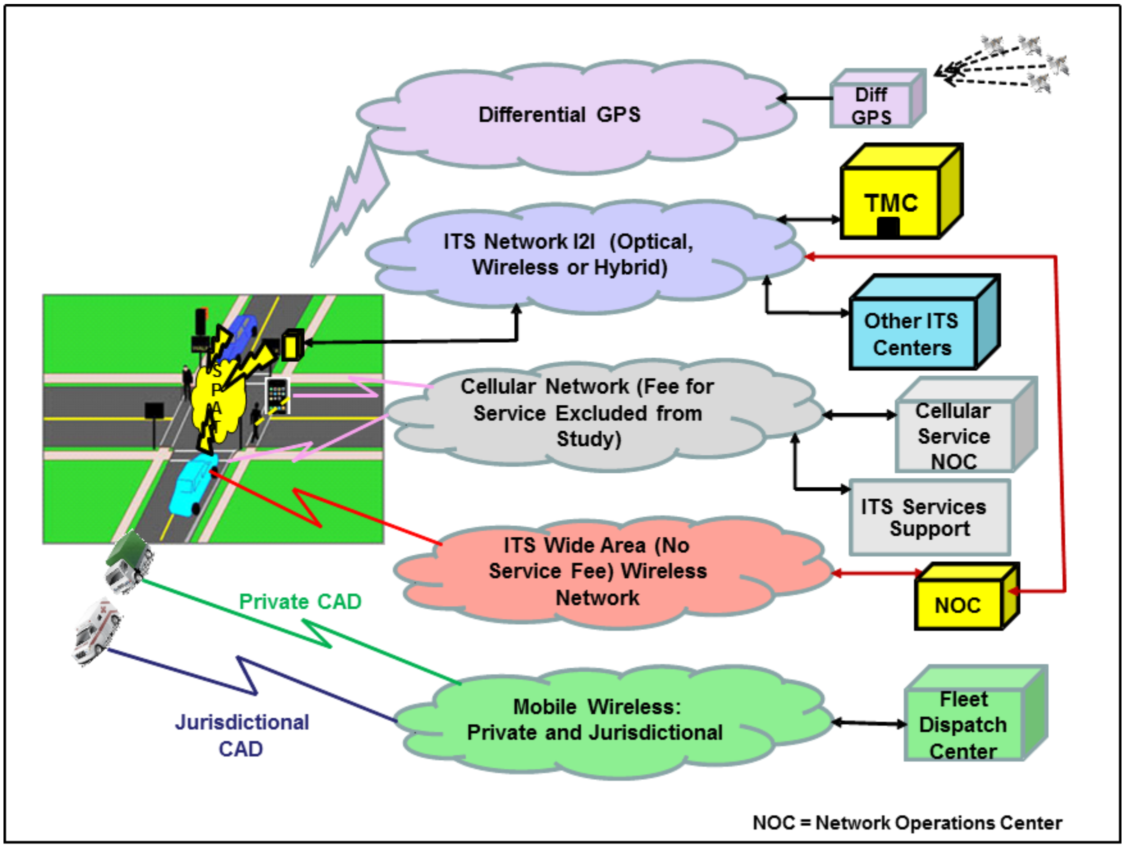


Figure ES-4. Communications Paths from Infrastructure to Vehicles
Source: ARINC April 2012

Referring to Figure ES-4, there are a number of alternate communications paths that could possibly be utilized to transmit GIDs and other non-time critical, safety support data from infrastructure to the vehicle. Considering "no fee for service" must be associated with a candidate communications technology solution, a jurisdictionally owned HD Radio (digital terrestrial radio) broadcast station is an option as is the long term evolution (LTE) cellular network infrastructure designated by FCC to be deployed to support emergency, interoperable communications using the 700 MHz emergency frequency band. Jurisdictions will have LTE infrastructure with bandwidth capable of being shared for safety information broadcast, although it is yet to be determined if this system has available bandwidth, or if those jurisdictions implementing it will allow it to be used for this purpose. Another possible link is from the ITS center responsible for GID and other safety related information distribution via the ITS network (as shown in National ITS Architecture), to fleet dispatching centers and which is then distributed to fleet vehicles via the associated computer aided dispatching (CAD) link. However, use of fleet CAD does not provide a universal solution for GID and other safety related data to be transmitted to vehicles and centralized quality oversight is lost. Furthermore, many of the CAD wireless communications links have narrow bandwidths and would require transition to broadband services such as planned for emergency vehicle fleets. Reliance on the CAD system reduces probability of safety data delivery due to additional communications systems added to the communications path to vehicles.

In Task 2 of this project, SPaT applications were defined and analyzed as related to communications requirements (Ref: "Communication Systems Analysis for SPaT Applications in Advanced ITS Vehicles - Task 2 Technical Memorandum [1] and Task 2 Report [2]). The following are the applications requiring SPaT messages that were analyzed in Task 2 and communications requirements addressed in this report:

Intersection Red Light Running (RLR);

Left Turn Assist (LTA);

Right Turn Assist (RTA);

Emergency Vehicle Preemption (PREEMPT);

Transit Signal Priority (TSP);

Freight Signal Priority (FSP);

Pedestrian Signal Assist System (PED-SIG); (Addressed as part of LTA and RTA);

Rail Crossing Red Light Violation (RCRLV).

Figure ES-5 presents a graphical overview the applications from which SPaT related communications were derived. Also in the Task 2 Report the detailed message analysis associated with each of these applications is presented. The resulting communications requirements for the SPaT applications are summarized in Table ES-1. (Note that the requirements represent the most stringent of all SPaT applications analyzed). SAE J2735 Standard was utilized as a baseline in analyzing message content and low requirements and any deficiencies noted in the Task 2 Report and in Appendix E.

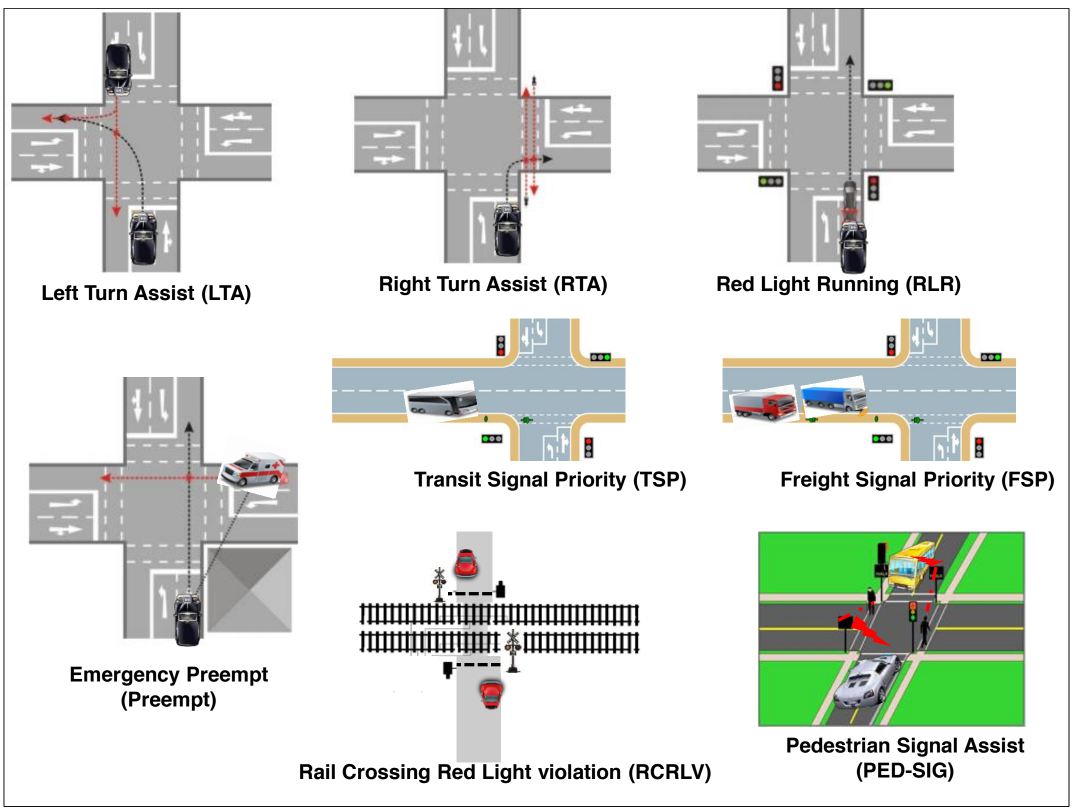


Figure ES-5 SPaT Related Application Diagrams
Source: ARINC April 2012

- Table ES-1. Summary of Key SPaT Applications Related Communications Requirements Source: ARINC April 2012

SPaT Applications Related Communications Requirement	Specification Requirement
Communications Range (High Probability of Message Receipt)	High End Range: 331 m (1087 ft.); High End Range is Based on Signal Preemption and Time to Clear the Intersection Based on Posted Speed and stopping sight distance at 0.2 G deceleration from 45 mph. Nominal Range: 176 m (579 ft.); Nominal Range is Based on Stopping Sight Distance at 0.3 G deceleration from 75 mph.
Maximum Bit Error Rate (BER) and Confidence Factor	10^{-4} Achieved by 4 message transmissions based on SIL = 1 (Message reliability = PER = 10^{-2})
Data Throughput, SPaT Messages	40 kbps Includes single intersection GID associated with the application. Does not include other message traffic in channel.
Background Data Load on DSRC (BSM/HIA Message) in which SPaT Messages Must Compete	4.77 mbps considering J2735 part 1; 29.44 mbps considering J2735 part 1 & 2; Based on 176 vehicles within communications range.
Data Rate Required for Geometric Intersection Descriptions Using Wide Area Broadcast	Function of Population and Number of Intersections: 200K population = 54 kbps; 500K population = 135 kbps; 1M population = 270 kbps.
Weather	Meet SPaT Communications Requirements in all Weather conditions (rain, sleet, snow and fog)
Radio Frequency Environment	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)
Size and Weight	Compatible with Small Car (Approx. Size 500 cu in/8195 cm^3; Approx. Wt. 2 lbs./0.91 kg)
Cost	Affordable to Purchaser of a Private Vehicle: Generally considered to be < $300

The basic concept of operations associated with this project is that as a mobile entity approaches an intersection, it enters the communication zone of the intersection RSE, and receives at regular intervals (every 100 msec) messages containing the current and future states of the traffic signal(s). With this information, the geometric intersection description, and its speed and position, an advanced ITS vehicle's OBE can make, with a fairly high degree of confidence, predictions of interference that the vehicle may encounter when entering the intersection, and recommend actions to safely avoid these interferences. Depending on the situation and vehicle type (e.g., emergency vehicle), the OBE may also request status of, or changes to the current signal phase and timing.

There are two basic communications architectures that can support the applications associated with SPaT (see Figure ES-6):

1. SPaT, GID for the Intersection, and differential GPS correction data is transmitted to the vehicle using the DSRC wireless link in the local vicinity of the intersection. This link must operate with background communications including Basic Safety Messages (BSM)/Here-I-Am (HIA) messages, and various other road safety related messages;

2. The time critical SPaT messages are transmitted to the vehicle via DSRC (competing with BSM/HIA background messages), and GIDs, DGPS correction messages are transmitted via a wide area coverage wireless link along with background roadway safety related messages.

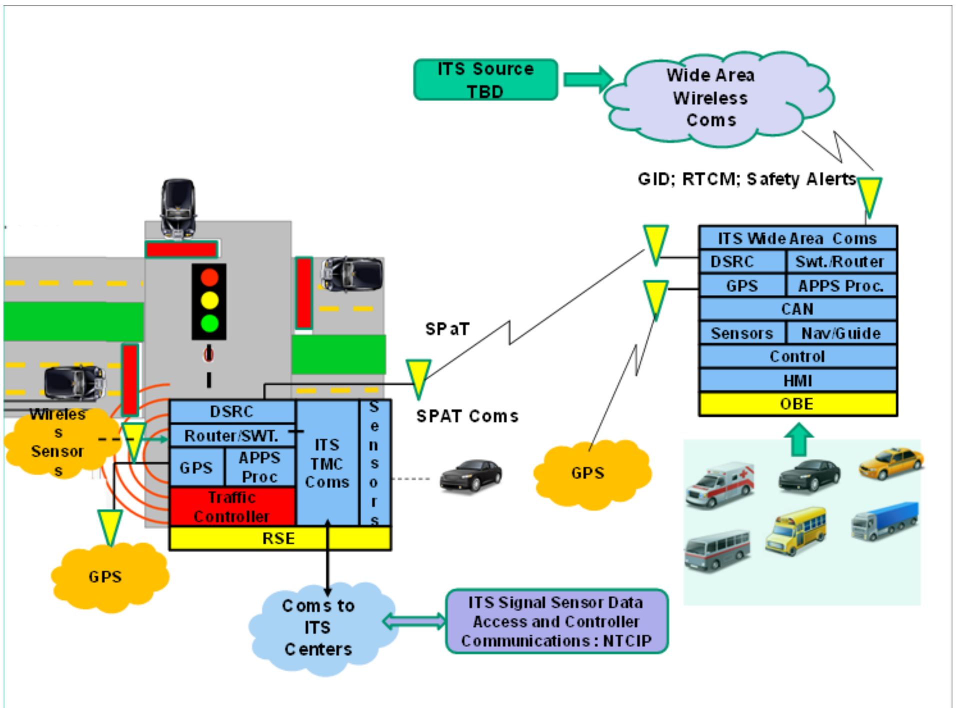


Figure ES-6. Communications Architecture Showing the DSRC Communications Link and Supplemented by a Less Time Critical, Broadcast Mobile Wireless Link
Source: ARINC April 2012

Communications technologies short listed in the Task 3 report are summarized in Table ES-2.

- Table ES-2. Shortlisted Communications Technology and Results of Analysis

Communications Technology Short Listed	Positive Features	Areas Requiring Further Consideration	Recommendations
DSRC (IEEE Std. 802.11p and IEEE Std. 1609 series)	Low latency; Low Cost in Production; Small Footprint	Multipath and Doppler; Adjacent Channel Interference; Reduced Packet Error Rate	Best Candidate For SPaT; Focus on improvements
HD Broadcast Digital Radio	Low Cost Infrastructure and Onboard Equipment; Scalable Coverage; Can support 300 kbps off load of DSRC	Requires FCC License	Formal Test Documenting Latency and mobility performance
LTE (Jurisdictional Configuration with Broadcast; 700 MHz); (Long Term Evolution) Standard)	Possible Shared Communications Resources with Emergency Management; Can Support Broadcast and GeoNet; Good data rate with MIMO	Coverage footprint versus data load and Latency (especially connect time and handoff).	Formal Test Documenting Latency; Footprint vs. Data Load; packet errors versus Doppler and Multipath
WiMAX (per IEEE 802.16)			No Advantage over LTE, which is designated by FCC for Jurisdictional Emergency Broadband communications
ATSC Digital TV Mobile/Handheld (ATSC M/H Standard)	Possible Data Rate Similar to DSRC	Area Coverage (90%/50% of Time); FCC License or lease BW from Broadcaster; Ability to Reliability Operate with High Mobility	Only Consider if HD Radio or LTE Not Prove Capable of Meeting Requirements
IEEE802.22	Cognitive Radio White Space Adaptation	Latency and Probabilistic communications not suitable for safety	No Further Test Recommended for Safety. Possible applicability of Service Communications

Source: ARINC April 2012

Technology identified as possibly improving DSRC performance is summarized in Table ES-3.

- Table ES-3. Technology Summary to Possibly Improve DSRC Performance
  Source: ARINC April 2012

Technology	Perceived Benefits	Recommendations
Multiple In/Multiple Out (antenna and transceiver design)	Reduction in bit errors; possible data throughput improvements	Conduct comparative test of MIMO, SISO, SIMO
Improved OBE Antenna Design and Placement	Reduced deformation of antenna patterns; improved coverage and reduced BER	Conduct Comparative Testing
SMART and Tailored RSE Antennas	Improved on-corridor coverage, reduction in multipath and improved BER	Conduct Comparative Testing at Intersection
Software Defined Radios	Easy to make changes as DSRC technology evolves	Some DSRC Manufacturers are using SDRs; Select DSRCs incorporating SDR technology
Message Repeat Timing	Reduced data load and improved probability of error free message delivery at ranges beyond 200m	Conduct Test

Figure ES-6 illustrates the radio frequency environment that may possibly be encountered by DSRCs. Currently jurisdictions deploy a variety of wireless sensors and sensors using wireless links to the intersection traffic controller cabinet. High power emitters that can saturate the RF front end of DSRCs as well as devices which have harmonics within the 5.85-5.92 GHz frequency band can negatively impact safety communications. Radio Frequency modeling of the intersection is recommended and several geometries are suggested in this report.

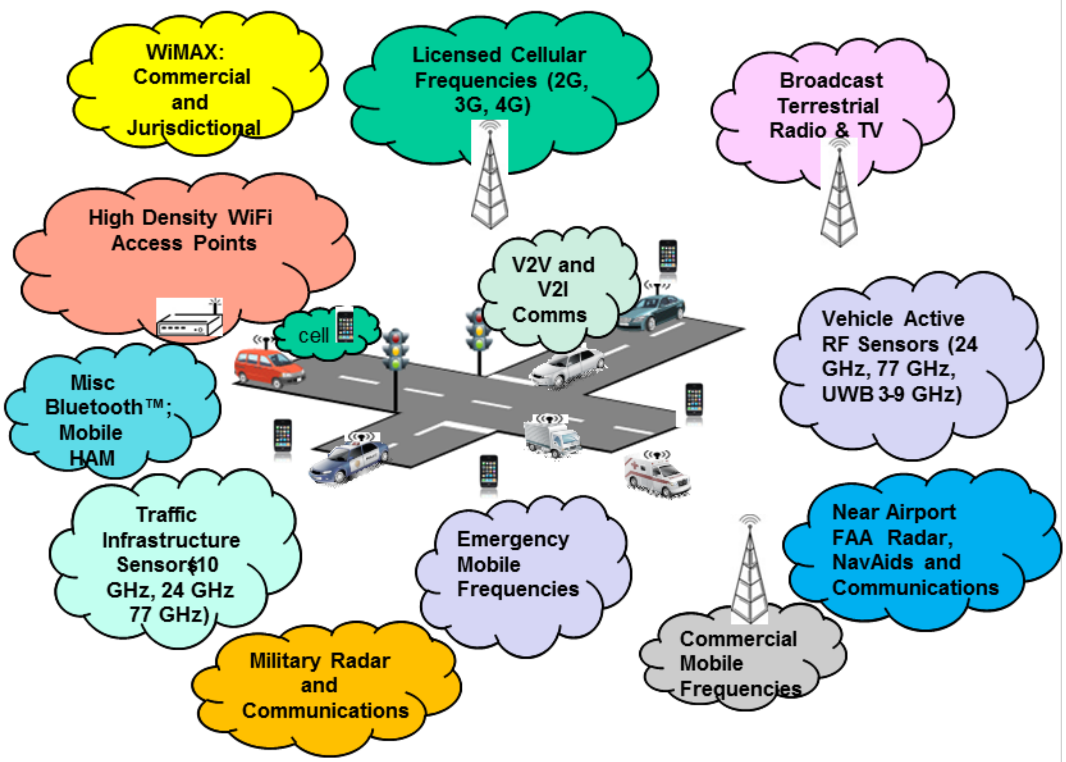


Figure ES-7. Radio Frequency Environment around a Signalized Intersection and Approach Corridors
Source: ARINC April 2012

Key project findings are described below.

DSRC Communications Technology*:*

SPaT applications alone (not considering Basic Service Messages) can be adequately met with DSRC with some improvements to the technology related to probability of error free packet delivery at ranges above 200 m (656 ft.);

Basic Service Messages will saturate the DSRC link as vehicles within communications range increases to approximately 150, considering SPaT broadcast and SAE J2735 part 1 Basic Service Message transmission. With SAE J2735 part 2 added to the communications load, the link exceeds design specifications;

Previous test indicates a possible negative impact on error free packet delivery probability caused by multipath and Doppler; Additional test and analysis is recommended;

Study indicates that DSRC performance could possibly be enhanced by improvements in message timing (Different from that defined by SAE J2735);

Even though DSRC is designed with selectable data rates/modulations to accommodate interference negatively impacting signal to noise, there is no adaptive communications related to broadcast. Thus a reasonably reliable data rate must be manually selected and this is typically 3, 4.5 or 6 mbps with 4.5 mbps being prevalent in many of the field tests. For normal SPaT related applications, 27 mbps is not usable due to its high bit error rate;

Field Test of DSRC clearly shows multipath issues in an urban tunnel, even though spreading loss of 1.6 μsec is accommodated. Test also show nulling effect of multipath (where multipath signal is 180 degrees out of phase and results in signal cancellation) at similar ranges from test to test. More studies are recommended related to antenna design (patterns, angular mounting on different vehicles, Fresnel Zone as related to RSE antenna height, etc.) to better understand possible improvements. A more detailed analysis of multi-input multi-output (MIMO) antenna technology and space diversity improvements on DSRC performance should be considered;

Field Test of the DSRC indicates interference issues when vehicles are close to each other and using adjacent channels simultaneously. With a channel switching scheme as originally laid out in the DSRC standards, this simultaneous operation did not occur. However, recent initiatives to move to a non-switched scheme (for capacity reasons), means that adjacent channels will be being used simultaneously, and this will result in interference. It is recommended to examine policies related to the use of specific channels for specific applications, and to possibly prohibit some uses of channels 174, 176 and 180, and 182 in certain areas;

Additional analysis is recommended related to radio frequency interference, including modeling the RF environment. Analysis should include high power mobile transmitters, close to a vehicle (or RSE) with RF power level bypassing the RF front end of the DSRC. Mobile dispatching radios and mobile armature (HAM) radios, military convoys with mobile military radios, roadside TV News Vans, etc. should be considered as possible sources of high level RF energy;

There is a need for defining the effective antenna pattern (horizontal and vertical coverage) that must be met for vehicles, which means that designers must consider impact of vehicle ground plane and roof angles on resulting antenna patterns;

DSRC devices are not generally qualified to NEMA TS-2 environmental specifications for roadside equipment and SAE environmental requirements for vehicle onboard equipment.

Other Communications Technology:

- There is an advantage to utilizing an overlay, wide area broadcast wireless link to augment DSRC communications. The reasons are:
  - Simpler distribution for less time critical messages;
  - Offloads the DSRC wireless link which becomes saturated as additional vehicles enter communications range of an RSE;
- HD Digital Radio can support broadcast transmission of information from infrastructure to vehicle including GIDs, DGPS Augmentation and background roadway safety and weather messages. It is not clear if these systems exhibit low enough latency to support transmission of SPaT messages.
- HD Radios are relatively inexpensive and coverage area can be tailored to the required number of intersections supported; jurisdictions also have experience with deploying broadcast radio communications in the form of highway advisory radio;
- There is no clear advantage of WiMAX over LTE to be used as a broadcast communications link from infrastructure to vehicle. Since FCC designated LTE to be the interoperable, mobile emergency communications technology to be used by jurisdictions, 700 MHz, LTE equipment is in deployment by jurisdictions and has the capability to support safety broadcast and emergency communications. Further analysis of a combination jurisdictional Safety/Emergency communications network is recommended;
- ATSC M/H can support SPaT related, supplemental broadcast requirements. However, it is doubtful if a public/private partnership can be developed with a television service provider, due to the limited bandwidth available to support mobile TV service. Also, current requirement for mobile TV coverage is 50% within the minimum usable signal level contour with 50% probability (90% coverage with 90% confidence is used by other countries) which would not meet SPaT supplemental broadcast confidence level needs).

Functional Safety:

There is a need to formally establish the automotive safety integrity level (ASIL) as defined in IOS 26262, and its relationship to safety of life related messages defined in SAE J2735 as a basis for developing required bit error rate, requirements and requirements for reliability and availability of the associated subsystems. This is needed as a basis for establishing design specifications as well as providing a prudent, *legal* basis for the design.

SAE J2735 Messages:

- Some deficiencies were found in the SAE J2735 message set as related to SPaT application messages that were analyzed in Task 2. Improvements as related to accommodating dynamic changes are recommended. The trend in signal timing is for traffic responsive and adaptive signal control;
- High confidence level in the error free delivery of SPaT related messages at distances required by the specific application based on required safety actions and vehicle speed require multiple broadcasts of messages. While the 10 Hz messages are adequate, the broadcast frequency of some of the 1 Hz messages should be reconsidered based on contribution to probability of error free message delivery;
- Geometric Intersection Description (GID) messages (also called MAP messages, require additional analysis as related to data content, ability to accommodate temporary changes to the intersection, and phase relationships for cross-track clearance and driver warning before barrier closure. There is also evidence that the size of the GID message as defined in SAE J2735 is much larger than needed. The CICAS project sponsored by NHTSA developed a substantially smaller GID message format that should be considered as a replacement.

Operation and Maintenance*:*

- Additional study is recommended related to the roles and responsibilities for generating, configuration management, providing quality oversight and responsive distribution of GIDs; GIDs must be available to vehicle OBEs when the configuration change becomes effective;
- With OBEs taking action based on safety related information received from the infrastructure, there is a clear need for improved geo-location and time frame accuracy of the broadcast safety data and any changes to messages. It is further important that all forms of safety message distribution be consistent (dynamic message signs, highway advisory radio, and digital broadcast to advance ITS vehicles). Additional study is recommended related to roles and responsibilities related to generation, quality oversight, and distribution responsibility of road network related safety messages;
- Configuration management and interoperability per active standards is a concern for SPaT related OBE communications sold by third parties to the aftermarket and serviced and maintained by private vehicle service centers not related to car dealerships;
- Some application approaches (specifically versions of LTA and RTA) assume that the presence of other vehicles will be communicated by BSM/HIA messages. If these systems are not operational, either because the vehicle is not equipped, or because the vehicle system is inoperative, the applications will fail. If these systems are to be relied upon, some form of certification and testing processes will need to be put in place.

Communications Architecture:

This report considers a complimentary wide area broadcast link operating with DSRC as shown in Figure ES-7 as the best architecture, based on current technical status of the DSRC technology. Application communications that can withstand 5 or more seconds of latency are candidates for the wide area broadcast wireless link from infrastructure to vehicle. All time critical safety related data communications between the infrastructure and the vehicle should be implemented on the DSRC link. DSRC should support applications requiring latencies of 100 msec to less than 5 seconds from the generation of the safety related event as identified by the associated applications processor of the RSE (and/or OBE).

Summary

This report includes a summary of the communications requirements development, analysis of shortlisted communications technology and recommendations for formal testing of identified technology candidates. The appendix includes the operations and maintenance considerations related to deploying SPaT-related communications technology for vehicles and infrastructure.

cture to vehicle

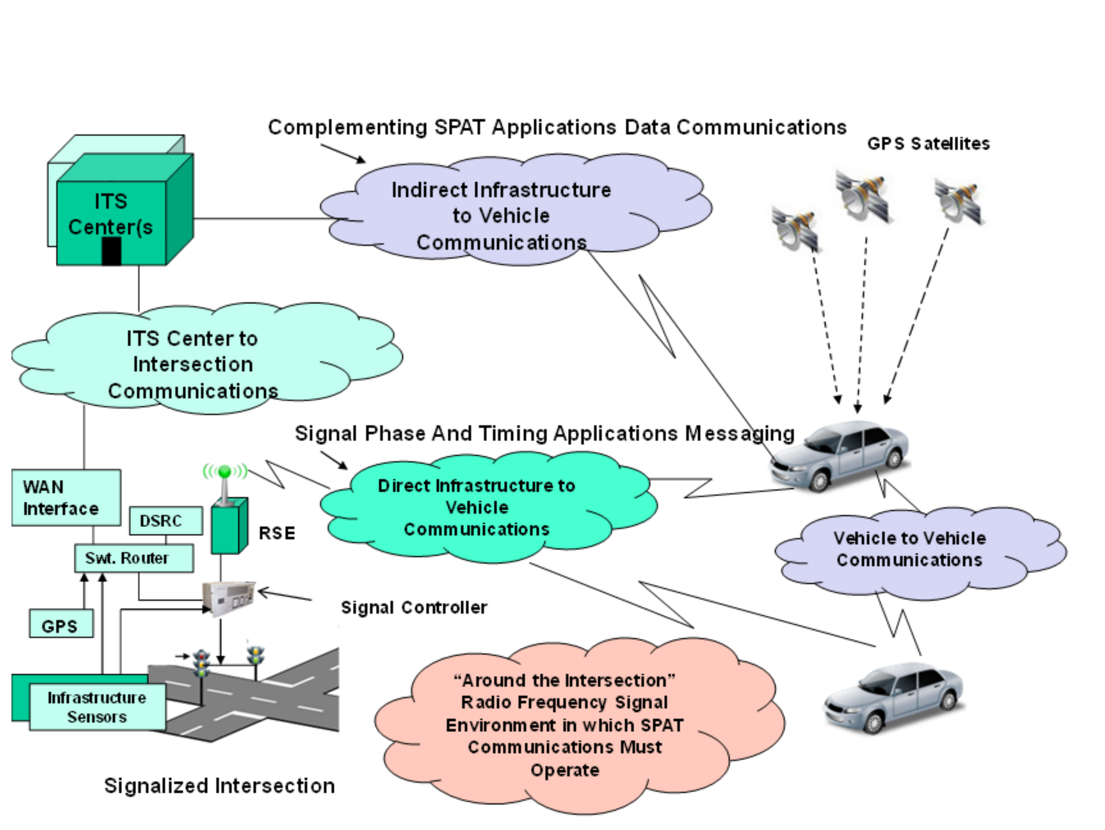


Figure ES-8. Recommended Communications Architecture
Source: ARINC April 2012

Chapter 1 - Introduction

1.1 Project Overview

This Technical Report is submitted in compliance with Task 4 and 5 requirements of the *Communications Systems Analysis for SPaT Applications in Advanced ITS Vehicles* Project. The project includes 5 tasks:

Task 1 is the development of the project plan and project kick-off meeting.

Task 2 focuses on defining high stakeholder interest applications requiring signal phase and timing (SPaT) messages to execute the applications, analysis of message content and flow associated with each application and development of communications requirements for the applications independent of a specific communications technology. SPaT related messaging requirements were then translated to communications related specifications required to meet the needs of the associated application, such as data rates, latency, tolerable bit error rates, communications range, etc. Part of the Task 2 analysis also identified the radio frequency (RF) environment at and around a signalized intersection in which SPaT related communications devices must reliably operate. Any communications technology supporting SPaT applications, including those in vehicles and those associated with infrastructure must be capable of operating in this RF environment and meeting communications requirements of SPaT applications. Task 2 also addresses intersection geometry and configurations as related to intelligent transportation systems (ITS) sensors and associated communications equipment. The intersection configurations are candidates for future modeling of potential radio frequency interference (RFI) between wireless communications devices.

Task 3 of this project focused on conducting a market scan of communications technology and screening the technology, identifying which is most appropriate to consider for the implementation of SPaT related communications requirements developed under Task 2. Task 3 also identified communications technology that is emerging through research and development (R&D), that seemingly has potential to improve SPaT related communications, but is not available in production product form.

Task 4 includes a more detailed analysis of communications technology identified in the Task 3 report, and analyzing its capability to meet communications requirements as defined in the Task 2 report. Task 4 further addresses operations and maintenance considerations of communications technology identified by this study to be the most appropriate for deployment supporting SPaT related applications. Gaps in technology solutions and improvement needs are part of the Task 4 analysis.

This report summarizes findings of the Task 2 and 3 report, and documents the results of the Task 4 analysis; it represents the final project report with findings and recommendations. The overall scope of the project can be summarized as:

- Identify applications requiring signal phase and timing (SPaT) messages generated by advanced ITS traffic controllers and associated roadside equipment (RSE) at signalized intersections and at-grade rail crossings needed to support Advanced ITS Vehicle safety and mobility;
- Develop message flows, geometry (relative distances) and timing associated with SPaT applications to determine the required message content, communications range and reliability, and timing constraints for each identified application;
- Examine existing published documentation and standards for messages related to the each application, compare required message content to existing definitions of messages and identify differences;

- Determine approximate size of transmitted messages and required frequency of transmission to determine data rate and channel bandwidth requirements;
- Identify communication system requirements for each identified application, such as:
    - Latency and response times;
    - Minimum message repetition rates;
    - Operating range;
    - Data rate;
    - Link reliability;
    - Impact on safety with message communication failure;
    - Quality of service, etc.
- Identify the communications requirements as time critical, safety critical or both;
    - SPaT messaging identified in this project is both safety critical and time critical;
- Characterize the radio frequency environment at three example signalized intersections;
    - Include multiple RSEs serving the same intersection with overlapping and non-overlapping coverage with at least one of the DSRC Road Side Equipment (RSE) providing safety critical data (others may provide non-safety data);
    - Include the impact of multiple vehicles in a realistic congested traffic density emitting basic safety messages as part of the RF interference environment;
    - Address both same-protocol interferers (e.g., competing DSRC users) and different-protocol emitters (e.g., adjacent band interferers) in the analysis;
- Perform a scan of available communication systems technology and associated products and:
    - Classify by major characteristics;
    - Recommend systems for further study providing rationale;
- Analyze characteristics of candidate communication systems for:
    - Coverage areas in which the systems can be used;
    - Performance characteristics and latency;
    - Protection from interference and multipath;
    - Inherent weaknesses or challenges;
    - Maturity of the system (i.e., how long has it been available and how widely is it used);
    - Costs and supportability;
    - Compliance with communications requirements associated with applications requiring SPaT messages;
- Provide a Final Report documenting findings and recommendations.

The USDOT initiative, referred to in this report as *Advanced ITS Vehicle*, provides improvements in road safety and mobility, and provides positive contributions to the environment by reducing pollution caused by congestion and inefficient operations of vehicles.

The *Advanced ITS Vehicle* combines advanced wireless communications; on-board computer processing; advanced vehicle-sensors (both relative and absolute position); advanced human-machine interface (HMI); information exchange with smart infrastructure and other advanced ITS vehicles to provide the capability to automatically identify threats and hazards on the roadway, communicate this information over wireless networks to give drivers alerts and warnings, and to activate automatic vehicle control functions designed to avoid a collision.

Intelligent intersections use wireless communications to convey information about the current and future state of the intersection to Advanced ITS Vehicles operating in the vicinity of the intersection. By combining signal phase and timing (SPaT) information with the locations and velocity vectors of vehicles and pedestrians in a common time base, the ITS vehicle can determine if a hazard exists, and can either warn the driver or take some other action.

The *Advanced ITS Vehicle* combined with *intersection safety systems* supports reduction of accidents at intersections, and also supports reducing delays for emergency and public transportation vehicles through signal preemption (*Preempt)* and transit signal priority (*TSP*); it also supports minimizing delays of commercial vehicles near major intermodal transportation ports through *freight signal priority* (FPS). Furthermore, *Advanced ITS Vehicles* combined with *intelligent intersections* facilitate the maintenance of platoon flow on signalized corridors, meeting traffic progression objectives established for the corridor, thus improving mobility.

Under Task 2.1 of this study, ARINC provided a technical memorandum to USDOT that included the list of applications requiring SPaT messages that are to be addressed. The recommended list of SPaT related applications was based on interviews with stakeholders. The following summarizes the applications (see section 2.1 of this report for more details) identified to be of high interest and importance. These applications are also documented in the Task 2 Report:

- Intersection Red Light Running (RLR);
- Left Turn Assist (LTA);
- Right Turn Assist (RTA);
- Emergency Vehicle Preemption (PREEMPT);
- Transit Signal Priority (TSP);
- Freight Signal Priority (FSP);
- Rail Crossing Red Light Violation (RCRLV).

Pedestrian Signal Assist System (PED-SIG) is only addressed from the vehicle perspective and included in the LTA and RTA message analysis. There is no communications standard for infrastructure to mobile pedestrian device, except for LED message signs at cross walks, currently controlled by the PED function of intersection traffic controllers. There are sensors deployed in some jurisdictional traffic signal systems to detect presence of pedestrians in cross walks and even to track their progress across the intersection. With such pedestrian detection sensors, RSEs are capable of warning vehicles of pedestrian presence in cross walks. The current description of PED-SIG also assumes the use of a cellular phone, which implies a user fee for service, and this project does not address communications solutions requiring a continuing fee for service.

Signalized intersections and signalized at-grade rail crossings are both applicable to this study since these are the two configurations that can be supported by sending SPaT or “SPaT-Like” (rail signalization) messages. Intersections and rail crossings are assumed to have the capability to generate GPS time referenced SPaT messages in accordance with SAE J2735 or as defined in the analysis of the application and message flow as documented in the Task 2 report. The Task 2 report also contains the detailed analysis identifying requirements specified for the related SPaT applications. In addition, it is assumed that the RSE at a signalized intersection will include sensors capable of providing any additional and timely information required by the application, for example, detection of speed and distance for vehicles approaching the intersection, pedestrians in cross walks and bicycles in bicycle crossings.

Figure 1.1-1 illustrates applications at a signalized intersection using SPaT, together with some of the RF emitters typically present. Applications including RLR, LTA, RTA, Preempt, TSP and FSD apply to signalized intersections of different configurations (Ref: “Manual on Uniform Traffic Control Devices/2009” [6; “Signalized Intersection Information Guide”, FHWA-HRT-04-091 [7]; and “Traffic Control Systems Handbook”, FHWA-HOP-060006 [8]). Figure 1.1-1 illustrates a communications link from the traffic management center (TMC) to the signalized intersection in compliance with National ITS Architecture; it also illustrates a communications path from the information service provider (identified as a traveler information center) to vehicles, which also follows the National ITS Architecture.

A critical element required by the Advanced ITS Vehicle is a digital map of the intersection, known as a geometric intersection description (or GID). The GID includes the physical geometry of the various lanes and allows the Advanced ITS Vehicle to relate the information in the SPaT message to the real world and to its own dynamic situation. While the GID is critically important to these applications, there is little definition of how it is created, to what quality assurance standards and by whom. Additional analysis is recommended to define roles and responsibilities, including configuration management and quality oversight for the GID.

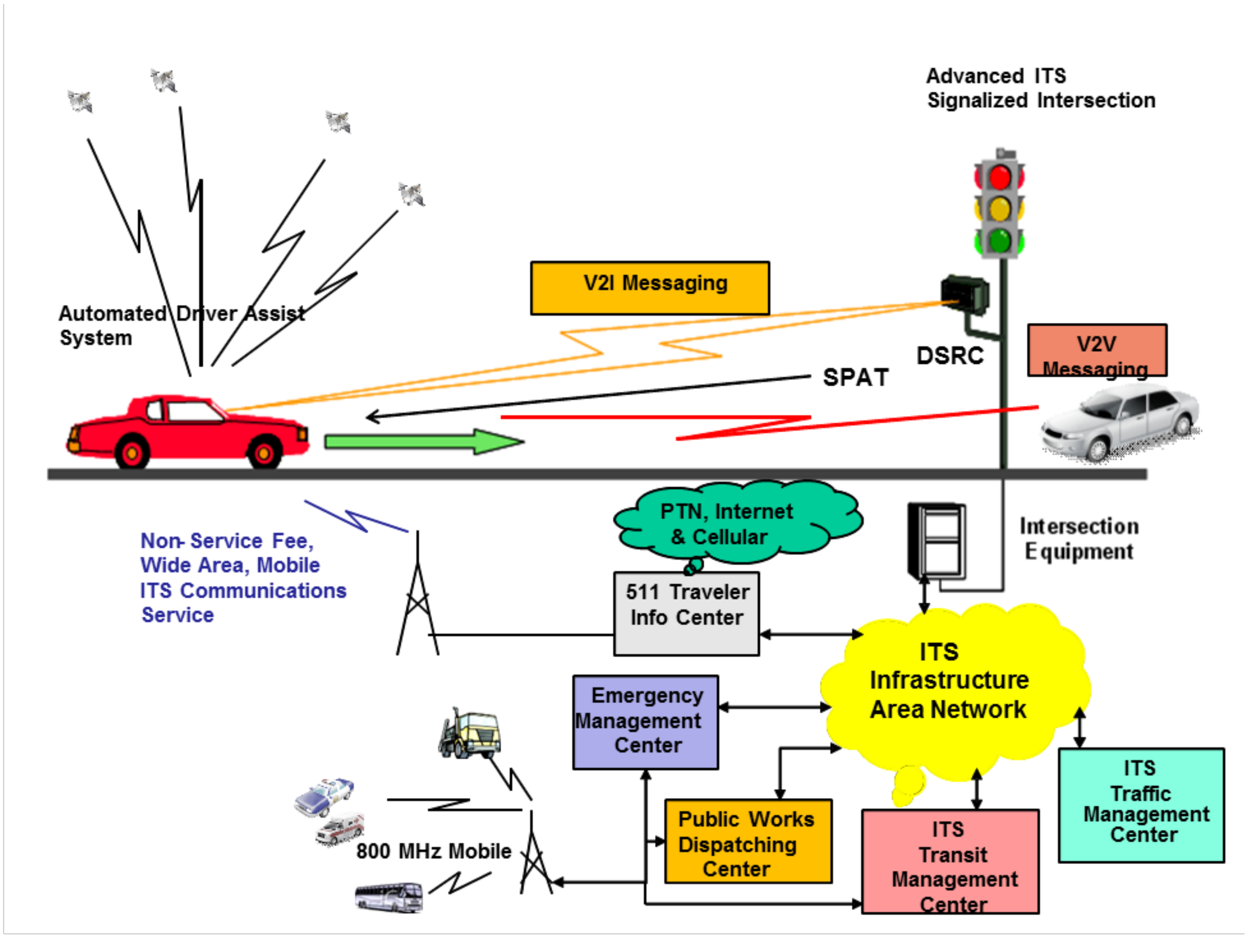


Figure 1.1-1. Typical Intelligent Intersection
Source: ARINC April 2012

Figure 1.1-2 shows examples of signalized intersections.

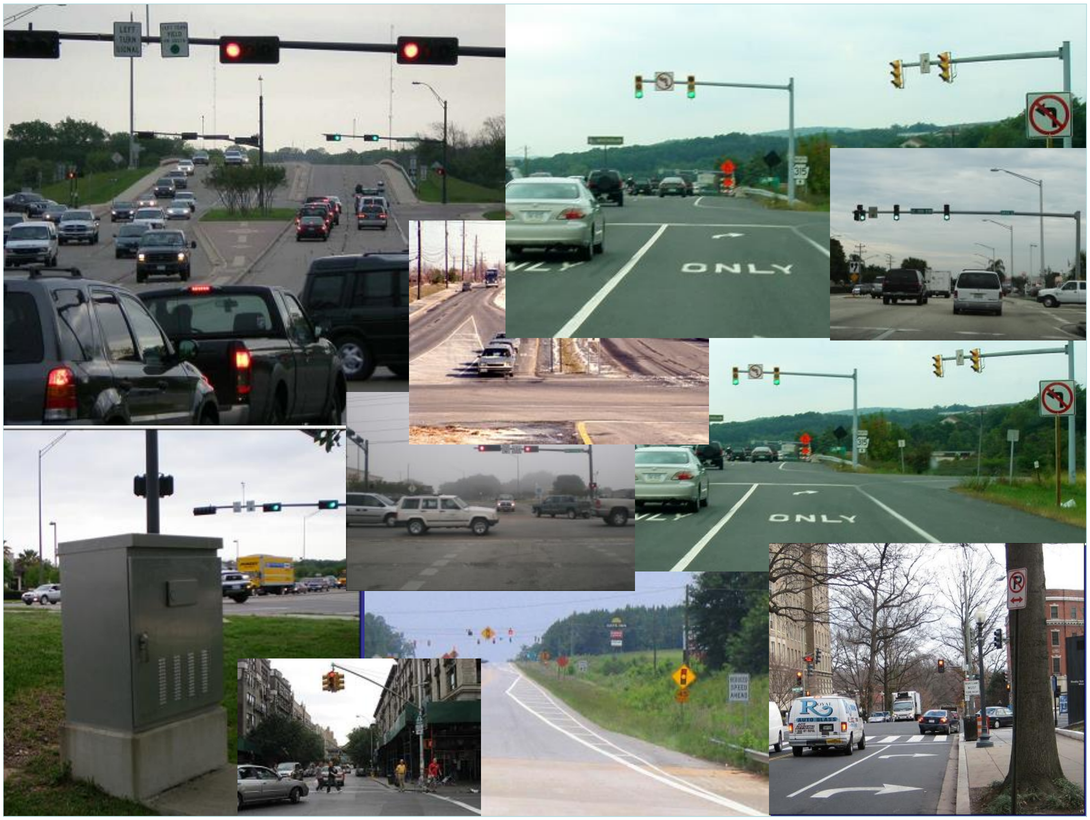


Figure 1.1-2. Examples of Signalized Intersections

(Ref: USDOT FHWA, "Signalized Intersection Information Guide", FHWA-HRT-04-091. [7] and USDOT FHWA, "Traffic Control Systems Handbook", FHWA-HOP-060006. [8])

At grade rail crossings represent a slightly different type of intersection. The Rail Crossing Red Light Violation (RCRLV) application is associated with at grade rail crossings (see *Railroad-Highway Grade Crossing Handbook*, FHWA-SA-07-010[9] and USDOT-FHWA *Guidance on Traffic Control Devices at Highway-Rail Grade Crossings*[10]). Figure 1.1-3 illustrates the communications associated with at-grade, signalized rail crossings and Figure 1.1-4 presents examples of typical rail crossings. The RCRLV application is similar to the RLR application associated with signalized intersections. In this application the vehicle is alerted that a train is approaching and the rail crossing is being closed. RSE activates the flashing red lights and the barrier is lowered. The driver is warned if the vehicle is not decelerating sufficiently to stop prior to the barrier limit line; the application can also warn that a collision will occur if the vehicle proceeds through a barrier-less rail crossing with flashing red lights. Train presence sensors detect the train as it approaches the intersection. This activates the signal and barrier control, and also activates the transmission of the RCRLV message. After the train clears the intersection, train presence sensors detect clearance and cause the rail-crossing controller to raise the barrier, deactivate the red flashing lights, and terminate transmission of the RCRLV message.

Advanced Train Control System (ATCS) and at-grade crossing concepts include the train communicating with the RSE (position, GPS referenced time, velocity and direction of travel) as it approaches the intersection using its 220 MHz digital mobile communications link. This can provide the RSE with the ability to determine the red phase start time with greater accuracy. In addition, rail-crossing sensors may be used to detect a stalled vehicle (and/or obstruction such as freight fallen from a truck) in the intersection and communicate the intersection safety issue to the train via the 220 MHz communications link to avoid a rail crossing incident. This same information can be communicated to the TMC and relayed to the ATCS (as shown in National ITS Architecture). In this case, the rail crossing RSE would message approaching vehicles of the stalled vehicle and/or obstruction at the rail crossing.

Note that this project does not address the detailed messaging via a wireless link from train to RSE and vice versa but recommends such a link. Both the Positive Train Control System 220 MHz wireless link, and a DSRC communications capability on the train are candidate solutions.

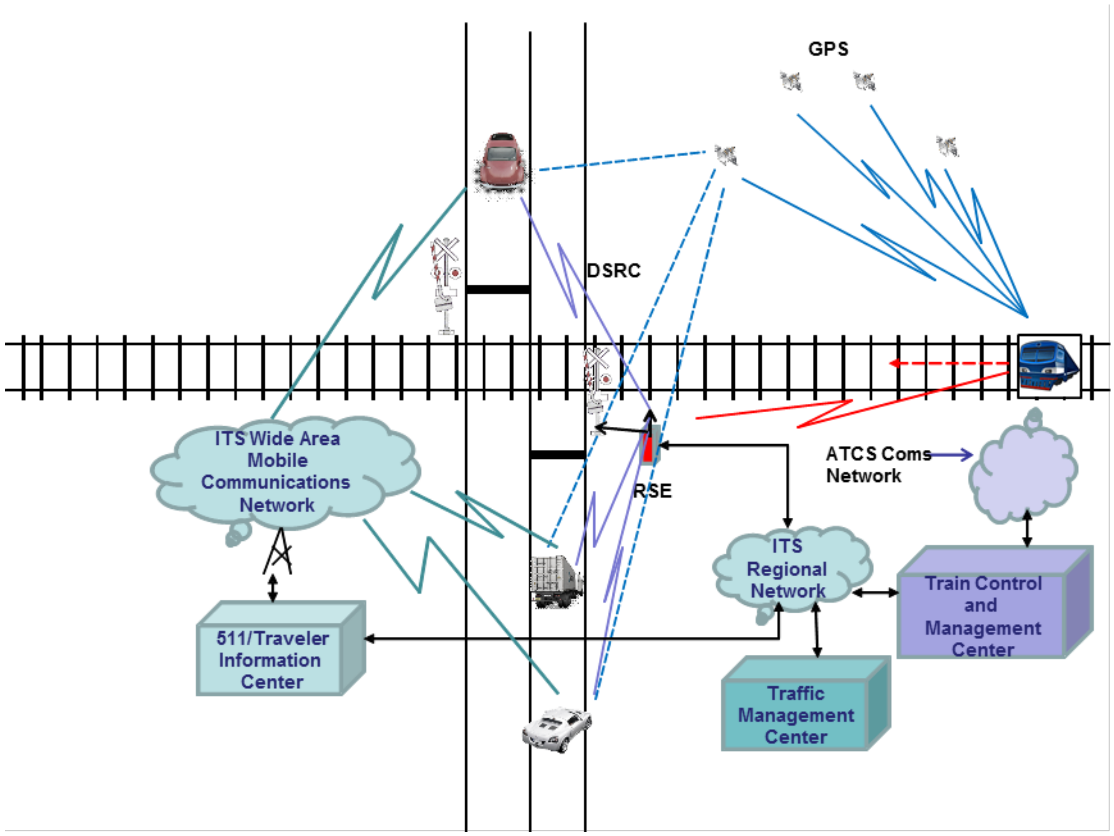


Figure 1.1-3. Illustration of Communications Related to At-grade Rail Crossing Safety Application
Source: ARINC April 2012

Figure 1.1-4. Examples of At-Grade Rail Crossings

(Ref: USDOT Document; "Secretary's Action Plan for Highway-Rail Crossing Safety and Trespass Prevention" [11])

The applications developed in Task 2 came from sources such as ITS National Architecture, Advanced ITS Vehicle Dynamic Mobility, the VSCA work on CICAS-V and CICAS-SLTA, and from the study of applications requiring vehicle position (USDOT DTFH61-10-D-00015 TOPR1). USDOT project DTFH61-10-D-00015 included discussions and inputs from stakeholders as related to signalized intersections and at-grade rail crossings. The Advanced ITS Vehicle Dynamic Mobility Workshop conducted in November, 2010 included stakeholder inputs, evaluations and prioritization of many advanced ITS applications supporting safety, mobility, and the environment. Each of the applications listed above were analyzed in detail, and the results were presented in the Task 2 report. During Task 3, communications equipment manufacturers were contacted to obtain product information and test data for various communications technologies. Research reports on advanced technology were reviewed, and DARPA developments related to communications technology were scanned. Of high importance were ITS related V2I and V2V communications tests conducted in the USA, Europe, and Asia. High-level criteria were used to develop a "shortlist" of the communications technologies scanned. These criteria are listed in Table 1.1-1 below.

Table 1.1-1. Communications Technology Shortlist Criteria
Source: ARINC April 2012

Shortlist Criterion
Is the technology available for use without an ongoing service fee?
Can the technology be packaged for installation and operations in vehicles?
Are required antennas supporting the communications technology compatible with private, compact vehicle applications or does the operating wave length support development of a suitable antenna for mobile use?
Can the communications technology support user mobility at velocities required by ITS? If No the technology is not shortlisted;
Is the technology described in open standards, and is it available from multiple sources?
Is the technology available for test/use in a field test environment? (If No, and the technology has promise, it is short listed for additional analysis with a potential recommendation to follow progress.)
Is spectrum available and allocated to support a national deployment?
Does the technology provide reliable operation in both urban and rural environments?
Is user equipment affordably priced or with investment in large-scale integration chip development, could the technology become affordable?
Is the technology early enough in its lifecycle to be expected to be available in full production quantities in no more than 5 years but currently in a testable form?
Is performance in the “ball park” of ITS SPaT related communications requirements?

Technologies that met all of these criteria were added to the short list. In some cases the commonly available technology does not meet all of the criteria, but other sources are available that do. For example, LTE provided by commercial cellular companies does not typically implement broadcast functions, and it carries a user fee. Furthermore allocated bandwidth is associated with the contract quality of service level. However, LTE systems are available for non-carrier based applications, and these could be made to provide broadcast functionality per the 3GPP standards, and could be provided by a road authority without associated user fees.

Shortlisted communications technologies from Task 3 include:

- DSRC in accordance with IEEE802.11p and IEEE 1609.2/3/4;
- WiMAX in accordance with IEEE802.16 (jurisdictional deployment; no user fee);
- LTE (jurisdictional deployment; no user fee. Precedence with national selection for Emergency Communications in 700 MHz Emergency band);
- FM- HD Radio (“HAR Like,” Jurisdictional Owned FM station, or public/private partnership with no user fee);
- ATSC M/H mobile digital video (Public/Private partnership with no fee for service).

Advanced technologies recommended for more in-depth evaluation included:

- Software Defined Radios (SDR);
- SMART antennas and advanced antenna technology;
- Cognitive Radio;
- GeoNET.

Technology and associated products not shortlisted included communications devices with ranges less than as specified for DSRC, older cellular technology that is being replaced with Long Term Evolution (LTE) technology; local multipoint distribution service (LMDS) and Multichannel Multipoint Distribution Service (MMDS) which are reaching the end of their life cycle; National Differential GPS (NDGPS) 285-325 KHz wireless link that has no capacity to support additional data load; NOAA-National Weather Service 163 MHz wireless broadcast link which has no surplus capacity and is hybrid (analog voice and data); Satellite service (bandwidth limitations and fee for service), and others (see Task 3 Report).

Figure 1.1-5 presents a high-level task flow diagram associated with the analysis related tasks (Details can be found in the Task 1 Project Plan).

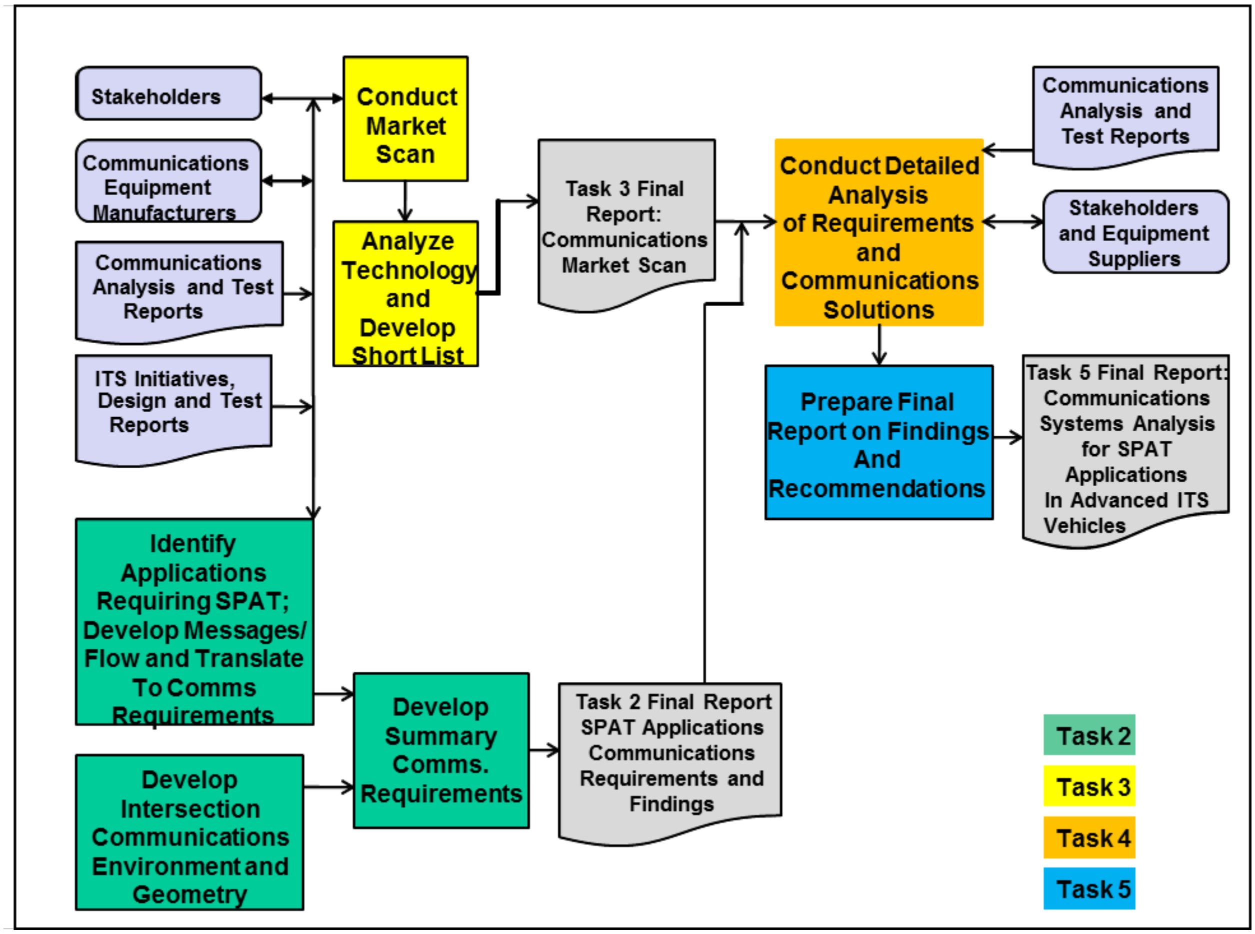


Figure 1.1-5. High Level Task Flow Diagram for Task 2 through 5
Source: ARINC April 2012

These stakeholders included representatives from the following stakeholder groups:

- University Transportation Research Groups: Virginia Tech Transportation Research Institute; Purdue University; and Texas A&M University, Texas Transportation Institute; University of Minnesota, Center for Transportation Studies; and UC Berkley, Institute for Transportation Studies; and University of Calgary, Institute for Transportation Studies and Dept. of Geomatics Engineering;

- CAMP;
- NHTSA;
- Trucking Industry Mobility and Technology Coalition;
- IEEE J2735 Committee;
- European Programs such as InterSafe 2; GeoNET; Cooperative Network for Intelligent Road Safety (COOPERS) , PReVENT, COMeSafety, Intelligent Car Initiative, Cooperative Vehicle-Infrastructure Systems (CVIS);
- Car Manufacturers;
- USDOT;
- Communications developers and equipment manufacturers.

1.2 Project Constraints

The scope of this project includes the following limitations as defined in the Work Plan and project kick-off meeting:

- Applications addressed must include the requirement for SPaT messages;
  - Applications included in Task 4 are only those included and approved by USDOT as provided in the Task 2 Technical Memorandum, which identifies the selected applications and the rationale for selection;
- Primary focus of this project is Infrastructure-to-Vehicle and Vehicle- to- Infrastructure (referred to as V2I) communications;
- Vehicle to Vehicle (V2V) communications is only considered as it may impact the implementation of V2I communications supporting the SPaT related applications;
- RF modeling is not currently part of the scope of this project; however, to provide high confidence related to RF propagation and interference, RF modeling is recommended;
- Communications technology and associated products are limited to that which does not require a fee for service;
  - Products and associated communications technology where any fee is paid for as part of the purchase price of a vehicle is considered (not a recurring service fee);
- No proprietary communications technology is considered which precludes use of open system architecture and standards and prohibits competitive procurement of the technology for deployment and implementation;
  - Technology developed by an organization and offered, openly for use by others for a royalty fee is considered. (For example, QUALCOMM receives royalty fees for code division multiple access (CDMA) technology patents, which are utilized by many companies);
- Technology not in a field testable status, but still in a laboratory environment where research reports indicate potential performance which would be of benefit to SPaT related communications will be considered as “a technology for USDOT to monitor”;
- Specific manufacturer’s names and associated equipment models will not be used in reports.

1.3 Reality of Vehicle Life on US Corridor

Based on world economic conditions and the continued rise in vehicle cost, owners are keeping their vehicles longer. In an article by Jeremy Korzeniewski entitled, “Cars in the USA Increase to a Record High” (Mar. 2009; autoblog.com [12]), it is pointed out that an R. L, Polk & Co. Research Report states that the average car on a US road is 9.4 years old. In an article entitled, “Average Age of Vehicles in the U.S. Hits Highest in 15 Years”, by Stephen Calogera (DriveOn, egmcartech.com, 3-30-10 [13]) it states that the average age of a vehicle on a U.S. road is 10.2 years old. In a report entitled “Dynamics of the Introduction of a New Passenger Car Technology”, by Panayiotis Christidis, et al (Joint Research Center, European Commission Report 20762EN [14]), it is stated that the medium age of a car on corridors in the European countries having economic difficulties is 14 years. Reviewing statistics, the trend is for people to own cars longer and for a single vehicle to be driven longer by multiple owners. According to JD Powers & Associates, sales in the USA of light vehicles for 2011 are projected to be 12.6 million and 14.1 million in 2012 (about an 11% sales growth). The population of the USA is projected to grow by 10% from 2010 to 2020 per the US census bureau. This means that sales growth is about keeping up with population growth. In a paper entitled, "New Safety Technology Takes Decades to Hit the Entire Car Market", by Colin Bird, (In-News: Safety, Cars.com [15]) it states: "It typically takes three decades or longer for a new safety technology to spread to 95% of vehicles on the road, and it can take decades more for the technology to trickle down to the remaining 5% because of holdouts who love their vehicles too much to let them go, according to the Highway Loss Data Institute, an offshoot of the Insurance Institute for Highway Safety". Thus all vehicles will not instantaneously have the capability to transmit BSM messages to infrastructure and other vehicles.

It is also reasonable to assume that if people have a choice, they may not be willing to pay the cost of highly intelligent vehicles but choose less expensive vehicles with simpler safety technology. This means that it will most likely take several generations of vehicles before the majority of the vehicles on the road have medium intelligence with perhaps a smaller number having high intelligence. The conclusions that can be drawn are:

- Vehicle-only safety systems must be self-contained, since cooperative vehicle systems will take decades to provide any safety benefit (because of the low overall fleet penetration, and the lower probability that any given vehicle encounter will include two Advanced ITS vehicles);
- Early vehicle safety systems are likely to rely on infrastructure based systems (sensors and communications) since with this equipment, any equipped vehicle will be able to realize the safety benefits as soon as it is sold;
- Intelligent Infrastructure with advanced sensors to locate and track approaching vehicles and pedestrians should be maintained to allow safety systems to operate effectively in the presence of both Advanced ITS vehicles and conventional, non-equipped vehicles;
- Unless a high price is paid for fully redundant systems, planning must assume that there will be vehicles on the corridors with "failed intelligence" and failures will not be instantly fixed. (Time to repair and restore communications and/or intelligence will be a function of cost and time it takes to service the vehicle). Thus intelligent infrastructure must be available to augment failures of intelligent vehicles.

SPaT messaging competes with other applications for use of the available communications bandwidth. The scope of this project precludes the detailed analysis of all safety applications requiring communications between the intersection's RSE and approaching vehicle's OBE. An estimate is made of what is referred to in this report as "background communications", for which SPaT must compete for link access and bandwidth. Since SPaT messaging represents only a small percentage of the data load on the supporting communications link, this "background communication" load must be considered to provide a reasonable assessment of the performance of a given communications technology relative to the derived requirements.

Chapter 2 - Intersection Safety (SPaT) Applications, Operating Environment and Assessment of Communications Requirements

This section presents the results of the Task 2 analysis of SPaT applications and translation into communications requirements. In task 2 the contents, sequencing and timing requirements for messages associated with RLR, LTA, RTA, PREEMPT, TSP and RCRLV were developed. This report does not include the details of this analysis, which is extensive and consumes several hundred pages; details are included in the Task 2 report.

The communications requirements were developed from an analysis of the range, timing, and message sizes identified for each application. Range requirements were determined from the basic operational description of the application, and typical sight stopping distance computations. Data rates were determined from a combination of the number of bits in a given message, and the timing requirements on each message. The timing requirements are derived from a combination of the application timing (i.e., how often a message must be sent to meet the functional and delivery time objectives of the application) and the message repetition rate required to meet communications reliability objectives. In general, we have assumed that message repetition provides a measure of redundancy that can be used to improve the overall realized failure rate for the application.

System availability requirements were developed based on safety of life requirements of the applications. Considering all applications, the most demanding requirements were used to develop summary communications requirements to meet overall SPaT communications.

SPaT messaging competes with other applications for use of the available communications bandwidth. The scope of this project precludes the detailed analysis of all safety applications requiring communications between the intersection's RSE and approaching vehicle's OBE. An estimate is made of what is referred to in this report as "background communications", for which SPaT must compete for link access and bandwidth. Since SPaT messaging represents only a small percentage of the data load on the supporting communications link, this "background communication" load must be considered to provide a reasonable assessment of the performance of a given communications technology relative to the derived requirements.

2.1 SPaT Applications Addressed in this Project

2.1.1 *Intersection Red Light Running (RLR)*

The Red Light Running (RLR) application is intended to warn the driver if he/she is in danger of being in the intersection when the through signal is red.

SPaT messages are generated by the applications processor associated with the signal controller and are transmitted by a wireless communications device. They are received by the ITS vehicle's onboard equipment (OBE) wireless communications device and processed by the OBE applications processor to determine if a hazard exists.

Upon receiving the SPaT message, the RLR application on the OBE determines what state the traffic signal will be in when the vehicle reaches the intersection entry point, and what state it will be in when it reaches the intersection exit point, based on the lane of travel, the vehicle speed and acceleration, and the vehicle position relative to the stop line. Based on this analysis, the application provides alerts and/or warnings to the driver indicating that they should either proceed with caution (e.g., yellow light), or stop. Automated braking may be activated in some implementations.

The RLR application will be described in two different operational contexts: fixed signal timing, and variable signal timing. In the fixed timing context, the SPaT messages are consistent, and each subsequent message simply reflects the progression through the fixed timing plan. In this situation, a vehicle can generally determine the signal state at any time in the near future after receiving only a single SPaT message. In the variable timing context, the signal timing may change as a result of external influences such as traffic demand, generating allowable extensions of the green phase within the context of the signal timing plan. Examples of a variable timing situation include: a vehicle arriving at a protected left turn lane, a pedestrian being detected in a cross walk; an “all red” phase extension to avoid a collision; a transit vehicle being granted priority; or an emergency vehicle preempting the signal. These events can result in a dynamic modification of the signal timing and the signal phase sequence. In this context, the SPaT information may change, so the vehicle must be informed if the last signal phase and timing described in the last received SPaT message has changed. This situation also imposes limitations on the types of changes that may be allowed in the timing plan. A preempt, for example, must be requested sufficiently far away that the change in signal timing can be accommodated by vehicles in the vicinity of the intersection, otherwise the preemption may result in substantially higher risk. Specifically, if the change is made too quickly, vehicles already beyond the application event point (i.e., past the point where they can stop safely will be at risk). Essentially, a variable timing system must assure that the change in the timing plan be delivered to an approaching vehicle sufficiently far in advance of the change actually taking place in terms of the light changing, that it can properly react to the change.

Figure 2.1-1 provides a graphical representation of the RLR application. The figure illustrates the two times associated with the intersection, T_L is the time the vehicle will take to reach the limit line (entrance of the intersection), and T_E is the time required for the vehicle to exit the intersection. Depending on the signal phase and timing, the RLR application will need to either do nothing, provide a caution, or warn to stop. In the stopping case the vehicle could also decide to automatically brake to a stop. In this figure the signal phase is shown as green, T_Y represents the time from some time base (e.g., the last GPS epoch) until the signal will change to the yellow phase, and T_R is the time until the signal will change to the red phase.

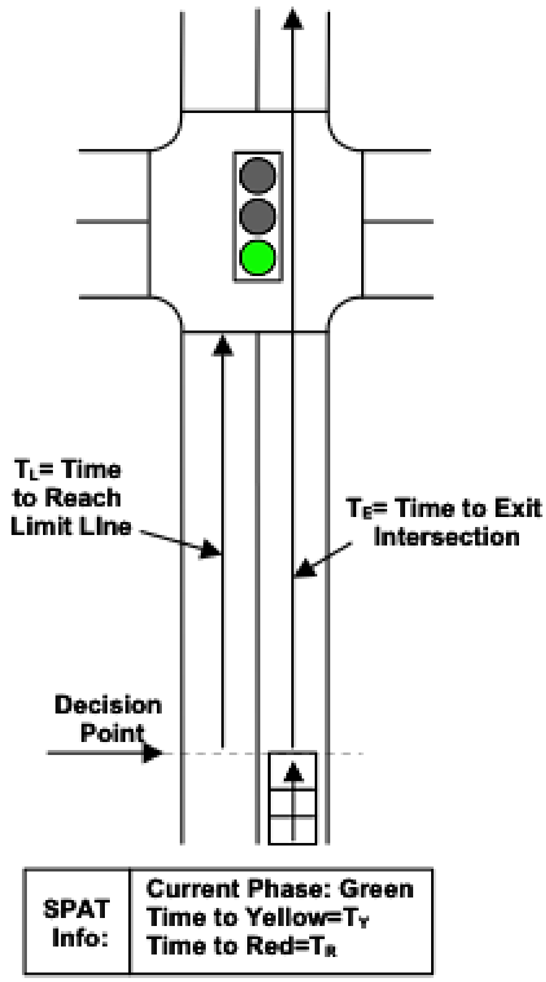
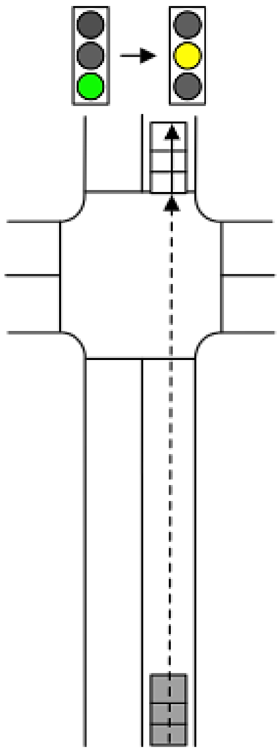
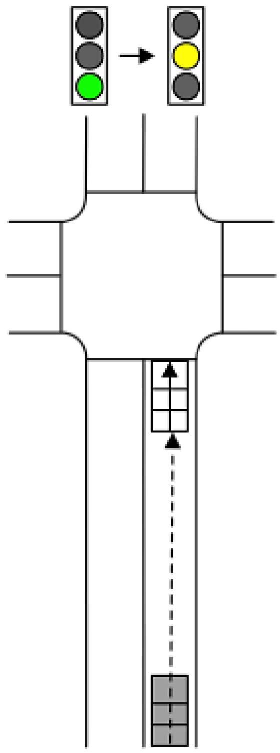
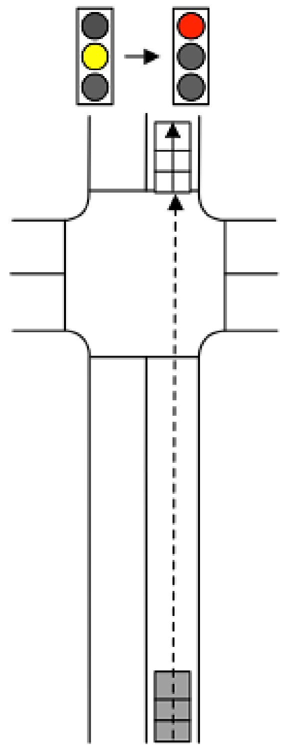
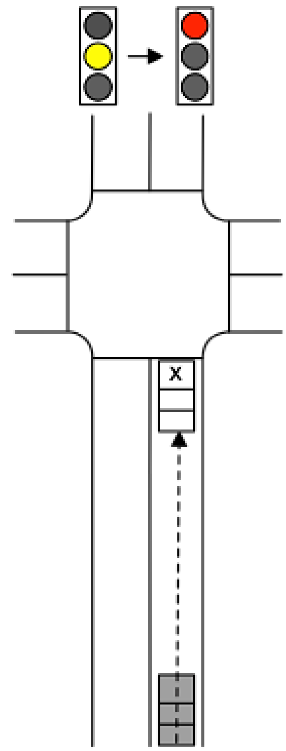


Figure 2.1-1. Graphical Representation of Red Light Running Application
Source: ARINC April 2012

Table 2.1-1 below shows typical scenarios associated with the RLR application. As can be appreciated from the table, knowing the timing to the next phase and the following phase (subsequent to the next phase) is useful to provide a timely alert if the phase may change while the vehicle is in the intersection. This is not strictly necessary since when the signal changes to the next phase, the SPaT message will be updated. However, this approach provides greater time for the driver to perceive and respond to the alert.

Table 2.1-1. Typical RLR Application Scenarios
Source: ARINC April 2012

			
$T_E<T_Y$	$T_E<T_Y$	$T_E<T_Y$	$T_E<T_Y$
No Warning	Caution	Extreme Caution	Stop!
Signal will turn yellow after/as vehicle exits intersection	Signal will turn yellow while vehicle is in intersection	Signal will turn red while vehicle is in intersection	Signal will turn red before vehicle enters intersection

2.1.2 *Left Turn Assist (LTA)*

The Left Turn Assist (LTA) application provides information to inform the driver of an approaching vehicle that is planning to turn left if it is unsafe to make the turn (i.e., there is insufficient gap to a vehicle approaching from the opposing direction).

This application can be implemented in two different ways. In the infrastructure-based implementation, the presence, position, and speed of vehicles approaching the intersection are sensed using infrastructure sensors (e.g., RADAR or LIDAR, or some form of in-road sensor). The intersection RSE then transmits this information for use by all approaching vehicles within communications range.

In the V2V supported implementation, approaching vehicles transmit Basic Safety Messages (BSM), or Here-I-Am (HIA) messages, and the Advanced ITS vehicle determines the presence of a hazard using this information. As noted in the positioning project associated with this project, reliance on the BSM/HIA data is problematic since, for whatever reason, if the approaching vehicle fails to provide this information (unequipped, failed equipment, poor communications, etc.) the system is unable to determine if it safe to execute the turn. In this implementation the vehicle may be able to identify an unsafe situation, but it cannot reliably differentiate between a safe and an unsafe situation if the opposing vehicle fails to provide any information. Since the probability of the opposing vehicle failing to provide this information is higher than the required ASIL value, the system is unlikely to ever achieve the necessary reliability. This is problematic from a user perspective since the user cannot be certain that it is safe to execute the turn based on the data from the system. This raises concerns about reliance on the system, and how users may interpret a “no data” response from the system. Typically “no warning” is interpreted by drivers as “safe”, but in this case “no warning” simply means that the system cannot provide any information. It may be wise to undertake some human factors analyses to determine the risks associated with this approach.

The ITS vehicle OBE receives the SPaT message from the RSE, and if the signal phase does not allow a left turn it will warn the driver to stop if he is not slowing quickly enough to stop before entering the intersection. If the signal phase and timing is such that when the vehicle reaches the intersection a left turn is permitted, then, using the information received from the RSE or from the BSM/HIA, the vehicle OBE determines if vehicles approaching from the opposing direction will either pass through the intersection before the ITS vehicle enters it, or if they will still be outside the intersection when the turn is completed. If either of these criteria is not met, the system will indicate that it is not safe to make the turn.

Figure 2.1-2 provides a graphical representation of the RLR application. The figure illustrates the two times associated with the intersection, T_L is the time the vehicle will take to reach the limit line (entrance of the intersection), and T_E is the time required for the vehicle to exit the intersection. Depending on the signal phase and timing, the LTA application will need to either do nothing, provide a caution, or warn to stop. In the stopping case the vehicle could also decide to automatically brake to a stop. In this figure the signal phase is shown as green, and T_Y represents the time from some time base (e.g., the last GPS epoch) until the signal will change to the yellow phase, and T_R is the time until the signal will change to the red phase.

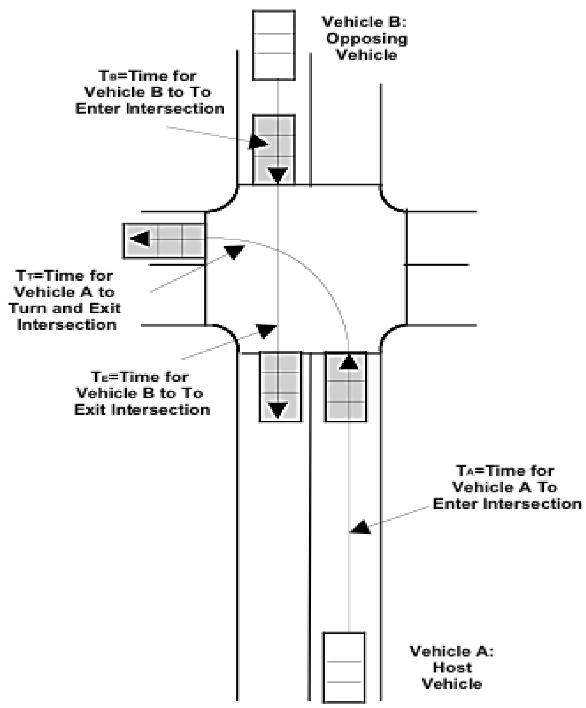
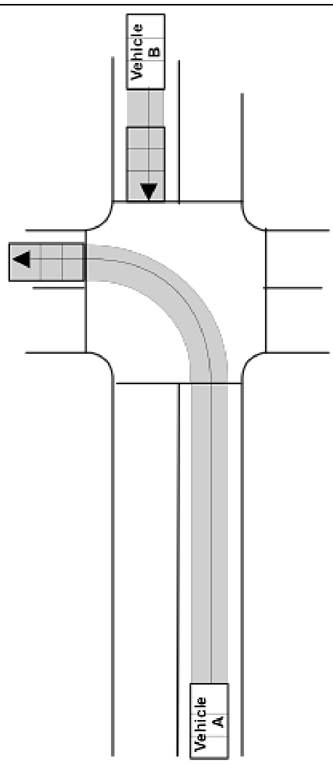
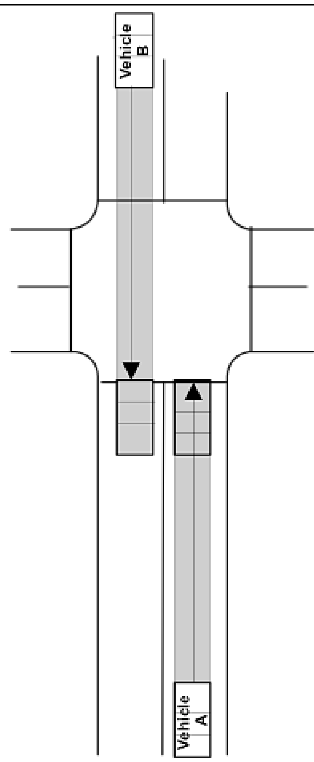
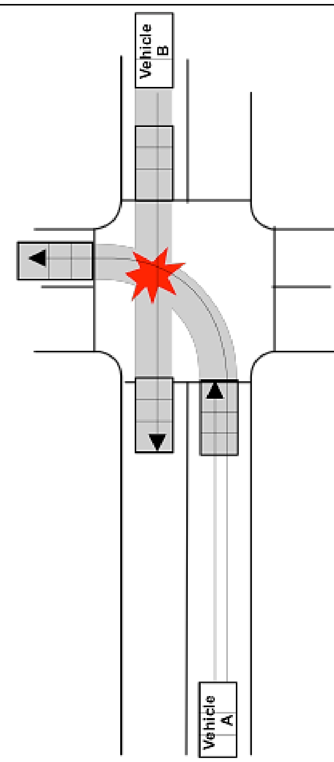


Figure 2.1-2. Graphical Representation of Left Turn Assist Application
Source: ARINC April 2012

Table 2.1-2 below shows typical scenarios associated with the LTA application. As can be appreciated from the table, knowing the timing to the next phase and the following phase (subsequent to the next phase) is useful to provide a timely alert if the phase may change while the vehicle is in the intersection. This is not strictly necessary since when the signal changes to the next phase, the SPaT will be updated. However, this approach provides greater time for the driver to perceive and respond to the alert.

Table 2.1-2. LTA Application Scenarios
Source: ARINC April 2012

		
$T_A + T_T < T_B$	$T_B + T_E < T_A$	$T_A + T_T \sim T_E + T_B$
No Warning	No Warning	Do Not Turn!
Vehicle A Completes Turn Before Vehicle B Reaches Intersection	Vehicle B Exits Intersection before Vehicle A Reaches Intersection	Vehicle B Reaches Intersection as/after Vehicle A Enters Intersection, and Before Vehicle A Exits Intersection

2.1.3 *Right Turn Assist (RTA)*

The right Turn Assist (RTA) application provides information to inform the driver of an approaching vehicle that is planning to turn right if it is unsafe to make the turn (i.e., there is insufficient gap to a vehicle approaching from the left direction).

As with LTA, the RTA application can be implemented in two different ways: using infrastructure sensors to determine the position and speed of approaching vehicles, or using information in the BSM/HIA messages transmitted by the approaching vehicles.

SPaT messages are generated and transmitted by the traffic signal controller RSE, and are received by the ITS vehicle OBE. Based either on information provided by the infrastructure sensors, or on information derived from received BSM/HIUA messages, the vehicle OBE determines if other vehicles are approaching from the crossing left direction, and if there is not sufficient gap to safely complete the right turn within the permissive green phase. If it is not safe, the RTA application presents a warning to the driver. In other advanced implementations, the system may sense pedestrians in the crosswalk, and either include this information in an “unsafe to turn” message, or generate a separate “pedestrian present in the cross walk” message to warn the driver that a pedestrian is crossing. Figure 2.1-3 is a graphical representation of the RTA application. Table 2.1-3 presents LTA applications scenarios.

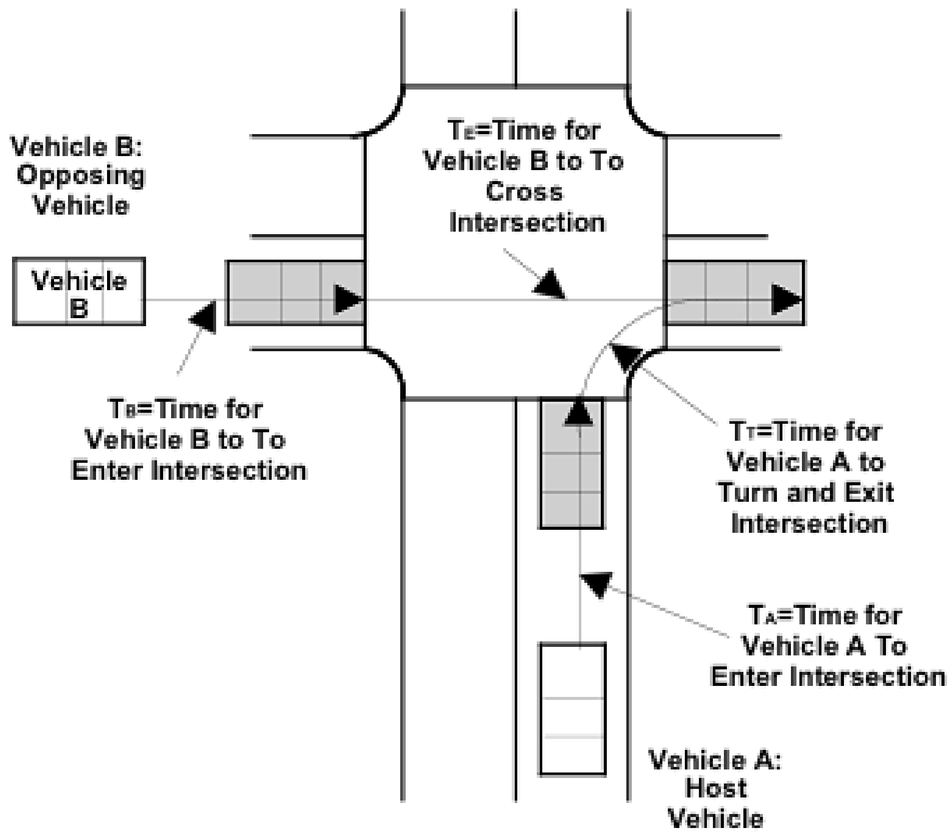
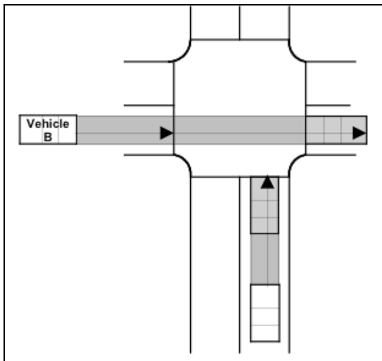
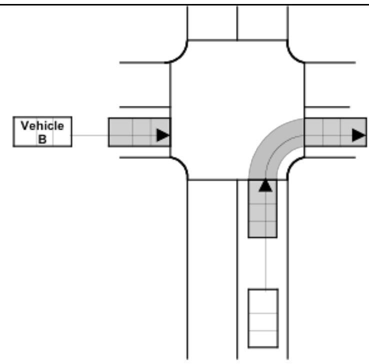
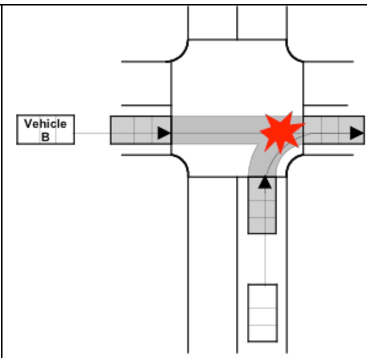


Figure 2.1-3. Graphical Representation of Right Turn Assist Application
Source: ARINC April 2012

Table 2.1-3. LTA Application Scenarios
Source: ARINC April 2012

		
$T_B + T_E < T_A$	$T_A + T_T < T_B$	$T_A + T_T \sim T_B + T_E$
No Warning	No Warning	Do Not Turn!
Vehicle B Exits Intersection before Vehicle A enters	Vehicle A completes turn and exists intersection before Vehicle B enters	Vehicle A and Vehicle B Are in Intersection At the Same Time

2.1.4 *Emergency Vehicle Preemption (PREEMPT)*

The emergency vehicle preemption application provides a mechanism for an emergency vehicle to request that the signal either be extended to allow it to pass through on the green phase, or to change the light so that the emergency vehicle can pass through in the green phase. As with other related applications, SPaT messages are generated and transmitted by the traffic signal controller RSE. An approaching emergency vehicle receives the SPaT message, and if it determines that the signal phase will be red when it reaches the intersection, it requests signal preemption. Depending on the phase of the signal, the signal controller either changes the signal timing to hold the green phase longer, or it initiates a change sequence to cycle the opposing path from green to yellow to red, so that it can change the through path for the emergency vehicle to green. The system may include a confirmation message sent from the RSE to the emergency vehicle to indicate that the preemption has been implemented, although in most cases an updated SPaT message provides this confirmation. With multiple emergency vehicles, the RSE determines the required extension of cross street red phase. The RSE must consider the length of large fire trucks to assure clearance of the intersection. Figure 2.1-4 provides a graphical representation of the PREEMPT application.

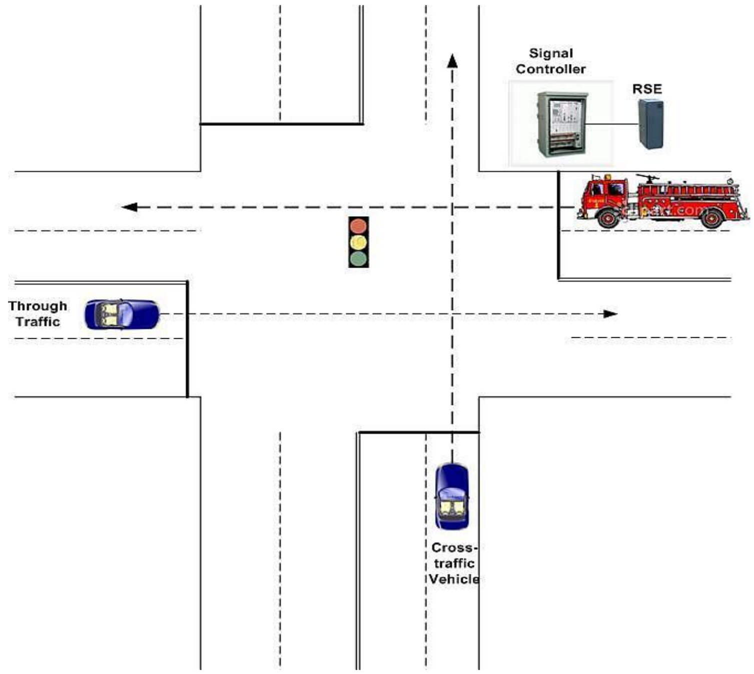


Figure 2.1-4. Graphical Representation of the PREEMPT Application
Source: ARINC April 2012

2.1.5 *Transit Signal Priority (TSP)*

The transit vehicle preemption application provides a mechanism for a transit vehicle to request that the signal be extended to allow it to pass through on the green phase. As with other related applications, SPaT messages are generated and transmitted by the traffic signal controller RSE. An approaching transit vehicle receives the SPaT message and if it appears that the signal phase will be red when it reaches the intersection, and it is more than some pre-determined amount of time behind schedule, it requests a transit signal priority. This request typically includes some indication of the rationale for requesting the priority (e.g., running X minutes late). The signal controller extends the signal green phase to allow the transit vehicle to pass through the intersection without stopping. The system may include a confirmation message sent from the RSE to the transit vehicle to indicate that the signal priority has been implemented, although in most cases the updated SPaT message provides this confirmation. In some jurisdictions, TSP is only executed if the transit vehicle is 5 or more minutes behind schedule; in this case, a denial of TSP message may be required. Because of the size of the transit vehicles, the signal timing must account for the time required for the vehicle to transit the intersection before resuming normal timing. Figure 2.1-5 provides a graphical representation of the Transit Signal Priority application.

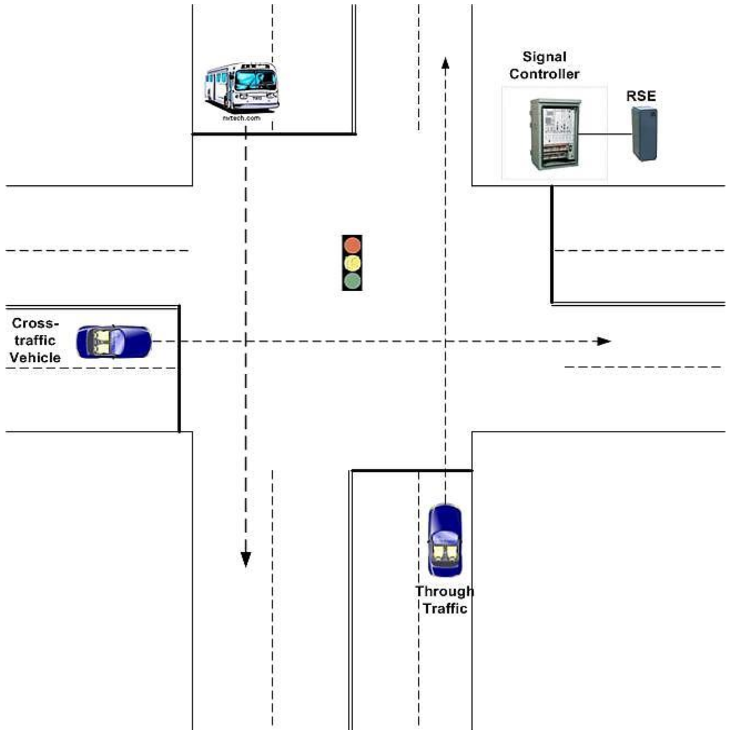


Figure 2.1-5. Graphical Representation of the Transit Signal Priority Application
Source: ARINC April 2012

2.1.6 *Freight Signal Priority (FSP)*

This application applies to signalized intersections near major intermodal commercial freight terminal areas where there is significant congestion. The process is similar to that of a transit vehicle. The FSP request message includes the identification of the truck authorizing the freight signal priority. (Ref: FHWA 11-3-10 Mobility Work Shop [16]). Figure 2.1-6 provides a graphical representation of the Freight Signal Priority Application.

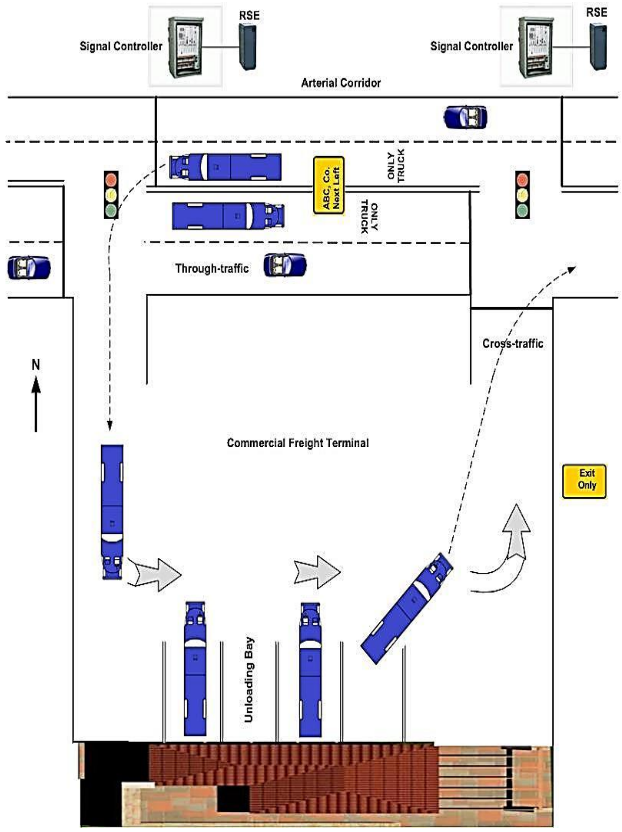


Figure 2.1-6. Graphical Representation of the Freight Signal Priority Application
Source: ARINC April 2012

2.1.7 *Rail Crossing Red Light Violation (RCRLV)*

This application is intended to provide a warning if a vehicle is in danger of violating the red lights at an active rail crossing. Whenever a train is in or approaching a grade crossing as determined by a rail sensor that detects the presence of the train relative to the rail crossing, the rail crossing controller generates and transmits Rail SPaT (RSPaT) messages. Once the rail-crossing controller receives the oncoming train information, it activates a non-permissive crossing (flashing red rail crossing signals), and closes the crossing barrier. The time between the activation of the flashing red signals and the barrier closing allows vehicles in the crossing to clear. This is the equivalent of a yellow phase. The ITS vehicle receives the RSPaT message, which defines the amount of time before barrier activation and, based on the receiving vehicle's speed and position relative to the stop line, and the RSPaT information, the OBE determines the state of the vehicle; These states are:

- The vehicle speed and position is such that it will have exited the crossing by the time the barrier is activated, and thus must continue as expeditiously as possible; in this case the vehicle application might present an alert to the driver indicating that they should clear the crossing as soon as possible
- The vehicle speed and position are such that the vehicle cannot exit the crossing before the barrier is activated. In this case the application should warn the driver to stop immediately

- The vehicle speed, position and deceleration indicate that the vehicle is stopping and will stop at the stop line before or as the barrier closes. In this case, no warning is needed

For non-barriered rail crossings with flashing red, the equivalent of the yellow signal phase is the time allowed for rail crossing clearance (considering vehicle location, standard deceleration and time to transition across the rails). Figure 2.1-7 presents a graphical representation of Rail Crossing Red Light Violation.

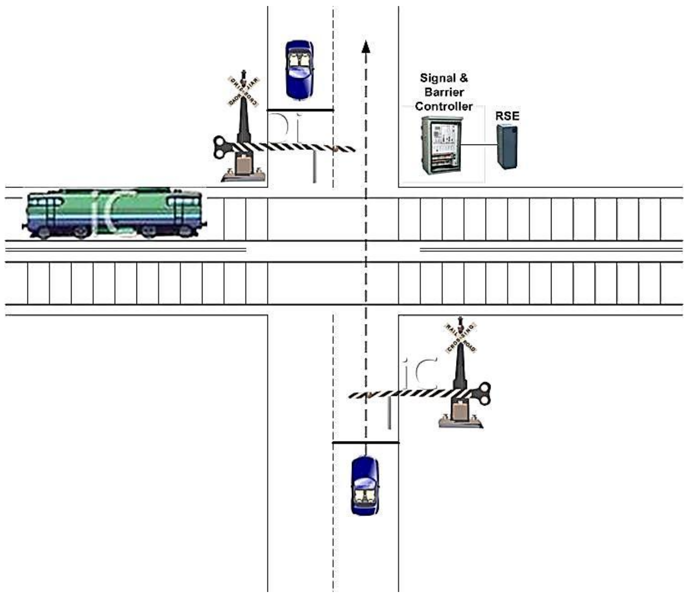


Figure 2.1-7. Graphical Representation of Rail Crossing Red Light Violation
Source: ARINC April 2012

2.2 Intersection Safety Related Message Sets

SAE J2735 describes Message Sets supporting advanced ITS vehicle messaging (V2I and V2V). ASN.1 and XML representations of message structures are provided. The J2735 message set includes 16 different message frames which use 54 different data frames parameterized using 162 different data elements.

Table 2.2-1 summarizes message types included in SAE J2735 and Table 2.2-2 lists standards associated with DSRC. Details of DSRC technology are provided in Section 3 of this report.

Table 2.2-1. Overview of SAE J2735 Message Types
(Ref: FDOT Sunguide® Concept of Operation; 2-2010 [213])

J2735 Message	Description
Ala Carte	Any data frame or element or combination defined in J2735. Primarily used for testing.
Basic Safety Message (BSM)	Sent from every vehicle at 10 Hz continuously. Contains the following vehicle information: location (latitude, longitude, elevation), heading, speed, 4-D acceleration (latitudinal, longitudinal, vertical, yaw), brake status (brake applied for each wheel, traction control state, ABS state, stability control state, brake boost applied, auxiliary brake status), and vehicle size (length, width). Typically a vehicle-to-vehicle message; however, it can be received by the RSE to provide additional vehicle probe data to the infrastructure.
Common Safety Request (CSR)	Vehicle- to- vehicle message that allows a vehicle to request additional information from specific other vehicles to determine their ability to utilize certain safety applications.
Emergency Vehicle Alert (EVA)	A v2V message sent by incident responders to notify surrounding vehicles to exercise caution.
Intersection Collision Avoidance	Sent from vehicle to an intersection collision application containing path and acceleration information.
MAP Data	Wrapper to relay any defined map data in the standard to vehicles (Geometric Intersection Descriptions, curve outlines, roadway segments for platooning, etc.).
NEMA Corrections	NEMA 183 standard differential GPS correction messages to GPS applications in a vehicle.
Probe Data Management (PDM)	Sent from the infrastructure to vehicles to specify (non-default) vehicle probe data frequencies, regions and event thresholds.
Probe Vehicle Data (PVD)	Periodic data snapshots sent from vehicles to infrastructure, containing vehicle location, heading, speed, and various optional data from available sensors on the vehicle including weather data, information on lights, information on wipers, etc.
Roadside Alert	Sent from infrastructure to vehicles regarding hazards in the immediate area.

J2735 Message	Description
RTMC Corrections	RTMC Message Data from Infrastructure to vehicles to provide differential GPS correction for positioning applications in the Vehicle OBE.
Signal Request Message	Sent from a vehicle to an RSE associated with an intersection signal controller to request signal priority or signal preemption.
Signal Status Message	Sent from an intersection RSE to vehicle's OBE with the current status of the signal and active preemption/priority event acknowledgements.

Table 2.2-2. Key Standards Associated with DSRC
Source: ARINC April 2012

Standard	Title	Date Published
IEEE 802.11p	Physical and MAC Layers for 5.9 GHz WAVE/DSRC	2010
IEEE Std. 802.11, 1999 Edition (ISO/IEC 8802.11:1999)	EEE Standard for Wireless LAN Medium Access Control (MAC)	
IEEE 1609.0	Standard for Wireless Access in Vehicular Environments (WAVE)- Architecture Guide	Draft; In Progress
IEEE 1609.1	Standard for Wireless Access in Vehicular Environments (WAVE) – Remote Management Service	Draft; In Progress
IEEE P1609.2	Standard for Wireless Access in Vehicular Environments (WAVE) - Security Services for Applications and Management Messages	Draft; In Progress
IEEE P1609.3	Standard for Wireless Access in Vehicular Environments (WAVE) – Networking Services	Published
IEEE P1609.4	Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operations	Published
IEEE P1609.11	Standard for Wireless Access in Vehicular Environments (WAVE) - Over-the-Air Electronic Payment Data Exchange Protocol for Intelligent Transportation Systems (ITS)	Completed
IEEE P1609.12	Standard for Wireless Access in Vehicular Environments (WAVE) - Provider Service Identifier (PSID) Allocations	In Progress
IEEE 1489-1999	Standard for Data Dictionaries for Intelligent Transportation Systems - Part 1 Functional	Published 1999

Standard	Title	Date Published
	Area Data Dictionaries	
SAE J2735	DSRC Message Set Dictionary (V2)	2009
SAE J2540 -	Messages for Handling Strings and Look-Up Tables in ATIS Standards	Published
SAE J2630	Converting ATIS Message Standards From ASN.1 to XML	Published
AASHOT/NEMA NTCIP 1202	National Transportation Communications for ITS Protocol; Object Definitions for Actuated Traffic Signal Controller (ACS) Units (Possible Source Data for SAE J2735 Message Generation)	Published

The SAE J2735 Basic Safety Message has 2 parts: Part 1 is the basic message definition, and part 2 defines the data structure with essential information to support V2V safety communications as shown in Figure 2.2-1. Part 1 is mandatory. Part 2 may be sent optionally, but the specifics and the volume of data is not currently defined. It is also unclear if this second part should actually be part of the BSM, since, in general, it is application specific, and a receiving application set up to receive the BSM PSID will need to also be set up to parse and understand the wider variety of data encoded in part 2 of the message. An alternative approach would be to limit the BSM to Part 1 and separate the various components of Part 2 into application specific messages with separate PSIDs.

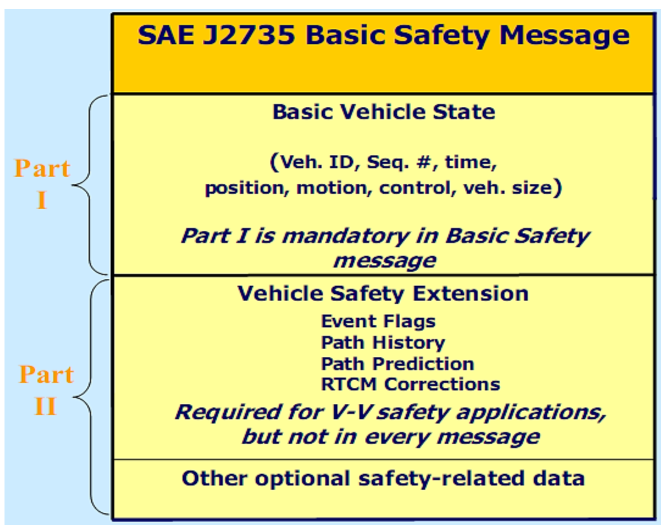


Figure 2.2-1. SAE J2735 Part 1 and Part 2 High Level Description
(Ref: "V2V and V2I Communications Based Safety Applications", Michael Maile [17])

Figure 2.2-2 illustrates the content of the so-called *Here I Am (HIA)* message. The HIA message is essentially a BSM, although it is intended to be transmitted by vehicles without any ability to make use of received BSMs. This message is 330 octets and represents a 27.12 kbps data load per vehicle on the wireless link.

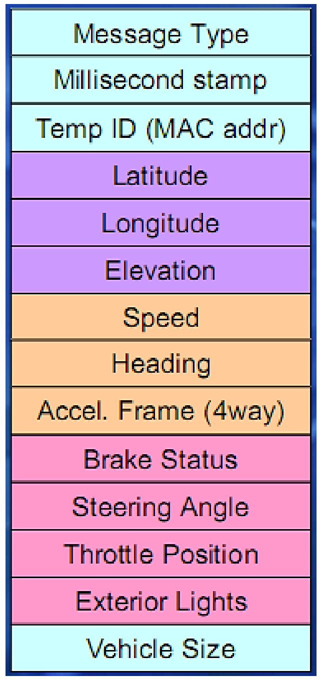


Figure 2.2-2. "Here I Am" Message Content
(Ref: SAE J2735 [18])

The SPaT message includes the current movement state of each active phase and values from which the OBE can project the duration of the permissive phase (unless it is changed by an event such as preemption).

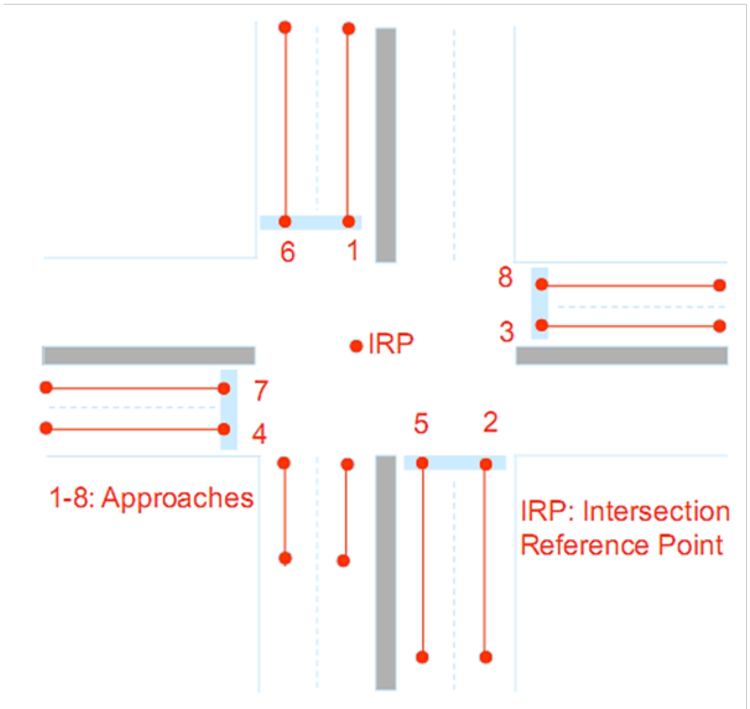
The structure of the SPaT Message is shown in Figure 2.2-3 below.

Data Elements		**Type/Size**
Object ID		Unsigned 8 Bit Integer
Object Size		Unsigned 8 Bit Integer
Approach ID		Unsigned 8 Bit Integer
Signal Phase Indications		32 Bit Bitmask
Countdown Timer Confidence	2x Unsigned 4 Bit Integers	32 Bit Bitmask
Time to Signal Phase Change (Countdown Time)		Unsigned 16 Bit Integer
Yellow Duration		Unsigned 8 Bit Integer

Figure 2.2-3. SPaT Message Structure
(Ref: SAE J2735 [18])

Figure 2.2-4 illustrates the MAP-GID message content. SPaT applications such as RLR, LTA, RTA and RCRLV require some understanding of the lane and signal structure for the intersection.

The MAP-GID message conveys this information so that the application can determine how to interpret and use the information in the SPaT message. With this information the OBE can determine the state of the signal phasing and when the next phase associated with the lane of travel will occur. The MAP-GID message includes specific lane numbers that correspond to SPaT message information.



Stop Line Location for all lanes;

Geo-reference for the intersection;

Lane Geometry and coordinates of lane centers;

Start location/point for a new lane;

Correspondence between lanes and signal phases;

Accuracy of measurements: 30 cm or better.

Figure 2.**2-**4**. MAP-Geometric Intersection Description Message Content Overview**
(Ref: “V2V and V2I Communications Based Safety Applications”, Michael Maile [17])

2.3 Intersection Safety Communications Requirements

2.3.1 *Summary of Communications Requirements for Intersection Safety Applications*

Communications requirements related to SPaT applications as defined in the above sections is summarized in Table 2.3-1. Communications technology short-listed in Task 3 will be compared with these requirements.

Table 2.3-1. Summary of Intersection Safety Applications Related Communications Requirements
Source: ARINC April 2012

SPaT Applications Related Communications Requirement	Specification Requirement
Communications Service	Best Effort based on DSRC design and broadcast of SPaT and GIDs; however, multiple transmissions provide high confidence communications and differential service is supported. (SPaT competes with BSM messages for transmission time using DSRC and CSMA/CA IEEE802.11p [19] protocol).
Communications Range (High Probability of Message Receipt)	High End Range: 331 m (1087 ft.); High End Range is Based on Signal Preemption and Time to Clear the Intersection Based on Posted Speed and stopping sight distance at 0.2 G deceleration from 45 mph. Nominal Range: 176 m (579 ft.). Nominal Range is Based on Stopping Sight Distance at 0.4 G deceleration from 75 mph.
Maximum bit error rate (BER) and Confidence Factor	10^{-4}, achieved by 4 message transmissions based on SIL = 1 (Message reliability = PER = 10^{-2})
Data Throughput, SPaT Messages	40 kbps (Includes single intersection GID associated with the application. Does not include other message traffic in channel).
Background Data Load on DSRC (BSM/HIA Message) in which SPaT Messages Must Compete	4.77 mbps considering J2735 part 1; 29.44 mbps considering J2735 part 1 & 2; Based on 176 vehicles within communications range.
Data Rate Required for Geometric Intersection Descriptions Using Wide Area Broadcast	Function of Population and Number of Intersections: At 0.033Hz message rate: 200K population = 54 kbps; 500K population = 135 kbps and 1M population = 270 kbps.
Differential GPS Correction (Candidate for Wide Area Broadcast)	2.4 kbps
Background Safety Related Messages on Wide Area Broadcast	Function of Population and Number of Intersections: At 0.033Hz message rate: 200K population = 12 kbps; 500K population = 30 kbps and 1M population = 60 kbps

SPaT Applications Related Communications Requirement	Specification Requirement
Background Emergency or Severe Weather related messages (NOAA/NWS) on Wide Area Broadcast	2400 bps (periodic)
Bandwidth for SPaT defined Applications	BW at usable BER and Applications range = 3 to 6 mbps; typical in test of DSRC = 4.5 mbps
Maximum Transit Delay	10 Hz Message Transmit Frequency = 76 msec; 1 Hz Transmit Frequency = 998 msec
Error Free Message Delivery Time (includes latency) associated with SPaT Applications	400 msec to 4,000 msec (depending on specific application and assuming SIL requirements are met)
Vehicle Speed/Doppler Accommodation	200 km/h (124 mph) (Ref: IEEE Std. 802.11p PAR); 1100 Hz
Multipath Environment	Rural and Urban Canyon (Maximum spread accommodated by DSRC is 1.6 μsec)
Quality of Service	Different Class of Services Supported with Highest Class having Highest Priority; Meets SPaT communications requirements at all times when operational including providing error free message related to SPaT and based on intersection approach speed, within a distance from the stop line to allow the vehicle to safely stop (recognition+ reaction + braking time for speed). Control Channel dedicated to safety messaging (no service)
Availability	50,000 hr MTBF and 48 hr MTTR = 99.9% Availability; using redundancy achieves 99.999% 99% to 99.9% for Safety Integrity Level 1 (IEC 61508)
Weather	Meet SPaT Communications Requirements in all Weather conditions (rain, sleet, snow and fog)
Radio Frequency Environment	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)
Vehicle Separation Distance with no Radio Frequency Interference	Parallel lane adjacent vehicles and same lane with 4.6 m separation (low speed- 8 km/h; 5 mph) approach to a signalized intersection
Dual Transceiver Simultaneous Operations in a Single Vehicle	No Co-channel or In-band Interference when one DSRC dedicated to safety messaging and another devoted to service messaging
Impact of Intersection or Rail Crossing Geometry	Communications Performance Not Impacted by Intersection Geometry
Environmental and Power Compatibility	RSE: Compatible with NEMA TS-2 Specification;

SPaT Applications Related Communications Requirement	Specification Requirement
	OBE: Compatible with SAE Specifications for Light and Heavy Vehicles
Size and Weight	Compatible with Small Car (Approx. Size 500 cu in/8195 cm^3; Approx. Wt. 2 lbs./0.91 kg)
Cost	Affordable to Purchaser of a Private Vehicle: Generally considered to be < $300
Supportability	Maintenance supportability by vehicle service centers over deployment life of equipment; all DSRCs comply with national interface standards (no proprietary or special interface protocol). Useful Life of 20 years

2.3.2 *Range Requirements*

The range for each intersection safety application depends on the typical approach speed for the intersection and the closest point to the intersection that the user vehicle can receive the SPaT or other intersection safety message and respond appropriately.

The closest point that the system can respond was determined as the “False Negative Point” in the referenced report. This represents the absolute minimum range requirement absent of any other factors that may add to this range as described below.

As described in the Vehicle Positioning Trade Study for ITS Applications final report, submitted as a part of this overall project effort, the absolute minimum range requirements for the various intersection safety applications as a function of approach speed are provided in Table 2.3-2 below. As can be seen in the table, many intersection applications involve either deciding to enter the intersection or stop, and so these have generally the same range requirements.

Table 2.3-2. Absolute Minimum Range Requirements for Intersection Safety Applications.
Source: ARINC April 2012

Application	Speed (mph)			
	30	45	60	75
Red Light Running **Left Turn Assist** **Right Turn Assist** **Rail Crossing Light Violation**	119 ft. (36 m)	235 ft. (72 m)	388 ft. (118 m)	579 ft. (176 m)
PREEMPT	649 ft. (197 m)	1087 ft. (331 m)	N/A	N/A
Transit Signal Priority **Freight Signal Priority**	194 ft. (60 m)	403 ft. (122 m)		

PREEMPT range is determined by the time the emergency vehicle will travel while stopped vehicles are accelerating and pulling to the side of the road (estimated at 6.9 seconds) plus the false negative stopping distance for larger vehicles (max deceleration 0.2 G).

Transit and Freight priority ranges are determined by the time required for the transit or freight vehicle to stop at 0.2 G deceleration, if the priority is denied.

For PREEMPT, TSP and FSP the analysis assumes that the maximum vehicle approach speed to the signalized intersection is no greater than 45 mph.

These absolute minimum range requirements (based on stopping sight distance) must be supplemented to account for latency associated with the delivery of the message and travel time associated with message repetition to meet reliability objectives (four message repeats required to comply with ASIL reliability level requirements). In general, the range requirement also depends on the type of communication system. For example, if the delivery system is a wide area communication system, then the range must be sufficient to assure that vehicles approaching an intersection near the edge of the RF signal will still receive the message(s) in time that the application can operate effectively. Where a wide area communications solution is used, time to transmit SPaT messages and/or GIDs for every signalized intersection within the communication "foot print" must also be considered. For this reason SPaT communications requirements significantly limits the number of intersections that can be serviced by a single wireless communications transceiver. Figure 2.3-1 illustrates distance considerations from the intersection stop line that influence message delivery timing related to SPaT applications.

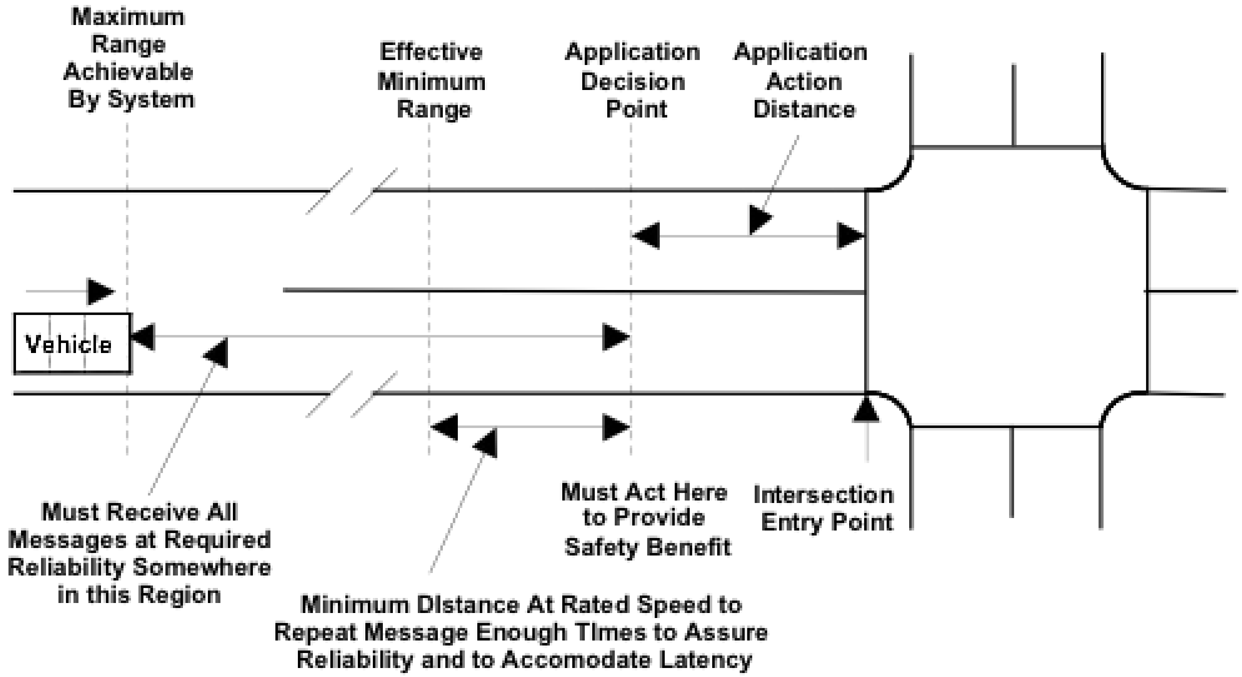


Figure 2.3-1. Range Related to Application Dimensions
Source: ARINC April 2012

2.3.3 *Reliability Requirements*

The generally accepted approach for defining safety level requirements is the Safety Integrity Level or SIL. SILs are measures of the safety risk of a given process, and essentially define to what extent can a process be expected to perform safely? And, in the event of a failure, to what extent can the process be expected to fail safely? This process is described in the IEC 61508 [20] standard. More recently the concept of Automotive SIL has been developed and is specified in ISO 26262 [21].

Under the ASIL approach, safety is stratified into five discrete levels: QM, A, B, C and D, with D being the highest level of safety required. Each level represents an order of magnitude of risk reduction.

The ASIL for an application or a system that implements an application is based on three core factors: Severity, Exposure and Controllability.

- Severity is a measure of the potential for injury, and the severity of those possible injuries, should a fault occur.
- Exposure is a measure of how frequently the system may be experience a situation in which the fault is relevant (i.e. a hazardous event).
- Controllability is a measure of the probability that the driver or other endangered persons are able to gain control of the hazardous event, and are able to avoid harm.

These factors are combined as shown in Figure **2.3-2** below to determine the ASIL for the specific situation under consideration.

		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

Figure 2.3-2 **ASIL Levels**
(Ref: "ISO 26262 for Safety-Related Automotive E/E Development - Introduction and Concept Phase", Michael Soden; June 2011[22])

Proper assessment of these (S, E & C) factors requires that a detailed hazard analysis be carried out based on how the application would react to a failure. These are described in Table 2.3-3 below

Table 2.3-3 ASIL Parameters
Source: ARINC April 2012

		Metric	**Example**
Severity			
S0	No Injuries	AIS* 0	Rear Collision at ΔV<10 kph
S1	Light and Moderate Injuries	>10% Probability of AIS 1-6 (and Not S2 or S3)	Rear Collision at ΔV<20 kph
S2	Severe Injuries, and Life-Threatening Injuries (Survival Probable)	>10% Probability of AIS 3-6 (and Not S3)	• Rear Collision at ΔV<20-40 kph; • Urban Ped/Cyclist Collision
S3	Life-Threatening Injuries (Survival Uncertain), and Fatal Injuries	>10% Probability of AIS 5-6	• Rear Collision at ΔV>40 kph; • Suburban Ped/Cyclist Collision
Exposure			
E0	Incredible (Force Majeure)	<0.01% of Operating Time	Flash Flood, Meteorite
E1	Very Low Probability	<0.1% of Operating Time Situations that occur less than once a year for the great majority of drivers	• Stop at railway crossing, which requires the engine to be restarted • Jump start

		Metric	Example
E2	Low Probability	<1% of Operating Time Situations that occur a few times a year for the great majority of drivers	• Driving on a mountain pass with an unsecured steep slope • Driving situation with deviation from desired path
E3	Medium Probability	<10% of Operating Time Situations that occur once a month or more often for an average driver	• Fuelling • Overtaking • Tunnels • Hill hold • Car wash • Wet roads • Congestion
E4	High Probability	>10% to Always All situations that occur during almost every drive on average	• Starting • Shifting gears • Accelerating • Braking • Steering • Using indicators • Parking
Controllability			
C0	Generally controllable	Generally possible to control	• Unexpected increase in radio volume • Situations that are considered distracting
C1	Simply controllable	99% or more drivers and other participants can avoid harm	When starting the vehicle with a locked steering column, the car can be brought to stop by almost all drivers early enough to avoid a specific harm to persons nearby
C2	Normally controllable	90% or more drivers and other participants can avoid harm	Driver can normally avoid departing from the lane in case of a failure of ABS during emergency braking
C3	Difficult or uncontrollable	Less than 90% of drivers and other participants can avoid harm	Driver normally cannot bring the vehicle to a stop if a total loss of braking performance occurs

For most connected ITS applications, the exposure rate is greater than 10% of the time (e.g. braking, turning, etc.), so this would make the typical exposure level E4. Similarly, for non-automated applications, the controllability is generally greater than 99% (C1). This is because the driver is assumed to be in control, and the system is simply providing added safety benefits. For automated control applications, such as automatic braking the controllability is likely to be less than 90% (C3) since the driver is not in control, and if the system fails it is probably too late for the driver to react properly.

Table 2.3-4 below provides the ASIL as a function of degree of automation and severity. These attributes are more directly relatable to the various ITS applications described in this report.

The reliability (confidence) levels included in the table are based on a 5,000 hour usage life for a vehicle. This is nominally 150K miles at an average speed of 30 mph, or a 5% duty cycle over a 12 year average life span using the well-known reliability formula:

Reliability = $e^{-\lambda T}$

Using these assessments, the ASIL levels for different applications were developed characterized by the consequence of the failure.

Table 2.3-4. ASIL Levels by Application Type
Source: ARINC April 2012

<table>
<tr><th colspan="2"></th><th colspan="3">Type of Application</th></tr>
<tr><th colspan="2">Severity</th><th>Non-Automated
(e.g. Warning)</th><th>Automated
Discontinuous
(e.g., Braking)</th><th>Automated
Continuous
(e.g., Steering)</th></tr>
<tr><td>S0</td><td>ASIL QM (not safety critical)
PDF< 10^{-4}
Conf.=59.1%</td><td>ASIL QM (not safety critical)
PDF< 10^{-4}
Conf.=59.1%</td><td>ASIL A
PDF= 10^{-6} to 10^{-5}
Conf.=97.4%</td><td>ASIL B
PDF= 10^{-7} to 10^{-6}
Conf.=99.7%</td></tr>
<tr><td>S1</td><td>ASIL QM+
PDF= 10^{-5} to 10^{-4}
Conf.=76.9%</td><td>ASIL QM+
PDF= 10^{-5} to 10^{-4}
Conf.=76.9%</td><td>ASIL B
PDF= 10^{-7} to 10^{-6}
Conf.=99.7%</td><td>ASIL C
PDF= 10^{-8} to 10^{-7}
Conf.-99.97%</td></tr>
<tr><td>S2</td><td>ASIL A
PDF= 10^{-6} to 10^{-5}
Conf.=97.4%</td><td>ASIL A
PDF= 10^{-6} to 10^{-5}
Conf.=97.4%</td><td>ASIL C
PDF= 10^{-8} to 10^{-7}
Conf.-99.97%</td><td rowspan="2">ASIL D
PDF< 10^{-8}
Conf.=99.997%</td></tr>
<tr><td>S3</td><td>ASIL B
PDF= 10^{-7} to 10^{-6}
Conf.=99.7%</td><td>ASIL B
PDF= 10^{-7} to 10^{-6}
Conf.=99.7%</td><td>ASIL D
PDF< 10^{-8}
Conf.=99.997%</td></tr>
</table>

Per the USDOT FHWA *Safety at Signalized Intersections (2008*) [23], there were 41,059 fatalities in 2007 on US corridors with 79% at non intersections and 21% at intersections (8,622) with 32% (2,759) being at signalized intersections. The total number of intersection accidents per year in 2008 (reference) was 1,700,000 accidents/year. Of these, 302,000 occurred at signalized intersections. The 8,622 fatalities at intersections thus represent 0.005 fatalities per intersection accident and 0.001 fatalities per signalized intersection accident. Of the total intersection fatalities, 39% were rural and 61% were urban. Red-light running accounted for approximately 32.7% of the signalized intersection fatalities. Thus, for accidents at a signalized intersection, there is a 0.1% probability of a fatality.

Per the Insurance Institute for Highway Safety, Q*&A: Urban Crashes* (March, 2011) [24] there were 1.2 million urban crashes in 2009 with 55% at signalized intersections and 21% at stop signs. Of the 660,000 crashes at signalized intersections, 52% resulted in injuries (342,200) or 0.52 injuries/signalized intersection accident, with approximately 10,000 fatalities or 0.02 fatalities/signalized intersection accident. Of the 342,200 injuries, 61% involve injuries to pedestrians.

In a Caltrans report entitled, “Why Manage Access to the State Highway System”, by Philip Demosthenes (10-18-2007) [25], the yearly accident rate of 0.7/intersection for a rural un-signalized intersection versus 1.4 accidents per year per urban un-signalized intersection is presented. The Rural signalized intersection accident rate is specified to be 4.8/intersection/year and the urban signalized intersection accident rate is specified to be 6.2/ intersection/year.

From this it can be concluded that if an accident occurs at a signalized intersection, there will be a 52% probability of an injury (presumably typically minor), and a 3% probability of a fatality.

Following the ASIL method, a 3% probability of fatality equates to ASIL A, and for an automated braking application (where controllability is lower), this corresponds to ASIL B.

To determine the confidence in the communications element of the system, it is necessary to develop a failure model that allocates failure rates across the various components of the application. These components and their associated failure rates are summarized in Table 2.3-5 below.

Table 2.3-5. Failure Rate Allocation
Source: ARINC April 2012

Element	Failure Rate
Traffic signal controller provision of signal phase and timing (SPaT) information	$1x10^{-5}$
Generation of a SPaT message	$1x10^{-5}$
Communication of the SPaT message	Based on minimum established, 0.7 probability of packet delivery, BER = $2.5x\ 10^{-4}$.
Decoding of the SPaT message	$1x10^{-5}$
Assessment of vehicle state (speed and position) relative to the application decision point	$1x10^{-5}$
Human execution of the application action. (Note: varies with age, complexity of Task and stress level; FR provided is typical; see *Reliability, Maintainability and Risk* by Dr. David J. Smith, 2005. Also note that under high stress conditions with reasonably complex human actions FR of 0.16 is applicable.)	$0.75x10^{-3}$

The communication of the message and the determination of vehicle state are expected to relatively high failure rate steps. The failure rate of the application action step depends on the action. For example, if the action is to automatically apply the brakes to achieve a desired deceleration level, the failure rate is relatively low (Braking systems are among the most reliable components on a vehicle). If, on the other hand, the application action is to warn the driver to take evasive action, we must then consider the failure of the warning to elicit the desired response.

These situations are analyzed below.

2.3.3.1 **Automated Braking Case:**

The automated braking application requires SIL 2, or a failure rate less than about $0.5x10^{-2}$. If we assume that the failure rates of the communications and positioning steps are the same, and if we assume that the failure rates of the other steps are all $1x10^{-5}$, then, based on a required failure rate of $0.5x10^{-2}$, the required failure rates for the communications and positioning elements are:

$\lambda_{POSITIONING}=\lambda_{COMM}=1/2(0.5x10^{-2}-4x10^{-5}) = 2.48x10^{-2}$, or a confidence level of 97.5%.

2.3.3.2 **Intersection Warning Case:**

The general error rate for a task performed incorrectly is given in Appendix 3 as $1x10^{-3}$. The failure to notice major crossroads is given as $0.5x10^{-3}$. So, we can be reasonably assured that the failure to respond correctly to a warning is about $0.75x10^{-3}$. Using this value with the failure rates for the other steps in the process, the failure rate for the communications and positioning elements is given by:

$\lambda_{POSITIONING}=\lambda_{COMM}=1/2(0.5x10^{-2}-3x10^{-5}-0.75x10^{-3}) = 2.11x10^{-3}$, or a confidence level of 99.8%.

It is interesting to note that a substantial portion of error budget is consumed by human error, leaving each of the other elements of the application being required to perform with relatively low failure rates. If the human error level is higher (the reference identifies routine error rates as high as $0.5x10^{-1}$), then the entire error budget and more may be consumed by the human error component. Again, human failure rate increases with stress level and complexity of a task, which could result in a high human failure rate for a multi-vehicle collision avoidance action. This may explain why warning systems have a history of somewhat inconsistent performance.

For situations where the response is relatively intuitive, the error rate may be relatively low, but in situations where the appropriate response is not intuitive, for example, responding to a skid, the error rate is likely to be much higher.

Figure 2.3-3 illustrates the probability of failure for a typical CSMA (e.g., DSRC) system as a function of message repeats (Ref: “Design and Analysis of Highway Safety Communication Protocol in 5.9 GHz Dedicated Short Range Communication Spectrum”, Jiang, Xu and Sengupta, IEEE) [26]). As can be seen in this figure, to achieve a communications failure rate of 10^{-3} requires about 11 message repeats.

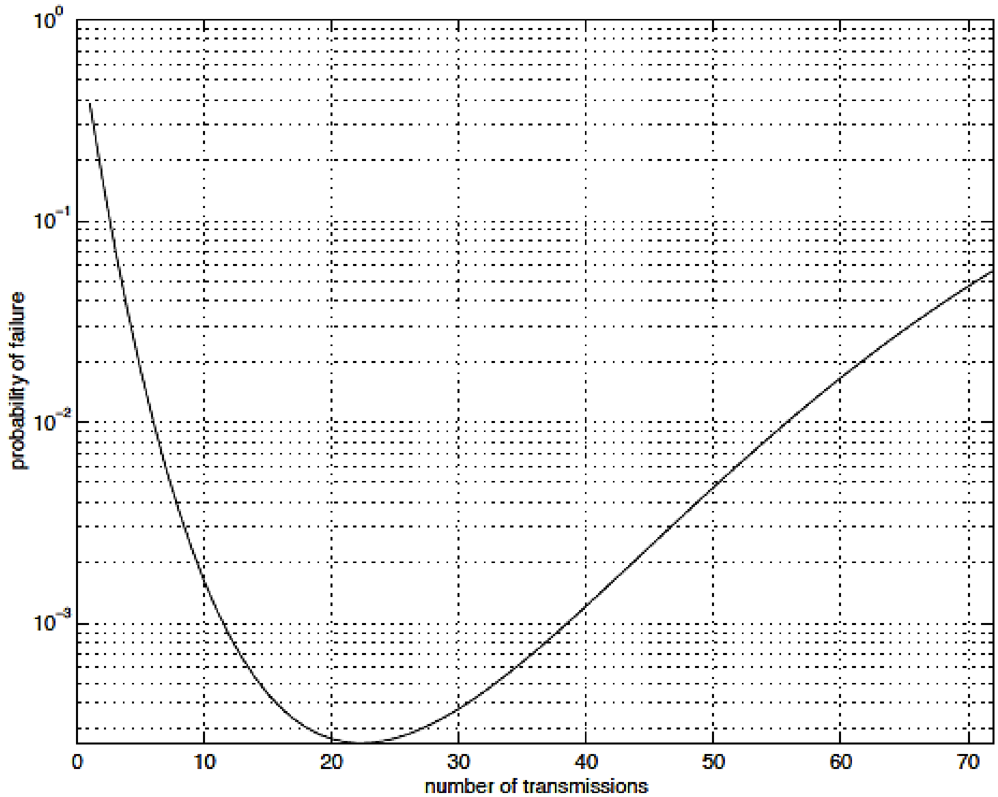


Figure 2.3-3. Communications Reliability versus Message Repeats (for CSMA, See Appendix 3)
(Ref: "Design and Analysis of Highway Safety Communication Protocol in 5.9 GHz Dedicated Short Range Communication Spectrum", Jiang, Xu and Sengupta, IEEE [26])

2.3.4 *Latency Requirements*

This section summarizes the key elements in the RSE and OBE architecture that contribute to communications latency. These architectures are derived from a variety of different implementations that are described in more detail in Appendix D.

The basic architecture from a latency perspective is shown in Figure 2.3-4 below. Here we can see that there are time consuming steps associated with acquiring data from external sensors, processing the data, generating an appropriate message, accessing the communications system, sending the message, receiving the message and then decoding it and taking appropriate action. The activities if acquiring data, generating the message, decoding the message and acting on the message can be considered to be independent of the type of communications system. The type communication system, however, will have a substantial impact on the latency. This is described below.

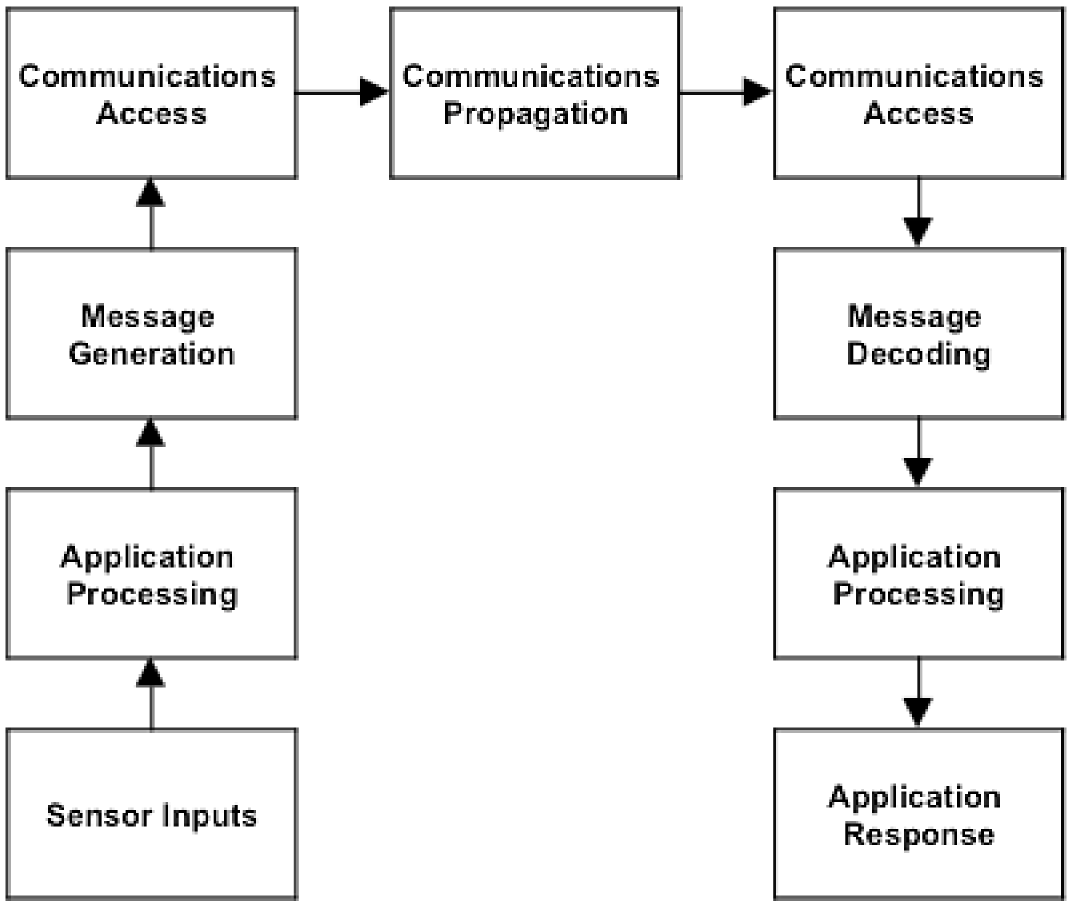


Figure 2.3-4. Basic Latency Blocks in Typical End To End Architecture
Source: ARINC April 2012

The latency diagram above does not change depending on whether the transmitter is the RSE or the OBE, although, obviously, the resulting delays for each step are likely to be different. For a Wave Short Message of 1500 bytes and a 3 mbps data transmission rate, transmission time is 4 msec. Applications processing time using a multi-core computer is small (tens of nanoseconds range). The largest latency comes from sensor data processing which could be several seconds, considering target tracking and fusion. Application response time, that can also be several seconds, especially with a human in the sensing and control loop.

Table 2.3-6 presents basic latency associated with preparing a message though the reception and execution of the application action. These times are based on a 3 GHz, multi-core, applications processor, data rate and propagation distance shown in the table and no time allocation for link access. As can be seen in the table, the total latency is 22.5 msec plus the network and communications system delays. This assumes that the propagation delay is only an over the air delay (3×10^8 m/s = 1.7 µsec for 500 m distance, which is insignificant). If a land side network is used to distribute messages to a remote broadcast transceiver, then routing delays must be considered over an IP network.

For safety applications 100 msec latency is considered to be maximum acceptable, (Ref: “A Secure VANET MAC Protocol for DSRC Applications”, Yi Qian, et al, National Institute of Standards and Technology [27]). DSRC specifications define a basic latency of 50 msec, which is generally based on the assumption of a 100 msec channel-switching interval, so the CCH or SCH may be unavailable for up to 50 msec. In a report titled, *Communications Performance Evaluation of Cooperative Collision Warning Applications* [25], simulation results for DSRC indicated an average latency of 20.5 msec and a maximum latency of 218 milliseconds.

Table 2.3-6. Basic Allocation of Latency Associated with Transmitting a SPaT Message to a Vehicle

Source: ARINC April 2012

Event	Functional Unit	Basic Latency Budget
Generate Interrupt Based on Time of Required Message Response	Management Processor	12 nsec
Extract Data, Format Message, Time Stamp and Transfer to Communications Function	Applications Processor	120 nsec
Add Communications Protocol and Message Data and send to Modem/Transmitter	Communications Processor and Switch/Router	60 nsec
Modulate Protocol and Data and Transmit	Modem/Transmitter	800 μsec (300 byte @ 3 mbps)
Network Access	Modem/Transmitter	Depends on Communications System
Network Routing	Communications Network	Depends on Communications System
Message Propagation Delay	RF Propagation	1.7 μsec (500 meters)
Receive and Demodulate Signal	Receiver/Modem	10 nsec
Identify Message Type and Transfer to Applicable Processor	Switch/Router and Communications Management Processor	40 nsec
Interpret Message, Determine Time Delay (Current time - Time Stamp), Retrieve Current Position, and Issue Action Command	Applications Processor	120 nsec
Action	Control Devices	20 msec; (Human = 2 sec)

(Note: No Link access latency is included nor retransmission of packets; also no sensor data latency is included, which could be several seconds, depending on the type of sensor and associated algorithms used)

The network access and network routing latencies identified in the table above depend heavily on the type of communication system being used. For example, broadcast systems do not include any network access time, since the receiver can be considered to be always on, and waiting to receive a broadcast message. For networked systems that require an address to deliver a message (for example, any IP network), the worst-case latency will be observed at a local link handoff. In this case the mobile terminal will have entered a region served by a base station or hub that has a new link local address. In order to receive a message, the mobile terminal must, at a minimum learn this link local address. If the system is using addressed communication, then the system must learn the address and location of the terminal to determine if it should send a particular message, and this will involve added latency. Similarly, with or without addressing, a short-range system is likely to involve point-to-point communications, so the routing delay will be negligible. For a wide area system, the worst-case delay will be if the signal controller must send the signal state information over a backhaul link to a wide area system. This may involve the message passing through a variety of routers and traveling over relatively long distances. Quality of service level for the service can impact latency through the wide area network. For example, the LTE base may be located 1 Km from the mobile unit, but the access point to the LTE system may be miles from the RSE cabinet, so the overall propagation delay (assuming all of the propagation is at the speed of light) will be on the order of 300 to 500 microseconds. (Signals propagate via optical fiber at 2×10^8 m/s and about 1.8×10^8 via copper lines.)

It is also important to consider that latency may or may not matter, depending on how the application is configured. If the SPaT information is relative to a common time frame (for example, relative to a GPS time mark), then, unless the message arrives too late for the application to act, the application can still determine the proper actions and timing. For example, if the SPaT message says that the signal is currently green and will change to yellow 5700 milliseconds from the last GPS time mark (e.g., the PPS epoch), even if the message took a full second to arrive, the application would still have 4700 milliseconds to respond. As a result, it does not appear that for the SPaT application, latency is a significant requirement unless the latency approaches the time required for a vehicle to travel some portion of the distance between the first reception of the SPaT message, and the intersection entry point. The distance to the first SPaT reception is about 820 feet (250 meters) (nominal urban I2V range with multipath), and the worst case intersection entry point is located between 119 feet/36 meters (at 30 mph/48 kph) and 579 feet /176 meters (at 75 mph/121 kph). This time period ranges from 15.9 seconds (at 30 mph/48 kph) to 2.2 seconds (at 75 mph/121 kph). Thus, in the worst case situation, the vehicle would have to start receiving its first SPaT message at 2.2 seconds from the stop line, assuming 4 messages are required to provide the required probability of error free message reception). Under nominal road situations (45 mph/72 kph) this time period is 8.9 seconds.

2.3.5 *Bandwidth Requirements*

2.3.5.1 **Intersection Safety Related Data Load**

The Task 2 report (Ref: "Communication Systems Analysis for SPaT Applications in Advanced ITS Vehicles; Task 2 Technical Report: Interim Report on Application Identification using SPaT, Characterization of the RF Environment, and Communication Requirements"; July, 2011 [2]) analyzed the data communications demands associated with intersection safety applications. These are summarized in Table 2.3-7 below.

Table 2.3-7. Summary Results of SPaT Related Applications Communications Requirements Analysis from the Task 2 Report
Source: ARINC April 2012

SPaT Applications Requirements & Characteristics Summary									
Requirements		**RLR**	**LTA**	**RTA**	**PREEMPT**	**TSP**	**FSP**	**RCRLV**
GID Msg.	Size (octets)	2,857	2,857	2,857	2,857	2,857	2,857	2,857
	Tx. Window (msec)	998.98	998.98	998.98	998.98	998.98	998.98	998.98
	Repeats	4	4	4	4	4	4	4
SPaT Msg.	Size (octets)	383	379	383	354	357	357	335
	Tx. Window (msec)	76.23	75.17	77.26	97.07	97.07	97.07	76.23
	Repeats	4	4	4	4	4	4	4
HIA Msg.	Size (octets)	N/A	339	339	N/A	N/A	N/A	N/A
	Tx. Window (msec)	N/A	98.42	98.42	N/A	N/A	N/A	N/A
	Repeats	N/A	4	4	N/A	N/A	N/A	N/A
Request Msg.	Size (octets)	N/A	N/A	N/A	376	376	376	N/A
	Tx. Window (msec)	N/A	N/A	N/A	997.28	997.28	997.28	N/A
	Repeats	N/A	N/A	N/A	4	4	4	N/A
Status Msg.	Size (octets)	N/A	N/A	N/A	347 / 354	347 / 354	347 / 354	N/A
	Tx. Window (msec)	N/A	N/A	N/A	977.2 / 76.9	977.2 / 76.9	977.2 / 76.9	N/A
	Repeats	N/A	N/A	N/A	4 / 4	4 / 4	4 / 4	N/A
RT Msg.	Size (octets)	N/A	N/A	348	N/A	N/A	N/A	N/A
	Tx. Window (msec)	N/A	N/A	97.27	N/A	N/A	N/A	N/A
	Repeats	N/A	N/A	4	N/A	N/A	N/A	N/A
Comm. Type		V2I	V2I – V2V	V2I – V2V	V2I	V2I	V2I	V2I

SPaT Applications Requirements & Characteristics Summary

Requirements		RLR	LTA	RTA	PREEMPT	TSP	FSP	RCRLV
Min. Data Rate (Kbps)		40.194	40.335	39.648	36.78	36.78	36.78	35.26
Min. Com. Range (m)		320	332.08	324	557.33	557.33	557.33	132.5
QoS	Comm. Svc.	BE	BE	BE	BE	BE	BE	BE
	Throughput (kbps)	41	41	40	37	37	37	36
	Bandwidth (Mbits)	6	6	6	6	6	6	6
	Transit Delay (msec)	77 – 999	76 – 999	77 – 999	77 – 999	77 – 999	998	76
	BER**	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
	Char.	T&S C	T&S C	T&S C	T&S C	TC	TC	T&S C
References		3.2	3.3	3.4	3.5	3.6	3.7	3.8

Notes: 1) TC= Time Critical; BE = Best Effort; 2) GID Msg: I2V; SPaT Msg: I2V; HIA Msg: V2I/V2V; Preempt Request Msg: V2I; Status Msg: I2V; RT Msg: V2I; 3) Data Rate for CCH = 6 mbps

As described in the Task 2 report, these requirements were derived based on the operational scenarios, and the assumptions about the use of the SAE J2735 messages, specifically the 100 msec repeat intervals for SPaT messages. Appendix B includes an alternate analysis based on the Automotive Safety Integrity Level analysis initially developed as part of the positioning project that is a companion to this project. In that analysis, no assumptions about message repeat intervals were made. Instead the message repeat intervals were based on required QoS/reliability, and the physical range of the radio system. Thus, the system was required to provide SPaT information at the communications reliability level needed, to assure a failure rate required by the specified Automotive Safety Integrity Level (ASIL) corresponding to the application. The application geometry defines a minimum range at which this message must be delivered; unfortunately with a broadcast communications the SNR is not known and the data rate/modulation is preselected. The RSE does not know the maximum usable range, so the channel reliability must be based on an average measurement of BER over the typical usable range of the system, This is estimated at 70%. To comply with the ASIL for the application, the message must be repeated a sufficient number of times during the time interval, that a typical vehicle passing between the outer limit of range, and the closest application decision point will have received the message with the required probability. This approach makes use of the fact that, up to a point (where the repeats congest the channel itself), repeating a message increases the communications reliability through redundancy. The standard formula for probability of providing an error free message (P_{ef}) based on repeated transmissions is:

$P_{ef} = 1 - (1 - P_{st})^N$

Where P_{st} = probability of error free message delivery with one transmission, and N = the number of transmissions.

Assuming a $P_{st} = 0.7$ (which is typical of DSRC reception at 200 meters), then 4 transmissions of a SPaT message would provide: $P_{ef} = 1 – (1- 0.7)^4 = 0.9919$.

In general, the data load offered by intersection safety applications is low, on a per intersection basis, relative to what is referred to in this report as DSRC “background communications”. This background includes BSM/HIA messages, safety alerts, roadway weather messages, etc. The SPaT related applications represent approximately 1% of the total load assuming RSE and OBE DSRC devices are operating at 6 mbps data rate. (Note that 6 mbps is insufficient bandwidth to accommodate background communications requirements at/near a congested intersection).

However, if a wide area, wireless communications technology is considered, the number of intersections within the “footprint” becomes significant. A 500 signalized intersection footprint would place a 22 mbps data load on a wide area wireless link and a 2000 signalized intersection footprint would require 88 mbps for only SPaT broadcast.

2.3.5.2 **Basic Safety Message Load**

In order to determine the background communications data load for the Basic Safety Message, it is necessary to model the system under various vehicle packing densities.

With an average vehicle length of 4.6 m (15 ft.) plus 4.6 m headway, each lane can carry 0.11 vehicles per meter. Assuming a minimum of one lane in each direction, and, thus, 8 lanes for each intersection, the maximum vehicle density is 0.88 vehicles per meter of range. For a 4-lane intersection, the density will be double this value. Table 2.3-8 below provides the total number of vehicles communicating in range as a function of range for 2-lane crossings and 4-lane crossings.

Table 2.3-8. Wore Case Vehicle Counts versus Communications Range for Intersections
Source: ARINC April 2012

	Crossing Type	
Range (m)	**2-Lane**	**4-Lane**
50	44	88
100	88	176
200	176	440
500	440	880
1000	880	1760

As can be seen in the table, for realistic V2V ranges of 200 meters or less, between 176 (2 lanes) and 440 (4 lanes) vehicles may be competing for communications access and bandwidth.

The BSM message SAE J2735 Part 1 is 339 bytes (2,712 bits). Part 2 of the message is 2091 bytes (16,728 bits). The BSM is transmitted 10 times per second per vehicle equating to a 27,120 bps data load for Part 1, and 167,280 bps per vehicle for Parts 1 and 2 (Part 2 is not sent by itself). Table 2.3-9 below illustrates the bandwidth required to communicate these volumes of data at the desired 10 Hz message rate under various vehicle density and messaging assumptions.

Table 2.3-9. BSM Bandwidth Demand versus Vehicle Density
Source: ARINC April 2012

Vehicle Count	BSM Part 1 Only	BSM Parts 1&2
88	2.39 Mbps	14.72 Mbps
176	4.77 Mbps	29.44 Mbps
440	11.93 Mbps	73.60 Mbps

Each conventional 10 MHz DSRC channel is capable of sustaining a data rate of about 6 Mbps, assuming no channel access contention (although researchers indicate that 4.5 mbps is an optimum compromise between message delivery reliability and data rate; see Optimal Data Rate Selection for Vehicle Safety by Daniel Jiang, et al, Mercedes Benz R&D America, 9-15-08) [29]. So if the SPaT and other messages must compete with these V2V messages, the system cannot operate with more that about 100 meters range (176 vehicles) using BSM Parts 1 &2. If V2V messages are restricted to only use BSM Part 1, then the range can be increased to about 200 meters. It is also important to point out that using DSRC, the V2V applications themselves will be limited to about 100 meters range, and that, unless the range is severely reduced, BSM Part 2 cannot be used in congested areas.

In cities with 2 or more lanes in each direction and during major congestion, BSM messages will consume most of the channel bandwidth, and are likely to disrupt SPaT message transmission, thus impacting the quality of service below an acceptable limit.

2.3.5.3 **Safety Message Load**

Other safety related broadcast messages include:

- Road Hazards (potholes, debris in road; etc.) warning;
- Accident/incident warnings;
- Weather Conditions Warnings;
- Roadwork Information and Lane Closures;
- In-Vehicle Variable Speed Limit Information;

- Traffic Congestion Warning;
- Road Closure and Detour Warning;
- Special Event Route;
- Reversible Lane Change Warning.

Incidents per population density are around 0.15 per 1000 population per year. For other traffic safety related events, an estimate of 0.3 per 1000 population is used, so a typical city of population 100K would experience about 45K events per year, Each event is expected to last for about 30 minutes, so this equates to about 2.6 parallel incident events during each 30 minute segment, per 100K population. Message size related to a safety warning is estimated to be 1.5 kb (12 Kbits), so the total data volume related to incidents at any given time is about 31Kbits, per population of 100K.

For DSRC, each event would be location specific, so the total number of messages being sent from a given DSRC RSE would depend on the number of intersections in the city. This is developed below.

2.3.5.4 **DGPS Message Load**

Vehicle OBEs also require differential corrections for the vehicle GPS receiver. Current Radio Technical Commission for Maritime Service (RTCM) SC-104 message standards Version 2.3 applies to differential GPS (DGPS) using a 283.5 to 325 KHz frequency band providing a 200 bps data rate. Improved performance is required with 1 kbps needed to support the higher accuracy, compressed DGPS augmentation data message format (as used in HA-DGPS test), or 2.4 kbps to comply with RTMC Version 3, message type 18 (which supports high accuracy augmentation).

Each reference station covers an area about 120 miles in diameter, so data from a single reference station would be sufficient to support a metro region.

2.3.5.5 **GID Message Load for Wide Area Communications Systems**

The data load associated with SPaT applications provided in Table 2.3-6 included GID message data load. However, the GID messages may optionally be distributed to vehicles using a wide area broadcast communications technology. The GID distribution load on a wide area broadcast link compatible with wireless, mobile operations is developed in this section.

The GID or MAP (J2735) data payload is 1,318 octets (10,544 bits). This includes description fields and security overhead. Generally any wireless system will add about 30% to this message size due to system overhead (e.g., message headers and such).

The GID only needs to be received once by a vehicle while in the jurisdictional area (assuming that the vehicle has data storage capability for the GIDs), although the GID must still be sent regularly to assure that vehicles that have recently entered the region receive this information, and that any changes or updates to the GID (for example, to account for roadwork or an accident) are communicated in a timely manner. Generally it is expected that each GID would be sent every 30 seconds to allow a vehicle that had just started to receive any GID in the region. Obviously a GID sent from a DSRC RSE would be unique to either the intersection associated with that RSE or that intersection and those nearby.

2.3.5.6 **Data Load Analysis by City Type**

The typical city has 59 signalized intersections per population of 100,000 (Ref: "Traffic Signal Maintenance and Design", Ramsford McCourt [30]). Table 2.3-10 presents population and geographic attributes of a variety of metro regions and cities in the continental United States (Ref: Wikipedia [31] and National League of Cities [32]). These cities represent a typical cross-section of U.S. cities.

Table 2.3-10. Size of Cities and Towns in the Continental USA
(Ref: Wikipedia [31] and National League of Cities [32])

Metropolitan Combined Statistical Area	Population	Traffic Signals (GIDs)	Incidents (average No. at any time)	Geographic Area (sq-mi)	Geographic Radius (mi)
New York/Newark	18M	10,260	450	6,400	46
Los Angeles/Riverside	17M	9,690	425	34,000	104
Dallas/Ft. Worth	6M	3,420	150	9,100	54
Minneapolis/St. Paul	3M	1,710	75	6,360	45
Indianapolis	1.7M	969	43	3,215	32
Dayton, OH	800K	456	20	1,808	24
Ann Arbor, MI	350K	200	9	706	15
Joplin, MO	175K	100	4	28	3
Pocatello, ID	90K	51	2	1,800	24
Carson City, NV	50K	28	1	153	7
Petaluma, CA	57K	32	1	13	2
Nevada City, CA	3K	2	.1	3	1

Table 2.3-11 summarizes the number of bits associated with GID, Safety and DGPS (non-SPaT) messages for each of the major city types described above.

Table 2.3-11. Typical Non-SPaT Data Loads
Source: ARINC April 2012

Metropolitan Combined Statistical Area	Traffic Signals	Total GID Bits	Total Incident Bits	Total DGPS Bits	Total Non-Intersection Bits
New York/Newark	10,260	108 Mbit	5.4 Mbit	72 Kbit	114 Mbit
Los Angeles/Riverside	9,690	102 Mbit	5.1 Mbit	72 Kbit	107 Mbit
Dallas/Ft. Worth	3,420	36 Mbit	1.8 Mbit	72 Kbit	38 Mbit
Minneapolis/St. Paul	1,710	18 Mbit	900 Kbit	72 Kbit	19 Mbit
Indianapolis	969	10 Mbit	510 Kbit	72 Kbit	10.6 Mbit
Dayton, OH	456	5 Mbit	240 Kbit	72 Kbit	5.3 Mbit
Ann Arbor, MI	200	2 Mbit	105 Kbit	72 Kbit	2.2 Mbit
Joplin, MO	100	1 Mbit	52 Kbit	72 Kbit	1.1 Mbit
Pocatello, ID	51	540 Kbit	27 Kbit	72 Kbit	640 Kbit
Carson City, NV	28	300 Kbit	15 Kbit	72 Kbit	387 Kbit

Metropolitan Combined Statistical Area	Traffic Signals	Total GID Bits	Total Incident Bits	Total DGPS Bits	Total Non-Intersection Bits
Petaluma, CA	32	342 Kbit	17 Kbit	72 Kbit	431 Kbit
Nevada City, CA	2	18 Kbit	1 Kbit	72 Kbit	91 Kbit

The data rate required to deliver this data depends on the footprint of the wide area communications system and the message transmission frequency. HD radio and Digital television typically have a range of about 30 miles and cover an area of about 3000 square miles. LTE range depends on the installation. For example, a municipal LTE setup is likely to have the maximum achievable range in order to minimize equipment cost. This range is about 5 miles, or about 78 square miles. Femtocell installations can have range on the order of DSRC (e.g., 100 meters or so), but in this sort of installation the cost would be equivalent to a DSRC approach. Table 2.3-12 below illustrates the number of base station installations of each type required to deliver the required data rate, and required to cover the required area. Fractional installations in the table indicate that a portion of the installation capacity would be available for other uses. As can be seen in the table, some cities are area limited, while others are data rate limited. For example, while New York and Los Angeles could technically be served by a single LTE base station from a bandwidth perspective, the geographic areas for either of these regions is so large that a single LTE installation would be unable to effectively serve the entire region. Similarly, HD Radio and TV are almost perfectly suited for smaller cities with populations around 100K because of their limited data rate (and assuming that the total bandwidth is dedicated to safety applications. In general, the smaller footprint of LTE means that the available bandwidth is not entirely used, and the dominant driver of the number of base stations is the geographic coverage. For smaller cities this approach appears to be viable, but as the geographic area increases the number of base stations requires grows rapidly (e.g., 435 for the greater Los Angeles area). In cities smaller than Indianapolis either approach is viable. It should be noted that broadband LTE service per eNodeB is based typically on a 30% subscriber utilization and that data rates are asymmetrical (down link much greater than up link); a jurisdictional LTE network would be required to appropriately allocate and manage bandwidth assigned for safety applications.

Table 2.3-12. Wide Area Stations Required to Serve Non-SPaT Data Load
Source: ARINC April 2012

Metropolitan Combined Statistical Area	Number Base Stations Required for Bandwidth		Number Base Stations Required for Area		LTE Limitation	HD Radio/TV Limitation
	Municipal LTE	Digital Radio/TV	Municipal LTE	Digital Radio/TV		
New York/Newark	1.140	380/12.667	82	2.2	Area	Data Rate
Los Angeles/Riverside	1.070	357/11.889	433	11.3	Area	Data Rate
Dallas/Ft. Worth	0.380	127/4.222	116	3.1	Area	Data Rate
Minneapolis/St. Paul	0.190	63.3/2.111	81.	2.1	Area	Data Rate
Indianapolis	0.106	35.3/1.178	41	1.1	Area	Data Rate
Dayton, OH	0.053	17.7/0.589	23	0.6	Area	Data Rate
Ann Arbor, MI	0.022	7.3/0.244	9	0.2	Area	Data Rate
Joplin, MO	0.011	3.7/0.122	0.4	0.01	Area	Data Rate
Pocatello, ID	0.064	2.1/0.071	23	0.6	Area	Data Rate
Carson City, NV	0.039	1.29/0.043	2	0.1	Area	Data Rate
Petaluma, CA	0.043	1.44/0.048	0.2	0.004	Area	Data Rate
Nevada City, CA	0.009	0.3/0.010	0.04	0.001	Area	Data Rate

Note: Based on LTE data rate max = 100mbps (2x2 MIMO and 20 MHZ BW); Digital Radio data rate = 300 kbps and M/H TV data rate = 9 mbps. LTE eNodeB radius = 5 mi; Digital Radio/TV radius = 30 mi.

If all communications is based on DSRC, since the DSRC installations to support SPaT messages would be located at intersections, each intersection RSE would be responsible for delivering a smaller subset of the overall data load. This means that each RSE would be responsible for one GID, a portion of the incident data (e.g., all incidents distributed across all intersections), and all of the DGPS correction data (since this is required everywhere), and the DSRC channel(s) in the vicinity of an RSE would be required to support this load, plus the BSM elements described above. This data load must be carried over either the Service Channel or the Control Channel.

This data load is summarized by message type for various allocations of message types to channels for DSRC distribution in Table 2.3-13 below. For BSM we have assumed a 176 vehicle count.

Table 2.3-13. DSRC Data Load for Various Message-Channel Distributions
Source: ARINC April 2012

Scenario	Channel	BSM-1	BSM 1+2	SPaT	GID	Incident	DGPS	Total
All CCH	CCH	4.77 Mbps	29.44 Mbps	40 Kbps	400 bps	5 Kbps	2.4 Kbps	34.26 Mbps
Mixed CCH/SCH	CCH	4.77 Mbps	29.44 Mbps	40 Kbps				34.25 Mbps
	SCH				400 bps	5 Kbps	2.4 Kbps	7.8 Kbps
No BSM-2 All CCH	CCH	4.77 Mbps		40 Kbps	400 bps	5 Kbps	2.4 Kbps	4.82 Mbps
No BSM-2 Mixed	CCH	4.77 Mbps		40 Kbps				4.81 Mbps
	SCH				400 bps	5 Kbps	2.4 Kbps	7.8 Kbps

2.3.6 *RF Interference*

2.3.6.1 **Co-Channel Interference (Hidden Terminal Effects)**

Hidden terminal effects arise when the transmitter density is such that two transmitters out of range from each other will sense that the channel is open and will transmit simultaneously (since each will determine that the channel is clear). Figure 2.3-5 illustrates the "Hidden Terminal" situation (in this case one RSE is hidden from the other).

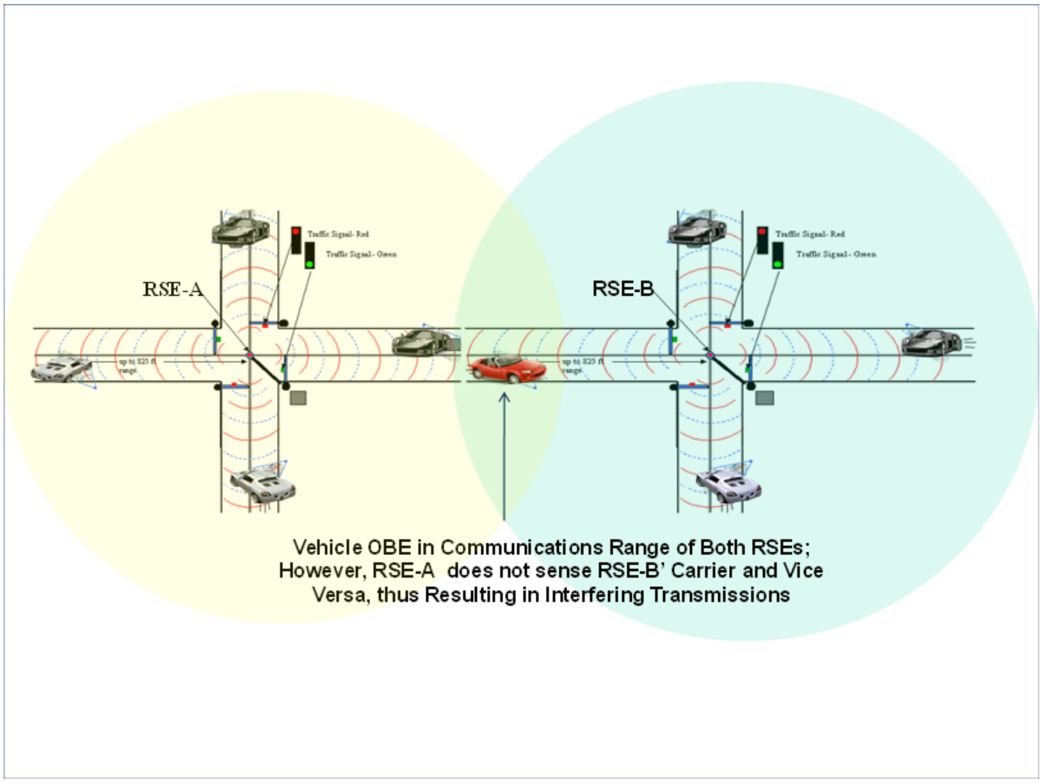


Figure 2.3-5. "Hidden Terminal" Interference Situation
Source: ARINC April 2012

A paper published in the Intelligent Transport Systems Telecommunications, (ITST), 2009 9th International Conference on ITS, (Ref: "An Analysis of Performance Degradation caused by Hidden Terminal and its Improvement in Inter-Vehicle Communication", by Takamasa Kuge, Kohei Ohno, and Makoto Itami, IEEE 2009 [33]) provided an analysis of the hidden terminal effect in vehicle to vehicle communications.

Figure 2.3-6 illustrates the packet error rate as a function of offered load from carrier sensing errors and from hidden terminal collisions.

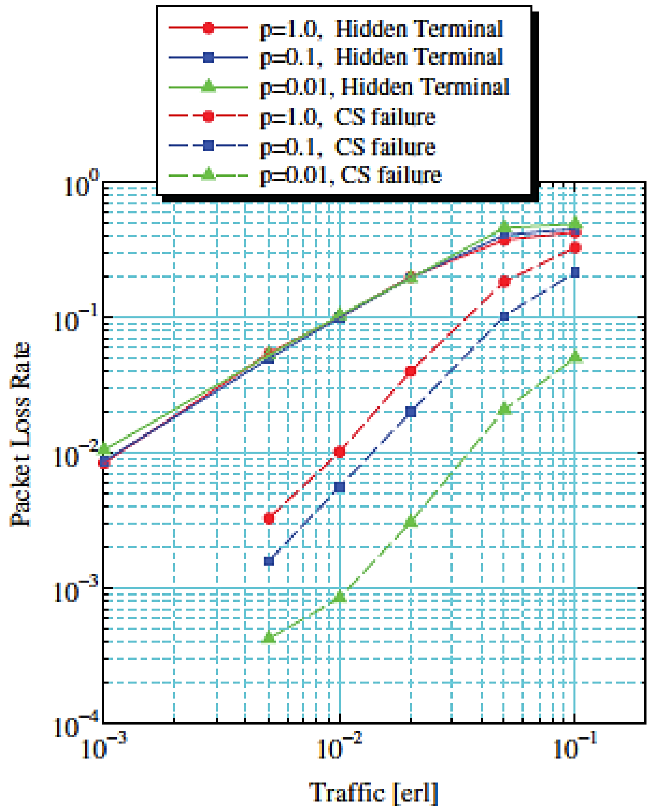


Figure 2**.3-**6**. Packet Losses from Carrier Sensing and Hidden Terminal Errors**
(Ref: "An Analysis of Performance Degradation caused by Hidden Terminal and its Improvement in Inter-Vehicle Communication", by Takamasa Kuge, Kohei Ohno, and Makoto Itami, IEEE 2009 [33])

This analysis was done with a range of 100 meters and 100 vehicles. The result indicates that, depending on the load, hidden terminal effects will contribute up to a 35% packet loss. In the situations described above, the channel load is maximum (all of the available channel resources are being demanded), so the reliability of the channel will be quite low. Hidden terminal testing is recommended considering performance with overlapping coverage and with non-overlapping coverage.

2.3.6.2 **Adjacent Channel Interference**

Adjacent channel interference occurs when transmissions on one channel between two communication terminals are disrupted by transmissions on a different (adjacent) channel. Most commercial communications systems have been developed so that adjacent channels do not interfere under typical operating conditions. Tests by the Vehicle Safety Communications consortium (VSC-A) indicate that this may be a serious issue for DSRC. Figure 2.3-7 below illustrates the issue.

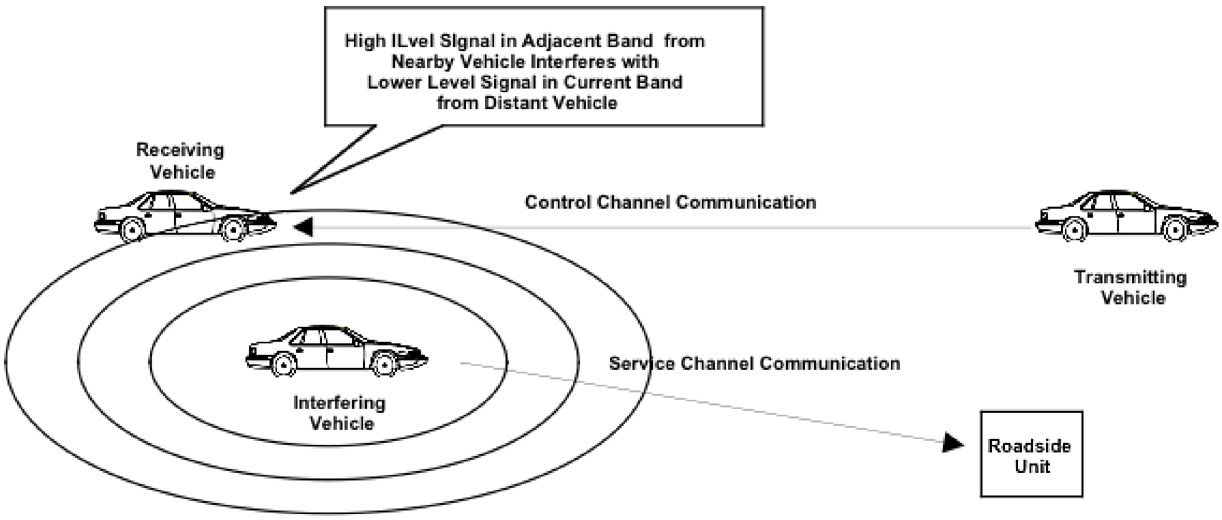


Figure 2.3-7. Interference from Emitter Operating in Adjacent Band
Source: ARINC April 2012

The FCC Report and Order (Ref: FCC December 17, 2003 Report and Order [34]), which established licensing and service rules for the Dedicated Short Range Communications (DSRC) Service in the Intelligent Transportation Systems (ITS) Radio Service in the 5.850-5.925 GHz band (5.9 GHz band), allocated spectrum in seven 10 MHz wide channels as shown in Figure 2.3-8 below. This channel allocation included identification of specific channels for specific purposes, for example, channel 174 was set aside as the control channel, 172 and 184 were set aside for V2V and intersection safety, and channels 174, 176, 180 and 182 were set aside for service operations.

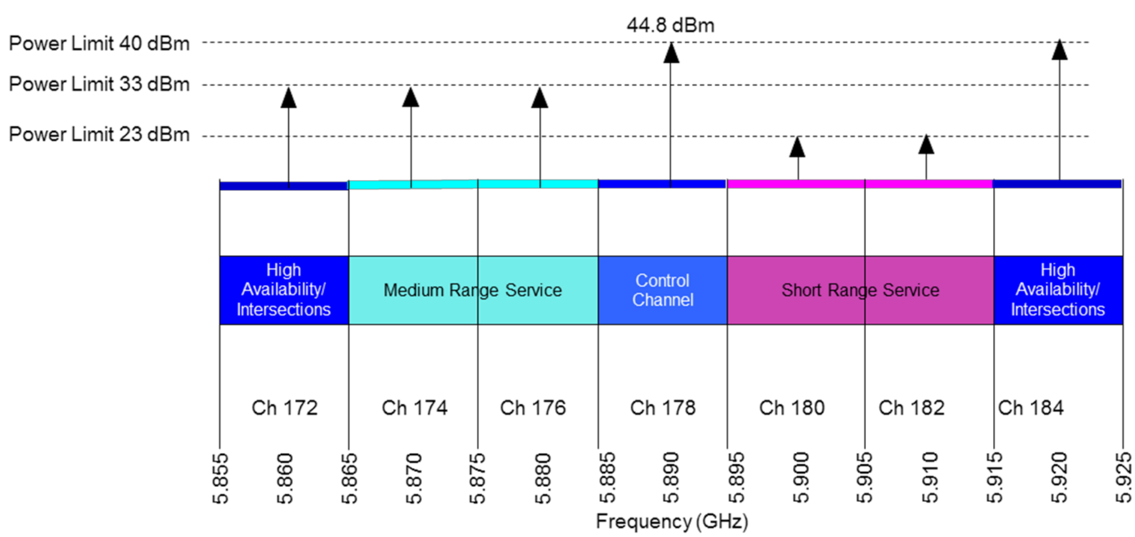


Figure 2.3-8. DSRC North American Spectrum Allocation
Source: ARINC April 2012

In order to achieve the highest channel bandwidth possible, the 802.11p specification only allows a few hundred kilohertz of band separation. This is defined by the “spectral mask” specification. Table 2.3-14 below provides the spectral mask requirement, and Figure 2.3-9 illustrates the spectral mask for a Class A transmitter for DSRC in North America (Ref: IEEE 802.11p specification [19]).

Table 2.3-14. Spectral Mask Requirements for DSRC in North America
(Ref: IEEE 802.11p Specification [19])

Station Class	± 4.5 MHz Offset	±5.0 MHz Offset	± 5.5 MHz Offset	±10 MHz Offset	±15 MHz Offset
Class A	0	-10	-20	-28	-40
Class B	0	-16	-20	-28	-40
Class C	0	-26	-32	-40	-50
Class D	0	-35	-45	-55	-65

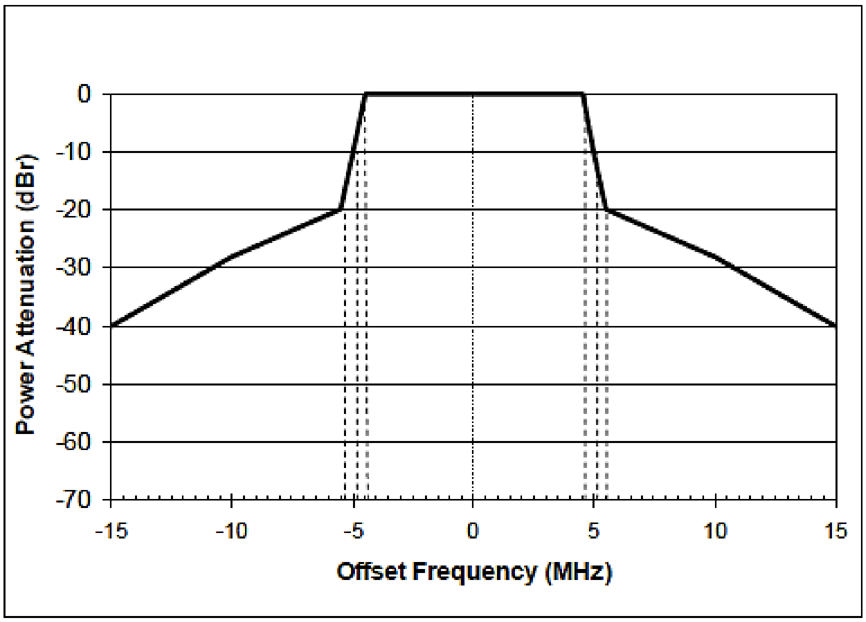


Figure 2.3-9. Spectral Mask for 802.11p Class A Transmitter
(Ref: IEEE 802.11p Specification [19])

Tests performed by the VSC-A indicate that using typical vehicle separations and ranges adjacent channel interference can produce up to about 25% packet error rate depending on channel load. The test setup is shown in Figure 2.3-10 below, and the results are summarized in Table 2.3-15.

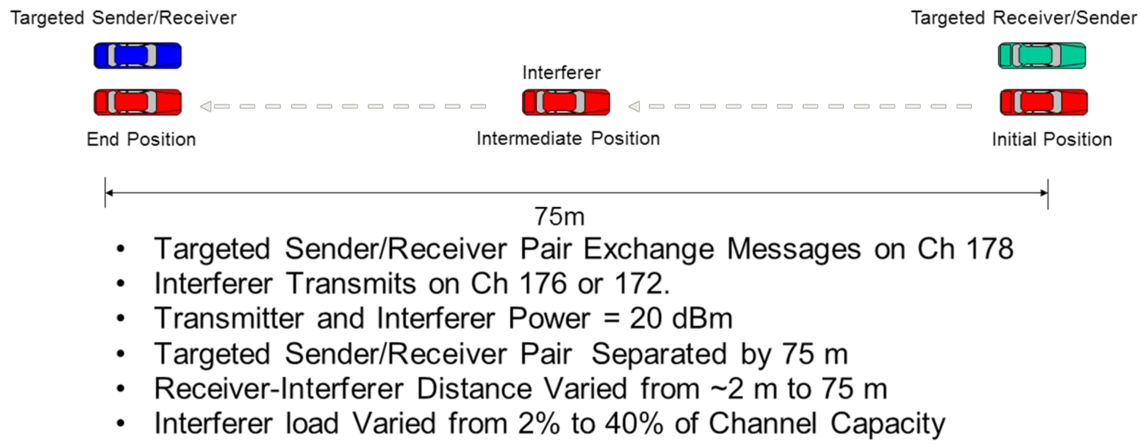


Figure 2**.3-**10**. VSC-A DSRC Interference Test Setup**
(Cross-Channel Interference Test Results: A Report from the VSC-A Project; July 17, 2007) [35]
Source: ARINC April 2012

Table 2.3-15. Adjacent Channel Interference Test Results
(Cross-Channel Interference Test Results: A Report from the VSC-A Project; July 17, 2007) [35]
Source: ARINC April 2012

Interferer Channel	Interferer load	PER range*
none	n/a	2.6%-7.5%
172	20%	2.7%-9.1%
172	40%	2.9%-11.5%
176	20%	14.4%-15.7%
176	40%	21.5%-27.1%

These test results imply that the simultaneous use of adjacent channels must be avoided. This was possible when the DSRC standard required channel switching (alternating intervals between the control channel and service channels, but, for capacity reasons, this has since been changed to allow for continuous control channel operation. It also raises concerns about the use of the bands immediately adjacent above and below the DSRC band. To support continuous channel operation, the channel allocation described above probably needs to be revised, since the control channel (Channel 178) will be used all the time, and this means that to avoid interference from adjacent service channels and adjacent non-DSRC bands, the only other usable channels are 174 and 182.

2.3.6.3 RF Emissions from Intersection Related Systems

The RF environment determines the communication performance and influences the SPaT applications. A qualitative and quantitative characterization of RF environments in which SPaT communications must operate is provided. Such a characterization may help to understand the expected performance of SPaT message communication. A qualitative description is presented first. Thereafter, a quantitative characterization is presented on two fronts. First, models are described that attempt to characterize the RF environment in terms of small and large-scale fading. The models can be used for efficient simulation-based evaluation to predict expected behavior of SPaT applications. Secondly, direct experimental results evaluating metrics such as packet loss and latency are also described. These experiments are performed in environments where SPaT applications are expected to operate including urban canyons.

In addition to commercially provided and private Wi-Fi access points along the approach corridors and in buildings adjacent to the intersection, are jurisdictionally owned emitters installed at or near the intersection. These emitters support traffic control and management functions. Figure 2.3-11 illustrates a typical wireless network architecture that jurisdictions use to supports both local area network connection around an intersection and also interconnection with a wireless communications node, typically installed on a jurisdictional water tower, with a back haul link to the traffic management center (TMC). The local area wireless Ethernet subnet (typically 2.4 GHz) connects wireless sensors (such as radar and video detectors) to the traffic controller cabinet that contains a hardened Ethernet Switch/Router. The LAN network uses an omni-directional antenna at the interconnection to interconnect devices to the roadside equipment cabinet. A high gain, directional antenna is utilized to interconnect the intersection to the ITS wide area network communications node located on a water tower, building, or existing communications tower. The communications node is linked to the Traffic Management Center. Other configurations have been deployed using mesh WiMAX (IEEE 802.16) networks; however the intersections-to-node/node-to-TMC architecture is less costly to deploy and maintain, compared with a mesh network.

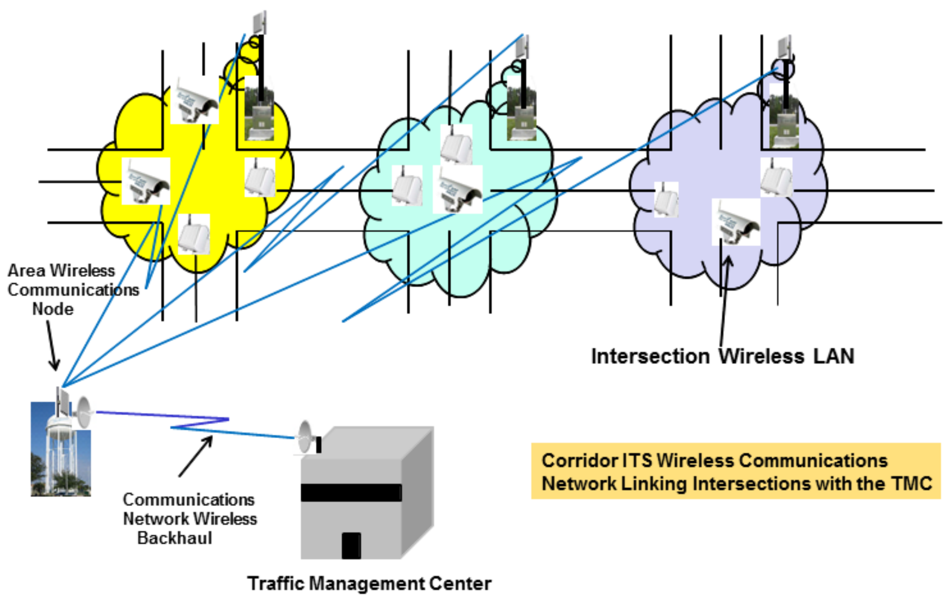


Figure 2.3-11. Typical Wireless Communications Environment Around a Conventional Signalized Intersection

Source: ARINC April 2012

The RF environment at an intersection, disregarding mobile communications, is a function of the sensors deployed and whether the sensors are interconnected with an optical Ethernet, EIA 232 (copper twisted pair), or wireless. Earlier wireless interconnections of ITS sensors at intersections were conducted using the 900 MHz (6th harmonic of 5.85 GHz band), ISM band with EIA 232 interfaces. Today, the majority of wireless devices are Wireless Ethernet devices, operating in the 2.4 GHz, ISM frequency band. Figure 2.3-12 illustrates some of the available wireless sensors supporting vehicle detection and surveillance at signalized intersections. Consideration should be given to include active RF vehicle detectors with wireless interconnects during testing of V2I communications technology.

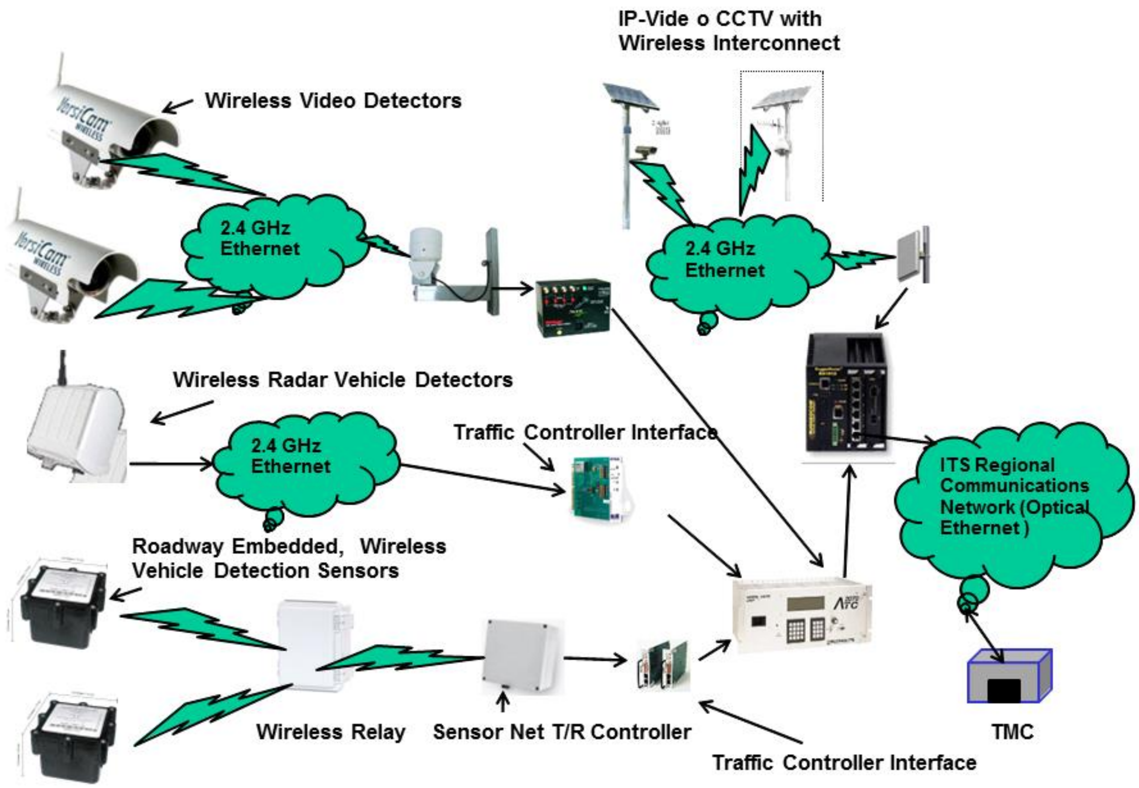


Figure 2.3-12. Examples of Wireless Traffic Detection and Management Support Sensors Utilized at Signalized Intersections
Source: ARINC April 2012

2.3.6.4 Other Potential RF Interferers

Communication in scenarios with mobile vehicles is increasingly complex and hard to characterize due to factors such as multipath from reflections off of other objects, vehicles and buildings, Doppler effect on signals caused by vehicle motion (called Doppler spread), and interference from other wireless devices. Undulations on the roadway and hills as well as any foliage within the signal path also have a significant bearing on the propagation characteristics. Specifically, the communication characteristics are NLOS and radio propagation models (e.g., Hata) that do not capture the vehicular environments, because they were developed based on no or low mobility signal measurements. Furthermore, possible application offerings such as safety, traffic signal timings etc. have vastly different Quality of Service (QoS) needs and several ideas have been proposed to support the broad variety of application requirements. For example, the need for antenna design in order to support multiple, active communications devices on a vehicle have been considered including plans to support 2 DSRC transceivers on a vehicle; one for safety, and one for services. SMART antennas or sector beams may also be applicable at urban intersections so as to provide maximum coverage for vehicles on the roadway and to minimize multipath from surrounding buildings.

While the RF environment largely varies depending on the location e.g., urban, suburban, open roads etc., communication in an urban environment is most difficult due to the significant variation in environmental factors.

An urban intersection poses several challenges due to the presence of additional RF emitters, the presence of vehicles and mobility and the obstructions posed by objects such as buildings. The wireless devices that may interfere with communication of SPaT messages and the associated radio frequency signals are listed in Table 2.3-16.

More details related to the RF environment are included in the Task 2 Report associated with this project. Of concern are military RF emitters equipment that operate in the 5.85-5.925 GHz band (see NTIA Report 00-373) [36], harmonics of non-DSRC intersection RF emitters, adjacent channel interference from DSRC devices in close proximity, RF Receiver front end overload by out-of-band high power emitters (such as may be found in emergency related vehicles), inter-modulation from transmitting antennas closely mounted on a shared structure, and uncontrollable in-band RF emissions adjacent to international borders (as has been experienced with older DSRC transceivers at international border crossings).

We list several factors that may influence the communication performance achieved for SPaT messages. Interference from wireless devices within the same frequency band may result in reduced SNR levels at receivers. Similarly near-field interference from co-located devices may significantly influence communication performance. However, the influence is typically limited to $\lambda/2\pi$ where λ is the wavelength. For example, the near-field region for radios operating at 700 MHz is less than 10 cm. As such device separation plays role while arranging wireless devices and antennas within/on a vehicle (see: *Effect of Antenna Placement and Diversity on Vehicular Network Communications*; S. Kaul, et al; Rutgers University) [37].

Table 2.3-16. Radio Frequency Emitters at or Near a Signalized Intersection Creating the Environment in Which SPaT Communications Must Reliably Operate

Source: ARINC April 2012

Sensor or Device Supported	Function	Where Installed	Number	Standard & Frequency	Emitter Power
VIVDS	Video Detection of Vehicles	Intersection	4	2.4 GHz ISM Band Ethernet	36 dBm
SenSys™ Wireless Detectors	Vehicle Detectors at Intersections	In Road; Relay on Pole at /near Intersection	2 per lane (Minimum)	2.4 GHz ISM Band Ethernet 16 Ch., 2 MHz BW	0 dBm
Radar	Vehicle Detection	Intersection on Pole	4	24.125 GHz Doppler and FMCW; 50 deg Elevation/ 12 deg Azimuth	6.99 dBm
Radar	Pedestrian Detection	Intersection on Pole	4	24.125 GHz Doppler 90 deg	6.99 dBm
CCTV	Intersection Surveillance (Emergency Management)	100 meters of Intersection	2	2.4 GHz Ethernet or 4.9 GHz (Police); Directional Antenna to Node	36 dBm
Traffic Controller Interface to Traffic Management Center	Traffic Controller Management and Control	At Intersection	1	902 to 928 MHz or 2.4 to 2.4835 GHz ISM Band; Directional Antenna to Node	36 dBm
Wireless Interconnects from Radar, Active IR, Passive Acoustic, etc. to Traffic Controller	Wireless Sensor Interconnect to Traffic controller	At Intersection; Sensors mounted on Pole or on Mast Arm	1 per sensor	902 to 928 MHz or 2.4 to 2.4835 GHz ISM Band; Directional Antenna to Node. Directional Antenna at Sensor; Omni Antenna at or Near Traffic Controller	36 dBm Max; 20 dBm Typical
Wireless Access Point Jurisdictional	RSE Wireless Ethernet Access	At Intersection	1	2.4-2.4835 GHz; Omni Antenna	36 dBm
Wireless Access Point	RSE DSRC Transceivers	At Intersection	1 to 5	5.85 to 5.92 GHz, IEEE	36 dBm

Sensor or Device Supported	Function	Where Installed	Number	Standard & Frequency	Emitter Power
Jurisdictional				802.11p; Omni and Directional Ant.	
Wireless Access Point	Emergency Management	Near Intersection (100 meters)	1	4.94 to 4.99 GHz; Omni Ant., Vert. 10 deg.	36 dBm
Wireless Access Point (Public) Commercial	Commercial Ethernet Hot Spot in/at Businesses	100 meters Minimum Distance	10	2.4-2.4835 GHz and 5.15-5.35 GHz; Omni Antenna	24 dBm
Wireless Access Point Private	Private Ethernet Access Point (Homes, Apartments, Businesses)	50 meters Minimum Distance	20 of a Signal Level Detectable at the Intersection	2.4-2.4835 GHz and 5.15-5.35 GHz; Omni Antenna	24 dBm
Emergency Mobile Radio Transceiver/ Repeater Tower	Emergency Management Computer Aided Dispatching (CAD) and Automatic Vehicle Location (AVL)	500 meters Minimum Distance	1	700 MHz Emergency Interoperability and 800 MHz Emergency Mobile; Omni Antenna	50 dBm
Emergency Vehicle Radio Transceivers	Emergency Management	Passing Through Intersection	2	700-800 MHz Emergency Mobile Band; Omni Ant.	43 dBm
Public Transit Mobile Radio Transceiver /Repeater Tower	Public Transit for CAD and Automatic Vehicle Location (AVL)	1000 meters Minimum Distance	1	800 MHz (may use emergency channel assigned to city or county police); Omni Antenna)	50 dBm
Public Transit Vehicle Radio Transceivers	Public Transit Dispatching	Passing Through Intersection or Approaching Intersection	2	800 MHz Mobile Band; Omni Ant.	43 dBm
Taxi and Commercial Vehicle Transceiver Tower	Taxi and Commercial Vehicle CAD and AVL	1000 meters from Intersection Minimum Distance	1	470-512 MHz or 805 to 821 MHz Bands; Omni Ant.	50 dBm
Taxi and Commercial Vehicle Mobile Radio Transceiver	Computer Aided Dispatching and Vehicle Tracking of Taxis, Limos, and Commercial Delivery Vehicles	Passing Through or Approaching the Intersection	6	470-512 MHz or 805 to 821 MHz Bands; Omni Ant.	43 dBm
Cellular Telephone Cell Sites	Public Mobile	3 cells per service provider within 200	6	Mix of 3G and 4G	40 dBm

Sensor or Device Supported	Function	Where Installed	Number	Standard & Frequency	Emitter Power
	Communications	meters minimum distance; 2 service providers			
Private, Commercial and Jurisdictional Vehicle Communications Devices	Cell Phone Handsets	Mix of Service Providers and Standards; Used in Vehicle	Vehicle Density TBD; Assume 30% Communicating	Mix of 3G and 4G Services; Omni Ant.	30 dBm
Private, Commercial and Jurisdictional Vehicle Communications Devices	Blue Tooth Wireless, Short Range Links	Used in Vehicle to Link electronic Devices Such as Cell Phones to with Ear Devices and Portable Devices with OBE	Vehicle Density TBD; Assume 50% of Vehicles Have Active Blue Tooth	2.4 to 2.4835 GHz; Omni Ant.	4 dBm; Possibly 20 dBm Devices on Computer
Private, Commercial and Jurisdictional Vehicle Communications Devices	Wireless Ethernet on Portable Computing Devices	Used by Passengers in Vehicle, Including Buses	Vehicle Density TBD; Assume 20% of Vehicles Have Active Wireless Ethernet	2.4 to 2.4835 GHz; Omni Ant.	24 dBm
DSRC All Vehicles	Safety and Mobility	Passing Through and Approaching the Intersection	TBD Vehicle Density	IEEE 802.11p; 5.85-5.92 GHz	30 dBm
Digital TV Transmitter Towers	Broadcast Digital TV	5 Stations in Region at varied ranges from the Intersection	5	ATSC Standard, Mixed Transmitter Power Per License for Urban Area	Varies from 84.8 to 90 dBm
Pedestrian Communications Near Intersection	Cell Phone Handsets	Mix of Service Providers and Standards; Used in Vehicle	Pedestrian Density TBD; Assume 30% Communicating	Mix of 3G and 4G Services; Omni Ant.	30 dBm
Pedestrian Communications Near Intersection	Blue Tooth Wireless, Short Range Links	Link Cell Phones to with Ear Devices	Pedestrian Density TBD; Assume 30% Communicating	2.4 to 2.4835 GHz; Omni Ant.	4 dBm; Possibly 20 dBm Devices on Computer if Ped. At Bus Stop Seating
AM/FM Broadcast Radio	Radio Broadcast	Transmission Tower	1	AM 535 to 1705 kHz FM 88 to 108 MHz	Per granted station power budget
HD Broadcast Radio	Radio Broadcast	Transmission Tower	1	AM 535 to 1705 kHz	Typically up to 10%

Sensor or Device Supported	Function	Where Installed	Number	Standard & Frequency	Emitter Power
				FM 88 to 108 MHz	of analog effective radiated power (ERP)
Satellite Radio	Satellite Broadcasting	Satellite	1	2.31 GHz to 2.36 GHz	-50 dBm
GPS	Satellite Broadcasting	Satellite	3	L1: 1575.42MHz L2: 1227.6MHz L5: 1176.45MHz	L1 and L2: –157 dBW (-127 dBm) for the C/A code signal and –160 dBW (-130 dBm) for the P(Y) code signal. L5: 154 dBW

Environmental structure and mobility have a significant bearing on the communication performance achieved. These include the presence of moving vehicles, buildings, intersections, tunnels, bridges, etc. Measurements in tunnels using sounding equipment at 5.85 GHz are reported in (Ref: “Tunnel Propagation Channel Characterization for DSRC Applications”, Ching et al, *Proceedings of Asia-Pacific Microwave Conference, 2007* [38]). The dominant scatter sources are found to be the ground and the sidewalks. The delay spreads are reported to be less than 100 nanoseconds. Measurements reported in (Ref: “Performance Evaluation of IEEE 802.11p Infrastructure-to-Vehicle Measurements”, Shivaldova, et al, 978–1–4244–9538–2/11, 2011 [39]), report severe loss of performance in non-LOS conditions inside tunnels. Further, instantaneous situation and vehicle positions have a strong impact on the performance inside tunnels with presence of trucks resulting in blocking.

Multipath effects arise due to the presence of buildings and other objects as well as bounce off the road surface, which results in multiple received signals. Each signal may be attenuated differently and may suffer from different delays and phase shifts. Destructive interference where signals cancel out can result in deep fades, significantly hampering the communication performance. Large objects such as buildings and hills in the line of sight result in shadowing. Multipath fading has been identified in a number of DSRC test in both Europe and the USA. Michigan POC test identified multipath fading as a concern.

Mobility of vehicles further results in increased Doppler spread and reduced coherence time resulting in a fast fading channel. One major DSRC manufacturer identifies the combination of both multipath and high Doppler as a concern (Ref: “Mobility and Multipath”; Cohda Wireless White Paper [40]).

Another concern is possible Intermodulation products or RF front-end bypass of high power RF signals generated by high power, mobile transmitters on a corridor or near a corridor such as illustrated in Figure 2.3-13.

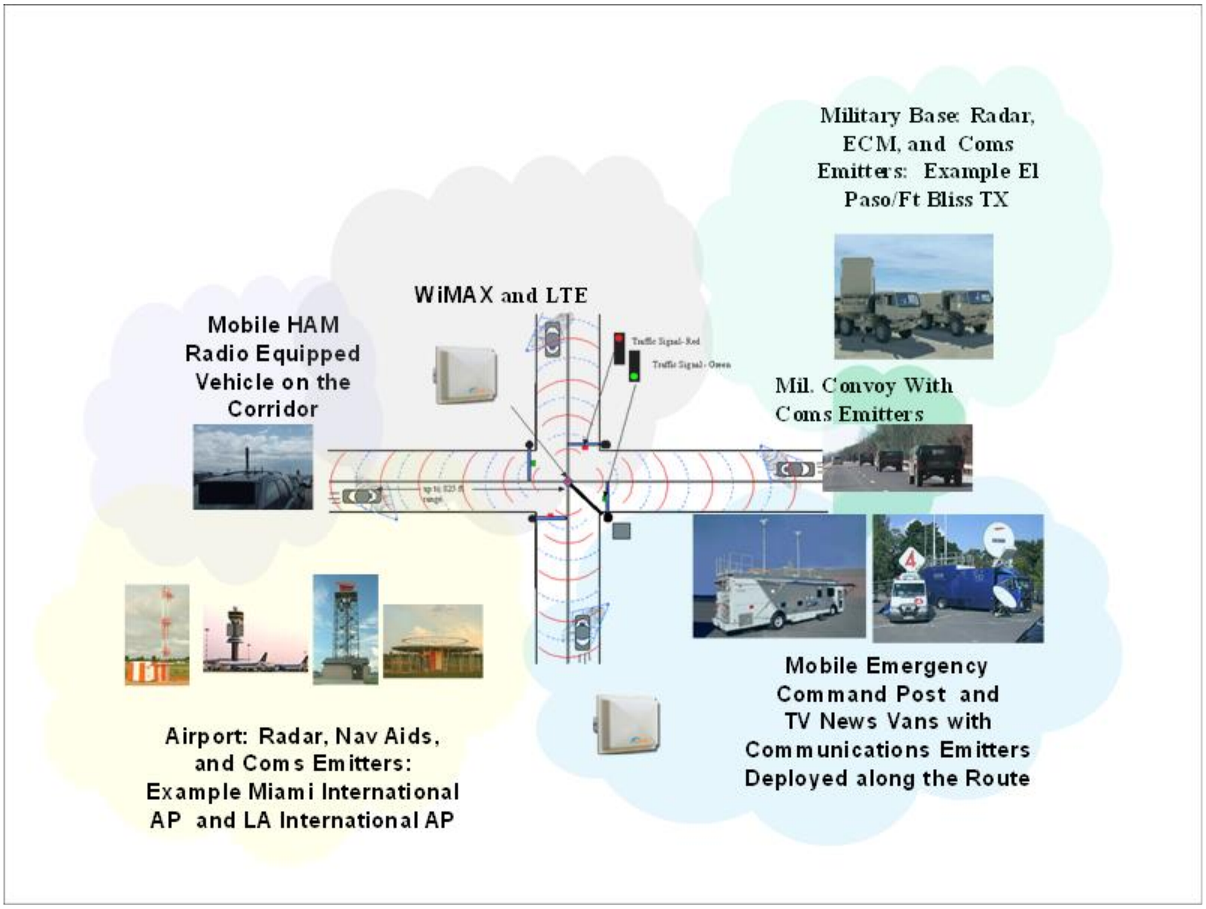


Figure 2.3-13. Examples of High Power Emitters that Could Negatively Impact the DSRC Radio Frequency Operating Environment Source:

ARINC April 2012

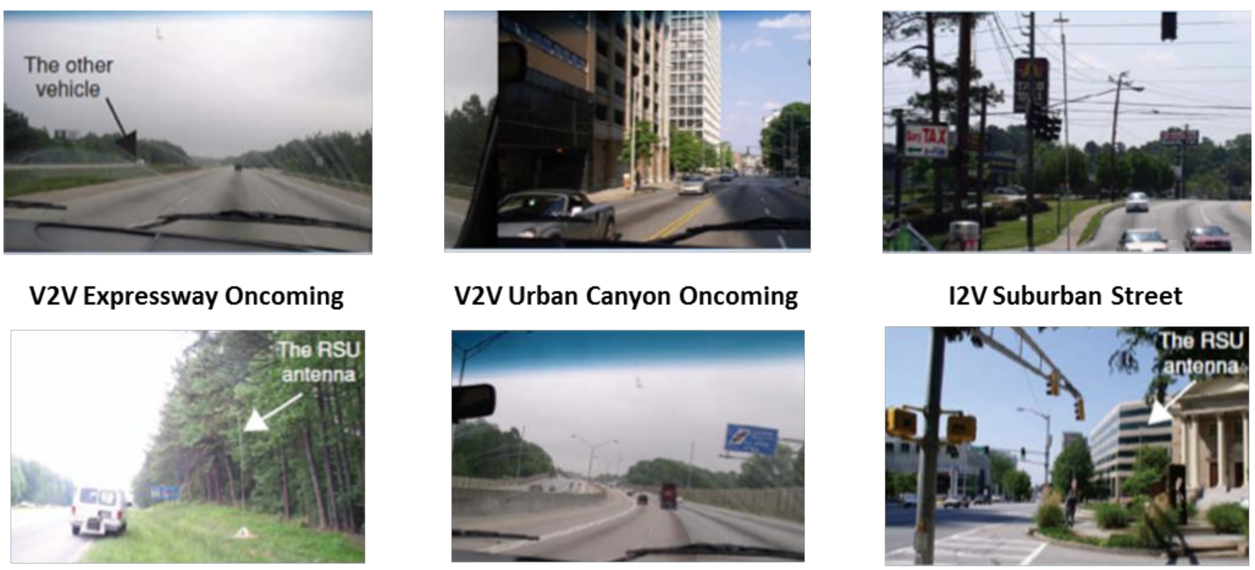
2.3.7 *Other Intersection Safety Communications Considerations*

2.3.7.1 **RF Channel Characterization**

RF communication is seldom a simple matter of pure point-to-point radio signal propagation. Because the RF environment contains many elements that can impede and/or reflect radio signals, a signal sent from a single transmitter will arrive at a receiver as a series of signals, each with slightly different amplitude and a slightly different amount of time delay. This is known as delay spread. As the vehicle moves through this environment, this complex combination of signals will change, since the relationship between the transmitter, the environmental elements, and the vehicle are all changing as the vehicle moves. This is known as Doppler spread. IEEE802.11p compliant design provides approximately 1.6 µsec multipath spread protection and Doppler accommodation to 1100 Hz (200 km/hr). The combined result of delay spread and Doppler spread is that the performance of communications system on a moving vehicle in a real world environment may be substantially different from the same communications system operating in an open field with a stationary vehicle.

Several experimental efforts have attempted to characterize the communication performance observed. Although these results provide useful insights in terms of packet error rates and latency, they are limited in the ability to infer expected behavior in target environments. Towards this a modeling based approach is needed.

Channel measurements have been reported in (Ref: “Six Time- and Frequency Selective Empirical Channel Models for Vehicular Wireless LANs”, Ingram, et al, *IEEE VT Magazine*, 2007 [41]). Figure 2.3-14 shows the scenarios under which measurements have been taken and include highway, suburban and urban conditions.



V2V Expressway Oncoming | **V2V Urban Canyon Oncoming** | **I2V Suburban Street**

I2V Expressway | **I2V Expressway in Same Direction with Wall** | **I2V Urban Canyon**

Figure 2.3-14. Channel Model Test Environments Considered
Source: ARINC April 2012

To characterize the channel, a tapped delay line model is used. The delay line model can model multipath as a series of amplitude weighted delayed copies of the transmitted signal. Since multipath poses a big challenge in receiver design and performance evaluation, such a method becomes critical in understanding the RF environment in vehicular scenarios. The understanding can result in development of realistic simulation and performance evaluation methods. Future simulation studies of vehicular environment to evaluate the performance of SPaT messaging will require RF model calibration. Such field trial data and the model can assist with the calibration process to ensure consistency with realistic scenarios.

A representative diagram of the model is shown for four taps in Figure 2.3-15 below. In this model each delay T represents a different path length (one of the “multi” paths), and each gain g describes the signal strength of that path. Depending on the physical environment, more or fewer taps might be used.

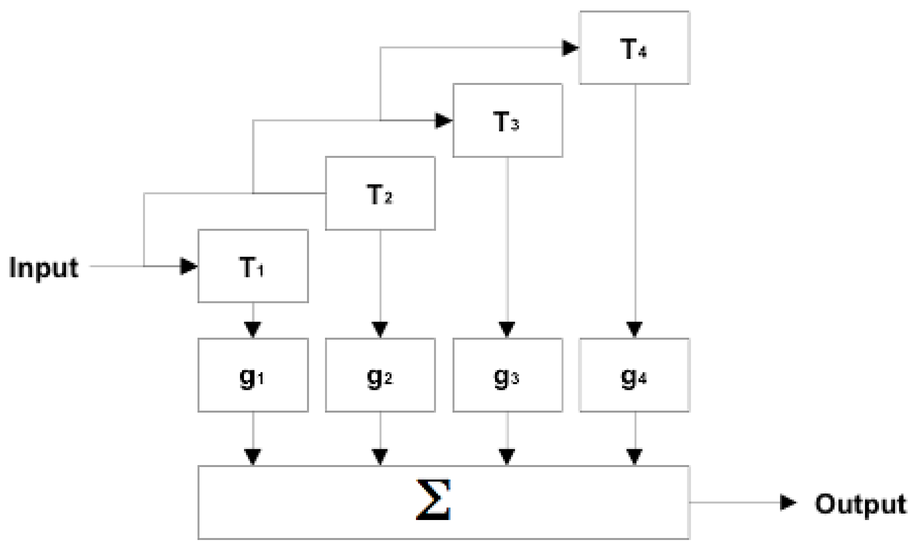


Figure 2.3-15. Example of Tapped Delay Line Model
Source: ARINC April 2012

The model parameters (gains and delays) can be determined from measurements carried out in representative operating environments. Model parameters for DSRC are provided for 65 mph in urban environments, and 25 mph in urban environments in (Ref: “Six Time- and Frequency Selective Empirical Channel Models for Vehicular Wireless LANs, Ingram et al, *IEEE VT Magazine*, 2007 [41]).

Efforts have also been made to characterize the channel using statistical models that are parameterized based on field measurements. Such statistical models can enable simulation of the channel to estimate the expected performance of messages.

For characterizing large-scale path loss in mobile vehicular environments, a dual-slope model has been evaluated to be a better fit than a conventional model with a single path-loss exponent. (Ref: “Mobile Vehicle-to-Vehicle Narrow-Band Channel Measurement and Characterization of the 5.9GHz DSRC Frequency Band”, Cheng, et. al., *IEEE JSAC*, Oct. 2007 [42]). Such a model is shown in Figure 2.3-16 below.

$$P(d) = \begin{cases} P(d_0) - 10\gamma_1 \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma_1} & \text{if } d_0 \leq d \leq d_c \\ P(d_0) - 10\gamma_1 \log_{10}\left(\frac{d_c}{d_0}\right) - & \text{if } d > d_c \\ \quad 10\gamma_2 \log_{10}\left(\frac{d}{d_c}\right) + X_{\sigma_2} & \end{cases}$$

Figure 2.3-16. Dual-slope Path Loss Model
Source: ARINC April 2012

(Ref: Cheng, et al, "Mobile Vehicle-to-Vehicle Narrow-Band Channel Measurement and Characterization of the 5.9GHz DSRC Frequency Band", *IEEE JSAC*, Oct. 2007. [42])

The model is parameterized by a path-loss exponent γ_1 and standard deviation σ_1 within distance $d_{c,}$ which is related to the Fresnel distance. Beyond $d_{c,}$ the signal falls off with a larger path-loss exponent γ_2 and standard deviation σ_2. The Fresnel distance is $4h_th_r/ \lambda$ where h_t and h_r are the antenna heights of the transmitter and the receiver. As an example, with antenna heights of 1.5 m and 2 m and a frequency of 5.9 GHz, the Fresnel distance is approximately 240m.

Based on measurement tests, Table 2.3-17 below shows a set of parameters characterizing the large-scale path loss model for vehicular communication in urban environments.

Table 2.3-17. Large-Scale Path Loss Parameters
(Ref: Miucic, Radovan, "Experimental Characterization of DSRC Signal Strength Drops", Honda Research Institute. [43])

Parameter	Data Set 1	Data Set 2
Single slope y	2.75	2.32
Single slope x (dB)	5.5	7.1
Dual slope y_1	2.1	2
Dual slope x_1(dB)	2.6	5.6
Dual slope y_2	3.8	4
Dual slope x_2 (dB)	4.4	8.4
Critical distance d_c(m)	100	100

Figure 2.3-17 depicts a typical power-distance profile for vehicular communication measured at varying distances from the DSRC transmitter. Typically, received signal levels lower than -90 dBm have unacceptable BER caused by low SNR. This figure presents Received Signal Strength Indicator (RSSI) levels versus range for an IEEE802.11p DSRC. As shown, signal level beyond 250 m becomes marginal from a SNR standpoint resulting in unacceptable packet errors.

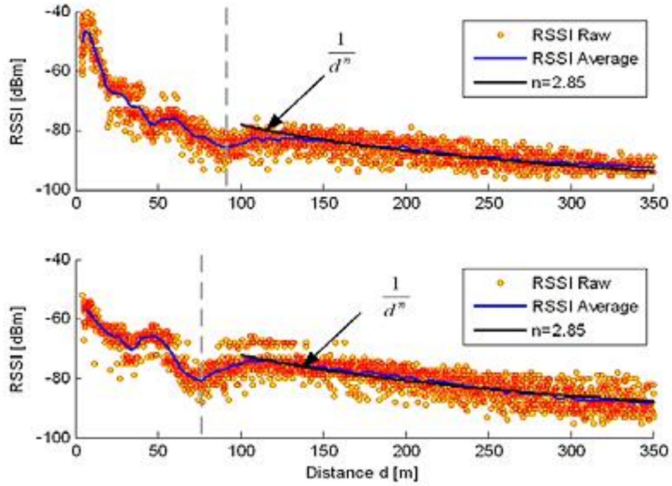


Figure 2.**3-**17**. Measured RSSI Vs Distance Profile**
(Ref: "Experimental Characterization of DSRC Signal Strength Drops", Radovan Miucic, Honda Research [43])

Mobility of vehicles further results in small-scale fading due to the short coherence time relative to the Doppler delay spread of the channel. This behavior has been characterized using the Nakagami model as shown in Figure 2.3-18. In this relation, μ is the shape parameter and ω estimates the average power of the fading envelope.

$$f(x;\mu,\omega) = \frac{2\mu^{\mu}x^{2\mu-1}}{\omega^{\mu}\Gamma(\mu)}e^{\frac{-\mu x^2}{\omega}}$$

Figure 2.**3-**18**. The Nakagami Distribution for Modeling Fading**
(Ref: **http://en.wikipedia.org/wiki/Nakagami_distribution** [219])

Table 2.3-18 lists the parameter μ that best fits the measurements based on different distances between the source and the receiver. The distribution is normalized to ω=1. μ values are larger than 1 at short distances, and fading is characterized as a Rician distribution. For large distances μ values are less than 1, indicating fading more severe than indicated by Rayleigh models as the LOS component becomes less dominant.

The large-scale path loss model defines the average power i.e., ω for the Nakagami distribution. Combined, the models can help to characterize the channel in vehicular environments. The models are especially helpful to understand expected communication behavior in a target environment.

Table 2.3-18. Parameter Values for the Nakagami Model
(Ref: **http://en.wikipedia.org/wiki/Nakagami_distribution [219]**)

Distance bin (in meters)	*μ*
From 0.0 to 4.7	3.01
From 4.7 to 11.7	1.18

Distance bin (in meters)	*μ*
From 11.7 to 28.9	1.94
From 28.9 to 71.6	1.86
From 71.6 to177.3	0.45
From 177.3 to 439.0	0.32

Experimental efforts have also attempted to characterize the performance of DSRC in terms of Doppler and delay metrics and attributes like packet error rates, latency etc.

Channel-sounding results reported in (Ref: "Measurement and Analysis of Wireless Channel Impairments in DSRC Vehicular Communications", Tan, et al, Technical Report, UC Berkeley, April 2008 [44]), describe the effect of reflections in urban line of sight environments. Figure 2.3-19 shows the power delay profile calculated from the measured data. As shown, although a strong initial tap is observed at 250ns, a number of reflections are present. The RMS delay spread in this scenario is approximately 500ns demonstrating the significant effect of the reflections from objects. On the other hand, in a highway scenario, the power delay profile has fewer taps due to reduced reflections and an RMS delay spread of 190 ns.

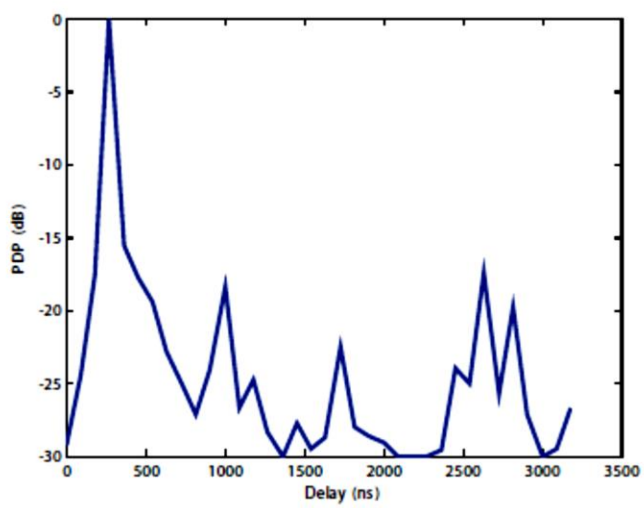


Figure 2.3-19. Power Delay Profile of an Urban LOS Channel
(Ref: USDOT Report FHWA-JPO-09-043, "Final Report: Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary – Vehicle", May 19, 2009. [50])

Table 2.3-19 summarizes results of field test using a DSRC with BPSK modulation and 1.6 μsec guard interval.

Table 2.3-19. Results of DSRC Doppler and Delay Spread Test
(Ref: "Measurement and Analysis of Wireless Channel Impairments in DSRC Vehicular Communications", Ian Tan, et al [44])

Locale	Distance (m)	Delay Parameters (NS)			Frequency Parameters (Hz)	
		Mean Excess	RMS	Max Excess (30 dB)	Frequency Shift	Avg. Doppler Spread
Rural LOS	100	85.8	21.6	272.7	201	782
Urban LOS	200	303.2	157.5	1681.8	-20	341
	400	370.1	320.6	3781.8	203	263
	600	515.9	286.6	3625	-21	294
Urban NLOS	200	521.7	295	2454.5	103	298
Highway LOS	300	154.1	156.8	2026	209	761
	400	175.4	141.1	1575.8	261	895
Highway NLOS	400	558.5	398	4772.7	-176	978

Field trials have reported empirical distributions for the delay and the Doppler spread that are consistent with previous measurements (Ref: Alexander, et al, "Cooperative Intelligent Transport Systems: 5.9-GHz Field Trials", *Proceedings of the IEEE*, 2011 [45]). The data is based on the baseband channel captures while disregarding taps that are 30dB below the strongest tap. Figure 2.3-20 shows the cumulative distributions for the RMS and the maximum excess delay spread in different vehicular environments. For urban non-line of sight (NLOS) environments, the RMS delay spread is less than 200ns with probability > 99%. Also, the maximum delay spread is typically less than 1.4-1.6 microseconds; however in both Urban LOS (3.8 μsec) and Urban NLOS (2.6 μsec) and in highway NLOS (4.8 μsec), delay spread exceeded the 1.6 μsec guard of DSRC. Consequently, the cyclic prefix in DSRC is deemed to generally be sufficient for most situations. Clearly, non-line of sight conditions result in larger delay spreads due to increased influence of scattering.

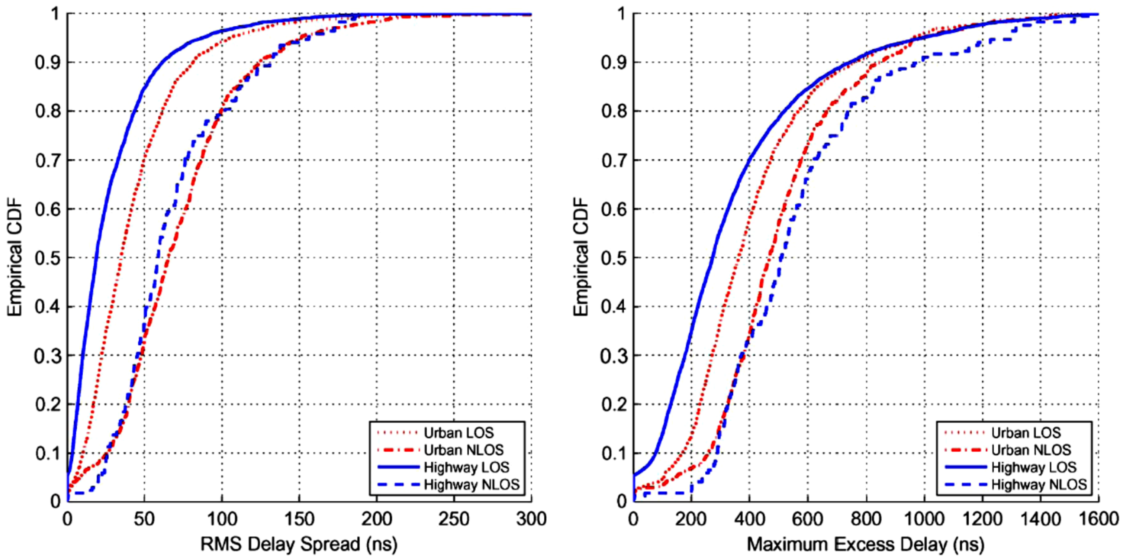


Figure 2.**3-**20**. Distributions for the RMS and Maximum Excess Delay Spread**
(Ref: Alexander, et al, “Cooperative Intelligent Transport Systems: 5.9-GHz Field Trials”*, Proceedings of the IEEE*, 2011 [45])

Figure 2.3-21 shows the cumulative distributions for the RMS and the maximum Doppler spread in different vehicular environments. The distributions are derived from a dataset consisting of both V2V and V2I measurements. Non-line of sight situations on the highways have high probabilities of increased Doppler spread. In urban situations, the Doppler spreads are typically less than 1000 Hz. Additionally, the RMS Doppler spreads in line of sight highway scenario are small since the high frequency Doppler taps have reduced power. However, as shown in Figure 2.3-21, maximum Doppler spread exceeded the design protection of 1100 Hz for the DSRC in situations for both LOS and NLOS in both urban and highway scenarios.

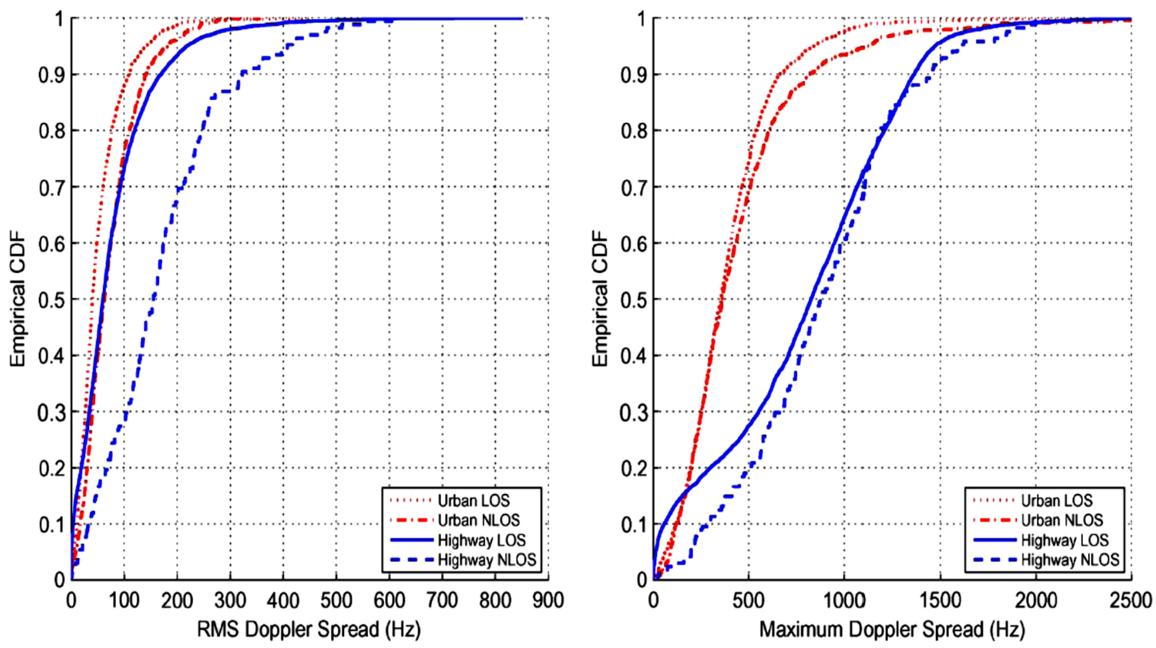


Figure 2.3-21. Distributions for the RMS and Maximum Doppler Spread
(Ref: Alexander, et al, "Cooperative Intelligent Transport Systems: 5.9-GHz Field Trials", *Proceedings of the IEEE*, 2011 [45])

The statistics from the cumulative distributions are summarized in Table 2.3-20 and serve as guidelines for defining requirements.

Table 2.3-20. Delay and Doppler Statistics for Different Roadway Environments
(Ref: Alexander, et al, "Cooperative Intelligent Transport Systems: 5.9-GHz Field Trials", *Proceedings of the IEEE*, 2011 [45])

Quantile	Delay Spread (ns)				Doppler Spread (Hz)			
	RMS		Maximum		RMS		Maximum	
	50%	90%	50%	90%	50%	90%	50%	90%
Urban LOS	34.	81.6	362.0	756.6	40.0	108.3	353.4	665.0
Urban	65.4	124.7	468.9	848.4	63.1	140.9	360.7	814.2

NLOS								
Highway LOS	18.7	61.7	272.3	744.0	59.7	169.8	826.1	1361.6
Highway NLOS	58.8	131.3	509.7	971.9	154.9	322.4	875.2	1446.5

2.4 Intersection Geometry Considerations

A task under this project required the definition of several intersection test configurations that may identify issues with RF coverage and RF compatibility. This section discusses intersection geometries that would be candidates for simulaion and testing as related to SPaT related communications technoloy testing. The intersection configurations recommended represent typical deployment of wireless devices supporting signal control and traffic managments. Simulation should include different traffic loads as well as a mixture of vehicle types and RF emitter configurations on vehicles as discussed above, related to potential radio frequency interference. Different "around intersection" building structure configurations should be considered during simulation as well as foliage along and within the median of the approach corridors. Intersection geometry and deminsions should comply with USDOT and AASHTO standards and placement of devices should comply with the MUTCD [6]. For SPaT related communications the maximum distance, per analysis on this project that is required is 515 meters (1690 ft); however, most research reports define reliable communications range of 300m (984 ft) for safety applications and up to 1000 meters (3281 ft) for service applications and simulation should cover maximum specified distance for DSRC per IEEE 802.11p. Maximum effective isotropic radiated power (EIRP) per FCC for the DSRC control channel is 44.8 dBm for RSE and 33 dBm for OBE.

NTIA spectrum surveys show that the ambient environment in the 5.85-5.925 GHz frequency band may be -90 dBm with noise in the DSRC frequency band in an area near military radars being as high as -40 dBm (see NTI Reprt 00-373) [36]. Effects of varying noise floors on SPaT performance should be addresse in simulations.

Simulation velocities of vehicles should consider typical posted speeds on urban, suburban, and rural corridors as well as speed limit violaton considerations (a minimum of 25% over posted speed). .

The geometry of the intersection as well as traffic volume, history of accidents at the intersection, and jurisdictional need for intersection traffic statistics, as well as the signal control strategy, dictates the numbers and deployment locations of sensors relative to the intersection stop lines. Figure 2.4-1 illustrates two examples of sensor deployment, all having a contribution to the RF environment in and around the signalized intersection. The geometry is 2 lanes in each direction, plus right turn lane. Pedestrian walkways are included with RF PED detection sensors for at least one scenario. Distance between stop lines is 120 ft. This represents a typical intersections deployment.

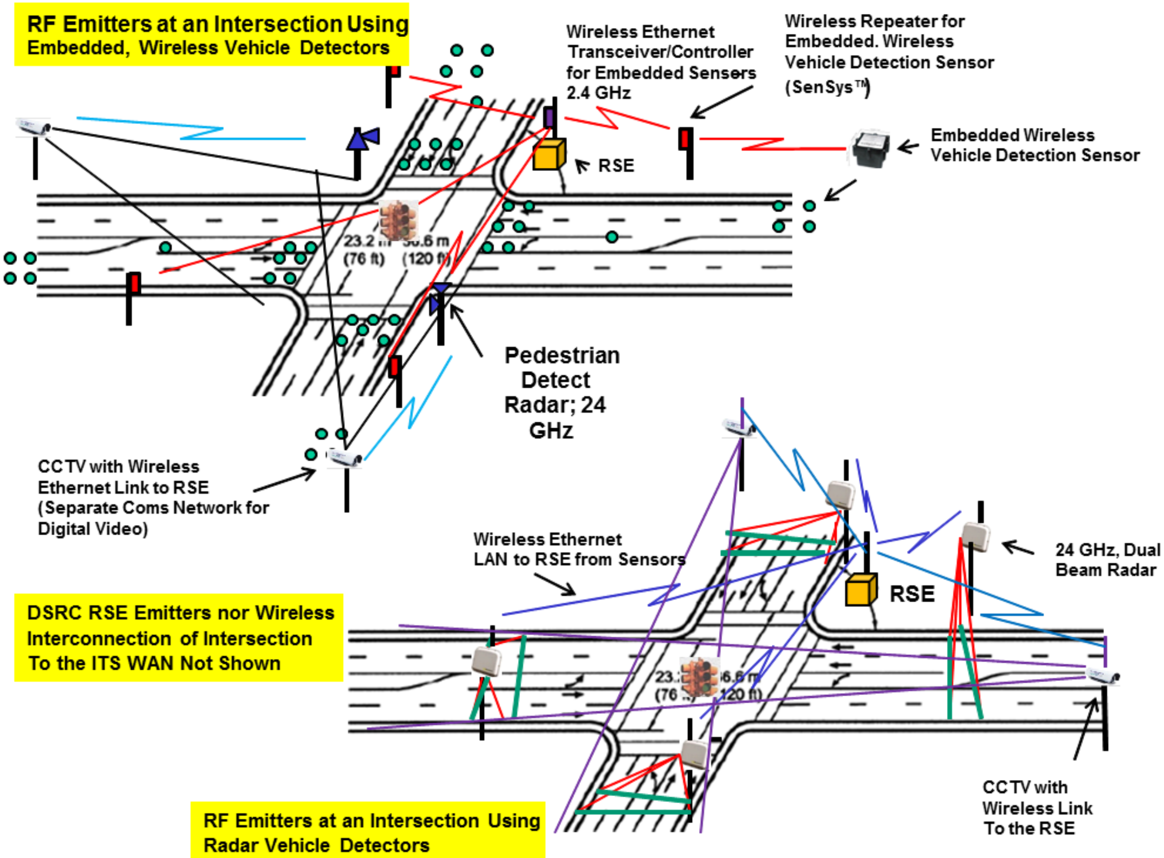


Figure 2.4-1. Examples of Two Different RF Environments within and Around a Signalized Intersection Based on Type of Sensors Deployed
Source: ARINC April 2012

Several experimental efforts have attempted to characterize the communication performance observed as possibly applicable to an LTE communications link operating in the 700 MHz mobile public safety frequency band. Although these results provide useful insights in terms of packet error rates and latency, they are limited in the ability to infer expected behavior in target environments. An evaluation effort for a UHF band prototype for roadside to vehicle communications performed in an urban canyon yielded insightful results [Ref: *Field Evaluation of UHF Radio Propagation for an ITS Safety System in an Urban Environment*, S. Sai et. al., IEEE Communications Magazine, 2009.] [46]. The experiment used varying antenna heights (1.8 m (6 ft.) and 5 m (16.4 ft.)) at 800MHz and a bandwidth of 8.5MHz. The results (Figure 2.4-2) show vastly different performance based on the number of intersections encountered. In particular, the packet reach is greatly reduced as the number of intersections increased regardless of the actual distance. As observed in Figure 2.4-2, the packet range is higher along horizontal lanes than the vertical lanes. This highlights the influence of edge-diffracted waves on communication performance.

Further network and application-level analysis of roadway environments is provided in the analysis section.

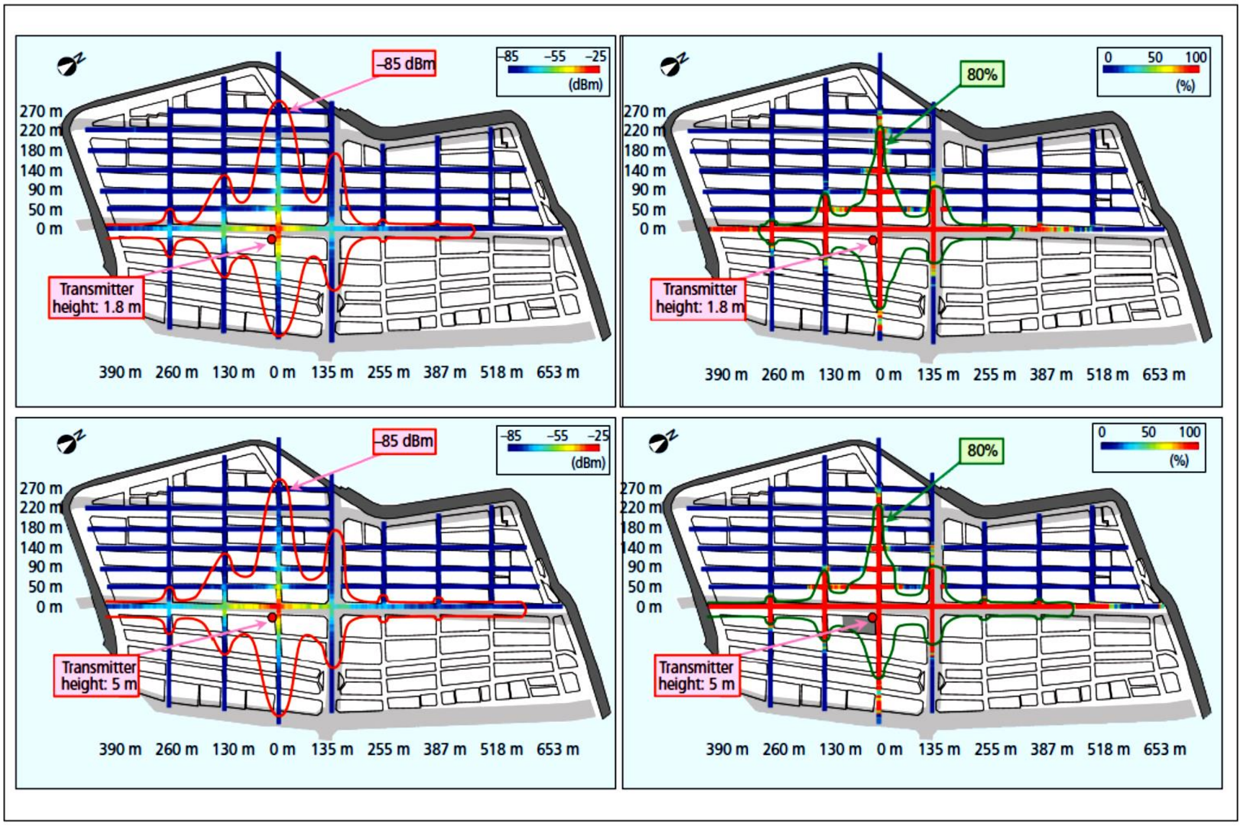


Figure 2.**4-**2. **Urban Area: Received Signal Strength and Packet Reception**
(Ref: "Field Evaluation of UHF Radio Propagation for an ITS Safety System in an Urban Environment", S. Sai, et al, *IEEE Communications Magazine*, 2009 [46])

The RSE may include dual DSRC transceivers (one for safety and one for service) and may also include dual locations to support coverage of complex geometry intersections. RSE DSRC transceivers may utilize omni-directional antennas or antennas with patterns tailored to the corridor geometry to reduce multipath and to enhance range and signal/noise (which reduces bit error rate).

Figure 2.4-3 illustrates DSRC transceivers with omni-directional antennas providing overlapping corridor coverage, which may result in hidden terminal effects. This configuration includes a corner parking lot that also uses DSRC for parking service. This is a potential geometry to be considered in simulation.

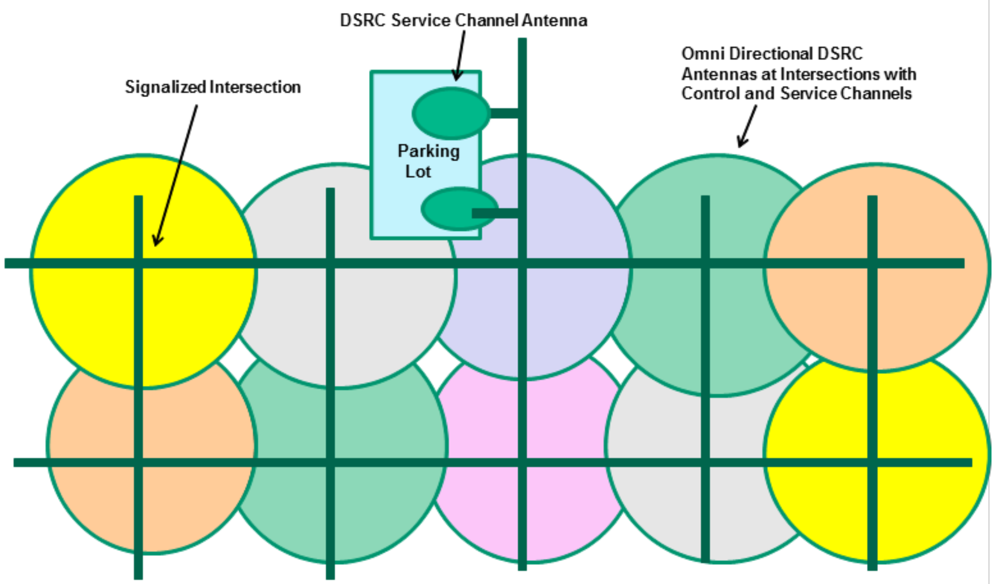


Figure 2.4-3. Example of Overlapping Coverage by RSE DSRC Transceivers Along a Signalized Corridor

Source: ARINC April 2012

Figure 2.4-4 illustrates a sectioned antenna coverage pattern, tailored to corridor coverage and potentially reducing multipath. This is not a smart antenna but an antenna designed with a “clover leaf” pattern.

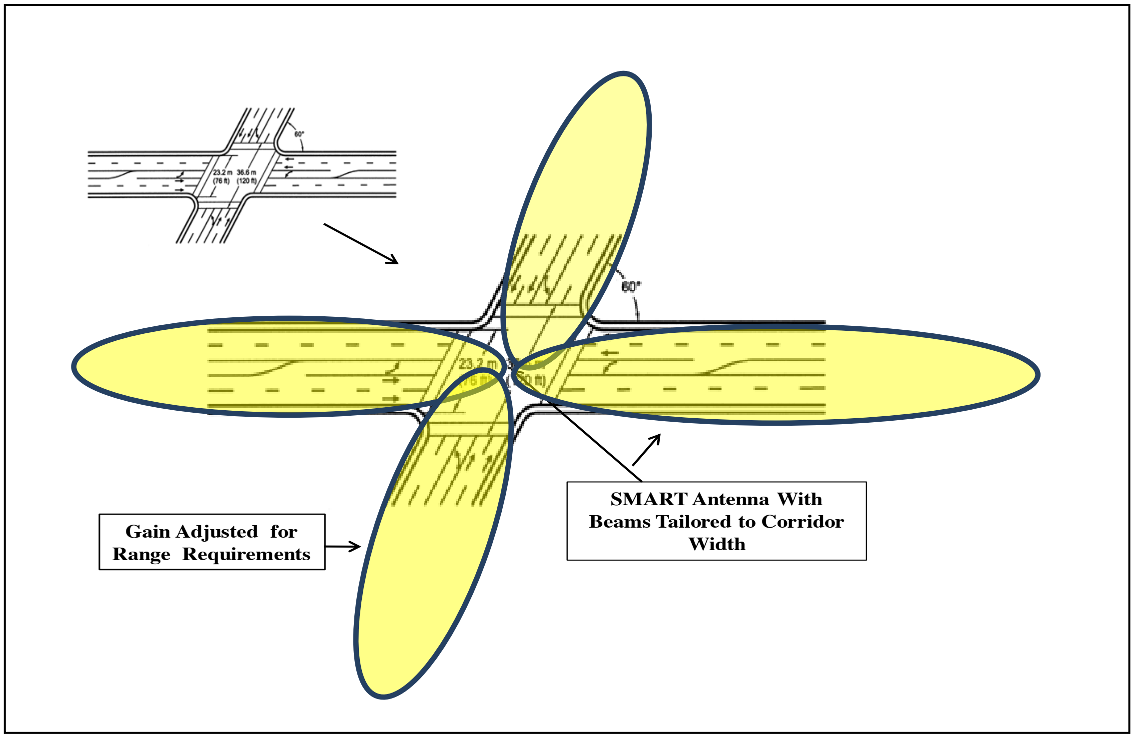


Figure 2.4-4. Example of a DSRC Antenna Pattern Tailored to Sector Coverage
Source: ARINC April 2012

Figure 2.4-5 provides a comparison of antenna pattern coverage options for DSRC applications. Testing should consider both options comparing the results to see if signal/noise is improved with the sector antenna pattern, by reducing multipath and perhaps the single level of interfering signals from buildings.

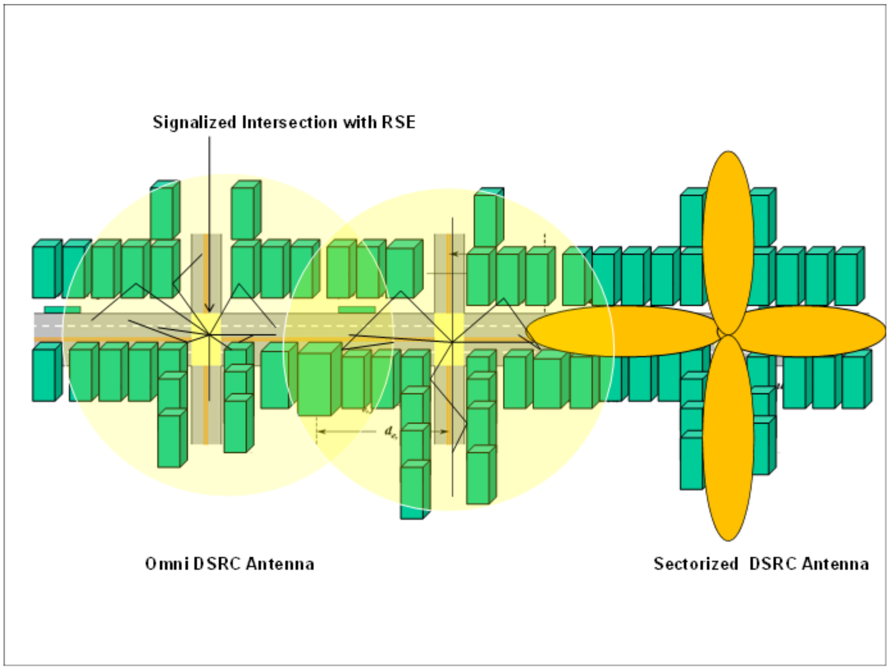


Figure 2.**4-**5**. Comparison of Omni and Sectorized Antenna Pattern for DSRC**
Source: ARINC April 2012

Figure 2.4-6 presents an intersection geometry illustrating associated emitters. Video detectors are illustrated with 2.4 GHz wireless Ethernet links to the RSE. Radar Sensors (24 GHz) are utilized for pedestrian detection in crosswalks. The RSE utilizes an optical Ethernet interconnect to the traffic management center. The DSRC(s) must coexist with the 2.4 GHz Wireless Ethernet environment supporting intersection sensor interconnects to the RSE and the 24 GHz radar emitters. This is a candidate architecture testing related to RF compatibility of devices at a signalized intersection. Figure 2.4-7 illustrates another possible test configuration. This figure presents another intersection geometry illustrating associated emitters. Radar detectors (24 GHz) for both vehicle and pedestrian detection are illustrated with 2.4 GHZ wireless Ethernet links to the RSE. The RSE utilizes an optical Ethernet interconnect to the traffic management center. The DSRC(s) must operate with the 24 GHz radar sensors and the 2.4 GHz Wireless Ethernet WLAN active.

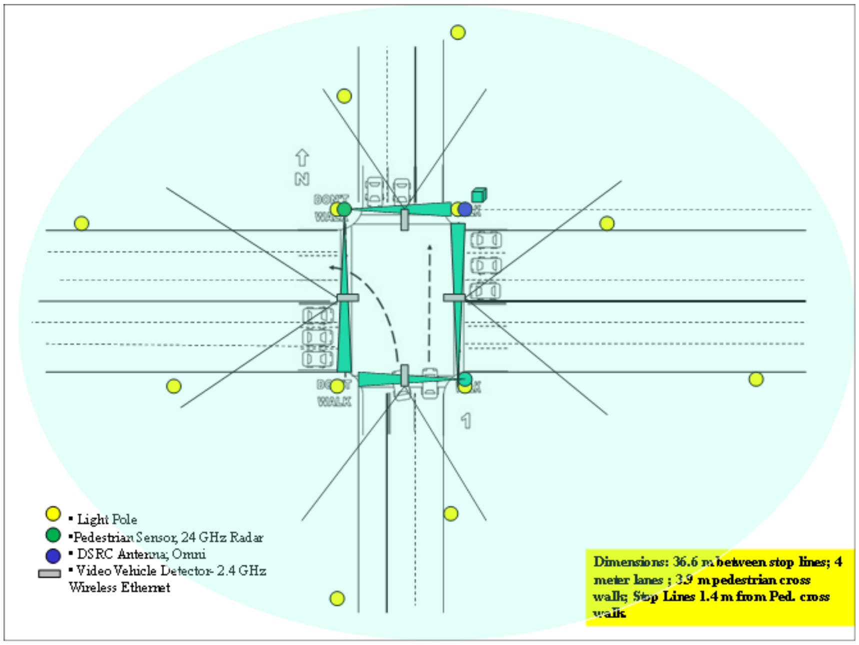


Figure 2.**4-**6**. Signalized Intersection with DSRC Transceiver, 24 GHz PED Radar, and Sensor WLAN**

Source: ARINC April 2012

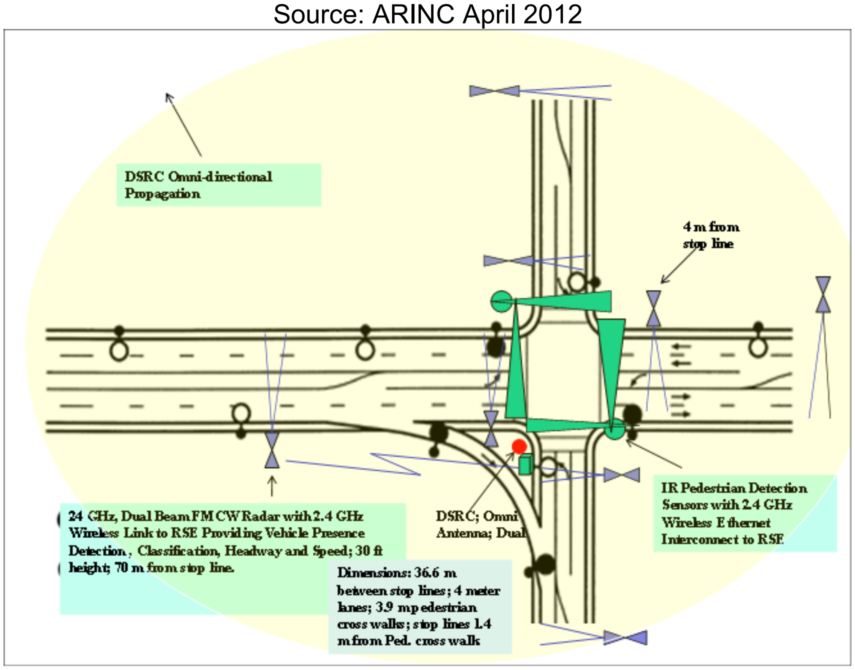


Figure 2**.4-**7**. Signalized Intersection with DSRC Transceiver, Radar Sensors and a 2.4 GHz Wireless Interconnect for Sensors to the RSE**

Source: ARINC April 2012

Figure 2.4-8 presents a signalized and barriered, at-grade rail crossing geometry illustrating the DSRC transceiver(s), 24 GHz vehicle and pedestrian detection radar, a 2.4 GHz WLAN and a 220 MHz digital link between a train and the RSE that is a candidate for testing and simulation. The RSE utilizes an optical Ethernet interconnect to the traffic management center. The DSRC(s) must coexist with the 2.4 GHz Wireless Ethernet and 24 GHz radar environment, 220 MHz digital link from an approaching train, in addition to any combination of emitters as defined in the RF environment section of this report.

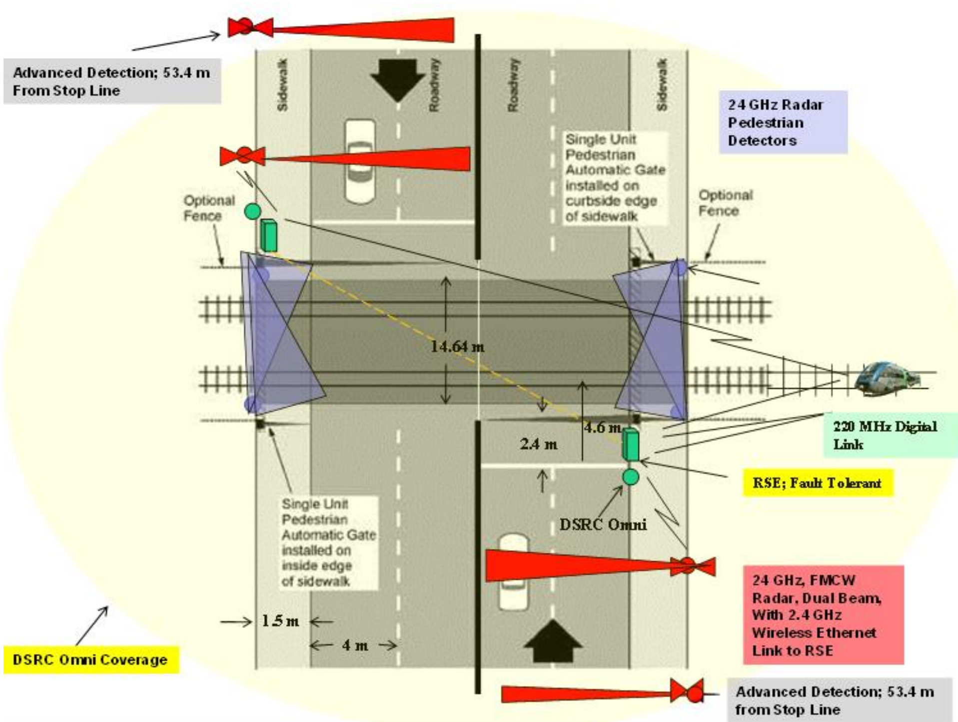


Figure 2.4-8. Signalized Rail with DSRC Transceiver, 24 GHz Radar Sensors for Vehicles and Pedestrians, 2.4 GHz Wireless Interconnect for Sensors to the RSE, and a 220 MHz Digital Link from a Train to the RSE

Source: ARINC April 2012

In summary, the test geometry should include RSE antenna placements over the corridor and beside the corridor and include sectorized antenna pattern for comparison with omni antenna performance. Typical ITS wireless sensors and interconnect links should be included to identify any potential radio frequency interference problems. This test can also include deterring the noise floor caused by RF emitting devices at varying operating ranges from the intersection and determine appropriate modulation and data rates to use for the DSRCs.

2.4.1.1 **Intersection Coverage Range and Intersection Overlap Consideration**

Intersection test should also be conducted considering both overlapping and non-overlapping RSE DARC antenna coverage. Purpose of this test is to investigate issues with "hidden terminal" coverage. Figure 2.4-9 illustrates the non-overlapped RSE coverage between two intersections; test using overlapping coverage would also be conducted investigating PER within the overlap and comparing it with the non-overlap coverage architecture.

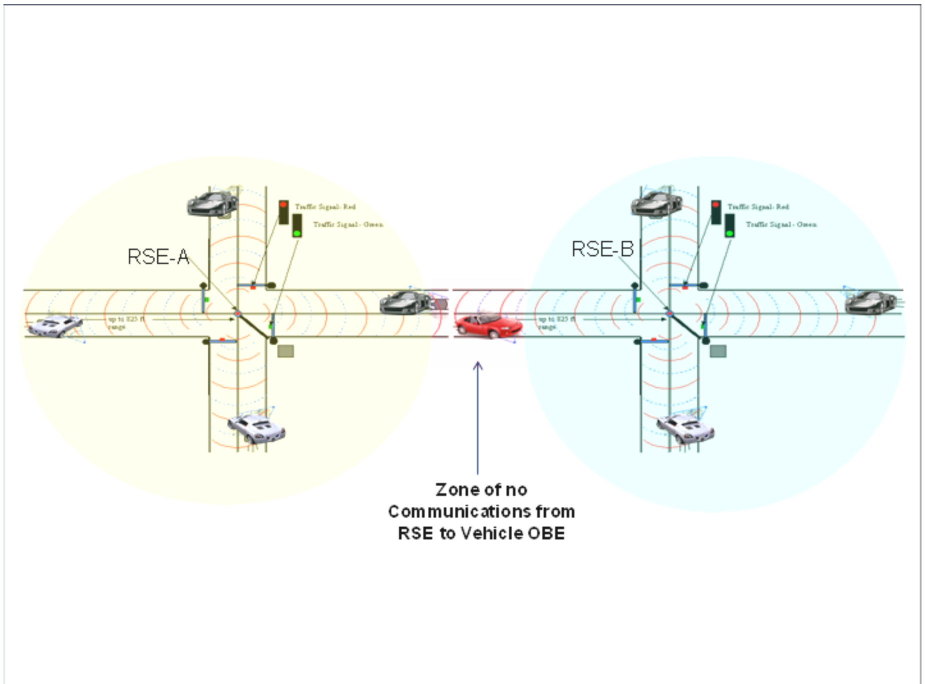


Figure 2.4-9. Example of Non-Overlapping RSE DSRC Coverage
Source: ARINC April 2012

Chapter 3 - Candidate Communications Technologies and Associated Products to Meet SPaT Related Communications Requirements

In the first part of this section, the communications technologies that were addressed in Task 3, the criteria for short-listing communications technologies and the high-level assessment of communications technologies conducted using the criteria are briefly reviewed.

The short listed candidate communications technologies include DSRC, LTE (jurisdictional deployment), WiMAX, digital terrestrial broadcast television, and digital terrestrial broadcast radio. However, since LTE has been selected for broadband, jurisdictional Emergency communications and since WiMAX has been accepted to comply with LTE Advanced standards, LTE will be considered as the primary candidate to support safety applications.

In the second part, the candidate communications technologies are analyzed in detail, including performance, results of simulation and testing, and available product information. This section provides a more detailed analysis of short listed communications technologies identified in Task 3 of this project.

3.1 Review of Communications Technologies Addressed in the Task 3 Market Scan and Short List

The wireless communication technologies considered in Task 3 were classified into three categories, namely wireless communication technologies applicable to wide area, medium range, and short-range coverage. Wide area coverage in this context refers to coverage that is greater than 1 km (0.6 mile) in distance. Medium range coverage refers to coverage between 100 m (approximately 300 feet) and 1 km (0.6 mile) in distance. Short-range coverage refers to coverage that is less than 100 m (approximately 300 feet) in distance. DSRC is classified as Medium range since it is specified to operate up to 1000 m (0.6 mi) for service applications.

Wide area technologies considered include:

- Cellular (LTE, UMTS, HSPA, HSPA+ and EV-DO);
- WiMAX;
- Multichannel Multipoint Distribution Service (MMDS);
- Local Multipoint Distribution Service (LMDS);
- Digital terrestrial broadcast television and radio;
- Satellite Digital Audio Radio Service (SDARS);
- Meteorburst;
- NOAA Weather Radio;

- National Differential GPS wireless network;
- P-25 Emergency Mobile Wireless/TETRA.

Medium range technologies include:

- DSRC;
- Wi-Fi;
- Femtocell.

Short-range technologies include:

- Bluetooth;
- ZigBee;
- Ultra-Wide Band (UWB);
- Infrared (as used in Europe for electronic toll collection).

The market scan of communications technologies is provided in the Task 3 report. This report includes expanded details of the short listed technologies. Details include RF characteristics, performance (bandwidth, modulation, supported data rates, bit error rates versus signal/noise and modulation, Federal Communications Commission (FCC) radio frequency (RF) radiated power limitations, latencies, etc.) and Quality of Service (QoS) including differential services and other features assuring operations in accordance with specifications in support of communications within a mobile (vehicular speeds of 120 mph/200 km/h) environment.

Also addressed in the market scan is susceptibility of the technology to adverse radio frequency environments, technology and standards maturity, availability of the technology in product form, and services, regulatory requirements such as spectrum licensing and transmission power, and product size/weight and environmental compatibility as related to deployment in vehicles and roadside electronic equipment cabinets.

In addition, advanced communications technologies are discussed. These technologies are generally not yet available in commercial products or are just emerging. These technologies include:

- SMART antennas (emerging in commercial products)
- Cognitive Radio (generally in development phase)
- Software-Defined Radio (prototype DSRC devices use)
- Connected Radio (generally in development phase)
- Advanced modulation techniques and protocols (studies and simulation phase)

These advanced communication technologies are still under research and development, but have been identified as potentially beneficial to SPaT applications or some components of the technology may potentially be useful. Due to the challenging environment for vehicular communications, a multi-faceted approach involving some combination of these complementary technologies may need to be taken to improve communication systems for roadway environments, and for the success of SPaT applications.

A high-level assessment of the wireless communication technologies was conducted in Task 3 to obtain a shortlist of candidate technologies for further evaluation. The assessment is conducted using the following high-level selection criteria:

Shortlist Criterion
Is the technology available for use without an ongoing service fee?
Can the technology be packaged for installation and operations in vehicles?
Are required antennas supporting the communications technology compatible with private, compact vehicle applications or does the operating wave length support development of a suitable antenna for mobile use?

Shortlist Criterion
Can the communications technology support user mobility at velocities required by ITS? If No the technology is not shortlisted;
Is the technology described in open standards, and is it available from multiple sources?
Is the technology available for test/use in a field test environment? (If No, and the technology has promise, it is short listed for additional analysis with a potential recommendation to follow progress)
Is spectrum available and allocated to support a national deployment?
Does the technology provide reliable operation in urban and rural environments?
Is user equipment affordably priced or with investment in large scale integration chip development, could the technology become affordable?
Is the technology early enough in its lifecycle to be expected to be available for at least 5 years?
Is performance in the "ball park" of ITS SPaT related communications requirements?
Does the Technology have a reasonable probability of being affordable to the purchaser of a vehicle and for jurisdictional deployment in production quantities?

Source: ARINC April 2012

Technologies that met all of these criteria were added to the short list. In some cases commonly available technology does not meet all of the criteria, but other sources are available that do meet the criteria. For example, LTE provided by commercial cellular companies does not typically implement broadcast functions, allocates bandwidth and QoS based on type of fee paid for service and charges a service fee to users. However, LTE systems are available for non-carrier based applications, stress multicast and geo-cast features, and could be made to provide broadcast functionality needed for SPaT applications (using the 3GPP standards). Furthermore emergency vehicles need to implement SPaT safety functional capability. Small, portable configurations have been produced for military applications, literally in "suitcase configuration."

The results of the high-level assessment of wireless communication technologies for wide area, medium range and short-range coverage are summarized in Table 3.1-1. The following wireless communication technologies have been shortlisted for further study:

- DSRC;
- Digital terrestrial broadcast television;
- Digital terrestrial broadcast radio;
- LTE (Jurisdictional Deployment in the 700 MHz Emergency Frequency Band allocated for jurisdictional operations);
- WiMAX (IEEE 802.16) (with priority given to LTE or WiMAX in LTE-A configuration).

Table 3.1-1. Summary of Communications Technology Reviewed in Task 3 and Shortlisted or Not Shortlisted

Source: ARINC April 2012

Communications Technology	Short Listed?	Reason Not Short Listed In Task 3 Report
Short Range Communications Technology		
Bluetooth, ZigBee, and UWB	No	Inadequate range and incompatible with high

Communications Technology	Short Listed?	Reason Not Short Listed In Task 3 Report
		speed vehicle mobility
Medium Range Communications Technology		
IEEE802.11p DSRC	Yes	N/A
WiFi	No	Incompatible with high speed vehicle mobility and less robust than IEEE802.11p
Wide Area Communications Technology		
Cellular Technology (UMTS, HSPA, HSPA+,EV-DO)	No	Requires fee for continued service
Jurisdictional LTE (700 MHz) – (including Femtocell)	Yes	N/A
Commercial LTE	No	Commercial communications service requires a fee for continued use
WiMAX (IEEE802.16) (including Femtocell)	Jurisdictional WiMAX – Yes;	LTE option is preferable
HD Radio (Digital Terrestrial Broadcast Radio)	Yes	N/A
Satellite Digital Audio Radio Service (SDARS)	No	Fee for continuing service and limited bandwidth availability for public use
ATSC M/H Mobile Digital TV	Yes	N/A
LMDS	No	Incompatible with high speed vehicle mobility, technology reaching end of life cycle
MMDS	No	Incompatible with high speed vehicle mobility, technology reaching end of life cycle
Emergency Mobile Wireless (P-25 and TETRA)	No	Bandwidth limitations (narrow band wireless link)
NWS Wireless Network	No	Bandwidth limitations
NDGPS Wireless Network	No	Bandwidth limitations (MF link is saturated and has no additional capacity)

3.2 Detailed Studies of Candidate Communications Technologies

This section presents detailed studies of candidate communications technologies shortlisted in Task 3, including performance, results of simulation and testing, and available product information. The candidate communications technologies include DSRC, LTE (jurisdictional deployment), WiMAX, digital terrestrial broadcast television, and digital terrestrial broadcast radio.

3.2.1 *Dedicated Short Range Communications*

This section provides details of the DSRC, current DSRC standards, associated products and test results.

3.2.1.1 **DSRC Background**

Dedicated Short Range Communications (DSRC) is a short to medium range communications service that supports both Public Safety and Private operations in roadside-to-vehicle and vehicle-to-vehicle communication environments. Current DSRC/WAVE is not to be confused with earlier tolling communications systems developed for the 915 MHz band. The technology that is the primary candidate for SPaT communications is what is now known as Dedicated Short Range Communications Wireless Access for Vehicular Environments (DSRC/WAVE) emerged in 1996 as part of the National Intelligent Transportation Systems Architecture developed by the USDOT and using IEEE802.11p standards.

In 1999 the Federal Communications Commission (FCC) reserved 75 MHz of spectrum in the 5.9 GHz band (5.85-5.925 GHz) for vehicle safety applications, and in 2003 the FCC adopted the ASTM E2213-02 standard for PHY and MAC layers for the ITS-DSRC band that invoked IEEE802.11a. Since IEEE802.11a did not adequately support mobility requirements, in 2004 the Institute for Electrical and Electronic Engineers (IEEE) created a task group to develop an amendment to the 802.11 standard to include vehicular environments (IEEE 802.11p), and also created the 1609 working group to develop higher layer standards. Today the 802.11p element is known as DSRC, and the higher layer standards are known as WAVE, and the combined system is referred to as DSRC/WAVE. The amendment to 802.11 modified the protocol to allow for an association-less communications capability. The rationale for this was that at road speeds communicating entities (i.e., vehicle and the roadside) would only be in range of each other for short periods of time. Conventional 802.11 protocols operate under a networking concept that requires an association process (sometimes described as a “network attachment” process). This is the process whereby a new terminal acquires an IP address, provides its MAC address to the network management function, and discovers the addresses of the other nodes on the network. Using the broadcast WAVE Short Message Protocol described in IEEE 1609.3, or the stateless auto-configuration protocol described in IPv6, the DSRC terminals do not need to associate with a network, so the processes described for this in 802.11 are not applicable. The IEEE 802.11p specification essentially describes the modifications required to eliminate these functions. In addition the 802.11p specification describes (in an annex) the frequency spectrum requirements for North America associated with the above, described FCC spectrum allocation.

The PHY layer of DSRC is defined essentially based on IEEE Std. 802.11a, with slight changes in the frequencies for North America. It uses Orthogonal Frequency Division Modulation (OFDM), and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as is defined for other 802.11 wireless protocols.

DSRC is capable of supporting multiple configurations of modulation, data rates, and effective transmission ranges. Depending on the desired transmission range and interference, DSRC is expected to provide latency shorter than 100 msec on MAC layer, supports up to 27 Mbps data rate in a 10 MHz channel, and provides a transmission range up to 1000 meters (3000 ft.). The system has the potential to dynamically adjust the data rate according to the interference; however, since it is used primarily in a broadcast mode, “handshaking” requirements to support adaptive communications has not been implemented and modulation/data rate is manually selected. Figure **3**.2-**1** illustrates the combinations of PHY parameters defined by 802.11p.

Modulation	Coded bits per periodic wave form	Coded bits per OFDM symbol	Coding rate	Data bits per OFDM symbol	Data rate for a 10 MHz wide channel (Mbps)	SINR threshold for frame reception (dB)
BPSK	1	48	1/2	24	3	5
BPSK	1	48	3/4	36	4.5	6
QPSK	2	96	1/2	48	6	8
QPSK	2	96	3/4	72	9	11
16-QAM	4	192	1/2	96	12	15
16-QAM	4	192	3/4	144	18	20
64-QAM	6	288	2/3	192	24	25
64-QAM	6	288	3/4	216	27	N/A

Figure 3.2-1. IEEE 802.11p OFDM PHY Parameters
(Ref: Institute of Electrical and Electronic Engineers, IEEE-802.11p, IEEE Standard for Information Technology - Local and Metropolitan Area networks - Specific Requirements - Part 11: Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments. [19])

IEEE 802.11p defines the physical and lower MAC layer interface. Key differences between 802.11a and 802.11p are the change to a slightly higher frequency band allocated for vehicle safety by the FCC, and elimination of the association processes whereby an 802.11 STA (station) establishes a networking connection to an 802.11 AP (access point).

IEEE 1609 series standards define link and higher layers of protocol. Specifically:

- IEEE 1609.2 defines the over the air security protocol
- IEEE 1609.3 defines the networking layer, including the WAVE Short Message Protocol (WSMP), and the differentiation by Ethertype between IP packets and WAVE short messages (WSMs)
- IEEE 1609.4 defines the upper MAC layer as well as various channel management functions

Together these standards provide the foundation for a broad range of applications in the transportation environment, including vehicle safety, automated tolling, enhanced navigation, traffic management and many others.

It is important to note that the IEEE 1609.3 standard describes two different networking layers. One is a conventional IPv6 layer that handles IP packets. The other is the WAVE Short Message Protocol (WSMP). This is a short, single packet protocol that is primarily used for non-networked broadcast communications. Using WSMP, a terminal need not be part of any network, and this substantially simplifies the operation of DSRC. In the dynamic world of vehicles on the road, the need to send a particular message to a particular vehicle is very low, yet the need to send any given messages to all vehicles in the local area is very high. WSMP allows this capability while eliminating the need to establish or manage an ever-changing network.

The SAE J 2735 standard describes a variety of application messages including the Signal Phase and Timing (SPaT) and Geometric Intersection Identifier (GID-MAP).

Task 2 utilized the work previously accomplished related to DSRC as a starting point for analysis. Figure 3.2-2 illustrates the related interface and protocol standards associated with DSRC.

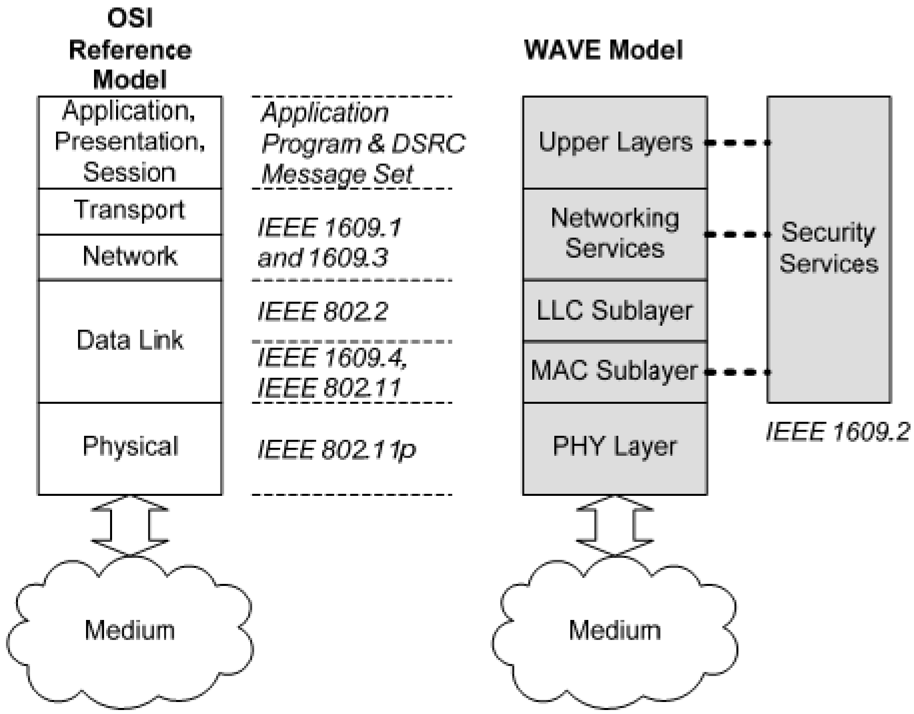


Figure 3**.2-**2**. Standards Associated with DSRC as related to the Open Systems Interface Model**
(Ref: "Overview and Use of SAE J2735 Message Sets for Commercial Vehicles", Chris Hedges [47])

As currently planned, DSRC/WAVE will support both V2I and V2V communications. The deployment scenario includes DSRC-enabled roadside equipment deployed along the roadway, to provide road information and hazard warnings, and in vehicles to support vehicle-to-vehicle applications. DSRC/WAVE terminals deployed at intersections will intersection safety applications using the SPaT and GID messages.

DSRC is specifically designed to support location based communications, that is, communication of data between terminals as a result of their physical proximity. This approach is unique in that it does not require any sort of location filtering at the terminal, as would be required for wide area communication such as HD radio or satellite, and it does not require any sort of network addressing. Instead, DSRC broadcasts messages at the location where they are most relevant (for example, at a location on the road where the message is likely to be relevant to passing vehicles) and any vehicles in the area receive the message. DSRC also supports IP communications through the IPv6 stateless auto-configuration protocol wherein the DSRC terminal generates its own IP address based on the link-local address of the RSE. In this application the terminal can initiate an IP message exchange with a remote server, and the packets are routed back to the RSE which then broadcast then locally to the terminal. This approach is effective, but, as with any addressed communication, if the terminal leaves the proximity of the network attachment node, any packets addressed to it will not be delivered. In the case of DSRC, the RF footprint is somewhat small, so IP communications can only be carried out over a relatively brief interval while the terminal is in range of an RSE.

Several manufacturers have developed DSRC/WAVE compatible equipment, although, since there has been no commitment to deploy the technology on a large scale, most of this equipment is aimed at research and prototype development applications and is still relatively costly. Also, several manufacturers are now in a development mode to improve performance by incorporating some features found in cognitive radios used for military applications. Most of the DSRC manufacturers are using software defined radio technology or subsets of it.

Figure 3.2-3 illustrates DSRC products that have been used in ITS testing.

Figure 3.2-3. Examples of DSRC Devices used in ITS Tests
(Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

3.2.1.2 **DSRC Packaged Technology (DSRC Product Specifications and Overview)**

As mentioned in the section above, most of the manufacturers of DSRC devices still consider the products to be in a development phase with final specifications to be developed once large-scale deployments are underway. Figure 3.2-4 through Figure 3.2-6 summarizes the features and specifications of a typical DSRC/WAVE product being offered on the market. This product is available in both a single and dual radio configuration supporting MIMO. A simple diagram is shown in Figure 3.2-7.

- Single-channel mode (1 or 2 antenna diversity operation).
- Dual-channel mode (1 or 2 antenna diversity operation), 2 independent IEEE 802.11p radios operating on different radio channels.
- 10MHz (DSRC) and 20MHz channel bandwidth modes.
- Operating bands:
  - 5.85-5.92GHz
  - 5.15-5.35GHz
  - 5.47-5.725GHz
  - 5.725-5850GHz
- Transmit mask meeting IEEE 802.11p Class C (5GHz band) [5].
- IEEE 802.11p enhanced adjacent channel receiver performance [5].
- Transmit antenna cyclic delay diversity (2 antenna operation only).
- Transmit power control (0.5dB steps).
- Fast mode changes for synchronised channel switching systems.

The MAC provides the following operating modes:

- Single channel operation. Simple single radio channel operation only.
- Single radio, time-synchronised multi-channel operation
  - channel switching between 2 or more channels with multiple sets of transmit queues.
- Dual-radio, multi-channel operation
  - Independent MAC/PHY entities operating concurrently on different radio channels.
  - Optional coordination between channels to avoid self-interference when operating on close radio channels.

Figure 3**.2-**4**. DSRC Product Features**
(Ref: Manufacturer of DSRC Product Literature [48])

Data Rate	Receive Sensitivity (dBm)
3 Mbps	-97
4.5 Mbps	-95
6 Mbps	-94
9 Mbps	-92
12 Mbps	-88
18 Mbps	-85
24 Mbps	-79
27 Mbps	-78

Receiver Sensitivity, 2 Antennas , 5.9 GHz, 10 MHz BW

Data Rate	0 Hz Doppler (dBm)	700 Hz Doppler (dBm)
3 Mbps	-96	-94
4.5 Mbps	-92	-91
6 Mbps	-93	-92
9 Mbps	-89	-88
12 Mbps	-85	-84
18 Mbps	-81	-80
24 Mbps	-77	-74
27 Mbps	-74	-70

Mobil, Outdoor Receiver Sensitivity, 2 Antennas , 5.9 GHz, 10 MHz BW

Data Rate	Adjacent Channel Rejection (dB)	Alternate Adjacent Channel Rejection (dB)
3 Mbps	28	42
4.5 Mbps	27	41
6 Mbps	25	39
9 Mbps	23	37
12 Mbps	20	34
18 Mbps	16	30
24 Mbps	12	26
27 Mbps	11	25

Adjacent and Alternate Channel Rejection

Specification	Performance
Maximum Transmit Power	+21dBm per antenna port (+24dBm effective transmit power in 2-antenna transmit mode) +18dBm per antenna port for 2.4GHz band operation.
Minimum Transmit Power	0dBm
Transmit power control	0.5dB steps monotonically increasing/decreasing
EVM	per IEEE802.11-2007 (clause 17.3.9.6.3)
Spectral Mask	Meets DSRC class C, • 5.0 MHz, -26 dBc • 5.5 MHz, -32 dBc • 10 MHz, -40 dBc • 15 MHz, -50 dBc

DSRC Transmitter Specifications

Note: Rec. Sensitivity at 25 deg. C.; May be 3 dB Higher at 85 deg C. ; Xmit specs apply across op temp.

Figure 3.2-5. DSRC Product Receiver & Transmitter Specifications
(Ref: Manufacturer of DSRC Product Literature [48])

Other DSRC Specifications	Product Performance
Output Center Frequency and Symbol Clock tolerance	+- 20 pps
Transmitter Spectral Flatness	< +- 2 dB in all Bandwidths and Modulation Modes
Transmitter Center Frequency Leakage	> 10 dB Below Average Sub-carrier Power in all Bandwidths and Modulation Modes
Transmitter Power Control Step Size	0.5 dB
Transmitter Power Control Accuracy	+- 2 dB Over Operating Temperature Range
Operating Temperature	-40 to + 85 deg C
Humidity	5 to 95%, Non-Condensing
Power	9 to 16 VDC; 560 mA Rec. and 900 mA Xmit 1 Radio; 650 Ma Rec. and 100 mA Xmit 2 Radios
Size (W, D, H)	RSE: 189 X 440 X 111 mm (17.3 X 7.4 X 4.4 in) OBE: 160 X 250 X 100 mm (9.8 X 6.3 X 3.9 in)
Weight	RSE: 1.5kg (3.3 lbs) OBE: 0.6 kg (1.3 lbs)

Figure 3**.2-**6**. Additional DSRC Product Specifications**
(Ref: Manufacturer of DSRC Product Literature [48])

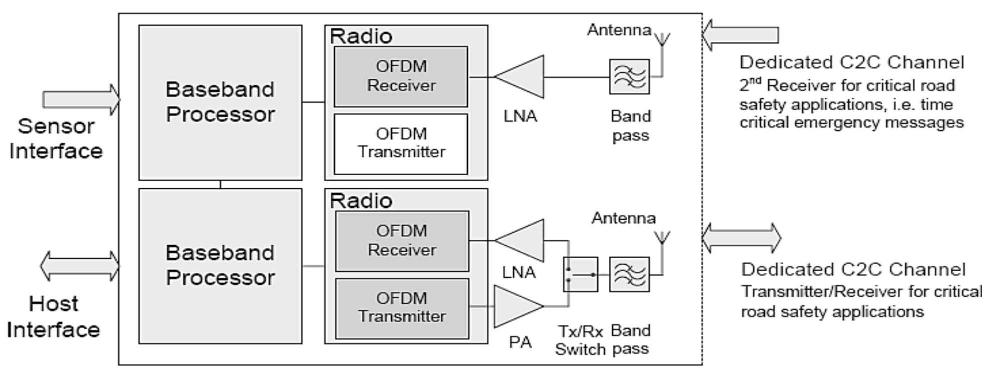


Figure 3**.2-**7**. DSRC Diagram Showing Dual Radios**
(Ref: “CVIS”, Knut Evensen, Q Free [49])

The manufacturer states that adjacent channel rejection is measured by “setting the desired signal strength to 3 dB above the receive sensitivity specified in Figure 3.2-5 and raising the power of the interfering signal until 1-% PER, results for a Physical Layer Service Data Unit (PSDU) length of 1000 octets. The power difference between the interfering and the desired channel is the corresponding adjacent channel rejection.”

The DSRC product is advertised to provide the following built in test and monitoring data, which can be utilized to manage QoS of DSRC/WAVE:

- Channel Utilization (ratio of channel busy time to measurement duration);
- Channel Activity Ratio (proportion of the time that the radio is tuned to the SCH or CCH channels, respectively);
- Per-channel Statistics (number of packets successfully transmitted; number of packets that failed to transmit; number of packets successfully received, and number of packets received in error: organized according to broadcast, multicast and unicast packets);
- Received Signal and Noise Power Levels.

The specifications included in this section are representative of DSRC/WAVE products that are available on the market today.

One manufacturer offers a DSRC with a -31 deg. C. to + 71 deg. C. environmental specification; however, these are not fully compliant with either NEMA TS-2 or SAE environmental specifications. Shock and vibration specifications are not provided on data sheets, which normally mean that the units do not comply with the requirements of the environment for which it is intended to operate.

3.2.1.3 **DSRC Test Results**

There have been numerous projects to analyze and/or test DSRC/WAVE operations in a field environment including V2I and V2V applications. Among them, the most comprehensive to date is the Proof of Concept field test performed by the Vehicle Infrastructure Integration Consortium in 2009 (Ref: "Final Report: VIIC POC Results and Findings Summary – Vehicle", May 19, 2009 [50]; and "Analysis of Detroit POC Trial Results and Use in Validating a DSRC Simulator", Adelin M. Miloslovav, et al, University of Virginia, October 2010 [51]).

In particular, the VII Proof of Concept test assessed DSRC range in different urban canyon situations. These results for infrastructure to vehicle transmission are shown in Figures 3.2-8 to 3.2-10. As can be appreciated from these tests, WAVE Short Message (WSM) transmissions are less reliable than UDP. This is because UDP, while a "non-guaranteed" system, still includes data packet acknowledgements. Using UDP, if a packet is not acknowledged, it is re-sent up to ten times. The figures also clearly show the effect of multipath. In the short urban canyon, the packet error rate deteriorates (more than 10%) between about 90 meters (295 ft.) and 220 meters (722 ft.) for UDP, and beyond 90 meters (295 ft.); it never recovers for WSM. In the medium urban canyon, by contrast, the PER for WSM and UDP is below about 2% out to over 300 meters 984 ft.). In tall urban canyons, the UDP PER is below 1% out to 400 meters (1312 ft.), and the WSM PER exhibits a multipath "hole" between 150 meters (492 ft.) and 310 meters (1017 ft.). It is important to note that these tests were carried out using a single diversity receiver (that is, no antenna diversity). Use of a diversity antenna and various PHY processing techniques has demonstrated the ability to substantially minimize these effects.

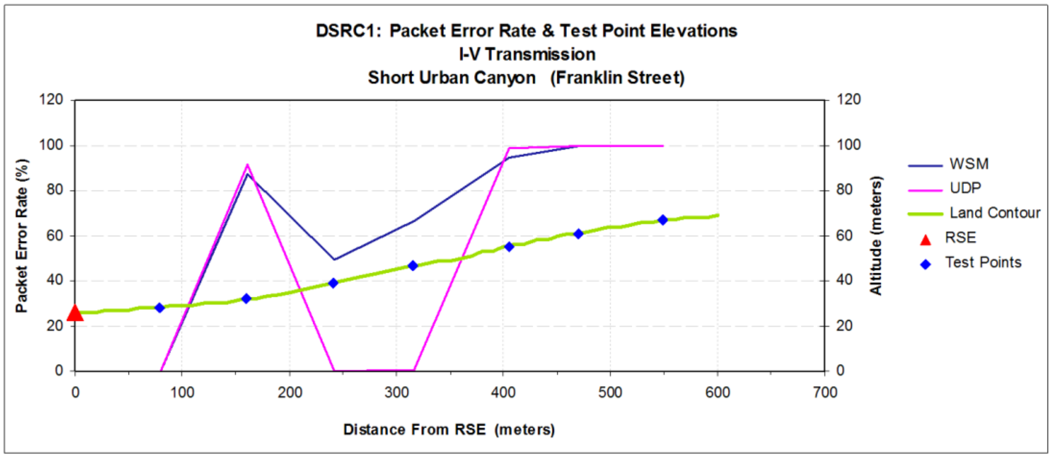


Figure 3**.2-**8**. Short Urban Canyon (I-V) Communications**
(Ref: USDOT Report FHWA-JPO-09-043, "Final Report: Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary – Vehicle", May 19, 2009. [50])

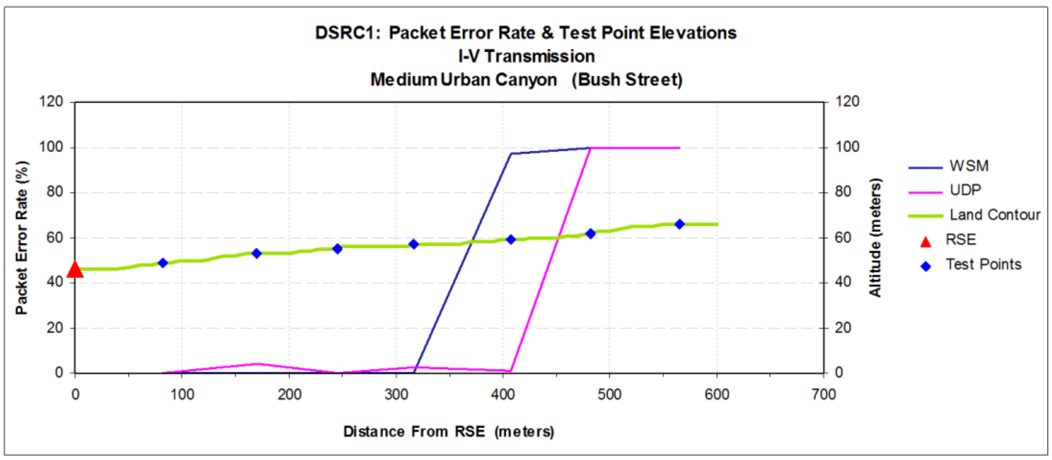


Figure 3**.2-**9**. Medium Urban Canyon (I-V) Communications**
(Ref: USDOT Report FHWA-JPO-09-043, "Final Report: Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary – Vehicle", May 19, 2009. [50])

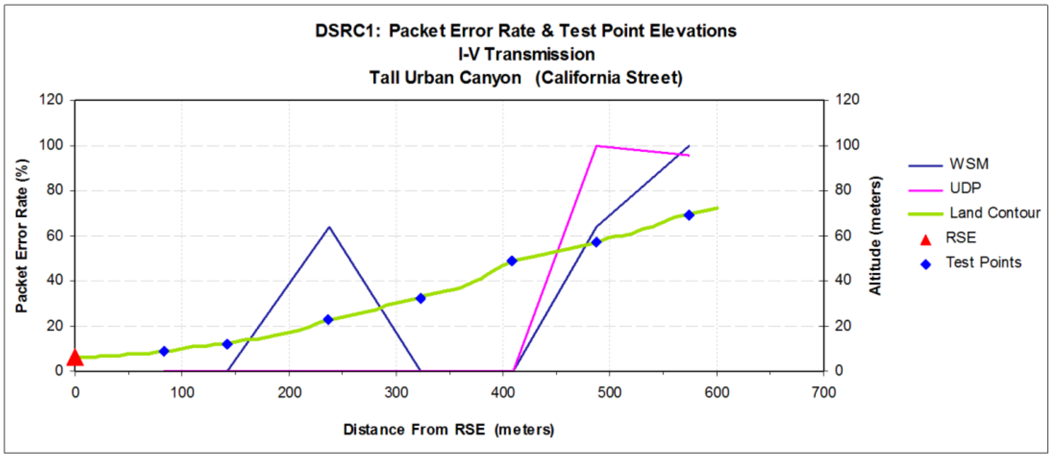


Figure 3.2-10. Tall Urban Canyon (I-V) Communications
(Ref: USDOT Report FHWA-JPO-09-043, "Final Report: Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary – Vehicle", May 19, 2009. [50])

In general, however, these ranges are within the required minimums for SPaT related applications below about 60 mph, as described in Table 2.3-6 above.

DSRC uses a carrier sense multiple access (CSMA) approach to manage multiple users, and in situations where there are a large number of users all seeking to transmit messages (e.g., dense traffic all sending BSMs), the system is unlikely to perform well.

A summary of the results of other research related to DSRC is presented in Table 3.2-1. Some of the key findings related to research analysis, simulation and field-testing are:

> In areas with nearby military bases, in-band interference may be present from military radar (see NTIA Report 00-373) [36]. The higher the radar PRF and radiated power, the higher the probability of packet interference (see NTIA JSC-CR-06-072; *Communications Receiver Performance Handbook*) [52]. Per NTIA Report TR-99-361[53], "radar interference occurs when out-of-band or spurious energy emitted from the radar transmitter falls within the pass-band of a receiver; the energy then passes through the receiver front-end with little or no attenuation. When the undesired emission level is high relative to the desired signal level, receiver performance degradation can occur."

DSRC has been subject to significant research because it is considered to be able to provide low latency, fast attach, high mobility, broadband wireless communications. There are significantly more research, test and evaluation reports available related to IEEE802.11p than is available on technologies such as LTE, HD Radio (all digital), and ATSC M/H TV broadcast. This provides an excellent basis for identifying DSRC specifications that work in "real world" applications and areas that should receive additional study and testing attention. Some of the research and test findings related to the DSRC are summarized in Table 3.2-1.

Table 3.2-1. Summary of Research Papers Related to IEEE802.11p DSRC Technology

Reference	Key Findings	Conclusion
"VSC-A Project Cross-Channel Interference Test Results"; IEEE	"Cross-Channel Interference calls into question the ability to use near-channels within moderate proximity simultaneously.	Issue with Co-Channel Interference with IEEE802.11p Standard

Reference	Key Findings	Conclusion
802.11, 11-07-2133-00-000p [35]		
"CVIS Communications Performance Results"*;* Sophia Antipolis*; 2nd ETSI TC ITS Workshop*; February 2010 [214]	M5 DSRC AUX channel provided 25.88 mbps data rate at 80 meters (263 ft.) and CCH channel provided 4.77 mbps at 500 meters (1640 ft.) for RSE to Vehicle communications test.	Test objectives for M5 DSRC of 24 mbps for AUX channel at 80 m (263 ft.) and 2 mbps for CCH channel at 500 meters (1640 ft.) were met.
"Reliability Analysis of DSRC Wireless Communications", Fan Bai, et al, GM Corp. R&D Center [215]	Packet Delivery Ratio is 0.7 at 200 meters (656 ft.) between vehicles falling to 0.55 at 425 meters (1394 ft.).	Possible issue with Communications Reliability at distances between vehicles greater than 200m (656 ft.).
"Vehicle Communications Standards", Katrin Bilstrup, et al, Halmstad University, Sweden, *SAFER Seminar*, Jan. 20, 2009 [216]	"Major problems with unbounded channel access delays with IEEE802.11p when the network becomes overloaded in terms of nodes/injected data."	IEEE802.11p has degraded performance as vehicle density increases.
"Performance Analysis of IEEE 802.11p in Urban Environments using a Multi-Agent Model", Juan Carlos Burguillo-Rial, et al, Universidad de Vigo, Spain [217]	The results of simulations show that IEEE 802.11p technology is adequate as long as the number of cars remains small. As the number of cars increases, bandwidth becomes lower, even with the use of Enhanced Distributed Channel Access (EDCA) mechanism.	Issue with vehicle density and DSRC link performance.
"Analysis of Detroit POC Trial Results and Use in Validation a DSRC Simulator"; Adelin Miloslovav, et al, 10-25-2010 [51]	Probability of a Successful Packet Delivery: • No Retransmission: 0.85 @ 50m; 0.8 @ 100m; 0.7 @ 200m; 0.4 @ 400m; 0.15 @ 800m; • One Retransmission: 0.95 @ 50m; 0.94 @ 100m; 0.9 @ 200m; 0.7 @ 400m; 0.25 @ 800m.	Achieving 0.95 probability of success of packet delivery requires as many as 5 retransmissions at 400m (1312 ft.) range between transmitter and receiver.
"NTIA Measured Occupancy of 5850-5925 MHz and Adjacent 5 GHz Spectrum in the USA"*;* Frank Sanders [36]	Identifies military radar operating within the DSRC band and other emitters operating in adjacent bands. Indicates potential interference issues of DSRC devices operated in locations near military installations.	Possible RF interference with the DSRC.
"Reflections on Cooperative Urban Applications"*;* Jaap	Field Test indicated acceptable M5 DSRC data rate achieved at 300 m (984 ft.).	DSRC met applications requirements at distances to 300 meters

Reference	Key Findings	Conclusion
Vreeswijk; Peek, Sept 2009 [218]		(984 ft.).

Source: ARINC April 2012

As near-production equipment is available for DSRC, multiple field trial initiatives are in progress. Table 3.2-2 provides a summary overview of the 5.85-5.92 GHz, IEEE 802.11p compliant DSRC.

Table 3.2-2. Summary Specifications (Published and Test Results) for DSRC

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
Applicable standards	IEEE 802.11p, IEEE1609 and SAE J2735	Same
Link Access	CSMA/CA	Same
Simplex, half duplex, or full duplex service	Half duplex	Same
Frequency Band and Licensing	5.85 to 5.925 GHz; Special License for USDOT Applications	Same
Operating Bandwidth and Channel Bandwidth	75 MHz; 10 MHz (7 channels)	Same
Wireless Mobility with Velocities Supported:	200 km/hr	200 km/hr
Maximum Range	1000 m	200 m with packet delivery in urban conditions of 0.7 with one message transmission.
Multipath Spread Protection	1.6 μsec tolerated	Some Doppler impact identified t speeds above 60 mph.
Selectable Communications Data Rates	3 to 27 Mbps	3 to 6 Mbps typical throughput; 4.5 mbps recommended by some researchers.
Receiver Sensitivity	-110 dBm	Same (Noise floor varies from -100 to -40 dBm; -90 to -100 dBm typical)
BER	BER 10^{-6} with: -82 dBm @ 3 mbps; -81 dBm @ 4.5 mbps; -79 dBm @ 6 mbps; -77 dBm @ 9 mbps; -74 @ 12 mbps; -70 @ 18 mbps; -66 @ 24 mbps; and -65 @ 27	BER not generally achieved at distances beyond 200m; however, this may be attributed to higher level ambient noise, channel congestion, and multipath.

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
	mbps. Assumes ambient noise floor above -110 dBm	
Latency	1) Attachment Latency< 10 msec 2) Terminal to terminal latency < 100 msec (using channel switching; about 1 μsec without channel switching)	1) 18 msec average with 25 vehicles in communications range. 2) Same
Adjacent Channel Interference Protection	-40 dB	Some field test indicates interference at close separations of vehicles.
Quality of Service N/A	8 Level Differential Service	Same; However, a dedicated DSRC for Safety and a second for services is being considered.
Current Design Vehicle Environmentally Compatible	Yes	Most manufacturers are not currently SAE compliant for light and heavy vehicles. Should be no barrier to meeting requirement other than cost impact.
Equipment Approximate Size /Weight for Mobile Applications	0.004 cu meters (244 cu in); 0.6 kg (1.3 lbs.)	Same; however, most manufacturers are not focusing on developing the smallest, lightest weight package but making the unit multifunctional, including dual DSRC devices and integrated GPS receiver.
Equipment Approximate Power Load for Mobile Applications	12 W.	Same; however, multifunctional units are being produced; a single DSRC would most likely require less power.
Approximate Cost of Mobile Unit	$300	Most manufacturers are pricing their DSRCs higher because demand is low. Manufacturers are including multiple functional capabilities in the DSRCs, supporting exploring of applications which it can support.

Source: ARINC April 2012

3.2.2 *LTE*

Long Term Evolution (LTE) is a next generation of cellular technology based on the 3GPP specifications. It boasts increased speeds and improved performance over 3G technologies in order to support higher bandwidth uplink and downlink applications and higher system capacity. LTE is currently being rolled out by commercial network providers. It has also been identified by the FCC for public safety communications. A comparison of the 2G, 3G and 4G technologies is provided in Table 3.2-3.

Table 3.2-3. Comparison of 2G/3G/4G Wireless Technologies

Cellular Technology	Max Data Rates Downlink / Uplink	Air Interface Technology	Channel Bandwidth	User Plane Packet Latency	Latency of Call Setup from Connected
2G **(GSM/GPRS/EDGE)**	14.4 kbps - 474 kbps DL 14.4 kbps - 355 kbps UL	TDMA/FDMA	200 kHz	300 msec - 600 msec	3-4 seconds
3G **(UMTS/HSPA/HSPA+)**	384 kbps - 28 Mbps DL 384 kbps - 11.5 Mbps UL	W-CDMA	5 MHz	50 msec – 200 msec	82 msec – 242 msec
4G **LTE**	300 Mbps DL 75 Mbps UL	OFDMA/SC-FDMA	Up to 20 MHz	10 msec	13 msec – 173 msec

Source: ARINC April 2012

Figure 3.2-11 shows the main architectural components of an LTE network. The Enhanced UMTS Terrestrial Radio Access Network (E-UTRAN) consists of evolved Node Bs (eNBs) providing the user plane and control plane protocol terminations for the user device. The eNBs also support a many-to-many relation between Mobility Management Entities (MMEs) and Serving Gateways (SGW), as well as other eNBs. The MME primarily performs mobility management and is a signaling-only functional element. The SGW routes and forwards user data packets.

Figure 3.2-11. LTE Network Architecture

(Ref: *3GPP LTE*, http://www.3gpp.org/LTE). [54])

The LTE air interface uses orthogonal frequency division multiplexing (OFDM) on the downlink and single carrier frequency division multiple access (SC-FDMA) on the uplink. In addition, LTE uses multi-antenna techniques (e.g., MIMO) as well as QPSK, 16QAM, 64QAM modulation schemes to improve performance. LTE can support flexible channel bandwidths from 1.4 MHz to 20 MHz allowing for variable data rates. For a 20 MHz channel, LTE peak rates can increase to 300 Mbps on the downlink and 75 Mbps on the uplink. The peak rates are shown below in Figure 3.2-12 (Ref: “3GPP LTE”, http://www.3gpp.org/LTE [54]).

Category		1	2	3	4	5
Peak rate Mbps	DL	10	50	100	150	300
	UL	5	25	50	50	75
Capability for physical functionalities						
RF bandwidth		20MHz				
Modulation	DL	QPSK, 16QAM, 64QAM				
	UL	QPSK, 16QAM				QPSK, 16QAM, 64QAM
Multi-antenna						
2 Rx diversity		Assumed in performance requirements.				
2x2 MIMO		Not supported	Mandatory			
4x4 MIMO		Not supported				Mandatory

Figure 3.2-12. LTE Peak Rates per User Equipment Category

(Ref: *3GPP LTE*, http://www.3gpp.org/LTE). [54])

LTE operating spectrum has been defined in 3GPP TS 36.141 Release 8 and a summary of the frequency bands is provided in Table 3.2-4.

A number of performance requirements have been defined for LTE in the standards (Ref: "3GPP TR 25.913 V8.0.0, 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Requirements for Evolved UTRA (EUTRA) and Evolved UTRAN (E-UTRAN) (Release 8)", December 2008 [55]). LTE requirements include user plane round trip latencies of 10 milliseconds and control plane latencies of 50-100 milliseconds after connection establishment which can require an additional 200 to 1000 msec. The LTE base station or eNB is required to be optimized for low mobile speeds from 0 to 15 km/h (~9 miles/hour) but should also support speeds of 15 to 120 km/h (~9 to 75 mph) with high performance. LTE uses 4.69 µs guard period to accommodate multipath variations of up to 1.4 km. LTE should support at least 200 active data clients in every 5 MHz allocation. An LTE base station is required to support a coverage range of 5-100 km (3 miles to 62 miles) with slight degradation after 30 km (19 miles). However, due to the practical deployment constraints, such as the needed antenna height to reach 100 km coverage radius, it is extremely rare to plan and deploy such a large cell. For dense urban planning, 0.5 km is typical. Figure 3.2-13 shows examples of LTE equipment.

Table 3.2-4. LTE Frequencies

E-UTRA Operating Band	Uplink (UL) operating band BS Receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex Mode
	$\mathbf{F}_{\text{UL low}}$ – $\mathbf{F}_{\text{UL high}}$	$\mathbf{F}_{\text{UL low}}$ – $\mathbf{F}_{\text{UL high}}$	
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz MHz	
2	1850 MHz-1910 MHz	1930 MHz - 1990 MHz	
3	1710 MHz - 1785 MHz	1805 MHz - 1880 MHz	

E-UTRA Operating Band	Uplink (UL) operating band BS Receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex Mode
	$F_{UL\ low}$ – $F_{UL\ high}$	$F_{UL\ low}$ – $F_{UL\ high}$	
4	1710 MHz - 1755 MHz	2110 MHz - 2155 MHz	
5	824 MHz - 849 MHz	869 MHz - 894 MHz	FDD
6	830 MHz - 840 MHz	875 MHz - 885 MHz	FDD
7	2500 MHz - 2570 MHz	2620 MHz - 2690 MHz	FDD
8	880 MHz - 915 MHz	925 MHz - 960 MHz	FDD
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD
10	1710 MHz - 1770 MHz	2110 MHz - 2170 MHz	FDD
11	1427.9 MHz – 1447.9 MHz	1475.9 MHz – 1495.9 MHz	FDD
12	699 MHz - 716 MHz	729 MHz - 746 MHz	FDD
13	777 MHz - 787 MHz	746 MHz - 756 MHz	FDD
14	788 MHz - 798 MHz	758 MHz - 768 MHz	FDD
…			
17	704 MHz - 716 MHz	734 MHz - 746 MHz	FDD
…			
33	1900 MHz – 1920 MHz	1900 MHz - 1920 MHz	TDD
34	2010 MHz - 2025 MHz	2010 MHz - 2025 MHz	TDD
35	1850 MHz - 1910 MHz	1850 MHz - 1910 MHz	TDD
36	1930 MHz - 1990 MHz	1930 MHz - 1990 MHz	TDD
37	1910 MHz - 1930 MHz	1910 MHz - 1930 MHz	TDD
38	2570 MHz - 2620 MHz	2570 MHz - 2620 MHz	TDD
39	1880 MHz - 1920 MHz	1880 MHz - 1920 MHz	TDD
40	2300 MHz - 2400 MHz	2300 MHz - 2400 MHz	TDD

Source: ARINC April 2012

Figure 3.2-13. Examples of LTE Equipment

(Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

As with other cellular technologies, LTE suffers performance degradation at cell edges, indoors and in hotspots. FCC has set limits on power output to less than 50 dBm for eNB and typically uses 46 dBm; the mobile terminal has a 23 dBm power limit (Ref: “Practical Introduction to LTE Radio Planning”, J. Salo, et al [56]).

LTE is an IP packet based communications system, so in order to communicate; a terminal device must acquire an IP address from the base station (a process known as network attachment. Packets are then sent to and from the device based on its IP address. This means that each LTE terminal is normally communicated with individually (i.e., one message or packet per terminal). LTE includes specifications for Multimedia Broadcast and Multicast Services (MBMS), initially defined in the UMTS/HSPA standards. More recent standard releases include multicast/broadcast single-frequency network (MBSFN) operation to optimize MBMS by allowing simultaneous transmission of the exact same waveform from multiple cells (a broader type of broadcast). The disadvantage of using MBMS is that the granularity of the broadcast area is limited to the cell size which can be large (i.e., up to 30 km), so this means that any messages meant for a specific place must be broadcast over a relatively wide area, and the wider area may include many different locations that require location specific messages.

The MBMS capability is standardized and although major network carriers do support live streaming applications such as TV on demand and live sports, it is not evident that the MBMS features are used for these applications.

LTE was first defined in 3GPP Release 8 with the latest standard in Release 9**.** Evolved MBMS (eMBMS) is part of 3GPP Release 9 and provides specifications for using broadcast and multicast for localized information dissemination in LTE networks, although as described above, these are limited to the entire cell area, and cannot be made more granular. The specifications define nine different Quality of Service classes supporting packet loss rates of 10^{-2} to 10^{-6} and packet delays of 50 milliseconds to 300 milliseconds.

Although 3GPP LTE is referred to as 4G, the Release 8 LTE does not fully comply with the International Telecommunication Union (ITU) IMT-Advanced requirements and the ITU designation for 4G. The LTE standards are being further enhanced in order to meet the IMT-Advanced requirements such as enhanced peak data rates to support advanced services and applications (100 Mbps for high and 1 Gbps for low mobility). The necessary enhancements are specified in 3GPP Release 10 and beyond and are known as LTE-Advanced. LTE-Advanced, which would be truly 4G, would support downlink data rates of 1 Gbps and uplink data rates of 500 Mbps with latencies of 5 milliseconds. LTE-Advanced is expected to support scalable channel bandwidths up to 100 MHz and spectrum aggregation where non-contiguous spectrum is used. The LTE-Advanced standards are still in the process of being evaluated and finalized. 3GPP Release 10 is targeted to be frozen in 2011.

The infrastructure side of the technology is deployed by a cellular service provider, and the user equipment is built to their specifications. LTE is currently being deployed by multiple commercial carriers. As of March 2011, Verizon LTE coverage reached about 147 major cities. AT&T plans to begin roll out of its LTE network in mid-2011. The LTE base stations can support roadway environment using cabinet standards NEMA 3, 3R, 4, 4X as well as ETS 300 019-1-4 Class 4.1E (OD) GR-63-CORE, GR-487-CORE. The LTE base stations can operate in outdoor conditions with temperatures ranging from -45°C to 45°C (-49°F to 113°F) and humidity ranging from 8% to 100%.

A number of 4G USB modems are available for LTE with costs ranging from $100 to $300.

Another network provider for 4G, LightSquared, will use a combination of terrestrial cellular base stations and satellites to support LTE. There is concern by the GPS community that the LightSquared licensed 1525-1559 MHz spectrum will cause interference to GPS operating in nearby frequencies (1559-1610 MHz) with lower signal strength. As a result, LightSquared formed a working group with the US Global Positioning System Industry Council to study the interference issues. Its report was delivered to the FCC in July 2011. The report identified that LightSquared transmissions in the channels nearest to the 1559-1610 MHz GPS band will most adversely affect the performance of a significant number of legacy GPS receivers. The report recommended that LightSquared "(1) operate at lower power than permitted by its existing FCC authorization; (2) agree to a standstill in the terrestrial use of its upper 10 MHz frequencies immediately adjacent to the GPS band; and (3) commence terrestrial commercial operations only on the lower 10 MHz portion of its spectrum and to coordinate and share the cost of underwriting a workable solution for the small number of legacy precision measurement devices that may be at risk." The FCC opened a 30-day public comment period on the report and recommendations, with a comment deadline of July 30, 2011. GPS advocates note that even the 10MHz-low plan would not solve problems caused by LightSquared transmissions and are pushing for additional testing of the "10MHz-low" plan, which was not the focus of the working group evaluation (Ref: Gibbons Media and Research LLC, "GPS Interference Test Results May Not Slow FCC Decision on LightSquared Deal" [192]). Additionally, the Government's National Space-Based PNT Systems Engineering Forum (NPEF) completed its own testing in June 2011 and also found interference to military and civilian GPS users from LightSquared's network. The PNT has proposed that another six months be allocated for more tests, during which time LightSquared should not go forward with commercial operations. (Ref: "Space-Based Positioning Navigation and Timing, LightSquared and GPS", http://www.pnt.gov/interference/lightsquared/ [57]). In mid-February, 2012 FCC withdrew its approval and LightSquared is planning to challenge the decision in court. (Ref: "LightSquared Prepares Legal Challenge to FCC Decision", by C. Wilson; *Investor Place*; 3-15-12 [58]).

3.2.2.1 **LTE Performance Details**

Table 3.2-5 presents key specifications associated with LTE. The practical uplink data rate is 50 Mbps and the downlink data rate is 100 Mbps per LTE radio channel. The data rate varies with bandwidth (5, 10 or 20 MHz as allocated by FCC), modulation and MIMO antenna configuration. Advanced LTE promises 1 Gbps data rates. Radio data rate can be allocated to up to 200 users. The ability to adjust modulation schemes based on signal quality allows LTE to use higher-order modulation, up to 64QAM, with less robust encoding in strong signal areas. In poor signal quality areas, LTE switches to lower-order modulation, such as QPSK, for more robust encoding to minimize errors. Thus the highest throughput occurs closer to the base station. Additionally, the use of multipath-resistant wireless techniques such as Orthogonal Frequency Division Multiplexing (OFDM) also minimizes the impact of faded, multipath signals in a mobile wireless environment, enabling non-line of sight (NLOS) operation. LTE offers flexibility in configuration of wireless communications networks and its design supports IP.

Table 3.2-5. LTE Key Specifications

(Ref: "4G LTE Advanced Tutorial"; *Radio Electronics* [59])

Parameter	Details
Peak downlink speed 64QAM (Mbps)	100 (SISO), 172 (2x2 MIMO), 326 (4x4 MIMO)
Peak uplink speeds (Mbps)	50 (QPSK), 57 (16QAM), 86 (64QAM)
Data type	All packet switched data (voice and data). No circuit switched.
Channel bandwidths (MHz)	1.4, 3, 5, 10, 15, 20
Duplex schemes	FDD and TDD
Mobility	0 - 15 km/h (optimized), 15 - 120 km/h (high performance)
Latency	Idle to active less than 100ms Small packets ~10 msec
Spectral efficiency	Downlink: 3 - 4 times Rel. 6 HSDPA Uplink: 2 -3 x Rel. 6 HSUPA
Access schemes	OFDMA (Downlink) SC-FDMA (Uplink)
Modulation types supported	QPSK, 16QAM, 64QAM (Uplink and downlink)

Figure 3.2-14 illustrates the transport channel allocation; Figure 3.2-15 illustrates the logical channel allocation. Both multicast and broadcast are supported.

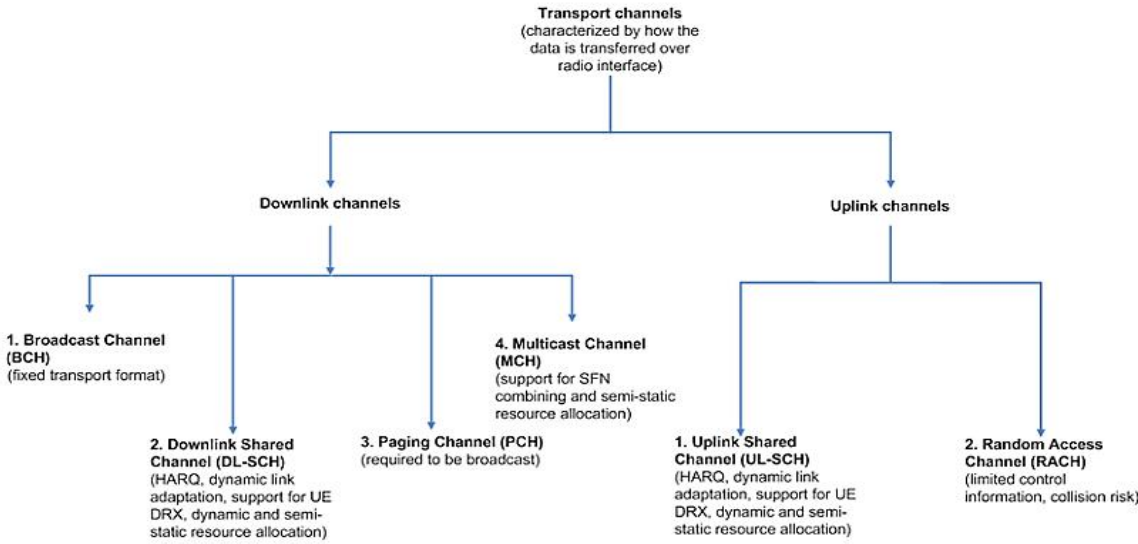


Figure 3.2-14. LTE Transport Channels

(Ref: "LTE- A Technical Overview"; Motorola White Paper [60])

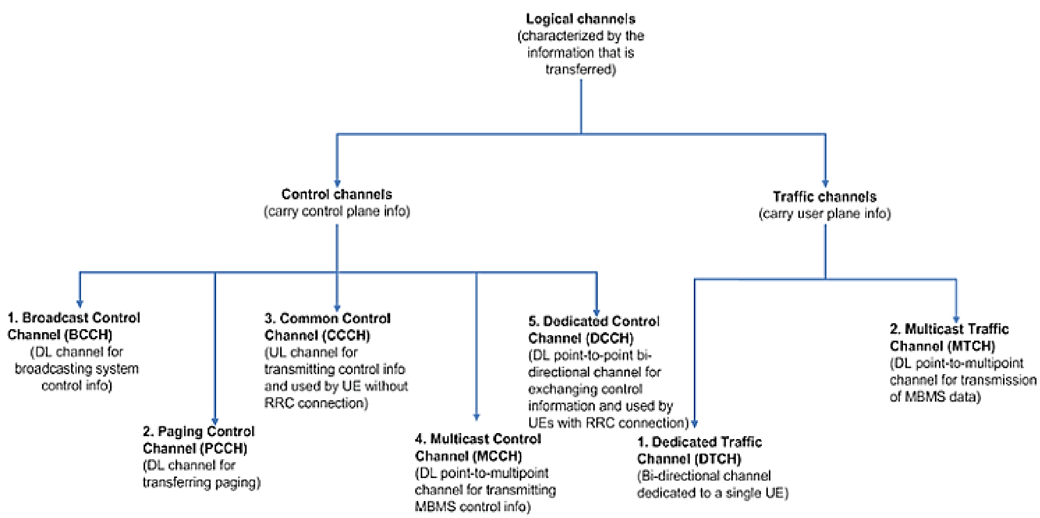


Figure 3.2-15. LTE Logical Channels

(Ref: "LTE- A Technical Overview"; Motorola White Paper [60])

Figure 3.2-16 presents the QoS scheme for LTE with associated latencies and error rates. Note that classes of service 1 – 4 include guaranteed bit rate (GBR).

QCI	Bearer	Priority	Delay	PELR	Examples
1	GBR	2	100 ms	10^{-2}	Conversational voice
2		4	150 ms	10^{-3}	Conversational video
3		3	50 ms	10^{-3}	Real-time games
4		5	300 ms	10^{-6}	Streaming video
5	Non-GBR	1	100 ms	10^{-6}	IMS signalling
6		6	300 ms	10^{-6}	Streaming video, web, EMail
7		7	100 ms	10^{-3}	Voice, video, games
8		8	300 ms	10^{-6}	Streaming video, web, EMail
9		9			

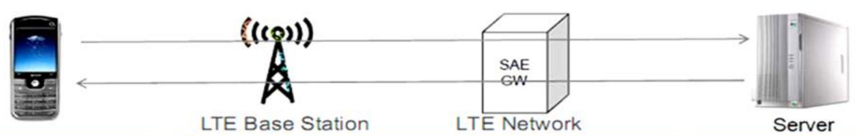
GBR: Guaranteed Bit Rate

Source: 3GPP TS 23.203

Figure 3.2-16. Quality of Service in LTE: Classes, Priorities, Latencies, and Error Rate

(Ref: 3GPP TS23.203; Policy and Charging Control Architecture; ref Part of Figure)

Latency components are summarized in Figure 3.2-17. Field-testing of LTE in Europe indicates an average latency of 36 msec with a high of 43 msec (Ref: "TeliaSonera's LTE Network Delivers on Latency More than Speed", Catherine Haslam, *Fierce Wireless:Europe* [61]).



Delay Components	Delays (ms)
Transmission Time: Uplink+Downlink	2
Buffering Time (0.5 x Transmission Time)	1
Retransmission: 10%	0.1*2*8=1.6
Uplink Scheduling Request	0.5*5=2.5
Downlink Scheduling Grant	4
Phone Delay Estimated	4
eNodeB Delay Estimated	4
Core Network	1
Total Delay: with Pre-Allocated Resources	13.6
Total Delay: with Scheduling	20.1

Figure 3.2-17. Latency Components
Source: ARINC April 2012

Table 3.2-6 presents the specifications of the LTE Frequency Division Duplex (FDD) and Time Division Duplex (TDD) interfaces and the differences are graphically illustrated in Figure 3.2-18. These interfaces exhibit comparable performance (20 MHz TDD vs. 10 MHz up link and 10 MHz down link). The FDD interface is most utilized, and best performance is with 20 MHz UL + 20 MHz DL.

By using antenna diversity leveraging MIMO techniques, LTE data rates can be increased. Table 3.2-7 presents MIMO deployment options and associated downlink data rates. With 4X4 MIMO and 20 MHz BW, a data rate of 345.6 Mbps is supported by the LTE standard

Table 3.2-6. LTE Frequency Division Duplex (FDD) and Time division Duplex (TDD) Interfaces

(Ref: "LTE FDD and TDD Measurement Applications"; Agilent Technologies [62])

	LTE FD	**LTE TDD**
Radio access mode	FDD	TDD
Radio fram length	10ms (20 slts, 10 sub-frames)	10ms (20 slts, 10 sub-frames)
Transmission Scheme	Downlink OFDMA Uplink SC-FDMA	Downlink OFDMA Uplink SC-FDMA
Channel bandwidth, 1 Resource Block (RB) = 180 kHz	1.4 MHz (6 RB), 3 MHz (15 RB), 5 MHz (25 RB), 10 MHz (50 RB), 15 MHz (75 RB), 20 MHz (100 RB)	
Data type	Packet switched for both voice and data. No circuit switched	
Data modulation	Downlink: OPSK, 16 OAM, 64 OAM	
	Uplink: OPSK, 160AM, 640AM, (UE category 5 only)	
Peak data rate (Mbps)	Downlink (using 640AM): 100 (SSIO): 172.8 (2x2 MIMO); 326.4 (4x4 MIMO)	
	Uplink (single transmit antenna): 50 (OPSK): 57.6 (16OAM): 86.4 (64OAM)	
	Note: TDD Rates are a function of up/downlink asymmetry	
MIMO technology	Downlink (up to 4 transmit antennae): Single user (SU-MIMO) spatial multiplexing (open loop and close loop), transmit diversity, cyclic delay diversity, dedicated beam-forming (beam-forming is particularly interesting for LTE TDD).	

	Uplink (single transmit antenna per UE): multi-user MIMO (MU-MIMO) – more than one UE transmit in the same time-frequency resource.

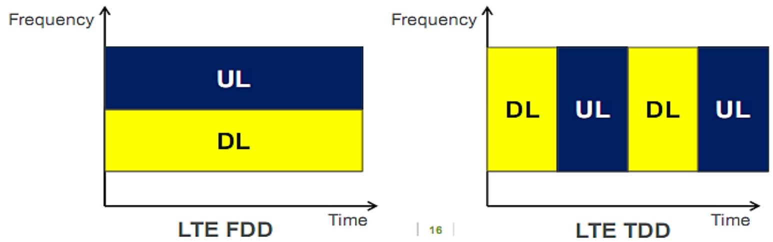


Figure 3.2-18. FDD and TDD Interface with Uplink and Downlink Payloads

Source: ARINC April 2012

Table 3.2-7. MIMO Configurations and Downlink Data Rates – Mbps

(Ref: LTE Standards [63])

Bandwidth → MIMO ↓	**1.4 MHz**	**3 MHz**	**5 MHz**	**10 MHz**	**15 MHz**	**20 MHz**
Single Stream	0.9	2.2	3.6	7.2	10.8	14.4
Single Stream	2.6	6.5	10.8	21.6	32.4	43.2
Single Stream	5.2	13.0	21.6	43.2	64.8	86.4
2x2	10.4	25.9	43.2	86.4	129.6	172.8
4x4	20.7	51.8	86.4	172.8	259.2	345.6

Table 3.2-8 represents specifications for LTE-Advanced (approved March 2011) as compared to LTE. LTE-A is still in a development status with the primary deployment being LTE. Jurisdictional LTE is being deployed using the 700 MHz, 10 MHz BW and using 2x2 MIMO supports 86.4 Mbps.

Table 3.2-8. LTE Advanced Specifications, from Release 10, March 2011

Technology	LTE	LTE Advanced
Peak Data Rate (DL)	300 Mbps	>1 Gbps

Peak Data Rate (UL)	75 Mbps	500 Mbps
Maximum Channel Bandwidth (DL)	20 MHz	100 MHz
Maximum Channel Bandwidth (UL)	20 MHz	40 MHz
Spectral Efficiency (bps/Hz)	16.3	30
Scalable Channel Bandwidth	1.4, 3, 5, 10, 15, 20	Up to 20-100 MHz
Capacity (active session)	200 in every 5 MHz bandwidth	Three times higher than LTE

(Ref: "4G LTE Advanced Tutorial"; Radio-Electronics.com.)

3.2.2.2 LTE Simulation and Test Results

Table 3.2-9 presents available information on simulation and test results related to LTE technology. Field-tests of LTE infrastructure indicates performance obtained is less than achieved in lab tests. A good reference point is the test conducted on the LTE network deployed in Finland, which provided a 36.1 Mbps downlink and 1.7 Mbps uplink with a 36 msec latency. Verizon test showed 40-50 Mbps on the downlink and 2-5 Mbps on the uplink. AT&T tests were similar. These tests did not include MIMO or advanced LTE. These test results indicate that "real world" results of data rate may be less than specification; however, the test includes impact of noise and multipath. Also, some of the test indicated latency greater than specification.

Table 3.2-9. Published Information on LTE Simulation and Test Results

Reference	Simulation (S), Demonstration (D); Field Test of Deployed LTE (FT)	Location	Results
"Nokia-Siemens Network Demonstrates TD-LTE Technology in India", Softpedia.com, 10-20-10 [193]	D	India	110 Mbps downlink with 10-20 msec latency.
"Freescale Semiconductor Demonstrates 182 mbps Downlink and 86 mbps Up Link Over LTE Link", *2008 Mobile World Congress* News Release [194]	D	Barcelona, Spain	182 Mbps downlink and 86 Mbps uplink.
"TeliSonera's LTE Network Delivers Latency More than Speed", Catherine Haslim, *Fierce*	FT	Finland	Average data latency = 36 msec; max latency = 43 msec. Voice call set up time = 600 msec and latency = 165 msec. Average

Reference	Simulation (S), Demonstration (D); Field Test of Deployed LTE (FT)	Location	Results
Wireless: Europe, April 13, 2011 [61]			downlink data rate = 36.1 Mbps with lowest = 5.6 Mbps. Average uplink data rate = 1.7 Mbps.
"Long-Term Evolution"; *IEEE Vehicular Technology Magazine*, June, 2011 [195]	S	Japan	NTT DOCOMO achieves transmission rates of approximately 1 Gbps in down link and 200 Mbps in uplink. Service cost is $80 per month for 5 GBytes plus $32 for an additional 2 GBytes.
TD-LTE; IEEE Vehicular Technology Magazine, June, 2011 [196]	FT	Australia	Two month trial test shows average downlink data rates of 40 to 70 Mbps; peak download data rate was 128 Mbps.
Verizon LTE Wireless Clocking 60 mbps in US Test; Wilson Rothman; Gizmodo.com; 2-09 [197]	FT	Minneapolis, Columbus (OH), Northern NJ	Downlink data rates of 50 to 60 Mbps peak, "though average downlink results have not been determined."
Verizon Wireless 4G LTE Network Testing Supplies 50 Mbps Speed; Kim Poh Liaw; Splashphone.com, 3-8-10 [198]	FT	Not Specified	Downlink data rates achieved = 40 to 50 Mbps and uplink = 20 to 30 Mbps peak. Average down link = 5 to 12 Mbps and average uplink = 2 to 5 Mbps.
LTE Speeds Faster than Expected in Verizon Trials; Matt Hamblen; Computer World; 3-2010 [199]	FT	Boston and Seattle	Downlink average data rate achieved was 5 – 12 Mbps and average uplink was 2 to 5 mbps.
NTT DOCOMO Launches Its LTE Network; Mobile.engadget.com, 12-2010 [200]	FT	Japan	Downlink test achieved 38 Mbps average and uplink achieved 13 Mbps.
LTE Deployment Status in the USA; LTE World, 6-9-2010 [201]	FT	USA	Cox LTE trials showed peak downlink speeds of 25 Mbps with 2X2 MIMO over 2 X 5 MHz channels.

Reference	Simulation (S), Demonstration (D); Field Test of Deployed LTE (FT)	Location	Results
Mobiatar Successfully Completes First Test of its Experimental LTE Network in Belgium; Corporate.mobistar.be; Apr. 2, 2010 [202]	FT	Belgium	Peak download data rate of 60 mbps with recorded response time of 18 msec. Customer service to be increased to 28.8 Mbps by 2011.
AT&T Lab Test Shows LTE Speeds of Almost 29 Mbps; Paul Goldstein; Fiercewire.com; 5-20-2011 [203]	D	Plano, TX	Demonstrated 28.87 Mbps downlink and 10.4 mbps uplink; fully loaded average up link speed is 2-5 Mbps. And downlink speeds of 5 to 12 Mbps.
Globe Trying Out LTE Deployment as Part of Region Wide Sing Tel Trial; Sunstar.com*;* 11-15-2010 [204]	FT	Philippines	Phase 1 Field Trials achieved 60 mbps downlink throughput at 10 MHz BW.

Source: ARINC April 2012

The purpose of MIMO is to use multiple antennas and spatial redundancy to improve link capacity. The theoretical channel capacity defined by Shannon-Hartley (Ref: "Communications in the Presence of Noise", C. Shannon, *Proceedings of the IRE*, V37 #1 [64]) is given by the formula Capacity = BW x $\log_2$(1 + SNR). Using multiple antennas and associated link paths, the capacity formula becomes Capacity= N x BW x $\log_2$(1 + SNR).

Figure 3.2-19 illustrates the impact of MIMO on performance based on simulation of LTE networks conducted by Ericsson. Figure 3.2-20 illustrates field test performance, which shows the dominant network throughput to be 34 Mbps, even with 2X2 MIMO. Figure 3.2-21 illustrates the benefits of a 4X4 MIMO, which improves throughput to about 67 Mbps.

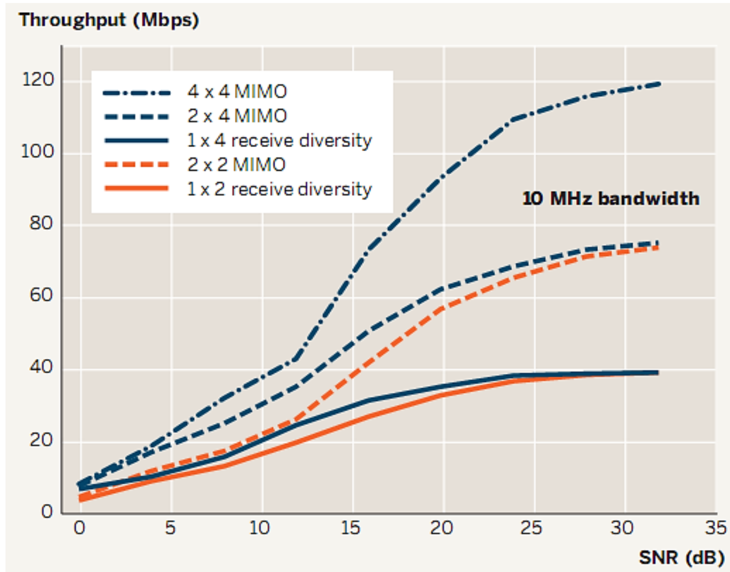


Figure 3.2-19. Simulation Results of MIMO in a 10 MHz BW using a Fully Ranked AWGN Channel

(Ref: "Initial Field Performance Measurements of LTE", Jonas Karlsson, et al, Ericsson Review, 3-2008 [65])

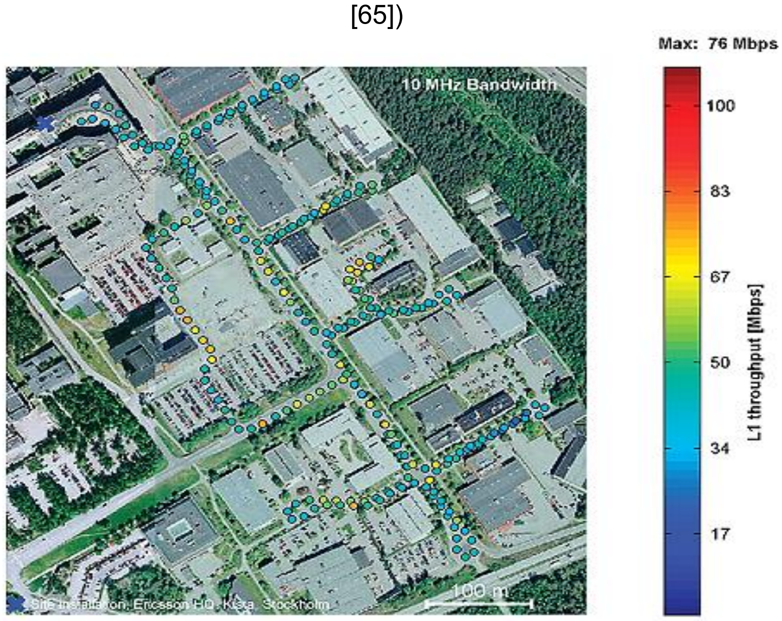


Figure 3.2-20. Field Test Results of 2X2 MIMO in a 10 MHz BW using a Dual Polarized Antenna; Base Station at "X"

(Ref: "Initial Field Performance Measurements of LTE", Jonas Karlsson, et al, Ericsson Review, 3-2008 [65])

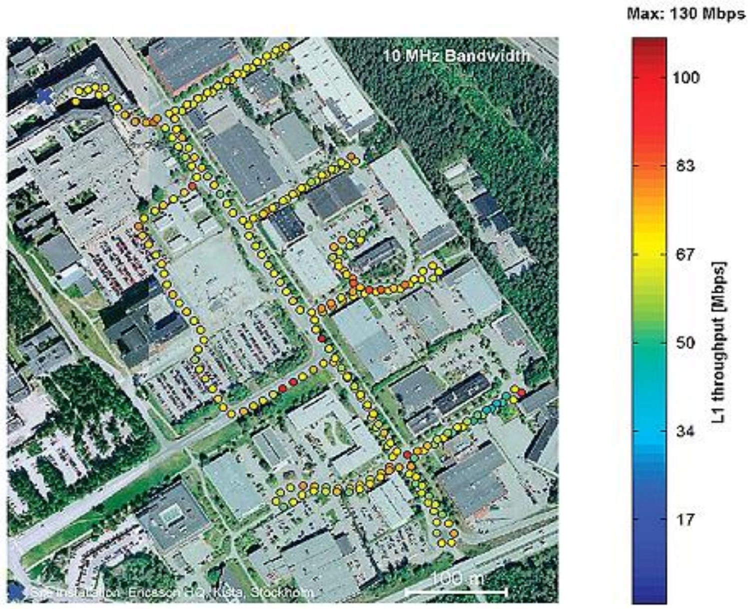


Figure 3.2-21. Field Test Results of 4X4 MIMO in a 10 MHz BW using a Dual Polarized Antenna; Base Station at "X"

(Ref: "Initial Field Performance Measurements of LTE", Jonas Karlsson, et al, Ericsson Review, 3-2008 [65])

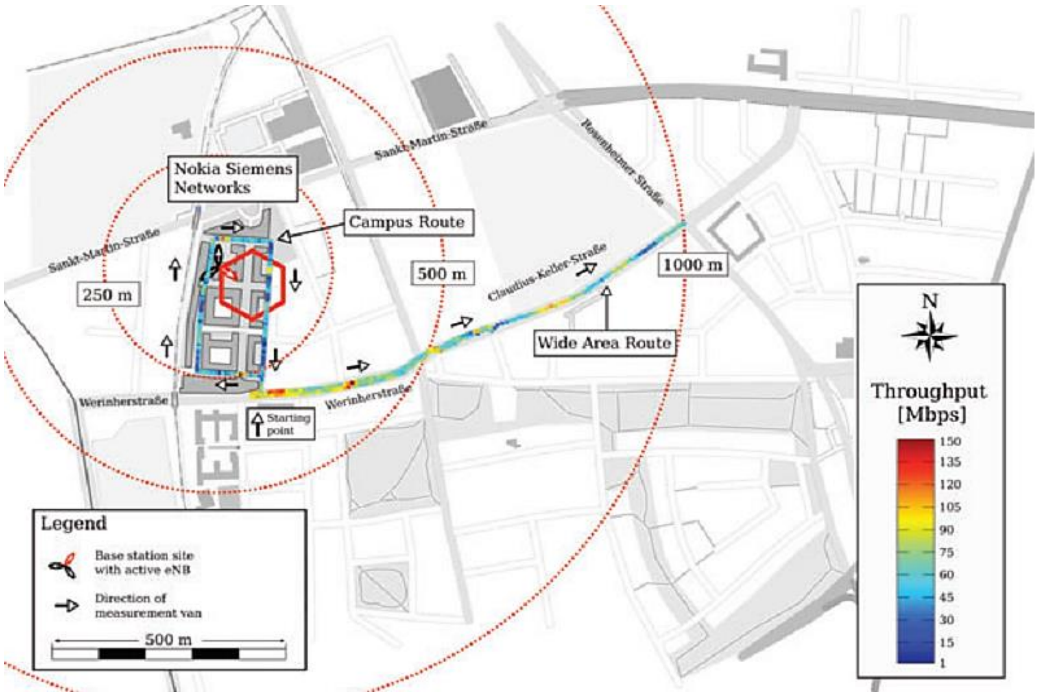


Figure 3.2-22. LTE Field Test Results for 2.6 GHz LTE (40 dBm DL; 23 dBm UL) with 20 MHz BW, 2X2 MIMO and Adaptive Modulation (QPSK, 16 QAM and 64 QAM)

(Ref: "LTE Performance for Initial Deployments"; Nokia Siemens White Paper [66])

Nokia Siemens field tested LTE as shown in Figure 3.2-22 for 20 MHz bandwidth at 2.6 GHz with a 2x2 MIMO antenna system. Figure 3.2-23 shows an approximate throughput of 35 Mbps at 1 km range from the base station. Figure 3.2-24 illustrates the impact of vehicle speed on LTE throughput for different modulation schemes in lab simulations using SIMO. Using 64QAM modulations, about 35 Mbps throughput is achieved for a velocity of 75 km/hr with rapid fall off as speed increases. The 16QAM modulation supports 25 Mbps until about 130 km/hr speed with rapid fall off. QPSK modulation supports about 12 Mbps to a velocity of 250 km/hr. This simulation indicates the need to modify modulation type and associated data rate to support high speed vehicle motion.

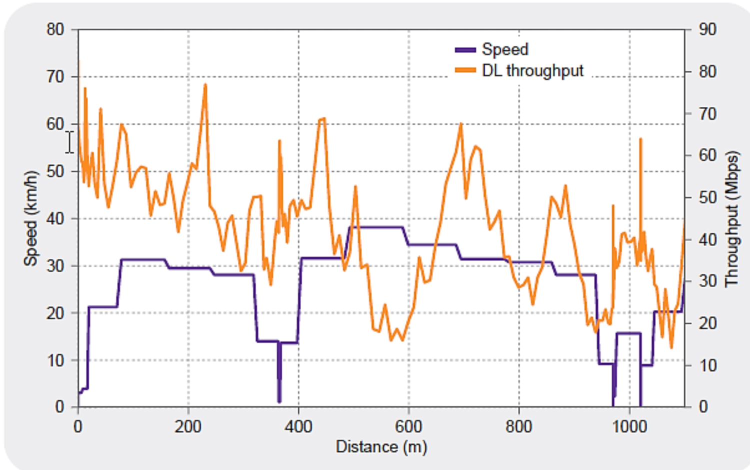


Figure 3.2-23. LTE Field Vehicle Speed Test Results for 2.6 GHz LTE (40 dBm DL; 23 dBm UL) with 20 MHz BW, 2X2 MIMO and Adaptive Modulation (QPSK, 16 QAM and 64 QAM)

(Ref: "LTE Performance for Initial Deployments"; Nokia Siemens White Paper [66])

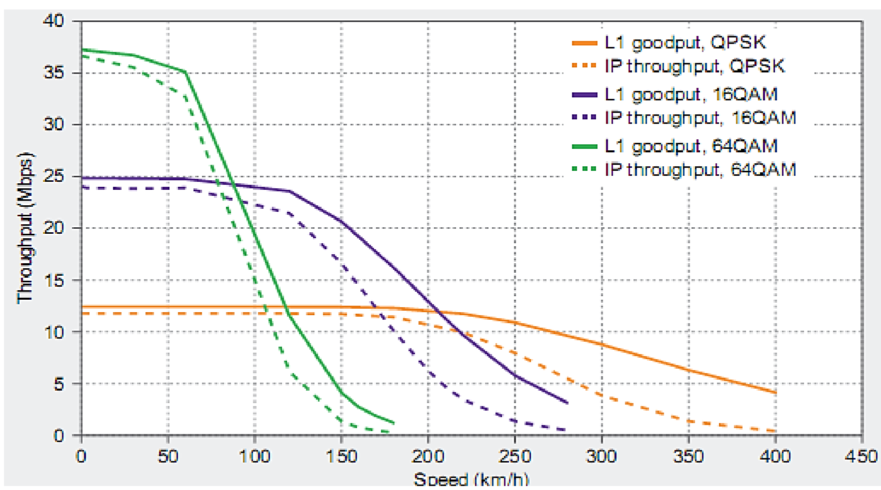


Figure 3.2-24. LTE Lab Speed Test Results for 2.6 GHz LTE

(Ref: "LTE Performance for Initial Deployments"; Nokia Siemens White Paper [66])

Mobile transceiver/modems compatible with LTE standards are available and packaged in highly mobile configurations. Base Station equipment meets telecommunications standards. Mobile LTE communications devices should emerge compliant with SAE environmental standards as LTE deployments grow.

3.2.2.3 **LTE Deployment to Support Emergency Broadband Communications**

The Association of Public Safety Officials (APCO) and the APCO Global alliance have adopted LTE technology as the worldwide standard for broadband emergency communications. This follows the position of FCC specifying deployment of LTE in the 700 MHz frequency band to support emergency communications (Ref: "APCO Approves LTE as Public Safety Standard", Marc Speir, *RCR Wireless*; 4-15-2011 [67]; and "APCO International President Bill Carrow Applauds FCC's Adoption of LTE", psc.apcointl.org/2011/01/25 [68]). In addition, the National Emergency Number Association (NENA) has also endorsed LTE as the technology standard to be used in the development of a national, interoperable, broadband network in the 700 MHz frequency band designated by FCC for emergency communications use (Ref: "APCO & NENA Endorse LTE Technology Standard for Development of Nationwide Broadband Network", *APCO New*; www.apco911.org [69]). FCC has further granted waivers to use the 700 MHz Block D frequency band to start deployment of LTE (Ref: "FCC Grants Public-Safety Agencies Waivers to Build LTE Networks"; Lynnette Luna; fiercebroadbandwireless.com; 5-16-2011 [70]). This is in compliance with the National Broadband Plan for Public Safety (Ref: Broadband.Gov [71]). Figure 3.2-25 illustrates the architecture as defined in the National Broadband Plan for Public Safety and Figure 3.2-26 illustrates the associated frequency band applicable to LTE deployment supporting emergency services and Figure 3.2-27 presents a high level architecture of an LTE jurisdictional deployment supporting emergency management.

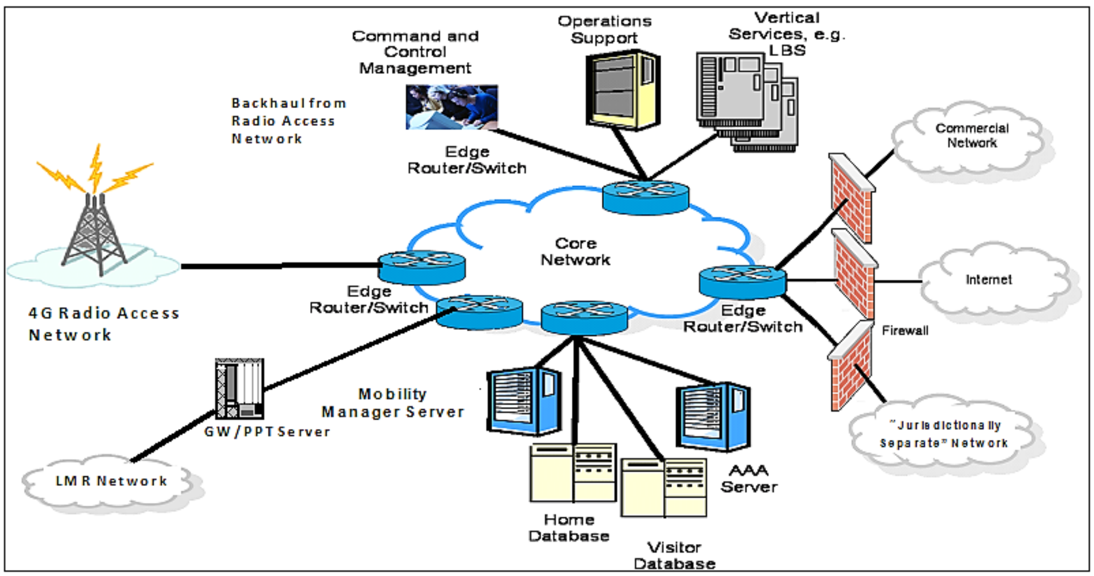


Figure 3.2-25. High-level Architecture of the Public Safety National Broadband Plan

(Ref: National Broadband Plan-Public Safety; Broadband.gov [71])

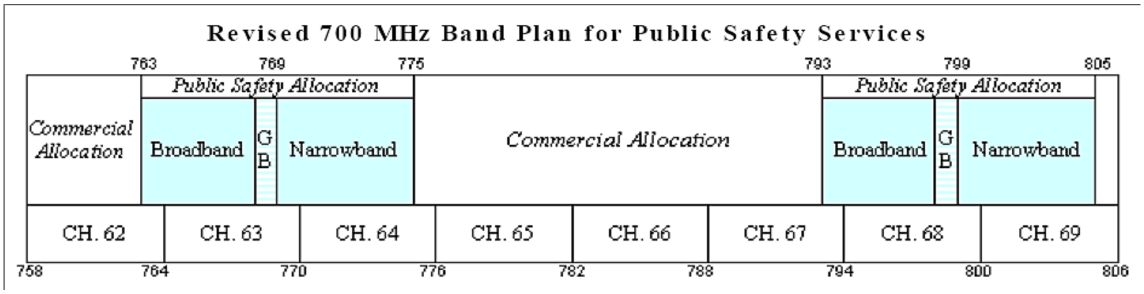


Figure 3.2-26. 700 MHz Frequency Band for Mobile Communications (Block D is CH. 62 and 64)

(Ref: "700 MHz National Public Safety Broadband Communications Network", Kevin McGinnis, NASEMSO [72])

In FCC OBI Technical Paper #2, entitled, "A Broadband Network Cost Model: A Basis for Public Funding Essential to Bring Nationwide Interoperable Communications to America's First Responders", (May 2010) [205], the cost of deploying a nationwide LTE network is developed. The cost of the network is projected to be $15.7 billion (2010 dollars) for deploying 41,600 base stations in urban and suburban areas and 3,200 in rural sites, plus hardening some of the existing tower sites. With public/private partnership the cost was projected to be $6.3 billion. The deployment plan is presented as 10 years with O&M cost projected to be $100 million for year 1 growing to $1.3 billion in year 10. Proposed funding was from frequency band auctions to private service providers. Base Station cost is estimated to be $79.443K for a 75-foot tower and $94 K for a 150-foot tower with base station electronics (included in cost) around $45K.

What is significant about this is that deployment has started in some of the major cities, using Department of Homeland Security funding. If a national, broadband, jurisdictional LTE network is deployed supporting emergency management, it may also be able to support ITS safety applications, although the usage would presumably need to be non-interfering, and would also presumably not be allowed to consume any substantial fraction of the LTE resources.

This potential use of jurisdictional LTE is speculative, and it is possible that no access would be allowed, or that access would be allowed for some municipalities, but not others. In addition, one use of ITS safety communications would be to provide information to drivers during emergency situations, which is the time that the jurisdictions are least willing to have any compromise to, or additional load on the system. However, there is precedence for Traffic and Emergency Management to share resources and information as well as the need by emergency vehicles for SPaT related data. Furthermore, SPaT augmentation data (GID, DGPS, and safety alerts) would provide a very small data load on the emergency LTE network and is thus worthy of consideration.

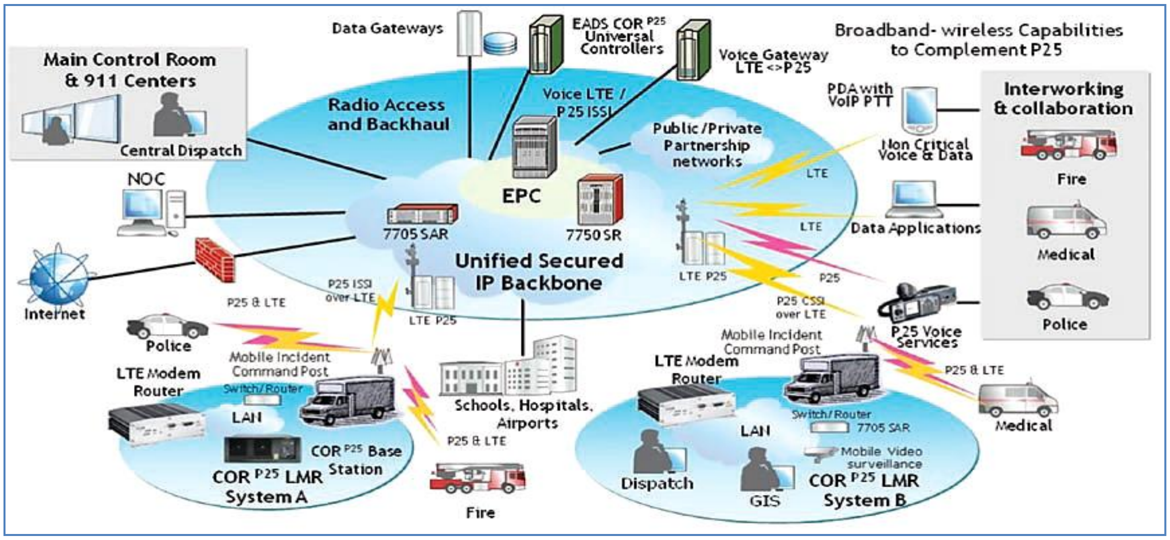


Figure 3.2-27. Example of a Jurisdictional LTE Architecture Supporting Emergency Services

(Ref: “Interoperable Mission Critical Broadband/Narrowband Solution for Public Safety Communications”, White Paper, Alcatel Lucent [73])

3.2.2.4 LTE Architecture for SPaT Applications

It is technically feasible to use LTE for SPaT applications. However, access to LTE network requires user subscription fees. Alternatively, local governments can deploy the LTE infrastructure and employ a cost structure to avoid user service fees. However, the issue is available spectrum in which jurisdictions can operate LTE networks and the fact that private users would have to obtain jurisdictional LTE network compatible cellular devices (transceiver/modem/processor). It would also be necessary that all jurisdictional LTE systems would need to be the same, and that terminals for the general public would have some level of controls to prevent excessive or improper use of the network.

There are several possible scenarios using LTE in support of SPaT applications. Considering jurisdictional deployment of LTE that would support emergency management and traffic safety applications, a typical system architecture for this is shown in Figure 3.2-28. Figure 3.2-29 illustrates the use of a Jurisdictional LTE network for interactive emergence management applications and for “broadcast only” traffic safety applications. In the second LTE system architecture, DSRC is still utilized. The architecture presented in Figure 3.2-29 would be utilized if available bandwidth was not available for interactive safety functions, thus requiring DSRC deployment. This cannot be determined without an in-depth analysis of bandwidth requirements for emergency management, where traffic safety would be an extension of the National Broadband Public Safety network, and without establishing national policies requiring all jurisdictional LTE systems to support these applications. Based on the data in Table 2.3-10, broadcast safety data would require less than 1% of a jurisdictional LTE network.

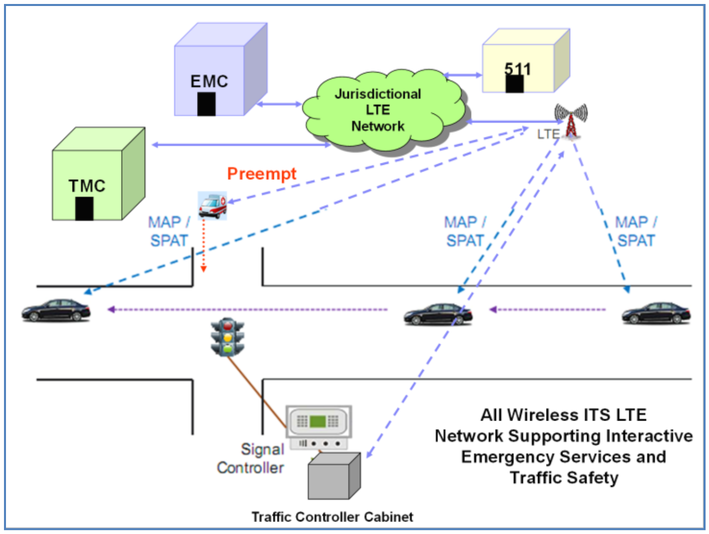


Figure 3.2-28. Both Interactive Emergency Management and Traffic Safety Applications Supported by a Jurisdictional LTE Network

Source: ARINC April 2012

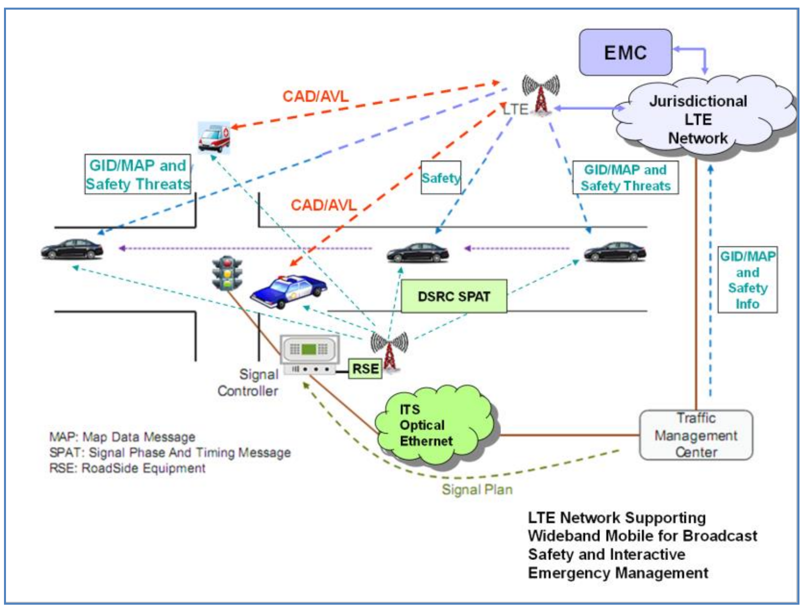


Figure 3.2-29. Interactive Emergency Management and Wide Area, Broadcast Traffic Safety Applications Supported by a Jurisdictional LTE Network; DSRC Still Used for Short Range SPaT Communications

Source: ARINC April 2012

One issue with interactive LTE used for traffic safety applications is the impact of the number of vehicles on both throughput and latency. For a jurisdictional application, cost pressures are likely to motivate use of the largest LTE footprints that are able to support the user community expected to be within the footprint. For a typical LTE footprint of 1 Km radius, the number of vehicles served can be relatively large. The analysis of system capacity demand in Section 2.3 indicates an average lane capacity of 0.11 vehicles per lane meter, or 161 vehicles per lane mile. The worst-case density scenario would be a major urban grid, which has street spacing, of about 1/3 mile (1760 feet, 535 meters). Assuming two major 4-lane streets crossing with smaller two lane streets 1/3 mile away from the crossing, this scenario includes 16 lanes, or 859 vehicles.

Assuming a saturated corridor scenario with 859 vehicle density, and assuming an LTE link performance of 110 Mbps as demonstrated by Nokia-Siemens, then each vehicle could be serviced with 128 kbps. However, under the most generous assumptions about the use of jurisdictional LTE, the most capacity that is likely to be allowed is 10% of the link; so each vehicle in this scenario would be served by 12.8 Kbps. It is also unclear how interactive use of such a network would be managed so that capacity would not rise above this level, since the vehicles themselves are capable of consuming the entire link capacity. Thus the conclusion is that LTE is applicable to only SPaT broadcast related applications.

Table 3.2-10. Mobility Impact on Communications Performance (References)

Research Report References	Performance with Mobile T/R Density
"Small Scale and Large Scale Routing in Vehicular ad Hoc Networks", Wending Wang, et al, *IEEE Transactions on Vehicular Technology*, Nov. 2009. [206]	45 – 50% overhead increase with 250 vehicles, from 10% with 50 vehicles.
"Towards Efficient Routing in Vehicular ad Hoc Networks", Moez Jerbi, et al, France Telecom R&D [207]	End-to-end delay of 16 sec. for 100 mobile nodes.
"Exploiting the Wisdom of the Crowd: Local, Distributed Information-Centric VANETs", Fan Bai, et al, *IEEE Communications Magazine*, May 2010 [208]	Detroit test show distance between vehicles impact PDR (Average 0.95 for 50 m; about 0.6 got 100 m and about 0.35 for 150 meters between vehicles.
"LTE Performance Verification", Sadayuki Abeta, 3GPP-TSG-RAN WG-1 Report R1072580 [209]	1X2 Means Throughput @ 500 m = 0.05 bits/Hz/User; edge = 0.02 bits/Hz/user. At 1750 m = 0.05 and 0.02 bits/Hz/user. For 2X2 MIMO, Means throughput is 0.17 bits/Hz/User and 0.05 bits/Hz/user at the edge for 500 meters. At 1750 m and 2X2 Means throughput is 0.16 and edge is 0.04 bits/Hz/User.

Source: ARINC April 2012

A summary of the LTE specifications and field test results are provided in Table 3.2-11.

Table 3.2-11. Summary Specifications (Published and Test Results) for LTE

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
Applicable standards	3GPP Release 8,9 and 10	Same
Link Access	UL: SC -FDMA	Same

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
	DL: OFDMA	
Simplex, half duplex, or full duplex service	Full Duplex	Same
Frequency Band and Licensing	700 MHz, 1600 MHz; Licensed	Same
Operating Bandwidth and Channel Bandwidth	Scalable BW: 1.4 MHz to 20 MHz	Same
Wireless Mobility with Velocities Supported	Optimized for low speeds 0 – 15 km/h; High performance for speeds up to 120 km/h; Mobility supported for speeds 120 km/h – 350 km/h	Same
Maximum Range	Performance should be met for 5 km range, and with a slight degradation for 30 km range	0.5 km for urban planning Up to 12 km tested (August 2010, Alcatel-Lucent)
Multipath Spread Protection	4.69 μs to accommodate path variations of up to 1.4 km	Same
Selectable Communications Data Rates	DL: 10 to 100 Mbps UL: 5 to 50 Mbps	Downlink throughput 45 Mbps at vehicle speed 40 km/h and distance 500m (for 2.6 GHz with 20 MHz BW, 2x2 MIMO and Adaptive Modulation)
Receiver Sensitivity	-97 dBm minimum for QPSK in 5 MHz channel (3GPP 36.101)	>2dB better than required by standards
BER	-QoS classes support PER of 10^{-3} to 10^{-6} -Adaptive modulation, MIMO and selectable channel bandwidth to achieve desired data rate for varying SNR	~60 Mbps for SNR=20 dB (2x2 MIMO in a 10 MHz BW using a Fully Ranked AWGN Channel)
Latency	Control plane latency: <100 msec User plane latency: ~10 msec	<50 msec
Quality of Service	9 Level Differential Service	Same
Current Design Vehicle	Yes	Yes

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
Environmentally Compatible		
Equipment Approximate Size /Weight for Mobile Applications	Size: 122 x 66 x 13 mm Weight: 164 g	Same
Equipment Approximate Power Load for Mobile Applications	1400 ma	Same
Approximate Cost of Mobile Unit	$300	Same

Source: ARINC April 2012

3.2.3 *WiMAX*

WiMAX is a broadband communications technology defined by the IEEE 802.16 standard. It is an IP based communication link originally intended to provide high data rate backhaul communications over relatively large areas. It originated from the computer industry and data communications, and was slow to be adopted by major commercial carriers. WiMAX was conceived and designed with lower deployment cost as an objective considering data rates and area covered. Early deployment supported private and jurisdictional wireless mesh networks. With the approval of the mobile WiMAX standard, IEEE 802.16e, WiMAX became a competitor to cellular communications technology that could support fixed, portable and mobile communications deployments. WiMAX is a fully open standard. The IEEE 802.16m release incorporates advanced technology, such as smart antennas and MIMO to improve communications reliability and throughput.

In October 2010, The ITU approved the IEEE802.16m standard as compliant with ITU-R, IMT-Advanced Technology. Thus products compliant with IEEE 802.16m are considered 4G and networks deployed compliant with IEEE802.16m are considered to be 4G networks. Networks deployed compliant with IEEE802.16e are not considered as 4G by ITU, even though a number of service providers advertise these networks as 4G. In an article entitled, “IEEE Approves Next WiMAX Standard”, by Stephen Lawson (*Computer World*, 3-2011) [74], demonstration of WiMAX conforming to IEEE802.16m by Samsung achieved 330 mbps in 20 MHz of spectrum. WiMAX has been deployed on an international basis and has been competing with LTE solutions, although it has steadily lost ground, and today few carriers are deploying WiMAX networks.

WiMAX was originally defined for use in the 10 to 66 GHz frequency range in line-of-sight (LOS) environments. Later revisions have included sub 10 GHz and sub 6 GHz frequency ranges for non-line-of-sight (NLOS) environments.

WiMAX cells can provide coverage of about 6 to 8 KM (4 to 5 miles), but smaller cells are used in more heavily loaded areas. Service availability of WiMAX has increased significantly over the last few years with major commercial rollouts focused on “last mile” non-mobile applications. However, service availability is mainly focused in more heavily populated urban and suburban areas. Service coverage in rural areas remains sparse. In its effort to expand broadband access in remote underserved and un-served communities in rural America, the US Department of Agriculture (USDA) made a number of awards for the roll out of WiMAX networks in those communities under its Broadband Initiatives Program; WiMAX has also been adopted by city and local governments. A recent announcement (March 29, 2011) indicated that the City of Houston would deploy WiMAX, among other objectives, to improve traffic safety and congestion throughout the city through remote control of 2500 traffic intersections and 1500 school zone flashers. A number of jurisdictions in the USA have deployed WiMAX mesh network operating in the 4.9 GHz emergency frequency band to provide wideband communications services to emergency vehicles.

Figure 3.2-30 illustrates the main architectural components of a WiMAX network. Figure 3.2-31 shows examples of WiMAX equipment currently available. WiMAX equipment is widely available and WiMAX user devices are available in small form factors such as in an embedded form or a USB device.

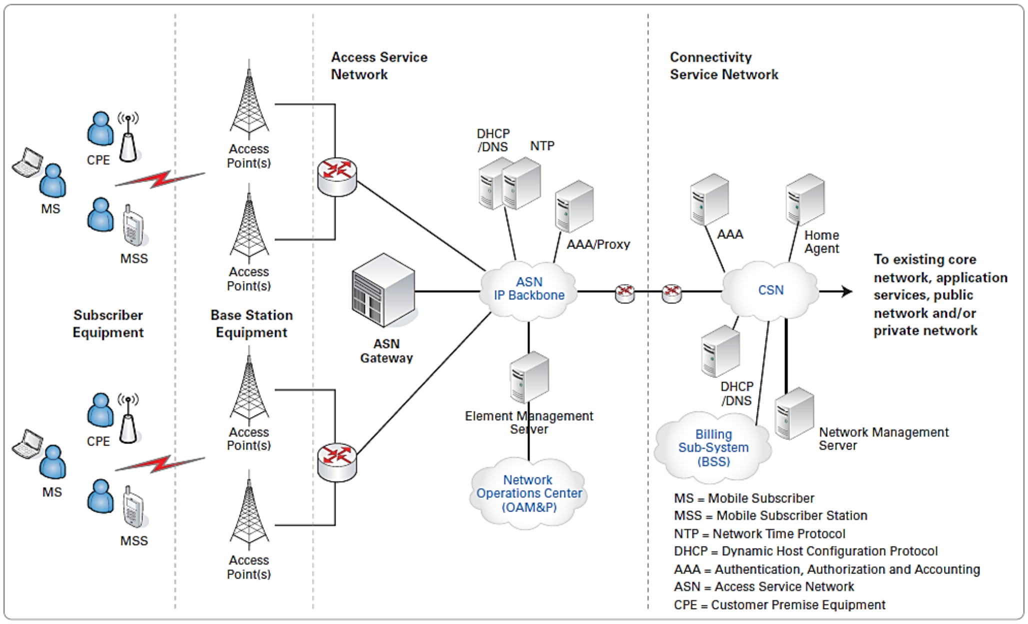


Figure 3.2-30. Main Architectural Components of a WiMAX Network

(Ref: "WiMAX Security for Real-World Network Service Provider Deployments", Motorola 2007 [75])

Figure 3.2-31. Examples of WiMAX Equipment

(Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

WiMAX is based on the IEEE Std. 802.16 air interface standard. The current widely deployed version is IEEE Std. 802.16e-2005 (see IEEE Std. 802.16e-2005, IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems, Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1, 7 December 2005). Earlier versions of the 802.16 standard only support fixed access, and do not support user mobility. The 802.16e version adds support for user mobility at up to vehicular speeds to provide combined mobile and fixed broadband wireless access. It includes a number of features to address mobility, performance, and multipath issues. Its PHY modes include Orthogonal Frequency Division Multiplexing (OFDM), and Orthogonal Frequency Division Multiple Access (OFDMA). In an OFDM system, an input data stream is divided into a number of parallel streams, each of which is transmitted over a separate orthogonal sub-carrier. This increases the symbol duration and enables it to better address delay spreads in a multipath environment. Other features in 802.16e include the use of cyclic prefix to address Inter-Symbol Interference (ISI), MIMO antenna techniques, adaptive modulation, error correction schemes including convolution turbo code (CTC) and low density parity check (LDPC) code, frequency-diverse and frequency-specific sub-channelization schemes, and handoff between base stations or sectors supporting subscriber station mobility at vehicular speeds.

The IEEE Std. 802.16 air interface standard is developed by the IEEE. However, not all features defined in the standard are implemented by vendors. In order to promote interoperability between equipment from different vendors, the WiMAX Forum develops profiles that specify subsets of the 802.16 standard as mandatory and optional features in implementations. The WiMAX Forum Mobile System Profile Release 1.0 is based on IEEE Std. 802.16-2004, as amended by IEEE Std. 802.16e-2005. The WiMAX Forum also provides certification of vendor equipment for compliance to the profiles.

Most WiMAX equipment supports frequency bands of 2.3 GHz, 2.5 GHz and 3.5 GHz. There are also some that operates in the 700 MHz, 900 MHz, 4.9 GHz and 5 GHz bands

The IEEE Std. 802.16 standard has continuously been evolving through various amendments and revisions. The latest amendment is IEEE Std. 802.16m and was approved by IEEE-SA Standards Board on 31 March 2011. The 802.16m amendment (Ref: “WiMAX and the IEEE 802.16m Air Interface Standard”, *WiMAX Forum*, April 2010 [76]) is intended to provide an advanced air interface while maintaining backward compatibility. Figure 3.2-32 and Figure 3.2-33 show respectively the downlink and uplink peak channel data rates of 802.16m compared to 802.16e (Ref: “WiMAX and the IEEE 802.16m Air Interface Standard”, WiMAX Forum, April 2010 [76]).

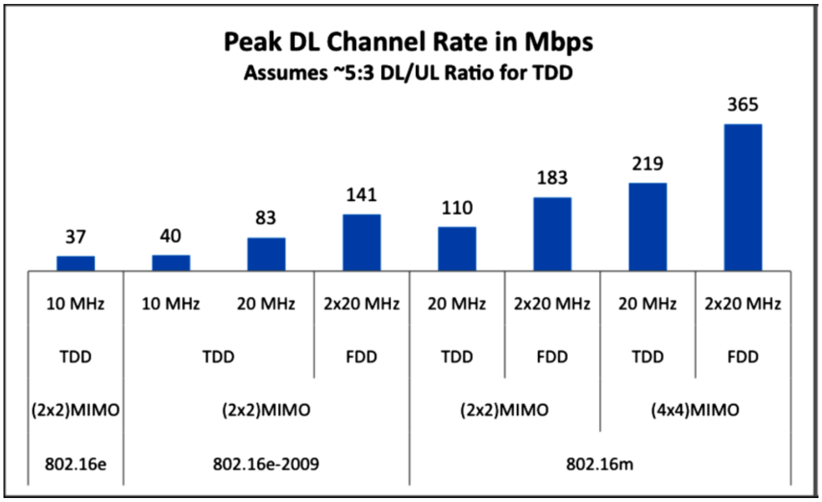


Figure 3.2-32. Peak Downlink Channel Data Rate Summary

Ref: ("WiMAX and the IEEE 802.16m Air Interface Standard", *WiMAX Forum*, April 2010.[76])

Another goal of 802.16m is to better support latency-sensitive real-time applications, by reducing air link delay, state transition delay, access delay, and handover interruption time. The latency objectives are:

- Link Layer/User Plane: < 10 msec DL or UL;
- Hand-Off Interruption: < 30 msec;
- Control Plane, Idle to Active: < 100 Ms.

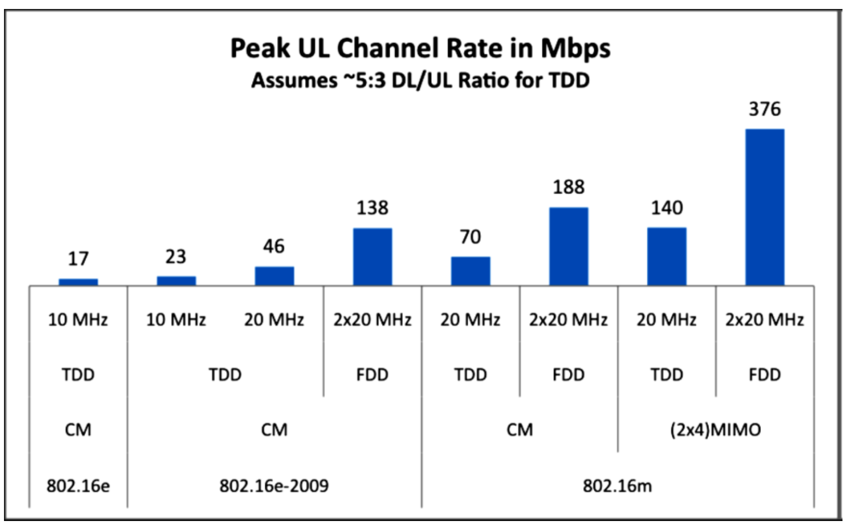


Figure 3.2-33. Peak Uplink Channel Data Rate Summary

Ref: ("WiMAX and the IEEE 802.16m Air Interface Standard", *WiMAX Forum*, April 2010.[76])

Mobility support is significantly enhanced in 802.16m where mobile stations will be able to maintain connections at speeds up to 350 km/hr (220 mph). For more efficient power management, 802.16m based mobile stations in Sleep Mode will be able to dynamically adjust the duration of sleep windows and listening windows based on traffic conditions. In Idle Mode, mobile stations may become available periodically for broadcast traffic without the need to register with a base station.

The WiMAX Forum is developing its Release 2.0 profile based on IEEE Std. 802.16m. Certification of Release 2.0 equipment is expected by end of 2011, with general commercial availability in 2013. Table 3.2-12 compares the IEEE 802.16e to the IEEE802.16m standard. The improvements in latency, spectral efficiency, average throughput and peak data rates can be seen with the IEEE 802.16 standard. Figure 3.2-34 presents the protocol structure of IEEE 802.16m. Figure 3.2-35 provides a comparison of Mobile WiMAX with LTE, with IEEE 802.16m having very comparable specifications.

WiMAX supports five Quality of Service (QoS) classes with various data rates, latency, jitter, and priority requirements. The QoS classes are summarized in Table 3.2-13.

As with other systems, the bandwidth available in a WiMAX cell is shared by users in that cell. This imposes a constraint on the number of simultaneous connections that can be supported. However, it is a routine practice for operators to evaluate the performance of the WiMAX system, and to tune or restructure the cells where necessary to address changes in performance needs, including modifying the cell footprint and adding cell sites.

WiMAX base stations may be installed indoor or outdoor and support environmental standards such as ETSI 300 019 part 2-1 T 1.2 and part 2-2 T 2.3 for indoor and outdoor, Part 2-3 T 3.2 for indoor and Part 2-4 T 4.1E for outdoor, and radio standards such as ETSI EN 302 326 and FCC Part 15 and Part 27. Operating conditions include temperature range from -40C to 55C (-40F to 131F), and humidity from 8% to 100%.

Table 3.2-12. WiMAX IEEE 802.16e and IEEE802.16m Comparison

(Ref: “IEEE802.16m WiMAX Technical Overview”; Rhode & Schwarz [77])

		WiMAX™ Release 1.0 IEEE802.16e	**WiMAXX™ Release 2.0 IEEE802.16m**
Duplexing mode		TDD	TDD, FDD
Channel bandwidth		3.5/5/7/8.75/10 MHz	5/10/20 MHz per carrier, multi-carrier support
MIMO scheme	Typical	DL: 2x2	DL: 2x2, 2x4, 4x2, 4x4
	Typical	UL:1x2	UL: 1x2, 1x4, 2x2, 2x4
	Standardized	8x8	8x8
Latency	Link layer access	Approx. 20 ms	<10 ms

	WiMAX™ Release 1.0 IEEE802.16e		**WiMAXX™ Release 2.0 IEEE802.16m**	
	Approx. 35 to 50 ms		<30 ms	
Spectral efficiency (per sector)	Peak	DL: 6.4 bit/s/Hz	Peak	DL: 15 bit/s/Hz
		UL: 2.8 bit/s/Hz		UL: 6.75 bit/s/Hz
	Sustained	DL: 1.55 bit/s/Hz	Sustained	DL: 2.6 bit/s/Hz
		UL: 0.9 bit/s/Hz		UL: 1.3 bit/s/Hz
Average Sector throughput TDD (DL:UL = 2.1)	DL: 25 Mbit/s (AMC)		DL: >35 Mbit/s	
	UL: 6 Mbit/s at 10 MHz		UL: 8.7 Mbit/s at 20 MHz	
Peak data range (DL)	128 Mbit/s (20 MHz, 2x2 MIMO, TDD)		3Gbit/s (3x20 MHz multicarrier, 4x4 MIMO, TDD)	
Number of active VoIP users	Approx. 25 users/sector/MHz		>60 users/sector/MHz	
Maximum coverage	30 km (optimum at 5 km)		30 km (optimum at 5 km)	

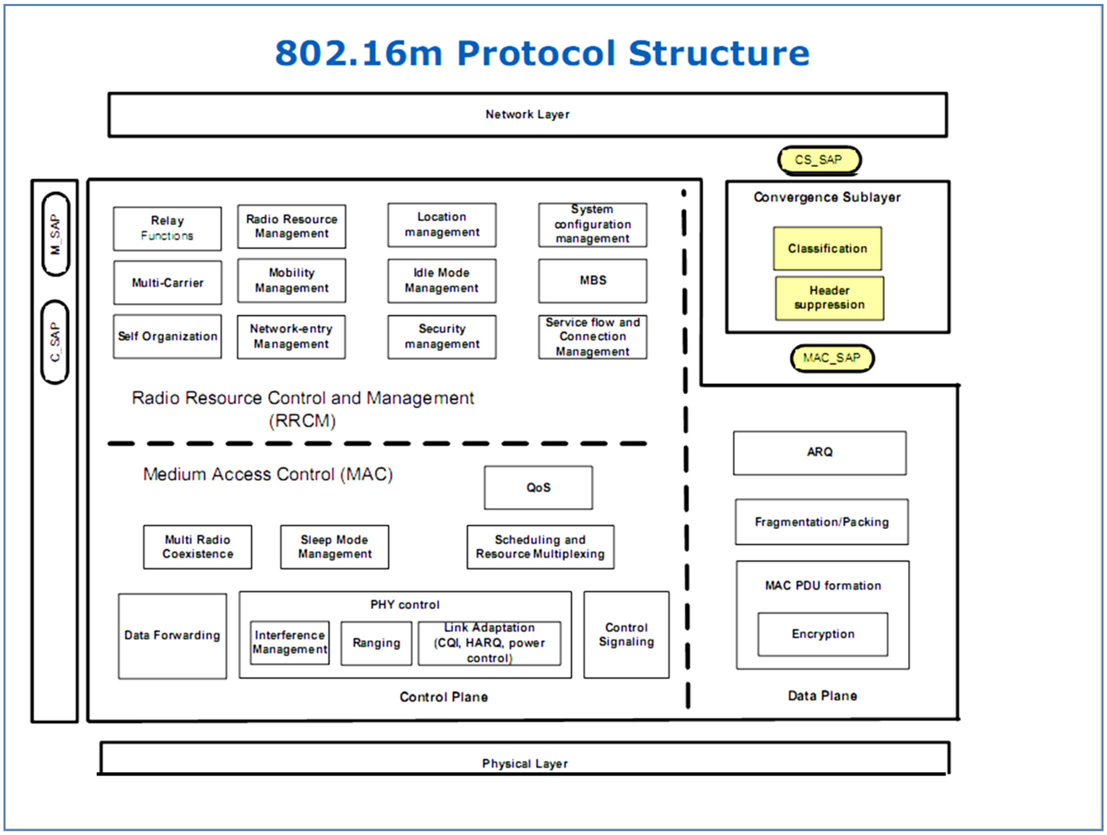


Figure 3.2-34. IEEE802.16m Protocol Structure

(Ref: "Mobile WiMAX Update and IEEE802.16m"; Hassan Yaghobbi, Intel Corp. [78])

	WiMAX 802.16e	WiMAX 802.16m	LTE
Network Equipment Availability	2007	2010	2009
Handset Availability	2008	2011	2010
Standard Body	IEEE & WiMAX Forum	IEEE & WiMAX Forum	3GPP
Spectrum band Plan	TDD	TDD, FDD	FDD
Frequency*	2300, 2500, 3300 3500, 3700	Under 6 GHz TBD	700, 850, 900, 1800 1900, 2100, 2500
Channel Bandwidth	3.5, 5, 7,8.75,10 MHz	Scalable bandwidth 5 – 20 MHz TBD	1.4,1.6,3.5.10.15.20 MHz
Channel Throughput	~3.5 Mbps / Hz downlink *35 Mbps, 1 Sector, 10 MHz channel*	~5.0 Mbps / Hz downlink *50 Mbps, 1 Sector, 10 MHz channel*	~5.0 Mbps / Hz downlink *50 Mbps, 1 Sector, 10 MHz channel*
Spectrum Type	Licensed		
Radio Technology DL	Scalable OFDMA		
Radio Technology UL	Scalable OFDMA		
Antennas	MIMO & Advanced Antenna Techniques		
Core Technology	Flat, All IP		
Application Layer	IMS		
IPR	More distributed than existing 3GPP & 3GPP2 networks		
Application	VoIP, Data, Video		
Terminal Variety	Fixed CPE, Mobile handsets, Data Cards, Consumer Electronics		
User Plane Latency	<20 ms	<5 ms	<5 ms
Control Plane Latency	<100 ms	<100 ms	<100 ms

* WiMAX Forum Certification Profiles currently specified for 2300, 2500, and 3500 MHz.

Figure 3.2-35. IEEE802.16e, IEEE802.16m and LTE Comparison

(Ref: "Comparing Mobile WiMAX with HSPA+ and LTE"; Doug Gray, WiMAX Forum [79])

Table 3.2-13. WiMAX Quality of Service Classes Supported

(Ref: IEEE 802.16 Standard [80])

WiMAX QoS Class	WiMAX QoS Class Details
Unsolicited Grant Service	The Unsolicited Grant Service, UGS is used for real-time services such as Voice over IP, VoIP of for applications where WiMAX is used to replace fixed lines such as E1 and T1.
Real-time Packet Services	This WiMAX QoS class is used for real-time services including video streaming. It is also used for enterprise access services where guaranteed E1/T1 rates are needed but with the possibility of higher bursts if network capacity is available. This WiMAX QoS class offers a variable bit rate but with guaranteed minimums for data rate and delay.
Extended Real Time Packet Services	This WiMAX QoS class is referred to as the Enhanced Real Time Variable Rate, or Extended Real Time Packet Services. This WiMAX QoS class is used for applications where variable packet sizes are used - often where silence suppression is implemented in VoIP. One typical

WiMAX QoS Class	WiMAX QoS Class Details
	system is Skype.
Non-real time Packet Services	This WiMAX QoS class is used for services where a guaranteed bit rate is required but the latency is not critical. It might be used for various forms of file transfer.
Best Effort	This WiMAX QoS is that used for Internet services such as email and browsing. Data packets are carried as space becomes available. Delays may be incurred and jitter is not a problem.

3.2.3.1 Analysis and Testing of WiMAX

Simulations and tests have been conducted in support of WiMAX deployment. A research report, *Comparison of IEEE802.16 Scenarios with fixed and Mobile Subscribers in Tight Reuse*, by C. F. Ball, et al (Siemens- Munich, Germany) documents research results. Figure 3.2-36 presents received signal level versus range between receiver and transmitter for 2 and 30 Watt, 2.3 GHz, WiMAX transceivers. Figure 3.2-37 presents cell utilization as a function of offered channel load. Offered channel load is a function of noise floor and signal strength.

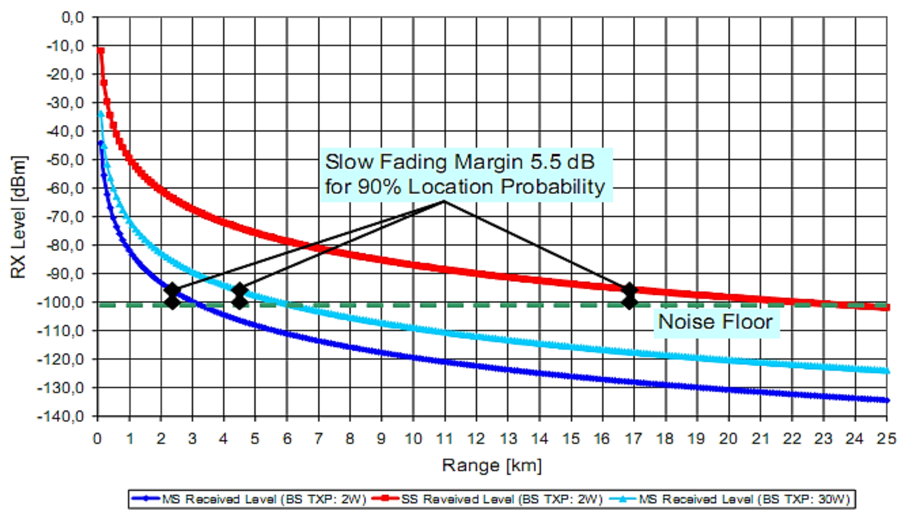


Figure 3.2-36. Received Signal Level vs. Distance for 2 and 30 Watt WiMAX Devices

(Ref: "Comparison of IEEE802.16 Scenarios with fixed and Mobile Subscribers in Tight Reuse", C. F. Ball, et al, Siemens- Munich, Germany [81])

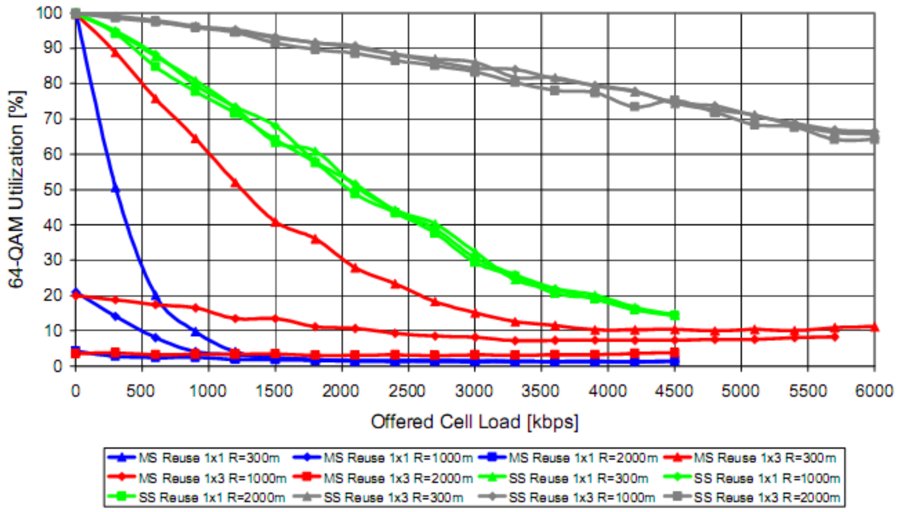


Figure 3.2-37. Cell Utilization vs. Offered Load per Channel and Different Modulations

(Ref: "Comparison of IEEE802.16 Scenarios with fixed and Mobile Subscribers in Tight Reuse", C. F. Ball, et al, Siemens- Munich, Germany [81])

Field test and simulation results associated with mobile WiMAX are documented in research report, "Mobile WiMAX: Performance Analysis and Comparison with Experimental Results", by *Mai* Tran, et al, (Center for Communications Research, University of Bristol, UK) [82]. Figure 3.2-38 presents results of field tests and simulations, providing packet error rate (PER) versus SNR for various WiMAX modulations. The simulation results in Figure 3.2-38 and Figure 3.2-39 show that at PER of 10^{-3}, WiMAX can deliver throughput of approximately 1.1, 2.3, 3.5 and 5.2 Mbps using modulation and code rate of QPSK 1/2, 16 QAM 1/2, 64 QAM 1/2 and 64 QAM 3/4 respectively. The study also shows that with EIRP of 61 dBm, the downlink range is increased to 2.1 km as shown in Figure 3.2-40.

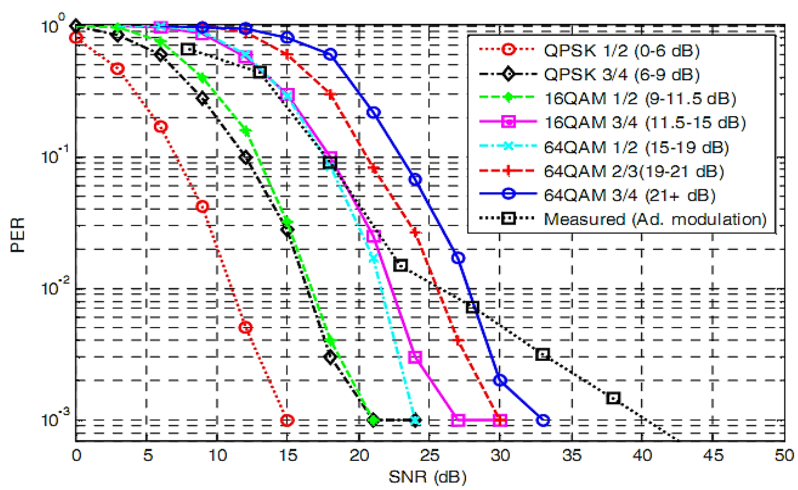


Figure 3.2-38. Simulated and Measured Results of Packet Error Rate vs. SNR for Selected WiMAX Modulations

(Ref: “Mobile WiMAX: Performance Analysis and Comparison with Experimental Results”, Mai Tran, et al, Center for Communications Research, University of Bristol, UK [82])

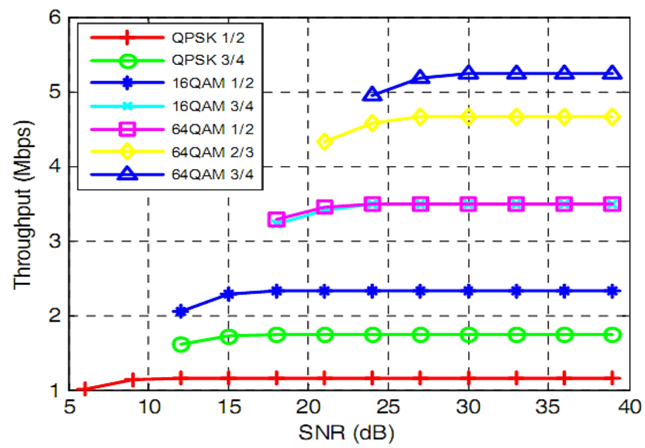


Figure 3.2-39. Simulated WiMAX Mobile Channel Throughput vs. SNR for Selected WiMAX Modulations

(Ref: “Mobile WiMAX: Performance Analysis and Comparison with Experimental Results”, Mai Tran, et al, Center for Communications Research, University of Bristol, UK [82])

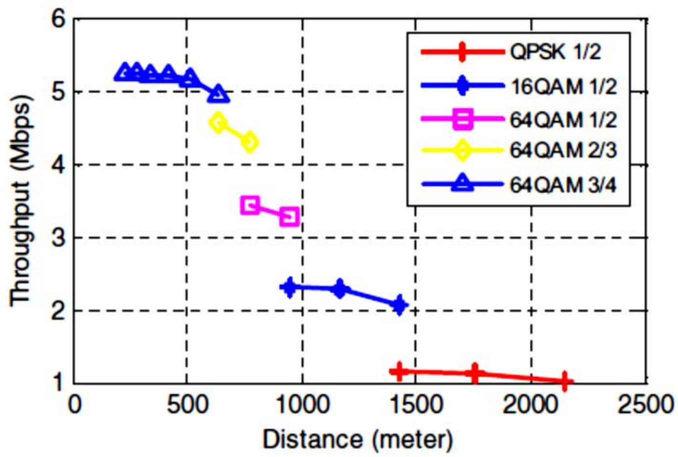


Figure 3.2-40. Simulated WiMAX Operating Range at EIPR of 61 dBm

(Ref: “Mobile WiMAX: Performance Analysis and Comparison with Experimental Results”, Mai Tran, et al,Center for Communications Research, University of Bristol, UK [82])

Real-world performance of a commercial WiMAX network in Portland, Oregon, and a commercial HSPA+ network in Melbourne, Australia, were captured and analyzed in drive tests conducted in 2009, as reported in “HSPA+ and Mobile WiMAX Network Performance Benchmark Results and Analysis”, Signals Research Group, November 4, 2009 [83]. Five WiMAX devices from different manufacturers were used in the tests. Both drive tests and pedestrian tests were conducted. Figure 3.2-41 and Figure 3.2-42 show the distribution of uplink and downlink data rates, and MIMO configurations in drive tests through downtown Portland and Hillsboro respectively in mid-afternoon.

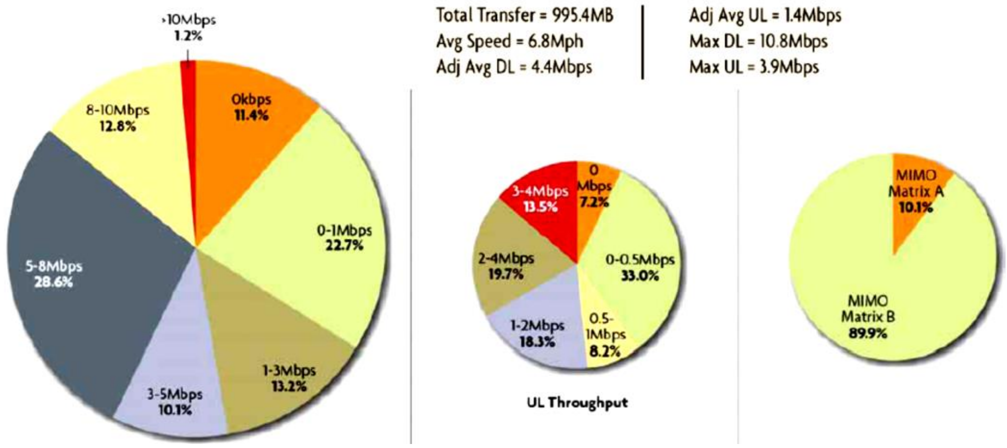


Figure 3.2-41. Distribution of Uplink and Downlink Data Rates and MIMO Configurations in Downtown Portland Drive Test

(Ref: "HSPA+ and Mobile WiMAX Network Performance Benchmark Results and Analysis", *Signals Research Group*, November 4, 2009 [83])

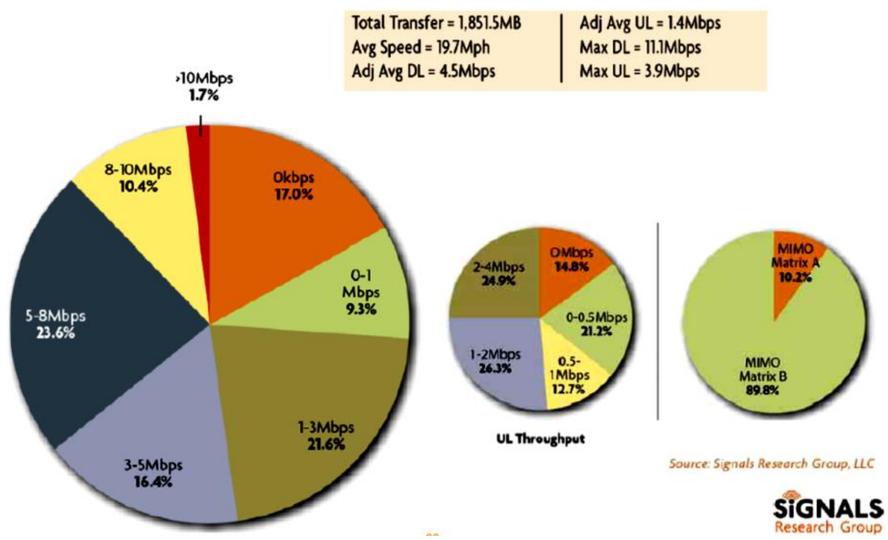


Figure 3.2-42. Distribution of Uplink and Downlink Data Rates and MIMO Configurations in Hillsboro Drive Test

(Ref: "HSPA+ and Mobile WiMAX Network Performance Benchmark Results and Analysis", *Signals Research Group*, November 4, 2009 [83])

Latency for WiMAX IEEE802.16e is specified as 20 msec for link access and 30 to 50 msec for handoff; 802.16m specifies 10 msec for link access and 30 msec for handoff. In a report entitled, “4G Networks Tested, WiMAX vs. HSPA+” (http://www.phonescoop.com) [84], the results of data rate and latency test conducted on several Philadelphia wireless service providers was presented. The details of how these tests were conducted were not provided; however, the results seem to be similar to those reported by users on the Internet, and are provided in Table 3.2-14. Measurement results indicated a WiMAX access latency of 199 msec and a HSPA+ latency of 93 msec. In an article entitled, “Battle HSPA+ vs. WiMAX” *(Mobile Phone News, 12-23-2010)* [85], similar results were discussed (HSPA+ = 74 – 122 msec and WiMAX = 116 to 206 msec). In a white paper by Sprint, entitled, “Mobile Wireless, the 4G Revolution has Begun (V 1.0)” [86], it is stated that “Best Efforts” class QoS test of their WiMAX network shows an 80–100 msec latency. Figure 3.2-43 presents the data rates achieved for both up and down link associated with the latency measurements presented in Table 3.2-14.

Table 3.2-14. WiMAX and HSPA+ Wireless Communications Measurements Conducted in Philadelphia

(Ref: “4G Networks Tested, WiMAX vs. HSPA+”; http://www.phonescoop.com [84])

Tech	Averages		Location	Down (kbps)	Up (kbps)
WiMAX Service Provider			A	2,924	679
	2,785	kbps down	B	3,664	436
	589	kbps up	C	3,139	978
	199	msec latency	D	4,066	971
			E	2,170	409
			F	748	60
HSPA+ Service Provider			A	976	1,250
	2,960	kbps down	B	2,149	1,151
	1,283	kbps up	C	3,416	1,229
	93	msec latency	D	4,528	1,242
			E	1,249	938
			F	5,442	1,888

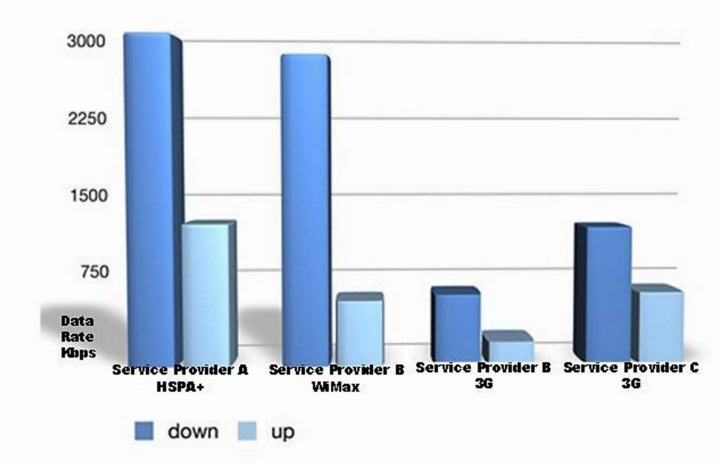


Figure 3.2-43. Measurements Made in the Philadelphia Area of Data Rates Provided by Wireless Services

(Ref: “4G Networks Tested, WiMAX vs. HSPA+”, http://www.phonescoop.com [84])

A research report entitled, “A Comparative Study Between 802.11p and Mobile WiMAX-Based V2I Communications Networks”, by Ikbal Masadaa, et al (EUROCOM Mobil Communications Center) [87], investigates the performance of IEEE802.11p and WiMAX (IEEE802.16e) in several ITS V2I scenarios. Table 3.2-15 was presented in the research report as an objective for communications latency. Table 3.2-16 presents the parameters of the two communications technologies utilized in the simulation. Figure 3.2-44 presents the coverage scenarios utilized for comparing the two technologies and Figure 3.2-45 presents the results, comparing packet delivery ratios with range. (Note that the packet delivery ratio = transmitted packets/received packets). The results were that the IEEE802.11p link supported a reliable range of +- 800m and WiMAX supported a range of +- 4 km. It is unclear if this represents an advantage, since, with longer range the link will be required to support more vehicles, so the overall bandwidth per vehicle will be less.

A second scenario was utilized, incorporating multiple RSEs along a corridor as shown in Figure 3.2-46. Figure 3.2-47 presents the results illustrating the impact of vehicle speed and source data rate on link throughput and delay. The results of this study indicate:

WIMAX:

- Source data rate and throughput are about equal up to 15 mbps;
- Latency is about 15 msec for vehicle speeds up to 160 km/hr;
- Latency is about 15 msec for source data rates of 15 mbps increasing to 50 msec at 20 mbps;
- Link throughput is about 1 mbps for velocities up to 160 km/hr for a single RSE (BS); for two RSEs, the throughput is 0.95 mbps at 40 km/hr decreasing to about 0.85 mbps at 160 km/hr;

IEEE802.11p DSRC:

- Link throughput remains about 1 mbps with source data increases to 20 mbps;
- Latency is about 50 msec for source data rates of 1 mbps increasing to 200 msec at source data rates of 5 mbps;
- Latency is around 45 msec for vehicle velocities up to 160 km/hr;
- Link throughput is about 0.8 mbps at vehicle speed of 40 km/hr decreasing to 0.55 mbps at a vehicle speed of 160 km/hr.

Table 3.2-15. Latency Requirements of ITS Applications

(Ref: “A Comparative Study Between 802.11p and Mobile WiMAX-Based V2I Communications Networks”, Ikbal Masadaa, et al, EUROCOM Mobil Communications Center [87])

Application category	Latency tolerance	Range	Example (delay requirements)
Road safety	Low latency	Local Range	Pre-crash sensing/warning (50 ms)
			Collision risk warning (100 ms)
Traffic efficiency	Some latency is acceptable	Medium range	Traffic information – Recommended itinerary (500 ms)
Value-added services	Long latency is accepted	Medium range	Map download update 0 Point of interest notification (500 ms)

Table 3.2-16. Key Parameters Utilized in the Research Model

(Ref: “A Comparative Study Between 802.11p and Mobile WiMAX-Based V2I Communications Networks”, Ikbal Masadaa, et al, EUROCOM Mobil Communications Center [87])

	802.11p	802.16e
Frequency	5.87 GHz (G5SC3)	3.5 GHz
Channel bandwidth	10 MHz	10 MHz
RSU Tx power	23 dBm (=200 mW)	33 dBm (=2 W)
RS antenna height	2.4 m	32 m
RSU antenna gain	3 dBi	15 dBi
MS Tx power	23 dBm (=200 mW)	23 dBm (=200 mW)
MS antenna height	1.5 m	1.5 m

	802.11p	802.16e
MS antenna gain	0 dBi	-1 dBi
Type of antenna	Omnidirectional	
Pathloss	Two-ray	
Fading model	Ricean	

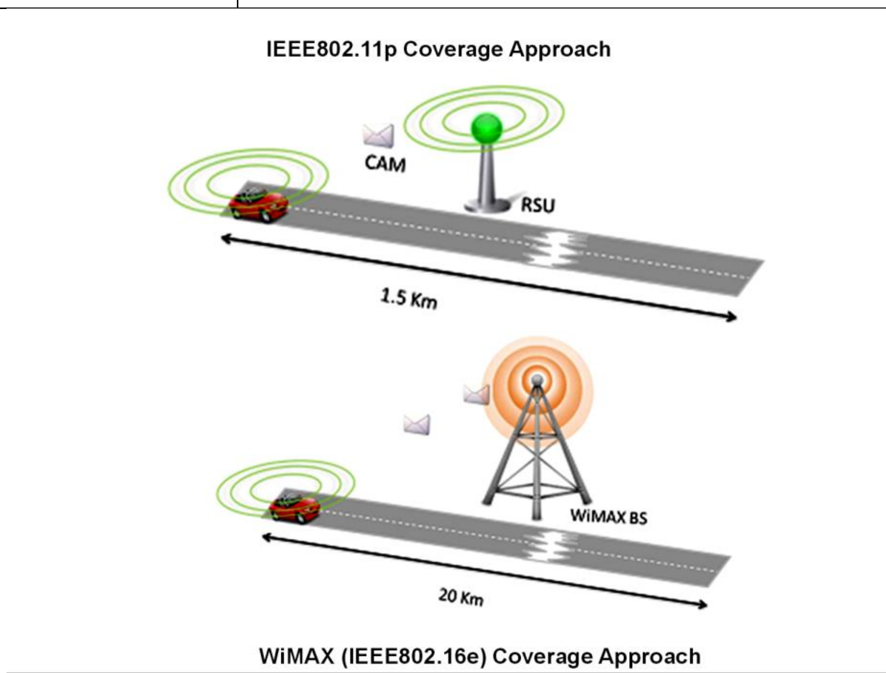


Figure 3.2-44. Two Coverage Scenarios Utilized Studying Comparative Performance of IEEE802.11p with IEEE802.16e

(Ref: "A Comparative Study Between 802.11p and Mobile WiMAX-Based V2I Communications Networks", Ikbal Masadaa, et al, EUROCOM Mobil Communications Center [87])

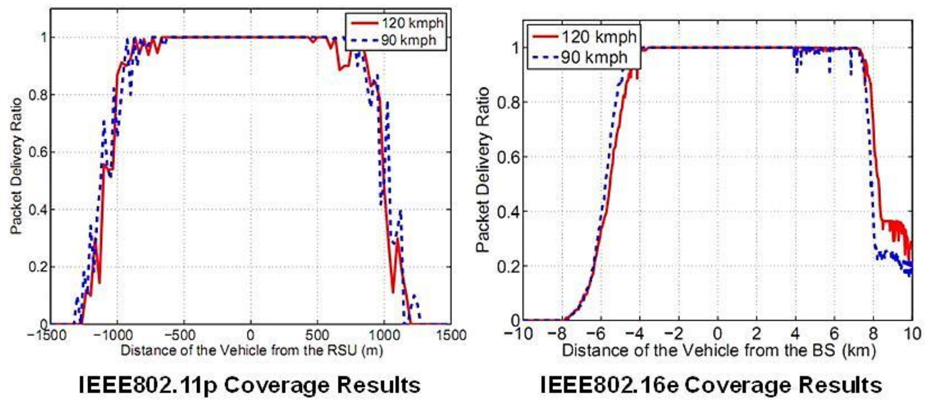


Figure 3.2-45. Comparative Coverage and Packet Delivery Ratios for IEEE802.11p and IEEE802.16e

(Ref: "A Comparative Study Between 802.11p and Mobile WiMAX-Based V2I Communications Networks", Ikbal Masadaa, et al, EUROCOM Mobil Communications Center [87])

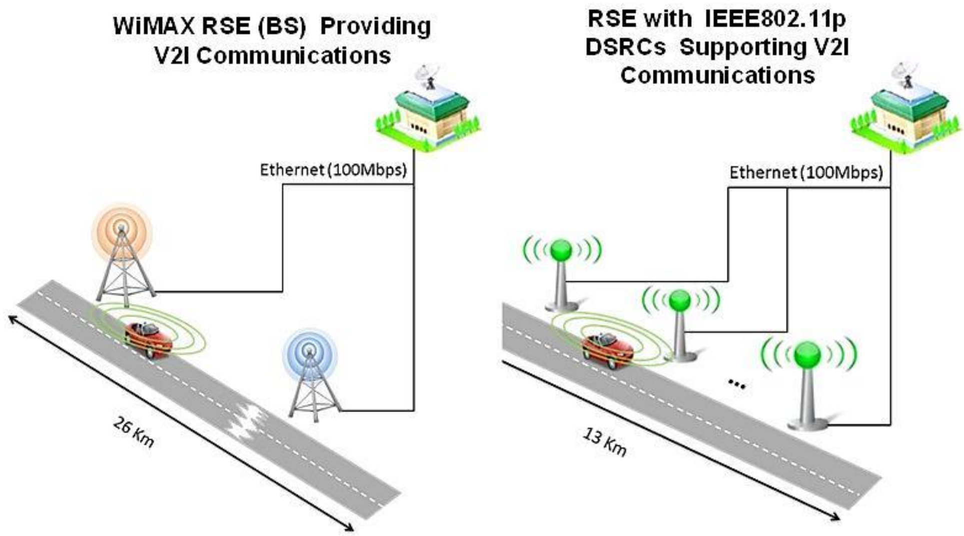


Figure 3.2-46. Multiple RSE Scenarios Supporting Analysis of IEEE802.11p and IEEE802.16e

(Ref: "A Comparative Study Between 802.11p and Mobile WiMAX-Based V2I Communications Networks", Ikbal Masadaa, et al, EUROCOM Mobil Communications Center [87])

The study did not consider multiple vehicle impact on performance and link access latency that would be associated with multiple devices seeking link access. It does indicate:

- WIMAX has superior performance compared to a DSRC designed to IEEE802.11p standards as vehicle speed increases to 160 km/h;
- WIMAX has superior link throughput compared with an IEEE802.11p link.

However, Mobile WiMAX is specified to have 30 msec intra-frequency and 100 msec inter-frequency handoff latency; latency results presented in the study report do not indicate that handoff delays were considered. Also, test by other researchers (Ref: “A Mobility Handover Scheme for Mobile-WiMAX”, by Arun Khosla, et al, *International Journal of Computer Applications*, V2, # 3, Dec. 2010 [88]), indicates that handoff delays start increasing from the 30 msec specification around 20 m/sec vehicle velocity and increase to 100+ msec at 40 m/sec vehicle velocity, again indicating that handoff was not considered in these test.

For broadcast communications, such as SPaT, handoff delays are not applicable to the latency; thus latency results of the WiMAX vs. IEEE802.16e study are perhaps appropriate.

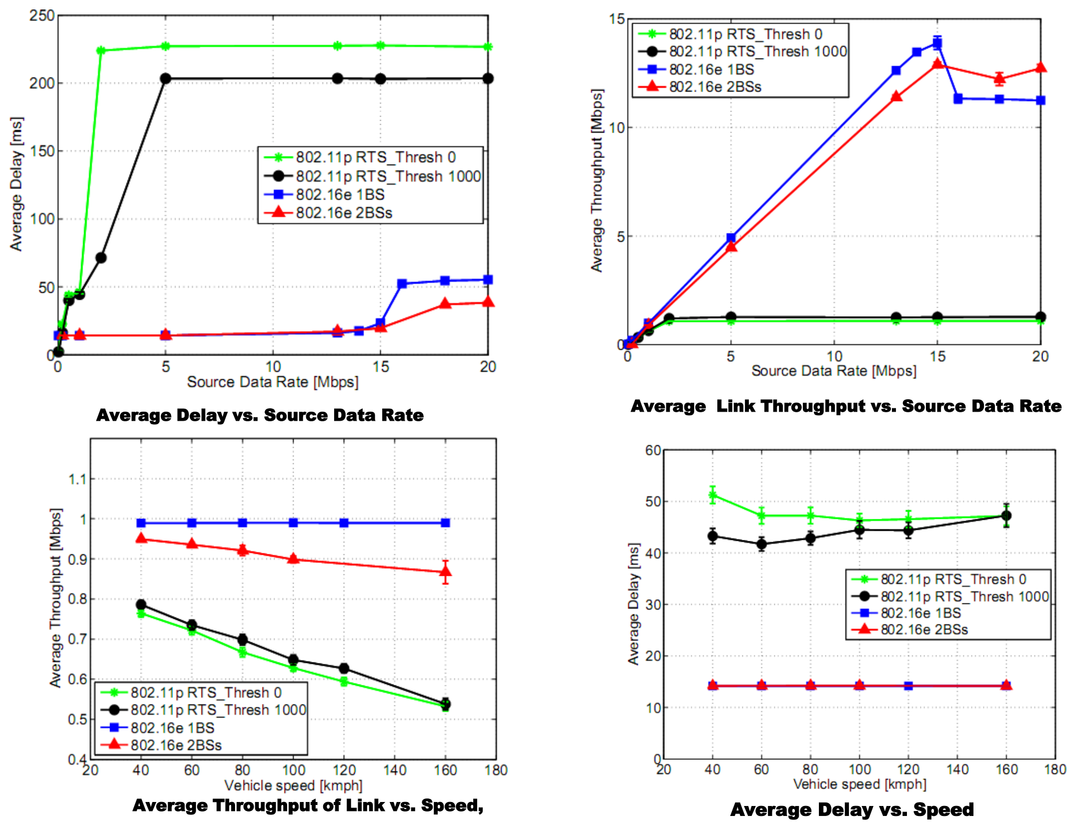


Figure 3.2-47. Results of Comparative Analysis of IEEE802.11p and IEEE802.16e

(Ref:” A Comparative Study Between 802.11p and Mobile WiMAX-Based V2I Communications Networks”, Ikbal Masadaa, et al, EUROCOM Mobil Communications Center [87])

3.2.3.2 **Applicability to SPaT Applications Communications**

WiMAX deployed as a 4G wireless network by service providers will have a service fee for users of the network. This means that commercial and private vehicle users would be required to pay a use fee for communications services. This eliminates the technology for consideration, when deployed by a communications service provider. However, should public/private partnerships be developed, by perhaps jurisdictions allowing publically owned infrastructure (land, public communications towers, water towers, buildings owned by the jurisdiction, etc.) to be used by service providers to support deployment of the broadband mobile service infrastructure, in return for perhaps several WiMAX channels that would be utilized to support broadcast of safety messages, then WiMAX could support distribution of GID information such as GIDs, updates to GIDs, temporary changes to the GIDs (such as a special event that requires no turns at the intersection or lane closure due to intersection maintenance)) and other related information. The bandwidth of a WIMAX channel is sufficient to support GID and other traffic safety related information to vehicles.

It is also possible for jurisdictions to deploy WiMAX as a wireless jurisdictional network. Jurisdictions are using the 4.9 GHz frequency band allocated for emergency services to support police, fire, emergency medical, and traffic related mobile and fixed broadband communications. The 4.9 GHz WiMAX system could be utilized to provide SPaT related messaging support to jurisdictional vehicles. For WiMAX to be utilized to provide reliable communications to general public and private commercial vehicles, a protected frequency band should be considered. Jurisdictions have deployed WiMAX to provide a communications network from ITS centers to roadside, thus integrating traffic controllers and sensors with ITS centers and also supporting center-to-center integration. Assuming WiMAX is used to connect the roadside RSEs, and then GID and other SPaT applications related information could be provided to the DSRC for transmittal to the vehicles. Figure 3.2-48 illustrates this application of WiMAX technology. The approach of developing a public/private partnership for distribution of GID and other SPaT related data to vehicle is illustrated in Figure 3.2-49. Again, unless a public/private partnership can be developed, the solution shown in Figure 3.2-49 does not meet the criteria of “no service fee” for mobile communications supporting SPaT applications.

In summary, WIMAX has the bandwidth and latency to support SPaT applications for broadcasting data to vehicles. Because it has longer-range coverage, fewer base station deployments will be needed, but the overall data load will be higher due to the larger area covered. If jurisdictions use WiMAX to integrate RSEs with ITS centers, then perhaps the best application for WiMAX is to link roadside DSRC based equipment to ITS centers. Communications service providers own the protected (licensed) operating frequencies for WiMAX (with the exception of 4.9 GHz). It may be difficult to sell private users a WiMAX cellular device that only supports ITS data transfer to vehicles; thus justifying emphasis on public/private partnership solutions.

A summary of WiMAX specifications and field test results is presented in Table 3.2-17.

The FCC has allocated 10 MHz of spectrum in the 700 MHz band for public safety broadband communications nationwide. LTE has been designated by the FCC as the technology for this nationwide broadband communication network and deployment has started in cities such as San Francisco, NYC, Charlotte (NC) and others as well as in counties such as Adams in CO. LTE has also been endorsed by organizations such as APCO and NENA for public safety broadband communications. Deployment of LTE public safety networks by local governments have also started. In contrast, WiMAX has not received the same level of support or endorsement for public safety. In view of these developments and the momentum behind LTE as the preferred technology for public safety, WiMAX will not be investigated further for supporting SPaT applications.

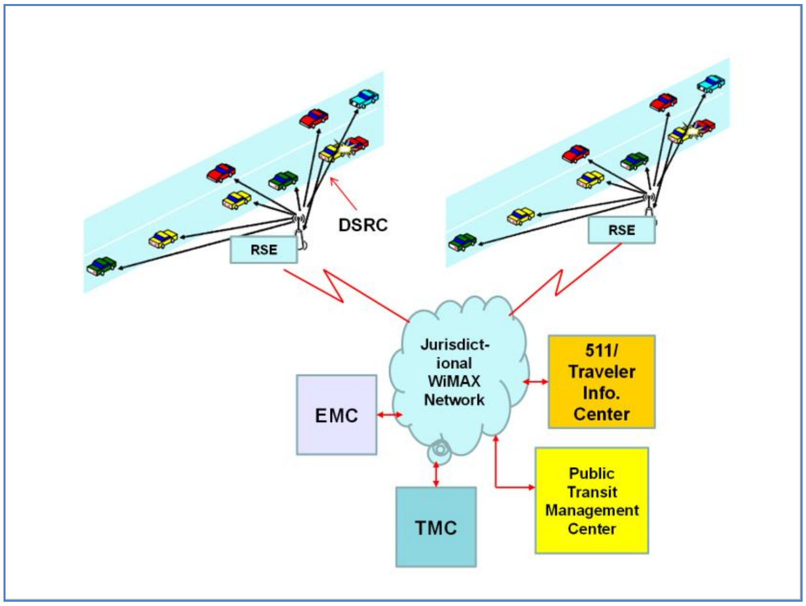


Figure 3.2-48. SPaT Supporting Information Relayed from WiMAX to Vehicles
Source: ARINC April 2012

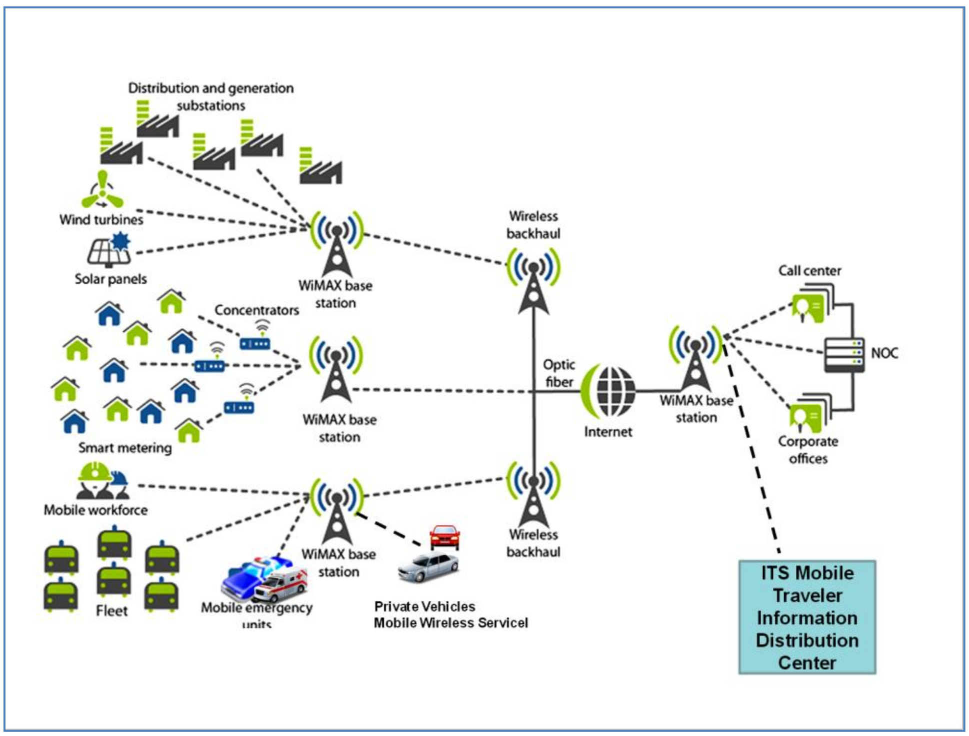


Figure 3.2-49. Public/Private Partnership to Distribute SPaT Applications Support Information to Private and Public Fleet and Private-Individual Vehicles

(Ref: “Empowering the SMART Grid with WiMAX”, Monica Paolini, PhD, Senza Fili [89])

Table 3.2-17. Summary Specifications (Published and Test Results) for WiMAX

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
Applicable standards	IEEE Std. 802.16e, WiMAX Forum	Same
Link Access	OFDMA	Same
Simplex, half duplex, or full duplex service	Full duplex	Same
Frequency Band and Licensing	2.3, 2.5 and 3.5 GHz; Licensed	Same
Operating Bandwidth and Channel Bandwidth	3.5, 5, 7, 8.75 and 10 MHz	Same
Wireless Mobility with Velocities Supported:	120 km/h	Same
Maximum Range	30 km (19 mile)	6 – 8 km (4 – 5 miles)
Multipath Spread Protection	11.4 μsec	Same
Communications Data Rates (Peak)	DL 31 Mbps UL 14 Mbps (10 MHz)	DL 11 Mbps UL 4 Mbps
Latency	20 msec	Same
Quality of Service	5 classes	Same
Current Design Vehicle Environmentally Compatible	Yes	Yes
Equipment Approximate Size /Weight for Mobile Applications	42 x 34 x 28 cm 15 kg	Same
Equipment Approximate Power Load for Mobile Applications	48V DC	Same
Approximate Cost of Mobile Unit	$300	Same

Source: ARINC April 2012

3.2.4 *Digital Terrestrial Broadcast Television*

While there are several digital broadcast television standards, the one adopted by FCC is developed by Advanced Television Systems Committee, Inc. (ATSC). It was approved in 1996 and revised in 2008 to add H.264/AVC (MPEG 4 Part 2) to the standard. In 2009 the mobile, digital TV standard, called ATSC M/H, was approved and TV broadcasting in the U.S. has started its transition to support the ATSC M/H standard. ATSC M/H uses a portion of the total available 19.4 Mbps bandwidth of ATSC and is backward compatible with the ATSC standard. To support high-speed reception, central to the M/H system are additions to the physical layer of the ATSC transmission system that are easily decodable under high Doppler rate conditions. Additional training sequences and additional forward error correction (FEC) assist reception of the enhanced stream(s). Similar to the ATSC main service, ATSC M/H uses 8-level Vestigial Sideband (8VSB) modulation for broadcasting in the same 6 MHz channel. While the total available bandwidth is 19.4 Mbps, multiple configurations are supported to deliver both main and M/H services. Based on the enhancement and robustness, ATSC M/H is capable of supporting user mobility of up to 300 km/h (187.5 mph).

Unlike the ATSC main service that uses standard MPEG-2 transport stream packets to deliver data, ATSC M/H system encapsulates the data payload using special M/H Encapsulation (MHE) packets as the transport data unit. Within the data payload of this special MHE packet, ATSC M/H encapsulates the media data into Internet Protocol (IP) datagram and User Datagram Protocol (UDP) packets. To achieve compliance with mainstream Internet streaming data technology, ATSC M/H adopts IP; currently IPv4, as the Network Layer protocol, supports User Datagram Protocol (UDP) for the real-time steaming media in the Transport Layer, and uses Real-Time Streaming Protocol (RTSP) in the Session Layer. Figure 3.2-50 illustrates the similarity between the ATSC M/H system and the standard OSI reference model (Ref: “ATSC-Mobile DTV Standard, Part 3 – ATSC Mobile Digital Television System” [90]).

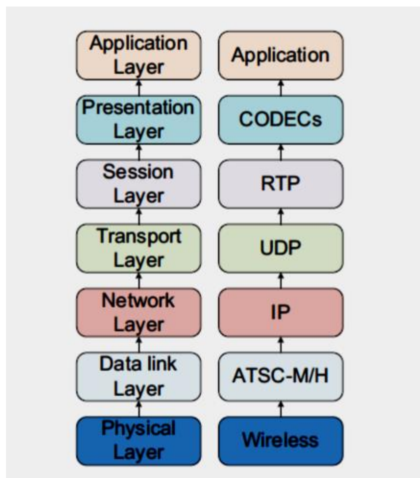


Figure 3.2-50. OSI Reference Model with ATSC M/H Components
Source: ARINC April 2012

ATSC and ATSC M/H support configurable bandwidth allocation for simultaneous broadcast of both standard and mobile services. Thanks to this flexibility, a broadcast TV station can provide both standard and mobile services without incurring much additional cost and investment. One example of configuring bandwidth for both standard and mobile services based on a recent commercial demonstration is to utilize 15 Mbps for main ATSC TV signal and 4.4 Mbps for ATSC M/H (Ref: “ATSC-Mobile DTV Standard, Part 1 – ATSC Mobile Digital Television System and ATSC M/H Station Implementation”, Jay Adrick, Harris Corp. [91])

As ATSC M/H standards were only officially finalized in late 2009, there are few manufacturers offering equipment to the broadcasters and end users at the current stage. Figure 3.2-51 illustrates some available products. At the time this report is developed, there are a few consumer-grade electronic devices available to provide ATSC M/H service to personal portable devices, mobile phones and home A/V system. For the aftermarket devices for in-vehicle use, the cost of equipment is expected to be similar to HD radio or satellite radio receivers. Cost of equipment is typically below three hundred dollars. If the device is integrated with a display, the cost could be higher. For broadcasters, ATSC M/H supports 100%

backward compatibility and transmits data on the same spectrum so no additional FCC license is required. Broadcasters only need a few additional pieces of equipment, such as an ATSC M/H Encoder and Exciter, to support transmitting programs to ATSC M/H-enabled receiving devices. This evolution path requires minimum investment from broadcasters.

Figure 3.2-51. Examples of ATSC M/H Devices

(Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

In addition to the broadcast audio/video services, ATSC M/H also supports additional features, including:

- **Announcement**: Announcement subsystem is used to announce available services from a particular provider to receivers.
- **Application Framework**: The Application Framework enables the broadcaster of the audio-visual service to author and insert supplemental content to define and control various additional elements to be used in conjunction with the M/H audio-visual service. It enables definition of auxiliary (graphical) components, layout for the service, transitions between layouts and composition of audio-visual components with auxiliary data components. Furthermore, it enables the broadcaster to send remote events to modify the presentation and to control the presentation timeline. The Application Framework further enables coherent rendering of the service and its layout on a variety of device classes and platforms, rendering of action buttons and input fields, and event handling and scripting associated with such buttons and fields;
- **Service Protection**: Service Protection refers to the protection of content, be that files or streams, during its delivery to a receiver. Service Protection is an access control mechanism intended for subscription management. It establishes no controls on content after delivery to the receiver.

Figure 3.2-52, Table 3.2-18, and Figure 3.2-53 illustrate the features and product specifications of ATSC M/H receivers in different form factors.

Key Features:

Compliant with ATSC A/153, with ATSC Mobile DTV standard
Use high performance ATSC demodulator
provides convenient VHF and UHF signal reception
Video format: MPEG-4 AVC/H.264 Baseline@Level 1.3
Audio format: MPEG-4 HE AAC V2
Automatic & Manual Channel Scan
UHF(470~862MHz)&VHF(176~245MHz)
R/F Sensitivity -95dBm±2dB @ BER=1 x 10-4
Favorite channel list
Closed caption supported
Basic Functions with OSD(On Screen Display)
Full Remote control control
Wide DC power input from DC 9V to 14V suitable for car
Video output,stereo audio output
HDTV signal scale to SDTV 720X480I output

Figure 3.2-52. ATSC M/H Product Features

(Ref: Manufacturer Literature of ATSC M/H Product)

Table 3.2-18. ATSC M/H Product Receiver Specification in Form Factor for Automotive Installation

(Ref: Manufacturer of ATSC M/H Product Literature)

Description	Specifications
DC Power	DC 12V/24V
Consumption Current	300 mA/160 mA
Audio Output Level	0.5 Vrms (10K Ohms)
Video Output Level	1 Vpp (75 Ohms)

Description	Specifications
Frequency Range	57 ~ 803 MHz (VHF/UHF)
Antenna Style	Pole
Antenna Input Impedance	50 Ohms
Reception of Signal	-90 dBm min
Operating Temperature	23° F (-5° C) ~ +140° F (+60° C)

Broadcasting Type	ATSC-M/H (Mobile/Handheld)
Frequency Range	VHF (57 ~ 240MHz) & UHF (470 ~ 700MHz)
Video Decoding	H.264/AVC (Frame Size: 416 x 240)
Audio Decoding	HE AAC+ v2 (Sampling Range: 24KHz/48KHz/Stereo/Mono – Stereo)
Input Voltage	DC 5V
Power Consumption	Under 140 mA(Max) / Average 80mA in Power Saving Mode (NOG3)
Antenna Connector	AMB Type
Antenna	Detachable Compact Antenna & External Antenna (5M) support

Figure 3.2-53. ATSC M/H Product Receiver Specification in USB Stick Form Factor

(Ref: Manufacturer of ATSC M/H Product Literature)

Potential applicability of ATSC M/H is to transmit GID and other SPaT application related support information messages to vehicles. This would require a public/private partnership with TV stations. However, TV stations have supported ITS applications in the past to distribute information to travelers as a public service and also in return for Traffic management Centers sharing traffic related information and video to TV News. Broadcast digital TV supports wide area coverage in urban and suburban areas. There is limited coverage in rural areas, except for satellite TV that requires a user service fee.

Europe has adopted the Digital Video Broadcasting-Handheld (DVB-H) standard, which is an extension of the DVB-Terrestrial standard. COFDM modulation is utilized. Also added to support mobility is a “time slicing” function, which facilitates a 90% reduction in receiver power consumption by supporting a “burst mode” of operation. Also “protocol encapsulation-forward error correction” (MEP-FEC) forward error correction code was added to the standard. COFDM supports signal synchronization required for distributed transmission. ETSI-TS-102 472, entitled “Digital Video Broadcast: IP Datacast over DVB-H” [92], defines the standard for IP Datacast using DVB-H, which would be a European candidate for GID distribution. Table 3.2-19 compares DVB-H standard with other mobile digital TV standards available. This seems to be a superior modulation to support mobile applications compared with ATSC M/H because of its easier adaptability to mobile communications requirements and performance of COFDM in the presence of interference.

Table 3.2-19. Comparison of International Standards for Mobile Digital TV

(Ref: "Comparison of Mobile TV Standards and Development of 3D Mobile TV Based on DMB", Jinwoong Kim, et al, *MIT Open Access* Articles [93])

Standards	**DVB-H**	**DMB**	**MediaFLO**	**OneSeg**
Base Technology	DVB-T	DAB	Qualcomm CDMA	ISDB-T
Standardization Body	DVB	WorldDMB	FLO Forum	ARIB in Japan
Video Codec	H.264	H.264	Enhanced H.264	H.264
Audio Codec	MPEG-4 AAC	MPEG-4 BSAC	MPEG-4 AAC	MPEG-2 AAC
Transmission Schema	OFDM	OFDM	OFDM	BST- OFDM
Power Saving Tech	Time Slicing	Bandwidth Reduction	Time Slicing	Bandwidth Reduction
Channel Switching Time	5 sec.	1.5 sec.	1.5 sec.	1.5 sec.
Tech for better mobility	MPE-FEC, RS (335, 191)	Forney Interleaving RS(204, 188)	Turbo Code & RS	Viterbi Coding RS(204, 188)
Frequency Bands	UHF	VHF (Band III)/L-band	VHF/UHF/L-band.S-band	VHF/UHF
Bandwidth	5/6/8 MHz	1.54 MHz	5/6/7/8 MHz	433 KHz/I segment
Data Rate (Mbps)	15	1.2	11.2	0.312/channel

Standards	DVB-H	DMB	MediaFLO	OneSeg
Service Country	Europe, USA, Asia	Korea, China, Europe	USA	Japan, Brazil
Characteristics	Nokia is leading	Easily migrated from DAB	Qualcomm is leading	HD/SD/Mobile service in 1 channel

Source: ARINC April 2012

3.2.4.1 **Details of Digital Terrestrial Broadcast Television System**

Figure 3.2-54 and Figure 3.2-55 present the system diagram of a single frequency digital terrestrial broadcast TV system. Figure 3.2-56 presents the ATSC M/H protocol stack. Figure 3.2-57 illustrates additions to the ATSC M/H transmission that support mobile communications. The training sequence addition supports determination of multipath and the serial concatenated convolutional coding improves error correction and SNR for mobile reception.

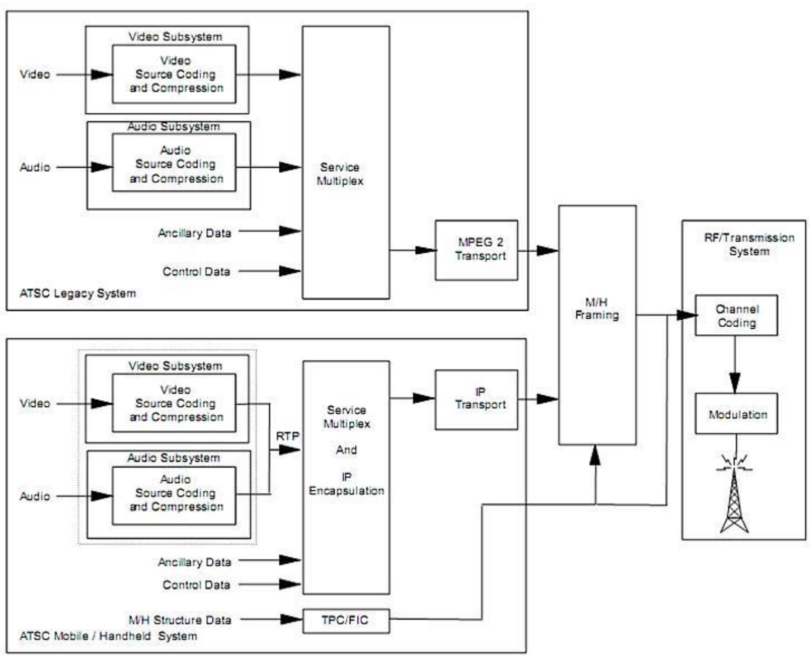


Figure 3.2-54. Single Frequency Digital Terrestrial Broadcast TV System Diagram Supporting Fixed and Mobile TV Service

(Ref: Advanced Television Standards Committee, “ATSC-Mobile DTV Standard, Part 3 – ATSC Mobile Digital Television System” [90])

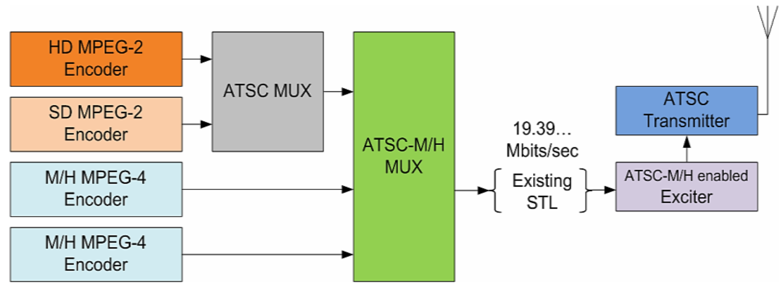


Figure 3.2-55. Simplified Diagram of an ATSC M/H Digital TV Transmission System

(Ref: Rhode & Schwarz Application Note 7EB01_0E, ATSC Mobile DTV [94])

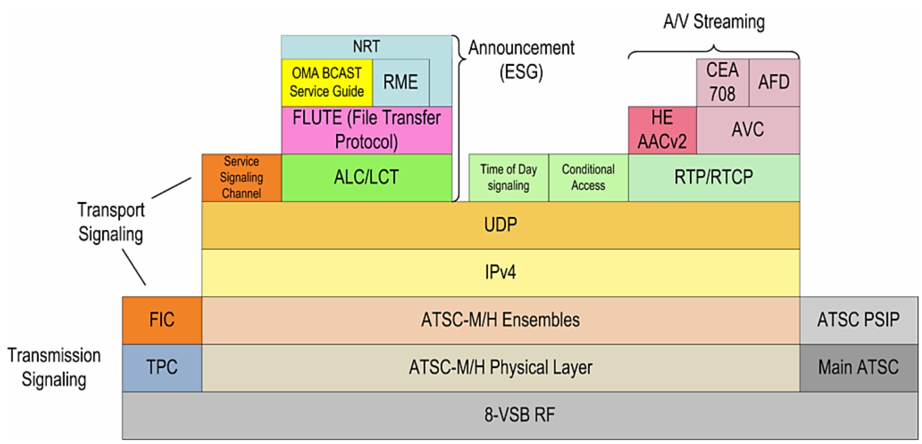


Figure 3.2-56. ATSC M/H Digital TV Protocol Stack

(Ref: ATSC Standard and Rhode & Schwarz Application Note 7EB01_0E, ATSC Mobile DTV [94])

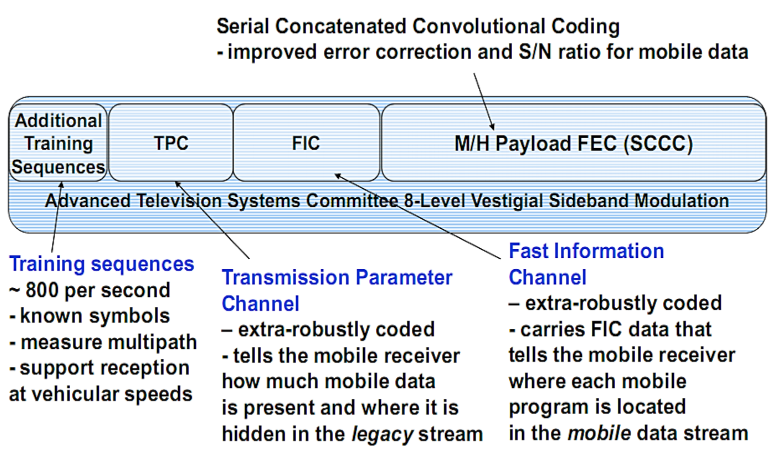


Figure 3.2-57. ATSC M/H Structure Illustration Features to Support Mobile Communications

(Ref: “Physical Layer for ATSC Mobile DTV”, Wayne Bretl [95])

Table 3.2-20 presents test results conducted by Zenith Electronics Corp. as included in a presentation by Wayne Bretl entitled, “Physical layer for ATSC Mobile TV” [95]. Reception at 30 km was demonstrated; basic 8-VSB modulation requires a SNR of 15 and supported a Doppler of 10 HZ; M/H using the enhancements and ½ rate, required 7.4 SNR and supported 150 Hz Doppler. This Doppler protection (150 Hz) is not compatible high speed mobility.

Two error protection approaches are incorporated into ATSC-M/H standard. Reed Solomon Code corrects byte errors after decoding the inner convolutional code in the receiver. Error correction is improved by use of CRC checksum, since bytes can be marked as defective before they are decoded. Per the ATSC A153 standard, “the symbols and the additional checksum form the outer elements of a data matrix which is allocated by the payload of the M/H Ensemble. The number of lines is fixed and the number of columns is variable according to how many slots per sub frame are occupied. The RS Frame is then partitioned into several segments of different sizes and assigned to specified regions. These regions are protected by a convolution code (SCCC), which together with the Trellis coder of the 8-VSB ATSC modulation forms an inner parallel concatenated code (PCCC) that can be repetitively decoded in the receiver”.

Table 3.2-20. Test Results for ATSC M/H Data Transmission

(Ref: “Physical Layer for ATSC Mobile DTV”, Wayne Bretl [95])

	8-VSB (A/53)	M/H (A/153) ½ rate (Regions A+B)	M/H (A/153) ½ rate	M/H (A/153) mixed rate	M/H (A/153) ¼ rate
SNR Required (dB)	15	7.4	7.9	7.3	3.4
Doppler (Hz) ~= max mph, with complex ghosts (TU-6)	~10 (depends on receiver)	150	80*	140	180

In ATSC M/H broadcast, either a high power transmitter can be utilized to cover 30 + km radius from the transmitter or lower power, distributed transmitters may be used. The distributed transmitters must use GPS time synchronization. The advantage of lower power, distributed transmitters is improved coverage of an area. However, repeaters (receiver/transmitter) may also be utilized to fill in coverage gaps perhaps caused by terrain.

When two or more ATSC M/H transmitters with an overlapping coverage transmit the same data stream on the same frequency, the signals must be synchronized. The ATSC M/H multiplexer inserts a time stamp in the transport stream and the transmitter has circuitry that analyzes the time stamp, delays the transport stream before it is modulated and transmitted as appropriate to maintain transmitted signal synchronization. Figure 3.2-58 illustrates a system diagram of a distributed transmission system supporting ASTC M/H broadcast. ATSC document, “ATSC Standard for Transmitter Synchronization” (A110: 2011) [96] provides the specifications related to transmission synchronization. Shown in this figure is the interface with Jurisdictional ITS Data based on an established public/private partnership.

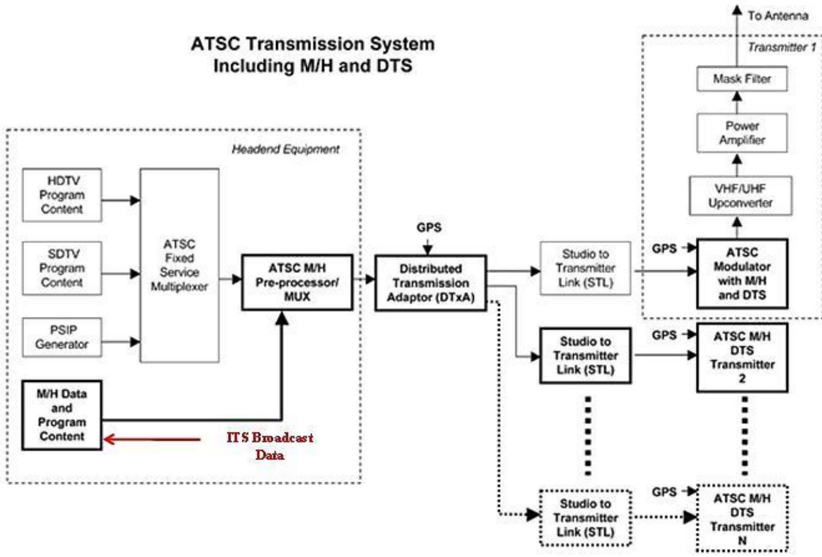


Figure 3.2-58. Modifications to an ATSC DTV Transmission System Supporting Mobility and Distribute Transmission

(Ref: "Integrating ATSC M/H into a Broadcast Transmission System", Richard Schwartz, Axcera LLC [97])

Since ATSC M/H standard is relatively new, not a significant amount of test data was found. It is found that to achieve the optimal service quality, it is more important to focus on better "signal saturation", rather than maximizing the coverage. There are three approaches for achieving signal saturation (Ref: "ATSC Mobile DTV, Not Just Technology", Screen Service and RRD USA, April 2011 [98]):

- Adopt circular polarization antenna: help minimize the polarization mismatch loss caused by misalignment between the transmitting and receiving antenna.
- Maximize power from main transmission site: low antenna gain and high transmitter output power provide more signal saturation.
- Deploy repeaters and gap fillers to cover weak or blind signal spots, and indoor environment.

3.2.4.2 **Use of Mobile Digital Television for Delivering ITS Messages to Vehicles**

The ATSC M/H standard is developed to support mobile requirements for TV signal access. The approach taken in the USA is to use single frequency transmission, adapting the original ATSC standard to accommodate multipath and Doppler. The original 8-VSB modulation has been maintained. ATSC standard supports adjustable bandwidth allocation for both ATSC main service and ATSC M/H service. Based on FCC's requirements, all broadcasters are required to provide at minimum one standard-definition NTSC quality free-to-air program. One typical standard-definition service in MPEG2 needs 2 – 4 Mbps bandwidth. One typical high-definition service in MPEG2 needs 10 – 14 Mbps bandwidth. The ATSC program guide (PSIP) requires about 0.5 Mbps. As shown in Figure 3.2-59, one bandwidth configuration has approximately 4.6 Mbps out of the 19.4 Mbps bit stream dedicated to mobile applications. Assume the bit rates of video and audio data used for ATSC M/H service are illustrated in Table 3.2-21.

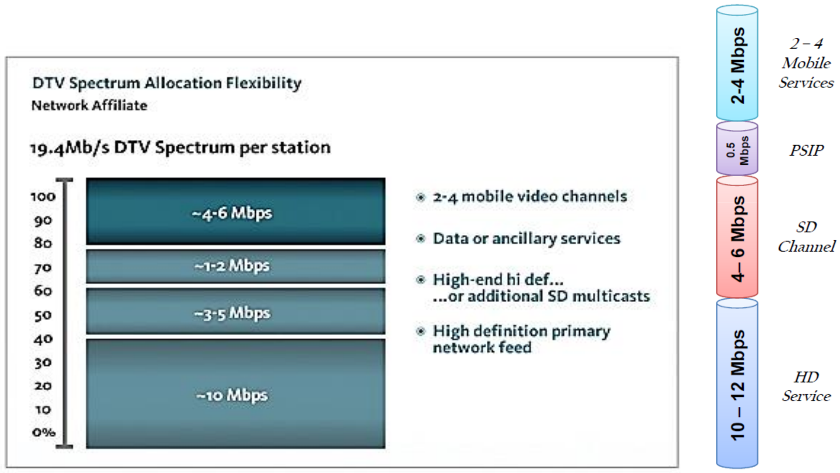


Figure 3.2-59. ATSC 19.4 Mbps Allocation for Affiliated Network Service Providers

(Ref: “Mobile Digital Video”, Open Mobile Digital Coalition [99])

Table 3.2-21. Bit Rates of Video and Audio Data

	High Quality	Medium Quality	Low Quality
Video Bit Rate (kbps)	512	384	256
Audio Bit Rate (kbps)	32	24	16

Source: ARINC April 2012

Given this allocated 4.6 Mbps bandwidth, several ATSC M/H services with different data bit rates may be planned as Table 3.2-22.

Table 3.2-22. ATSC M/H Service Planning for 4.6 Mbps Bandwidth

Assume Using Mixed Rate SCCC outer Code (1/2, ¼, ¼, ¼)		
Service Configuration	**Total Data Bandwidth (kbps)**	**Overhead (kbps)**
2 HQ Video + Audio	1088	127
2 MQ Video + Audio & 1 LQ Video + Audio	1088	127
4 LQ Video + Audio	1088	127
1 HQ Video + Audio & 1 MQ Video + Audio & 4 HQ Audio	1080	135

Source: ARINC April 2012

The specific service planning with a given bandwidth for ATSC M/H depends on each broadcaster's need. The overhead is essentially padded data to ensure each transmitted data packet is fully filled and can be reduce to minimum to be used to increase bandwidth for application data. The bandwidth needed for a SPaT application is logically similar to the video or audio data and it can be carried as one of the service data streams. For instance, a station may configure two medium-quality broadcast channels and allocate the bandwidth for one low-quality service to transmit SPaT-related information.

The standard supports IP encapsulation and also supports data grams. To receive the signal, requires a portable, digital TV receiver with ATSC M/H standards compatibility. These receivers are available in chip form today and are being embedded in portable devices, such as smart cell phones to provide enhanced capability. Report, "Topics in Digital IV: ATSC Mobile DTV", by Rich Chernock (Triveni Digital) [100], indicates that data gram of 1500 bytes can be transmitted within the ATSC M/H bit stream with the RS Frame payload. Real time transport protocol (RTP) encapsulates elementary media streams directly into UDP packets with an RTP header including stream ID, timestamp and other information. RTP streams are synchronized via a sender report that relates payload time stamp to the overall stream time base. If the TB broadcast station has available bandwidth to support public service applications, then the flexibility of the protocol should allow it to support transmitting ITS related safety messages to vehicles. Table 3.2-23 summarizes the pros and cons of this communications technology to support ITS communications.

Table 3.2-23. Pros and Cons of Using ATSC M/H to Support ITS Communications

Pros	Cons
Wide area Coverage (30 km radius from the transmitter possible; function of transmitter power and terrain).	Possible gaps in area coverage; coverage not under control of jurisdiction. FCC requires only 50% area coverage to 90% probability.
Low cost receivers (< $200), Receivers available in chip form to embed into OBE equipment.	Possible issues with high multipath in urban areas. UHF and VHF are highly susceptible to multipath.
Low cost deployment with establishment of a public/private partnership.	Must share bandwidth; Less than 1 mbps availability and could be as low as 12 kbps. Each broadcast station may have different available bandwidths requiring prioritization of data transmitted.
Would not require a service fee if public broadcasting stations were used.	Would require two ATSC M/H stations for high reliability with automatic station switching. Safety apps would also require automatic seeking of the channel supporting ITS safety broadcast as it leaves one area and transitions o another.
IP-V4 compatible link (will be upgraded to IP V-6 in the future. This is compatible with most ITS regional communications networks.	Electronically small antennas limited to -15 dB gain, which limits reception range.
Frequencies support better performance in weather compared with DSRC.	Requires a public/private partnership.

Pros	Cons
Latency of the TV network may be 10+ seconds (Ref: ATSC Implementation Subcommittee Findings: “Findings Report on Latency and Timing Issues” [101]); cannot support time critical message transmissions.	Requires a link from the ITS Traveler Information Center to the Broadcast TV Station.
	Standard recently approved, technology emerging onto the market. Probability of deficiencies and modifications to the standard and associated hardware/software.

Source: ARINC April 2012

In summary, use of the ATSC M/H broadcasting systems to support complementary messages to the SPaT DSRC messages would be the lowest cost solution for the urban and suburban areas. Coverage is limited in the rural areas and only 50% coverage is guaranteed 90% of the time in suburban and urban areas. Doppler protection is also of concern. These issues require further investigation and testing. The solution is not unilateral because a public-private partnership is required and may not represent a universal solution to SPaT communications needs.

A summary of ATSC M/H Mobile TV specifications and field test results is presented in Table 3.2-24.

Table 3.2-24. Specifications (Published and Test Results) for ATSC M/H Mobile TV

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
Applicable standards	Advanced Television Standards Committee A/53 and A/153	Same
Link Modulation	8-VSB	Same
Simplex, half duplex, or full duplex service	Simplex	Same
Frequency Band and Licensing	UHF: 470-806 MHz; VHF: 54-88 MHz and 174-216 MHz; Licensed Broadcast TV Spectrum per FCC	Same
Channel Bandwidth	6 MHz	Same
Wireless Mobility with Velocities Supported:	300 km/hr	300 km/hr
Maximum Range/ Maximum Transmitted Power	30 to 40 km/ (Compliant with FCC Licenses).	Typical coverage 90 % Of area; Requirement is -61 dBm signal contour 50% coverage 90% of time.
Multipath Spread Protection	4.46 μsec Max	5.56 μsec

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
M/H Communications Data as % of Payload	Typically 2-4 mbps allocated to M/H; Possible to allocate up to 75% (4-8 M/H data streams at 9 to 14 mbps). HD-MPEG 2 = 10-14 mbps of 19.4 mbps. Protocol and Program Guide = 0.5 mbps	Same
Receiver Sensitivity	-95 dBm	-95 dBm
Selectable Bandwidth, Modulations and Data Rates to accommodate reliable communications with noise	8-VSB Physical Layer, 19.4 mbps, 6 MHz BW (Symbol rate = 10.76 mbauds); OFDM Modulation for M/H. 19.2 mbps bit stream allocated to both fixed and mobile	Same
BER at Specified SNR	7 dB SNR for M/H TV Signal Reception (15 dB for Fixed TV); BER 3E-6 or SER=2.5 packets/sec for a 20 sec duration. PER specified as 1.9E-4	3E-5 to 8.9E-6 in Field Test at Receiver Specified SNR
Probability of Error Free Message Delivery within 4 msec based on SPaT Short Message	99.99%	Same
Latency	Processing Delay= 84 to 156 msec; Xmit delay 2.4 sec in 1 μsec steps;	Same
Signal Timing	M/H Slot = 12.2 msec; M/H Subframe = 193.6 msec and M/H Frame = 968 msec. (GPS Reference at 1 and 10 Hz)	Same
Adjacent Channel Interference Protection	-60 dB	Same
Quality of Service	3E-6 BER	3E-5
Availability	99.998%	Same
Current Design Vehicle Environmentally Compatible	Not SAE Standards Compliant but Advertised for Vehicle Applications	Yes
Equipment Approximate Size /Weight for Mobile Applications	180,048 cu mm (10.1 cu in); 102 g (0.22 lbs.)	Same
Equipment Approximate Power Load for Mobile Applications	300 mA / 12 VDC	Same
Approximate Cost of Mobile Unit	$200	Same

Source: ARINC April 2012

3.2.5 *Digital Terrestrial Broadcast Radio*

Hybrid Digital Radio (HD Radio) is a digital broadcast radio technology to transmit audio and data on either AM or FM channels. HD Radio, officially known as NRSC-5 with the latest revision NRSC-5B, was selected by the US Federal Communications Commission (FCC) in 2002 as a digital audio broadcasting method for the United States; it is the only digital system approved by the FCC for digital AM/FM broadcasts in the United States. It is also referred in as In-Band On-Channel (IBOC), which is the name provided by iBiquity Digital Corp., which developed the system approach and basic specifications. Figure 3.2-60 illustrates representative products and Figure 3.2-61 summarizes the high-level performance specifications of HD Radio.

Figure 3.2-60. Examples of HD Radio Devices

(Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

Specifications

Power Requirements	12Volt DC (10-16 Volts DC)
Receiver Dimensions	127mm x 52.3mm x 25.2mm (W x H x D) (5" x 2-1/16" x 1" (W x H x D))
Mass (approx.)	121g (0.266 lbs) (excluding accessories)
Remote Control Dimensions	50mm x 90mm x 9mm (W x H x D) (2" x 3-9/16" x 3/8" (W x H x D))
FM Receiving Frequencies	87.9~107.9MHz
AM Receiving Frequencies	530~1710KHz
FM Hybrid	-88dBm
FM All Digital	-108dBm
AM Hybrid	-90dBm
AM All Digital	-105dBm
Input	2.5 mm Jack
FM Transmission Output Interface	2.1 mm Jack
Audio Output Interface	3.5 mm Stereo Jack
Audio Output	2.8V(Peak-to-Peak) maximum
Digital Audio Total Harmonic Distortion (THD)	<0.1%
Digital Audio Stereo Separation @1KHz	>70dB

Figure 3.2-61. Portable HD Radio Tuner Specification

(Ref: Manufacturer of HD Radio Product Literature)

HD Radio is capable of transmitting in both AM and FM channels. The digital information is transmitted using Coded Orthogonal Frequency Division Multiplexing (COFDM), essentially identical to OFDM, modulation method. The audio compression algorithm is High-Definition Coding (HDC) with Spectral Brand Replication (SBR). One characteristic of HD Radio is the capability to revert the transmission to analog signal if the digital signal is lost.

The HD Radio hybrid AM mode offers two options which can carry approximately 40 or 60 Kbit/s of data when using an extended 30 kHz channel, but most AM digital stations default to the more-robust 40 Kbit/s mode using a standard 20 kHz channel, which features redundancy (same signal broadcast twice). HD Radio also provides a pure digital mode, which lacks an analog signal for fallback and instead reverts to a 20 Kbit/s signal during times of poor reception.

The HD Radio FM mode offers four options supporting different data rates of 100, 112, 125, and 150 Kbit/s, depending on the power budget and/or desired range of signal. Similar to AM mode, the FM mode also provides several pure digital options with up to 300 Kbit/s bit rate and supports fallback condition to revert the transmission to a 20 Kbit/s signal. FM stations have options to further subdivide their carrier into sub-channels of varying audio quality. Data bit rate will vary depending on the configuration of each sub-channel. See Table 3.2-25 below.

The data service supported by HD Radio has been adopted and used by many stations or advertising firms to bring rich media experience and useful data, such as real-time traffic or weather information, to the end users. The same data service may also potentially be used to support SPaT applications through the delivery of supplementary non real-time information such as geometric intersection description (GID) messages. As a digital technology used by AM and FM radio stations, HD Radio adequately supports user mobility up to vehicular speeds. Multiple automotive manufactures and aftermarket vendors have offered HD Radio-enabled vehicle radios. Low cost COTS portable consumer devices are also available. There are currently thousands of radio stations offering HD Radio signal across the US.

Table 3.2-25. HD Radio Tuner Specification in Form Factor for Automotive Installation

(Ref: Manufacturer of HD Radio Product Literature)

Tuner Section (HD Radio System Compatible)			
Frequency range	FM	With channel interval set to 100 kHz or 200 kHz	87.5 MHz to 107.9 MHz
		With channel interval set to 50 kHz	87.5 MHz to 108.0 MHz
	AM	With channel interval set to 10kHz	530 kHz to 1710 kHz
		With channel interval set to 9 kHz	531 kHz to 1602 kHz
FM tuner	Usable sensitivity		8.3 dBf (0.7 µV/75 Ω)
	50dB quieting sensitivity		14.3 dBf (1.5 µV/75 Ω)
	Alternate channel selectivity (400 kHz)		65 db
	Frequency response		200 Hz to 20,000 Hz (HD radio broadcast)
			40 Hz to 15,000 Hz (conventional broadcast
	Stereo Separation		70 dB (HD radio broadcast)
			50 dB (conventional broadcast

Tuner Section (HD Radio System Compatible)		
	Capture ratio	3.5 dB
AM tuner	Sensitivity	13 μV
	Sensitivity	80 dB
	Frequency response	40 Hz to 15,000 Hz (HD radio broadcast)
	Stereo separation	70 dB (HD radio broadcast)

Since HD Radio is a radio broadcast technology for radio stations, the specific transmission power and range depend on each station's license. In order to provide HD Radio signal, the radio stations will need to upgrade the broadcasting equipment and infrastructure. The typical conversion cost of an analog radio station to an HD Radio station is $30,000 to $200,000 (USD) per station (Ref: "Overview of HD Radio Technology"; hd-radio.com [102]) depending on transmitter power and digital data storage and retrieval system requirements. As for the end users, multiple commercial products are available, including personal portable devices, automotive radio units, marine radio units, home A/V units, etc. The cost of equipment for in-vehicle use is expected to be similar to satellite radio receivers, typically below one hundred dollars. Unlike subscription-based satellite radio services, HD radio services generally do not require subscription fees. Note that iBiquity Inc. developed the HD radio design and standards which have been accepted by FCC; they receive a royalty for use of their patents by other manufacturers (which is a common practice in the communications industry).

3.2.5.1 **Details of HD Radio**

Figure 3.2-62 presents a high level diagram of a basic HD Radio system. The studio subsystem can be co-located with the transmitter/antenna or interconnected using an optical or wireless communications link. GPS synchronization is used. Gap filler transmitters may be used by synchronizing to the primary transmitter, and providing an interconnecting communications link. Figure 3.2-63 illustrates the FCC specified mask for a Hybrid HS Radio transmitter. Table 3.2-26 illustrates the upper and lower sub bands that are utilized to support digital transmission. Each of the sub bands has 10 partitions supporting 191 subcarriers.

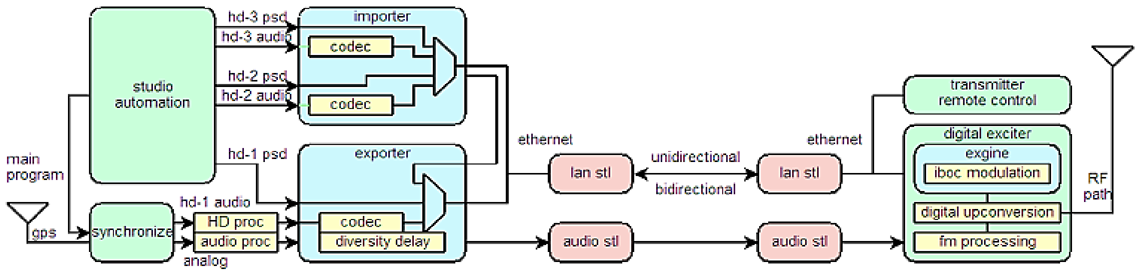


Figure 3.2-62. High Level HD Radio System Diagram

(Ref: "E2X Bandwidth and BER for Ethernet Synchronization", Philipp Schmitd [103])

Figure 3.2-64 illustrates the subcarrier configurations of Hybrid (A), Extended Hybrid (B) and all Digital HD (C) radio configurations.

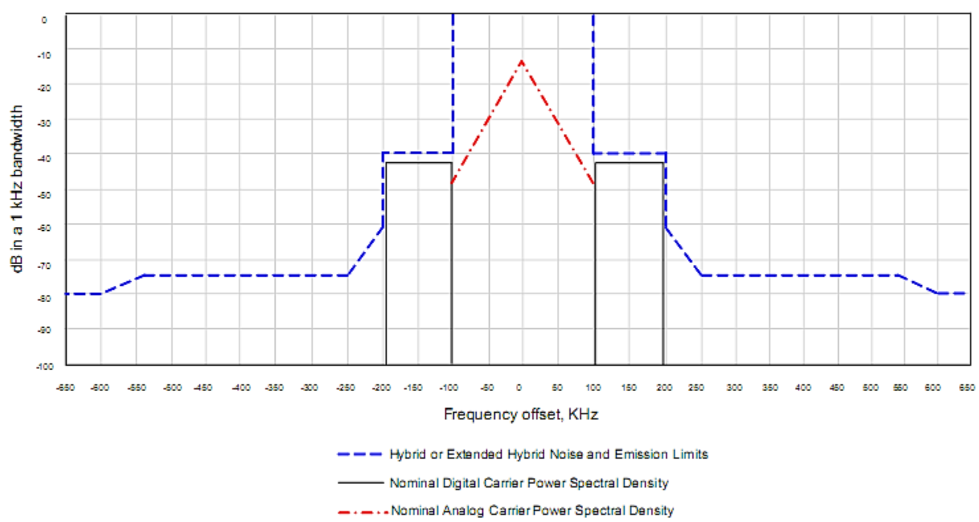


Figure 3.2-63. FCC Mask for Hybrid HD Radio Transmitter

(Ref: FCC [104])

Table 3.2-26. Upper and Lower Sidebands Utilized to Support Digital Radio Transmission

(Ref: "The Structure and Generation of Robust Waveforms for FM In-Band On-Channel Digital Broadcasting", Paul Peyla [105])

Sideband	Number of Frequency Partitions Ordering	Frequency Partition Ordering	Subcarrier Range	Subcarrier Frequencies (Hz from channel center)	Frequency Span (Hz)	Power Spectral Density (dBc per subcarrier)	Comments
Upper Primary Main	10	A	356 to 546	129,361 to 198,402	69,041	-45.8	Includes additional reference subcarrier 546
Lower Primary Main	10	B	-356 to -546	-129,361 to -198,402	69,041	-45.8	Includes additional reference subcarrier -546

Source: ARINC April 2012

Hybrid HD radios support 100 kbps data throughput with typically 96 kbps allocated to digital audio channels and 4 kbps to auxiliary data; Extended HD Radio configuration supports 151 kbps throughput with 96 kbps typically allocated to digital audio and 55 kbps allocated to auxiliary functions. The all-digital HD radio supports 300 kbps throughput with data allocated to meet applications.

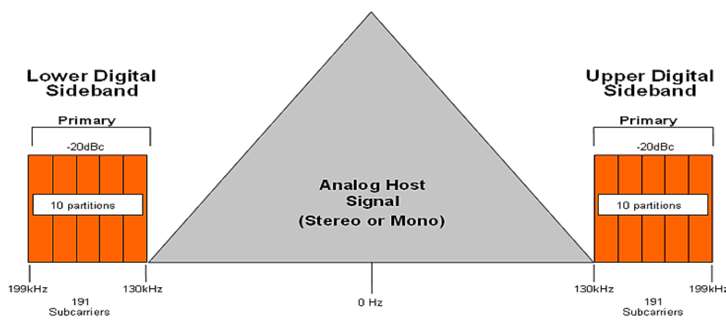
For a level 1 HD radio station, synchronization must be +- 0.01 ppm and the carrier frequency having a maximum deviation of +- 1.3 Hz (Ref: "HD Radio FM Transmission System Specifications", iBiquity Document SY_SSS_1026a [106]). Also error vector magnitude for QPSK and BPSK modulated, transmit subcarriers measured at the transmitter RF output is specified to be less than 10% averaged across all carriers and less than 20% for any individual carrier. Use of multiple subcarriers supports reception of multiple audio channels over a single frequency (typically 4). It also supports data casting, including support for ITS and navigation functions.

In a report entitled, "Digital Radio Coverage and Interference Analysis Project: Single Frequency Network Report # 6.1.4", (Jan. 21, 2008, National Public Radio) [107], it is pointed out that that the HD radio modulation provides Doppler protection up to 22 Hz and provides a guard interval of 156 μsec for multipath spread. This supports vehicle speeds to 120 km/hr (75.6 mph). A HD Radio test report entitled, Digital Radio Coverage and Interference Analysis Project: "Report on Potential Effects of Urbanization on IBOC DAB Reception, # 6.1.7", (National Public Radio, Jan. 31, 2008) [108], presents the HD radio block error versus carrier to noise radio, which indicates signal strengths required for reliable reception of data with multipath fading and in the presence of Gaussian noise. The National Public Radio DH Radio covered 48 km radius from the transmitting station and the report stated that 100% coverage of the area was not possible due to terrain.

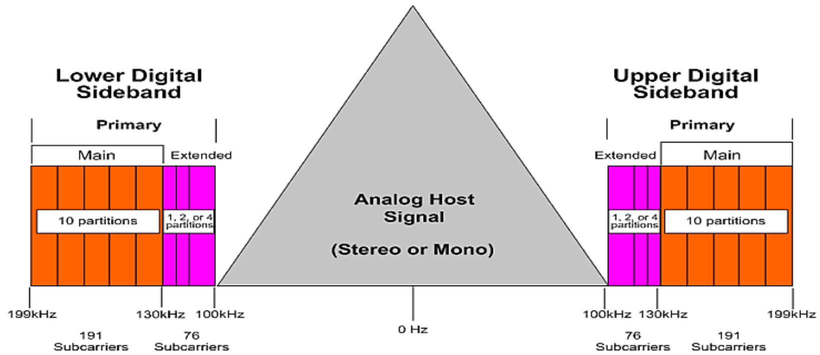
One of the major issues of AM broadcast radio is the noise floor (over 3 times that of FM band in urban areas). AM band noise significantly increases at night, impacting performance of HD FM Broadcast radio. The urban canyon application will have considerable multipath, with perhaps no direct path signal.

In an article, “What is HD Radio Broadcasting?”, (www.ibiquity.com/hd_radio) [109], it states: “Today, HD Radio™ is available or has been announced to be available on 17 different brands of new vehicles. ---- These announcements represent 109 different vehicles with HD Radio Technology, a total of 54 which will come with HD Radio Technology as a standard during 2011.” Terrestrial HD Radio has been competing with satellite, digital radio and car manufacturers were offering satellite radios with new vehicles rather than HD Radios. While satellite radios have the advantage of much broader coverage, the service fees and performance during harsh weather conditions has perhaps changed the market. Most travelers stay within a 50 km radius of where they live and the performance of HD Radio, with no fee for service, meets their needs. In the rural areas, there are a limited number of HD Radio stations, which provides an advantage to satellite radios.

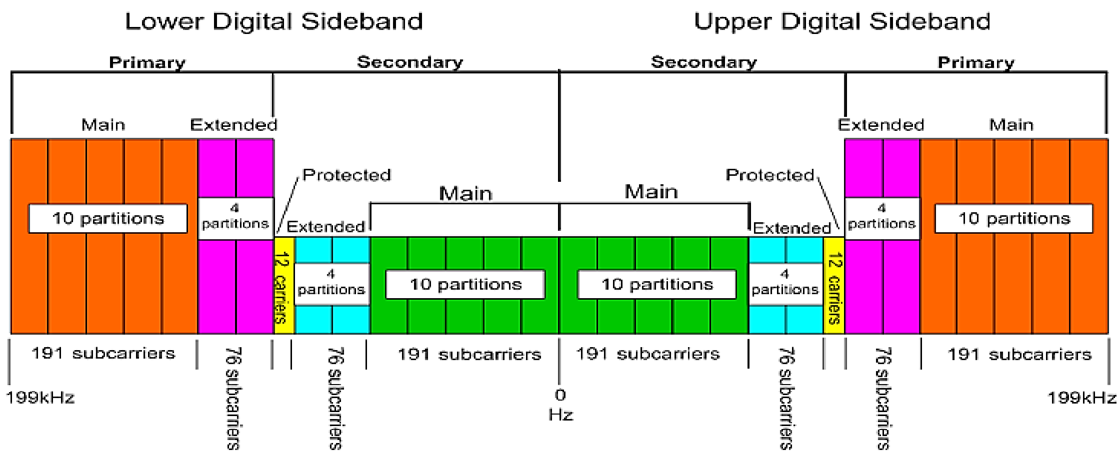
In summary, the COFDM modulation provides some protection against both multipath and Doppler spread. Area coverage is a function of radio station license and allowed EIRP by FCC under the license, and 100% coverage will require, distributed “gap filler” transmitters that are all synchronized. AM broadcast radio experiences significant interference at night due to signal impact of the ionosphere. During daytime, AM radio signals (due to their longer wavelength) reflect off the D Layer; however, at night the waves reflect off the F Layer, thus expanding their transmission range. Interference at coastal areas is even worse due to signal ducting over water. FM Stations would be preferred to support ITS applications.



A) Hybrid HD Radio: 100 kbps (96kbps Audio and 4 kbps aux data)



B) Extended Hybrid HD Radio: 151 kbps (96 kbps audio and 55 kbps digital aux data)



C) Full digital HD Radio: 300 kbps allocated to meet applications (Best Configuration for ITS)

Figure 3.2-64. Subcarrier Configurations in HD Hybrid, Extended Hybrid, and All Digital HD Radios

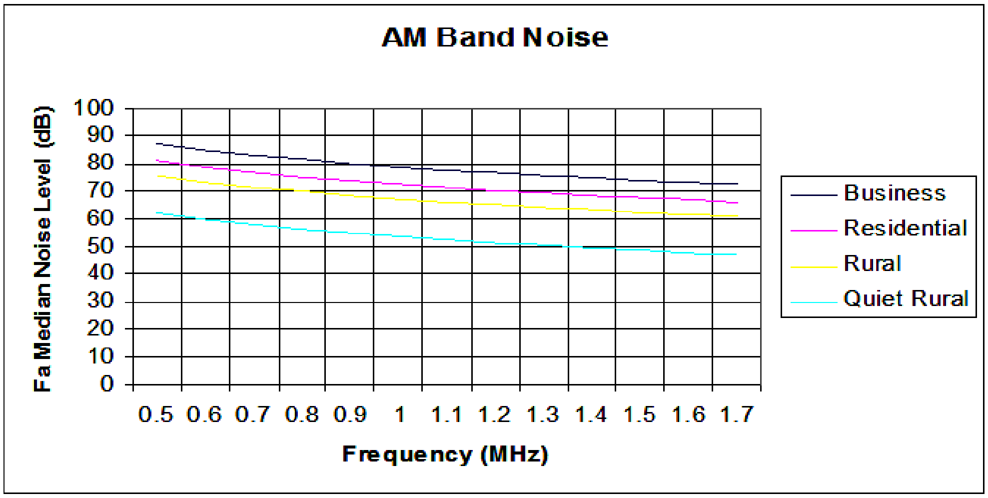
(Ref: "Digital HD Radio AM/FM Implementation Issues", Charles Kelly [110])

3.2.5.2 HD Radio Support for ITS

FM digital sub band communications using both radio and TV stations was one of the first ITS I2V communications links through use of FM sub band technology. This technology has been available since the early days of the ITS initiative. There were several problems with the early radio data service: (1) Limited Intelligence in vehicles; (2) Limited data rate of using a FM sub band; (3) Cost of high speed FM sub band vehicular communications at the time. With interest in I2V communications and vehicle safety plus the emergency of higher performance HD Radio supporting digital audio and data services, the business case has changed. HD Radios with capability to support the driver's need for quality audio (music and news), plus also receiving safety information during travel, are becoming a standard part of vehicles and they are being purchased (considered affordable and beneficial by users). Thus it is appropriate to consider HD Radio for meeting SPaT application needs.

HD Radio does not support bi-directional communications. It can support infrastructure to vehicle communications. Full regional coverage is probably not achievable nor a high priority of broadcast radio stations. Typical coverage listed by NTIA for radio station is around 95% of an urban area. According to

Radio World, the number of licensed radio stations in the USA is over 14,000, including 4736 AM stations (36%), 6309 FM stations, 2892 educational FM stations and 831 low power FM stations. In the mid 1990's there were 11,000 radio stations with 43% AM. Figure 3.2-65 shows a comparison of AM and FM band noise levels. Table 3.2-27 shows the results of tests of testing of IBOC fading performance in urban environments under different fading conditions.



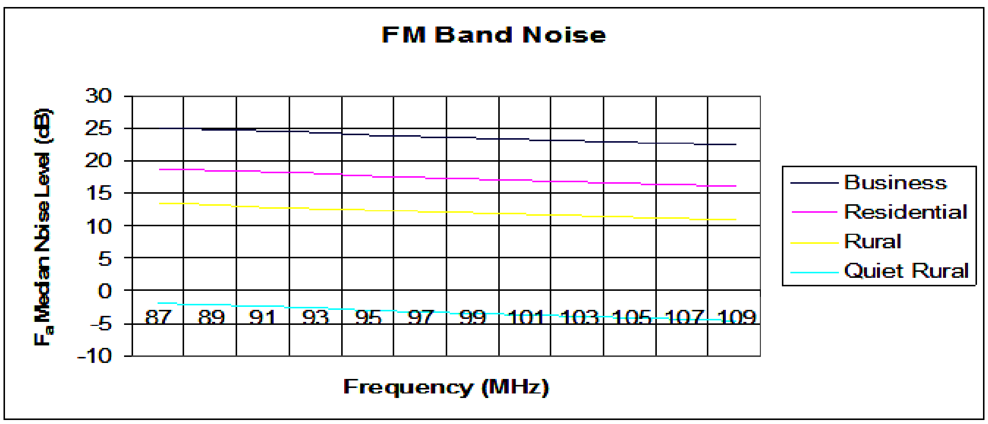


Figure 3.2-65. Ambient RF Noise in the AM and FM Radio Bands for Different Locations

(Ref: "Implications of Increasing Man Made Noise Floor Levels on Radio Broadcast", Charles Kelly Jr. [111])

Table 3.2-27. National Public Radio Test Results: Carrier/Noise versus Block Error Rate

(Ref: "Report on Potential Effects of Urbanization on IBOC DAB Reception, # 6.1.7", National Public Radio, Jan. 31, 2008 [108])

Test	Cd/No (dB-Hz)	Fading Type	Block Error Rate	Δ Gaussian (dB)
Gaussian Noise (No Fading / Interference)	54.1		0.16	
	54.5		0.032	
	55.1		0.0029	
9-Ray Fading	55.4	Urban Fast	0.8	
	56.4		0.056	
	57.3		0.012	2.2
	59.3	Urban Slow	0.106	
	60.4		0.054	
	61.4		0.0202	6.3
	55.9	Rural Fast	0.6	
	56.8		0.087	
	57.8		0.007	2.7

According to Rural Radio Network, approximately 75% of the rural farms are covered by terrestrial radio service in the North East part of the USA. Statistics on percent coverage of rural farm areas in states like Texas and Wyoming and Montana were not available; however, it is most likely significantly less than a state like NY which does have 75% coverage. FCC, NOAA and USDA have been encouraging rural radio station deployment, especially to provide weather information and disaster warnings to rural population.

There are two approaches to using HD Radio to support SPaT applications. One is to deploy a jurisdictionally owned HD Radio station. This has been previously done (example: WHMI; 935 FM;

Livingston County, MI) and the FCC has provided jurisdictional approval for the deployment of FM Highway Advisor Radio (HAR) Stations. The second approach is to develop public/private partnerships where an HD Radio station provides public service broadcast of traffic safety information at no cost to the jurisdiction. The jurisdiction would fund any modification cost required to the station to support broadcast of traffic data. Figure 3.2-66 illustrates the use of an HD Radio station to support broadcast of traffic related information to vehicles. With a jurisdictionally owned HD Radio station (all digital), up to 300 kbps could be transmitted to the vehicle.

HD Radio could easily provide a cost effective way to deliver SPaT and GID messages to vehicles. A jurisdictionally deployed, all digital HD Radio sporting 300 kbps of data would support the data distribution requirements of most medium size cities. Distributed transmitter configurations would support larger city coverage, based on needed data rate for footprint of coverage (i.e., the number of signalized intersections within the footprint). Jurisdictions are familiar with Highway Advisory Radio technology (typically AM but FM has had FCC approval) and the technology is reasonably priced (under $50K, considering availability of a jurisdictional tower; Low power HD Radio transmitters are available for under $20K based on quotes from manufacturers received under this project).

The key issue for SPaT delivery will be latency. The SAE J2735 standard defines that SPaT messages must be sent every 100 msec. However, an analysis of the application requirements indicates that repeat rates could be far lower, depending on how the application uses the messages. SPaT communications requires around 40 Kbps per intersection; for GID and other less time critical data, 3 Kbps per intersection is required. Considering a data load of 3K bits per intersection, an FM all digital HD radio footprint will support approximately 100 intersections repeated every 1 sec. It could also service 7 intersections with all SPaT related data transmitted every second (which does not comply with timing requirements of SAE J2735). If non-time critical SPaT related data could be transmitted every 5 seconds (every 330 ft of travel by a vehicle traveling at 45 mph), then 500 intersections could be supported by HD FM All Digital radio or 1000 with a 0.1 Hz intersection broadcast rate. This is easily sufficient for statically timed intersections (fixed timing plan that perhaps changes at specific time of day/day of week, but it is not usable in the more common dynamic timed (traffic responsive) intersections. To consider this situation we need to consider the impact of a timing change. Today, a timing change is accompanies by a yellow/red cycle time, since once the timing change is decided, the system must turn the current through phase to yellow, allow vehicles to clear, go to an all red phase and then start the new timing sequence. Under a typical cycle the signal timing change is communicated instantly to the driver via the signal lights. Thus the maximum allowable latency is the tolerable increase in time between when a change is decided and when it is implemented. This additional time is required to allow the revised SPaT message to be sent. Obviously adding 5 to 10 seconds to the timing sequence is unrealistic; so unless some other priority scheme is used, or unless the number of signals served by an HD radio system is substantially reduced, the HD system can only be used for more slowly time varying messages such as GIDs, RTCM and roadside safety messages.

An Extended Hybrid HD Radio supports 24 kbps per digital audio channel plus 55 kbps of data; possibly one audio channel and 15 kbps of the data channel could be provided for jurisdictional use, accommodating 39 kbps for safety. An Extended Hybrid HD Radio supports 24 kbps per digital audio channel plus 55 kbps of data; it is questionable if a public/private partnership could be developed allowing public use of adequate bandwidth to support SPaT related functions. Implementation of this system in vehicles would require an all-digital, dedicated radio for the vehicle, which is an adaptation of current technology and would be much smaller than the conventional hybrid. Production cost of an all-digital, HD Radio receiver is estimated to be under $150.

In summary, HD Radio technology provides high percentage coverage of urban and suburban areas and perhaps 50 to 75 percent coverage of rural areas with population. Cost of using this technology is comparatively low. ITS has a precedence of using FM sub-band as well as HAR to communicate with vehicles. The cost is lower than using mobile TV stations and receivers are affordable by purchasers of vehicles. This technology should be considered as a possible technology to offload DSRCs of less time critical data.

A summary of HD Radio specifications and field test results is presented in Table 3.2-28.

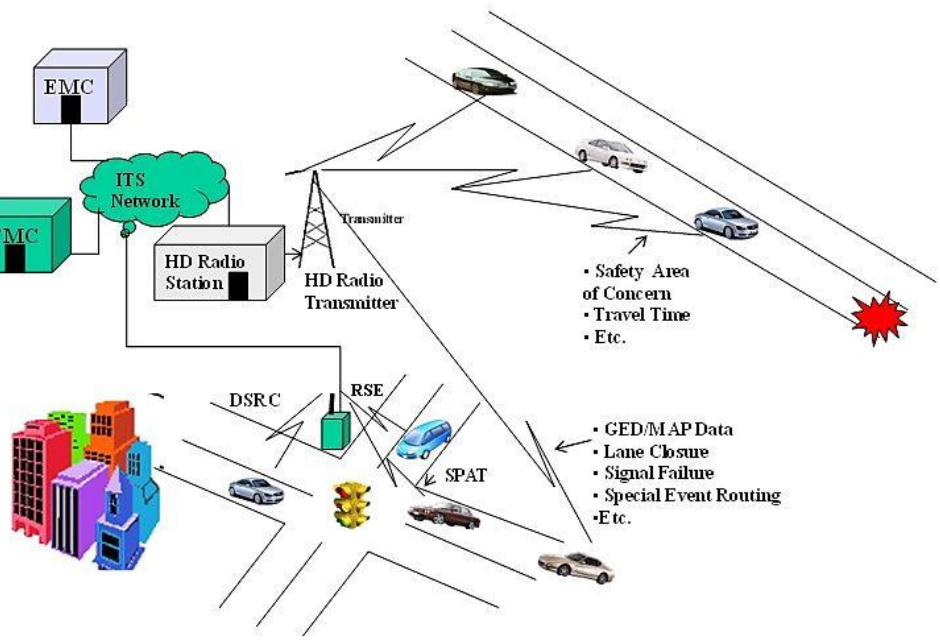


Figure 3.2-66. HD Radio Station Supporting Broadcast of Digital Traffic
Source: ARINC April 2012

Safety Information to Vehicles, Including GID

Table 3.2-28. Summary Specifications (Published and Test Results) for HD Radio

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
Applicable standards	National Radio System Committee, NRSC-5B (all digital)	Same
Link Access	OFDM	Same
Simplex, half duplex, or full duplex service	Simplex	Same
Frequency Band and Licensing	AM: 535 to 1610 kHz (extended band: 1610 to 1710 kHz) FM Broadcast Frequencies (87.9 to 107.9 MHz;	Same

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
	Licensed)	
Channel Bandwidth	AM: 20 kHz (extended channel: 30 kHz) FM: 100 KHz, requiring 200 KHz of Spectrum	Same
Wireless Mobility with Velocities Supported:	120 km/hr	120 km/hr
Maximum Range/ Maximum Transmitted Power	30 to 40 km/1 to 50 KW (Compliant with FCC Licenses)	Same
Multipath Spread Protection	156 μsec Max	Same
Communications Data Rates (Peak)	300 kbps (Digital HD Radio)	Same
Receiver Sensitivity	45 dBu	50 – 75 dBuV
BER at Specified SNR	10^{-4}	3E-5 to 8.9E-6 in Field Test at Receiver Specified SNR
Latency	17 msec typical (3 – 80 msec)	Same
Signal Synchronization	OFDM symbol clock frequency will be maintained to within 1 part per 10^{8}	Same
Adjacent Channel Interference Protection	AM: 1st adjacent station to be no less than 6 dB below the desired station FM (Desired to Undesired D/U): Co-channel: 20 dB 1st Adjacent: 6 dB 2nd Adjacent: -40 dB 3rd Adjacent: -40 dB	FM: Hybrid to Analog Co-channel: 38 dB D/U 1st Adjacent: 3 dB D/U 2nd Adjacent: -42 dB D/U 3rd Adjacent: -43 dB D/U FM: Hybrid to Hybrid Co-channel: 2 dB D/U 1st Adjacent: -29 dB D/U 2nd Adjacent: -64 dB D/U
Quality of Service	PER < 0.01%	Same

Communications Specification	Performance Value Per Specification	Typical Field Test Performance
Availability	99.998%	Same
Current Design Vehicle Environmentally Compatible	Yes	Yes
Equipment Approximate Size /Weight for Mobile Applications	1573 cu cm (85 cu in); 0.54 kg (2.2 lbs.)	Same
Equipment Approximate Power Load for Mobile Applications	1.42 Amp/12 VDC	Same
Approximate Cost of Mobile Unit	$150	Same

Source: ARINC April 2012

Chapter 4 - Advanced Wireless Communications

Several platforms for realizing SPaT applications and infrastructure to vehicle communications are slowly being introduced. Typically, the devices are in compliance with the 802.11p WAVE standard with higher guard intervals at the physical layer for robustness in mobile scenarios. Communication in scenarios with mobile vehicles is increasingly complex and hard to characterize due to factors such as multipath from reflections off other objects, vehicles and buildings, Doppler, and interference. Undulations on the roadway and hills also have a significant bearing on the propagation characteristics. Specifically, the communication characteristics are NLOS and radio propagation models (e.g., Hata) do not capture the vehicular environments. Furthermore, possible application offerings such as safety, traffic signal timings etc. have vastly different Quality of Service (QoS) needs, and several ideas have been proposed to support the broad variety of application requirements. For example, the need for antenna design in order to support multiple, active communications devices on a vehicle have been considered including plans to support 2 DSRC transceivers on a vehicle; one for safety and one for services. SMART antennas or sector beams may also be applicable at urban intersections so as to provide maximum coverage for vehicles on the roadway.

In parallel, significant efforts have been made to test the performance of available equipment in such communication scenarios, and to evaluate the efficacy of the DSRC system in infrastructure to vehicle scenarios including the influence of urban canyons etc. Based on the testing results, various techniques to enhance the performance of the physical layer and MAC layer operations have been considered and proposed. This section provides a brief overview of the efforts in these directions.

Several advanced wireless communication technologies that may be crucial for the eventual success of SPaT applications have been described. Due to the challenging communication environment, a multi-faceted approach needs to be taken for developing communication systems for roadway environments. Four complementary advanced technology areas have been discussed that include antenna technologies, Cognitive and Software-defined Radio, Connected Radio, and advanced modulation techniques and protocols. These advanced communication technologies are still under research and development, but have been identified as potentially beneficial to SPaT applications. The section on antenna technology provides an overview of antenna technology and their performance in the context of vehicular environment, smart antennas and MIMO systems. The section on cognitive and software-defined radio outlines the technology and its potential application to SPaT messages. In the section on Connected Radios, we describe supporting protocols for ad-hoc vehicular communication including V2V communication. Such communication may be helpful in increasing the reach of SPaT messages through relaying; however, relay adds both latency to the message and increases the load on the wireless communications link. The section on protocols and modulation describe recent communication protocols developed for vehicular networking keeping in mind the importance of location. Newer modulation techniques for DSRC-based systems are also discussed.

In summary, given the challenging conditions and the stringent requirements due to safety considerations, a combination of the advanced techniques can assist in the eventual success of SPaT applications.

4.1 Antennas

Antenna technology for communication with vehicles is a topic of significant interest due to the unique nature of communication environment. Due to the diverse nature of communication needs including GPS, Cellular and short-range communication, various antenna systems have been developed for installation on the vehicle. Under the European ITS (Ref: “CVIS Project”, http://www.cvisproject.org [112]), an integrated antenna prototype has been developed (Figure 4.1-1). The system includes GPS, 2G/3G and antennas for DSRC system. Significant mobility and the presence of large objects such as buildings, trucks and vehicles have a significant bearing on communication performance achieved. Advancements in antenna system could lead to improved delivery of SPaT messages due to enhanced coverage, efficient use of spatial diversity and reduced channel contention. Mindful of this, several measurement campaigns have been performed to verify the efficacy of existing systems to characterize the communication performance in terms of received signal strength, packet errors, range etc.

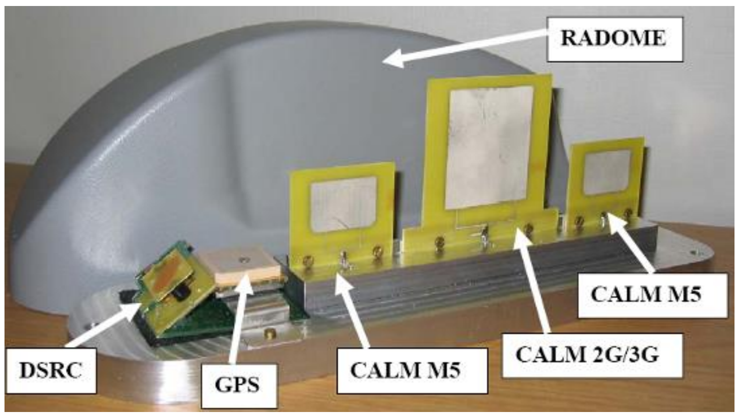


Figure 4.1-1. Multiple Antenna Systems for Vehicles

(Ref: “CVIS Project”, http://www.cvisproject.org [112])

An evaluation effort for a UHF band prototype for roadside to vehicle communications performed in an urban canyon yielded insightful results (Ref: “Field Evaluation of UHF Radio Propagation for an ITS Safety System in an Urban Environment”, S. Sai, et al, *IEEE Communications Magazine*, 2009 [113]). The experiment used varying antenna heights (1.8 m (6 ft.) and 5 m (16.4 ft.)) at 800MHz and a bandwidth of 8.5MHz. The results (see Figure 2.4-2 in previous section) show vastly different performance based on the number of intersections encountered. In particular, the packet reach is greatly reduced as the number of intersections increased regardless of the actual distance. As observed in Figure 2.4-2, the packet range is higher along horizontal lanes than the vertical lanes. This highlights the influence of edge-diffracted waves on communication performance. Measurements have also been performed in urban areas to calibrate the communication range for DSRC as the transmission power is varied. The maximum radiated power for DSRC stipulated by the FCC is 33 dBm. The reference (Ref: “Characterization of DSRC Performance as a Function of Transmit Power”, Hong, et al, *Proceedings of VANET 2009* [114]) demonstrates that the packet error rate rapidly falls off beyond a range of 100 meters (see Figure 4.1-2).

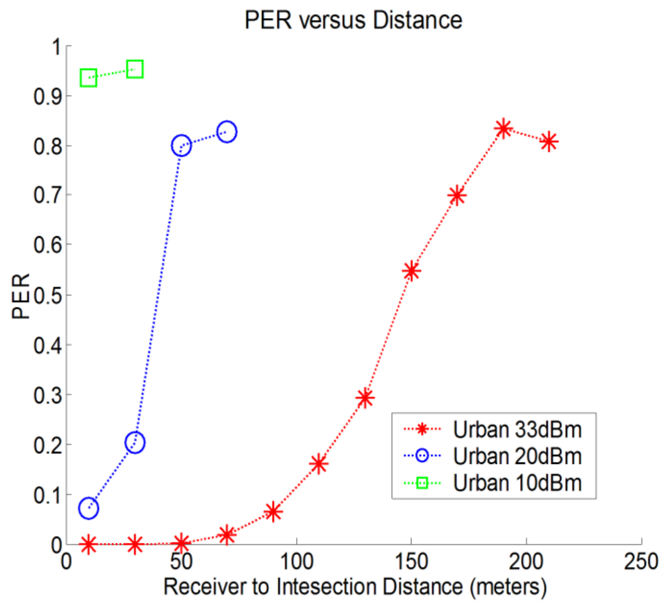


Figure 4.1-2. Urban area: Range and Packet Error Rate for Varying Power

(Ref: DSRC Transmit Power: "Characterization of DSRC Performance as a Function of Transmit Power", Hong, et al, *Proceedings of VANET 2009* [114])

In a research report entitled, "Effect of Antenna Placement and Diversity on Vehicular Network Communications", by S. Kaul, et al (Rutgers University) [115], the link performance based on various mounting locations of antennas on a vehicle was explored as well as use of multiple antennas for diversity. Figure 4.1-3 illustrates the mounting location of vehicular antennas. Tests were conducted at 5.18 GHz, 6 Mbps, 56 byte packets and a packet transmission rate of 1 KHz. The test illustrate that antenna mounting location on a vehicle can impact Cumulative Percentage Packet Error (CPPE) by as much as 20% and using a dual antenna with diversity (IEEE802.11n approach), an improvement in CPPE of 15% can be achieved as shown in Figure 4.1-4 (antenna placement per Figure 4.1-3). This is because:

- Antenna mounting location and associated ground plane impacts antenna pattern, thus changing the gain/direction characteristics (See Figure 4.1-5 and 4.1-6 with antenna placement as shown in Figure 4.1-3);
- Multiple antenna diversity using MIMO reduces interference and enhances SNR thus reducing BER and PER (Figure 4.1-6);

The research further illustrates the distortion of the vehicular antenna pattern caused by ground plane differences and antenna interaction.

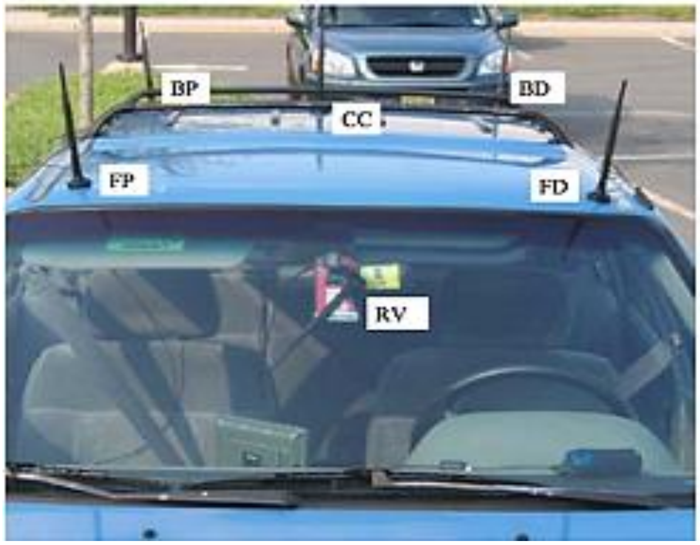


Figure 4.1-3. Antenna Mounting Locations of a Vehicle Supporting Communications Link Testing

(Ref: "Effect of Antenna Placement and Diversity on Vehicular Network Communications", by S. Kaul, et al, Rutgers University [115])

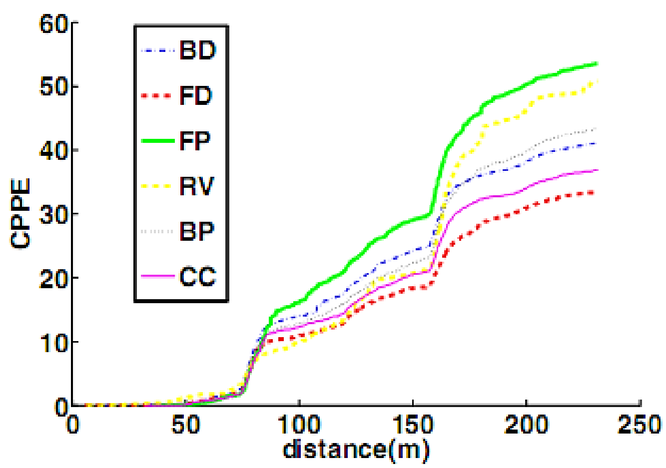


Figure 4.1-4. Cumulative Percentage Packet Errors (CPPE) Versus Communications distance and Various Vehicle Antenna Mounting Locations with no Diversity at Livingston Test Site

(Ref: “Effect of Antenna Placement and Diversity on Vehicular Network Communications”, by S. Kaul, et al, Rutgers University [115])

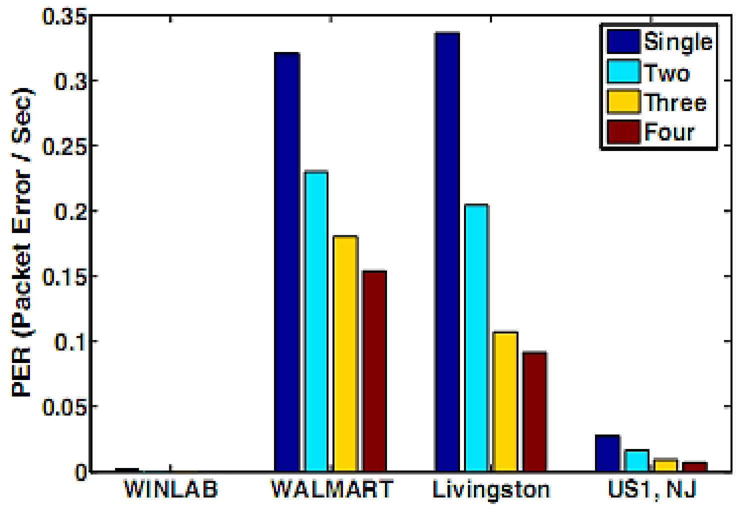


Figure 4.1-5. Cumulative Percentage Packet Errors (CPPE) Versus Communications distance and Various Vehicle Antenna Mounting Locations with Diversity and at Several Test Locations

(Ref: “Effect of Antenna Placement and Diversity on Vehicular Network Communications”, by S. Kaul, et al, Rutgers University [115])

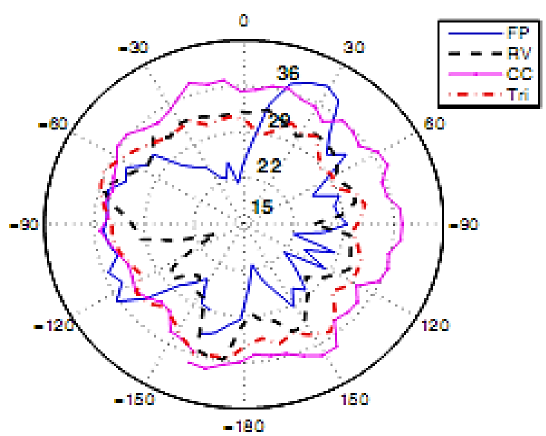


Figure 4.1-6. Horizontal Antenna Pattern Changes Based on Antenna Mounting Location on a Vehicle (5.88 GHz)

(Ref: “Effect of Antenna Placement and Diversity on Vehicular Network Communications”, by S. Kaul, et al, Rutgers University [115])

The Research report, “Novel Antenna Configuration with Wireless Broadband Vehicular Communications”, by Andrew Nix, David Halls, et al, University of Bristol (*2010 Sixth International Conference on Wireless and Mobile Communications*) [116], presents test results comparing various types and mounting locations of vehicular antennas as well as use of diversity. Without MIMO throughput received over the DSRC was an average of 700 kbps as shown in Figure 4.1-7. Figure 4.1-8 illustrates the link performance improvement using MIMO.

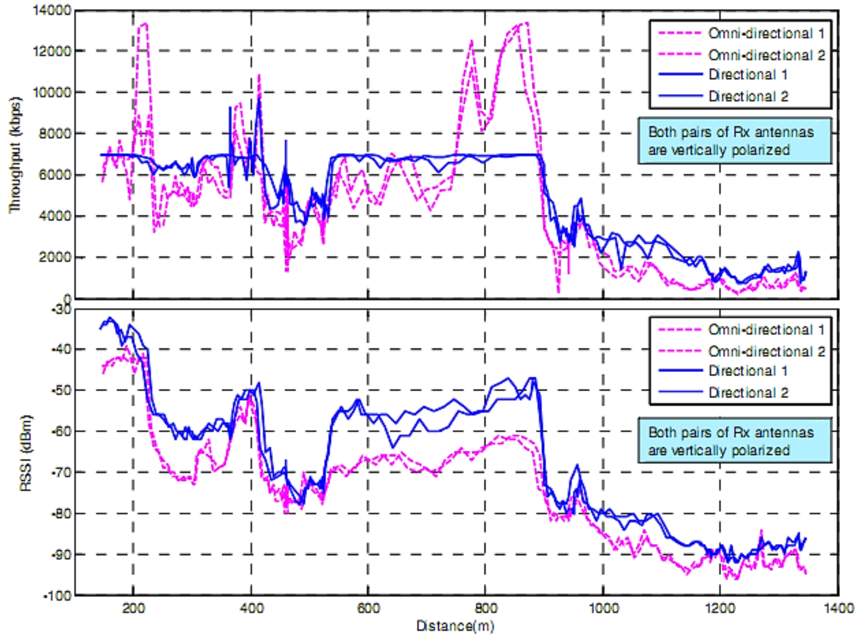


Figure 4.1-7. Link Performance Using Different Types of Omni and Directional Vehicular Antennas

(Ref: “Novel Antenna Configuration with Wireless Broadband Vehicular Communications”, Andrew Nix, David Halls, et al, University of Bristol, *2010 Sixth International Conference on Wireless and Mobile Communications* [116])

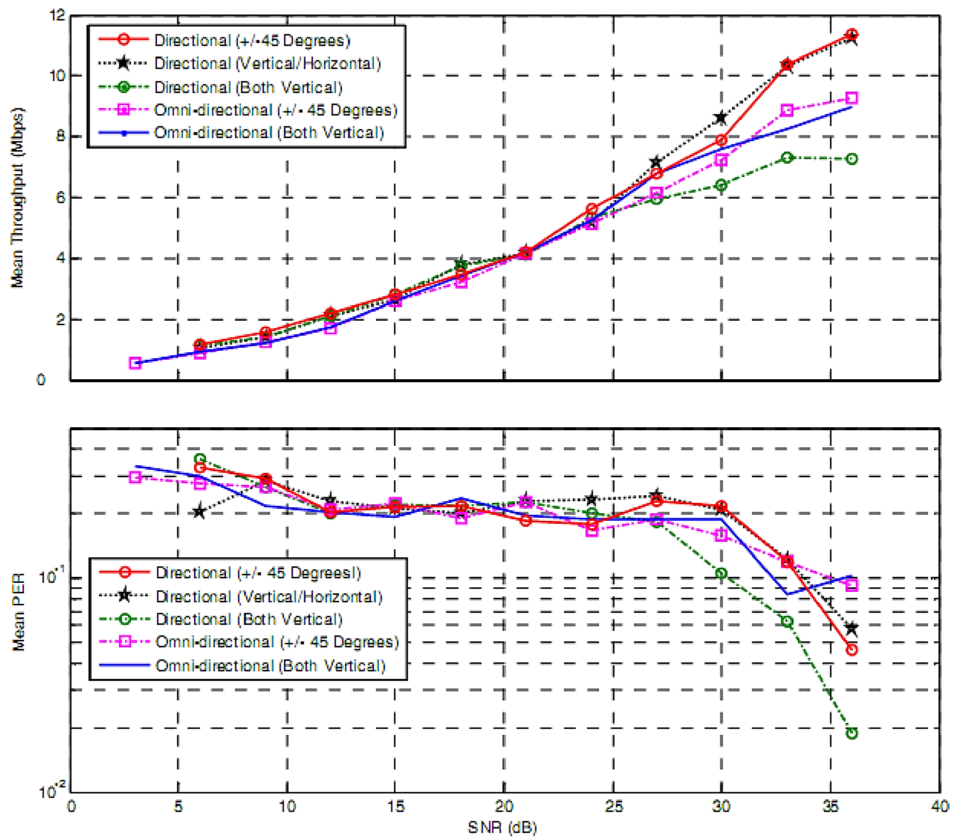


Figure 4.1-8. Link Performance Using MIMO and Different Types of Omni and Directional Vehicular Antennas

(Ref: "Novel Antenna Configuration with Wireless Broadband Vehicular Communications"*;* Andrew Nix, David Halls, et al, University of Bristol, *2010 Sixth International Conference on Wireless and Mobile Communications* [116])

Today's antenna design capability allows antennas to be developed with beam patterns tailored to the geometry of the application. Basically, at a signalized intersection in an urban environment with buildings along both sides of intersection corridors, it is possible to use a cloverleaf antenna pattern, which minimizes creation and reception of multipath signals. Similarly, with hundreds of unlicensed band emitters in buildings with harmonics that are within the DSRC band, cloverleaf pattern may reduce reception of these signals. Figure 4.1-9 illustrates a cloverleaf antenna pattern developed by a company in Europe. This antenna has rapidly reducing gain beyond that required for corridor coverage (and as compared with a sectorized horn antenna). Antenna systems such as the cloverleaf may help to improve results at intersections as compared to observations in Figure 4.1-2 which are performed using an omni-directional antenna system. This is because the transmission energy can be focused in the direction of the roadways and the vehicles can achieve a better signal to noise ratio for reception. Additionally, focusing energy using a cloverleaf antenna may also help to mitigate spurious reflections from surrounding objects further enhancing the reception. Consequently, better dissemination of SPaT messages from intersections to vehicles would be possible.

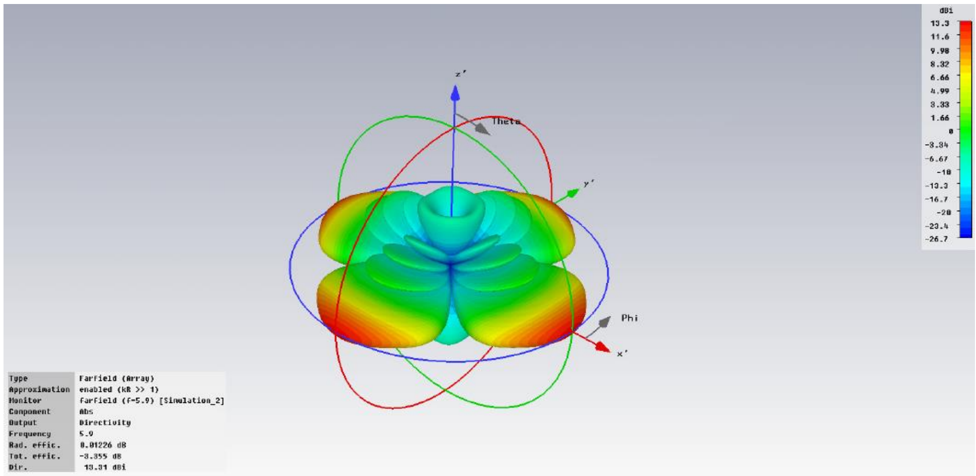


Figure 4.1-9. Clover Leaf Antenna for Roadside Intersections

(Ref: Major Antenna Manufacturer's Published Product Specifications)

SMART Antenna systems have been considered to achieve better adaptability to the wide variety of situations expected for infrastructure to vehicle communication. The systems incorporate direction of arrival (DOA) estimation and beam forming and can improve communication in urban intersection areas.

There are two types of smart antennas. One is a switched beam system that has several available fixed beam patterns. A cognitive radio makes the decision as to which beam to access, at any given point in time, based upon the application function being performed, and established policies of operation. The second type is an adaptive array that supports antenna beam steering in the direction of interest while simultaneously nulling interfering signals. Antenna beam direction is determined by received signal analysis and use of direction of arrival (DOA) techniques. Spatial information processing also includes Spatial information coding, diversity coding as well as beam forming. Using DOA and identification of any interfering signals, smart antenna control circuitry optimizes the directional and gain characteristics of the antenna, thus enhancing performance of the radio.

Figure 4.1-10 illustrates beam forming to enhance communications performance.

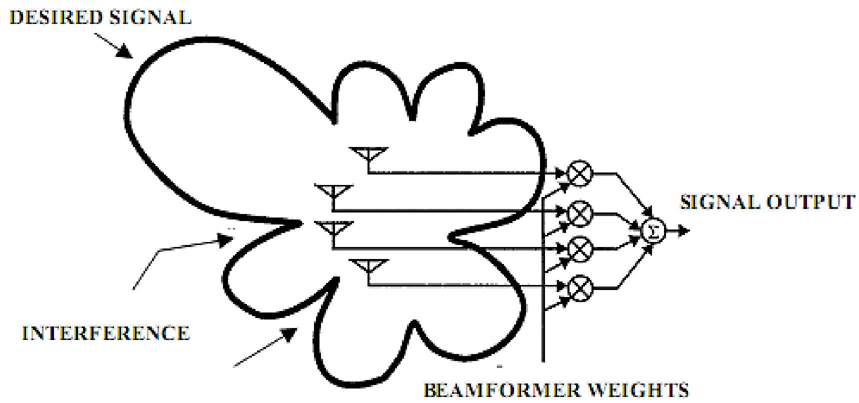


Figure 4.1-10. Example of SMART Antenna Beam Forming

(Ref: “SMART Antennas”; Jack Winters [117])

SMART antennas have several benefits as compared (Table 4.1-1) to conventional antennas (omni-directional and sectorized):

- Supports greater cell coverage for each cell;
- Supports improved rejection of co-channel interference;
- Supports reduction of delay spread by reducing multipath paths;
- Can enhance frequency reuse;
- Supports longer range coverage in rural areas;
- Can be used to support special emergency communications requirements;
- Supports improvement in data rates by enhancing signal strength and reducing interfering noise;
- Supports improvement in BER and PER.

Table 4.1-1. Comparison of SMART Antenna Technology

(Ref: “SMART Antennas and Space-Time Processing”, Jens Baltersee [118])

Multiple Antenna Approaches	Diversity	Switched Beam Forming	Adaptive Beam Forming	MIMO
Pro	Simple to implement and supports multipath protection	Simple to implement	High capacity and reduced interference	Supports high data rates
Pro	Low cost	Low cost	Best for LOS applications	Best for rich scattering environment

Multiple Antenna Approaches	Diversity	Switched Beam Forming	Adaptive Beam Forming	MIMO
Con	Limited benefits and configuration flexibility	Limited configuration flexibility	Medium Complexity; Cost	High Complexity; Cost

Multiple Input Multiple Output (MIMO) communications methods further rely on rich multipath channels to provide multiple parallel data pipes. The system utilizes multiple antennas at both the sender and the receiver (Figure 4.1-11). Each of the receiver's antennas obtains copies of the signal that have traversed over multiple paths from each of the sender's antennas. The decoding is achieved through spatial signal processing in receiver channels. The receiver estimates the channel matrix H (Figure 4.1-12). The matrix H can be inverted and used to retrieve the original signal from the received signal.

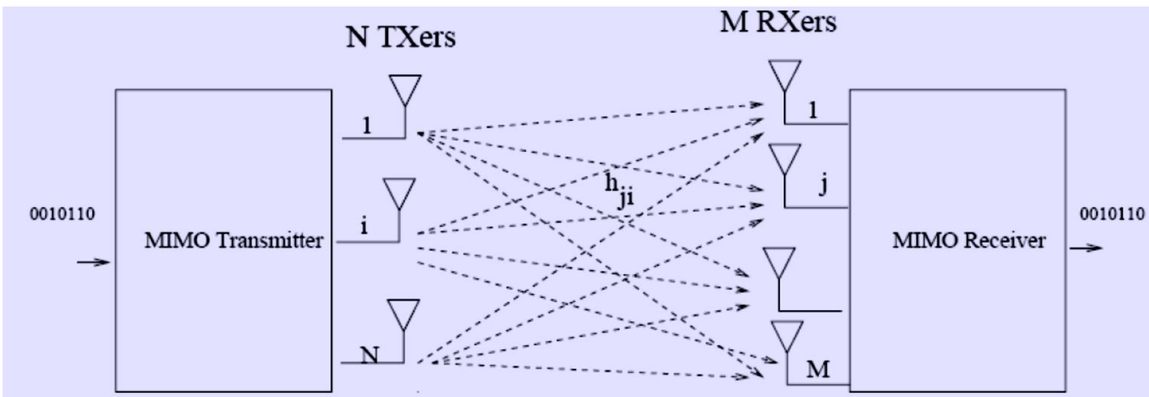


Figure 4.1-11. Multiple Sending and Receiving Antennas with h_{ji} as the Gain between Antenna j and i

(Ref: Bharadwaj, Rishi et al, *MIMO Antennas for 802.11n Based WLAN Systems*, www.antenna.com. [119])

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \\ h_{41} & h_{42} & h_{43} \end{bmatrix} \qquad \begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \\ \hat{b}_3 \end{bmatrix} = \mathbf{H}^{-1} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

Figure 4.1-12. The Matrix H is Estimated at the Receiver for Decoding the Received Signal B to Retrieve X

(Ref: Bharadwaj, Rishi et al, *MIMO Antennas for 802.11n Based WLAN Systems*, www.antenna.com. [119])

Due to the rich multipath in vehicular environments, the receiver antennas can de-correlate the incoming signals. Specifically, the rank of the estimated channel matrix increases due to multipath and scattering objects in the vicinity as multiple uncorrelated signals arrive at the receiver antennas. This results in an invertible channel matrix at the receiver. MIMO also utilizes linear pre-coding matrices to deal with time-varying channels. As such MIMO (Figure 4.1-13) can be a useful technology for vehicular communication

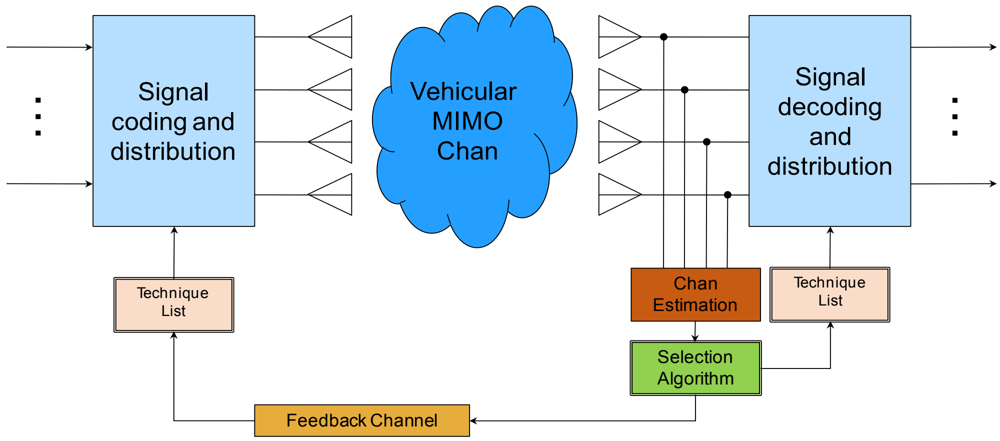


Figure 4.1-13. MIMO System for Vehicular Environments

Source: ARINC April 2012

MIMO literature describes both open loop and closed loop approaches. Closed loop is also known as transmitter adaptive antenna (TX-AA) or "beam forming." Open loop includes a Matrix A and a Matrix B configuration (see Figure 4.1-14).

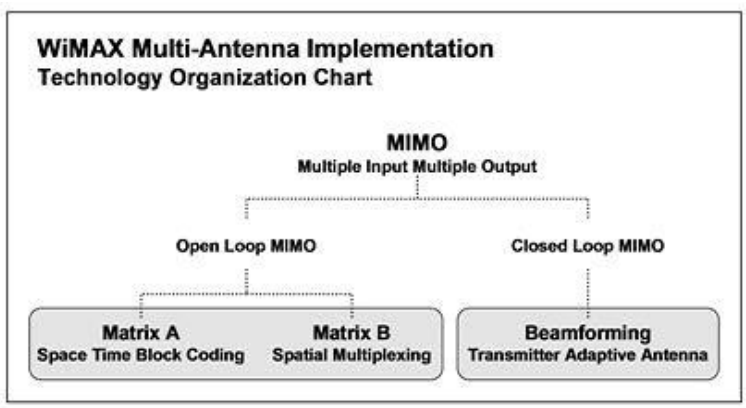


Figure 4.1-14. SMART Antenna Technology per MIMO

(Ref: "MIMO Antennas for 802.11n Based WLAN Systems", Rishi Bharadwaj, et al, www.antenna.com [119])

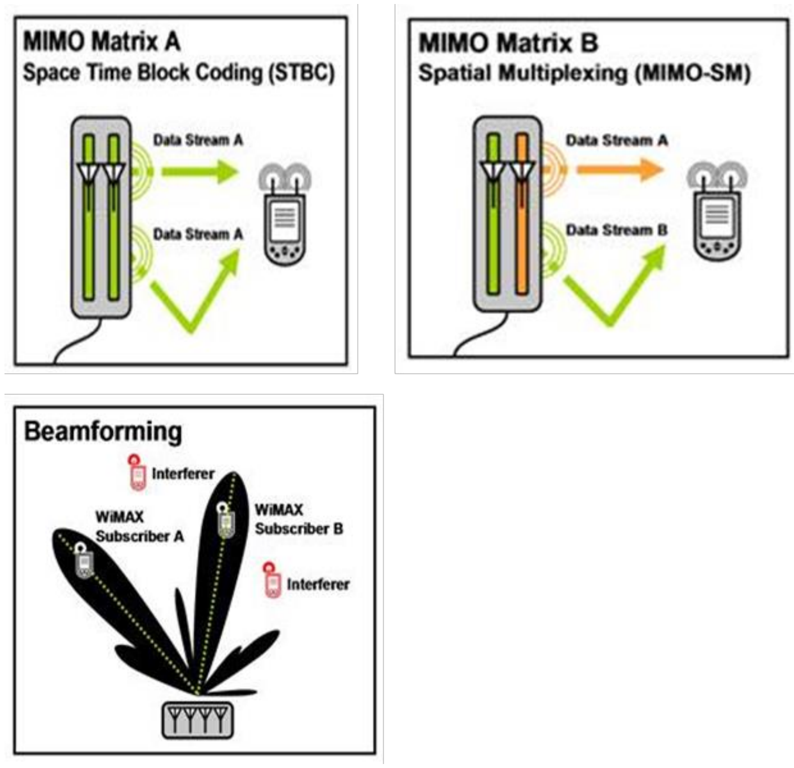


Figure 4.1-15. SMART Antenna Technology Classification per MIMO

(Ref: “MIMO Antennas for 802.11n Based WLAN Systems”, Rishi Bharadwaj, et al, www.antenna.com [119])

Open Loop MIMO uses space-time block coding (STBC, which is matrix A in WiMAX), SPaTial multiplexing (SM-MIMO, which is matrix B in WiMAX) and collaborative uplink MIMO (Figure 4.1-15). Closed loop MIMO uses intelligence to optimize communications with the intended receiver; techniques such as maximum ratio transmission (MRT) and statistical Eigen Beam- forming (EBF) are utilized. Per “MIMO Antennas for 802.11n Based WLAN Systems”, Rishi Bharadwaj, et al, www.antenna.com [119]), matrix A is superior to matrix B at the edges of a cell with a weak signal; matrix B outperforms matrix A in situations with a high SNR. Advanced WiMAX systems dynamically calculate the switching point between matrix A and B to improve overall communications performance. Matrix A is recommended where high mobility communications is required. A MIMO system performs efficiently if the receiver feeds back channel conditions for use at the transmitter. However, when the feedback rate is slower than the rate at which the channel changes, the performance suffers. In such cases, when the channel changes quickly, open-loop MIMO can outperform dominant Eigen vector mode beam forming.

Although SMART antenna systems are being considered for general wireless networks, cellular networks etc., techniques specific to vehicular communication scenarios are also being developed. These techniques are at more preliminary stages and being researched and proposed for vehicular environments. These include:

1. Beam control techniques: The objective of these methods is to mitigate the fading effect caused by the presence of large objects such as buildings, trucks etc. The methods can result in reliable delivery of SPaT messages from the transmitting antenna to the vehicles. In antenna beam switching (see Figure 4.1-16), a narrow beam is transmitted repeatedly at varying angles so as to

enhance the received signal power at the intended destination region. Using ray-tracing and link-level models, the performance is observed to be significantly higher with beam switching (Ref: “Performance Evaluation of a Roadside-to-Vehicle Communication System Using Narrow Antenna Beam Switching Based on Traffic Flow Model”, K. Mase, et al, *Proceedings of Globecom Autonet 2008* [120]). Another approach is to use a steerable beam using phased antenna arrays to direct the beam to vehicle locations. The phased arrays combine radio signals by introducing different phase differences and gains. As such several beam patterns are possible by altering the phase and gain, including omni-directional, directional with variable side lobes etc. (Ref: “Using Steerable Beam Directional Antenna for Vehicular Network Access”, V. Navda et al, *Proceedings of MobiSys, 2007* [121])

2. Advanced MIMO techniques: MIMO techniques improve communication performance by leveraging transmit and receive diversity. MIMO system performance can be further enhanced if the received signal conditions are fed back to the transmitter. However, when the channel changes rapidly, the feedback rate may not be sufficient and performance may actually suffer in roadway environments. Techniques have been proposed to check channel variability and accordingly provide feedback to the transmitter for vehicular environments (Ref: “System and Method for Improving MIMO Performance of Vehicular Based Wireless Communications”, Patent Application 61/226,886 [122]).

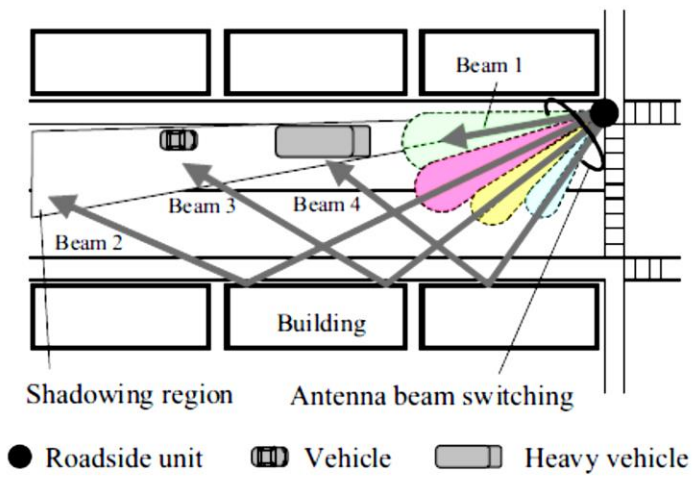


Figure 4.1-16. Antenna Beam Switching

(Ref: “Using Steerable Beam Directional Antenna for Vehicular Network Access”, V. Navda, et al, *Proceedings of MobiSys, 2007* [121])

In summary, antenna design is a significant challenge for realizing vehicular communication including roadside-vehicle communication. Significant multipath has been experienced in urban areas during DSRC test, both in the USA and in Europe. A more in-depth analysis of used of SMART antennas and tailored, fixed beam for RSEs is recommended as well as placement of antennas on vehicles considering ground plane, antenna patterns and required azimuth/elevation coverage and antenna gain required. Vehicle metal ground planes can distort antenna pattern when mounted on a vehicle. Antennas mounted on the sloped surface on the rear-top of the vehicle can impact coverage. Distortion of the vertical antenna pattern can impact performance when the vehicle is going up/down hills; ground plane distortion of the horizontal antenna pattern can impact gain in various directions. Due to the fact that vehicles must be capable of receiving signals from other vehicles as well as the RSE DSRC, omni coverage in required, possibly minimizing the value of SMART antennas with dynamic beam forming.

4.2 Cognitive Radios and Software-defined Radios

Cognitive Radios (CR) are a combined application of software defined radios (SDR) and intelligent signal processing, which provide benefits of radio flexibility, spectral awareness and intelligent adaptation to the signal environment to enhance communications performance. The CR's knowledge of the RF environment allows it to select the best available frequency, bandwidths and modulation to accomplish communications. Because the CR incorporates SDR capability, it can be dynamically adaptable to communicate with radios using different modulations and bandwidths; this results from its ability to be aware of the RF spectrum and RF energy which could interfere with its communications, and can dynamically select "gaps or white space" within the spectrum to use for communications. Because it senses the signal level of noise, it is capable of adjusting transmit power and antenna beams to overcome interference. The adaptability of the CR to an optimal communications channel not only avoids interference to other users but also to improve spectrum efficiency. CR benefits include:

- Enhance communications performance by optimizing bandwidth, modulation, data rate and antenna beams to the real time, RF environment;
- Avoiding spectrum congestion;
- Opportunistic Spectrum Utilization;
- Providing dynamic spectrum access to improve spectrum efficiency;
- Managing communications priorities based on available bandwidth, signal/Noise, and associated data rate achievable;
- Achieving interoperability among varying communications devices and enhance collaborative techniques.

A software-defined radio provides the capability to dynamically configure the radio to transmit and receive different waveforms and modulations; the cognitive radio function provides the intelligence related to the optimum selection of radio transceiver parameters, based on acquired knowledge and established communications policies. Table 4.2-1 provides the definition of CR and SDR. Figure 4.2-1 illustrates a functional diagram of a CR; Table 4.2-2 provided levels of CR capability. Figure 4.2-2 presents the "cognitive cycle" as defined by Dr. Joseph Mitola III (who is known as the "father of cognitive radios"). DARPA has invested a considerable amount of research supporting the development and testing of cognitive radio technology. The basic concept of cognitive ratios is, "sense and learn from the RF environment, maintain awareness and adapt to maximize communications performance." FCC Docket 05-57 defines the elements of a cognitive radio as having:

- **Frequency Agility:** The ability of the radio to change its operating frequency to optimize use under certain conditions;
- **Dynamic Frequency Selection:** The ability of the radio to sense signals from nearby transmitters in an effort to choose an optimum operating environment;
- **Location Awareness:** The ability for the radio to determine its location and the location of other transmitters, and first determine whether it is permissible to transmit at all, then to select the appropriate operating parameters such as power and frequency (per policy);
- **Negotiating Use:** Radio incorporates a mechanism that enables sharing of spectrum under terms of a prearranged agreement;
- **Adaptive Modulation:** Radio has ability to modify transmission characteristics and waveforms to exploit opportunities to use spectrum;
- **Transmit Power Control:** Radio has ability to permit transmission at full power limits when necessary, but constrain the transmitted power to lower levels to allow greater sharing of the spectrum when higher power is not required.

Table 4.2-1. Definition of Software Defined Radio and Cognitive Radio

(Ref: "Cognitive Radio: From Spectrum Sharing to Adaptive Learning and Reconfiguration", Feng Ge, Center for Wireless Telecommunications, Virginia Tech, *IEEE Aerospace Conference, 3-2008* [123])

Software defined radio (SDR) definition
Radios that provide software control of a variety of modulation techniques, wide-band or narrow-band operation, communications security functions (such as hopping), and waveform requirements of current and evolving standards over a broad frequency range.
Cognitive radio (CR) defintition
A transceiver that is *aware* of its environment and can combine this awareness with knowledge of its user's priorities, needs, operation procedures, and governing regulatory rules. It *adapts* to its environment and configures itself in an appropriate fashion. The radio *learns* through experience and is capable of generating solutions for communications problems unforeseen by its designers.

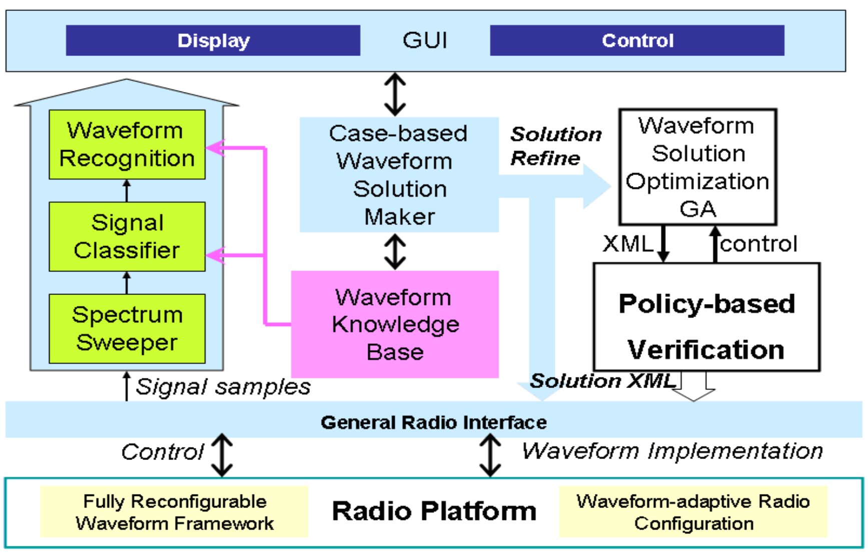


Figure 4.2-1. Example of a Cognitive Radio Functional Diagram

(Ref: "The Future Cognitive Radio", Jeffery Reed, Virginia Technical Institute [124])

Table 4.2-2. Levels of Cognitive Radio Capability

(Ref: "Analysis and Design of Cognitive Radio Networks and Distributed Radio Resource Management Algorithms", James Neel, PhD Thesis, Virginias Polytechnic Institute [125])

Level	Capability	Comments
0	Pre-programmed	A software radio
1	Goal driven	Chooses waveform according to goal. Requires environment awareness.
2	Context awareness	Knowledge of what the user is trying to do
3	Radio aware	Knowledge of radio and network components environment models
4	Capable of planning	Analyze situation (levels 2 and 3) to determine goals (QoS, power). Follows prescribed plans.
5	Conducts negotiations	Settle on a plan with another radio
6	Learns environment	Autonomously determines structure of environment
7	Adapts plans	Generates new goals
8	Adapts protocols	Proposes and negotiates new protocols

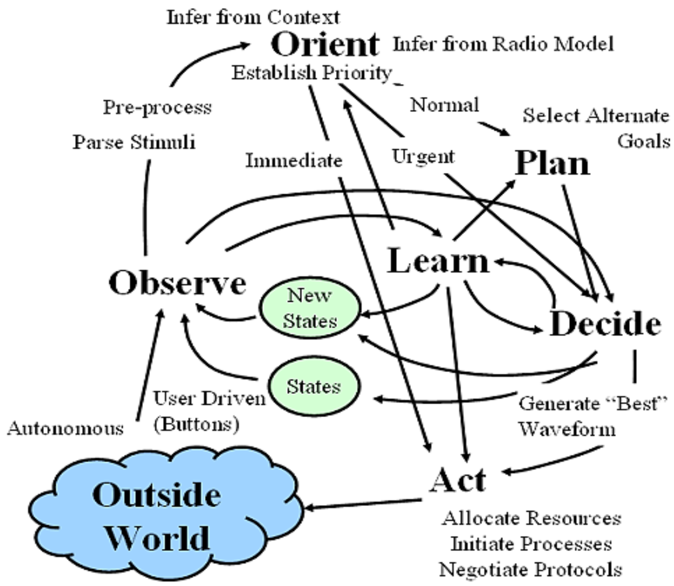


Figure 4.2-2. "Cognitive Cycle" for Radios

(Ref: "Cognitive Radio", J. Mitola III, June 2000 [126])

Use of software defined radio technology supports adaptive modulation, frequency agility and dynamic frequency selection and control functions of a cognitive radio.

The idea of cognitive radio was first presented officially by Dr. Joseph Mitola III in a seminar at KTH, The Royal Institute of Technology, in 1998, published later in an article by Mitola and Gerald Q. Maguire, Jr. in 1999. It was a novel approach in wireless communications that Mitola later described as:

> "The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs".

The current focus of much of the research work is on Spectrum Sensing Cognitive Radio, particularly in the television bands. Although there is no single definition for Cognitive Radio, it would at minimum contain the following key concepts:

- Spectrum Sensing: detecting the unused spectrum and uses it without harmful interference with other users;
- Spectrum Management: captures the best available spectrum to meet user communication requirements such as ranges and data rates required for specific applications;
- Spectrum Mobility: defined as the process when a cognitive radio user exchanges its frequency of operation;
- Spectrum Sharing: providing the fair spectrum scheduling method.

The IEEE 802.22 working group on Wireless Regional Area Networks [127,128] is focusing on enabling rural broadband wireless access using cognitive radio technology in TV whitespaces. It is developing a standard for a cognitive radio-based PHY/MAC/air interface for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV Broadcast Service.

DARPA's Wireless Network after Next (WNaN) project is developing advanced radio technology that is scalable, adaptive, ad hoc network compatible and that use very inexpensive, yet flexible software radios with cognitive capability. WNaN includes Dynamic Spectrum Access (DSA) techniques that sense which spectrum is in use and which is available for use. IEEE 802.11-22 and IEEE 1900 standards were considered related to technique for determining spectrum availability. With policy compliance logic, the WNaN radios dynamically select available spectrum for use, shifting. Frequency selection is made considering availability as well as optimization to support network topology and traffic load. Multichannel operation is supported. The WNaN radio is targeted to cost around $500, is multi-channel, and spectrum-agile, with MIMO-capable wireless nodes. WNaN radios also support Disruption Tolerant Networking (DTN) technology, which allows nodes to store packets temporarily during link outage situations. DARPA test indicate that 100% of the traffic data was delivered following an outage (as compared with traditional IP networks that deliver less than 10% of traffic data after an outage. DTN can operate under the IP stack. In November 2009 DARPA tested 12 mobile nodes, which operated successfully (Ref: "DARPA's Test of Cognitive Radios Goes Well", Donny Jackson, Urgentcommunications.com [129]). In August 2010, DARPA tested WNaN with 102 nodes in a simulated tactical environment. In an article by John Cox, entitled, "DARPA Looks to Adaptive Battlefield Wireless Nets", Computerworld.com [130], it is pointed out that DARPA has successfully tested:

- Next Generation (XG), cognitive, policy based radios with dynamic spectrum access;
- Knowledge Based Networking with successful testing of 50 nodes MANET that included cognitive radio mobile nodes with peer-to-peer networking and no single point of failure.

ITS has a dedicated frequency spectrum (5.85 to 5.92 GHz), unlike a battlefield that may have uncontrolled emissions. However, use of a wide area broadcast frequency that may have interfering frequencies (such as a HD Radio AM receiver at night) would be enhanced with spectrum awareness and adaptable use of "white space." The peer-to-peer, MANET technology developed by DARPA may also be applicable to ITS. The article, "Wireless Gateway to Connect Warfighters", by Henry Kenyon (*Signal Magazine, Nov. 2009*) [131], discusses the DARPA supported, DOD *Maingate* project. It utilized DARPA XG radio technology for automatic spectrum access. It utilized IP addressing, supporting a mobile, wireless ad Hoc network. MIMO is used. The MANET protocol allows vehicles to serve as communications nodes and to relay messages, thus supporting "over the horizon" communications capability. It also supports "store and forward" capability where there is a momentary loss in connecting to the network. Field test showed a data throughput of 10.3 mbps for low band and 50 mbps throughput for high band. Node entry to the network required 10 seconds. Latency with 10% link load was < 200 msec to 90% of the time. After network connection is lost, automatic reconnection is supported based on nearest, assessable node. The radio cost $60K each in production quantities of 1000.

4.2.1 *IEEE 802.22 Standard*

The IEEE 802.22 WG (or simply, 802.22) for Wireless Regional Area Networks (WRAN) was established in November 2004. It developed the 802.22 standard, which is the first standard for cognitive radios and is focused at unlicensed use of unused frequencies within the television band. (See "IEEE 802.22: An Introduction to the First Wireless Standard based on Cognitive Radios", Carlos Cordeiro, et al, *Journal of Communications*, Vol. 1, No. 1, April 2006 [132]). The standard defines the requirements for distributed spectrum sensing, measurement, and spectrum management. It is restricted to the television bands and addresses both detection and interference avoidance. Top-level requirements are summarized below and in Table 4.2-3 and Table 4.2-4.

Figure 4.2-3 illustrates spectrum utilization by IEEE802.22 devices and Figure 4.2-4 illustrates the approach for determining "white space" within the TV broadcast spectrum. Figure 4.2-5 presents the architecture of an IEEE802.22 system and Figure 4.2-6 illustrates a prototype of an IEEE802.22 compliant radio.

- ***System topology:*** The system is a point to multipoint with a base station supporting a number of users. Spectral sensing is performed on a distributed basis to determine signal levels of possible television (or other) signals using the various channels at their individual locations. The base station uses cognitive processing to determine “white spaces” to be used within the TV spectrum.

- ***Coverage area:*** 33 km and in some instances base station coverage may extend to 100 km. Transmitted power is specified as 4 Watts EIRP (effective radiated power relative to an isotropic source).
- ***System capacity:*** Downlink data rate: 1.5 Mbps at the cell periphery; uplink data rate of 384 kbps. (Assume 12 simultaneous users; requires 18 mbps downlink capability). Using a 6 MHz television channel requires a spectral efficiency of around 3 bits / sec / Hz. ODFM modulation is required.

Table 4.2-3. Top-level Requirements of IEEE802.22

(Ref: “Introduction to IEEE802.22”, Somayeh Mahmoodi [133])

Items	Requirements
Service coverage	Typical 33 km ~ Max 100 km
Active subscribers	Minimum 12 users
Minimum peak throughput at cell edge	Forward link: 1.5 Mbps / subscriber (18 Mbps in total)
	Reverse link: 384 kbps / subscriber
Spectral efficiency	Minimum: 0.5 bps/Hz
	Typical: 3 bps/Hz > 18 Mbps for 6MHz BW
Service availability	50% of locations & 99.9% of time

Two techniques are specified for spectrum sensing: Fast and Fine. Fast sensing uses a simple RF energy detection algorithm providing results in 1 msec. Fine sensing utilizes up to 25 msec to determine presences of “white space” within the TV spectrum. Overlapping cells are synchronized so that mutual interference can be detected and frequencies adjusted. Some of the test results as reported in the reference, “Introduction to IEEE802.22”, Somayeh Mahmoodi [133], include:

- Channel use detection time of up to 2 sec;
- 85% of Test Sites had Delay Spread of 35 msec. caused by multipath;
- Some test indicated deep and flat multipath fading;
- Peak Throughput achieved is 22.69 mbps (5/6, 64 QAM); however, test indicated issues with achieving maximum data rate at 30 km range.

There are several issues with this standard related to consideration for use for communicating GID and other SPaT related information to vehicles. The first is that it is probabilistic, in that “white space” must be available in the frequency spectrum to support operations. The specification calls for 50% of the users to have 99.9% availability; thus full area coverage is not required by the standard. The second issue is the supportability of widely distributed 802.22 cell sites providing cell coverage of 33 to 100 km. The third issue is that the specifications support 12 users. Another issue is the size of antenna required for TV frequencies and compatibility with small vehicles. The OFDM modulation supports a Doppler spread of 3.3 KHz; however, the standard was developed for fixed point communications. Production cost of an IEEE802.22 Radio, in large quantities, would be less than $500 per unit.

Table 4.2-4. Physical Layer Specifications for IEEE802.22 Radios

(Ref: "Cognitive Radio Communications and Networks: Principles and Practices", A. M. Wyglinski, et al, Elsevier, Dec. 2009 [134])

TV channel bandwidth (MHz)	**6**	**7**	**8**
Total number of subcarriers		2048	
Number of guard subcarriers N_G (L, DC, R)		368 (184, 1, 183)	
Number of used subcarriers N_T=N_D+N_P		1680	
Number of data subcarriers N_D		1440	
Number of pilot subcarriers NP		240	
Signal bandwidth (MHz)	5.6240625	6.5625	7.494375

PHY Performance: SNR (dB)			
Mod.		Rate	SNR
QPSK		1/2	4.3
		2/3	6.1
		3/4	7.1
		5/6	8.1
16 QAM		1/2	10.2
		2/3	12.4
		3/4	13.5
		5/6	14.8
64 QAM		1/2	15.6
		2/3	18.3
		3/4	19.7
		5/6	20.9
PHY capacity		**Mbit/s**	**Bit/(s*Hz)**
QPSK	1/2	3.74	0.624
	2/3	4.99	0.832

	3/4	5.62	0.936
	5/6	6.24	1.04
16 QAM	1/2	7.49	1.248
	2/3	9.98	1.664
	3/4	11.23	1.872
	5/6	12.48	2.08
64 QAM	1/2	11.23	1.872
	2/3	14.98	2.496
	3/4	16.85	2.808
	5/6	18.72	3.12

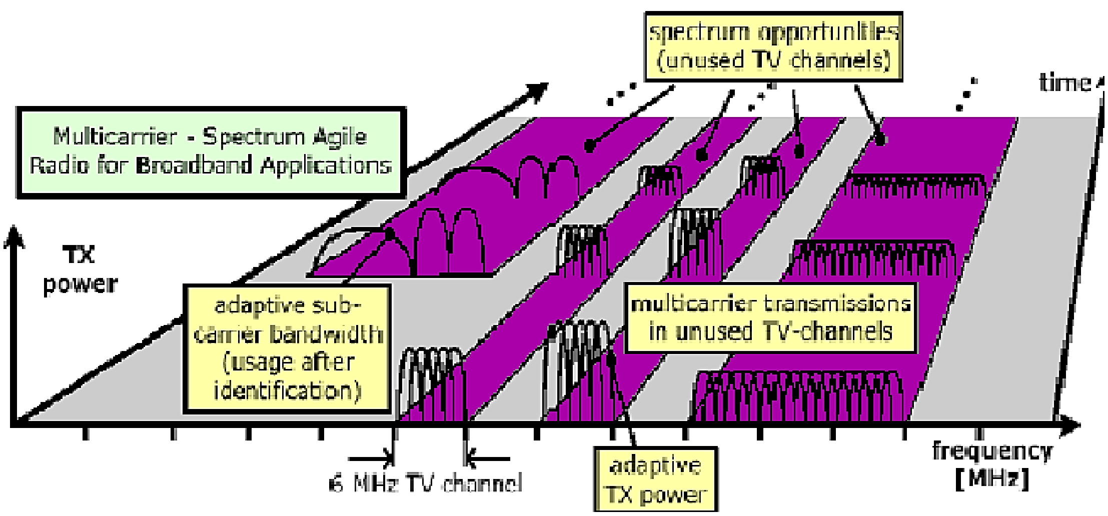


Figure 4.2-3. Example of Unused TV Broadcast Spectrum utilized by IEEE802.22 Devices

(Ref: “Introduction to IEEE802.22”, Somayeh Mahmoodi [133])

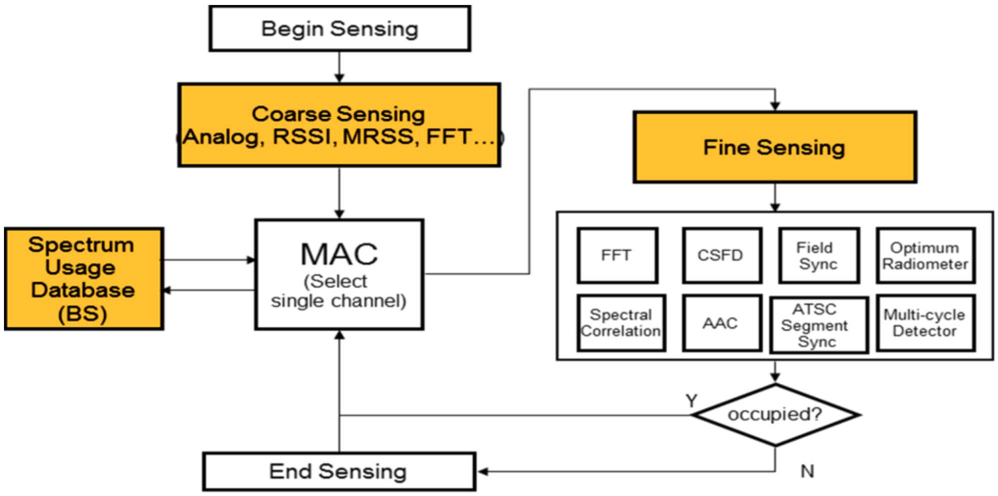


Figure 4.2-4. "White Space" Spectrum Sensing per IEEE 802.22

(Ref: "Cognitive Radio Communications and Networks: Principals and Practices", A. M. Wyglinski, et al, Elsevier, Dec. 2009 [134])

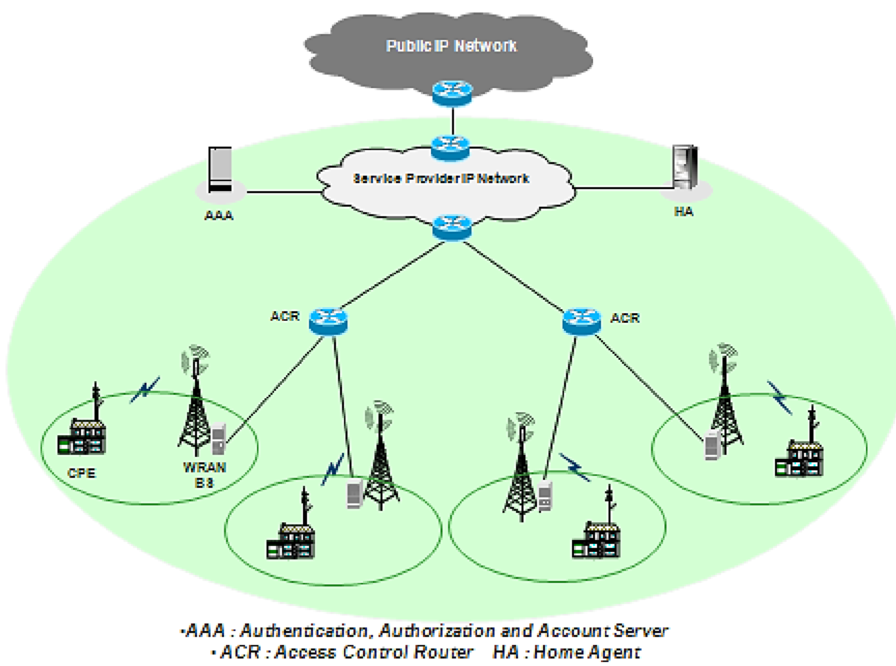


Figure 4.2-5. Wireless Regional Area Network (WRAN) Architecture and Hierarchy

(Ref: "Introduction to IEEE802.22", Somayeh Mahmoodi [133])

Figure 4.2-6. Prototype IEEE802.22 Compliant Radio Transceiver

(Ref: "Recommended Practice for the Installation and Deployment of IEEE 802.22 Systems", Carl Stevenson, et al [135])

There has been some interest in developing a version of IEEE802.22 that supports reliable mobility. However, WiMAX seems to be the technology of choice by service providers, perhaps limiting deployment of IEEE802.22 networks.

Cognitive radio technology and "white space" access and utilization using IEEE802.22 techniques possibly has an application in service data access by vehicles. However, using white space is probabilistic communications which generally is not applicable to time critical, high safety integrity level related communications.

4.2.2 *Software-Defined Radio Overview*

Similar to Cognitive Radio, there are also multiple definitions regarding Software-defined Radio proposed in different areas and institutes. The general concept of SDR is as the following:

- **Wikipedia Definition of SDR:** A software-defined radio system, or SDR, is a radio communication system where components that have been typically implemented in hardware (e.g., mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a generic computing device, such as personal computer, or embedded computing devices. A basic SDR system may consist of a generic computing device equipped with an adequate analog-to-digital converter, such as a sound card, or others, preceded by some form of RF front end. Significant amounts of signal processing are handed over to the general-purpose processor, rather than being done in special-purpose hardware. Such a design produces a radio which can receive and transmit widely different radio protocols (sometimes referred to as a waveforms) based solely on the software used;
- **International Telecommunications Union (ITU) Definition:** A radio, that includes a transmitter, in which the operating parameters of frequency range, modulation type, and/or maximum output power (either radiated or conducted) can be altered, post-manufacturing, by making a change in software or adapting parameters under software direction without making changes to the hardware components. (Ref: ITU-R WP 8A [211]);
- **Federal communications Commission Definition of SDR:** A radio that includes a transmitter in which the operating parameters of frequency range, modulation type or maximum output power

(either radiated or conducted) can be altered by making a change in software without making changes to hardware components that affect the radio frequency emissions.

Generally, SDR would contain the following key concepts:

- Wideband spectrum sensing: capable of characterizing frequencies over which it can operate, identifying and analyzing the signals, and mitigating the interference;
- Dynamic frequency selection: driven by applications or operations and capable of choosing multiple channels/frequencies to operate;
- Channel characterization and adaptation: capable of managing channel error rate, model correction and usage;
- Transmit power control (TPC): capable of controlling and optimizing the transmit power, and minimizing the interference;
- Policy selection and intelligence: capable of checking sensed environment against regulatory requirements and setting limits of operation based on selected spectrum.

Typical components of a software radio include:

- Analog Radio Frequency (RF) receiver/transmitter which can support RF operations in the 200 MHz to multi-gigahertz range;
- High-speed A/D and D/A converters to digitize a wide portion of the spectrum at 25 to 210 Mega-samples/sec;
- High-speed front-end signal processing that includes Digital Down Conversion (DDC) consisting of one or more chains of mix + filter + decimate or up conversion;
- Protocol-specific processing such as Wideband Code Division Multiple Access (W-CDMA) or OFDM, including spreading/de-spreading, frequency-hop-and chip-rate recovery, code/decode functions, including modulation/demodulation, carrier and symbol rate recovery, and channel interleaving/de-interleaving.

In a white paper entitled, “Software Defined Radios”, Wipro Technology Publication, August 2002 [210], SDRs were categorized as shown:

- ***Tier 0:*** A non-configurable hardware radio (Cannot be changed by software);
- ***Tier 1:*** A software controlled radio where limited functions are controllable, such as power levels, interconnections, etc. but not mode or frequency;
- ***Tier 2:*** In this tier of software-defined radio, a significant proportion of the radio is software configurable. Often the term software controlled radio, or SCR, may be used. There is software control of parameters including frequency, modulation and waveform generation / detection, wide/narrow band operation, security, etc. The RF front end still remains hardware based and non-reconfigurable;
- ***Tier 3:*** The ideal software radio or ISR where the boundary between configurable and non-configurable elements exists very close to the antenna and the RF "front end" is configurable; it is essentially full programmable;
- ***Tier 4:*** The ultimate software radio (USR) is a stage further on from the Ideal Software Radio (ISR). It has full programmability, and is also able to support a broad range of functions and frequencies at the same time (Figure 4.2-7).

Benefits of SDR radios are:

- Lower cost;
- Dynamically Adaptable to the RF environment;
- Can interoperate with multiple radios with different frequencies, bandwidths and modulations;
- A Lower priority, different functional radio can be dynamically adapted to back up a higher priority functional radio;
- Can enhance performance by having an intelligent understanding of the RF environment;
- Low cost upgrade as standards change.

DSRC units should incorporate SDR technology and several on the market use a hybrid form of SDR.

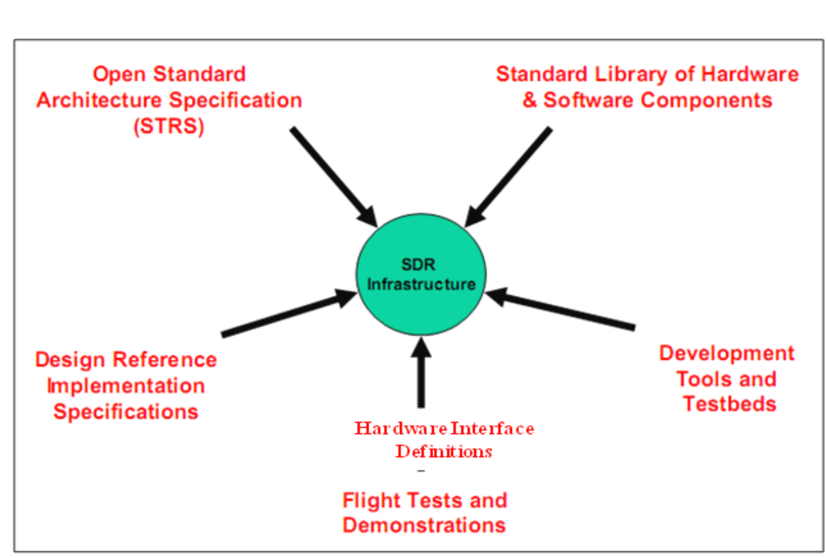


Figure 4.2-7. Elements of an Software Defined Radio

(Ref: “SDR/STRS Flight Experiment and Role of SDR-Based Communications and Navigation System”, Richard Reinhardt, et al, NASA, *6th Annual Software Radio Summit* [136])

Along with Software-defined Radio, similar concept can be applied to Software-Defined Antenna (SDA). SDA is an idea of antenna system that can be adjusted in such way, to keep similar characteristics for any frequency. Once installed, SDA could be used to support any radio-based telecommunication system in any band.

4.2.3 *Software-Defined Radio and Cognitive Radio Evolution*

As the research and development on Cognitive Radio gain more momentum, there is a need to standardize processes, terms, and so on. Further, the efforts so far by many individual groups are incoherent due to the lack of common understanding. To foster the development of Cognitive Radio, the IEEE Dynamic Spectrum Access Networks (DYSPAN) Standards Committee, (formerly IEEE Standards Coordinating Committee SCC-41) on Next Generation Radio and Spectrum Management has initiated a series of standards, the IEEE 1900 series. Figure 4.2-8 illustrates the focus of IEEE 1900 work groups and Figure 4.2-9 illustrates the objective of interoperability between air interface standards using SDR and cognitive radio technology. Table 4.2-5 outlines the scopes of the IEEE 1900 standards.

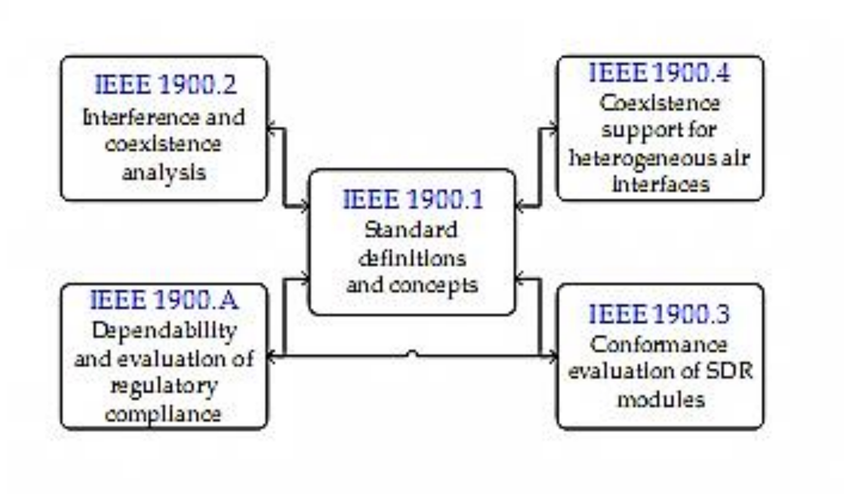


Figure 4.2-8. IEEE 1900 Work Group Focus

(Ref: "Cognitive Functionality in Next Generation Wireless Networks: Standardization Effort", R. V. Prasad [137])

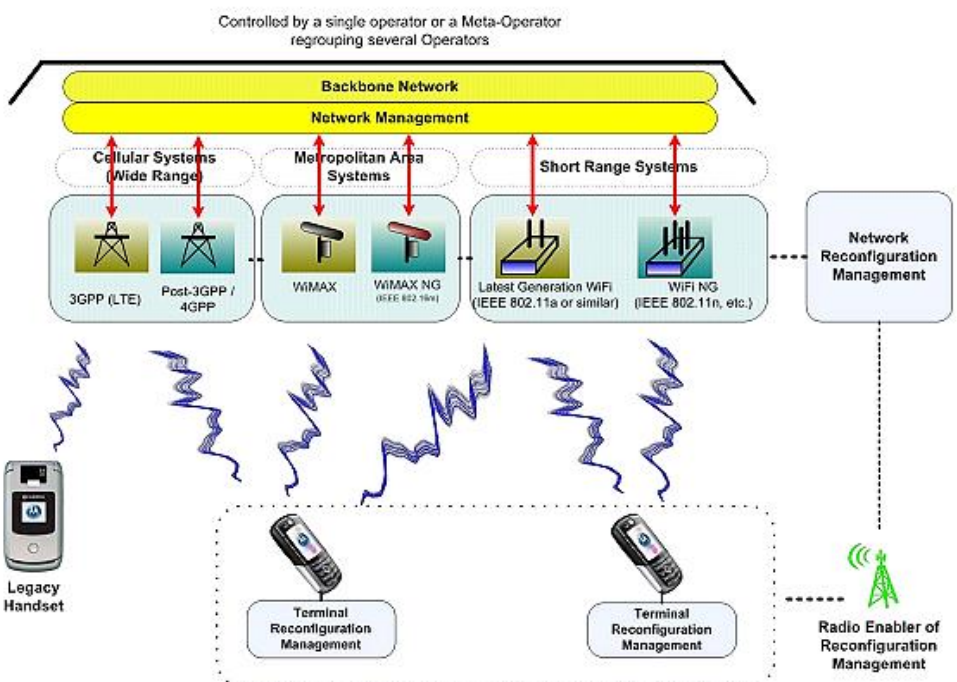


Figure 4.2-9. An Objective of IEEE 1900 is Adaptation top Multiple Interfaces using Software Define Radio and Cognitive Capability

(Ref: "IEEE 1900.B: Coexistence Support for Reconfigurable, Heterogeneous Air Interfaces", Markus Muck, et al [138])

Table 4.2-5. IEEE 1900 Standards for Cognitive Radio

(Ref: "Standardization and Research in Cognitive and Dynamic Spectrum Access Networks", IEEE SCC 41 Efforts, Fabrizio Granelli, et al, *IEEE Communications Magazine*, 1-2010 [139])

Working Group	Objective	Status
IEEE 1900.1	Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management	Standard Published on September 26, 2008
IEEE 1900.2	Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence Between Radio Systems	Standard Published on July 29, 2008
IEEE 1900.3	Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules	Disbanded
IEEE 1900.4	Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks	Standard Published on February 27, 2009
IEEE 1900.5	Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications	Active
IEEE 1900.6	Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems	Active

The most significant organization to develop and promote Software-Defined Radio is Wireless Innovation Forum, formerly SDR Forum. It is a non-profit "mutual benefit corporation" dedicated to driving technology innovation in commercial, civil, and defense communications around the world. The scope of this forum is no longer limited to SDR but forum members bring a broad base of experience in Software-defined Radio, Cognitive Radio and Dynamic Spectrum Access technologies. The Forum acts as the premier venue for its members to collaborate to achieve these objectives, providing opportunities to network with customers, partners and competitors, educate decision makers, develop and expand markets and advance relevant technologies.

4.2.4 *Summary and Potential Benefits to SPaT Applications*

With the advancement of cognitive algorithm and leveraging SDR and SDA as the enabling technologies, combination of CR, SDR, and SDA have great potentials for future communications. There are numerous vendors providing products supporting Cognitive Radio, SDR-based GSM base stations, or next-generation cellular network infrastructure equipment. Evaluation efforts have been made to investigate the possible use of the TV spectrum for secondary access provides an avenue for usage for vehicular communications. For example, spectrum measurements have been carried out in Massachusetts in collaboration with a major automaker to evaluate the presence of vacant UHF TV channels to be used for vehicular communication (Ref: "Characterization of Vacant UHF TV Channels for Vehicular Dynamic Spectrum Access, Pagadarai, et al, *Proceedings of IEEE VNC*, 2009 [140]). Consequently, the use of cognitive radios can allow for reliable communication in challenging environments through flexibility and adaptability, as well as spectrum sensing and dynamic access. Methods for collaborative sensing have been proposed where multiple vehicles make decisions based on a spatially distributed set of observations. It is anticipated that such combination of technologies will benefit the vehicular communications in the foreseeable future. One potential scenario may be to leverage the cognitive algorithm to decide the best choice of wireless communication based on key criteria, such as latency, bandwidth, and interference, while utilizing SDR module integrated with vehicle OBU to form the corresponding wireless communication system, such as DSRC, cellular, digital terrestrial broadcast television or other communication technologies, and SDA to tune the configurable antenna array to the available spectrum. If vehicular communication is based on the designated spectrum and DSRC, the Cognitive Radio may not contribute major improvements in this case. While considering long-term operation and maintenance perspective, leveraging this method, the vehicle on-board units can be upgraded using software, instead of replacing hardware whenever a system upgrade is needed. The later conventional upgrade practice is usually much more expensive and requires more time to accomplish the objective. This approach supports flexible technology evolution as the on-board communication technologies are more dependent on software, instead of hardware as compared with the conventional approaches. The down side of this advanced technology approach is that it does not support the low latency requirements of SPaT and other safety related communications, and that cellular communications requiring a fee for continuing service is not a candidate for SPaT. Unless perhaps jurisdictional LTE augmented DSRC could perhaps be a back-up link in the presence of significant interference in the 5.85-5.925 GHz frequency band, adaptable link alternatives supporting low latency, rapid attach communications is not available for the vehicle OBE, making the cost of cognitive radios unjustifiable. SDR technology is emerging in the early development DSRC products and is recommended for both OBE and RSE communications equipment, especially since V2V and V2I communications technology and protocols will most likely evolve and SDR technology is the least cost approach supporting evolutionary development.

Roadside equipment and OBE radios can be upgraded using software, instead of deploying new hardware whenever a system upgrade is needed. This could provide long-term maintenance cost benefits and reduce efforts for upgrade/technical evolution. While there are issues with using IEEE 802.22 for SPaT complimentary data support (such as GID Distribution), progress in adding mobility to the standard and supporting perhaps “GEONET like” intelligent distribution of GIDs makes it worth following the progress of the standard and related technology. Certainly SDR technology has a role in DSRC products. Some of the cognitive radio features and SMART antenna features could reduce multipath and interference impact on DSRC messaging. MIMO technology supports improved data rates within a given bandwidth, and using spatial diversity, improves performance in the presence of multipath. DSRC has a dedicated frequency band and does not have to share “white space” in which to communicate as does military radios.

LTE radios include SDR technology as well as some of the features of cognitive radios (such as MIMO). The mobile WiMAX standard also includes MIMO.

4.3 Connected Radios

Connected radios have been considered for tactical military operations. The applications rely upon extensive research and development carried out in the field of Ad hoc networking technology over the past two decades. The use of ad hoc networks to communicate between vehicles, known as vehicular-to-vehicular (V2V) or inter-vehicular networks, also presents promising opportunities for supporting vehicular applications. Specifically, Inter-vehicular communication may provide an attractive way for vehicles to communicate in a local area. To this end, work has been carried out on various aspects including information forwarding, medium access control, RF and propagation models, mobility analysis etc. Various methods have been proposed at the MAC layer to manage contention caused due to local message flooding. In addition to safety applications, inter-vehicular message may also assist in local coordination and messaging between vehicles to efficiently obtain information from the infrastructure via cellular networks. For example, it may be possible for vehicles to coordinate and designate a vehicle that pulls the traffic signal phase and timing information from a remote server (Figure 4.3-1). It is also possible that vehicles collaborate to relay SPaT messages received from intersections. This could result in increased coverage and more reliable dissemination. Major automakers are actively pursuing inter-vehicle communication to enhance safety and information services to the drivers.

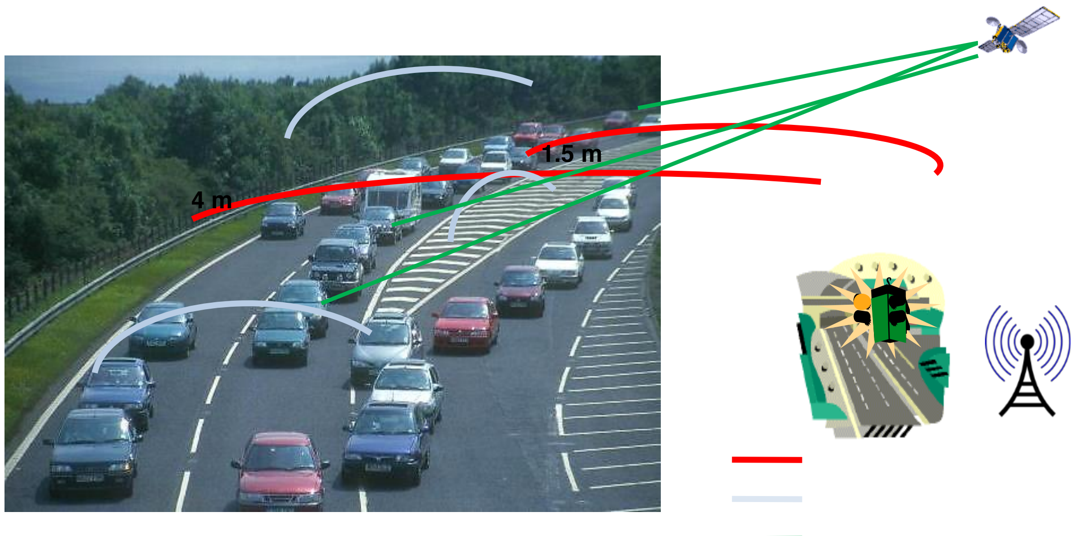


Figure 4.3-1. Vehicular Communication for Enhanced Access

Source: ARINC April 2012

This project focused on communications technology required to support SPaT related applications from an infrastructure to vehicle perspective. It does not address vehicle-to-vehicle communications, except for considering impact on V2I communications. The SPaT related applications are primarily supported by transmission of the SPaT messages to vehicles using DSRC broadcast or a similar performing communications technology. Supplementary information required to support SPaT applications, such as GID/MAP data, is also broadcast to vehicles; supplementary data may be delivered to vehicles utilizing a number of communications technologies, including DSRC, HD Radio, ATSC Mobile TV, WiMAX and LTE. The ranking and recommendations are included in the summary section of this report.

ITS initiatives in Europe, Asia, and the USA, include connected vehicles supported by V2V and V2I communications. Applications and systems architecture include linking vehicles with the Internet using a variety of technologies including Network Mobility (NEMO) router, MANET with IPV6, and some version of geo-location subnets (also called geonets). Communications architecture includes message relay from infrastructure to a specific vehicle-using relay and also including extension of DSRC communications range using message relay. Figure 4.3-2 illustrates message relay. Figure 4.3-3 illustrates modes of communications, including unicast, broadcast and geocast. Note that multicast in fixed networks is similar to geocast, where members of the multicast group are included in the multicast address. Geo-multicast relates to communicating with a selected group within the geo-area, such as public transit vehicles. Geocast protocol can be used to communicate with vehicles within a segment of corridor associated with a major accident or to communicate with vehicle within a selected distance of a signalized intersection. Geonet protocol requires the OBE to maintain knowledge of addresses and their location, based on messages received. Some geonet related protocols also maintain velocity vectors and thus are capable of selecting vehicle addresses not only within a given location area but also going in specific directions.

The geonet address/location table supports message relay as well as selecting addresses associated with a geographic of interest (such as vehicles within an area that represents a potential safety issue with "own vehicle"). Geonet protocol assists in communications distribution management by each mobile node maintaining knowledge of the communications environment through beaconing to determine the identity, presence and location of neighbors, allowing:

- Developing next hop for a message
- Understanding final destination of the message
- Developing a recovery strategy if the next hop fails

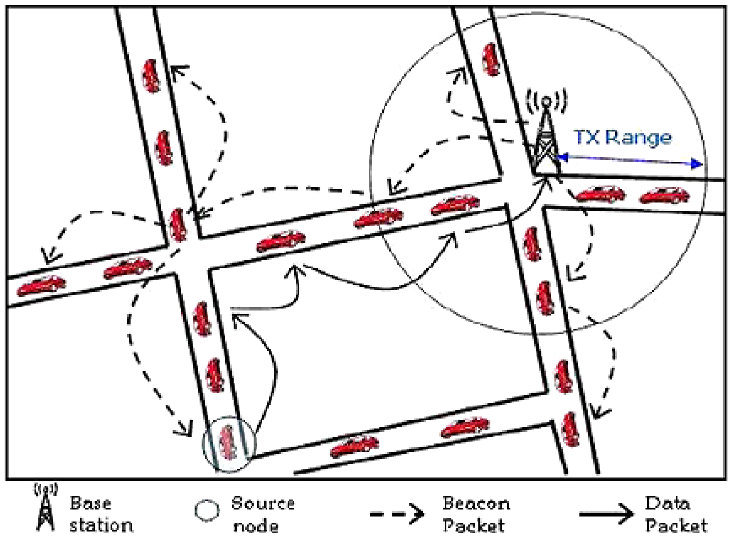


Figure 4.3-2. Example of Message Relay via Mobile Nodes

(Ref: "A Survey of Cross-Layer Design for VANETs", Boangoat Jarupan, et al, Ohio State University, November 2010 [141])

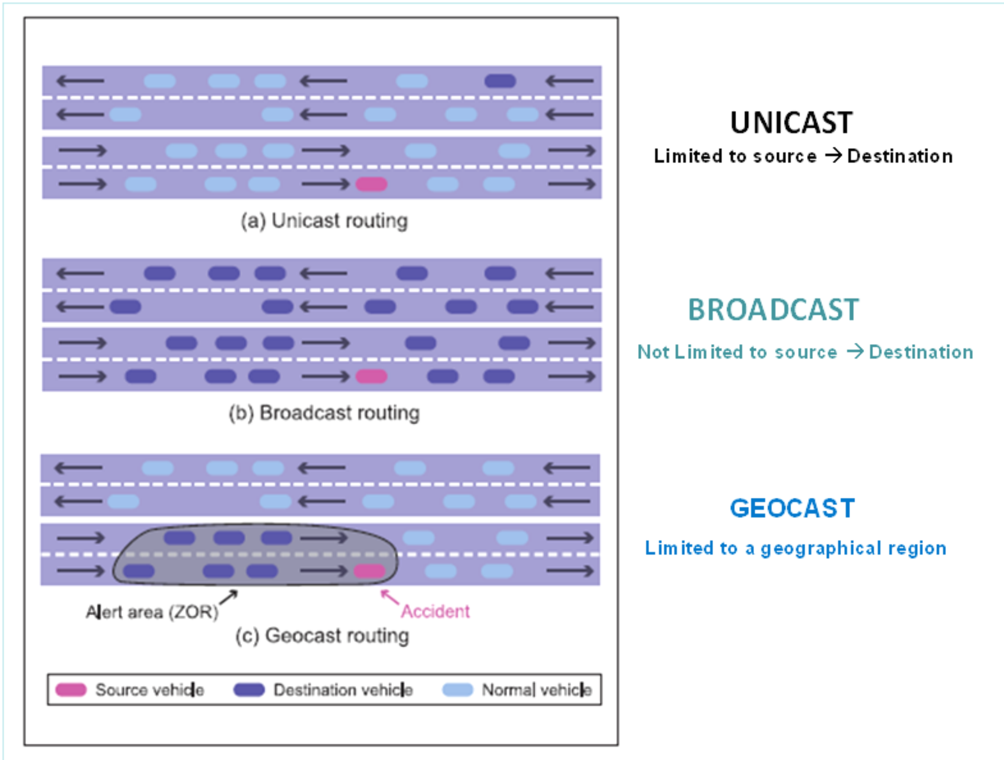


Figure 4.3-3. Examples of Unicast, Broadcast and Geocast within a Mobile Network

(Ref: "Routing Protocol with Prediction Based Mobility Model in Vehicular Ad Hoc Networks", A. Banik, Pennsylvania State University, April 2010 [142])

Unlike fixed networks, mobile networks have:

- Limited bandwidth compared with fixed networks;
- Limited node processing capability compared to fixed networks;
- Prone to higher error rates and frequent disconnects;
- May dynamically adjust to reliable communications at the "edge" (selecting modulation and data rate to improve BER/PER) thus impacting overall data throughput;
- Continually changing network topology and available of node resources (must be dynamically, self-organized);
- Limited communications range of individual nodes.

As mobile nodes enter the network, overhead is added and delays increase. When the mobile subnet interfaces with the fixed network, Home Agent (HA) access for addresses access can become a cause of significant latency.

Some of the basic protocols associated with MANET are:

- Dynamic Source Routing (DSR);
- Ad hoc On-Demand Distance Vector (AODV).

Table 4.3-1 presents some of the vehicle ad hoc network routing protocols. Other protocols include:

- ZRP: Zone routing Protocol;
- IARP: Inter-zone Routing Protocol;

- LSR: Link State Routing;
- OLSR: Optimized Link State Routing;
- LSDVR: Link State and Distance Vector Routing.

Research continues related to wireless mobility related protocols to support reduction in overhead, processing and latency.

Table 4.3-1. VANET Routing Protocols

(Ref: "Routing in Vehicular Ad Hoc Networks: A Survey", Fan Li, et al, *IEEE Vehicular Technology Magazine*; Vol. 2, # 2; 6-2007 [143])

Routing protocols	Routing type	Position information? (How to use)	Hierarchical structure?	Network simulator	Simulation scenario
AODV	Unicast	No	No	--	--
DSR	Unicast	No	No	--	--
GPSR	Unicast	Packet forwarding	No	--	--
PRAODV/ PRAODV-M	Unicast	Route selection (life time prediction)	No	NS2	Simple highwar model (20 Km segment only)
AODV-bis	Unicast	Route-req forwarding	No	--	--
GSR	Unicast	Packet forwarding	No	NS2	Real city model (from map)
GPCR	Unicast	Packet forwarding	No	NS2	Real city model (from map)
A-STAR	Unicast	Packet forwarding (also use traffic info.)	No	NS2	Grid city model

COIN	Unicast	Cluster formation	Yes	Own	Real highway model
LORA-CBF	Unicast	Packet forwarding (also location prediction)	Yes	Opnet	Simple circle and square road
Flooding	Broadcast	No	No	--	--
UMB	Broadcast	Packet forwarding	No	Own	Simple intersection road
V-TRADE / HV-Trade	Broadcast	Classify forwarding group	No	Own	Simple intersection
BROADCOMM	Broadcast	Formation of cells	No	Own	Simple highway model (15 modes only)
Msg Dis Protocol	Geocast	Packet forwarding	No	Own	Simple highway model (10 Km long)
IVG		Packet forwarding	No	Glomosin	Simple highway model (10 Km long, 100/200 nodes)
Cached Geocast	Geocast	Packet forwarding	No	NS2	Quadratic network (size from 1 Km to 4 Km, 100 nodes)
Abiding Geocast	Geocast	Packet forwarding	No	--	--

4.4 Protocols and Modulation

Transmission of information to vehicles in a given area is the cornerstone for several vehicular applications including SPaT messaging. The addressing of vehicles in such cases poses a challenge under several scenarios. For example, when location-specific information is sent from a Traffic Management Center directly to the vehicles, the addressing needs to take location into account. However, addressing each vehicle individually for e.g., using IP, is a challenge due to the large number of vehicles that may be the target of a message. Even in a small area such as in a few blocks, some degree of localization is needed to send relevant information to specific vehicles. As a consequence the addressing and forwarding needs to take location into account schemes for directed transmission for messages from RSE to vehicles involve techniques such as Geocast (Figure 4.4-1). Here the location information from vehicles is taken into account when the vehicles relay the packets. Geocast supports the addressing of individual nodes and of geographical areas based on location services, which resolve a node's ID to its current position. Geo-networking or GeoNet (Ref: "Geonet Project", http://www.geonet-project.eu/ [144]) is a packet forwarding and routing approach used in the C2C-CC, COMeSafety, ETSI ITS, and ISO CALM. The method involves an additional layer in the protocol stack at each end-point and resolution of IPv6 addresses to location. Senders in the Packet network forward over IPv6 until the packet reaches the relevant RSU for local forwarding. Some of the advanced communication protocols pertaining to efficient transmission of information (Ref: "A Survey and Challenges in Routing and Data Dissemination in Vehicular Ad-hoc Networks", Chen et al, *Wiley Wireless Communication and Mobile Computing Journal*, October 2009 [145]) for enabling vehicular communication include Geographic routing in city scenarios (GPCR), Local Peer Group (LPG) etc. The objective in these protocols is to enable communication from RSU to vehicles and between vehicles through forwarding mechanisms and network management. SPaT messages where area of relevance is usually geographically defined can benefit from the above protocols as information may be sent to defined locations effectively.

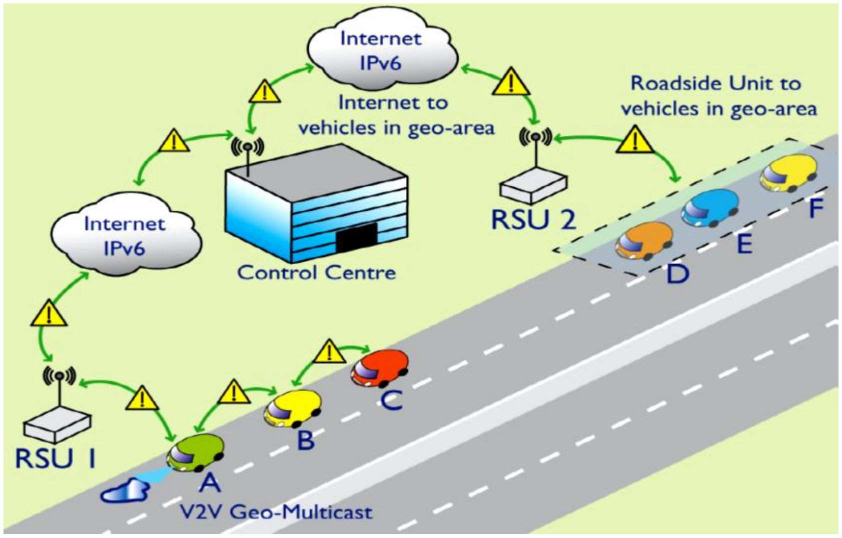


Figure 4.4-1. Geocast to Send Information to Vehicles in Relevant Area

(Ref: "Geonet Project", http://www.geonet-project.edu/. [144])

While early in the development of DSRC technology different countries utilized different modulation, the trend is for countries to adopt IEEE802.11p using OFDM modulation. Europe calls this DSRC M5. Each OFDM subcarrier may be modulated with BPSK, QPSK or QAM for the higher data rates. Modulation schemes dictate the bit error performance and enhanced modulation schemes specific to roadway environments may help in higher packet delivery ratios for SPaT applications under similar conditions. Typically, coherent OFDM is used where the channel is estimated at the beginning of the packet and assumed invariant for the packet duration. Differential OFDM (Ref: "A Differential OFDM Approach to Coherence Time Mitigation in DSRC", Zhang, et al, *Proceedings of VANET, 2008* [146]) has been proposed where the channel is assumed to be invariant over two OFDM symbols. Figure 4.4-2 shows simulation-based evaluation demonstrating the efficacy of differential OFDM. The error performance is shown to be generally better, but suffers under high noise levels. Various other methods for improved modulation formats for OFDM and multi-band protocols are being tested using SDRs for vehicle applications.

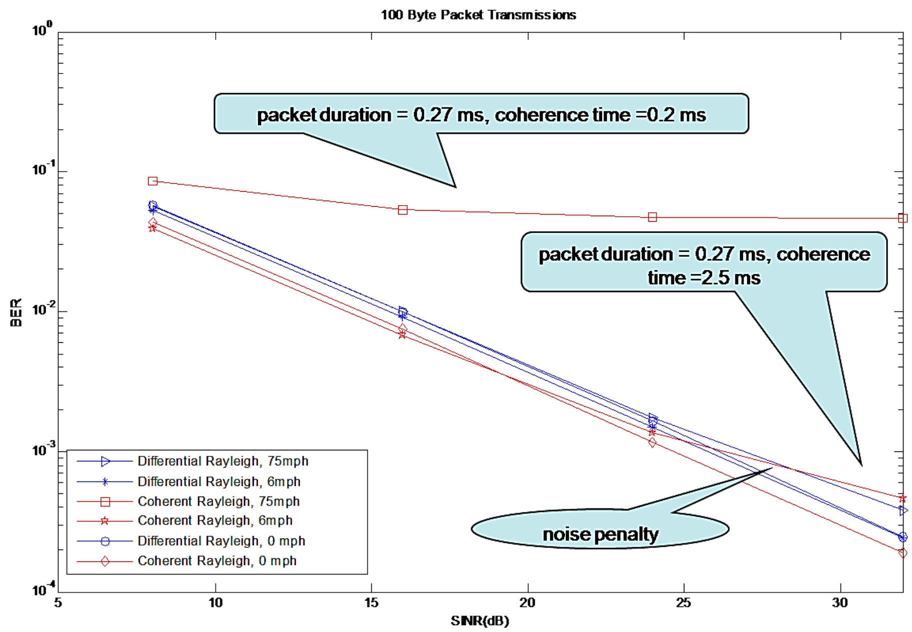


Figure 4.4-2. Simulation Based Evaluation of Differential OFDM

(Ref: Zhang, et al, "A Differential OFDM Approach to Coherence Time Mitigation in DSRC", *Proceedings of VANET 2008*. [146])

4.5 Applications of Advanced Wireless Communication Technologies

Several advanced wireless communication technologies that may be important for the eventual success of SPaT applications have been described. The importance of these technologies arises due to the challenging environment for vehicular communications. Not only is the wireless propagation influenced by surrounding objects such as buildings, but significant mobility further effects signal reception. At the same time, the QoS requirements for SPaT applications are quite stringent as low latency and high delivery ratio are necessary. Due to the combination of the above factors, a multi-faceted approach needs to be taken for developing communication systems for roadway environments. Four complementary advanced technology areas have been discussed that include antenna technologies, Cognitive Radio, Software-defined Radio, Connected Radio, and advanced modulation techniques and protocols. These advanced communication technologies are still under research and development, but have been identified as potentially beneficial to SPaT applications.

From the standpoint of communication performance, some of the technology areas may be more effective than others. However, the ease of realizing the advancements may be quite different due to standardization and other business reasons.

Advanced modulation techniques and systems such as MIMO may be an effective way, but need prior configuration at vehicles as well as the infrastructure. Advanced antenna techniques such as beam forming and phased array methods may be implemented at intersections. Initial SPaT systems may directly benefit from advanced antenna. Additional study, analysis and testing of antenna technology for vehicle applications is recommended, especially related to vehicle ground plane impact on antenna patterns and slope of the vehicle's top versus impact on antenna coverage. Basic Design improvements of the antenna (not considering SMART antennas) can improve overall V2I communications as well as V2V communications can provide communications improvements with minimal cost in production and should be considered as a priority need in connected vehicle highway program.

Cognitive radio and adaptive modulation techniques may also help with SPaT applications as the RF environment may vary over a wide range. Further studies can involve characterizing the different modulation schemes and possible feedback-based methods for switching between different modulations methods

Relative mobility in communication between roadside equipment and the vehicles also influences communication performance especially on urban roadways. It also requires development of a low overhead, low latency protocol, that is compatible with the data load and data rates required for V2I and V2V safety related communications. Specifically, due to the presence of a large number of vehicles, the aggregate network capacity is insufficient to support SPaT messages in addition to part 1 and part 2 HIA. The major issues include the communications load as more vehicles are within communications range and the impact of incorporating both safety and service communications on a single network. Numerous simulations have shown the impact on PER and undelivered messages as the number of vehicles increase in a connected vehicle communications environment. Much more research is required in this area, and connected radios with multi-hop communication between vehicles may prove to be an effective way to disseminate messages for SPaT applications. The approaches may involve transmitting at reduced power and selective forwarding. Relaying-based approaches have been shown to have high reliability, and also help in achieving localized communication that is required of SPaT applications. However, these methods require interworking between different vehicles, and also the roadside communication equipment, and may benefit later generations of SPaT application deployment.

In summary, given the challenging conditions and the stringent requirements due to safety considerations, a combination of the advanced techniques can assist in the eventual deployment success of SPaT applications. Table 4.5-1 summarizes the benefits of advanced technologies in enhancing different communication methods.

Table 4.5-1. Benefits of Advanced Technologies

Advanced Technology	Application To DSRC	Application To LTE	Application To HD Radio
SMART Antennas	S/N Improvement; Range extension; Improved	Already in use	No Advantage

Advanced Technology	Application To DSRC	Application To LTE	Application To HD Radio
	reliability. **Recommended for further consideration**		
MIMO	Helps in environment with rich scattering. Being considered by DSRC manufacturers; **Further research recommended**.	Already in use	No Advantage
SDR	Already in use; Supports low cost evolution	Already in use; Supports low cost evolution and adaptive frequency	Low cost evolution advantage
Cognitive Radio (Policy-based Communications, White Space Automatic Acquisition and Cooperative use)	Limited advantage in the 5.85-5.925 MHz spectrum	No advantage in the 700 MHz Emergency Band	No Advantage; Licensed broadcast radio frequencies
Cognitive Radio (Adaptive Communications and cooperative use)	Significant benefit. **Recommended for further consideration, especially for service application implementation**	Already in use	Incompatible with modulation standard
Connected Radios (V2V Message Relay, Low overhead-low latency Protocol)	Issues with protocol standardization. Longer term recommendation. Relaying protocols shown to support higher aggregate throughput than broadcast with a large range	N/A	N/A
Protocols (Location/Area based multicast (geocast))	N/A for 1000 meter range	Useful for jurisdictional LTE to disseminate messages to certain areas; emerging from Emergency Communications Requirements using LTE	Possible using HAR-like deployment with tailored area messaging. Geocast protocol not needed

Source: ARINC April 2012

Chapter 5 - Comparative Analysis of SPaT Related Communications Requirements with Currently Available Technologies

In this section, the candidate communication technologies are analyzed to assess their ability to support SPaT applications communications requirements as identified in Task 2. The assessment includes comparing capabilities of the communication technologies against the requirements, assessing communication network capacity, issues such as impact of other traffic such as BSM (Basic Safety Message), and HIA ("Here-I-Am") messages, broadcast and unicast approaches to message dissemination, and partitioning schemes for broadcasting GID/Map Data and DGPS messages. The Task 3 report associated with this project provided the market scan of communications technology and section 3 of this document presents the communications technology determined to be most appropriate for SPaT applications.

5.1 Intersection Safety Communications Requirements Revisited

The requirements for intersection safety applications were described in detail in Section 2. The most critical operational requirements are summarized in Table 5.1-1 below.

Table 5.1-1. Communications Requirements Based on ARINC Task 2 Report

	Requirements Based on Task 2 Analysis		
Parameter	**RLR, LTA, RTA**	**RCRLV**	**TSP, FSP, PREEMPT**
Speed	60 mph	60 mph	60 mph
Range	656 ft. (324 m)	606 ft. (185 m)	1689 ft. (515 m)
Data Rate			
SPaT	6 Kbps	6 Kbps	6 Kbps
GID	34 Kbps	34 Kbps	34 Kbps
DGPS	2.4 Kbps	2.4 Kbps	2.4 Kbps
V2V (BSM Part1)	4.77 Mbps	4.77 Mbps	4.77 Mbps
Message Update Period			

	Requirements Based on Task 2 Analysis		
Parameter	**RLR, LTA, RTA**	**RCRLV**	**TSP, FSP, PREEMPT**
SPaT	0.1 sec	0.1 sec	0.1 sec
GID	19 sec	19 sec	19 sec
DGPS	30 sec	30 sec	30 sec
Comm. Failure Rate (BER)	10^{-3} to 10^{-4}	10^{-3} to 10^{-4}	10^{-3} to 10^{-4}

Source: ARINC April 2012

Table 5.1-2. Communications Requirements Based on Appendix B

	Requirements Based on Green Book			
Parameter	**RLR, LTA, RTA, RCRLV**		**TSP, FSP**	**PREEMPT**
Speed	30 mph	60 mph	45 mph	60 mph
Range*	243 ft. (74m)	661 ft. (202 m)	430 ft. (131 m)	1269 ft. (389 m)
Data Rate				
SPaT	6 Kbps	6 Kbps	6 Kbps	6 Kbps
GID	34 Kbps	34 Kbps	34 Kbps	34 Kbps
DGPS	2.4 Kbps	2.4 Kbps	2.4 Kbps	2.4 Kbps
V2V (BSM Part1)	4.77 Mbps	4.77 Mbps	4.77 Mbps	4.77 Mbps
Message Update Period				
SPaT	0.5 sec**	0.5 sec**	0.5 sec**	0.5 sec**
GID	19 sec	19 sec	19 sec	19 sec
DGPS	30 sec	30 sec	30 sec	30 sec
Message Failure Rate (PER)				
Warning (SIL1)	$2x10^{-3}$	$2x10^{-3}$	$2x10^{-3}$	$2x10^{-3}$
Automated Braking (SIL2)	$2x10^{-2}$	$2x10^{-2}$	$2x10^{-2}$	$2x10^{-2}$

Source: ARINC April 2012

*Note: This is the minimum range at which the SPaT message must be received with reliability greater than 99.9% (failure rate $<10^{-3}$)

** Note: SAE J2735 specifies 0.1 second update, but this does not appear to be an application requirement. The maximum update interval is primarily determined by the acceptable delay added to the signal timing sequence when the sequence changes (since the system must not change the signal sequence until all approaching vehicle that cannot respond in time have cleared the intersection). We have assumed that 0.5 seconds *at the required reliability level* is acceptable.

5.2 DSRC

DSRC is a short to medium range communication technology (specified to operate up to a range of 1000 m (3281 ft.), and designed to provide wireless communications necessary to meet SAE J2735 message transmission from RSEs to vehicle OBEs.

For intersection safety applications, typically a DSRC-enabled RSE will transmit SPaT and MapData messages that will be received and processed by approaching vehicles.

Range performance of DSRC varies widely depending on the test situation and specifics of the receiver arrangement. Line-of-Sight (LOS) performance was measured during the VII Proof of Concept testing

(Ref: “Final Report: Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary – Vehicle”, VII, May 19, 2009 [50]).

Figure 5.2-1 illustrates the LOS results of PER vs. communication range in an urban environment. These tests included WSM and UDP transmissions. It should be noted that a multipath null point is identified in the sub-urban like environment. To consider the maximum effective communication range, the impacts due to this null point are not included in the analysis. However, this communication null point must be addressed through diversity antennas and other processing if DSRC is to be considered for this application. The effective communication range when PER reaches 12% in an urban environment is around 420 meters. For a 1500 byte WAVE Short Message this corresponds to a BER of $1x10^{-5}$.

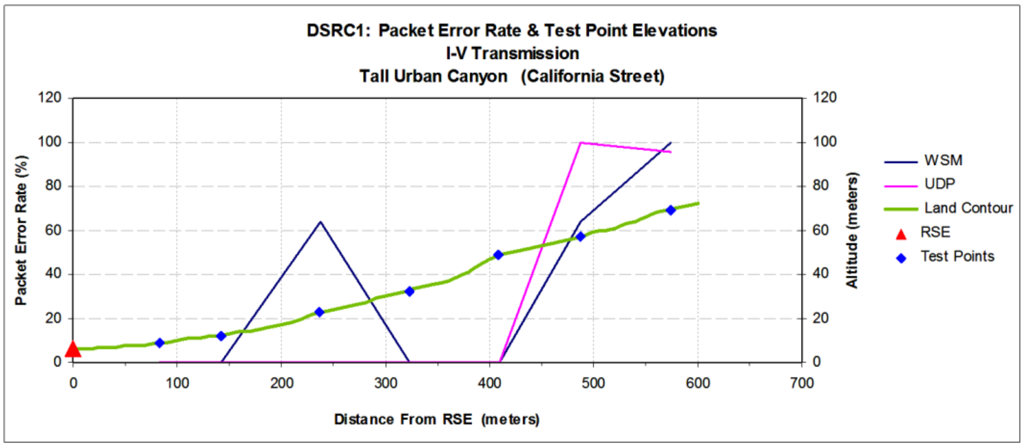


Figure 5.2-1. Tall Urban Canyon vs. Distance for Urban Environment

(Ref: USDOT Report FHWA-JPO-09-043, “Final Report: Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary – Vehicle”, May 19, 2009. [50])

Figure 5.2-2 illustrates the LOS results of PER vs. communication range in a modest urban environment. The effective communication range when PER reaches 12% in a modest-urban environment is 325 meters.

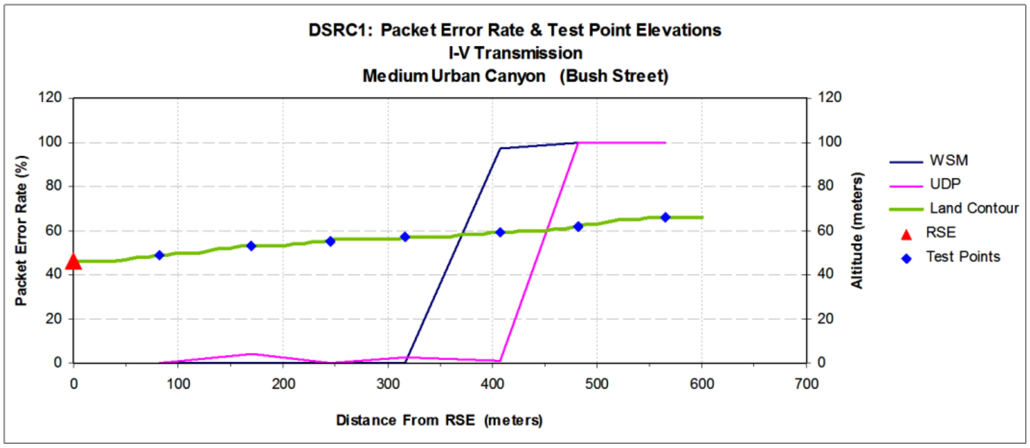


Figure 5.2-2. Packet Error Rate vs. Distance for Urban Environment

(Ref: USDOT Report FHWA-JPO-09-043, “Final Report: Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary – Vehicle”, May 19, 2009.[50])

A separate study of communications performance in urban and non-urban environments was carried out by (Ref: “Characterization of DSRC Performance as a Function of Transmit Power”, Kezhu Hong, et al, *VANET 2009* [147]). The goal of this field test was to quantify the relationships between transmit power level and communication performance in realistic propagation environment. The measurement scenario adopted in this study was to place the transmitter in one side of the intersection and the receiver in the other side of the intersection to artificially create controlled Non-Line-of-Sight testing environment. The effective communication range was derived based on the distance of transmitter to the intersection, and the distance from the receiver to the intersection. The key parameters configured in this study were:

- Maximum transmit power: 33 dBm
- Message size: 400 bytes
- DSRC data rate: 3 Mbps (therefore, BPSK is used in this study)

In addition to the maximum transmit power test, testing using two configurations of lower transmit power, 10 dBm and 20 dBm, was also performed. Other key parameters remained unchanged.

Figure 5.2-3 illustrates the PER as a function of transmit power and range. For a communication range of 200 meters (656 ft.) in the urban environment, the PER reached 80%. The PER was 65% for 175-meter communication range in the sub-urban environment.

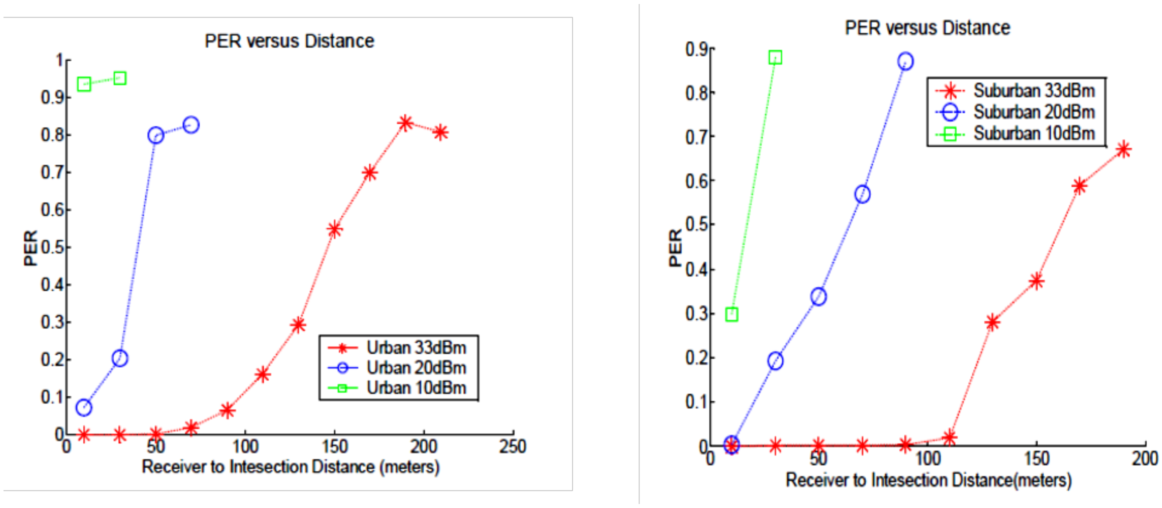


Figure 5.2-3. Packet Error Rate vs. Distance in Urban and Sub-Urban Environments

(Ref: Hong, Kezhu, et al, "Characterization of DSRC Performance as a Function of Transmit Power", *VANET 2009.*) [147])

Figure 5.2-4 illustrates an analysis of the Detroit POC field test and simulator results (Ref: "Analysis of Detroit POC Trial Results and Use in Validating a DSRC Simulator", Adelin Miloslovav, et al, 10- 2010 [148]). This figure shows a 30% PER at 200m and improvement to .01% PER with 4 transmissions. It also shows that 4 retransmissions will provide only a 95% probability of successful receipt at 400 meters range.

Comparing the requirements set for SPaT applications, the effective communication range can only satisfy four of the seven SPaT applications.

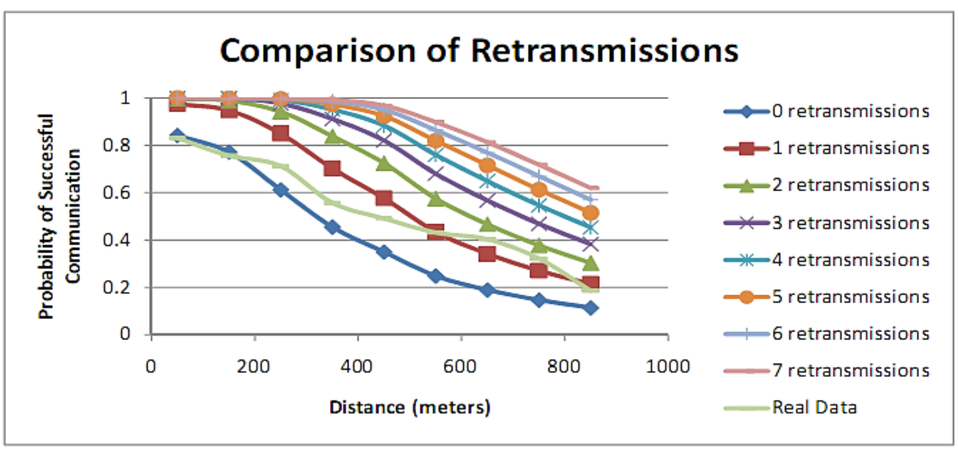


Figure 5.2-4. Example of Improved Probability of Error Free Message Receipt Based on Multiple Message Transmissions Using DSRC

(Ref: "Analysis of Detroit POC Trial Results and Use in Validating a DSRC Simulator", Adelin Miloslovav, et al, 10- 2010 [148])

Based on the SPaT applications requirements, the required message failure rate for RLR warning is less than $2x10^{-3}$. This will allow the application to achieve SIL 1 accounting for other errors such as positioning, and human response (See Appendix A). For a 383 byte SPaT message, this equates to a BER of $6.5x10^{-7}$.

Based on the measurements above this reliability can be achieved with about 7 message transmissions at about 200 meters.

Conclusions

DSRC range and communications reliability performance relative to the Task 2 requirements is summarized in Table 5.2-1.

Table 5.2-1. DSRC Performance vs. Task 2 Requirements

Requirement	Application							DSRC Capability	
	RLR	LTA	RTA	PREEMPT	TSP	FSP	RCRLV	Urban	Suburban
Comm. Range (m)	303	314	324	515	515	515	170	425	325
BER	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-5}	10^{-5}
Retries to Meet BER Requirement at Range	None	None	None	7	7	7	None	N/A	N/A

Source: ARINC April 2012

DSRC range and communications reliability performance relative to the Appendix B requirements is summarized in Table 5.2-2.

Table 5.2-2. DSRC Performance vs. Requirements Based on Appendix B

	Requirements Based on Green Book	DSRC Capability
Parameter	**RLR, LTA, RTA, RCLV**	
Speed	60 mph	60 mph
Range		325 m
RLR, LTA, RTA, RCLV	661 ft. (202 m)	
FSP, TSP	430 ft. (131 m) (45 mph)	
PREEMPT	1269 ft. (389 m)	
Data Rate		6mbps
SPaT	6 Kbps	OK
GID	34 Kbps	OK
DGPS	2.4 Kbps	OK
V2V (BSM Part1)	4.77 Mbps	OK
Message Update Period		

	Requirements Based on Green Book	DSRC Capability		
Parameter	**RLR, LTA, RTA, RCLV**			
SPaT	0.5 sec**	OK		
GID	19 sec	OK		
DGPS	30 sec	OK		
Message Failure Rate (PER)		I Transmission	5 Transmissions	8 Transmissions
Warning (SIL1)	$2x10^{-3}$	$3x10^{-1}$	$1.9x10^{-2}$	$2.3x10^{-3}$
Automated Braking (SIL2)	$2x10^{-2}$			

Source: ARINC April 2012

We assume that there is limited additional overhead as number of users increases i.e., the rate per user is inversely proportional to the number of users. This will be true below saturation point. In reality, the aggregate throughput achieved by the network users first increases as the number of users increases and then falls down.

The calculation in Table 5.2-3 evaluates the available capacity for SPaT message transmission in the presence of background traffic at an urban intersection. The vehicles are assumed to travel at approximately 30 mph leading to the presence of approximately 150 vehicles at the intersection. Further, we assume that all vehicles are equipped with DSRC radios and actively sending HIA (Here-I-Am) messages. We conclude that with background traffic consisting of HIA Part 1 messages, DSRC is capable of supporting a typical intersection with the parameters specified. However, when each vehicle sends HIA messages with Part 1 and Part 2, DSRC capacity is insufficient.

Table 5.2-3. Capacity Analysis for DSRC

Number of vehicles crossing per second per direction at intersection:	0.5 cars/sec
Carrier sensing range (2* Tx Range)	2*250=500m
Average speed of vehicles	30 mph
Average duration of a vehicle in sensing vicinity	1000m/30mph=75 seconds
Number of vehicles in the intersection area (assuming 2 streets i.e., 4 directions-2 way)	2*2*75*0.5=150 vehicles
Packet interval for Safety Message	100 milliseconds
Data rate per intersection (Safety related)	40 Kbps
Aggregate offered load (Part 1 HIA @ 10Hz)	4.09 Mbps with 150 vehicles
Aggregate offered load (Part 1+ Part 2) HIA @ 10Hz)	25.5 Mbps with 150 vehicles
DSRC Max throughput	6 Mbps

Source: ARINC April 2012

Table 5.2-4 summarizes the capability of DSRC in supporting SPaT application requirements.

Table 5.2-4. Comparison of DSRC against SPaT Applications Communications Requirements

SPaT Applications Related Communications Requirement	Specification Requirement	DSRC
Communications Service	Best Effort	Best Effort
Communications Range (High Probability of Message Receipt)	200 m RLR, LTA, RTA, RCRLV 131 m FSP, TSP (45 mph) 389 m (11269 ft.) PREEMPT	200 m with high reliability in urban conditions, may be improved with diversity antennas
Maximum bit error rate (BER) and Confidence Factor	10^{-3} with 99.9% Confidence Factor	10^{-4} (5 dB SNR @ 3 mbps; 15 dB SNR @ 6 mbps; 28 dB SNR @ 27 mbps)
Data Throughput, SPaT Messages	40 kbps (Includes single intersection GID associated with the application)	Aggregate 4-6 Mbps possible
Background Data Load on DSRC (HIA Msg) in which SPaT Messages Must Compete	4.7 mbps considering J2735 part 1; 29.3 mbps considering J2735 part 1 & 2; Based on 172 vehicles within communications range	Can accommodate SPaT with background J2735 part 1 at urban intersections. Part 1& 2 background will overload
Vehicle Speed/Doppler Accommodation	200 km/h (124 mph) Ref: IEEE Std. 802.11p PAR	Can support 200 km/hr
Multipath Environment	Rural and Urban Canyon	1.6 μsec delay spread tolerated (0.48 km path difference)
Quality of Service	Different Class of Services Supported with Highest Class having Highest Priority; Meets SPaT communications requirements at all times when operational	Best Effort
Availability	99.99% for Safety Integrity Level 4 (IEC 61508); Achieved through fault tolerant DSRC design	Can support 99.99% availability
Radio Frequency Environment	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)	Demonstrated to operate in urban, suburban and highway environments

SPaT Applications Related Communications Requirement	Specification Requirement	DSRC
Vehicle Separation Distance with no Radio Frequency Interference	Parallel lane adjacent vehicles and same lane with 4 m separation (low speed- 8 km/h; 5 mph) approach to a signalized intersection	Field test report interference issues
Dual Transceiver Simultaneous Operations in a Single Vehicle	No Co-channel or In-band Interference	Supported. (-40 dB adjacent channel interference rejection)
Environmental and Power Compatibility	RSE: Compatible with NEMA TS-2 Specification; OBE: Compatible with SAE Specifications for Light and Heavy Vehicles	Compatible: NEMA TS2-2003 v02.06, SAE J1113, SAE J1211 & SAE J551
Size and Weight	Compatible with Small Car (Approx. Size 500 cu in/8195 cm^3; Approx. Wt. 2 lbs./0.91 kg)	244 cu in with approx. Wt. 0.6 kg (1.3 lbs.)
Cost	Affordable to Private vehicle Purchaser	Cost under $300

Source: ARINC April 2012

5.3 LTE

In this section we consider the ability of LTE to support SPaT requirements using unicast or LTE broadcasting capabilities such as cell broadcast service and MBMS (Multimedia Broadcast Multicast Service). Based on these capabilities we analyze LTE capacity for SPaT data rates.

Note that LTE requires licensed frequencies, which have been purchased by the major cellular communications service providers. Use of the deployed, cellular LTE communications infrastructure will require a continuing fee for use of bandwidth, which is precluded as a consideration related to this project. However, FCC has dictated that jurisdictions will utilize LTE for their interoperable communications within the 700 MHz frequency band, licensed to jurisdictions for emergency mobile communications by the FCC. Since road safety information (GIDs, DGPS, roadway related weather, and other roadway safety information) is required by emergency vehicles, broadcast of road safety related information via a 700 MHz, jurisdictional LTE wireless network is reasonable to consider. However, a jurisdiction’s LTE network would have an unacceptable data load if it supported V2V messaging. Thus broadcast use of an LTE network is the only viable consideration.

The granularity of SPaT message dissemination using the public safety LTE network would be at the cell-level. Thus for each cell, the SPaT messages for those intersections covered by the cell would be disseminated using the local LTE eNB (base station). The advantage of using LTE is that the vehicle-to -vehicle communication such as HIA is not carried over LTE networks, thus it does not incur additional loading on LTE networks disseminating SPaT (as it would in the DSRC case). However, other public safety applications and vehicle density will affect loading on LTE networks.

As shown in Figures 5.3-1 and 5.3-2, the TMC or the signal controller can act as the content provider and send SPaT information via the LTE core to the relevant cell eNB.

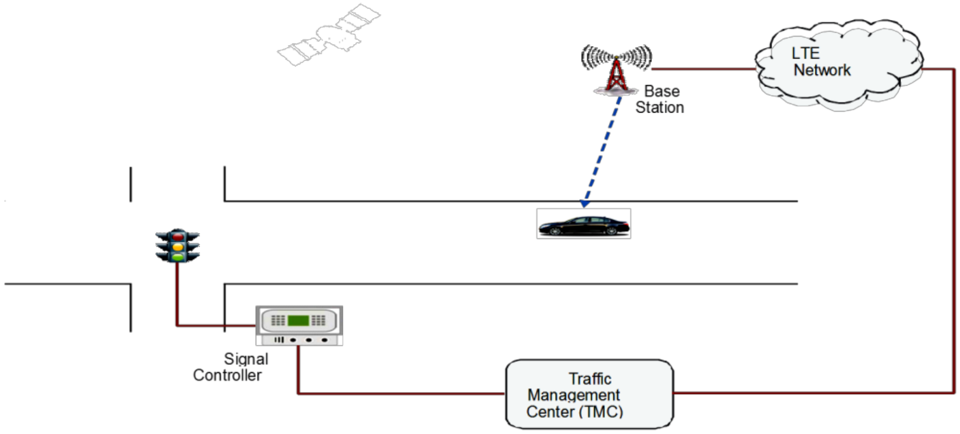


Figure 5.3-1. TMC Connected to LTE Network

Source: ARINC April 2012

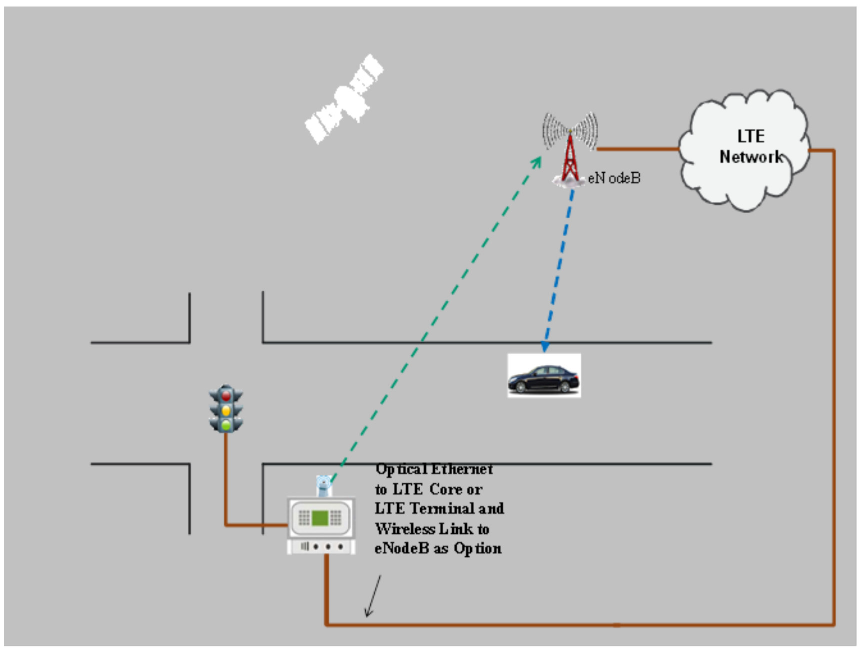


Figure 5.3-2. Signal Controller Connected to LTE Network

Source: ARINC April 2012

SPaT message sizes will vary depending on the size of the intersection. The SPaT message may be associated with only one intersection in the cell coverage area. This is especially true of the SPaT message is sent by the individual signal controllers. The size of the LTE cell will determine the number of intersections covered and the number of SPaT messages sent. As the number of intersections in the cell area and the size of intersection increases, higher data rates are required.

Multiple services can efficiently be delivered to user devices using advanced session management which makes it possible to bring in different services to the device over one radio connection. These services can be assigned different priorities during transmission via QoS as shown in Table 5.3-1. Additionally, since the vehicle will receive many SPaT messages, most of which will not be applicable to the current intersection the vehicle is approaching, the vehicle will need to filter the received messages. There are several challenges as related to LTE QoS, including competing with emergency messaging and high priority emergency video over a jurisdictional LTE network. As can be seen from Table 5.3-1, latency and PER are related to the QoS level of service assigned to the application; a QCI with packet delays of 50 to 300 msec is typical. Additionally, field trial results show average delays of less than 50ms but with no per QoS class behavior captured.

SPaT has a requirement of 185 meter communication range. This means that any vehicle closer than this range must have received the currently valid SPaT message with the required reliability. In addition, since the SPaT message may change as a result of preemption or signal priority, the minimum time between SPaT messages may be 0.5 seconds.

The LTE base station range can vary from typically several kilometers or less in urban environments. The LTE standard requires full performance at distances up to 5 km and allows for degradation at distances 5 km – 30 km. The LTE base station range can be sized to meet the number of users and bandwidth requirements of the Public Safety LTE.

Table 5.3-1. Quality Class Identifiers for LTE Communications Network

(Ref: “QOS over 4G Networks”, Harish Vadada, 8-2010 [149])

QC1	Resource type	Priority	Packet delay budget	Packet error loss rate	Example services
1	GBR	2	100 ms	10^{-2}	Conventional coice
2		4	150 ms	10^{-3}	Conventional video (live streaming)
3		3	50 ms	10^{-3}	Real time gaming
4		5	300 ms	10^{-5}	Non-conversational video (buffered streaming)
5	Non-GBR	1	100 ms	10^{-3}	IMS signaling

QC1	Resource type	Priority	Packet delay budget	Packet error loss rate	Example services
6		6	300 ms	10^{-5}	Video (buffered streaming)
					TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-5}	Voice, video (live streaming), interactive gaming)
8		8	300 ms	10^{-3}	Video (buffered streaming)
9		9		10^{-5}	TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)

SPaT has a requirement for BER of 10^{-3}. Unlike the Universal Mobile Telecommunications System (UMTS) and earlier systems, LTE has no requirements based on BER but uses QoS. There are different QoS classes, which can be used to meet appropriate bit rate errors and reliability for sessions. The QoS class packet error rate ranges from 10^{-2} to 10^{-6} and adaptive modulation and MIMO techniques can be used to maintain the BER below a predefined target value by modifying the signal transmitted to a particular user according to the instantaneous radio link quality. In 3GPP TS 36.101, performance requirements define SNR values required to achieve 70% throughput. For example, for a 5 MHz channel with a single antenna, the SNR is 6.7 dB at 16QAM and SNR is 17.4 dB at 64QAM to achieve 70% throughput. Additionally there have been simulation results considering the BER vs. SNR for various modulation rates. One such example considers ITU channel models, Pedestrian-A with speeds 3 km/h (“PA3”), Vehicular-A at 120 km/h (“VA120”), and Vehicular-A at 350 km/h (“VA350”) channel models as shown in Figure 5.3-3. Based on these simulations, it may not be possible to meet BER of 10^{-3} at vehicle speeds specified for SPaT of 200 km/hr (124.3 mph). However, there are no publicly available field trial results to confirm these simulations.

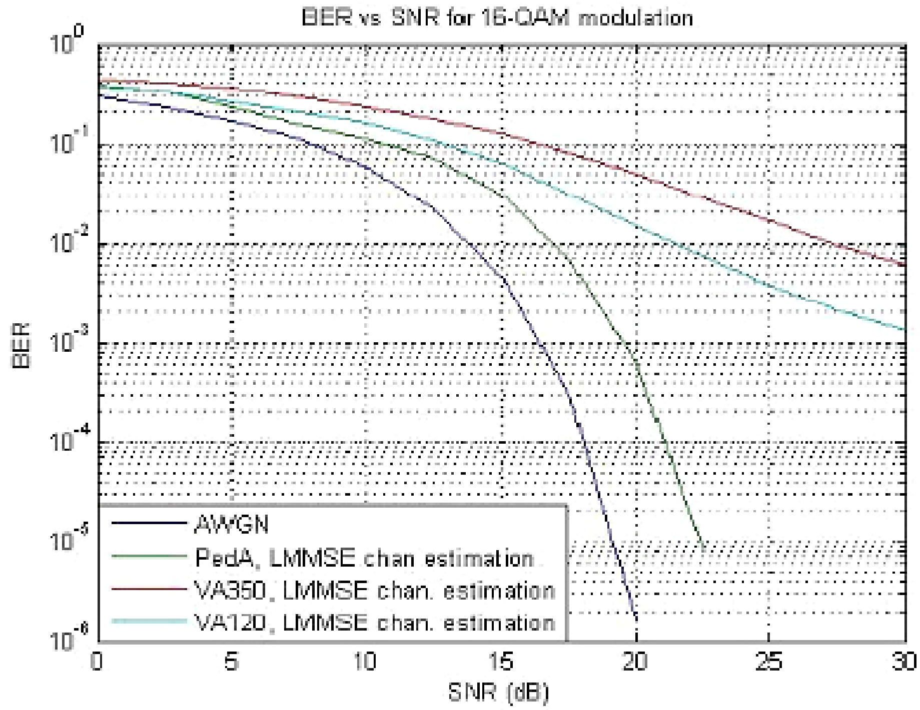


Figure 5.3-3. BER vs. SNR for 16QAM modulation on 20 MHz channel

(Ref: A. Osmana, et al, "Multipath Wave Propagation Effects on the Performance of OFDM UMTS-LTE Communications System", *AIP Conference Proceedings*, 2009 [150])

SPaT has a requirement of 99.9% availability (see appendix 3 and safety integrity level considerations for SPaT). Cellular network availability is designed to be high and can be engineered to support 99.9% availability. To achieve higher reliability or to compensate for less-reliable components, redundancy of base stations can be used. In addition access to resources and availability of bandwidth would be based on admission control and whether service requests are accepted. For this, LTE has allocation and retention priority (ARP) that operates in the eNB to determine whether a certain service can be accommodated (i.e., is available).

LTE standards support mobility for speeds up 350 km/h, which meets SPaT requirements to support vehicles speeds. LTE can also operate in rural and urban canyons with additional base stations placed as needed as part of cell planning to support number of users and bandwidth requirements. In areas where inter-symbol interference is expected, it can be avoided by inserting a guard period or cyclic prefix. For LTE, the standard length of the cyclic prefix has been chosen to be 4.69 μs. This enables the system to accommodate path variations of up to 1.4 km versus the 0.5 km path difference for DSRC.

The LTE user devices are small and are available in OBE compatible or hand held configurations; thus they can meet the SPaT requirement of size, weight and supportability within the vehicle. Additionally the LTE base station meets environmental requirements for outdoor use and is already deployed by commercial carriers.

SPaT requires a 40 kbps data rate. The LTE expected user data rate depends on many factors such as modulation, distance to cell, cell loading, etc. For unicast sessions, the LTE base station can adjust rate/ resources and modulation based on user feedback and distance from base station; for the broadcast modes this is not performed.

The MBMS broadcast capability is standardized in the LTE and can be applied in public safety networks for SPaT message broadcast. This would include the implementation of at least the MBMS gateway and the MCE. There is no limitation to the number of vehicles that can be served using broadcast mode since MBMS uses a dedicated multicast channel for MBMS services. The channel, however, would be shared with other broadcast/multicast applications services. Additionally when using MBMS, the user device will also need to be MBMS-enabled and provided with the key for the SPaT service channel. If the SPaT message is designated as a high priority type message then it can have a likely guarantee for availability of the network resources within MBMS. The typical latencies and availability of LTE networks would also apply to MBMS services, provided that the MBMS capability is enabled in both the eNB and the user device.

SPaT messages could also be broadcast using the cell broadcast service (CBS) but may require further analysis on operation of CBS in LTE and the loading of other public safety traffic on the CBS channel. The SPaT application may have the same message repeated or send out a new message at the 100 millisecond interval with the updated intersection information. The new message may be a repeat of the previous message (other than message time update) if no changes in SPaT have occurred.

5.3.1 *Scenario for High-level Capacity Analysis*

For our capacity analysis, let us assume a sample scenario in the NYC area. We use a cell radius of 0.5 km based on dense urban model for cell planning in NYC (Position: Lexington Ave and E 60th Street). Public safety LTE uses 10 MHz bandwidth in the 700 MHz spectrum with 5 MHz allocated for downlink and 5 MHz for the uplink. The cell is configured to have three sectors and can support a throughput of 150 Mbps in each sector (Ref: http://www.nec.com/global/solutions/nsp/lte/pdf/brochure.pdf [151]). Each sector can support up to 200 active users in a 5 MHz channel and up to 1000 idle users.

There are 13 streets and 7 avenues within the coverage area. There are 65 signalized intersections. If we consider a target time frame of 8 AM – 9AM, the total number of vehicles entering the cell coverage area is 6528 as shown in Figure 5.3-4. The total number of vehicles leaving the cell coverage area is 6045 as shown in Figure 5.3-5.

SECTION E
AUTOS, TAXIS, COMMUTER VANS AND TRUCKS BY FACILITY
60TH STREET SECTOR, 2009-INBOUND

HOURS	FDR DRIVE	YORK AVENUE	SECOND AVENUE	LEXINGTON AVENUE	PARK AVE	FIFTH AVENUE	SEVENTH AVE (C.P. EXIT)	BROADWAY	COLUMBUS AVENUE	WEST END AVENUE	WEST SIDE HWY	TOTAL
12:00am	1,588	490	1,697	779	395	605	-	631	838	269	756	8,048
1:00am	753	226	1,116	457	182	363	-	583	494	160	436	4,770
2:00am	508	163	846	344	119	241	-	419	335	105	319	3,399
3:00am	435	134	834	307	85	220	-	272	284	82	314	2,967
4:00am	698	217	1,090	353	108	353	-	211	297	95	513	3,935
5:00am	1,894	495	1,576	587	171	705	-	156	461	166	1,570	7,781
6:00am	3,901	823	1,987	1,064	443	1,338	-	164	829	412	4,029	14,990
7:00am	4,933	817	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	18,881
8:00am	5,273	828	2,066	1,506	1,502	1,454	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	21,416
9:00am	5,038	815	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20,675
10:00am	4,372	881	2,141	1,270	1,198	1,261	42	927	1,234	869	3,714	17,909
11:00am	3,975	986	2,349	1,160	1,112	1,187	-	872	1,325	858	3,120	16,944
12:00pm	3,960	1,021	2,273	1,196	1,100	1,176	-	827	1,115	847	2,844	16,359
1:00pm	4,024	1,072	2,273	1,199	1,118	1,082	-	797	1,305	850	2,804	16,524
2:00pm	4,242	1,147	2,272	1,288	1,193	1,074	-	736	1,327	879	2,845	17,003
3:00pm	4,440	1,217	2,250	1,302	1,078	1,212	-	731	1,329	868	3,234	17,661
4:00pm	4,260	1,193	2,188	1,168	1,066	1,161	-	738	1,259	875	3,411	17,319
5:00pm	4,680	1,262	2,218	1,296	1,148	1,208	-	670	1,252	858	3,774	18,366
6:00pm	4,774	1,181	2,384	1,386	1,264	1,414	-	643	1,519	956	3,605	19,126
7:00pm	4,623	1,143	2,643	1,499	1,377	1,565	-	681	1,478	1,111	3,319	19,439
8:00pm	3,827	1,031	2,494	1,506	1,224	1,428	-	696	1,386	992	2,204	16,788
9:00pm	3,190	882	2,375	1,400	1,022	1,465	-	747	1,302	771	2,087	15,241
10:00pm	2,973	834	2,360	1,421	980	1,467	-	747	1,489	733	1,873	14,877
11:00pm	2,678	770	2,262	1,229	711	1,255	-	683	1,284	609	1,439	12,920
TOTAL	81,039	19,628	47,966	26,436	21,181	26,195	1,809	14,869	25,676	16,056	62,483	343,338

Number of Vehicles: 6528

Figure 5.3-4. Inbound vehicles at 60th street

(Ref: "Hub Bound Report 2009", NYMTC, January 2011 [152])

SECTION E
AUTOS, TAXIS, COMMUTER VANS AND TRUCKS BY FACILITY
60TH STREET SECTOR, 2009-OUTBOUND

HOURS	FDR DRIVE	YORK AVE	FIRST AVE	QUEENSBORO RAMP	THIRD AVE	PARK AVE	MADISON AVE	SIXTH AVE (C.P. Entrance)	CENTRAL PARK WEST	BROADWAY	AMSTERDAM AVE	WEST END AVE	WEST SIDE HWY	TOTAL
12:00am	1,574	266	1,020	720	965	257	600	-	427	437	554	122	1,460	8,402
1:00am	823	123	704	414	630	121	335	-	241	258	336	65	795	4,845
2:00am	520	90	500	324	462	76	222	-	147	186	250	43	529	3,349
3:00am	480	97	436	440	394	60	175	-	106	146	207	38	409	2,988
4:00am	758	162	548	917	484	80	221	-	161	131	265	61	460	4,248
5:00am	1,737	280	815	1,947	674	185	367	-	203	196	489	134	638	7,665
6:00am	3,287	656	1,497	2,318	1,220	521	859	-	374	390	987	383	1,360	13,852
7:00am	3,966	1,035	2,122	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2,312	18,875
8:00am	3,689	1,100	2,217	1,713	1,807	1,287	1,238	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2,473	18,990
9:00am	3,357	990	2,015	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2,059	18,011
10:00am	3,008	830	1,849	1,679	1,693	1,124	954	368	741	653	1,206	589	2,078	16,772
11:00am	2,992	780	1,709	1,664	1,523	1,106	917	376	716	605	1,223	505	2,271	16,387
12:00pm	3,126	777	1,723	1,739	1,548	1,127	979	377	760	583	1,224	415	2,406	16,784
1:00pm	3,217	896	1,780	1,733	1,561	1,086	1,072	372	727	685	1,199	379	2,571	17,278
2:00pm	3,576	980	1,879	1,750	1,617	1,170	1,083	468	698	647	1,251	420	3,190	18,729
3:00pm	3,792	960	1,856	1,570	1,497	1,163	1,131	580	706	707	1,332	472	3,687	19,453
4:00pm	3,521	795	2,004	1,685	1,284	1,229	1,056	633	693	692	1,432	484	3,276	18,784
5:00pm	3,599	857	2,156	1,800	1,505	1,317	1,147	695	728	745	1,583	598	3,459	20,189
6:00pm	3,674	896	2,227	1,685	1,675	1,318	1,484	508	797	865	1,578	1,009	3,311	21,027
7:00pm	3,472	855	1,925	1,551	1,726	1,162	1,586	-	839	904	1,438	469	3,411	19,338
8:00pm	3,276	729	1,697	1,454	1,760	1,014	1,456	-	794	757	1,277	333	3,083	17,630
9:00pm	3,082	666	1,636	1,386	1,816	977	1,394	-	821	727	1,266	309	3,232	17,312
10:00pm	2,799	585	1,629	1,467	1,645	861	1,344	-	815	724	1,248	287	3,025	16,429
11:00pm	2,296	440	1,484	1,129	1,469	581	972	-	690	611	1,010	186	2,307	13,175
TOTAL	65,621	15,845	37,428	34,937	32,574	20,196	22,997	5,492	14,302	13,593	25,031	8,694	53,802	350,512

Number of Vehicles: 6045

Figure 5.3-5. Inbound vehicles at 60th street

(Ref: "Hub Bound Report 2009", NYMTC, January 2011 [152])

The total number of vehicles counted in one hour is therefore 12,573. The roads covered in the traffic data collections are one-way roads with the exception of Park Ave, which has bi-directional traffic. The total number of intersections used in the data collections is 8. By calculating the number of cars which crosses the 8 intersection over one hour we get the volume of one-way direction traffic across an intersection, 12573 car /3600sec / 8 = .44 vehicles per second.

5.3.1.1 Broadcast Analysis

LTE broadcast can be used to disseminate SPaT messages. If MBMS is used, then each vehicle device needs to listen to the SPaT MBMS service channel. It may be possible to designate a different channel for each intersection in the cell area. Then the MBMS would need to support 65 channels, each supporting a SPaT rate of 40 kbps. In this case, each vehicle would need to know which intersection it is approaching and listen on the MBMS SPaT service channel associated with the particular intersection. Table 5.3-2 shows the results of an analysis of the potential for using LTE for broadcasting SPaT messages.

Alternatively, SPaT information for all intersections can be sent on one shared channel via either MBMS or via CBS. Then the CBS or MBMS broadcast channel will need to support 2.6 Mbps (65 x 40 kbps). Each vehicle would receive SPaT information for all 65 intersections (receiving rate of 2.6 Mbps) and intelligently parse this information for the specific intersection of interest.

Table 5.3-2. LTE Broadcast Analysis

Parameter	Value
Total Number of Vehicles (Ref: "Hub Bound Report 2009", NYMTC, January 2011) [152]	6528 + 6045 = 12,573
One-way volume of vehicles per intersection	0.44 cars/sec
Number of vehicles across all intersections	0.44 x 65 = 28.6 (29 cars /sec)
Duration of an active SPaT session	10 seconds
Number of cars with active SPaT sessions over all intersections	29*10 = 290 cars
SPaT rate per intersection	40 kbps
SPaT broadcast rate	40 kbps * 65 intersections = 2.6 Mbps
Cell throughput	3*150 Mbps = 450 Mbps
Available bandwidth for broadcast with 2% loading by other traffic	0.98*450 Mbps = 441 Mbps broadcast bandwidth
Available bandwidth for broadcast with 50% loading by other traffic	0.5*450 Mbps = 225 Mbps broadcast bandwidth
Available bandwidth for broadcast with 98% loading by other traffic	0.02*450 Mbps = 9 Mbps broadcast bandwidth

Source: ARINC April 2012

In broadcast mode, LTE has sufficient bandwidth to support SPaT dissemination to vehicles in the cell. If vehicle devices have logic to track their direction, they can listen on the particular channel for the approaching intersection's SPaT with a broadcast data rate of 40 kbps via MBMS. In this case, about 290 vehicles would be receiving any particular SPaT message.

Alternatively, vehicle devices can receive SPaT for all intersections at a data rate of 2.6 Mbps using MBMS or CBS and have logic to parse for the relevant intersection, i.e., push method. In this case all 12,573 vehicles in cell coverage area would receive all of the SPaT messages.

Broadcast mode is recommended for SPaT broadcast since it can meet most of the SPaT requirements. However, for LTE to meet all requirements, several issues need be resolved:

1. Verify that SPaT BER requirements and latency requirements can be met
2. Include software in user device to filter SPaT messages to identify approaching intersection's SPaT information
3. Determine the load of other traffic on the CBS or MBMS channel in public safety networks
4. If using MBMS option, implement and validate MBMS performance
5. Obtain agreement from jurisdictions or from FCC to allow the use of the LTE network for this purpose.

In broadcast mode, additional messages such as DGPS and GID can also be sent to all vehicles in the cell area given there is sufficient capacity allocated for MBMS or CBS. However, if BSM messages use the public safety LTE, the high load of a large number of vehicles (~12,000) sending BSMs to an LTE base station with a typical urban range of 0.5.km will saturate the LTE link. Additionally, there is also other public safety traffic loading the network, i.e., the public safety LTE is not dedicated for vehicle safety messages alone, and the HIA loading can degrade the overall performance of public safety LTE. If the LTE base station deployment is planned such that the cell area is very small with a limited number of vehicles in each cell area, then BSM is possible. Although the cost of this approach would be very high, and it is unlikely the jurisdictions involved would agree to it. However, implementation and operation of uploading/collecting HIAs from individual vehicles for broadcast within the cell would require additional analysis. Thus HIA on LTE is not a recommended option.

If we consider femtocells, the LTE network could support vehicles only approaching the intersection by controlling radio range of the femtocell. However, since femtocell broadcast capabilities are not currently standardized, and even broadcast enabled, the femtocell broadcast would require backbone connectivity; femtocells are not recommended. In any event, the femtocell approach would not be useful to the jurisdictions implementing LTE to serve emergency services over a wide region.

5.3.1.2 **Unicast Analysis**

The public safety LTE could send the SPaT messages as unicast to each vehicle device. However, this involves maintaining a large number of unicast sessions in the cell area. If a vehicle approaching an intersection can determine which intersection information is needed, then it can make a unicast request for SPaT messages for the relevant local intersection (pull approach). If we use the NYC scenario, we have the analysis shown in Table 5.3-3 for SPaT with loading by other cellular traffic on the public safety LTE network.

Table 5.3-3. LTE Unicast Analysis

Parameter	Value
Total Number of Vehicles (Ref: "Hub Bound Report 2009", NYMTC, January 2011) [152]	6528 + 6045 = 12,573

Parameter	Value
One-way volume of vehicles per intersection	0.44 cars/sec
Number of vehicles across all intersections	0.44 x 65 = 28.6 (29 cars /sec)
Duration of an active SPaT session	10 seconds
Number of cars with active SPaT sessions over all intersections	29*10 = 290 cars
SPaT rate per intersection	40 kbps
Average bandwidth per vehicle (For 3 sector with each sector at 150 Mbps with 2x2 MIMO) (Based on NEC LTE)	(3*150 Mbps) / 290 cars = 1.55 Mbps per car
Maximum users per cell in 5 MHz band (Based on NEC LTE)	200 x 3 = 600
Saturation ratio for SPaT traffic	290/600 = 48.3 %
Available bandwidth per vehicle with 2% loading by other traffic	0.98*450 Mbps / 290 cars = 1.52 Mbps per car
Available bandwidth per vehicle with 50% loading by other traffic	0.50*450 Mbps / 290 cars = 776 kbps per car
Available bandwidth per vehicle with 90% loading by other traffic	0.10*450 Mbps / 290 cars = 155 kbps per car

Source: ARINC April 2012

In this scenario, each vehicle would have 155 kbps or more of bandwidth available which is sufficient for the single intersection SPaT data rate of 40 kbps. If vehicles cannot determine which intersection will be approached, then the LTE network may push SPaT messages for intersections to all vehicles in the cell. Then each vehicle will individually determine which SPaT message is relevant. In such a case, all vehicles within the cell area could have an active SPaT session. Without traffic optimization a single cell cannot support ~12k users using unicast.

Unicast is a feasible approach for SPaT under certain conditions, i.e., limited number of vehicles. However, it is not an efficient approach and is not recommended without additional analysis.

5.3.2 *Summary*

Using the broadcast mode via MBMS or CBS is feasible. LTE standards support broadcast capability using MBMS, but no implementation is currently publicized. However, if the MBMS approach is implemented, the SPaT messages can be efficiently disseminated to a large number of vehicles using broadcast mode without incurring excessive resource loading on the cellular network. Similarly cell broadcast service could be used to disseminate SPaT to all vehicles in the cell coverage area.

We find that unicast is feasible under certain conditions but not in others. Using the unicast approach for SPaT dissemination may provide sufficient bandwidth when there are a limited number of vehicles with active SPaT sessions, i.e., only those vehicles approaching intersection. If devices cannot track vehicle movement, the unicast approach may waste bandwidth by maintaining sessions to vehicles, which are not approaching an intersection. In addition this approach would require substantial server resources to support tens of thousands of simultaneous SPaT requests. The feasibility of unicast for SPaT dissemination requires further analysis.

As summary of LTE capability to support SPaT requirements is provided in Table 5.3-4.

Table 5.3-4. Comparison of LTE Capabilities against SPaT Applications Communications Requirements

SPaT Applications Related Communications Requirement	Specification Requirement	LTE
Communications Service	Best Effort	Best effort
Communications Range (High Probability of Message Receipt)	200 m (606 ft.)	up to 30 km
Maximum bit error rate (BER) and Confidence Factor	10^{-3} with 99.9% Confidence Factor	Use adaptive modulation, MIMO and selectable channel bandwidth for achieving BER but no field trial results to confirm this
Data Throughput, SPaT Messages	40 kbps (Includes single intersection GID associated with the application)	Data rate determined by network loading and modulation. DL could support data rate of 100 Mbps
Background Data Load		Not applicable to LTE network. LTE cannot handle BSM/HIA messages.
Vehicle Speed/Doppler Accommodation	200 km/h (124 mph) Ref: IEEE Std 802.11p PAR	High performance for speeds up to 120 km/h; Mobility supported for speeds 120 km/h – 350 km/h
Multipath Environment	Rural and Urban Canyon	Designed to handle multipath for up to 1.4 km using guard period of 4.69 μs
Quality of Service	Different Class of Services Supported with Highest Class having Highest Priority; Meets SPaT communications requirements at all times when operational	Support 9 QoS classes with PER varying from 10^{-2} to 10^{-6}
Availability	99.99% for Safety Integrity Level 3 (IEC 61508)	Can be engineered to support 99.99%
Radio Frequency Environment	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)	Currently operates in urban and suburban RF environments
Vehicle Separation Distance with no Radio Frequency Interference;	Parallel lane adjacent vehicles and same lane with 4 m separation (low speed- 8 km/h; 5 mph) approach to a signalized intersection	Designed to limit radio frequency interference
Dual Transceiver Simultaneous Operations in a Single Vehicle	No Co-channel or In-band Interference	Not applicable to LTE

SPaT Applications Related Communications Requirement	Specification Requirement	LTE
Environmental and Power Compatibility	RSE: Compatible with NEMA TS-2 Specification; OBE: Compatible with SAE Specifications for Light and Heavy Vehicles	LTE base stations are compatible for outdoor use.
Size and Weight	Compatible with Small Car (Approx. Size 500 cu in/8195 cm^3; Approx. Wt. 2 lbs./0.91 kg)	LTE devices are compatible Size: 122 x 66 x 13 mm Weight: 164 g
Cost	Affordable to Private Vehicle Purchaser	Under $300

Source: ARINC April 2012

5.4 Digital Terrestrial Broadcast Television

In this section, feasibility and capability of using digital terrestrial broadcast television to support SPaT applications is investigated. ATSC M/H makes use of a portion of the total available 19.4 Mbps bandwidth of one ATSC channel and is backward compatible with the ATSC standard. While the total available bandwidth is 19.4 Mbps shared by both ATSC standard and M/H services, multiple configurations are supported to deliver both main and M/H services simultaneously. Based on the enhancement and robustness, ATSC M/H is capable of supporting user mobility of up to 300 km/h (187.5 mph).

As digital terrestrial broadcast television typically covers a relatively large geographical area, its usage to support SPaT applications will be more practical in disseminating MapData information of all related road infrastructure within its coverage, rather than delivering intersection-specific SPaT messages. Since the number of intersections within the digital terrestrial broadcast television area can be large, especially in urban environments, it is important to investigate capability and feasibility if digital terrestrial broadcast television could support such demands.

The ATSC M/H standard is developed to support mobile requirements for TV signal access. The approach taken in the USA is to use single frequency transmission, adapting the original ATSC standard to accommodate multipath and Doppler. The original 8-VSB modulation has been maintained. ATSC standard supports adjustable bandwidth allocation for both ATSC main service and ATSC M/H service. Based on FCC's requirements, all broadcasters are required to provide at minimum one standard-definition NTSC quality free-to-air program. The bandwidth requirement of one typical standard-definition service in MPEG2 is 2 – 4 Mbps, and one typical high-definition service in MPEG2 needs the bandwidth of 10 – 14 Mbps. The ATSC program guide (PSIP) requires about 0.5 Mbps. ATSC and ATSC M/H support flexible bandwidth allocation based on the channel configurations according to broadcast stations' plan and permit. Figure 5.4-1 illustrates one example of bandwidth allocation for combining ATSC HD, SD, ATSC M/H services, and PSIP in one 19.4-Mbps channel bandwidth. In this allocation, proximately 4.584 Mbps out of the 19.4 Mbps bit stream is allocated for mobile services. Within this allocated 4.584-Mbps bandwidth, further bandwidth allocation to accommodate mobile services is needed. The bandwidth could be partitioned into multiple sub-channels to deliver multiple mobile services simultaneously, similar to partition bandwidth for ATSC standard service to deliver both HD and SD channels simultaneously. The station also has the option to allocate the entire bandwidth for one data stream. Consider the bit rates of video and audio data listed in Table 5.4-1 as examples of data streams with different data rates. For the allocated 4.584 Mbps bandwidth, multiple service configurations could be planned to deliver multiple ATSC M/H services simultaneously. Similarly, ATSC M/H bandwidth can be used to disseminate MapData information. The MapData information delivery is viewed as one data stream from ATSC M/H's perspective. Table 5.4-2 illustrates several service channel configurations. When considering delivering data over ATSC M/H, the effective data throughput is relatively small compared with the allocated bandwidth for ATSC M/H service. The effective data throughput depicted in Table 5.4-2 is about 1215 kbps over a 4.584 Mbps channel bandwidth (Ref: Table 6.1, ATSC-Mobile DTV Standard, Part 2 – RF/Transmission System Characteristics [153]).

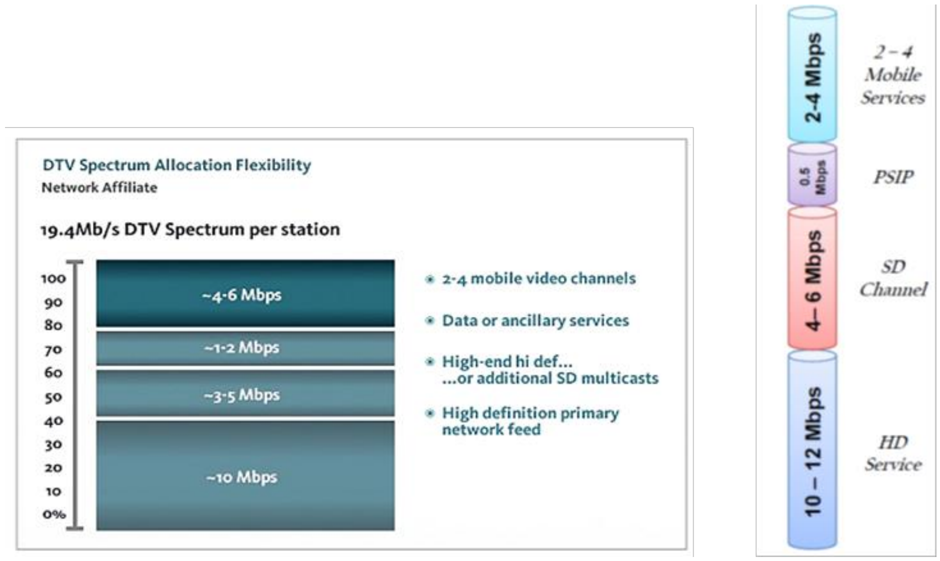


Figure 5.4-1. ATSC M/H 19.4 Mbps Allocation for Affiliated Network Service Providers

(Ref: "Mobile Digital Video"; Open Mobile Digital Coalition [154])

Table 5.4-1. Bit Rates of Video and Audio Data Stream

	High Quality	Medium Quality	Low Quality
Video Bit Rate (kbps)	512	384	256
Audio Bit Rate (kbps)	32	24	16

Source: ARINC April 2012

Table 5.4-2. ATSC M/H Service Planning to 4.4 Mbps Bandwidth

Assume using mixed rate SCCC outer code (1/2, ¼, ¼, ¼)		
Total Data Throughput: 1215 kbps		
Service Configuration	**Total Data Bandwidth (kbps)**	**Overhead (kbps)**
2 HQ Video + Audio	1088	127
2 MQ Video + Audio & 1 LQ Video + Audio	1088	127
4 LQ Video + Audio	1088	127
1 HQ Video + Audio & 1 MQ Video + Audio & 4 HQ Audio	1080	135

Source: ARINC April 2012

For data to be transmitted through ATSC M/H channels, it is required to encapsulate data into Internet Protocol (IP) packets. The standard also supports User Datagram Protocol (UDP) as transport layer protocol, and Real-Time Transport Protocol (RTP) for media streams. One essential use case scenario to use ATSC M/H to disseminated MapData information is to deliver MapData information through one of the service channels, based on the needed data rate. To determine the feasibility and capability using ATSC M/H to disseminate MapData, the following metrics will be introduced for further investigation:

- MapData message size of each intersection
- Number of intersections within the coverage
- Allocated data bandwidth

The challenge to disseminate MapData will be greater for dense urban environment, such as New York City. The amount of data and transmission time will be proportional to the amount of data associated with the number of intersections within the coverage. Assume the MapData message size is 1318 bytes. There were 11,871 signalized intersections Citywide in New York City, including 2,795 in Manhattan, 4,100 in Brooklyn, 2,942 in Queens, 1,536 in the Bronx, and 500 in Staten Island (Ref: NYCDOT, http://www.nyc.gov/html/dot/html/faqs/faqs_signals.shtml, 2006 [155]). Table 5.4-3 outlines the initial calculation based on numbers of intersections in all five boroughs in New York City, the corresponding MapData volume of each borough, and needed transmission time based on different data rate.

Table 5.4-3. Number of Intersections, MapData Size, and Needed Transmission Time

	NYC	Manhattan	Brooklyn	Queens	Bronx	Staten Island
Number of Signaled Intersections	11877	2795	4100	2942	1536	500
MapData Size (Kbytes)	15287	3597.47	5277.15	3786.68	1977	643.55
Transmission Time with 1215 kbps Data Rate						
Transmission Time (sec)	101	24	35	25	14	5
Transmission Time with 384 kbps Data Rate						
Transmission Time (sec)	326	77	113	81	42	14
Transmission Time with 128 kbps Data Rate						
Transmission Time (sec)	978	230	338	242	127	41

Source: ARINC April 2012

It is observed that the number of intersections in the coverage area and available data rate will have great impact on the overall performance. It is recommended to properly size the coverage, as well as the numer of intersections in the coverage to optimize the MapData dissemination performance. For the case study of New York City, although technically it is feasible to disseminate MapData information of the entire NYC using one television broadcast tower, the length of time duration needed to successfully finish this task may be undesirable.

To consider the needed transmission power to achieve sufficient signal strength within the coverage, the current FCC regulations may not be adequate. Currently, FCC Planning Factors for DTV, F(50,90), were chosen to provide service availability at 50% of locations 90% of the time. This is clearly unacceptable for M/H service, particularly to support MapData information dissemination. A significantly higher availability of service is mandatory for enabling disseminating MapData information and widespread consumer acceptance of the new wireless service. The European Telecommunications Standards Institute (ETSI) has put forward a definition of “good” DTV service as reception at 95% of locations for 99% of the time, F(95,99). Using these new grades, with the US standard deviations for location variation, as the minimum requirement for a successful M/H service results in an additional service margin of 21.7dB (Ref: “High Power Transmission – The Fast Track to successful Mobile/Handheld DTV”, Andy Whiteside, Nat Ostroff, Ray Kiesel, Acrodyne [156]).

Table 5.4-4 outlines the comparison of ATSC M/H capability against the SPaT applications communication requirements. As ATSC M/H is recommended for disseminating non-time-critical MapData information, instead of supporting all SPaT applications, there are a few requirements not applicable to ATSC M/H.

Table 5.4-4. Comparison of ATSC M/H against SPaT Applications Communications Requirements

SPaT Applications Related Communications Requirement	Specification Requirement	ATSC M/H
Communications Service	Best Effort	Best Effort
Communications Range (High Probability of Message Receipt)	515 m (1690 ft.)	Campus Area to tens of Kilometers depending on station’s license
Maximum bit error rate (BER) and Confidence Factor	10^{-4} with 99.99% Confidence Factor	Information Not Available
Data Throughput, SPaT Messages	40 kbps (Includes single intersection GID associated with the application)	Typically 2-4 mbps allocated to M/H; Possible to allocate up to 75% (4-8 M/H data streams at 9 to 14 mbps). HD-MPEG 2 = 10-14 mbps of 19.4 mbps
Background Data Load on DSRC (HIA Msg) in which SPaT Messages Must Compete	4.7 mbps considering J2735 part 1; 29.3 mbps considering J2735 part 1 & 2; Based on 172 vehicles within communications range	Not applicable. Recommended only for disseminating MapData information
Vehicle Speed/Doppler Accommodation	200 km/h (124 mph) [Ref: IEEE Std. 802.11p PAR]	300 km/hr
Multipath Environment	Rural and Urban Canyon	5.6 μsec delay spread tolerated (1.68 km path difference)
Quality of Service	Different Class of Services Supported with Highest Class having Highest Priority; Meets SPaT communications requirements at all times when operational	Best Effort
Availability	99.99% for Safety Integrity Level 3 (IEC 61508); Achieved through fault tolerant DSRC design	45% (FCC 50-90% rule) by current FCC planning factor; 89.1% by ETSI F(95,99) planning factor

SPaT Applications Related Communications Requirement	Specification Requirement	ATSC M/H
Radio Frequency Environment	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)	Capable to operate in urban, suburban and highway environments
Vehicle Separation Distance with no Radio Frequency Interference	Parallel lane adjacent vehicles and same lane with 4 m separation (low speed- 8 km/h; 5 mph) approach to a signalized intersection	No interference issues; Vehicle System is receive-only.
Dual Transceiver Simultaneous Operations in a Single Vehicle	No Co-channel or In-band Interference	Supported. Typical installation is one receiver.
Environmental and Power Compatibility	RSE: Compatible with NEMA TS-2 Specification; OBE: Compatible with SAE Specifications for Light and Heavy Vehicles	NEMA 4X UL508A Telcordia GR-487-CORE, Telcordia GR-63-CORE (for ground delivery of equipment)
Size and Weight	Compatible with Small Car (Approx. Size 500 cu in/8195 cm^3; Approx. Wt. 2 lbs./0.91 kg)	Varies. Can be installed in vehicles
Cost	Affordable to Private vehicle Purchaser	Cost under $300

Source: ARINC April 2012

5.5 Digital Terrestrial Broadcast Radio

In this section, feasibility and capability of using digital terrestrial broadcast radio to support SPaT applications is investigated. The HD Radio FM mode offers four options supporting different data rates of 100, 112, 125, and 150 Kbit/s, depending on the power budget and/or desired range of signal. FM mode also provides several pure digital options with up to 300/s bit rate and supports fallback condition to revert the transmission to a 20/s signal. FM stations have options to further subdivide their carrier into sub-channels of varying audio quality. Data bit rate will vary depending on the configuration of each sub-channel. Stations may eventually go all-digital, thus allowing as many as three full-power channels and four low-power channels (seven channels in total). As defined by iBiquity, these channels could be sub-divided into CD-quality (100/s), FM-quality (25-50/s), AM-quality (12/s), or Talk-quality (5/s) channels. Alternatively, they could broadcast one single channel at 300/s. In the later analysis, scenario assuming HD Radio operated by jurisdictional-owned or operated stations or through highway advisory radio will be investigated. It is possible that the stations may allocate the entire frequency or a major sub-channel for disseminating MapData information so two data rates are used for performance analysis.

Although HD Radio does not dictate a specific modulation or protocol for data transmission using the radio channels, iBiquity has developed high-level Data Service and streaming format to facilitate the demands to distribute radio content, supplemental information regarding the media content, such as song titles or artists, and real-time traffic information through Traffic Message Channel. iBiquity's 1st Generation Data Services, including Program Service Data (PSD) for Main (MPSD) and Supplemental Program Service Data (SPSD), utilizes the established ID3 (Ref: "HD Radio id3 Formats for Programs" http://www.id3.org/ [157]) standard format to provide HD Radio listeners program information regarding the media content. iBiquity also provides the high-level data service to support distributing real-time traffic information using HD Radio through Traffic Message Channel, similar to the existing approaching using analog FM Radio Data System for distributing traffic information (Ref: "Traffic Data Distribution via HD Radio", http://www.tisa.org/ [158]). It can be used for information purpose or offer dynamic route guidance. Comparing with the conventional FM-RDS supporting 1187.5 bps (Ref: "Radio Data System", http://www.radio-electronics.com/info/broadcast/rds/rds.php [159]), HD Radio can provide much better data bandwidth for information dissemination.

Similar to terrestrial broadcast television, since terrestrial broadcast radio typically covers a relatively large geographical area, it would perform better in supporting SPaT applications by disseminating MapData information for all intersections within its coverage, rather than delivering time dependent SPaT messages.

To determine the feasibility and capability using HDRadio to disseminate MapData, the following metrics will be introduced for further investigation:

- MapData message size of each intersection
- Number of intersections within the coverage
- Allocated data bandwidth

The challenge to disseminate MapData will be greater for a dense urban environment, such as New York City. The amount of data and transmission time will be proportional to the amount of data associated with the number of road infrastructure within the coverage. The same data set for analyzing the capacity and feasibility of ATSC M/H will be used in this section. Assume the MapData message size is 1318 bytes. There were 11,871 signalized intersections Citywide in New York City, including 2,795 in Manhattan, 4,100 in Brooklyn, 2,942 in Queens, 1,536 in the Bronx, and 500 in Staten Island (Ref: NYCDOT, http://www.nyc.gov/html/dot/html/faqs/faqs_signals.shtml, 2006 [155]). Table 5.5-1 outlines the initial calculation based on numbers of intersections in all five boroughs in the New York City, the corresponding MapData volume of each borough, and needed transmission time based on different data rate.

Table 5.5-1. Number of Intersections, MapData Size, and Needed Transmission Time

	NYC	**Manhattan**	**Brooklyn**	**Queens**	**Bronx**	**Staten Island**
Number of Signaled Intersections	11877	2795	4100	2942	1536	500
MapData Size (Kbytes)	15287	3597.47	5277.15	3786.68	1977	643.55
Transmission Time with 300 kbps Data Rate						
Transmission Time (sec)	408	96	141	101	53	18
Transmission Time with 150 kbps Data Rate						
Transmission Time (sec)	816	192	282	202	106	36

Source: ARINC April 2012

It is observed that the number of intersections in the coverage area and available data rate will have great impacts on the overall performance. It is recommended to properly size the coverage, as well as the number of intersections in the coverage to optimize the MapData dissemination performance. For the case study of New York City, although technically it is feasible to disseminate MapData information of the entire NYC using one HD Radio broadcast tower, the length of time duration needed to successfully finish this task could be deemed as undesirable. To meet the assumed GID latency requirement would thus require 21 different HD transmitters.

Table 5.5-2 outlines the comparison of HD Radio capability against the SPaT applications communication requirements. As HD Radio is recommended for disseminating non-time-critical MapData information, instead of supporting all SPaT applications, there are a few requirements not applicable to HD Radio.

Table 5.5-2. Comparison of HD Radio against SPaT Applications Communications Requirements

SPaT Applications Related Communications Requirement	Specification Requirement	HD Radio
Communications Service	Best Effort	Best Effort
Communications Range (High Probability of Message Receipt)	200 m RLR, LTA, RTA, RCRLV 515 m (1690 ft.) PREEMPT, FSP, TSP	Campus area to tens of kilometers depending on station's license
Maximum bit error rate (BER) and Confidence Factor	10^{-4} with 99.99% Confidence Factor	Information Not Available
Data Throughput, SPaT Messages	40 kbps (Includes single intersection GID associated with the application)	300 kbps
Background Data Load		Not applicable. Recommended only for disseminating MapData information
Vehicle Speed/Doppler Accommodation	200 km/h (124 mph) Ref: IEEE Std. 802.11p PAR	120 km/hr
Multipath Environment	Rural and Urban Canyon	156 μsec delay spread tolerated (46.8km path difference)
Quality of Service	Different Class of Services Supported with Highest Class having Highest Priority; Meets SPaT communications requirements at all times when operational	Best Effort
Availability	99.99% for Safety Integrity Level 3(IEC 61508); Achieved through fault tolerant DSRC design	Can support 99.99% availability; requires area survey for coverage
Radio Frequency Environment	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)	Capable to operate in urban, suburban and highway environments
Vehicle Separation Distance with no Radio Frequency Interference	Parallel lane adjacent vehicles and same lane with 4 m separation (low speed- 8 km/h; 5 mph) approach to a signalized intersection	No interference issues; Receive-only on vehicle. May have interference at fringe areas of wide area coverage. AM version unacceptable because of

SPaT Applications Related Communications Requirement	Specification Requirement	HD Radio
		interference at night
Dual Transceiver Simultaneous Operations in a Single Vehicle	No Co-channel or In-band Interference	Supported. Typical installation is one receiver
Environmental and Power Compatibility	RSE: Compatible with NEMA TS-2 Specification; OBE: Compatible with SAE Specifications for Light and Heavy Vehicles	Receivers part of standard vehicle equipment in 2012; will be compatible with vehicle manufacturer's electronic unit environmental specifications
Size and Weight	Compatible with Small Car (Approx. Size 500 cu in/8195 cm^3; Approx. Wt. 2 lbs./0.91 kg)	Designed for vehicle compatibility.
Cost	Affordable to Private vehicle Purchaser	Cost under $300

Source: ARINC April 2012

5.6 Partitioning Scheme for MapData Broadcast

As indicated in Section 5.3 and Section 5.4, the key performance factor to use ATSC M/H or HD Radio to support disseminating MapData information is the balance between available data rate and the amount of data for dissemination. To properly size the number of intersections and the associated data for better performance and user experience, the three partitioning schemes described below may be considered.

5.6.1 *Hexagon Partitioning*

This scheme is similar to what the cellular networks adopt to construct the land-based wireless communication networks. The concept of cell achieves a balance between effective coverage, network performance, and user experience, based on the scenario requirements. Similarly, using terrestrial broadcast television network to support SPaT applications could adopt this scheme or the same purpose. Considering deploying such service in New York City, the possible partition pattern could be deploying one tower in each of the five boroughs. Figure 5.6-1 illustrates the principles of this scheme.

The requirement of this scheme is that there is sufficient resources to deploy multiple transmitters in the target area. It is a practical concern that such physical locations for deploying transmitters can be rare.

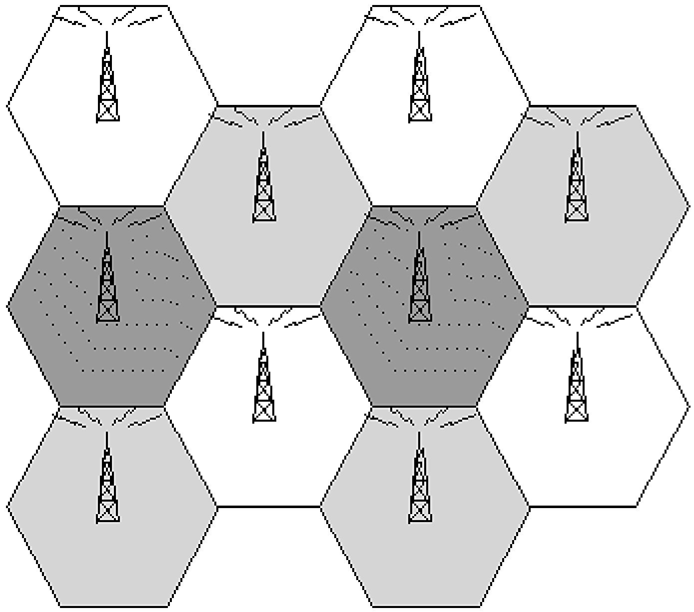


Figure 5.6-1. Hexagon Partitioning

Source: ARINC April 2012

5.6.2 *Onion Rings*

The second scheme is to partition the target coverage into a number of rings, each formed with virtual circles different radius, so only information of intersections within the area between each neighboring radius will be transmitted in each interval. Figure 5.6-2 illustrates the principle of this scheme. This scheme may provide additional benefits for out-of-town visitors or first-time users who do not possess the conerning MapData information in advance. The challenge is the right balance between the amount of data of intersections to be transmitted in each interval, the effective data rate, and the appropriate transmission interval. The onion could be sliced thinner or thicker and this is the result of the aforementioned factors. The disadvantage is the time latency for getting MapData information of a specific ring area. The worst case is that a user may need to wait for a cycle to get the desired information.

In this scheme, the transmitter should be allowed to operate in higher transmission power to provide sufficient signal strength through the target coverage. While this scheme requires less transmitters to be deployed, power budget of the transmitters will be a deciding factor for practical planning.

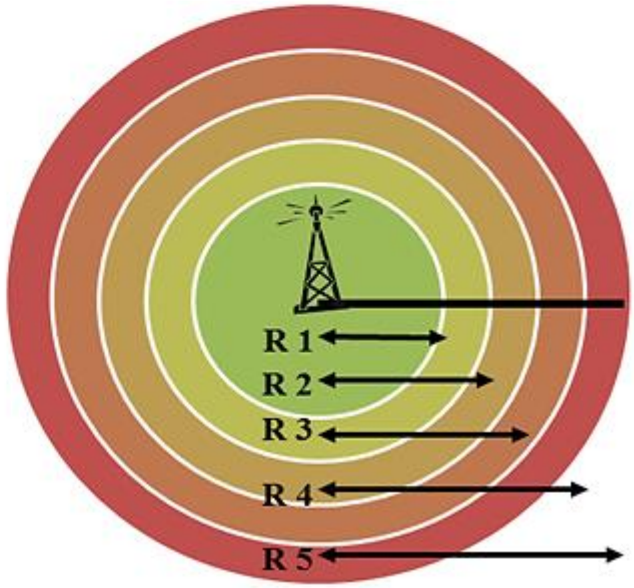


Figure 5.6-2. Onion Ring Diagram

Source: ARINC April 2012

5.6.3 *Pie Slicing*

The third scheme is to partition the target area into a number of “pie slices”, which size of each slice is not necessarily the same. Considering the case of New York City, the number of intersections in Queens is less than in Brooklyn. Therefore, coverage in Brooklyn may be partitioned into a slice twice the size of Queens. In this scheme, the size of the slice is inversely proportional to the number of intersections to be included. Figure 5.6-3 illustrates the concept of this scheme. In this figure, the coverage or size of red pie is larger than green, blue and purple. The principle behind this partition is because there are fewer intersections in the west side so the coverage of pie can be larger, comparing with the rest of partitions.

Similar to Onion Ring scheme, in this scheme, the transmitter should be allowed to operate in higher transmission power to provide sufficient signal strength through the target coverage. While this scheme requires less transmitters to be deployed, power budget of the transmitters will be a deciding factor for practical planning.

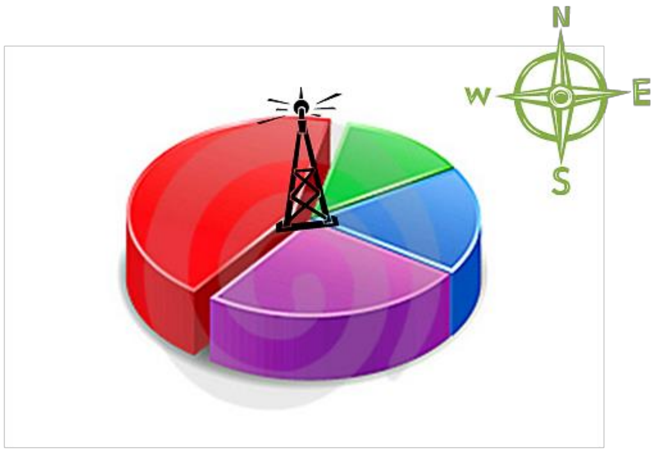


Figure 5.6-3. Pie Slicing Diagram

Source: ARINC April 2012

5.7 Key Findings

Table 5.7-1 presents a summary of key findings from the assessment of candidate communication technologies against SPaT applications communications requirements.

Table 5.7-1. Summary of Key Findings

Communication Technology	Key Findings
DSRC	• Subject to the given BER requirements, the effective communication range in NLOS is around 200 meters, which is shorter than the requirement for three of the eight SPaT applications. For optimistic LOS condition, the communication range is about 400 meters, which still falls short for several SPaT applications. Advanced antenna technologies and diversity to avoid major multipath fading are recommended for further consideration to address this requirement; • DSRC meets the capacity requirements for supporting SPaT applications in the presence of background traffic consisting of part 1 BSM/HIA messages with vehicle density around 150 vehicles. However, it does not meet the capacity requirements when all vehicles transmit both part 1 and part 2 BSM/HIA messages; • Field Test of DSRC technology under LOS conditions indicates a low probability of error free packet delivery at ranges greater than 300 meters, especially without antennas configured to provide multipath diversity; • Testing indicates that simultaneous use of service channels and safety channels (e.g., Control Channel) may result in deteriorated communications reliability. Thus attention must be given to properly arranging the band plan; • DSRC seems to be the best choice of available technologies to meet latency and mobility requirements; however improvements are needed.
LTE	• Broadcast mode via MBMS or CBS is feasible for SPaT messages. However, the capability of broadcast to meet BER and latency requirements needs to be

Communication Technology	Key Findings
	verified in field trials. Additionally, the expected load by other applications on the LTE network is unknown for the Public Safety LTE and this can affect the bandwidth available to support SPaT messages for all intersections in the cell area. In order for broadcast mode to work, vehicles may need to have some middleware functionality to parse for the correct intersection information; • MBMS has not been implemented by current network carriers and therefore no field tests are available to validate its performance; and • Using unicast mode may be feasible for LTE but it may only support a limited number of active SPaT sessions depending on loading by other cellular traffic. Additional in-depth capacity analysis may be required if unicasting is considered for SPaT.
ATSC M/H Mobile Digital Television	• Technically ATSC M/H is equipped with the capability to support efficient dissemination of MapData information; • Current FCC regulations on transmission power for ATSC M/H may be inadequate to support sufficient signal strength through the designated coverage area; • The feasibility and overall performance is a trade-off between the available data bandwidth and the amount of data of the included road infrastructure to be disseminated; • The needed transmission time to finish one set of MapData is the key performance metric for practical planning and deployment; • It is recommended to properly size the coverage and amount of road infrastructure that each ATSC M/H broadcasting transmitter covers to achieve optimized performance; • To achieve a balance between the information dissemination performance, coverage size and deployment cost, partitioning schemes should be considered for deployment planning to properly size the coverage; and • Currently there is no dedicated channel allocation in digital broadcast television for disseminating traffic information. Channel allocation with minimum bandwidth is required for supporting MapData information dissemination.
HD Radio	• HD Radio can support efficient dissemination of MapData information; • HD Radio is widely adopted by automobile manufacturers, and low cost components are available. • A dedicated HD Radio receiver will be to continuously receive MapData and other traffic-related information in the background without interrupting regular usage for entertainment. • The feasibility and overall performance is a trade-off between the available data bandwidth and the number of intersections to be served. • The needed trasnmission time to finish one set of MapData is the key performance metric for practical planning and deployment; • It is recommended to properly size the coverage and number of intersections that each HD radio broadcasting transmitter covers to achieve optimized performance; • To achieve a balance between the information dissemination performance, coverage size and deployment cost, partitioning schemes should be considered for deployment planning to properly size the coverage; • Consider disseminating MapData information through Traffic Message Channel

Communication Technology	Key Findings
	to minimize the impacts on other regular contents or incur additional cost. • Seems to be affordable for both jurisdictions and vehicle owners; • Best choice is all digital FM Requiring FCC License.

Source: ARINC April 2012

5.8 Summary and Recommendations

This section provides a summary of the results of analyzing candidate communication technologies against SPaT applications communications requirements defined in Task 2. The relative merits of each communication technology are discussed, and a final recommendation on the most appropriate communication technology for supporting SPaT applications is presented.

5.8.1 *Summary of Analysis*

The results of analyzing the candidate communication technologies are summarized in Table 5.8-1.

Table 5.8-1. Summary of Results of Comparing Communication Technologies against SPaT Applications Communications Requirements

SPaT Applications Related Communications Requirement	Requirement Specification	DSRC	LTE	ATSC M/H	HD Radio
Communications Service	Best Effort	Best Effort	Best effort	Best Effort	Best Effort
Communications Range (High Probability of Message Receipt)	200 m RLR, LTA, RTA and RCRLV 515 m (1690 ft.) PREEMPT, TSP, FSP	200 m with high reliability in urban conditions using no-diversity 500 m using diversity	up to 30 km	Campus Area to tens of Kilometers depending on station's license	Campus Area to tens of kilometers depending on station's license
Maximum bit Error Rate (BER) and Confidence Factor	10^{-4} with 99.99% Confidence Factor	10^{-4} (5 dB SNR @ 3 mbps; 15 dB SNR @ 6 mbps; 28 dB SNR @ 27 mbps)	Use adaptive modulation, MIMO and selectable channel bandwidth for achieving BER but no field trial results to confirm this	Information Not Available	Information Not Available
Data Throughput, SPaT Messages	40 kbps (Includes single intersection GID	Aggregate 4-6 Mbps possible	Data rate determined by network	Typically 2-4 mbps allocated to M/H; Possible	300 kbps

SPaT Applications Related Communications Requirement	Requirement Specification	DSRC	LTE	ATSC M/H	HD Radio
	associated with the application)		loading and modulation. DL could support data rate of 100 Mbps	to allocate up to 75% (4-8 M/H data streams at 9 to 14 mbps). HD-MPEG 2 = 10-14 mbps of 19.4 mbps	
Background Data Load on DSRC (HIA Msg) in which SPaT Messages Must Compete	4.7 mbps considering J2735 part 1; 29.3 mbps considering J2735 part 1 & 2; Based on 172 vehicles within communications range	Can accommodate SPaT with background J2735 part 1 at urban intersections. Part 1& 2 background will overload	Not applicable to LTE network. LTE cannot handle BSM/HIA messages	Not applicable. Recommended only for disseminating MapData information	Not applicable. Recommended only for disseminating MapData information
Vehicle Speed/Doppler Accommodation	200 km/h (124 mph) Ref: IEEE Std. 802.11p PAR	Can support 200 km/hr	High performance for speeds up to 120 km/h; Mobility supported for speeds 120 km/h – 350 km/h	300 km/hr	120 km/hr
Multipath Environment	Rural and Urban Canyon	1.6 μsec delay spread tolerated (0.48 km path difference)	Designed to handle multipath for up to 1.4 km using guard period of 4.69 μs	5.6 μsec delay spread tolerated (1.68 km path difference)	156 μsec delay spread tolerated (46.8km path difference)
Quality of Service	Different Class of Services Supported with Highest Class having Highest Priority; Meets SPaT communications requirements at all times when	Best Effort	Support 9 QoS classes with PER varying from 10^{-2} to 10^{-6}	Best Effort	Best Effort

SPaT Applications Related Communications Requirement	Requirement Specification	DSRC	LTE	ATSC M/H	HD Radio
	operational				
Availability	99.99% for Safety Integrity Level 3 (IEC 61508); Achieved through fault tolerant DSRC design.	Can support 99.99% availability	Can be engineered to support 99.99%	45% (F(50,90) rule by current FCC planning factor); 89.1% by ETSI F(95,99) planning factor.	Can support 99.99% availability; requires area survey for coverage
Radio Frequency Environment	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)	Demonstrated to operate in urban, suburban and highway environments	Currently operates in urban and suburban RF environments	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)	Must operate in an RF environment consisting of licensed and unlicensed emitters both in the intersection and near the intersection (see Report for details)
Vehicle Separation Distance with no Radio Frequency Interference;	Parallel lane adjacent vehicles and same lane with 4 m separation (low speed- 8 km/h; 5 mph) approach to a signalized intersection	Field test report interference issues	Designed to limit radio frequency interference	Parallel lane adjacent vehicles and same lane with 4 m separation (low speed- 8 km/h; 5 mph) approach to a signalized intersection	Parallel lane adjacent vehicles and same lane with 4 m separation (low speed- 8 km/h; 5 mph) approach to a signalized intersection
Dual Transceiver Simultaneous Operations in a Single Vehicle	No Co-channel or In-band Interference	Supported. (-40 dB adjacent channel interference rejection)	Not applicable to LTE	No Co-channel or In-band Interference	No Co-channel or In-band Interference
Environmental and Power Compatibility	RSE: Compatible with NEMA TS-2 Specification; OBE: Compatible with SAE Specifications	Compatible: NEMA TS2-2003 v02.06, SAE J1113, SAE J1211 & SAE J551	LTE base stations are compatible for outdoor use	RSE: Compatible with NEMA TS-2 Specification; OBE: Compatible with SAE Specifications	RSE: Compatible with NEMA TS-2 Specification; OBE: Compatible with SAE Specifications

SPaT Applications Related Communications Requirement	Requirement Specification	DSRC	LTE	ATSC M/H	HD Radio
	for Light and Heavy Vehicles			for Light and Heavy Vehicles	for Light and Heavy Vehicles
Size and Weight	Compatible with Small Car (Approx. Size 500 cu in/8194 cm^3; Approx. Wt. 2 lbs./0.91 kg)	244 cu in with Approx. Wt. 0.6 kg (1.3 lbs.)	LTE devices are compatible Size: 500 cu in/8194 cm^2; Weight: 500 g (1.0 lbs.)	Compatible with Small Car (Approx. Size 500 cu in/8194 cm^3; Approx. Wt. 2 lbs./0.91 kg)	Compatible with Small Car (Approx. Size 500 cu in/8194 cm^3; Approx. Wt. 2 lbs./0.91 kg)
Cost	Affordable to Private vehicle Purchaser	Cost under $300	Under $300	Affordable to Private vehicle Purchaser (Under $300)	Affordable to Private vehicle Purchaser (Under $300)

Source: ARINC April 2012

5.8.2 *DSRC*

Advantages

Several features and capabilities make DSRC suitable for supporting SPaT applications. DSRC meets the bandwidth and latency requirements for supporting SPaT applications. DSRC can support localized communication and has the ability to connect to the roadside equipment to transmit SPaT signal information with minimum latency. DSRC also meets the capacity requirements for supporting SPaT applications in the presence of background traffic consisting of part 1 BSM/HIA messages. It further meets requirements for reliability when messages are repeated. DSRC can support mobility communications at vehicular speeds; however there is some indication of exceeding Doppler protection at high speeds. Furthermore, it does not need a subscription fee.

Limitations

DSRC does not meet the capacity requirements when all vehicles transmit both part 1 and part 2 BSM messages. On the other hand, none of the technologies assess can support this either.

Field tests of DSRC technology under worst case multipath LOS conditions indicates a low probability of error free packet delivery at ranges between 200 and 300 meters, with overall good PER performance out to about 400 meters. Examination of the test results indicates that multipath fading is a significant factor in this performance. Under some conditions less than 1% PER has been observed out to 400 meters. Doppler possibly a limitation at velocities higher than normal posted freeway speeds.

DSRC is not suitable for PREEMPT applications without substantial changes to the antenna systems, and possibly changes to the application approach. Message delivery reliability at required ranges to assure clearance of the intersection is the major problem.

Conclusions

DSRC is suitable for supporting SPaT applications if deployed in conjunction with effectively designed antennas, including simple diversity antennas to reduce multipath fading. DSRC, when used on roadside units can send SPaT, GID, and DGPS correction messages to vehicles. Such a solution looks attractive due to the localized nature of the SPaT and GID application and the stringent temporal scope of the messages. Specifically, SPaT messages are relevant only to vehicles in the vicinity of an intersection and further dictated by stringent time-bounds and reliability constraints (Figure 5.8-1). Further, local broadcast is the method of choice for SPaT application where the roadside unit sends information to multiple vehicles that may be near the intersection.

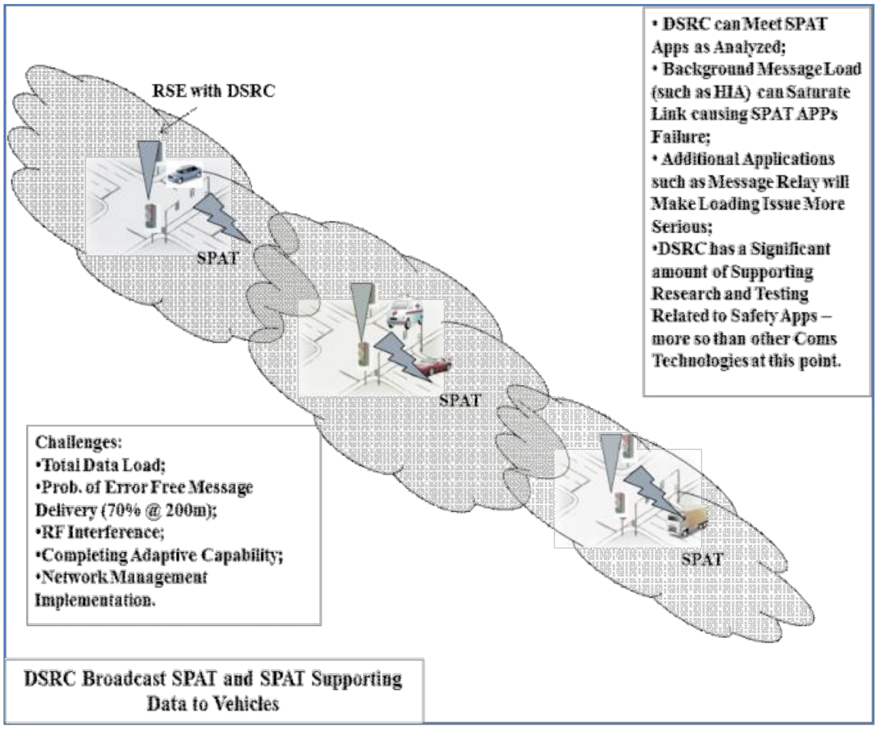


Figure 5.8-1. DSRC for SPaT Applications; Each Intersection has a Dedicated RSE for Supporting SPaT Applications

Source: ARINC April 2012

Further Study

DSRC performance varies widely depending on roadway situations e.g., LOS/NLOS, urban, highway etc. As such, near term consideration should involve studies for smart antenna design at roadside units, and multipath management through the use of diversity antennas. Advanced antenna technologies are recommended for further consideration to achieve the appropriate range-packet error performance required of SPaT applications.

For achieving the desired capacity, use of adaptive power control methods can be considered. Such methods can reduce the transmission range when the number of vehicles is large. Longer-term use of connected radios to support message relaying will help.

Of considerable concern is the potential for interference from V2V messaging, specifically if Part 2 of the Basic Safety message is used. If this occurs, it is highly likely that the DSRC channel will be overwhelmed, and SPaT, GID and DGPS correction reliability will suffer.

Another concern is the problem of adjacent channel interference. This was discussed elsewhere in this report. It appears that some revision of the planned band allocations (the uses of the different channels) may be required to avoid adjacent channel interference.

5.8.3 *LTE*

Advantages

LTE networks have several advantages with regards to intersection safety communications. While most LTE networks are commercial and require subscription fees, public safety LTE will be licensed to jurisdictions and can possibly be leveraged for broadcast of road safety related information without fees. Public safety LTE networks will have the advantage that they can support required SPaT data rates when in broadcast mode to all user devices in the cell coverage area (see Figure 5.8-2). In broadcast mode, additional messages such as DGPS and GID can also be sent to all vehicles in the cell area, given there is sufficient capacity allocated for the broadcast channel. LTE standards support mobility for vehicle speeds. LTE can also operate in rural and urban canyons with additional base stations placed as needed as part of cell planning to support bandwidth requirements. The LTE user devices are small and are available in OBE-compatible or handheld configurations. Additionally the LTE base station meets environmental requirements for outdoor use and is already deployed by commercial carriers. LTE network availability is designed to be high and can be engineered to support 99.99% availability. The LTE base station range can be sized to meet SPaT radio range requirements.

Limitations

There are some limitations in using LTE for SPaT. There is insufficient test data to show that the SPaT BER and latency requirements at vehicle speeds can be satisfied. Using LTE for SPaT may also require some software in the user device to filter SPaT messages to identify the correct approaching intersection's SPaT information. This is especially true when SPaT information for all the intersections in the cell area is transmitted on a single broadcast channel. Additionally, the willingness of the public jurisdictions to support the data load from SPaT messages is indeterminate.

Aside from being highly complex logistically (LTE has no peer-to-peer capability), BSM and HIA messaging would consume more than 100% of the available bandwidth on the network, and this would clearly not be acceptable to the jurisdictions implementing the systems.

Conclusions

The LTE broadcast mode is suitable for disseminating SPaT, DGPS and GID if BER and latency measures can be verified and provided that there is software in the user device to filter SPaT messages to identify the relevant intersection's information. LTE is not suitable for BSM/HIA. The data load, latency and delivery reliability requirements that safety related communications would add to an LTE "fee for service" network probably would not comply with the service provider's business case.

Before pursuing LTE further, it must be determined if jurisdictions will be willing to include these services and their accompanying data load, as well as any other design constraints (such as number of eNBs, location of eNBs, etc.) in their implementation plans.

Further Study

In order to improve the performance of the LTE technology in supporting SPaT applications, further investigation is required to verify the BER and latency values for LTE via field trial results. Additionally, when in broadcast mode, the load of other public safety traffic on the broadcast channels will impact the bandwidth available for SPaT, DGPS and GID messages. The public safety traffic load will need to be analyzed further based on usage by other public safety applications, and discussions with key LTE jurisdictional implementers must be held to determine if jurisdictional LTE is feasible. If the MBMS broadcast option is considered, its performance is unclear since there are no current public implementations. Thus further study and field trials to validate MBMS performance would be required.

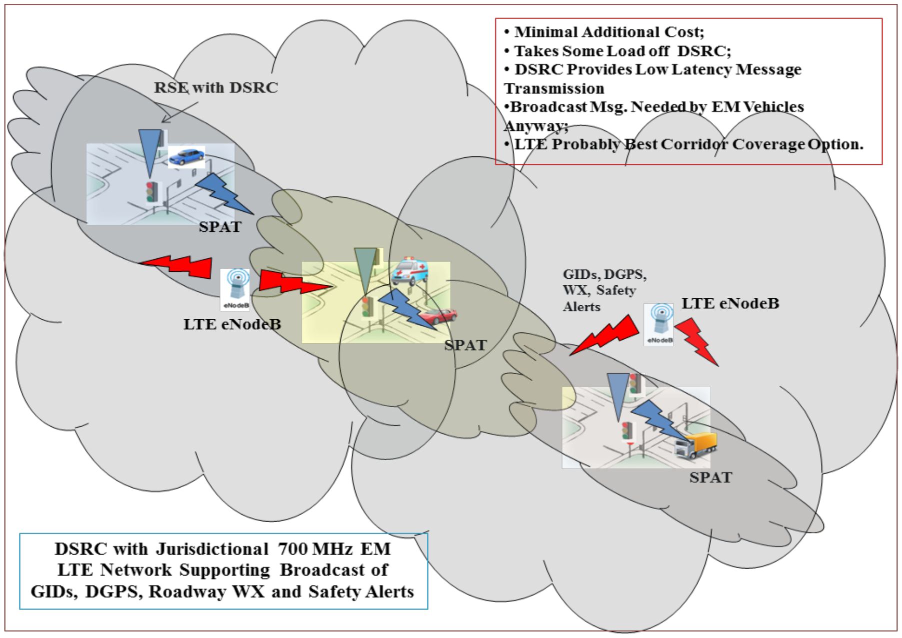


Figure 5.8-2. Emergency Management Jurisdictional LTE Communications Technology Augmenting DSRC with Safety Broadcast Information

Source: ARINC April 2012

5.8.4 *ATSC M/H Digital Mobile Television*

Advantages

ATSC M/H technology has several advantages in supporting SPaT applications. It is equipped with sufficient capability to support broadcasting of GID and DGPS information over wide area coverage of tens of kilometers. Its bandwidth and data rate provide sufficient communication capacity. The technology performs particularly well in handling Doppler spread caused by moving recipients, a critical factor to support intersection safety applications. This technology also has great potential to achieve key economical scale to drive down the out-of-pocket cost that each vehicle driver has to pay for the supported applications.

Limitations

The current FCC planning factors for ATSC M/H include service availability at 50% of locations 90% of the time. However, this is not sufficient for safety-related SPaT applications. The deployment would assume that local jurisdictions would need to have their own dedicated television channel to support SPaT applications. If not, they would need to make arrangements with and be dependent on commercial television stations allocating certain bandwidth for SPaT applications; which may be difficult based on the limited mobile digital TV content of an ATSC data stream and M/H digital TV multicast objective of service providers.

Conclusions

With wide area broadcasting capability and ability to tolerate Doppler spread, ATSC M/H is more suitable for disseminating GID/MapData information of large number of road infrastructure to many recipients simultaneously, instead of local area-specific SPaT messages. ATSC M/H is not suitable for supporting SPaT applications due to the current FCC planning factor of service availability at 50% of locations 90% of the time. While such planning factor for digital terrestrial broadcast television may be sufficient for broadcast media, it is not sufficient for safety-related SPaT applications. ATSC M/H may be considered if the service availability could be raised to a higher level.

Further Study

Since the current FCC planning factor of service availability at 50% of locations 90% of the time is not sufficient for safety-related SPaT applications, further study is needed to determine the appropriate level of service availability. Major issues to consider if ATSC M/H is used for broadcasting GID information include capacity, performance and coverage. These issues are affected by the number and locations of transmitters. Further study is recommended to determine optimal number and placement of transmitters and the associated performance metrics. If a partitioning scheme were adopted, a backend system would also need to be developed for distributing GID information to the corresponding transmitters.

5.8.5 *HD Radio*

Advantages

FM IBOC (HD Radio) technology has several advantages in supporting SPaT applications. It is equipped with sufficient capability to support broadcasting over wide area coverage of tens of kilometers. Its bandwidth and data rate provide sufficient communication capacity for medium size urban areas and can be tailored to meet large urban areas. This technology may be even more useful in this regard if the GID message size is reduced from the existing definition provided by SAE J2735. The technology performs particularly well in handling Doppler spread caused by moving recipients, a critical factor to support SPaT applications. This technology also has been adopted by many automotive manufacturers and offered as one of the in-vehicle options. This existing penetration helps drive down the out-of-pocket cost that each vehicle driver has to pay for the supported applications. There are also more initiatives to leverage IBOC to provide media and information-rich services to vehicles. The technical readiness and maturity help IBOC become one of the recommended technologies to support SPaT applications, particularly for disseminating GID/MapData information. Also, jurisdictions have experience deploying highway advisory radio, including FM versions (under special FCC consideration).

Limitations

Local jurisdictions would need to have their own dedicated radio channels, which are reasonably affordable, to support SPaT applications. If local jurisdictions do not have their own dedicated radio channel, they would need to make arrangements and be dependent on commercial radio stations to allocate certain bandwidth for SPaT applications, which would significantly limit data rate and negatively impact the ability of IBOC to meet SPaT related application requirements.

Conclusions

IBOC technology is suitable for broadcasting GID and DGPS information. If used as a supplemental communication technology to support SPaT applications, it could reduce the traffic load on the primary communication network (e.g., DSRC), although this effect would be minor, since these applications do not impose is substantial data load in comparison to other applications. A balance needs to be achieved between the amount of GID information to be sent for all of the intersections within the coverage area, and the amount of time needed to complete broadcasting this information. An appropriate partitioning scheme would also help to improve the overall system performance; however, GPS synchronization is included in the design, which can support distributed broadcasting.

Further Study

Major issues to consider when using HD Radio for broadcasting GID information include capacity, performance and coverage. These issues are affected by the number and locations of transmitters. A further study is recommended to determine optimal number and placement of transmitters and the associated performance metrics. If a partitioning scheme were adopted, a backend system would also need to be developed for distributing GID information to the corresponding transmitters.

5.8.6 *Final Recommendation*

DSRC is the preferred communication technology for supporting intersection safety applications. This includes using DSRC for broadcasting SPaT messages, GID/MapData, and DGPS information. Based on available test data, DSRC is able to meet BER, data throughput, delay, and mobility requirements of SPaT applications. Smart antennas need to be deployed in conjunction with DSRC in order to mitigate current limitations of DSRC communication range, which are primarily related to multipath issues. DSRC capacity becomes an issue in the presence of high levels of background network traffic and high vehicle densities. Using communication technologies such as LTE, HD Radio, and ATSC M/H to supplement DSRC do not offer significant advantages.

A critical issue to resolve with DSRC will be the allocation of applications to channels. The data load from BSM/HIA messaging, as it is currently envisioned will consume the control channel, and will render intersection safety applications effectively useless on that channel. Alternatives may lie in multichannel radios and development of policies that allocate specific applications to specific non-interfering channels.

Chapter 6 - Summary and Recommendations

6.1 SPaT Communications Analysis Findings

Table 6.1-1 summarizes the SPaT message analysis results. The DSRC is defined as a *Best Efforts* wireless communications network. Wikipedia defines *best efforts* communications as: “A best-effort network or service does not support quality of service. An alternative to complex QoS control mechanisms is to provide high quality communication over a best-effort network by over-provisioning the capacity so that it is sufficient for the expected peak traffic load. The resulting absence of network congestion eliminates the need for QoS mechanisms”.

Table 6.1-1. Summary of SPaT Applications Related Message Communications Requirements

(Ref: Section 2.3 of this report)

Communications Parameter	Minimum	Maximum	Communications Requirement
SPaT Message Size (octets)	273	383	383
SPaT Message Latency (msec)	76	76	76
SPaT Supporting Message Size (octets)	339	2857	2857
Range (m)	170	515	515
Transmit Window (msec)	76	999	76
Maximum Latency for Message (msec)	400	4000	400
Average Throughput for Message (kbps)	37	40	40
Bandwidth Requirements (mbps)	20	27	27
Bit error Rate (BER)	10^{-4}	10^{-3}	10^{-4}
Message Transmissions to Achieve Confidence Level of Error Free Message Receipt	4 / 99.9%	7/99.999%	If SPaT Considered Safety of Life Critical need 7 repeats; Otherwise 4 Repeats

Since reliable delivery of SPaT and SPaT related messages to vehicle OBEs from RSEs is required at a distance from the intersection stop line to allow drivers to take appropriate safety action, the wireless network must have adequate bandwidth to accommodate peak data load, with high confidence level of error free SPaT related message delivery to destination communications devices.

Wikipedia defines QoS as: “Quality of service (QoS) is the ability to provide different priority to different applications, users, or data flows, or to guarantee a certain level of performance to a data flow. For example, a required bit rate, delay, jitter, packet dropping probability and/or bit error rate may be guaranteed. Quality of service guarantees are important if the network capacity is insufficient.” Using this term for QoS, the wireless communications technology supporting SPaT related applications must have the capability of giving priority to SPaT related messages to assure that they are delivered to the receiving device at the appropriate time (referenced to GPS time) as related to the distance of the vehicle from the intersection stop line and associated approach speed (posted or 85 percentile plus safety margin).

6.2 BSM Message Load on the DSRC Link as a Function of Vehicles in Communications Range

SPaT applications message data load is small (40 kbps) and represents typically a 2% or less data load on the DSRC network. The major data load is related to the “here I am” (HIA) messages which are transmitted at a 10 Hz rate by each vehicle within communications range. The SAE J2735 part 1 HIA message is 339 bytes and part 2 is 1752 bytes for a total of 2091 for part 1 and part 2 transmissions. This equates to a minimum data rate of 27.12 kbps/vehicle or a maximum of 167.28 kbps/vehicle.

Increasing communications coverage only adds to the number of vehicles in communications range and thus increases the communications load on the DSRC network, as illustrated in Table 6.2-1 and Figure 6.2-1.

Table 6.2-1. Communications Load as a Function of Number of Vehicles

HIA Message Size	10 Vehicle Data Load	50 Vehicle Data Load	100 Vehicle Data Load	200 Vehicle Data Load	500 Vehicle Data Load
SAE J2735 Part 1 Message	271.2 kbps	1.356 mbps	2.712 mbps	5.424 mbps	13.560 mbps
SAE J2735 Part 1 & 2 Message	1.673 mbps	8.364 mbps	16.738 mbps	33.456 mbps	83.640 mbps

Source: ARINC April 2012

Cedar Rapids, Iowa (population 126,326 in 2010) has 15,551 vehicles on corridors during peak traffic covering 166.8 km^2 (64.4 sq mi) and with 140 signalized intersections (Ref: Cedar Rapids Gazette, 7-28-2011; “City Officials Support Traffic Cameras” [160]) for an average of 111 vehicles per intersection. Thus it can be seen that peak traffic with wide area communications can saturate a communications network just supporting SAE J2735 messaging and with cellular deployment, each cell’s coverage area would have to be tailored to the number of vehicles and data load associated with safety applications. (An LTE cell typically supports an 86.4 mbps down-link and a 43.6 mbps up-link (10 MHz BW) and 200 users; BSM/HIA up link bandwidth per vehicle would be 218 kbps (43.6 mbps/200 users) and BSM/HIA message load per vehicle (part 1 & 2) is 168 kbps which approaches cell saturation). Examining the need for BSM/HIA messages at 10 HZ should be considered or possibly reducing the communications range of the RSE to OBE communications range.

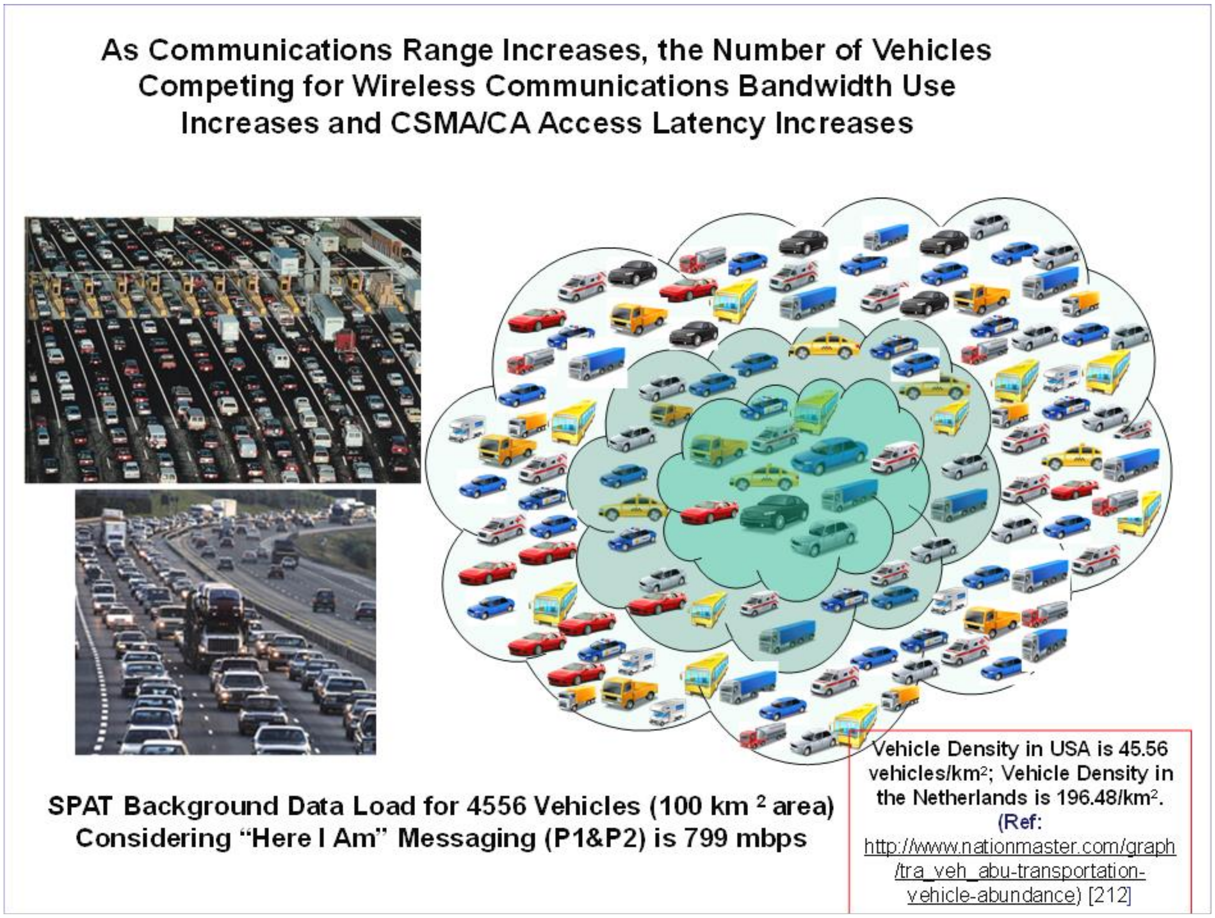


Figure 6.2-1. As Communications Range Increases, So Does Data Load on the DSRC Link
Source: ARINC April 2012

A primary finding is that, using the SAE 2735 data set and the DSRC wireless mobile communications link, the bandwidth demand of SPaT is relatively low. On the other hand, the potential competition for bandwidth is very high, especially considering BSM/ HIA message transmission load in high congestion situations. Each SPaT message provides a key safety benefit to vehicles approaching an intersection, while each BSM/HIA message may not. For example, since most vehicles are a) not in close proximity to other vehicles in radio range and b) most vehicles are not on collision trajectories relative to other vehicles, most BSM/HIA messages are *not* safety of life related. Obviously some are, but most are not. Possibly the data rate and range of the BSM/HIA may need to be revisited so that it provides safety benefit when needed, but does not overwhelm the system and prevent other applications from using the DSRC channel .

The SPaT applications message analysis identified deficiencies in the SAE J2735 message set, especially as related to supporting changes to the SPaT after the first message has been transmitted. Since traffic signal timing is transitioning from fixed to traffic responsive and adaptive signal timing, it is important that SPaT messaging supports dynamic changes to signal phase and timing. This is also true with PREEMPT, TSP and FSP, where a transmitted SPaT is changed based on changing of events. GIDs also have both temporary and semi-permanent changes. The effective date/time is necessary, whether the change is temporary or semi-permanent, expected duration/expiration date of the temporary change, and certified cancelation (date/time) of the temporary change. Temporary GID changes are required for intersection road work, accidents causing lane closure, special event prohibiting turns, emergency evacuation, etc. GIDs should also include information related to pedestrian and bicycle crossing sensor deployment, working status and ability to warn the OBE that pedestrians (or bicycles) are present in intersection crossings. Similarly GIDs defining rail crossings must define if the crossing only has a signal or has both a signal and a barrier and the definition of equivalent “yellow” state such as “time to clear the rail crossing before red time” or “time before barrier starts closing”.

The application concepts described in the Task 2 report, and anticipated by the SAE messages, appear to assume that the vehicle is approaching an intersection in isolation, i.e., free of other vehicles. In these situations, the point to decide to stop is based on the distance between the vehicle and the intersection limit line. This is technically only valid when there are no other vehicles present. If, for example, vehicles are stopped at a signal, the decision point will be moved farther from the intersection by about 4.6 meters (one car length) per queued vehicle. Currently planned systems do not account for this dynamic variation. To address this, the GID will probably need to include additional information related to the length of the vehicle queue, and the range of the system will need to be extended to account for this additional queue length.

BSM/HIA messages also need consideration related to the reference point that is being reported by the OBE DSRC. The GPS position is measured relative to the OBE GPS antenna. It must be translated relative to the vehicle’s center reference if the length and width of the vehicle is of use by receiving devices. There is also the requirement to address articulated vehicles and references associated with each segment as well as the length and width and reference angle (different segments will have different reference angles in a turn).

SPaT applications analysis indicates a range requirement of 515 m for PREEMPT, TSP and FSP applications. The signal propagation loss at 5.85 GHz over a 515 meter range is 142.46 db (Hata City Model), 128.36 dB (Hata Suburban Model) and 107.42 dB (Hata Open Space Model). Considering Hata-City propagation loss, provides a received signal level of -98.66 dB at the OBE DSRC receiver considering a 44.8 dBm RSE signal transmission power and an OBE DSRC with 0 dB antenna gain and 1 dB coupling loss. To obtain a 10^{-3} BER operating at 6 mbps using QPSK modulation requires an 18 dB SNR. With a minimum receiving sensitivity of -110 dBm and an 18 dB signal above the noise floor of the receiver provides a -92dBm signal requirement, which is not in compliance with the -98.66 dBm probable signal level per Hata-City propagation model. The resulting 11.34 dB S/N equates to a $10^{-0.5}$ BER (Ref: “Risk Analysis – IEEE802.11p”, by H. Viittal (ALMA, 12-2009) [161]). Many of the large cities have a noise floor in the 5.85-5.925 GHz frequency band of -90 dBm (Ref: NTIA Report 00-373, entitled, “Measured Occupancy of 5.850-5925 MHz and Adjacent 5- MHz Spectrum in the USA”, by Frank Sanders [36]) which would result in a signal level of -72 dBm required at the OBE DSRC receiver to achieve a 10^{-3} BER at 6 mbps. In addition to the required signal level above the noise to achieve a BER for a selected modulation/data rate, a signal margin to accommodate losses in received signal level caused by multipath and absorption by foliage is required. This illustrates the marginal signal level conditions at 515 meters range. A 3 mbps data rate using BPSK modulation required 15 db S/N at 10^{-3} BER with a 10^{-1} BER achieved at 8 dB S/N. The 3 mbps/BPSK modulation is the best performance achievable by the DSRC.

Field tests of DSRC technology indicates a low probability of error-free message delivery to another DSRC at ranges greater than 300 meters. Tests indicate error-free message delivery probability is around 55% at 300 meters, 65% at 250 meters and 70% at 200 meters range from RSE to OBE. Higher broadcast frequency of messages improves performance and is recommended for some of the more critical 1 Hz transmission frequencies (as defined in SAE J2735 Standard) messages. (The Task 2 report defined these recommended messages to increase broadcast frequency). Also, communications load analysis should consider required confidence level for the error free delivery of the message and the appropriate number of message transmissions to achieve the confidence level, versus required critical ranges associated with the application.

6.3 DSRC Related Findings

Reviewing research and test reports, the following are identified problems (discussed in both Task 2 report and this report) related to DSRC technology applied to SPaT applications:

- SPaT analysis indicates a requirement for 99.9% confidence in message delivery at ranges of 515 meters as related to the PREEMPT application. At this range the message reception probability is down to < 10% (Ref: "Design of 5.9 GHz DSRC-based Vehicle Safety Communications", Daniel Jiang, et al, DalmlerChrysler [162]), indicating that PREEMPT may not be a good DSRC candidate, at least not without additional application concept development.
- Analysis indicates that HIA messages at 10 Hz in a dense vehicle environment will saturate the DSRC link, especially using part 1 and 2 HIA messages. Adding the function of message relay to DSRC will make the overload situation worse.
    - Recommendation: in-depth modeling and analysis of the communications load impact on the DSRC link of all planned messaging functions. Eliminate the non-critical functions from the DSRC link.
- Field tests indicate adjacent channel interference when closely spaced vehicles are transmitting on adjacent channels at the same time. The problem will increase with dual DSRC devices installed in a vehicle (one for service and one for safety) and both simultaneously transmitting;
    - Recommendation: Modeling, Simulation and Field Testing to define the issue in detail and test corrective solutions such as improved filtering, or development of revised frequency policies.
- Field tests of DSRC indicate interference issues when vehicles are close to other types of transmitters;
- Additional analysis is recommended related to radio frequency interference, including modeling the RF environment. Analysis should include high power mobile transmitters close to a vehicle (or RSE) with RF power level by passing the RF front end of the DSRC. Mobile dispatching radios and mobile armature (HAM) radios, military convoys with mobile military radios, roadside TV News Vans, etc. should be considered as possible sources of high level RF energy;
- DSRC has adaptive capability with the selection of modulation and data rate to accommodate deteriorating conditions with S/N and protocol "hooks" to execute change. However, there is no current technique to support adaptive rate modulation due to lack of feedback at the MAC layer. Thus the DSRC must be set up for a specific data rate, and without a protocol controlling which modulation/data rate is being used in a specific area, all vehicle and RSE DSRC devices must use the same (which may not be optimum for the area (too high of data rate for the noise environment resulting in high BER/PER, or perhaps too low, decreasing the networks ability to accommodate the data load;
    - Recommendation: Additional analysis on wireless performance improvement based on adaptive communications techniques and protocol. Analysis of network management protocol and perhaps its role in determining link performance and data rate/modulation adjustment needs is also recommended;
- DSRC field tests indicate performance issues with multipath in urban canyon environments. Multipath signals 180 deg. out of phase with the primary signal results in communications loss at ranges which seem to be similar in different urban areas and across different test;
    - Recommendations: Additional analysis including modeling of MIMO and/or diversity antennas to reduce impact of multipath;
- Performance of the DSRC antenna on a vehicle is a function of the antenna design including consideration of antenna type, vehicle ground plane, slope of the vehicle's roof, and mounting location on the roof. One antenna design does not "fit all" vehicle models and types.

Consideration of MIMO antenna performance on DSRC performance will also necessitate consideration of antenna design, issues with antenna separation distance, and inter-modulation;

  - Recommendation: All sensitivity and EIRP specification should be developed from a vehicle perspective, as opposed to an antenna perspective, so that each vehicle will exhibit a specified RF envelope/pattern regardless of the body structure of the vehicle.
- DSRC transceiver/modem availability is 99.9% considering 50K hr. MTBF and 48 hours for a vehicle owner to get the DSRC repaired. Redundant DSRC devices are needed to meet 99.999% availability. The service related DSRC could be configured to be the back-up to the safety related DSRC to accommodate high availability (99.999%) for safety applications;
  - Recommendation: If SPaT, collision avoidance and other SAE J2735 defined applications are considered to be safety of life applicable, then use of the service DSRC as back up to the safety DSRC is recommended. Protocol additions should be developed to support failure monitoring and automatic back up switch over;
- Early versions of DSRC devices are emerging on the market designed using SDR technology and also dual DSRC capability. These systems are not being designed to be fully compatible with SAE vehicle environmental standards. Cost of early DSRC products are approximately $500. Size, weight and power are compatible with OBE applications. There is no issue with the ability to meet SAE environmental requirements other than design cost and perhaps impact on product cost. Manufacturers are waiting for the requirement and specifications to be completed and stable prior to committing to production design;
- DSRC bandwidth becomes saturated with approximately 150 vehicles in communications range primarily because of BSM/HIA messages. The addition of message relay between vehicles will only increase data load as well as increase “hidden Terminal” dual simultaneous transmissions causing in-band interference;
  - Recommendation: Additional studies on total communications load of DSRC with all applications operating and also with connected vehicle message relay. Possible solution is reduction in communications range.
- This study indicates that there is an advantage to utilizing an overlay, wide area broadcast wireless link to offload the DSRC from transmitting less time critical information to vehicles. Offload would include GID, DGPS correction, roadway weather and safety alerts. The reasons are:
  - Simpler distribution for less time critical messages (does not require distribution through multiple nets and subnets with associated increased probability of message error);
  - Provides some relief of the DSRC safety communications data load (however, the significant data load is still HAI messages as traffic density increases);
- DSRC is defined as a “Best Efforts” communications link and should not be applied to “safety of life” applications. However, by using multiple transmission of SPaT (and other safety critical) messages, the probability of delivery of an error free, broadcast message such as SPaT) is increased as well as the effective BER and confidence level related to message delivery approaches that required by emergency communications standards. DSRC also has a QoS capability, which is significantly improved by separating service related messaging from safety related messaging. Thus the DSRC link has improved capabilities over a basic “Best Efforts” communications link; however, the DSRC cannot truly assure priority delivery of safety messages because of the nature of CSMA/CA channel access scheme. All safety messages of the same priority; e.g., HIA and SPaT, contend for channel access;
- The DSRC supports multiple data rates and adaptive modulation; however, this feature cannot be fully exploited to improve performance due to lack of feedback in the broadcast mode employed by SPaT applications. CSMA/CA channel access results in “hidden terminal” issues. “Hidden terminal” results in transmission collisions;

- Recommendation: Modeling of the DSRC network to determine the load impact of the number of vehicles, transmission range, carrier sensing range, and impact of hidden terminals;

- The critical distance from the stop line that an approaching vehicle must have an *error-free* SPaT message, the MAP-GID message for the intersection and GPS augmentation (DGPS) is based on vehicle approach speed, friction of the road surface, and vehicle size/braking system (i.e., car versus truck). Perception and driver reaction time is generally specified as 1.5 seconds. For a vehicle traveling at 35 mph (51.3 ft./sec; 53 km/h) towards a signalize intersection, the vehicle must be warned before it reaches 136 feet (41.5 m) from the stop line which includes 1.5 seconds for perception and reaction time and 1.15 seconds to stop. Assuming 100 msec. transmission latency and another 100 msec possible link contention plus 100 msec OBE applications processing time adds an additional 0.3 seconds (15.39 ft.; 4.7m) for a total of 51.3 ft./sec X 2.95 sec = 152 ft. (46.3m). If the RSE receives the SPaT message from the applications processor with the vehicle at a distance of 152 ft. (46.3m) from the stop line, driver should be capable of stopping. On a rural corridor where the vehicle may be approaching the intersection as perhaps 60 mph (88 ft./sec; 97 km/h), stopping time would be 1.96 seconds and total time would be 1.96 + 1.5 + 0.3 = 3.76 sec which equates to 331 ft. (101m). At an approach speed of 90 mph (145 km/h) the required time is 4.73 sec or 625 feet (191m) from the stop line. Assuming that 4 SPaT messages are required to meet a 99.99% confidence level of message delivery, or that 7 SPaT messages must be transmitted to achieve 99.999% confidence level (as typically required in emergency communications) that the message has correctly been received by the vehicle, would essentially add 0.9 second (0.3 sec latency to the first message and 0.6 sec for 7 transmissions) to the warning time/distance. Thus at 35 mph (53 km/h) the time/distance becomes 3.55 sec/182 ft. (56m); 60 mph (97 km/h) is 4.36 sec/384 ft. (117m); and 90 mph (145 km/h) is 5.33 sec/704 ft. (215m). Thus a critical range of a vehicle from the stop line with high-speed approach is approximately 250 m, a medium speed approach is approximately 150 m and a low speed approach is around 90m. A SPaT message is 3100 bits, for 7 messages, this equates to 21.7 kbps. This equates to approximately 7.3 msec of transmission time at 3 mbps and 3.6 msec of transmission time at 6 mbps. It is possible to transmit a group of consecutive messages followed by a time gap. Assuming maximum reliable communications distance is 300 m then it takes a high speed vehicle 6.7 seconds to travel from maximum effective range to a range which the vehicle must start receiving a group of 7 SPaT messages. The time increases to reach the critical point of receiving SPaT messages by 0.1 seconds for compromise in message receipt confidence level, with confidence level being 70% at 200 m with one message transmission.

6.4 Technology Analysis Findings

Five communications technologies were short listed in Task 2 and include DSRC, Mobile WiMAX (IEEE 802.16e), LTE, In -Band on Channel (IBOC) digital mobile radio, and ATSC M/H standard mobile digital TV. IBOC and ATSC M/H are digital broadcast technologies, which are candidates to augment DSRC. Results are as follows:

- Using wide area broadcast technologies such as LTE, IBOC, and ATSC M/H to offload DSRC, does not offer a significant advantage since the major contributing load factor is the HAI messages and possibly safety message relay evolving from “connected vehicle” initiatives. However, some advantages of using a wide area broadcast are:
  - Less complex communications architecture (link from safety information distribution center directly to wide area broadcast transmitter, rather than through primary and subnets to intersection RSEs);

        - Has some impact on reliability of GIDs, DGPS, and safety alerts reaching a vehicle before approaching critical decision/reaction/stopping distance from the intersection stop line;
    - Eliminates the need for SPaT augmentation messages having to compete for DSRC transmission time during the critical period as the vehicle approaches the intersection dilemma zone. The GID, DGPS, and intersection applicable safety alerts reach the vehicle multiple seconds before the critical time window.
- IBOC, also known as HD Radios, can provide 300 kbps broadcast data transmission. They can be configured for wide area coverage or distributed for sector coverage using GPS signal synchronization. Since Highway Advisory Radio (HAR) has been utilized by ITS for supporting safety related information dissemination to vehicles and since FCC has allowed FM HAR to be deployed (Miami International Airport is an example), IBOC technology is suitable for GID, DGPS augmentation (RTMC DGPS Messages), roadway weather and other safety alert related data transmission to vehicles. IBOC radio technology is reasonably priced and vehicle manufacturers are providing IBOC radios in vehicle as standard equipment in 2012;
- ATSC M/H mobile receivers are available for vehicles and are affordable. ATSC M/H shares the 19.3 mbps data stream with fixed, non-mobile TV data distribution. Four mbps of mobile data may be available for safety use, but would require a public/private partnership for ITS applications use. With the sharing of the ATSC data stream between fixed and mobile TVs, TV service providers will most likely be reluctant to provide public partners with bandwidth. In addition, the current digital TV coverage planning factor does not guarantee more than 50% of area coverage, 90% of the time within received signal contour. This is not sufficient for safety-related, SPaT applications. Comparing ATSC M/H with IBOC for possible use by a jurisdiction to distribute GIDS and other less time critical information to vehicle OBEs, IBOC has a cost, deployment flexibility, and coverage advantage, while ATSC M/H has a bandwidth advantage (but most likely requires private partner use agreement);
- There is no clear advantage of WiMAX over LTE to be used as a broadcast communications link from infrastructure to vehicle and furthermore WiMAX has latency issues that can cause several hundred milliseconds delays. Since FCC designated LTE to be the interoperable, mobile emergency communications technology to be used by jurisdictions, 700 MHz mobile emergency band, LTE equipment is currently in deployment by jurisdictions (such as San Francisco and NYC) and has the bandwidth to support less time critical safety related information broadcast. Thus an LTE broadcast option may be available in jurisdictional areas for broadcasting GIDs, DGPS augmentation, and safety related alert/warning messages, which are also needed by emergency vehicles. However, there is no significant advantage in using LTE, except that it may be deployed by jurisdiction to meet the objective of national emergency communications interoperability and cost of use for traffic safety would be minimized (compared with other alternatives);
- Theoretically LTE can satisfy the majority of the SPaT applications communications requirements and it is feasible to use LTE in a broadcast mode. However, there is insufficient test data to verify that LTR broadcast can meet SPaT BER and latency requirements at specified vehicle speeds, and it is unclear if jurisdictional LTE systems can be made available for vehicle safety applications.
- Alternative wide area distribution system like LTE, IBOC and ATSC M/H need to be carefully assessed relative to the size of the RF footprint, the number of intersections served and vehicles served during peak traffic conditions and major congestion situations. Also alternative wide area distribution systems application must be considered relative to their associated business models. In urban areas the number of intersections rise as the square of the range, so using wide area systems for distribution of SPaT messages, while technically possible, is probably economically unrealistic. Using these technologies for distribution of GID and other types of messages is more realistic, but if one must also have a separate system to distribute SPaT messages, then these

alternate systems may be redundant. Public/private partnership using part of a private LTE network for public, interactive use most likely would not be possible due to the communications load placed on the private network sporting vehicle safety communications. Fees for continued service would also preclude a private LTE network from being used for applications such as SPaT. Deploying a public LTE network just to support safety applications would have frequency allocation as well as cost issues.

6.5 Operation and Maintenance (O&M) of Communications Technologies Supporting SPaT Applications

The O&M section of this report is in the appendix. The following are associated findings and recommendations:

- Additional study is recommended related to the roles and responsibilities for generating, configuration management, providing quality oversight and responsive distribution of GIDs. GIDs must be available to vehicle OBEs when the configuration change becomes effective. For temporary GIDs, the expiration of the temporary change and return to the semi-permanent GID must also be managed;
- With OBEs taking action based on safety related information received from the infrastructure, there is a clear need for improved geo-location and time frame accuracy of the broadcast safety data and any changes to messages. Geo-location includes the start and end location of the safety area of concern as well as the lanes and direction of travel impact. It is further important that all forms of safety message distribution be consistent (dynamic message signs, highway advisory radio, and digital broadcast to advance ITS vehicles) with no conflicting messages. Additional study is recommended related to roles and responsibilities related to generation, quality oversight, and distribution responsibility of road network related safety messages and the management of the associated quality of service;
- Maintenance analysis findings are that fleet service centers are experienced dealing with radio equipment in vehicles. Similarly private vehicle service centers are experienced with maintaining radio equipment (such as cellular wireless associated with vehicle monitoring services). Thus, no major issue is found related with servicing. For private users, maintenance cost will be a consideration and time to repair. Private users may not consider the communications equipment to be critical and thus delay repair. Availability of the safety related communications subsystem is directly related to the delay between equipment failure and when the owner takes action to get it repaired. A 30 day delay can result in the subsystem availability being reduces by several percentage points;
- IBOC compatible radios (mobile digital radios also called HD Radios) are being provided as part of standard vehicle equipment in 2012 and will be part of normal vehicle servicing by manufacturers;
- Many of the mobile communications product companies, (such as Motorola) have local radio repair shops in cities that have reasonably sized fleets. Cities with populations of 90,000+ have a high probability of having a local radio shop that repairs mobile radios (especially P-25 emergency radios). Thus, local radio shops can augment vehicle service centers in support of vehicle communications transceiver/modem equipment;
- RSE maintenance is within the skill set of jurisdictional signal technicians. Jurisdictional signal technicians have been maintaining WiFi, WiMAX and the older ASTM DSRC standards compliant wireless equipment for a number of years. They also have experience maintaining Ethernet switch/routers, roadside sensors, GPS time reference units, and ITS traffic signal controllers. Signal technicians, with training, are capable of maintaining the new IEEE 802.11p wireless transceiver equipment deployed along roadside as well as RSE related communications and

applications processing hardware. Spare electronic units for RSEs must be maintained by the managing jurisdiction;

- Network management should be addressed to support DSRC performance monitoring and maintenance;
- After market installation of OBE communications equipment has some issues. DSRC (or similar communications technology supporting SPaT applications). Both the communications device and firmware protocol must comply with ITS related, IEEE and SAE standards, including validation and certification (such as by OmniAir). Because V2V and V2I communications technology and associated standards will evolve, versions and updates must be managed. This is achievable through vehicle dealer servicing and with dealer certified devices. However, it becomes more complex with non-vehicle manufacturer certified hardware/firmware products, and private vehicle service centers (or even "do it yourself") installation of this safety related devices. Proper integration with other vehicle subsystems is required as well as communications antennas that are designed compatible with vehicle ground planes and sloping surfaces and interconnection of the Radio equipment is adjusted to eliminate standing waves.
    - Recommendation: Analyze the need for government regulations related to safety related communications equipment installed in vehicles and the responsibility and process to be used to assure that equipment is compatible with standards as well as the vehicle in which it is being installed as well as configuration management over the life of the vehicle;

6.6 Other Findings

Search of research literature did not identify that significant thought had been placed on risk analysis; safety of life issues associated with various applications, acceptable risk related to defined applications, which would become the basis for determining required reliability, availability and confidence level needed and impacts such parameters as BER/ PER and communications bandwidth versus data load. Accidents will occur because of equipment failure to meet operational requirements and the legal question that will be asked is: "was the safety device properly designed to meet its intended application"? Thus, manufacturers will be looking for national standards on which their product is based and will be judged in an accident situation. The appendix of this report includes a discussion of Safety Integrity Level including IEC EN 1508. It is about "understanding the odds" and establishing acceptable for which the safety related communications system must be designed.

- Recommendation: An in depth analysis of risk of injury and loss of life and what is considered to be acceptable is recommended, perhaps using SIL. Specification of the safety related subsystems, including communications would then be developed compliant with this analysis.

6.7 Technology Solution Recommendations

The following are the overall recommendations:

- While DSRC has some deficiencies, it still is the superior technology for the cost/performance and R&D attention should be focused on solving the identified issues.
- LTE technology is being deployed today by major jurisdictions in support of emergency management; bandwidth should be available to support broadcast of GIDs, DGPS and safety alerts. Exploration of the use of jurisdictional LTE to support safety broadcast is recommended.
- The second choice to augment DSRC broadcast is to offload GID, DGPS and safety alert messages to a jurisdictionally deployed, IBOC digital, terrestrial broadcast radio.

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Appendix A

A. Communications Reliability and Failure Rates

The generally accepted approach for defining safety level requirements is the Safety Integrity Level or SIL. SILs are measures of the safety risk of a given process, and essentially define to what extent a process can be expected to perform safely; and, in the event of a failure, to what extent can the process be expected to fail safely.

Under the SIL approach, safety is stratified into four discrete levels. Each level represents an order of magnitude of risk reduction. The higher the SIL level, the greater the impact of a failure and the lower the failure rate that is acceptable. Safety Integrity Level is a way to indicate the tolerable failure rate of a particular safety function.

The assignment of the target SIL requires a detailed hazard analysis that is outside the scope of this effort. However, a summary of the process is provided and estimates of the risks posed by failure of the various applications. These risks are estimates only and should be refined through additional, in-depth risk analysis.

The SIL assignment is based on the amount of risk reduction that is necessary to maintain the risk at an acceptable level.

The International Society for Automation (ISA) developed Safety Integrity Levels (SILs) which are described in the International Electrotechnical Commission (IEC) standard IEC 61508. This standard describes the SIL as shown in Table A-1.

Table A-1.International Society for Automation Safety Integrity Levels and Related Probability of Failures

Safety Integrity Level (SIL)	Low Demand Mode Of Operation (Average Probability of failure to perform its design function on demand)	Continuous/High Demand Mode Of Operation (Probability of dangerous failure per hour)
4	>= 10 E-5 to 10 E-4	>= 10 E-9 to 10 E-8
3	>= 10 E-4 to 10 E-3	>= 10 E-8 to 10 E-7
2	>= 10 E-3 to 10 E-2	>= 10 E-7 to 10 E-6
1	>= 10 E-2 to 10 E-1	>= 10 E-6 to 10 E-5

(Ref: IEC, IEC 61508 Standard, 6 Edition, Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems. [20])

The USDOT FAA utilizes a similar SIL approach as shown in Table A-2.

Table A-2. Severity of Consequence

(Ref: USDOT FAA, "System Safety Handbook Four Levels of Safety Integrity" [163])

Description	Category	Definition
Catastrophic	I	Death, and/or system loss, and/or severe environmental damage
Critical	II	Sever injury, severe occupational illness, major system and/or environmental damage
Marginal	III	Minor injury, minor occupational illness, and/or minor system damage, and/or environmental damage
Negligible	IV	Less than minor injury, occupational illness, or less than minor system or environmental damage

Determining the SIL for an application, or a system that implements an application is complex and requires an extensive analysis. Figure A-1 illustrates a risk graph that is the basis for determination of the required SIL.

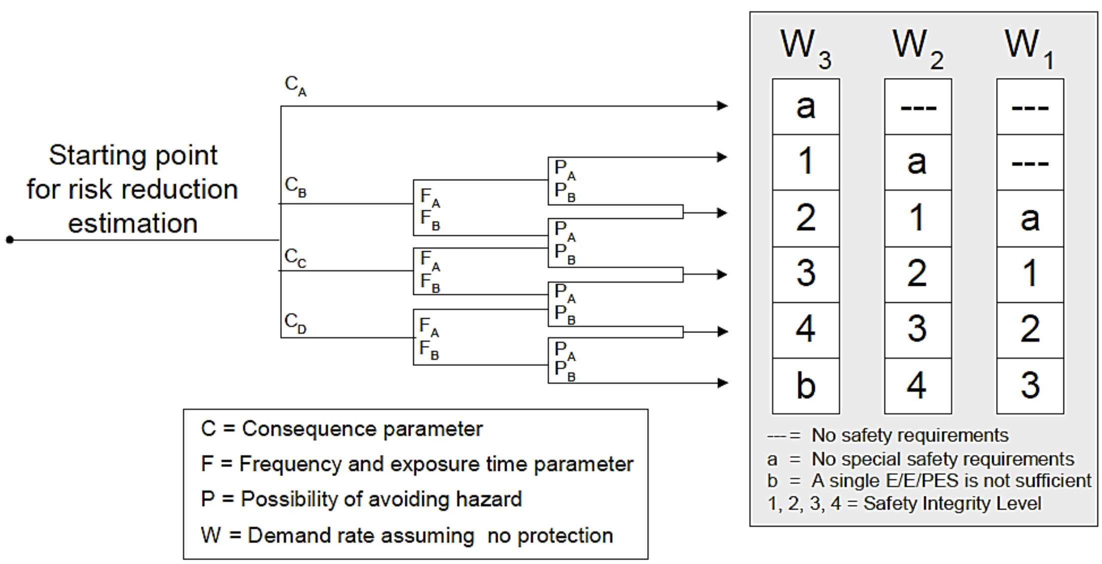

Figure A-1. Risk Graph

(Ref: "Methods of Determining Safety Integrity Level (SIL) Requirements - Pros and Cons", W. G. Gulland, April 2004 [164])

The parameters for this graph are provided in Table A-3.

Table A-3. Risk Graph Parameters

(Ref: "Methods of Determining Safety Integrity Level (SIL) Requirements - Pros and Cons", W. G. Gulland, April 2004 [164])

Consequence	
C_A	Minor Injury
C_B	0.01 to 0.1 Probable Fatalities per Event
C_C	>0.1 to 1.0 Probable Fatalities per Event
C_D	>1 Probable Fatalities per Event
Exposure	
F_A	<10% of Time
F_B	>10% of Time
Ability to Avoid Hazard	
P_A	>90% Probability that Hazard can be Avoided
P_B	$\leq$ 90% Probability that Hazard can be Avoided
Demand Rate	
W_1	<1 in 30 Years
W_2	1 in >3 to 30 Years
W_3	I in >0.3 to 3 Years

For most connected ITS applications, the exposure rate is less than 10% of the time. Applications where this is not the case would be, for example, automated driving where the system would be involved in continuous control of the vehicle as it drives along the road. Similarly, for non-automated applications, the ability to avoid a hazard is generally >90%. This is because the driver is assumed to be in control, and the system is simply providing added safety benefits. For automated control applications, such as automatic braking, the ability to avoid a hazard would be <90%. In general, the demand rate is potentially every time the vehicle is driven, so this value would be typically less than 0.3 years.

Table A-4 provides the ASIL as a function of degree of automation and the injury/fatality risk. These attributes are more directly relatable to the various ITS applications described in this report.

Table A-4. SIL Levels by Application Type

		Type of Application		
Severity		Non-Automated (e.g. Warning)	Automated Discontinuous (e.g., Braking)	Automated Continuous (e.g., Steering)
S0	ASIL QM (not safety critical) PDF< 10^{-4} Conf.=59.1%	ASIL QM (not safety critical) PDF< 10^{-4} Conf.=59.1%	ASIL A PDF=10^{-6} to 10^{-5} Conf=97.4%	ASIL B PDF=10^{-7} to 10^{-6} Conf.=99.7%
S1	ASIL QM+ PDF=10^{-5} to 10^{-4} Conf.=76.9%	ASIL QM+ PDF=10^{-5} to 10^{-4} Conf.=76.9%	ASIL B PDF=10^{-7} to 10^{-6} Conf.=99.7%	ASIL C PDF=10^{-8} to 10^{-7} Conf.-99.97%
S2	ASIL A PDF=10^{-6} to 10^{-5} Conf.=97.4%	ASIL A PDF=10^{-6} to 10^{-5} Conf.=97.4%	ASIL C PDF=10^{-8} to 10^{-7} Conf.-99.97%	ASIL D PDF<10^{-8} Conf.=99.997%

Severity		Type of Application		
		Non-Automated (e.g. Warning)	Automated Discontinuous (e.g., Braking)	Automated Continuous (e.g., Steering)
S3	ASIL B PDF=10^{-7} to 10^{-6} Conf.=99.7%	ASIL B PDF=10^{-7} to 10^{-6} Conf.=99.7%	ASIL D PDF<10^{-8} Conf.=99.997%	

Source: ARINC April 2012

In a similar manner that FAA specifies performance and reliability of sensors as well as quality assurance and testing, this will also be required for surface vehicle sensors and supporting communications devices and safety related, applications processors that are used to support applications associated with safety of life. The failure rate (FR) of components and design architecture must be used to develop the failure rate and mean time between failure (MTBF) for the sensor equipment (MTBF = 1/((failure rate)/(time period)). Mean time to repair (MTTR) is the time that it takes to restore the failed system to its normal operational performance and includes replacement, test and calibration time. Using field or shop replacement at the "black box" level, MTTR applies to unit replacements, test and calibration and not to circuit board or component replacement, test and unit calibration. Availability of the sensor or safety related communications device, in reliability terms, is:

Availability (A) = MTBF/ (MTBF + MTTR)

Reliability over a specific time period, (R_t), is determined by:

$R_t = e^{-Fr(t)}$

A typical failure rate (F_r) for a sensor is 0.00001 failures per hour, and reliability, R = 1 – F_r = 0.99999. Reliability for a specific trip time is R_t, and is calculated using the formula $R_t = e^{-Fr\,(t)}$ where t = trip or use time; for a commercial vehicle trip of 48 hours. R_t would be:

$R_t = e^{-(0.00001)\,(48)} = 0.9995$

This means that there is a 0.9995 probability that the sensor will perform to specification during the 48 hour trip time. The MTBF for the ITS safety related device would be one failure in 90,000 hours. If it required 2 day of repair time (delay in repair plus shop repair time) to take the vehicle to a repair shop, isolate the failure, replace the failed unit, test and calibrate the newly installed unit, the Availability of the OBE device would be 90,000/ (90,000 + 48) = 0.9995. Thus the OBE electronic unit (including sensors, communications devices and applications processors) used as a reference discussion has a 99.95% probability of being available to meet the safety requirement.

Where devices associated with safety are in series such as a position sensor, a switch/router and a Transceiver/modem, the subsystem failure rate, F_{rs}, is the summation of each series component of the subsystem. Considering an OBE subsystem composing a vehicle positioning sensor with a failure rate of 0.00001 (90K hrs MTBF), a mobile/switch router with a failure rate of 0.000017 (MTBF of 60k hrs) and a DSRC radio/modem with a failure rate of 0.00002 (MTBF of 50K hrs) the subsystem has a failure rate of 0.000045 per hour and an MTBF of 21.3K hours.

Where fault tolerant design is utilized (one back up), the fault tolerant Availability (A_{FT}) is:

$A_{FT} = 1 – (1- A)^2$ where A is the Availability of a single unit.

Using the DSRC as an example with an availability of 0.999 (50K hrs/50K hrs + 48 hrs), fault tolerance would provide an availability of 0.99999, which is a value expected for a confidence level of $C_{D,}$ Automated Discontinuous (see Table A3-4) "safety of life" application.

Integrity is the ability of a sensor to provide a position within its specification in terms of error radius and confidence (probability that the position provided is within the error radius) or for a communications device to provide error free message transmission to recipients at distances and within time constraints required by the application. Sometimes Integrity is related to Quality of Service (QoS) of a communications network, defining it as the ability of the network to meet performance specifications or to deliver the communications services per service agreement. For communications broadcast applications, it is difficult to measure compliance with Integrity (or QoS), which would be measured by the recipient of the message. Network management can be utilized to collect statistics on bit error rate (BER) and associated packet error rate (PER) as well as signal versus noise levels, peak and average data rates, and other parameters. However, this is not a real time measurement that can be utilized to instantaneously adjust broadcast communications. Similarly, for sensors, determining integrity requires either multiple coincident measurements, and subsequent determination of the variance between these measurements, or it requires a cross-check of a measurement using a different type of sensor. Absolute positioning systems like GPS can assess integrity by making multiple coincident (simultaneous) position measurements, and then determining how widely separated these measurements are. For example, the Receiver Autonomous Integrity Monitoring (RAIM) system required by the FAA uses the multiple position fixes available when five or more GPS satellites are available.

For relative positioning sensors such as RADAR or LIDAR, it is difficult to obtain Integrity for the measured location of a safety related target because there is no convenient ways to cross check the measurement. It is possible to determine the quality of the return signal in terms of signal to noise level (which is a function of target range and reflectivity or cross-section in the case of RADAR and LIDAR). But this approach does not generally validate the ranging measurement as much as it validates the existence of the target

Confidence level in communications systems can be enhanced by changing modulations and data rates to compensate for high radio frequency noise, which is possible in unicast but not possible in broadcast. It can further be enhanced by multiple transmissions of the same message, where each message transmitted improves the probability of reception of an error free message. For sensors, confidence level in determination of location within the tolerance of the sensor’s accuracy can be enhanced by:

- Correlating the measured position with a predicted position provided by a tracking system, such as a Kalman filter;
- Correlating the measured position with positions reported by other sensors; this is typically referred to as sensor fusion.

One major concern with sensor fusion approaches is latency in the various sensors, target trackers and fusion processors and its impact on position. The differences in accuracy for the different sensors must also be taken into account. Another concern is the differences in latency between various algorithms that will impact performance from one car manufacturer to another (assuming they use different manufacturers and sensors or sensor processing designs).

Some of the available relative positioning sensors have built in calibration and test features. A detailed analysis of these built in test and calibration features would be necessary to evaluate their effectiveness to determine performance failures. Where real time, built in test features are included with the sensor, an applications processor to manage the performance of OBE and manage failure reporting and inhibited use of information from a failed sensor, tracker and/or fusion processor. Corrupted data, caused by a failure should be prohibited from being propagated through the OBE subsystems and communicated to other vehicles and RSE.

There is a challenge to manage all of the evolutionary configuration updates considering the variations in sensor suites that may be deployed, even within one manufacturer’s model of a vehicle. In a similar manner, managing protocol change that evolves supporting V2V and V2I communications will be a challenge, including the task of model/configuration management. Software defined radios will at least minimize the cost of evolution of communications technology. Software upgrades must be backward compatible with hardware and supporting operating system and utilities. Software upgrades may also impact calibration and testing of sensor related equipment. This again will be a challenge to vehicle and vehicle equipment configuration management.

A paper entitled, "As Electronics Expand, So Do Challenges Facing Automobile Designers" (*Automotive News*, 9-29-2010) [165], illustrates some of the issues associated with maintenance, based on design. The article states: *"The major challenge facing automotive electronics designers is the high degree of connectivity required within the vehicle. In just the past decade, the magnitude and complexity of the interconnection of automotive electronics has increased dramatically. Depending on the vehicle, there can be 3 to 15 ECUs* [Electronic Control Units] *(over 50 in some high-end vehicles) with hundreds of embedded software modules; and each of these applications must inter-communicate. Adding to the complexity is that each ECU presents its own challenge, given that the software, middleware and application software is written by different companies, yet must be integrated together within the overall framework of the vehicle."* The paper also indicates the management complexity associated with advanced, distributed automotive systems since tier 1 and tier 2 suppliers are responsible for design and testing.

Another technical report entitled, "Challenges in Automotive Software Engineering", by Manfred Broy (Technical University of Munich, Germany) [166], which emphasized some of the maintenance challenges. The paper states that in the first three years of production of an advanced vehicle, 20% to 30% of the ECUs must be replaced with different versions because problems have been detected and/or improvements have been made. The issue is software compatibility of ECUs over the complete, distributed, vehicular system. Many of these ECUs are tightly coupled and even changes in latency cannot be tolerated. The report further discusses the growth in information multiplexing on an increasing number of vehicle data busses and the challenges of managing the protocol evolution. The report stresses the fact that vehicle designs are getting more complex and both design and diagnostic skills must evolve to meet the challenges of advanced vehicles.

Per USDOT FHWA "Safety at Signalized Intersections (2008)"[23], there were 41,059 fatalities in 2007 on US corridors with 79% at non intersections and 21% at intersections (8,622) with 32% (2,759) being at signalized intersections. The total number of intersection accidents per year in 2008 (reference) was 1,700,000 accidents/year. Of these 302,000 occurred at signalized intersections. The 8,622 fatalities at intersections represented thus represent 0.005 fatalities per intersection accident and 0.001 fatalities per signalized intersection accident. Of the total intersection fatalities, 39% were rural and 61% were urban. Red-light running accounted for approximately 32.7% of the signalized intersection fatalities. Thus, for accidents at a signalized intersection, there is a 0.1% probability of a fatality.

Per Insurance Institute for Highway Safety, "Q&A: Urban Crashes" (March, 2011) [168], there were 1.2 million urban crashes in 2009 with 55% at signalized intersections and 21% at stop signs. Of the 660,000 crashes at signalized intersections, 52% resulted in injuries (342,200) or 0.52 injuries/ signalized intersection accident and with approximately 10,000 fatalities or 0.02 fatalities/signalized intersection accident. Of the 342,200 injuries, 61% involve injuries to pedestrians.

In a Caltrans report entitled, "Why Manage Access to the State Highway System", by Philip Demosthenes (10-18-2007) [169], the yearly accident rate of 0.7/intersection for a rural un-signalized intersection versus 1.4 accidents per year per urban un-signalized intersection is presented. Rural signalized intersection accident rate is specified to be 4.8/intersection/year and urban signalized intersection accident rate is specified to be 6.2/ intersection/year.

The specific accident rate for a given intersection is a function of the traffic volume, intersection geometry and weather conditions in the area of the intersection.

From this it can be concluded if an accident occurs at a signalized intersection there will be a 0.52 probability of an injury and a 0.03 probability of a fatality if an accident occurs.

Considering Table A-4 a 0.03 probability of fatality equates to consequence level of C_B. So for a warning application this corresponds to SIL 1, and for an automated braking application, this corresponds to SIL 2.

To determine the confidence in the communications element of the system, it is necessary to develop a failure model that allocates failure rates across the various components of the application. The components of an intersection related application are listed below:

- Traffic signal controller provision of signal phase and timing (SPaT) information
- Generation of a SPaT message
- Communication of the SPaT message
- Decoding of the SPaT message
- Assessment of vehicle state (speed and position) relative to the application decision point
- Execution of the application action.

The provision of signal information, the generation of a message and the decoding of the message are generally based on software. Reference [164] provides a software failure rate of $1x10^{-5}$:

> "Following consideration of diversity and redundancy at the systems level, compliance to SIL 1 with respect to software requirements provides the strongest safety argument that a number around 1.00 E-5 per hour can be claimed, notwithstanding that failure modes of software are systemic rather than random".

(Ref: "A risk-based approach to supporting the operator role in complex monitoring systems", Kevin Anderson,Hyder Consulting Pty Ltd [170].)

The communication of the message and the determination of vehicle state are expected to relatively high failure rate steps. The failure rate of the application action step depends on the action. For example, if the action is to automatically apply the brakes to achieve a desired deceleration level, the failure rate is relatively low (Braking systems are among the most reliable components on a vehicle). If, on the other hand, the application action is to warn the driver to take evasive action, we must then consider the failure of the warning to elicit the desired response.

These situations are analyzed below.

Automated Braking Case:

The automated braking application requires SIL 2, or a failure rate less than about $0.5x10^{-2}$. If we assume that the failure rates of the communications and positioning steps are the same, and if we assume that the failure rates of the other steps are all $1x10^{-5}$, then, based on a required failure rate of $0.5x10^{-2}$, the required failure rates for the communications and positioning elements are:

$\lambda_{POSITIONING}=\lambda_{COMM}=1/2(0.5x10^{-2}-4x10^{-5})=2.48x10^{-2}$, or a confidence level of 97.5%.

Intersection Warning Case:

The same reference provides values for human failure rates relative to a variety of tasks. These are provided below:

Type of Activity	Probability of Error per Task
Simplest Possible Task	
Overfill Bath	0.00001
Fail to isolate supply (electrical work)	0.0001
Fail to notice major cross roads	0.0005
Routine Simple Task	
Read checklist or digital display wrongly	0.001
Set switch (multi-position) wrongly	0.001
Routine Task with Care Needed	
Fail to reset valve after some related task	0.01
Dial 10 digits wrongly	0.06
Complicated Non-routine Task	
Fail to recognise incorrect status in roving inspection	0.1
Fail to notice wrong position on valves	0.5

(Ref: Smith, D. J., "Human Error Rates", 1993. [171])

The general error rate for a task performed incorrectly is given in the reference as 1×10^{-3}. The failure to notice major crossroads is given in the table above as 0.5×10^{-3}. So, we can be reasonably assured that the failure to respond correctly to a warning is about 0.75×10^{-3}.

Using this value with the failure rates for the other steps in the process, the failure rate for the communications and positioning elements is given by:

$\lambda_{POSITIONING}=\lambda_{COMM}=1/2(0.5\times10^{-2}-3\times10^{-5}-0.75\times10^{-3})=2.11\times10^{-3}$,

or a confidence level of 99.8%.

It is interesting to note that a substantial portion of error budget is consumed by human error, leaving each of the other elements of the application being required to perform with relatively low failure rates. If the human error level is higher (the reference identifies routine error rates as high as 0.5x10-1), then the entire error budget and more may be consumed by the human error component. This may explain why warning systems have a history of somewhat inconsistent performance.

For situations where the response is relatively intuitive, the error rate may be relatively low, but in situations where the appropriate response is not intuitive, for example, responding to a skid, the error rate is likely to be much higher.

Appendix B

B. Alternative Requirements Development Approach

Task 2 developed basic communications requirements for various applications on the basis of the SAE J2735 specification s. These specifications included requirements to repeat SPaT messages every 100 msec.

It is not clear that these requirements were based on any formal systems analysis at the application level. This appendix revisits these requirements based on the application geometries outlined in Section 2, and based on the Stopping Sight Distance defined in the AASHTO Green Book [172], and the false positive and false negative Application decision thresholds developed in the Positioning Task Order and reported in the TOPR1 Final Report.

The AASHTO Green Book Provides stopping distances as described in Table B-1 below.

Table B-1. SSD (in meters) for various Speeds and Situations

(Ref: AASHTO Green Book, “A Policy on the Geometric Design of Highways and Streets” [172])

Speed (kph)	Nominal	Emergency (Wet)	Emergency (Dry)
40	50	27.7	14.2
60	85	59.6	40.3
100	185	163.4	93.4
120	250	235.7	127.9

The TOPR1 Final report included a development of false positive and false negative distances for warning applications. These are provided in Table B-2 below.

We have assumed that, since this is a warning application that there is a corresponding alert application, so the driver is already aware of the situation. As a result, we are using Stopping Sight Distances, not Decision Sight Distances.

MUTCD related warnings are intended to cause the driver to take some form of action. This is especially true for in-vehicle warnings that are triggered by vehicle speed. Traffic signals are placed at the stopping sight distance for the 85th percentile speed on the road segment. The SSD takes into account perception time, brake application time, and stopping time from the specified speed. The perception time is assumed to be 1.5 seconds.

Table B-2 below illustrates the response distances for these typical values and for emergency values.

Table B-2. Perception and Stopping Distance versus Speed

		Speed (mph) 30	45	60	75
Perception Reaction Time (Sec)	1.00	44.1	66.2	88.2	110.3
	1.50	66.2	99.2	132.3	165.4
	2.00	88.2	132.3	176.4	220.5
	2.50	110.3	165.4	220.5	275.6
Deceleration Level (g)	0.34	88.2	198.5	352.9	551.5
	0.51	58.8	132.4	235.3	367.6
	0.68	44.1	99.3	176.5	275.7
False Positive Distance		176.4	330.8	529.3	772.0
Nominal Distance		125.0	231.6	367.6	533.0
False Negative Distance		88.2	165.4	264.7	386.0

Source: ARINC April 2012

The false positive distance is the distance before which a warning would be perceived as coming too early. This is derived from an assumed 2-second perception time, and the minimum deceleration level of 0.34 g.

The false negative distance is the closest distance that the application can act. This distance is derived from an assumed 1-second perception time and a deceleration level of 0.68 g (emergency braking).

For RLR, LTA, and RTA, the longest range required, in the absence of any other errors, is thus the false negative distance plus any additional distance required to send messages multiple times to improve message reliability, or to account for positioning error. If we assume that the entire difference between the false positive and false negative thresholds is consumed by positioning error (as was assumed in TOPR1), then the minimum required range is the false positive distance plus any additional distance required to send messages multiple times to improve message reliability. The time required to cover this added distance at the rated speed will need to be added to the signal change time. The reason for this is that if the signal timing changes just before a vehicle reaches the required first reception point, the new SPaT message will need to be repeated some number of times to assure reliability, and the repeats must be complete by the time the vehicle reaches the false positive point. We have assumed that, in SPaT intersections, the maximum acceptable addition to a timing change cycle is 0.5 seconds. This means if a vehicle pulls up to a dynamically controlled intersection, the system would take 0.5 seconds longer to respond, thus allowing time for the new SPaT message to be repeated. The SPaT repeat rate must then be N SPaT messages within 0.5 seconds. If a longer delay is allowable, then the SPaT repeat rate can be reduced accordingly. These ranges are described graphically in Figure B-1 below.

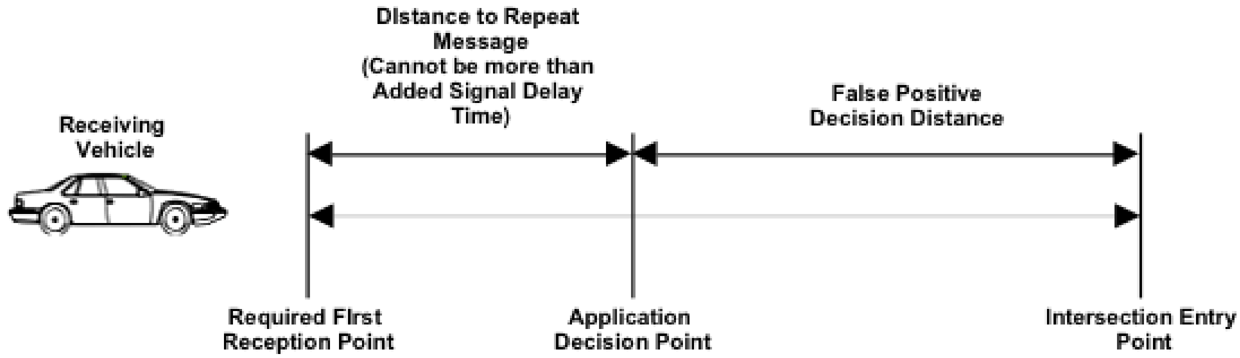

Figure B-1 Requirements Positions

Source: ARINC April 2012

The range for SPaT messages is provided for various vehicle speeds in Table B-3 below.

Table B-3. SPaT Range versus Speed (RLR, LTA, RTA, RCLV)

	Range (feet)			
Speed	**30**	**45**	**60**	**75**
Basic Range	176.4	330.8	529.3	772.0
Added Range To Support Timing Change	22.1	33.1	44.1	55.1
Minimum Range Required	198.5 (61 m)	363.9 (111 m)	573.4 (175 m)	827.1 (252 m)

Source: ARINC April 2012

The message reliability at these ranges must be SIL1 for warning, and SIL 2 for automated braking. As described in Appendix A, these levels correspond to message failure rates of $2x10^{-3}$ for warning and $2x10^{-2}$ for automate braking. The automated braking rate is lower because the failure rate of the human driver can be eliminated.

To the extent that the communication system cannot repeat the SPaT the required number of times within the 0.5 second margin interval, either the interval needs to be replaced, or the communication system is inadequate for the application.

The GID must also be received in time for the application to use it as the vehicle approaches. If DSRC is used, then either the GID must be provided at an approach to the intersection (for example, at all surrounding intersections, or it must be provided along with the SPaT message.

It is also important to consider that the “effective” GID may be very dynamic, since vehicles may be stopped, or stopping ahead, and this will effectively bring the limit line closer to the approaching vehicle. Exactly how this effect can be accommodated by the application has not been considered.

For FSP, TSP and Preempt, the SPaT message must be received sufficiently far in advance that the vehicle can send a request message and receive a denial message and still have time to stop. The turn-around time for this process is likely to be dominated by server response as opposed to communications latency. If we assume a 1 second delay between transmission of the request, and receipt of the denial, the SPaT range is as shown in Table B-4 below.

Table B-4. SPaT Range versus Speed (TSP, FSP)

	Range (feet)			
Speed	30	45	60	75
Basic Range	198.5	363.9	573.4	827.1
Added Range To Support Request/Response	44.1	66.15	88.2	110.25
Minimum Range Required	242.6 (74.0 m)	430.1 (131.1 m)	661.6 (201.7 m)	937.4 (285.8 m)

Source: ARINC April 2012

Alternatively, For the PREEMPT application, the request must be received sufficiently far in advance to allow the signal timing to be changed in a safe manner. The worst case for this is if the opposing signal is green, so the signal must go through a yellow and all red phase before changing to green for the emergency vehicle plus the time for stopped vehicles to accelerate and move off to the side of the road (about 8 seconds total) . This is illustrated in Table B-5 below.

Table B-5. Range Requirement for PREEMPT

	Range (feet)			
Speed	30	45	60	75
Basic Range	198.5	363.9	573.4	827.1
Added Range To Clear Intersection	352.8	529.2	705.6	882
Minimum Range Required	551.3 (168 m)	893.1 (272 m)	1279 (389 m)	1709.1 (521 m)

Source: ARINC April 2012

Appendix C

C. Maintenance and Operations Considerations

Task 4 Technical Memorandum

Maintenance and Operations Considerations for Vehicle OBE and Infrastructure RSE Communications Equipment Supporting SPaT Applications

Introduction

This is a technical memorandum on the activities of Task 4 of Task Order 3 under ARINC's Contract DTFH61-10-D-00015, entitled, "Communications Systems Analysis for SPaT Applications in Advanced ITS Applications." The Task 2 report described the communications requirements associated with SPaT applications and the Task 3 report presented the results of a market scan related to available and emerging communications technologies and associated products. In Task 4, a more in-depth analysis of communications technologies identified in Task 3 as the best candidates to meet application requirements were developed. Another requirement of Task 4 includes addressing operations and maintenance (O&M) requirements and issues related to deploying communications technology both in roadside equipment (RSE) and in vehicle onboard equipment (OBE). This Technical Memorandum provides the findings related operations and maintenance (O&M) of RSE and OBE communications equipment. For OBE applications, it addresses differences in maintenance approaches related to vehicle types and associated applications such as public transit, public works, emergency, commercial fleets, and private use. For the purpose of this report the SPaT communications technology relates to the radio frequency (RF) transceiver, modem, antenna, and communications switch/router.

Mobile communications equipment for police was first deployed by the Detroit Police Department in 1928 and deployment started growing in the 1930s. The US Military developed mobile tactical radios, which were utilized during WW2. In the 1940s commercial vehicles had mobile radios that operated under the Domestic Public Land Mobile Radio Service. Also in the 1940s Citizens Band (CB) radios came into existence and the mobile CB boom started in the mid-1970s, lasting perhaps 10 years. In the late 1970s Advanced Mobile Phone Service (AMPS) was tested and deployed in 1984. RFID technology was first patented in 1973 and deployed for V2I applications in the mid-1980s. WiFi was commercially deployed in 1999. Growth continues with mobile communications technology with the demand for more and more bandwidth. Because of the long history of mobile communications use in jurisdictional and commercial vehicles, well established procedures and infrastructure supporting maintenance and operations have evolved. Toll road and turnpike authorities have established procedures and capabilities to maintain roadside RF toll tag readers and to provide toll tag servicing (basically replacement) since deployment started in the early 1990s. Individuals have experience with repair of their failed mobile communication devices (CB radios, pagers, and cell phones) since the 1970s. Similarly General Motors Corp. formed OnStar™ in 1995 and thus has had over 15 years of experience with V2I communications and associated onboard equipment testing and maintenance. In addition, with the advent of wireless networks in homes and offices, individuals have become much more educated related to the basic aspects of wireless devices and associated switch/routers. Thus maintenance and operational support for communications products and technology related to SPaT applications is not entirely new and perhaps users have a better basic understanding of their operations.   What is new is the magnitude of the maintenance that will be required as multiple wireless devices are embedded in vehicles and numerous wireless devices are deployed roadside. This requires planning by service operations supporting maintenance not only as related to logistics and test equipment, but also to technical staff and training. The challenge also is perhaps the fact that technology continually changes and supporting applications will continue to grow, making the demand for continual update of maintenance support. Figure C-1 illustrates examples of equipment utilized to support mobile communications.

Figure C-1. Examples of Mobile Communications Related Products for both Roadside and Onboard Vehicle Applications

(Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

Types of Maintenance

Communications equipment supporting advanced ITS vehicles and associated applications have finite failure rates and generally require corrective maintenance. The nature of modern communications equipment is that they include technologies for monitoring performance and making dynamic adjustments to compensate for adverse impact of the radio frequency environment in which it is operating. The equipment monitors bit error rate and reports communications failures to appropriate applications processors. With modern network management technology and remote monitoring (RMON), the operating condition of ITS communications networks can be monitored by a maintenance system which can determine the location and nature of a failure and maintain a log of maintenance activity. Modern switch/routers that support internet protocol (IP) communications usually support a network management standard, such as simple network management protocol (SNMP).

Preventive maintenance for communications equipment is more related to assuring that there is no physical damage to antennas and interconnect cabling, especially corrosion of transmission line interconnects that are exposed to weather. There are no required precision installation references, and periodic adjustments that are typically required for OBE positioning sensors. Damage to antennas can result in a deformation of the antenna pattern and impact both transmit power and required received RF signal level. Any built in test functions probably will not detect the lower antenna gain caused by antenna damage, which would be detected as a lower signal/noise, thus impacting data rate associated with adaptive communications (as included in DSRC standards). When the vehicle is taken for periodic service, testing the effective radiated power and received level of a test signal by the OBE receiver could be easily conducted.

Corrective maintenance includes diagnostics to isolate a failure, correction of the failure, verification that the failure has been corrected. There are several approaches to corrective maintenance by vehicle maintenance centers, including:

- "Black Box" packaged functional unit replacement at the vehicle service center ("black box includes printed circuit board modules that have circuit components (integrated circuits and electronic components). A "black box" is also referred to as a "line replaceable unit" (LRU). The "black box" replacement may be "throw away" or sent to an electronic service center repair;
- Removable, plug in module (printed circuit board) replacement and either "throw away" or electronic service center repair.

Whether the "black box" or replaceable module is expendable is a function of replacement cost versus the cost of component level repair. For vehicle modules, car manufacturer usually consider the electronic units to be expendable, because they do not maintain the component level replacement skills and cost and time of repair would be unacceptable by vehicle owners.

The total approach to diagnostics and maintenance of advanced ITS vehicles need to be addressed in much the same manner that the military has addressed avionics in aircraft. Having many black boxes integrated through a vehicle network (CAN and Ethernet) is one approach; using larger electronic chassis with a high speed computer bus and functional, plug in modules is another approach. Getting functional, replaceable modules to a cost where they are expendable can reduce both corrective maintenance time and cost. Replacing a black box when the vehicle is taken in for maintenance, and then repairing or remanufacturing the assembly at a separate electronic service center (either at the manufacturer's facilities or a local facilities certified by the manufacturer) reduces the maintenance time associated with the vehicle. The electronic service center would then reassemble and test the black box and return it to inventory at the vehicle service center. One potential drawback is that the black box becomes a "used, refurbished unit" at this time and the cost of repair must be included in its price; however, this is a well-established and accepted practice in the automotive industry, especially for high value components. The preferred is expendable units (black boxes or plug in modules), which are replaced at the vehicle maintenance center and discarded.

Communications technology applicable to SPaT is being developed using both a "black box" approach and a modular chassis approach. In Europe the OBE mobile router/switch chassis includes plug in modules for the different wireless communications radio/modems.

Since OBE communications devices that support SPaT applications is considered to be part of the vehicle's safety equipment, most likely jurisdictions will establish requirements for rapid maintenance, if the device fails. This will be especially true for public transit vehicles, school busses, and taxis taxi. It may also be applicable to commercial vehicles and included as part of commercial vehicle safety inspections.

Certification

OmniAir Consortium is the designated organization for product certification testing to validate that it complies with established standards for DSRC technology. WiMAX Forum oversees certification testing related to WiMAX. The 3G Partnership Project (3GPP) working with the International Telecommunications Union (ITU) supports LTE standards development; the Global Certification Forum (GCF) supports LTE certification testing. Products that are associated with maintenance will have been pre-certified to be standards compliant prior to being deployed. As the associated standards evolve, standards version status compatibility testing will be necessary; configuration management will be a major task for maintenance organizations. Downward compatibility will be a necessity since there will be most likely many standard release versions in operations within RSEs and OBEs.

Test Equipment

There are a number of general purpose test equipment (some programmable) that are available to support wireless communications testing. These include RF Power meters, spectrum analyzers, modulation analyzers, as well as protocol test sets. Manufacturers may develop special purpose test sets, which are simpler to use and support quicker testing, verification of operation (or failure identification. Figure C-2 illustrates test equipment associated with communications testing. Under the special purpose test equipment, a DSRC test unit is shown that uses a laptop PC with special test software.

Figure C-2. General Purpose and Special Purpose Test Equipment Supporting Mobile Communications Equipment Testing
(Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

It is possible to build test capability into an RSE and OBE. Some of the older, 900 MHz DSRC devices included a test capability that identified low RF power and high Bit Error Rate (BER), with a message to the driver to have his DSRC tag checked. Knowing vehicle location and RSE location, relative distance can be determined and an estimate of expected RF power can be made. Similarly, noise floor can be detected and expected BER determined. Other test can be conducted related to changes in statistical averages of noise level, indicating a potential receiver and/or antenna connection problem. A test RSE could be used at a service center to support quick performance testing of an OBE. Similarly the signal technician's vehicle OBE could be utilized to test an RSE. Figure C-3 illustrates Using DSRC related hardware with test software to support maintenance. Test RSEs could be deployed at strategic locations to conduct dynamic testing of passing OBEs, providing messaging to the driver of any problem (assuming marginal communications capability still exist. With no OBE response, an electronic sign could message the driver to have his OBE repaired.

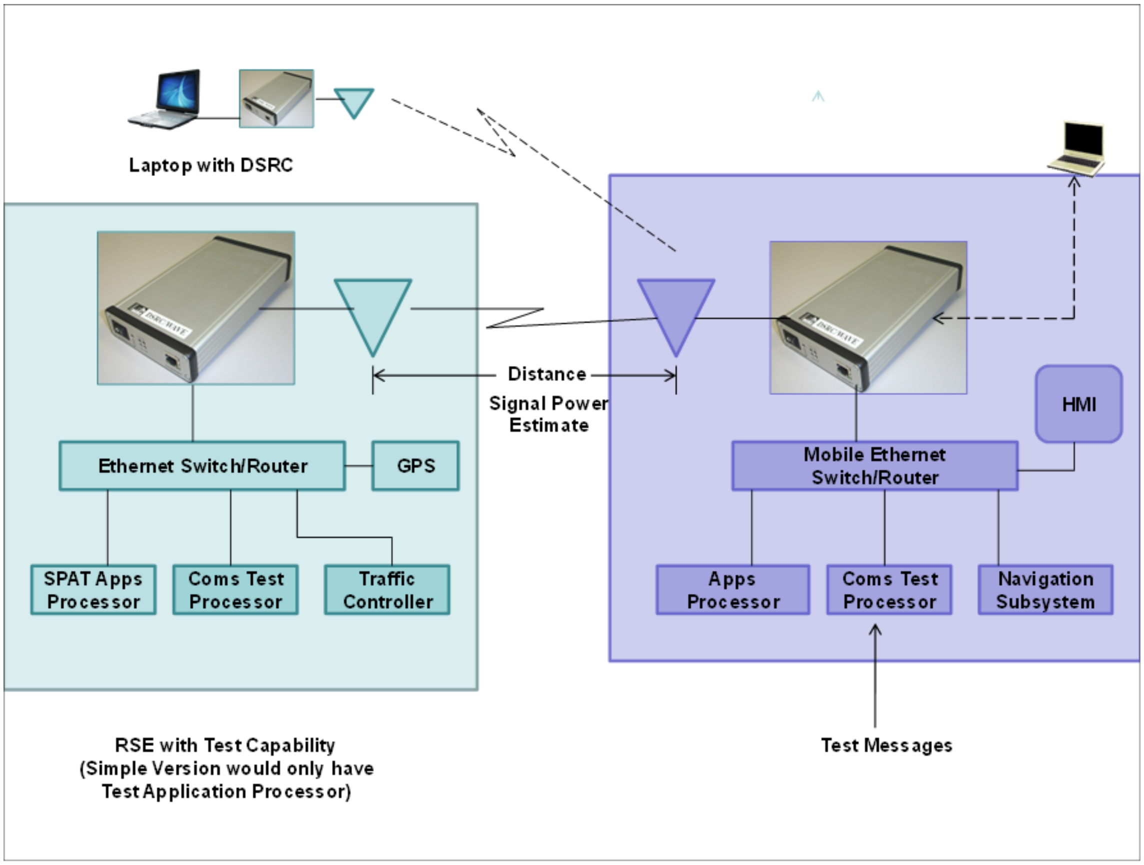

Figure C-3. Example of using DSRC Equipment and Test Software to Support Testing
Source: ARINC April 2012

Roadside Equipment Maintenance

Wireless communications has been deployed for years in the ITS roadside environment. Cities in most of the states utilize digital wireless transceiver/modems to interconnect sensor equipment with traffic controllers and traffic management centers. Roadside sensors are available on the market that has integrated wireless Ethernet interconnections. Today's traffic controllers have hardened, managed Ethernet switch/routers that integrate "around the intersection" communications devices with the traffic controller and link the traffic controller cabinet with the Traffic Management Center via a wide area network that may be optical Ethernet (Older networks may be SONET or ATM) or Wireless Ethernet (WiFi with microwave backhaul or WiMAX with WiMAX or microwave backhaul). Modern traffic controllers (such as the 2070) include Ethernet interface as a standard allowing the controller to be "plugged into" the hardened Ethernet switch/router, thus forming a field-to-ITS center network. Different subnets can be configured representing different corridors or areas of the jurisdiction.

Traffic signal technicians have maintained roadside equipment since the beginning of traffic signal controller deployment using mechanical motors and switches. The modern, jurisdictional signal technician is very capable of repairing electronic equipment associated with the RSE. Generally the signal technician uses "black box" replacement in the field and may do electronic module replacement at the signal shop. In the older NEMA TS-1 and Caltrans 170 controllers, signal technicians did component repair at the signal shop; however, the trend today is either to consider an electronic module to be expendable or to return it to the manufacturer for repair. When systems integrators deploy new equipment in a jurisdiction, the procurement typically requires training of the signal technicians and deliverer of spare parts to support field maintenance. Also procurement includes delivery of all test equipment required to install and maintain the ITS equipment.

Communications equipment deployed for ITS typically has built in test that support antenna alignment (for directional antennas), and verification that the communications link is working, using a laptop computer or PDA device. Since the typical Ethernet wireless transceiver/modem is self-contained with power and Ethernet port, installation is reasonably simple. Antennas are typically mounted on existing structures along roadside or on the mounting provisions for the traffic signal head over the corridor. For communications devices, jurisdictions typically return them to the manufacturer for repair or use a manufacturer certified electronic service center (locally) for repair. Some manufacturers offer overnight delivery of a replacement unit. There are various types of service agreements guaranteeing maximum repair time by the factory; shorter repair time generally costs more. Spares are maintained at the signal shop to support return-repair by the manufacturer.

While it is possible for jurisdictions to contract out maintenance monitoring and repair services, the majorities of the jurisdictions maintain their own signal shop and signal technicians. Since the Traffic Engineer is responsible to jurisdictional management to maintain the operation of the traffic control system and to responsively repair a failed signal controller, Traffic Engineers typically prefer to have their own maintenance resources. Since citizens quickly react to failed traffic signal controllers and will call senior city management, Traffic Engineers are sensitive to quickly respond to a failure and even maintain the ability to link into the operations and maintenance network from home.

In summary, jurisdictions currently maintain RSE communications devices and have established processes, typically based on the size of the jurisdiction and numbers of controllers and sensors deployed. Some smaller jurisdictions combine their maintenance (Example Burbank, Glendale, and Pasadena, CA) to reduce maintenance cost. In some jurisdiction the state DOT maintains the ITS field equipment (typically in smaller jurisdictions). SPaT related communications devices are very similar to those maintained today by jurisdictions. However, it is very important that RSE communications include a network management capability that is compatible with maintenance capability supported by jurisdictions.

Vehicle OBE Maintenance

OBE Maintenance by Public Transit Agencies

Depending on the size of the public transit system, several approaches are utilized for maintenance. In larger agencies, such as Houston Metro, preventive and light maintenance activities are performed at bus operating facilities (BOFs), which are located within the route structure of buses assigned to the facilities. There is also a central maintenance facility that supports logistics and major maintenance of the bus fleet. Buses are centrally dispatched and may include both automatic vehicle location and tracking as well as automatic vehicle maintenance monitoring of critical equipment. Some transit agencies use onboard maintenance information recording and “read” the maintenance information when the bus returns to the BOF for daily servicing. It is the responsibility of the driver to report any equipment operational problems to BOF maintenance, and BOF maintenance is responsible for checking equipment associated with performance and safety of the bus. For major repair and servicing, the bus is routed to central maintenance. BOF service technicians have the capability to conduct “black box” testing and replacement. OBE equipment would be sent to central maintenance for repair and return to inventory. “Black Boxes” considered to be expendable are discarded and sold for electronic scrap. (Note that a secondary market exist for discarded electronic devices, which are in demand by hobbyist). Generally central maintenance would send the OBE “black box” to the manufacture or the manufacturer’s local, authorized repair shop for servicing. Currently public transit agencies maintain digital radio, DSRC devices (ASTM Standard), GPS/IMU, on-board bus sensors, and HMI equipment at the black box replacement level. Public transit maintenance technicians are trained by the manufactures of OBE equipment (or the bus manufacturer) on methods for testing, replacement, and verification of performance of a replaced unit. Technicians are also trained in the process to upload software and database upgrades into associated OBE (such as the route guidance equipment). Figure C-4 illustrates larger transit agency maintenance facilities. Smaller transit agencies may have only one facility that is a combination BOF and full maintenance facility. Very small transit agencies may use an independent maintenance service, which will have trained service technicians.

It should be noted that public transit agencies will use the OBE DSRC for other functions such as toll way and HOT lane access, BOF gate access (security), as well as downloading trip and vehicle stats information into the maintenance computer when arriving at the BOF. Public transit agencies will be deploying RSE devices to meet their own service needs at their facilities. They may partner with jurisdictional signal maintenance to repair their own "RSE" devices, or may use their own electrical technicians for repair in much the same way that jurisdictional signal shops operate.

The TCRP #43 entitled, "Understanding and Applying Advanced On-Board Bus Electronics", by John Schiavone [173], stresses the fact that many of the advanced electronic modules on public transit vehicles have multiple functions and should be integrated into communications bus architecture so that information can be rapidly distributed. The article points out the importance of remote maintenance monitoring and quality preventive and corrective maintenance.

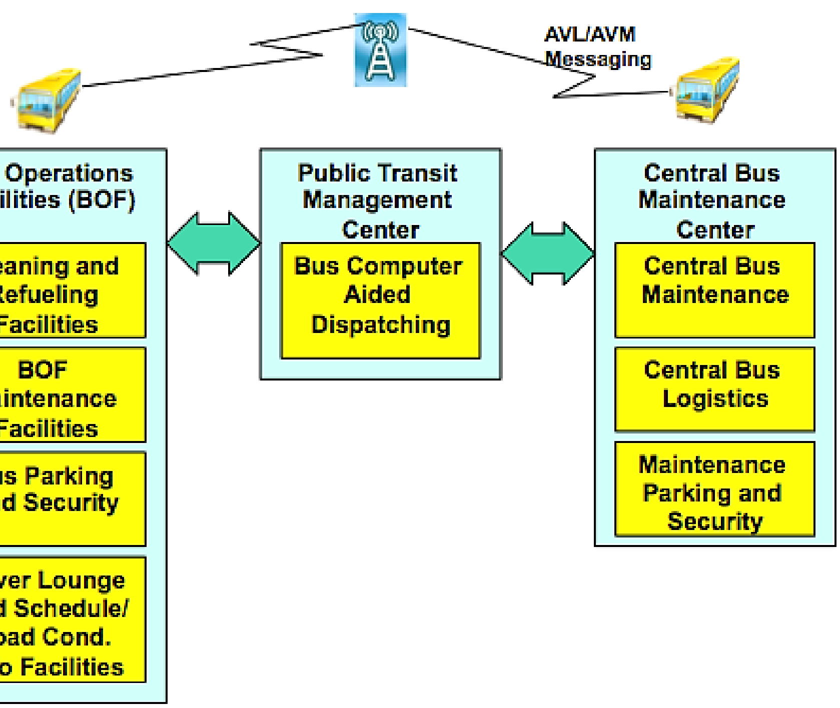

Figure C-4. Example of Maintenance Facilities of a Large Transit Agency
Source: ARINC April 2012

Maintenance by Public School Districts of School Bus OBE

Many public school districts operate in a manner similar to public transit agencies. Buses are picked up by drivers at centers similar to BOFs and returned to the facilities at night.

A central school district maintenance facility conducts repairs of the school buses. Typically the school bus operations center does not support maintenance at the same level supported by a public transit agency BOF. Cleaning, refueling, and minor maintenance is supported. Dispatching is usually included in school bus operations facility as well as driver check-in and briefing. Drivers report vehicle operations problems to the dispatcher, which coordinates with maintenance to initiate repair. OBE equipment repair would be conducted by central maintenance, which would most likely send the OBE "black box" back to the manufacturer (or his local, authorized repair shop) for servicing and calibration. Central maintenance would maintain spare "black boxes" supporting rapid maintenance. For the simple replacement of an OBE communications black box, school district central maintenance may dispatch a repair truck and repair the failed communications device at the BOF.

School districts most likely will have specialized applications for DSRC communications devices, including access to the BOF and identifying arrival at the school and access into any secure parking and loading/unloading lot. They may partner with city/county jurisdictional signal maintenance to repair "RSE" or the school district's own electrical technicians may repair the "RSE" device.

OBE Maintenance by Taxi and Limo Agencies

Few taxi and limo companies have their own maintenance facilities. In many cases the driver owns the vehicle and is responsible for its maintenance. The taxi and limo companies which have their own vehicles typically use vehicle dealer or a private service garage for vehicle repair. The repair shop would be responsible for training of service technicians, maintaining test equipment required to service OBE, and spare parts. These service centers would most likely use the manufacturer or his local service representative to repair "black boxes" found defective and removed from the vehicle. Since the OBE communications device is part of the vehicle safety equipment, jurisdictions may require repair within a specified period after failure. The DSRC device may be used for other functions such as notifying pedestrians waiting at a taxi stand that a taxi is approaching and also for curbside management of vehicles at airport terminals. Furthermore taxis would use the DSRC for toll collection on toll roads and at airports. Figure C-5 illustrates the typical repair process.

Commercial Vehicle Fleet Maintenance

The maintenance process utilized by commercial vehicle fleets depends on the type of vehicle and associated service. Long haul (18 wheels) vehicles are on the road most of the time and receive maintenance services during trips from truck stops, private service centers, and on-call road service. For commercial delivery services, smaller vehicles are used and they return to the terminal area on a frequent basis; these companies may have their own maintenance centers or use an independent truck service center.

The Federal Motor Carrier Safety Regulations, 49 CFR, Part 393 (Parts and Accessories) [174] and Part 396 (Inspection, Repair, and Maintenance) [175] regulations state:

- A carrier is responsible for ensuring that it properly inspects, repairs, and maintains vehicles under its control;
- A motor vehicle may not be operated when its mechanical condition is likely to cause an accident or breakdown;
- Parts and accessories must be in safe operating condition at all times;

- A vehicle must be maintained according to the vehicle manufacturer's recommended schedule or an improved schedule based on actual operating conditions; and
- Push out windows, emergency doors, and emergency door marking lights in buses must be inspected at least every 90 days.

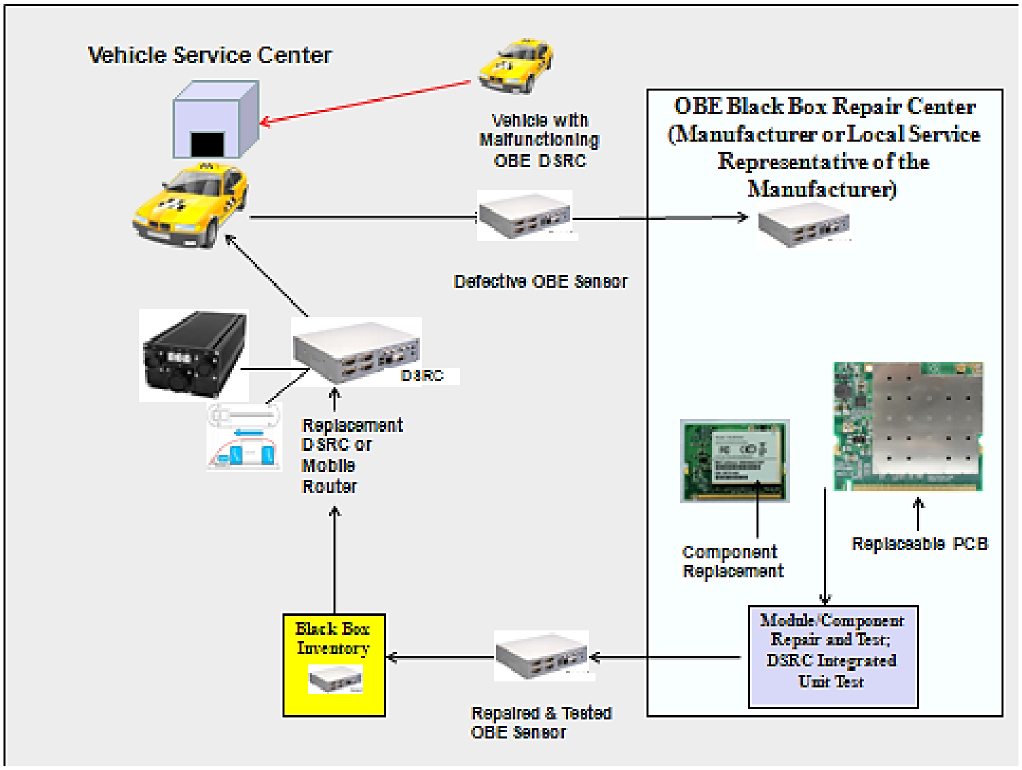

Figure C-5. Maintenance Process Typically Used by Taxi and Limo Companies for OBE Maintenance

(Ref: "FHWA-JPO-09-017", photos [176])

In addition, states require inspections of commercial vehicles. OBE-SPaT related communications equipment will probably be considered as a critical component of vehicle safety and most likely will be included in commercial vehicle inspections. Thus appropriate test equipment and training of inspectors must be established by businesses licensed by jurisdictions to perform the inspections. Similarly, roadside safety inspections are periodically conducted on commercial vehicles and jurisdictions inspectors will have to be trained and provided appropriate equipment to support testing of OBE that is critical to safety. For OBE communications equipment, a test RSE may be utilized at a service or inspection center and a mobile inspection vehicle may use his OBE communications device that would be augmented with measurement parameter display. In fact the automated commercial vehicle inspection station will have a DSRC to communicate with the vehicle and a dynamic test could be conducted (based on position of the commercial vehicle relative to the RSE which would determine performance) preventing any delay.

Figure C-6 illustrates various maintenance services associated with long haul commercial vehicles and also illustrates a CVO inspection station that could possibly conduct an in route inspection of safety related equipment on the vehicle.

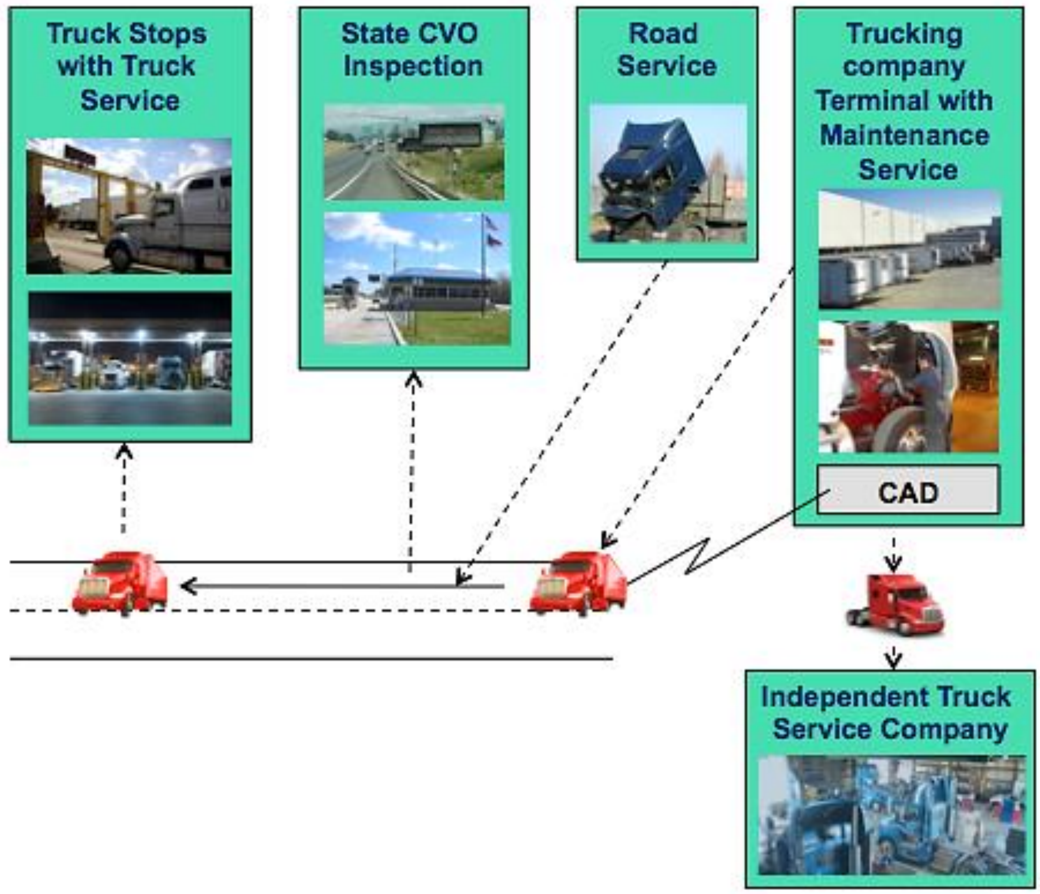

Figure C-6. Examples of Commercial Vehicle Maintenance and Roadside State Inspection (Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

Jurisdictional Vehicles Including Emergency Services and Public Works

Jurisdictions have fleets of vehicles supporting public works and emergency services. Depending on the size of the jurisdiction, they may have a centralized service center for all jurisdictional owned vehicles, may have separate service centers for emergency vehicles and for public works vehicle or may use a private vehicle service. In any case, the vehicles will be periodically inspected and serviced. The inspection would include verifying the operational performance of OBE, including communications devices supporting SPaT. Furthermore, jurisdictional vehicles are dispatched. Drivers will report vehicle problems to the dispatcher who will report the problem to vehicle maintenance. Maintenance work orders are processed to execute maintenance. Jurisdictional maintenance will most likely just perform failed "black box" replacement and send the failed unit to the manufacturer (or his local service representative) for repair. Spares inventory of OBE communications units will be necessary and jurisdictions must receive training on OBE test and repair process and use of test equipment. Jurisdictional maintenance will also have to procure any required test equipment to service OBE.

Private Vehicle Maintenance Considerations

Private vehicle owners are much more sensitive to maintenance cost, compared with commercial and jurisdictions users. Private vehicle owners are also concerned about the time that it takes to deliver their vehicle to a service center and to get it repaired. Therefore, repair cost and vehicle state safety inspection cost must not be significantly increased by installation of advanced OBE equipment in private vehicles. Similarly, cost of updating any software/firmware associated with the communications equipment must be low. For this reason the communications products must be well proven and design stable before being deployed to prevent frequent vehicle recall for updates. Many private vehicle users forgo updating the digital map data base in their current vintage, route guidance systems because of the $250+ cost.

During the first term of ownership, most private vehicle owners utilize dealer maintenance service. Reasons for this are:

- During the warranty, only the dealer can supply warranty service;
- Extended warranties are available through the dealer;
- Dealers have factory test/service equipment, factory training of their technicians and maintain factory parts;
- Factory recalls are made through the dealer;
- Dealers usually warrant their maintenance services and have the incentive to maintain good customer relations to support new car sales.

However, during subsequent terms of ownership, vehicle maintenance is generally less consistent; unless specific long term warranties are in effect, the second owner may use an independent repair shop which is generally less costly than dealer service (because of lower overheads and competition). In some cases, after warranty expiration, owners may endeavor to do simpler repair services themselves. The major issue with owner self-maintenance of the vehicle is that test equipment may not be available. There are centers, which, for a small fee, offer consultation and rental of special equipment required for servicing the vehicle by the owner.

From a private owner's perspective, an advanced OBE should not require any substantial servicing. In recent years, vehicle service intervals have increased from 3000 miles/3 months to about 15K miles/12 months. Annual service intervals usually only involve minor adjustments and fluid changes. Most vehicles require replacement of various wear parts at 30K mile increments, and many go as long as 60K miles without requiring substantial parts replacement. It is not uncommon for most electronic components to last at least the life of the vehicle, and in many cases electronic components are removed from scrapped vehicles and resold as used components. Many parts in this category may be in service for 20 or more years. In general, vehicle owners do not expect to replace major electronic components at all during the first ownership period (about 4-5 years). All electronic systems in modern vehicles include on-board diagnostics that typically identify failures or problems via the vehicle on-board diagnostic system, and the OBE communications equipment should be no different. This means that the identification of problems and the subsequent repair or replacement of the OBE should be consistent with the established on-board diagnostic processes, and it should contain some ability to determine if it is not operating properly (thus to indicate a problem to the diagnostic system).

OBE communications equipment supporting SPaT can use loopback testing and network management protocol to identify and assist in isolation of a problem with communications equipment.

From a private owners perspective the advanced OBE must:

- Be considered of value and affordable;
- Easy to use;
- Not require expensive software/firmware updates or hardware modifications;

- Require no special maintenance (no frequent servicing and have very low failure rates (MTBF of 80,000 to 100,000 hrs.) ;
- Not extend routine service wait time;
- Not preclude use of the vehicle if an OBE failure occurs, until it can be scheduled to be repaired;
- Have dealers with proper test so that a failure can be fixed with high confidence in a single visit in a short repair time;
- Not reduce the pleasure of driving for those who enjoy driving.

Figure C-7 illustrates the private owner options for maintenance. Possibly, since the OBE communications devices do not require extensive test equipment at the "black box" level, an owner could possibly use "do it yourself" auto repair center with consultants and parts access to replace a failed communications device.

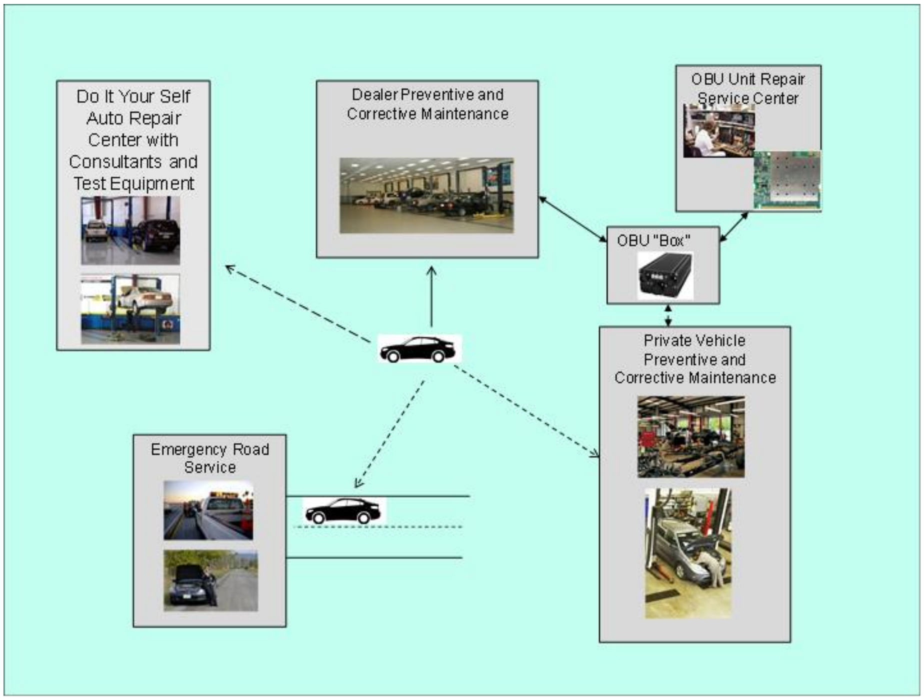

Figure C-7. Private Owner's Options for OBU Service and Repair
Ref: http://www.bing.com/images/search?q=Major+Manufacturers+Product+Advertisements+&qpvt=Major+Manufacturers+Product+Advertisements+&FORM=IGRE)

Other Considerations Related to Maintenance

In an article entitled, "Proactive Vehicle maintenance", by Harold Ness of the Oshkosh Corp. [177], it is pointed out that fleet maintenance challenges facing corporations:

- Availability of skilled maintenance technicians;
- Rapidly changing technology requiring continued training of maintenance technicians and associated cost;

- Local parts availability (without local parts availability, more inventory is required by the company maintenance organization).

Company maintenance must also have access to manufacturer's maintenance consultants to resolve complex maintenance issues. On-line service manual access is identified as a benefit. The article stresses that maintenance must be proactive. It is much more costly to send field maintenance to fix a failure than to repair it in the company maintenance facilities. For this reason critical parts are changed based on time/mileage in use; thus accurate records of vehicle operation must be maintained and periodic servicing is necessary.

Jens Eltze of NEC Electronics America, in an article, "Advanced Technology for Vehicles" [178], points out that the key to reliable vehicular electronics is use of high quality components, and designs that manage heat and prevent electromagnetic interference.

In an article entitled, "Boston Crash Highlights Need for Vehicle Preventative Maintenance", by Stephen Wilde [179], which discusses safety related to emergency vehicles, the following is recommended:

- Establish an out-of-service criteria that identifies when vehicle equipment must be repaired or the vehicle must be removed from service;
- Require a qualified technicians to determine the severity of the vehicle defect;
- Develop standards for equipment as related to critical role in vehicle safety;
- Requires qualified, trained technicians perform maintenance, inspections, diagnostic checks and performance tests as well as replacement of failed equipment;
- Requires daily/weekly operational checks be performed;
- Maintain records of all inspections, test and replacement of vehicle parts and equipment.

This article points out the importance of frequent inspections of emergency vehicle equipment by highly qualified technicians so that the vehicle operates reliably during an emergency response.

The City of Milwaukee Fleet Maintenance Manual (May, 2007) [180] states:

> "Nearly every service provided to the public, impact the productivity of nearly every employee, support emergency services making the difference between life and death, and support the maintenance of infrastructure which helps support local economy, and quality of life.
>
> The main goal of the department is to maintain City's fleet so that it is always available for the work performed by various departments and in keeping downtime to a minimum. By keeping a good preventative maintenance program we can accomplish our mission while preserving City of Milwaukee's major capital investment in fleet. The Preventative Maintenance (PM) program consists of scheduling periodic inspections and vehicle servicing based on time, mileage, engine hours, or gallons of fuel used. If PM services are not performed on a scheduled basis, safety, useful life of a vehicle or productivity could be compromised."

Vehicle technologies have advanced considerably, such as the use of electronic control modules (ECM) to control engine timing or fuel injection systems, anti-lock brakes, and airflow – sensors, evaporative emissions controllers, etc. Vehicles are no longer just mechanical machines but incorporate a variety of Electronic equipment. Today's mechanic must be skilled and knowledgeable in the use of electronic measurement and diagnostic equipment to perform a variety of tests and adjustments during the periodic preventative maintenance to keep the equipment operating safely and efficiently while reducing downtime, optimizing fuel use and help employees work efficiently". This manual defines the growing complexity of vehicles incorporating advanced electronics and the need to maintain skilled, trained technicians. It also stresses the importance of preventative maintenance and the cost impact of poor maintenance.

The future of advanced vehicle maintenance is possibly described in a paper entitled, "Smart Sensors and Prognostics for Self-Maintenance", by Advantech eAutomation [181], based on work with the National Science Foundation Industry/University Collaborative Research Center for Intelligent Maintenance Systems. This article advocates the ability for machines to perform self-assessment to a level where failures can be reasonably accurately predicted and then components changed. The article indicates that components causing high failures should be redesigned, thus moving the total vehicular system towards low frequency of failures and lower maintenance cost. Intelligent monitoring of vehicle modules and subsystems with intelligent maintenance diagnostics of the information considering performance trend data and using it to predict a near failure event in time to correct the problem before actual failure is advocated. Another similar research paper entitled, "A Hybrid Reasoning Architecture for Fleet Vehicle Maintenance", by Abhinav Saxena [182], discusses the use of artificial intelligence for predicting failures and assisting in maintenance management. Again, monitoring system performance and trend data is critical.

Aftermarket Add-On DSRC Considerations

In a presentation at the *SAE 2011 Government/Industry Meeting*, Gordon Peredo presented a paper entitled, "Vehicle-to-Vehicle Retrofit Feasibility Analysis" [183], that discussed issues with DSRC aftermarket retrofit of vehicles. Some of the conclusions of this research were:

- Retrofit solution types exhibited considerable variations in functionality, performance, development, and installation;
- Increases in retrofit solution performance required significant increases in installation time;
- Integrating retrofit HMI with original vehicle HMI is unlikely to be cost effective;
- DSRC products surveyed are suitable for research only;
- There is potential to provide some DSRC functionality to a broad range of post-production vehicles that would otherwise have none; however, careful consideration of design, development, and installation is needed to make retrofitting viable. Without connection to the vehicle networks, aftermarket devices may not support hard safety applications where vehicle data is essential;
- A dealer or other authorized merchant should be required for installation and certification of aftermarket DSRC devices supporting vehicle safety.

Aftermarket DSRC or other communications devices that are designated for use with SPaT applications may not have appropriate integration with other vehicle subsystems. Hybrid design architecture may be such that inappropriate latency results, even if integration is achieve. Built in test features that rely on integrated vehicle maintenance may not properly function. An example is perhaps a maintenance and diagnostic applications processor. For aftermarket DSRC devices to be effectively integrated there must be an industry standard that assures that all safety and maintenance features can be supported. Requiring a dealer to be utilized that will certify that the installation meets safety and maintenance performance standards is appropriate.

Operations

Jurisdictional Operations

From a SPaT operations standpoint, operational responsibility of the RSE is that of the associated jurisdictional Traffic Engineer and his staff. The Traffic engineer is responsible for developing signal timing plans and determining the appropriate traffic signal software and firmware to be utilized at the traffic management center (TMC) and in the traffic controller and associated RSE applications processor. Jurisdictional Engineering, working in conjunction with the traffic engineer is responsible for the corridor and intersection designs; the intersection designs will be converted to Geometric Intersection Data and provided to the designated center responsible for distributing information to users of the surface transportation corridors. Typically this is the responsibility of the Traveler Information Center (511 Center). The jurisdictional traffic engineer would be responsible for assuring that GIDs provided to the Traveler Information Center are current and accurate. The Traveler Information Center equally has the responsibility to assure that the latest GIDs are in their data base and are being distributed for vehicle use. Also the operational function includes the appendage of any temporary changes applicable to the intersection such as:

- Lane closure due to maintenance;
- Malfunction of the Traffic Controller;
- Special Event turn restrictions or turn requirements;
- Emergency Evacuation turn restrictions or turn requirements;

The TMC will be responsible for generating the GID for a new, signalized intersection and any updates to the GID related to intersection design modifications and associated construction and verifying their completeness and correctness. The center responsible for distributing the updates will also be responsible for maintaining a current data base of all GIDs and associated quality of the data base. It will also be responsible for assuring that the distribution communications to vehicles is operational and GIDs are responsively distributed. Figure C-8 illustrates the information flow from centers to vehicles.

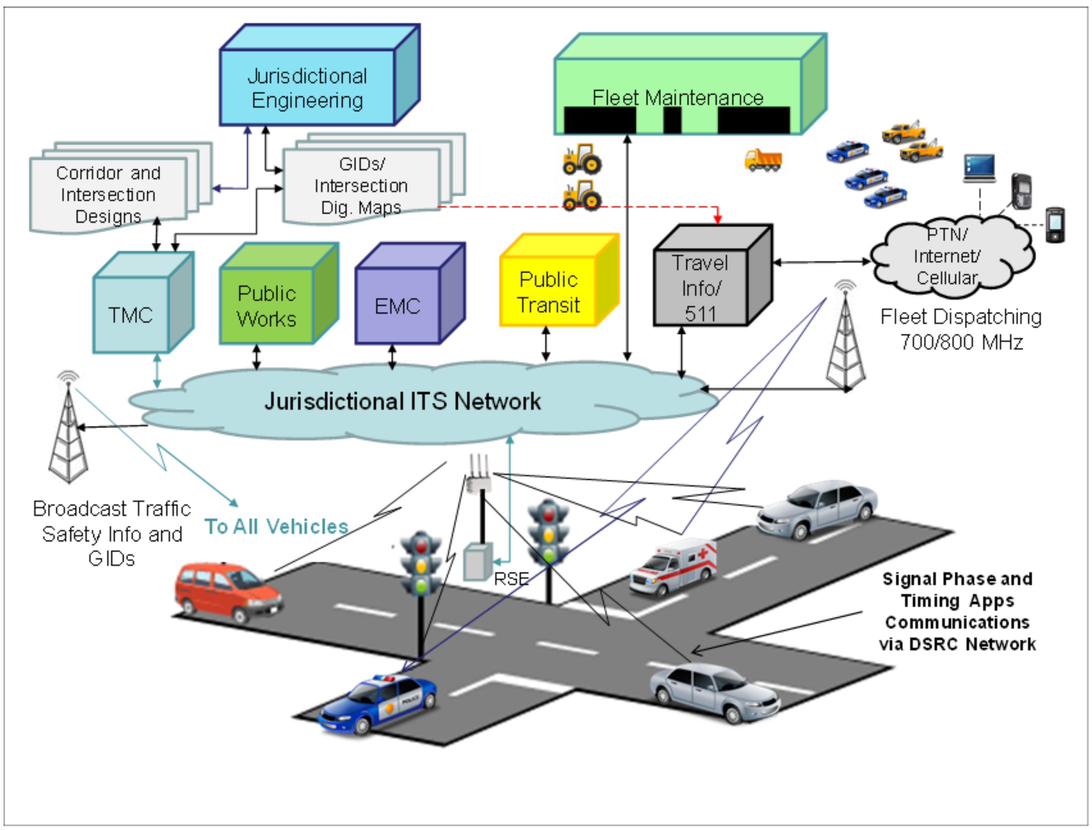

Figure C-8. SPaT Application Related Operations Concept Using the Traveler Information System for Broadcast Traffic Safety and GID Information to Vehicles and Travelers Mobile Devices
Source: ARINC April 2012

There are a number of issues related to development and timely distribution of real time corridor safety and GID information to vehicles. These include:

- Necessity for quality assurance and configuration management to assure accuracy and timeliness of safety related data being distributed;
- Liability issues if the distributed data is in error and results in an accident;
- Responsibility for the reliability and availability of the system supporting the development and distribution of the safety related data, including the wireless communications network;
- Public/Private partnerships for Traveler Information gathering and distribution and willingness of the private partner to accept a new level of responsibility and need for information correctness;
- When a failure exist, fallback procedure for maintaining safety on corridors.

A more in depth analysis of the overall, supporting operations and associated responsibilities is recommended.

Driver/Vehicle Owner Operational Considerations

From a vehicle standpoint, the driver is responsible for responding to safety messages on the vehicle's HMI and for reporting malfunctions of the safety system to the vehicle owner/manager. The fleet maintenance manager is responsible for repair of reported safety equipment failures and for managing the conduct of periodic vehicle inspections and analysis of automated vehicle monitoring data to identify possible indications of safety and failure issues. For private vehicles, the driver (or vehicle owner) is responsible for responsive repair of failed safety equipment as noted by the HMI. (Where the driver is not the car owner, his responsibility is to report failures of safety equipment to the car owner.) The driver of fleet vehicles and private vehicles has the responsibility to revert to manual driving mode where automated safety features have failed and failure has been messaged to the driver (or the driver becomes aware of the failure due to vehicle performance observations.

It is very important that operations of SPaT related communications and safety equipment within the vehicle be simple to operate and messaging on the HMI well understood. It is also important that safety related equipment on the vehicle and within roadside equipment include real time, built-in testing that can responsively detect and report failures. More attention is recommended related to failure mode effects analysis, required reliability and fault tolerance based on failure effects, and required means of detecting and reporting failures.

Summary

Mobile communications equipment is not new. Fleet maintenance has been responsible for maintaining mobile communications equipment in vehicles for over 60 years. The major difference is that the V2I and V2V communications has a significant impact on vehicle safety and thus responsive maintenance and high quality assurance over the maintenance are necessary. Jurisdictions signal maintenance has been successfully maintaining wireless digital communications equipment for over 20 years. Private vehicle users are more experienced with modern digital wireless communications based on their experiences with WiFi and cellular communications devices. However, private vehicle owners will be much more sensitive to repair cost and the time that it takes to repair the vehicle communications equipment. This is another reason that high availability is needed, as well as availability requirements normally associated with safety of life applications. With the magnitude of communications equipment deployment, the major impact on maintenance will be availability of trained technicians and the cost associated with continued training. More analysis is recommended for operational processes and responsibilities.

Appendix D

D. Architectures

Roadside Equipment (RSE)

Roadside Equipment is defined as that which is installed on the roadside and provides the interconnect link between infrastructure and the vehicle. The RSE may be permanently installed along the roadside or at an intersection or may be temporarily installed to support road work, a mayor incident (such as a HAZMAT spill), or an emergency evacuation related to a major disaster. For the purpose of this study, which is focused on applications requiring SPaT messages, the RSE is located at a signalized intersection or a signalized, at-grade rail crossing.

There are some differences in how RSE functions are viewed. Some architecture in research literature includes traffic controller and related electronics as part of the RSE cabinet as well as the communications switch/router, DSRC radio/modems, and a wide area network link to ITS related centers, possibly linkage with internet using IPV6 and applications processors associated with advanced ITS intersection safety applications. Other literature considers the RSE to be a separate cabinet dedicated to communications and associated interfaces and SPaT related applications processor. Figure D-1 illustrates the high level architecture utilized for the Cooperative Intersection Collision Avoidance System (CICAS) initiative. For the purpose of this report, the RSE is considered to include both the traffic controller and related equipment and the communications equipment. Also note that sensors utilized at roadside may have self-contained electronics and an interface to electronics in the controller cabinet that emulate loop detectors (such as Video, Passive Acoustic, Radar, and active IR). Roadside sensors may also be deployed with wireless interconnects to the RSE Ethernet switch/router.

As RSE technology evolves, it will perhaps become of modular construction with “plug in” functional modules, similar to the 2070 traffic controller, which utilizes 4U VME bus modules. It is also possible that the RSE may evolve into a communications hub that is configurable by using “plug in” modules such as communications modem/transceivers, fire wall/routing and Ethernet switch, “connected- vehicle-infrastructure” applications processer(s), and communications manager modules with the traffic controller being a standalone unit with Ethernet interface to the RSU electronic chassis.

The RSE includes a variety of functional elements, and is configured to meet the operational needs of the intersection and jurisdictional preference for sensors, signal controller, and communications architectures at the intersection. The following functional elements may be included in an RSE:

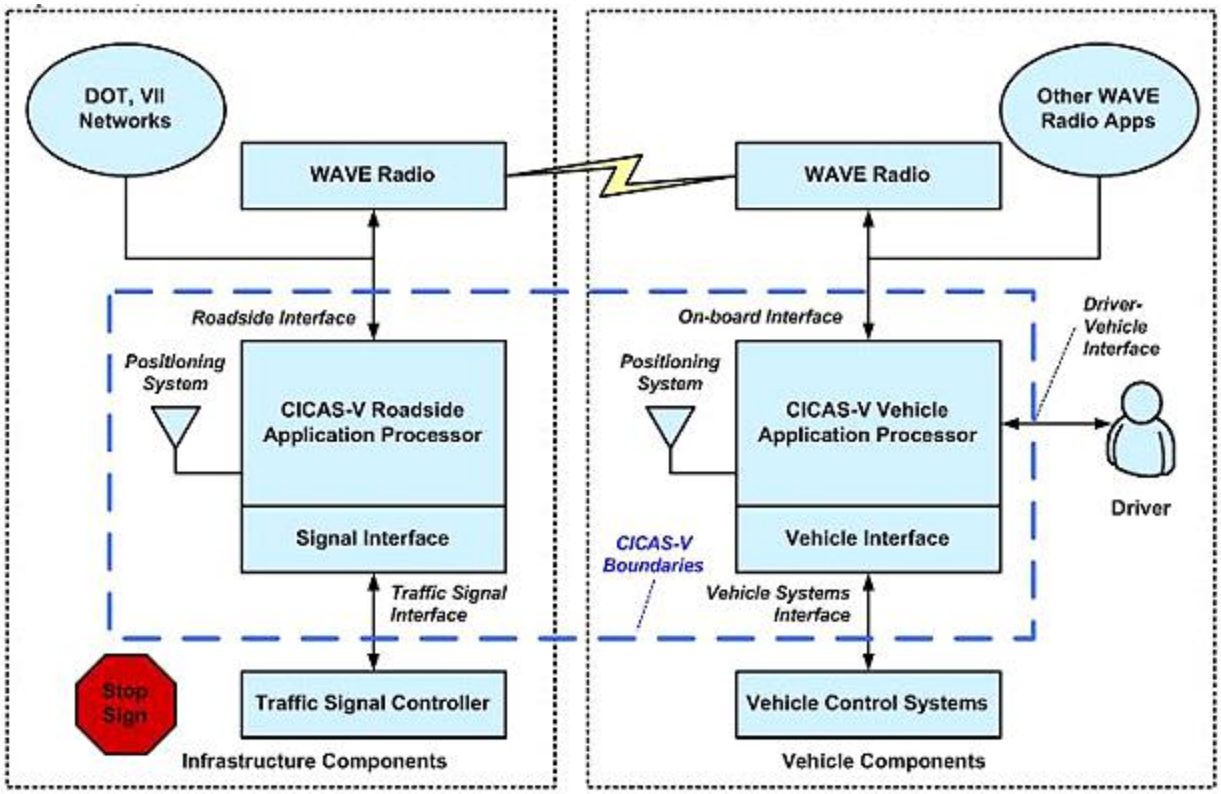

Figure D-1. High Level RSE and OBE Architecture as Defined for CICAS-V Project

(Ref: "Cooperative Intersection Collision Avoidance for Violations and for Avoidance of Violation-Based Intersection Crashes", Michael Maile, et al [184])

- Classical Traffic Controller Functions:
    - Signal Phase and Timing management and control;
    - Traffic Responsive SPaT adjustments;
    - Controller status and SPaT reporting to the TMC;
    - Timing plan update message receipts from the TMC and update execution;
    - Visual signal activation and deactivation (Signal Head and PED Displays);
    - Audible PED phase signal activation and deactivation;
    - Conflict monitoring and conflict prevention (Fail Safe);
    - Signal Call sensors signal processing;
    - PED Call devices signal processing;
    - Time Referencing and Synchronization (GPS Time);
    - Statistical data gathering and reporting;
    - Signal Preempt and Signal Priority Call and "SMART" Execution (SMART execution includes determining of a transit vehicle is off schedule by a specified amount justifying TSP and if multiple emergency vehicles are involved in the preempt Call);
    - Signal Phase extension of preemption to accommodate TSP or Emergency Preempt Call;
    - Extend all Red Phase to prevent an intersection collision by a red-light violating vehicle;
    - Sensor Interface: Inductive Loops, Video Detection, Radar, Ultrasonic, IR, Passive Acoustic, LIDAR, etc.

- Communications Functions:
    - Ethernet Switch/Router for local sensors, traffic controller, and interface to the TMC for wire line or optical interconnections; firewall router functions if wireless interconnections are utilized;
    - Wireless modem/transceivers supporting wireless network interfaces at the roadside location. (This would include wireless Ethernet interfaces for local sensors, DSRC wireless interface, and any Ethernet WAN interface utilized to link the RSE with the TMC);
    - Communications Management and Security Functions.
- Advanced ITS Functions:
    - Applications Processing associated with advanced ITS applications, including those associated with this project.
    - Timing synchronization and coordination of functions. (With extended function RSE, time coordination and synchronization will be at a higher level than traffic controller.).

Figure D-2 illustrates an RSE architecture where the traffic controller is a separate unit (such as a 2070 traffic controller). Figure D-3 presents the architecture of an advanced RTE cabinet where functional modules plug into a chassis data bus (similar to the 2070 controller VME bus). There may be different versions of this architecture, depending on the configuration of the wireless transceiver/modem utilized, which may be self-contained with an Ethernet interconnect to the RSE switch/router (also using power over Ethernet). Figure D-4 illustrates a Caltrans RSE configured cabinet utilized for V2I testing in California. The CALTRANS research report indicates that the RSE cost was around $20K (Ref: "Implementing Vehicle Infrastructure Integration: Real World Challenges", Ashkan Sharafsaleh, et al, California PATH [185]). Figure D-5 provides the functional hierarchal architecture of the InterSAFE 2 RSE.

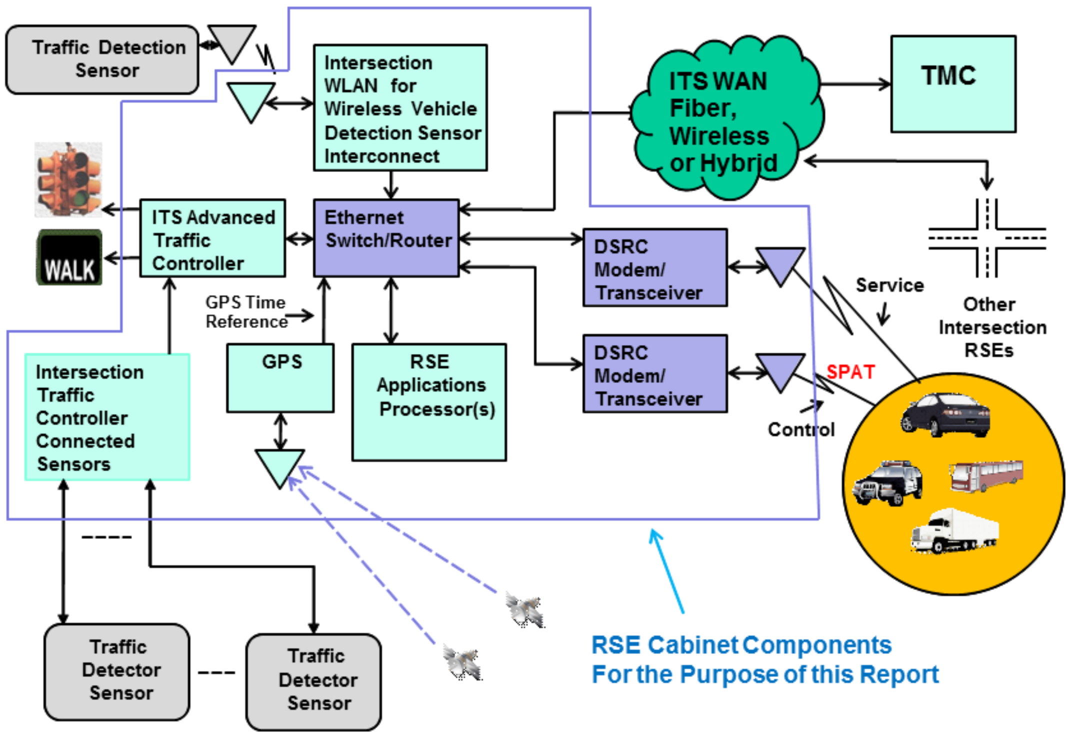

Figure D-2. RSE Architecture with a Separate Traffic Controller Interfaced Via an Ethernet 100BaseT Connection to the Remaining RSE Electronics via an Ethernet Switch/Router
Source: ARINC April 2012

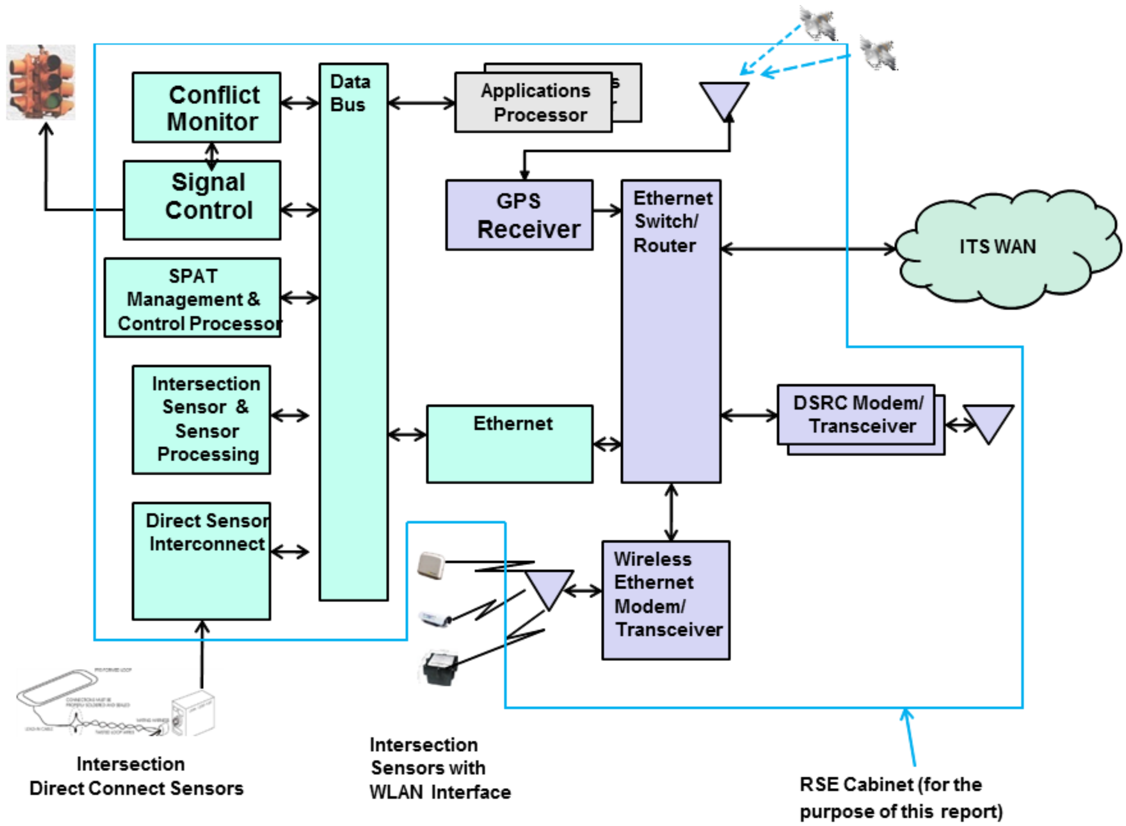

Figure D-3. Modularly Integrated RSE Architecture with Plug-In Functional Modules
Source: ARINC April 2012

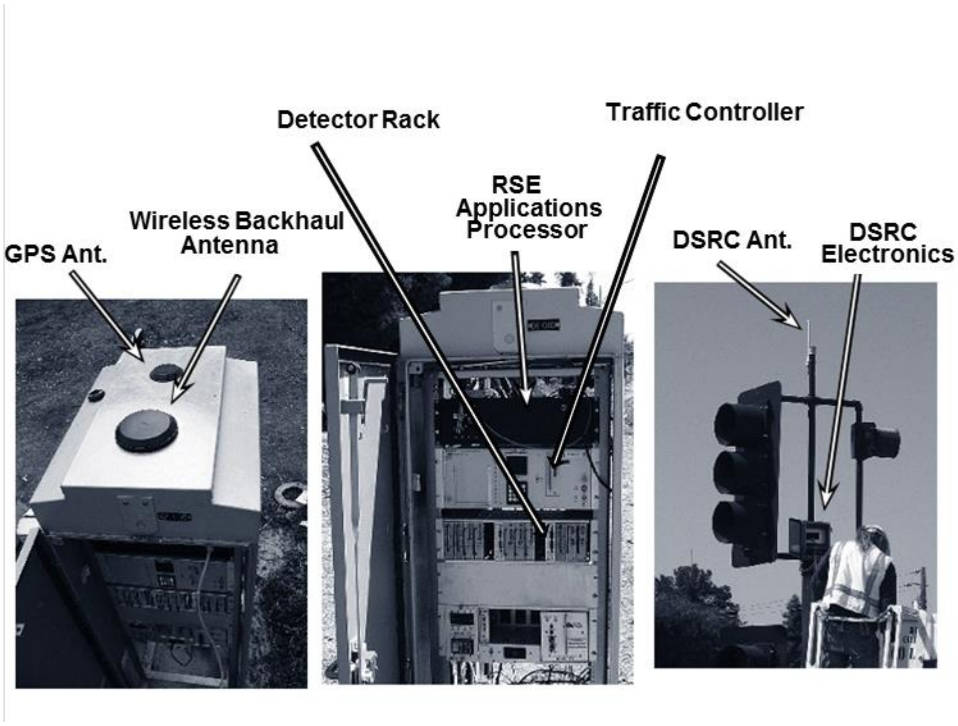

Figure D-4. Caltrans RSE Cabinet

(Ref: "Implementing Vehicle Infrastructure Integration: Real World Challenges", Ashkan Sharafsaleh, et al, California PATH [185])

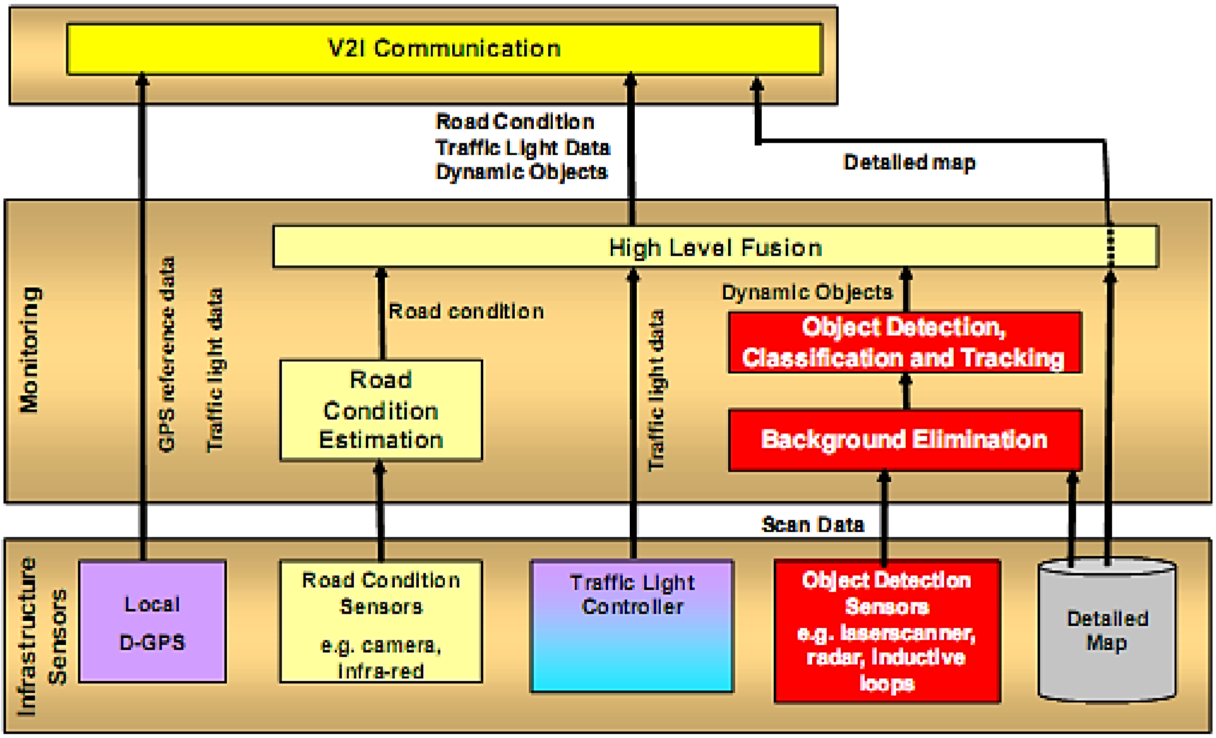

Figure D-5. Hierarchical architecture and Relationship between Sub-Systems for the InterSAFE 2 RSE

(Ref: "InterSAFE 2 Project Description, www.intersafe-2.eu [186])

Onboard Equipment Architecture

In a similar manner as with the RSE architecture, different researchers define the OBE in different ways. Some define the OBE as only the communications elements of the vehicle including antenna, radio/modems, mobile router/communications switch, and communications applications processor. Some include the GPS receiver as part of the communications suite and others consider it part of the navigation and positioning subsystem. Others consider the onboard equipment to include the onboard vehicle sensors, sensor data fusion, target tracking and safety related applications processing as well as the CAN bus and associated electronic controls. Similarly, some of the research reports show the mobile router/switch having Ethernet ports with a bridge to the vehicle CAN bus. Most of the wireless communications transceiver/modems have Ethernet interfaces rather than CAN bus interfaces. Applications processors are available with both CAN and Ethernet interfaces as well as USB. Sensors such as Radar, LIDAR and Video are available with both Ethernet and CAN bus interfaces. For the purpose of this report the vehicle system architecture is assumed to be as shown in Figure D-6.

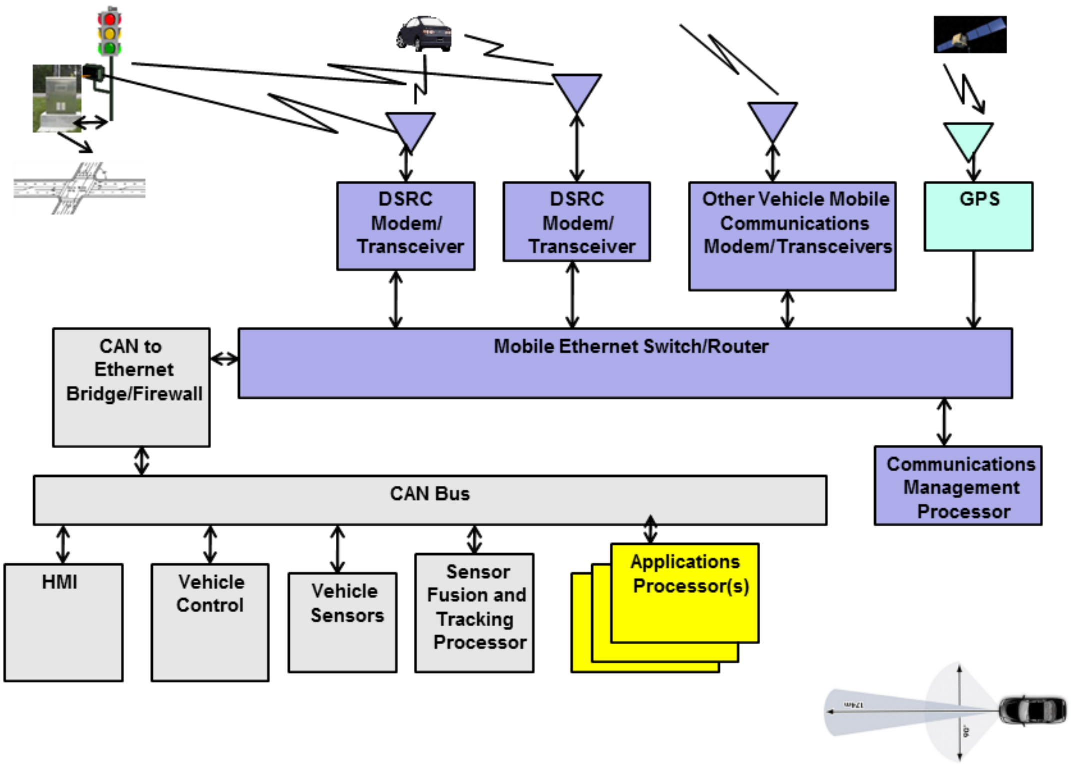

Figure D-6. Vehicle Architecture Considered for this Report

Source: ARINC April 2012

The SAE CAN bus is the standard for vehicles. Car manufacturers require light weight interconnect cabling, high reliability data networks in vehicles. However, there is perhaps some consideration for utilization of optical Ethernet. US DoD has replaced CAN bus as the primary data bus for the Expeditionary Fighting Vehicle (EFV); Figure D-7 illustrates the ruggedized switch/router utilized in the EFV and configured from commercial, off the shelf (COTS) modules. Test vehicles utilized by the ERTICO Cooperative Vehicle-Infrastructure System (CVIS) program in Europe also utilized a ruggedized Ethernet Switch Router, which is shown in figure D-8 to support the Continuous Air Interface for Long and Medium Distance Operations (CALM). Figure D-9 illustrates the European CVIS project OBE architecture that utilizes Ethernet and a firewall gateway/bridge to the vehicle CAN bus. Other vehicle architectures include device design with direct CAN bus interface. Figure D-10 illustrates the system architecture utilized in the USDOT VII test, which included a processor having both Ethernet and CAN bus interfaces. The different architectures do have an impact on latency and a standard architecture should be developed based on latency and performance analysis.

Figure D-7. Mobile Ethernet Switch Router Utilized in the USMC Expeditionary Fighting Vehicle

(Ref: “EFV Keeps Pace with Ethernet to Actualize Net-centric Warfare”, Mike Southworth, Military Embedded Systems [187])

Figure D-8. European CVIS Mobile Switch Router

(Ref: “CVIS Project Shows the Cooperative Way to Moblity, www.ertico.com [188])

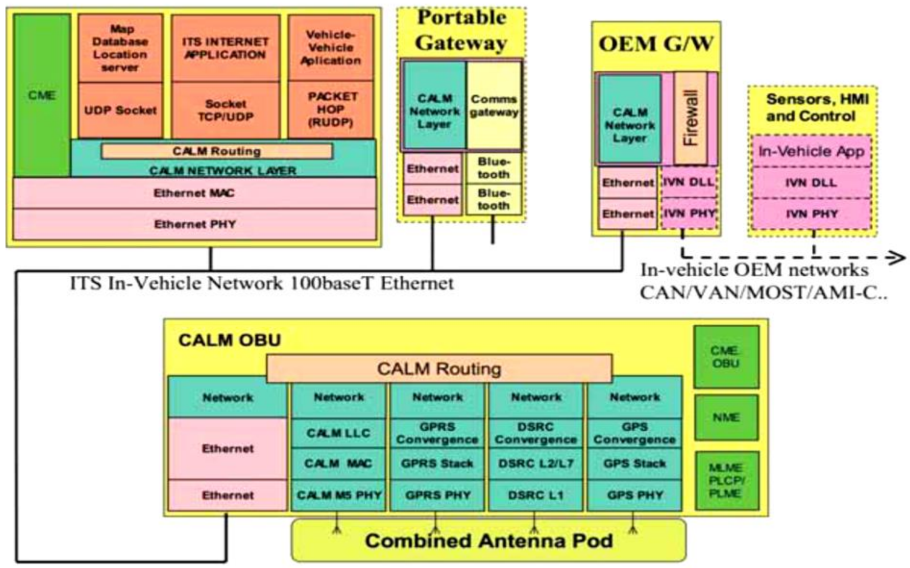

Figure D-9. ETRICO CVIS OBE Architecture Illustrating CALM
(Ref: ERTICO CVIS Project)

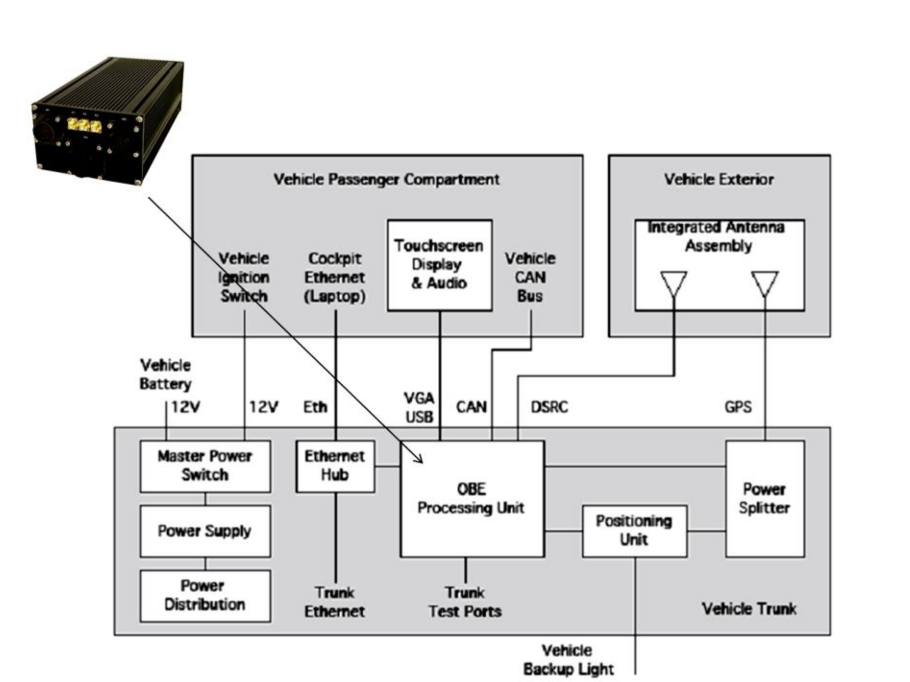

Figure D-10. OBE Processor and Associated Architecture used in VII Testing in the USA

(Ref: USDOT FHWA, “Final Report, Vehicle Infrastructure Integration Proof of Concept Technical Description-Vehicle”, FHWA-JPO-09-017, May 19, 2009 [176])

The major latencies are associated with information transfers between applications processors and latency associated with onboard sensors.

Connected RSE and OBE Architecture

The RSE and OBE are connected by a “through the air” or wireless interface. The basic ITS National Architecture illustrates the use of DSRC communications between RSE and OBE and between OBEs. Figure D-11 illustrates the V2I interconnect via DSRC communications. Both the RSE and OBE architecture supports utilization of multiple communications interfaces to the firewall switch/router. The European CVIS architecture includes an IEEE802.11p transceiver/modem referred to as M5; it also includes an IR DSRC module primarily utilized for toll applications as well as cellular and IPV6 WiMAX and Wi-Fi. ITS National Architecture Market Packages illustrate both V2I and VII architecture including:

- ATIS01: Broadcast Traveler Information from Center (to Vehicle Information Flow);
- ATIS02: Interactive Traveler Information (to/from Vehicle link);
- AVSS09: Intersection Safety Warning to Vehicle;
- AVSS10: Intersection Collision Avoidance;
- AVSS12: Cooperative Vehicle Safety System (V2I and V2V).

(Ref: “InterSAFE 2 Test and Evaluation Plan”, www.ec.europa.eu [190])

Considering the SPaT applications and DSRC-DSRC communications, the propagation of radio waves is 3- E8 meters/second. For 1000 meters, the propagation time is 3.33 microseconds. Time to transfer a packet of data is a function of packet size and supported data rate of the DSRC, based on noise floor caused by in-band and adjacent band interference.

Figures D-12 and D-13 illustrate the functional steps associated with message transmission and reception from RSE to OBE and vice versa. These processing steps add latency over and above latency associated data transmission and propagation delays. Any retransmission of message packets caused by bit errors adds to latency.

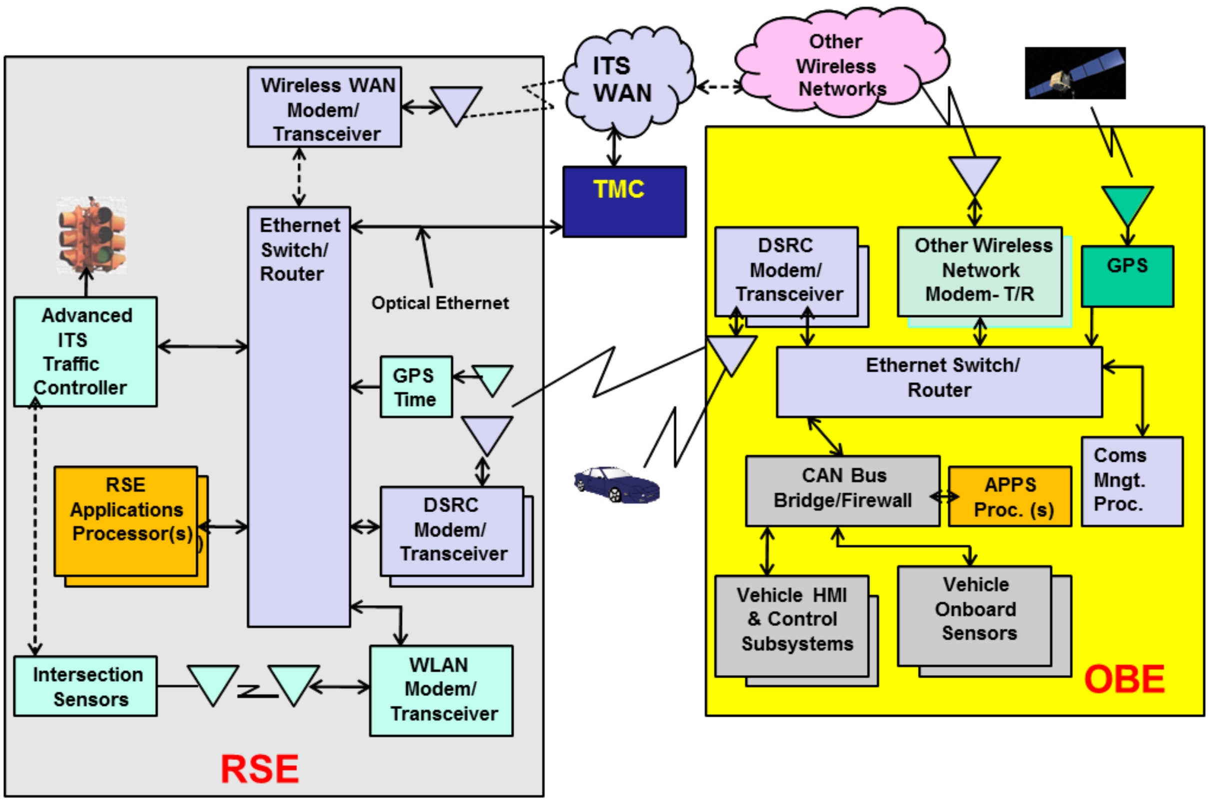

Figure D-11. Diagram of OBE and RSE Linked Via DSRC

Source: ARINC April 2012

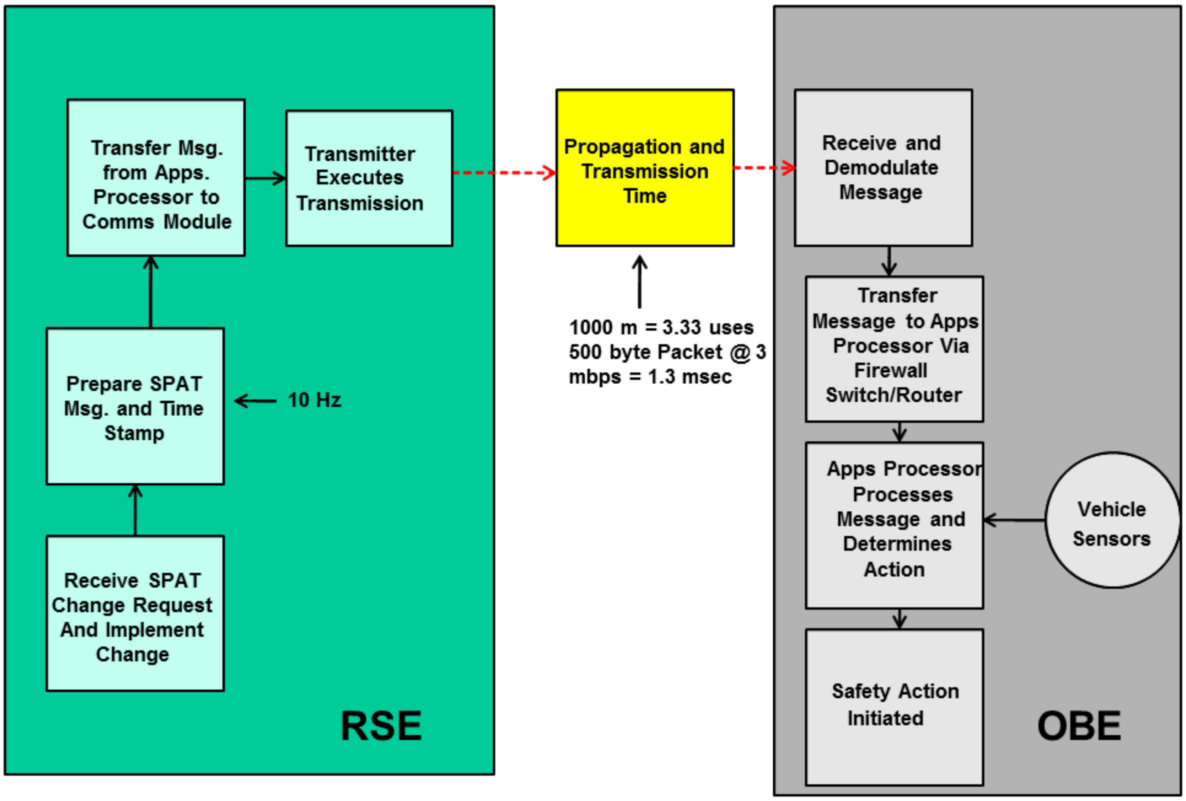

Figure D-12. Functions Adding to Latency Associated with RSE to OBE SPaT Message

Source: ARINC April 2012

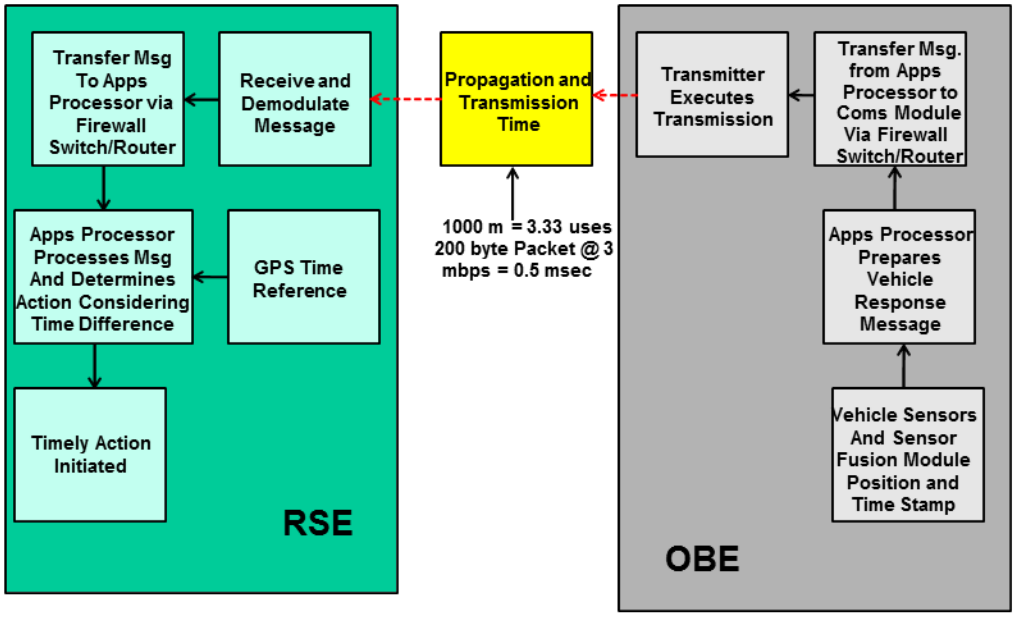

Figure D-13. Functions Associated to Latency Related to OBE to RSE Communications

Source: ARINC April 2012

Wide Area Communications Architecture

Most of the RSE and OBE system architectures include wide area links. National ITS Architecture shows traffic management centers linked to roadside devices (via optical, wireless and hybrid communications networks) and wirelessly to probe vehicles, motorist assistance patrols and signal maintenance. National ITS Architecture further shows Information Service Providers wirelessly linked to vehicles through wide area, wireless mobile communications networks. European intelligent vehicle projects include WiMAX, 3G and 4 G cellular, Radio Data Service (RDS; FM digital sub band) and terrestrial broadcast HD Radio as options for receiving both service and safety related information. Internet connectivity using IPV6 is included in most architecture with MANET and/or GeoNet protocol. Message relay from vehicle to vehicle is included in the mobile protocol, to essentially extend range of operations. This project precludes the consideration of fee for service communications and analysis of V2V communications requirements. For wide area, mobile wireless communications, jurisdictional owned communications infrastructure (WiMAX or LTE used for emergency and safety applications), jurisdictional HD Radio or private infrastructure where public/private partnerships can be developed are the only reasonable candidates. Due to the bandwidth required to support interactive V2V (caused by HAI messages transmitted 10 times per second and the number of vehicles in wide area communications range) as well as V2I functions, it is doubtful if private service companies would allocate free bandwidth to the public. Broadcast safety data bandwidth, is a possibility for public/private partnerships; however, broadcast bandwidth requirements increase as a function of area covered (number of intersections and safety events supported). Figure D-14 illustrates use of a modular, mobile switch/router to facilitate interconnection of the OBE to multiple communications links.

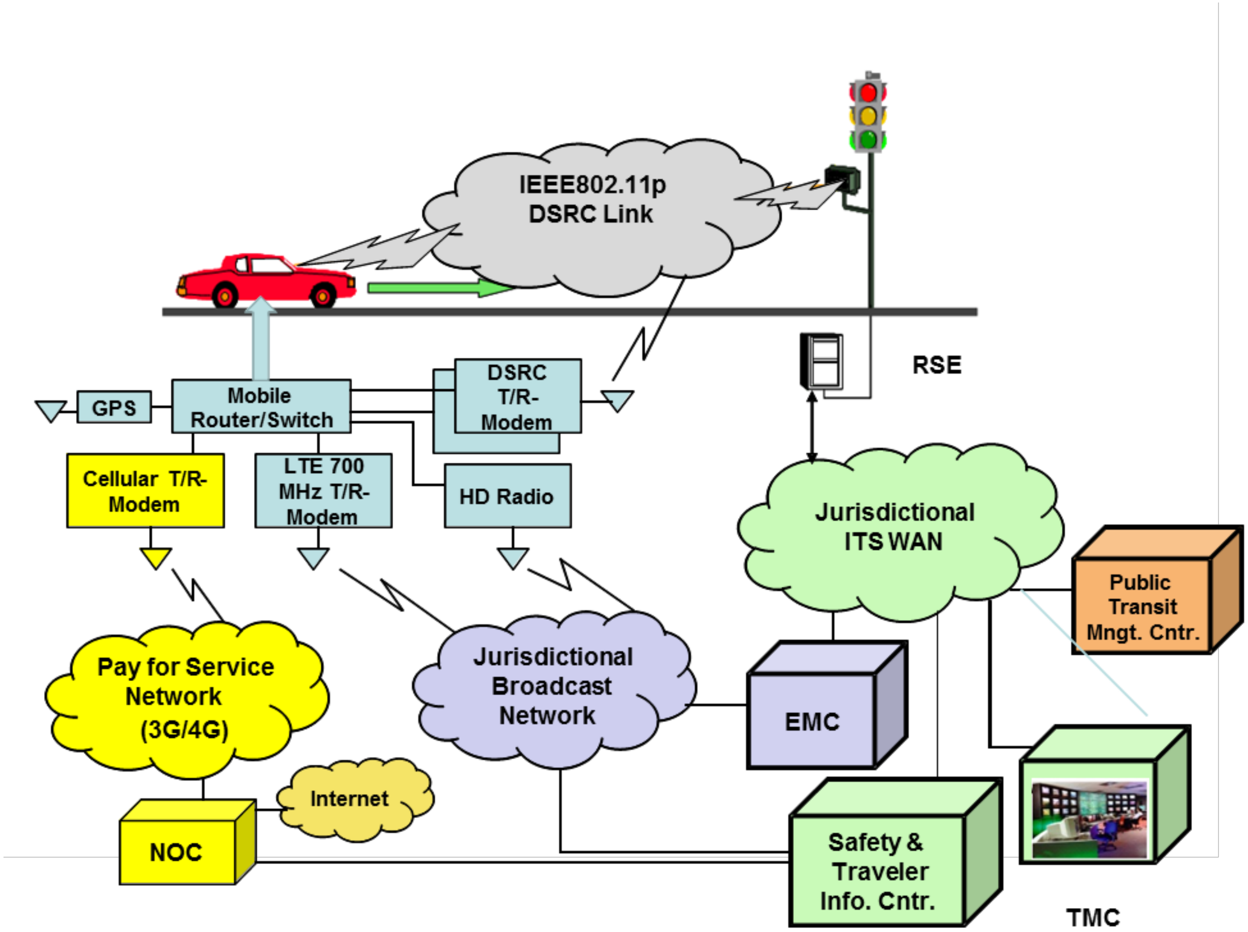

Figure D-14. Mobile Router Supports Modular Transceiver/Modem, Facilitating Wireless WAN Interconnect

Source: ARINC April 2012

The architecture considered for this project to meet specified SPaT applications includes:

1. RSE Interconnected to ITS Network communicating with the TMC and other ITS related centers as designated by National ITS Architecture via an undefined wide area ITS network (typically optical Ethernet, wireless or hybrid) and communicating with vehicles via the DSRC communications link;
2. RSE Interconnected with ITS centers and communicating time critical information to vehicles via DSRC and less time critical information to vehicles via a wide area, broadcast, mobile wireless link.
3. Wide Area, wireless mobile network provoking all information to vehicles.

Also for the purpose of this study, RSE and OBE architecture is considered to be as defined of the latency analysis above.

Appendix E

E. SAE J2735 Considerations

The SAE J2735 Standard “considerations” for SPaT applications are provided within the limited scope of the applications described in the Technical Memorandum. The first phase of defining SPaT communication requirements was to develop a set of scenarios (see Task 2 Report) for each specific application and establish the minimum set of information required to be exchanged between the “players” involved in the application to meet its functional requirements (Ref: ARINC, Task 2 Report: “Technical Memorandum; Applications Requiring SPaT Messages”, USDOT Contract DTFH-10-D-00015, March, 2011 [1]).

The SAE J2735 Standard (Ref: “DRAFT SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary”, September, 2009 [191]) and J2735 Working Group guidelines were used as a baseline to establish the minimum set of information required for each application. The specific messages associated with the applications were created, when applicable, from the J2735 pool of defined “data elements”.

The messages being used in the SPaT application analysis are associated with the following SAE J2735 message set:

- MSG_BasicSafetyMessage (BSM) Part I;
- MSG_MapData (MAP);
- MSG_SignalPhaseAndTiming Message (SPaT);
- MSG_SignalRequestMessage (SRM);
- MSG_SignalStatusMessage (SSM).

Within this limited framework, the following comments can be made relating to SAE J2735 Standard.

- The analysis was made based on a dated draft of the SAE J2735 Standard (2009). It is the only version available at this time for the SPaT Application analysis;
- The guidance from the SAE J2735 Working Group specifies two frequencies (repeat cycles) for the messages listed above and are as follow:
  - BSM = 10 Hz;
  - MAP = 1 Hz;
  - SPaT = 10 Hz;
  - SRM = 1 Hz;
  - SSM = 1 Hz.

The 1 Hz messages, such a SRM and SSM increases significantly the OBE action’s “decision making” period when a vehicle is approaching an intersection. The decision making period is further increased when DSRC is used. Multiple messages are required to decrease the theoretical BER. Thus, increasing the minimum communication range required;

- It is unclear how the SAE J2735 Standard data elements and data frames content associated with timing relates to UTC time. Perhaps, specifying the entire UTC time (e.g., 8 octets), when required, would simplify coding and decoding of the timing information;
- The SPaT Message, in SAE J2735, does not specify the “location” (latitude, longitude, and elevation). While this information is supposed to be available in the MAP message, it does not account for an outdated MAP or a when a temporary intersection is put in place which may not be reflected in the MAP message.

- The SPaT Message, in SAE J2735, specifies a "pedestrian presence" when applicable. However, the pedestrian crosswalk identification associated with the "presence" does not appear to be available. It would be logical that the location of "pedestrian present" should be identified.
- The GID defined in SAE J2735 is 2837 octets in length. This message size is large (nearly 12Kbits) and requires substantial communications bandwidth, especially if GIDs for many intersections is being distributed. Other intersection safety projects (e.g., CICAS) have developed substantially more compact representations of the intersection. These should be evaluated and considered for implementation in the standard.
- The SPaT Message, in SAE J2735, specifies signal phases using up to 127+ octets to identify lanes and signal phase. It would appear that a 2 octets entity would be sufficient to provide signal phase information for any intersection (e.g., up to 255 lanes, 255 signal sates). In the case of safety applications, 2 octet signal phase information would be more efficient in processing time;
- In addition of the current signal phase (at UTC time), the application scenarios calls for two additional phase and timing information:
    - "Time from UTC Time Stamp to Next Signal phase" – The SAE J2735 Standard's SPaT message provide this information using the "TimeMark" data element;
    - "Time from UTC Time Stamp to Next Subsequent Signal Phases" – It is not clear that information on the next subsequent signal phase can be extracted from the SAE J2735 SPaT message.
- The Right Turn Assist (RTA) application (see Technical Memorandum) requires a Right Turn (RT) message transmitted by the OBE to RSE indicating that the vehicle's intention to turn right. This message is not specified in the SAE J2735 standard. However, the elements within the RT message are similar to the HIA message (SAE J2735's BSM Part 1);
- For the PREEMPT, TSP, and FSP applications it is assumed that there are two ways to respond to a "request"; equivalent to J2735 SRM:
    - A status message; equivalent to the J2735 SSM message which basically indicates if the request has been granted with the related information;
    - The next SPaT message which basically provides the request's response via "preemption", TSP, or FSP state; 1 octet J2735 data element within the SPaT message;

  The main difference between the two is a question of timing as per J2735 guidelines. A SSM message repeat rate is 1000 msec. while the SPaT message is 100 msec.;
- When the messages are used in the DSRC context, a security field is added to each message. The size of this field has been approximate to 250 octets. The security filed is not specified in the SAE J2735 Standard.

Appendix F

F. List of Acronyms

A

AASHTO: American Association of State Highway and Transportation Officials

AC: Alternating Current

AC: Access Categories (IEEE 802.11e; Traffic prioritized to 4 ACs)

ACC: Adaptive Cruise Control

ADAS: Automated Driver Assist System

AM: Amplitude Modulated

AMC: Adaptive Modulation and Coding

ANSI: American National Standards Institute

Ant: Antenna

AOA: Angle of Arrival

AODV: Ad hoc On-Demand Distance Vector

APCO: Association of Public Safety Communications Officials

APE: Application Protocol Entities

API: Application Program Interface

Apps: Applications

ASTM: American Society for Testing and Materials

ATIS: Advanced Traveler Information System

ATSC: Advanced Television Systems Committee, Inc.

ATSC M/H: ATSC Mobile Digital TV

AWGN: Additive White Gaussian Noise

B

BCMCS: Broadcast and Multicast Service

BRS: Broadband Radio Service

BER: Bit Error Rate

BICM: Binary Interleaved Coded Modulation

BLOS: Beyond Line of Sight

bps: Bits per Second

BPSK: Binary Phase Shift Keying

BS: Base Station

BSM: Basic Safety Message

BSW: Blind Spot Warning

BW: Bandwidth

C

C2C: Center to Center

CA: Certificate Authority

CALM: Continuous communications Air interface for Long and Medium range

CAMP: Crash Avoidance Metrics Partnership

CAN: Controller Area Network

CBR Constant Bit Rate

CDMA: Code-Division Multiple Access

CLEC: Competitive Local Exchange Carrier

CCF: Channel Coordination Function

CCH: Channel Control

CCHI: Control Channel Interval

CDMA: Code Division Multiple Access

CER: Canonical Encoding Rules

CH: Channel

C/I: Carrier-to-Interference Ratio

CICAS: Cooperative Intersection Collision Avoidance Systems

CLK: Clock

CMRS: Commercial Mobile Radio Service

C/N: Carrier-to-Noise Ratio

CNR: Carrier -to-Noise Ratio

COFDM: Coded Orthogonal Frequency Division Multiplexing

CoS: Class of Service

CPSK:	Coherent Phase Shift Keying
CSI:	Channel State Information
CSMA/CA:	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD:	Carrier Sense Multiple Access with Carrier Detection
CSW:	Curve Speed Warning
CTC:	Convolution Turbo Code
CVO:	Commercial Vehicle Operations
CW:	Continuous Wave

D

DARPA:	Defense Advanced Research Projects Agency
dB:	Decibels
dBm:	Decibels relative to 1 Milliwatt
DBS:	Direct Broadcast Satellite (also Direct Broadcast Service)
dBW:	Decibels relative to 1 Watt
DC:	Direct Current
DCN:	Data Communications Network
DCS:	Dynamic Channel Selection
DF:	Data Frame
DFT:	Discrete Fourier Transform
DiffServ:	Differential Service (QoS; Layer 3)
DHCP:	Dynamic Host Configuration Protocol
DIFS:	Distributed Inter Frame Space
DL:	Downlink
DLL:	Data Link Layer
DNPW:	Do Not Pass Warning
DNS:	Domain Name Server
DOD:	Department of Defense
DOT:	Department of Transportation
DPSK:	Differential Binary Phase Shift Keying
DSRC:	Dedicated Short Range Communications
DS/SS:	Direct Sequence Spread Spectrum

DS-UWB: Direct Sequence - UWB
DVB: Digital Video Broadcasting

E

EAP: Extensible Authentication Protocol
EAP-TLS: Extensible Authentication Protocol- Transport Layer Security
EAP-TTLS: Extensible Authentication Protocol- Tunneled Transport Layer Security
EDGE: Enhanced Data rates for GSM Evolution
EESM: Exponential Effective SNR Mapping
EIA: Electronic Industries Association
EIRP: Effective Isotropic Radiated Power
EM: Electromagnetic
EMC: Emergency Management Center; Electromagnetic Compatibility
EMI: Electromagnetic Interference
EMS: Emergency Medical Services
EMP: Electromagnetic Pulse
EMR: Electromagnetic Radiation
eNodeB Evolved Node B (LTE Access Node)
EOF: End of File; End of Frame
EOP: End of Packet
EOT: End of Transmission
EPC: Evolved Packet Core
ETA: Estimated Time of Arrival
ETC: Electronic Toll Collection
ETSI: European Telecommunications Standards Institute
E-UTRAN: Evolved UMTS Terrestrial Radio Access Network
EV: Emergency Vehicle
EV-DO: Evolution-Data Only

F

FCC: Federal Communications Commission

FCS: Frame Check Sequence

FCW: Forward Collision Warning; Femtocell Convergence Server

FDD Frequency Division Duplex

FDM: Frequency Division Multiplexing

FDMA: Frequency Division Multiple Access

FEC: Forward Error Correction

FECN: Forward Explicit Congestion Notification

FFT: Fast Fourier Transform

FHSS: Frequency Hopping Spread Spectrum

FHWA: Federal Highway Administration

FLA: Fast Link Adaptation

FM: Frequency Modulated

FO: Fiber Optic

FS: Fixed Station

FSP: Freight Signal Priority

G

GFSK: Gaussian Frequency Shift Keying

GHz: Gigahertz

GI: Guard Interval

GID: Geometric Intersection Description

GPRS: General Packet Radio Service

GPS: Global Positioning System

GRE: Generic Encapsulation

GSM: Global System for Mobile Communications

GW: Gateway

H

HA: Home Agent

HAR: Highway Advisory Radio

HDC: High-Definition Coding

HD Radio: Hybrid Digital Radio

HDTV:	High Definition TV
HF:	High Frequency
HMI:	Human Machine Interface
HNB:	Home NodeB
HSPA:	High Speed Packet Access
HT:	High Throughput
HTC:	High Throughput Control
Hz:	Hertz (Cycles per Second)

I

IBOC:	In Band on Channel
IC:	Integrated Circuit
ICA:	Intersection Crossing Assist
ICMP:	Internet Control Message Protocol
IEEE:	Institute of Electrical and Electronics Engineers
IETF:	Internet Engineering Task Force
IFFT:	Inverse Fast Fourier Transform
IGP:	Internet Gateway Protocol
IMA:	Intersection Movement Assist
IMD:	Intermodulation Distortion
IMT:	International Mobile Telecommunications
I/O:	Input Output
IP:	Internet Protocol
IPv4:	Internet Protocol Version 4
IPv6:	Internet Protocol Version 6
IPDA:	Internet Protocol Destination Address
IPsec:	Internet Security Protocol
IR:	Infrared
ISI:	Inter-Symbol Interference
ISM:	Industrial, Scientific and Medical (radio spectrum band)
ISO:	International Standards Organization

ISP:	Information Service Provider
I-SIG:	Signal Timing Optimization
ITE:	Institute of Transportation Engineers
ITS:	Intelligent Transportation Systems
ITU:	International Telecommunication Union

J

JPO:	Joint Program Office

K

Kb:	kilobytes
KBPS:	Kilobits per Second
Kg:	kilograms
KHz:	Kilohertz
Km:	kilometer
KW:	Kilowatt

L

LA:	Link Adaptation
LAC:	Local Area Coverage
LAN:	Local Area Network
LAP:	Link Access Protocol
LCW:	Lateral Collision Warning
LDW:	Lane Departure Warning
LEC:	Local Exchange Carrier
LKA:	Lane Keeping Assist
LLC:	Logical Link Control
LLR:	Log-Likelihood Ratios
LMDS:	Local Multipoint Distribution Service

LMR: Land Mobile Radio
LRMS: Location Referencing Message Specification
LMS: Location and Monitoring Service
LOS: Line of Sight
LQM: Link Quality Metric
LSI: Large-scale Integration
LTA: Left Turn Assist
LTE: Long Term Evolution

M

m: Meters
MAC: Media Access Control
MAN: Metropolitan Area Network
MANET: Mobile Ad Hoc Network
MBA: Multiple Beam Antennas
MBMS: Multimedia Broadcast and Multicast Services
MB-OFDM: Multi-Band Orthogonal Frequency Division Multiplexing
MBSFN: Multicast/Broadcast Single-Frequency Network
MIB: Management Information Base
Mbps: Millions of Bits per Second
MCM: Multicarrier Modulation
MCP: Modulation and Coding Product
MCS: Modulation and Coding Scheme
MDS: Multipoint Distribution Service
MDT: Mobile Data Terminals
MEDS: Map Element Distribution Service
MER: Message Error Rate
M/H Mobile and Handheld
MHz: Megahertz
Mi: Mile
MIB: Management Information Base
MIMO: Multiple Input Multiple Output

ML: Maximum Likelihood

MMDS: Multichannel Multipoint Distribution Service

MMSE: Minimum Mean Square Error

mmW: Millimeter Wave

MN: Mobile Node

MNN: Mobile Network Node

MR: Mobile Router

MRCC: Multiple Rendezvous Control Channel

MS: Mobile Station

Msec: Millisecond

MTBF: Mean Time between Failures

MTTR: Mean Time to Repair

MUTCD: Manual on Uniform Traffic Control Devices

MW: Microwave

N

NAT: Network Address Translation

NEMA: National Electric Manufacturers Association

NEMO: Network Mobility

NF: Noise Figure

NHTSA: National Highway Traffic Safety Administration

NLOS: Non Line of Sight

nm: Nanometers (10^{-9} meter)

NMS: Network Management System

NOC: Network Operation Center

Ns: Nanosecond (also nsec)

NTCIP: National Transportation Communications for ITS Protocol

NTP: Network Time Protocol

O

OBE: Onboard Equipment

OFDM: Orthogonal Frequency Division Multiplexing

OFDMA: Orthogonal Frequency Division Multiple Access

OS: Operating System

OSA: Opportunistic Spectrum Access

OSI: Open Systems Interconnection (ISO 7498)

OSPF: Open Shortest Path First

OWA: Open Wireless Architecture

P

PAN: Personal Area Network

PDCP Packet Data Convergence Control

PDF: Probability Density Function

PED-SIG: Pedestrian Signal Assist

PER: Packet Error Rate

PHY: Physical Layer (OSI Layer 1)

PKI: Public Key Infrastructure

PL: Packet Length

PIM: Protocol Independent Multicast

PLCP: Physical Layer Convergence Protocol

PMP: Point to Multipoint

POC: Proof of Concept

PREEMPT: Emergency Vehicle Signal Preemption

ps: Picoseconds (also psec)

PSA: Provider Service Announcement

PSC: Provider Service Context

PSD: Power Spectral Density

PSDU: Physical layer Service Data Unit

PSK: Phase Shift Keying

PSMU: Public Service Mobile User

PSTN: Public Switched Telephone Network

PTP: Point to Point

PVM: Probe Vehicle Message

PW: Pico Watt

Q

QA: Quality Assurance
QAM: Quadrature Amplitude Modulation
QC: Quality Control
QoS: Quality of Service
QPSK: Quadrature Phase Shift Keying

R

RADIUS: Remote Authentication and Dial-In User Service
RCRLV: Rail Crossing Red Light Violation
RDS: Radio Data Service
RECPA: Rear End Collision Prevention Assist at Signalized Intersections
RF: Radio Frequency
RFC: Request for Coordination (Comments)
RFI: Radio Frequency Interference
RFID: Radio Frequency Identification
RIP: Routing Information Protocol
RLC Radio Link Control
RLR: Red Light Running
RMS: Root Mean Square
RO: Route Optimization
RSA: Road Side Alert
RSE: Roadside Equipment
RSSI: Received Signal Strength Indication
RSVP: Reservations Protocol (supports QoS)
RTA: Right Turn Assist
RTP: Real Time Protocol
RTSP: Real-Time Transport Protocol
RTT: Round Trip Time
Rx: Receiver

S

SAE: Society of Automotive Engineers
SAP: Service Access Point
SAT: Satellite
SBR: Spectral Brand Replication
SC-FDMA: Singe-Carrier Frequency Division Multiple Access
SCH: Service Channel
SDA: Software-Defined Antenna
SDARS: Satellite Digital Audio Radio Service
SDM: Space Division Multiplexing
SDN: Service Delivery Node
SDO: Standards Developing Organization
SDR: Software Defined Radio
SGW Service Gateway
SIFS: Short Inter Frame Space
SIG: Special Interest Group
SIG-FLOW: Automated Intersection Crossing Assist
SINR: Signal to Interference and Noise Ratio
SIP: Session Initiated Protocol
SISO: Single Input Single Output
SLA: Speed Limit Assist
SNMP: Simple Network Management Protocol
SNR: Signal to Noise Ratio
SPaT: Signal Phase and Timing
sps: Symbols per Second
SS: Spread Spectrum
SSA: Stop Sign Assist

T

TC: Traffic Controller

TCIP: Transit Communications Interface Profiles

TCP: Transmission Control Protocol

TCP/IP: Transmission Control Protocol/Internet Protocol

TDD Time Division Duplex

TDM: Time Division Multiplex

TDMA: Time Division Multiple Access

TDM-QPSK: Time-Division Multiplex Quadrature Phase-Shift Keyed

TDOA: Time Difference of Arrival

TIA: Telecommunications Industries Association

TMC: Traffic Management Center

TOA: Time of Arrival

TOM: Transportation Object Message

TP: Throughput

TRQ: Training (sounding) Request

TSF: Timestamp Field

TSP: Transit Signal Priority

TV: Television

Tx: Transmitter or Transmit

TXOP: Transmit Opportunity

U

UB: Unlicensed Band

UBR: Unspecified Bit Rate

UDP: User Datagram Protocol

UHF: Ultrahigh Frequency

UL: Uplink

UNI: User Network Interface

U-NII: Unlicensed National Information Infrastructure

UTC: Coordinated Universal Time

UMTS: Universal Mobile Telecommunications System

USB Universal Serial Bus

USDOT: United States Department of Transportation

UTRA Universal Terrestrial Radio Access

UWB: Ultra Wideband

V

V2I: Vehicle to Infrastructure
V2V: Vehicle to Vehicle
VBR: Variable Bit Rate
VCI: Virtual Channel Identifier
VII : Vehicle Infrastructure Integration
VHF: Very High Frequency
VLAN: Virtual Local Area Network (see IEEE 802.1Q)
VLSI: Very Large Scale Integrations
VME: Versa Module Eurocard BUS (IEEE 1014)
VoIP Voice over Internet Protocol
VPI: Virtual Path Identifier
VPN: Virtual Private Network
VSAT: Very Small Aperture Terminal
VSB Vestigial Sideband

W

W: Watt
WAE: Wireless Application Environment
WAN: Wide Area Network
WAP: Wireless Application Protocol
WAVE: Wireless Access in Vehicular Environments
WCDMA: Wideband Code Division Multiple Access
WEP: Wired Equivalent Privacy
WIDE: Widely Integrated Distributed Environment

WILLWARN: Wireless Local Danger Warning *(PReVENT subproject)*

WiMAX: Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Networks

WMM: Wireless Multimedia Extension (Based on IEEE802.11e)

WPMCM: Wavelet Packet Multicarrier Modulation

WSA: Wave Service Announcement

WSM: WAVE Short Message

WSMP: Short Message Protocol

WSP: Wireless Session Protocol

WTP: Wireless Transaction Protocol

WWAN: Wireless Wide Area Network

X

XMIT: Transmit

Y

Z

ZF: Zero Forcing

Numeric:

511: Traveler Information System

3G: Third Generation

3GPP: Third Generation Partnership Project

4G: Fourth Generation

511: Traveler Information System

8VSB: 8-level Vestigial Sideband

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