Department of Electrical and Computer Engineering

ECE 544 Communication Networks II

DESIGN OF A VEHICULAR SAFETY NETWORK

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1. Introduction

This report presents an attempt to design a simple vehicular safety network. A vehicular safety network aims to provide the means of communication to the vehicles on road so that they can collaborate with other vehicles and roadside devices to prevent some of the accidents before happening.

2. Motivation and Challenges

Even in the so called ‘information age’, traffic accidents still take thousands of lives each year (over 50.000 in 2000), outnumbering many deadly diseases [1]. Injuries exceed well over tens of millions per year. Apart from fatalities and injuries, material losses reached approximately to 43 billion USD in 1999 worldwide, and increased to 200 billion USD during year 2000 only in EU member countries [2, 3]. Fortunately, there is a strong belief among the automotive technology creating companies that the majority of the accidents due to roadway collisions could be avoided with the help of the advanced vehicular safety technologies.

So far as such vehicular safety applications are concerned, collision warning and collision avoidance enabling technologies will lead to the key success. This is in fact due to the recent advances in wireless communications and sensor technology which will effectively be the driving force behind such implementations.

Basic services expected from a collision warning and avoidance system can be listed as:

- Announcing abruptly braking and stopping cars to further away cars to overcome line of sight limitation of the brake lights.
- Determining out-of-control cars (i.e. due to skidding, collisions etc.) and announcing this information to further away cars.
- Relaying important road-condition information (i.e. icing, work zone, railroad crossing etc.) to the cars out of the road-side information delivery system coverage.
- Announcement of emergency vehicle presence within certain vicinity. This is necessary to help preempting the road for an approaching emergency vehicle or to secure a workspace for emergency personnel on duty.
- Announcement of intersection crossing violations (e.g., red light or stop sign violations) to nearby cars for imminent collision warnings.

Once a reliable network infrastructure for providing the above basic services are designed, many non-safety applications can also be integrated such as real-time road traffic estimation, high speed tolling, parking guidance, digital license plate, collaborative expedition, fleet management, information retrieval through Internet, and entertainment applications. However, for the purposes of this paper, we are mainly focused to the high level design of a vehicular safety network.

Use of the readily available wireless LAN hardware and widely used IP based protocols for a vehicular safety network is not a viable option due to the challenges imposed by mission critical applications of such a network. Some of those important challenges are given below.

- *Reliability of the delivery service*

No matter what the information in transit might be, it should be relayed towards other cars in a reliable manner. Packet losses are not tolerable and would lead to fatalities.

- *Stringent delay requirements of the applications*

Nearly all collision warning and avoidance applications need a very short notice packet delivery service for ensured operation. This requirement is not an easy one to satisfy with the systems designed for inherently fixed wireless access, considering vehicles moving at speeds of 80 mph and more. For example, in [4], deterioration in the performance of IEEE 802.11b protocol is presented to be drastic even with average vehicular speeds.

- *Limited performance degradation with increased number of users*

The vehicular safety network should allow only for reasonably small performance degradation, given a realistic increase in the number of participant vehicles.

- *Need for location and direction awareness*

Network of concern should provision location and direction determination to different levels of granularity. This is vital to determine intended communication scopes, so that unwanted warnings to total strangers are not announced.

3. Conceptual Structure of the Network

The vehicular safety network under investigation is composed of three broad categories of components into which the network elements can be classified. They are on-board equipment, roadside equipment and backhaul network. Overview of the components with their topological structure is illustrated in Figure 1.

On-board equipment category can be viewed as the infrastructure built into the vehicle itself. Although the number of devices on board and their capabilities might differ from one vehicle to the other, there should be a minimum standard set of devices and capabilities, such as the ones that are explained in this document, for ensured operation of the safety network. Details of the elements in this set are given in the proceeding paragraphs.

Fundamentally, inter-vehicle device communications are realized on a commonly shared bus. Among many propriety approaches to common bus communications, an open standard might be used for universal compatibility with after market on-board equipment.

At the heart of the on-board equipment is a powerful on-board computer that interacts with the rest of the on-board equipment and coordinates the safety precautions generated by the vehicle. The underlying hardware of the on-board computer should allow low latency operations with real time support from the operating system running on top (e.g. embedded RT Linux). All interfacing to this computer should be designed to have an inherently non-blocking nature, which will prevent any failing on-board equipment to bring the complete on-board system down.

On top of a commonly accessible bus, there are several radios installed, including a programmable software radio that is compatible with the (draft) Dedicated Short Range Communications (DSRC) standard. 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. DSRC is meant to be a complement to cellular communications by providing very

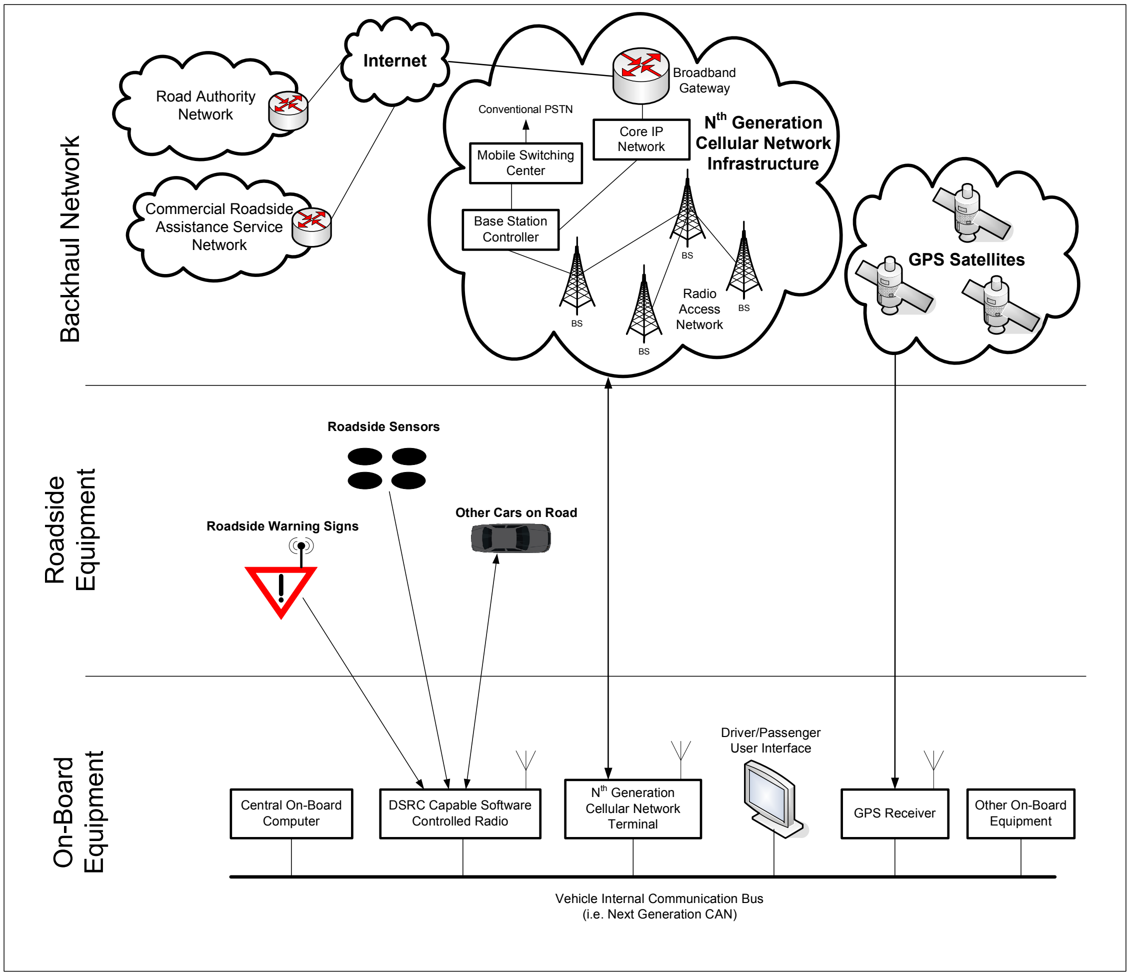

Figure 1. Topological structure and the components of the vehicular safety network

high data transfer rates in circumstances where minimizing latency in the communication link and isolating relatively small communication zones are important [6]. DSRC radio is the primary way of communicating with the roadside equipment (e.g. other cars, roadside sensors etc.). Having a programmable radio for the purpose creates a flexible communication structure that can provision compliance with more than one standard (e.g. backward compatibility with older DSRC radios operating at 900 MHz frequency). Another important radio in the standard set of on-board equipment is an Nth generation network terminal. Depending on the country and the region, this terminal has a subscription to the local cellular network operator, interfacing the on-board equipment to the global IP network, the Internet. On-board equipment also contains a GPS receiver to support applications that need location and direction information (e.g., reporting exact accident location to law enforcement authorities etc.). Depending on the exact radio types and frequencies, transceiving operation can be supported by a carefully designed multi-purpose combined antenna mounted on the vehicle chassis.

Another important part of the on-board equipment is the driver/passenger user interface. Although vehicular safety system might provide some autonomous actions in reaction to the perceived information from the outer world, still many of the decisions are to be taken by the driver of the vehicle. Therefore, the system must provide effective means to issue early warnings and suggestions to the driver and passengers. This includes one or more audio/video subsystems with advanced capabilities for easy data inputting (e.g., via touch-screen LCD displays and voice commands).

As part of an on-board safety system, an event recorder is also installed in vehicles. This black box, similar to the ones used in aircrafts, records the messages exchanged in the vehicular safety network and the actions taken in response to those messages. Recordings are written to a solid-state memory device, which is mechanically protected in a well-built housing. Events are retrieved from this black box in case of an accident, and can be used in the development of better safety systems, in addition to law enforcement related issues.

Roadside equipment part of the vehicular safety network mainly constitutes the outside view of the on-board equipment. Other than the vehicles traveling in the vicinity of a given vehicle, roadside sensors and wireless communication capable road signs are a part of this equipment class.

Roadside sensors might be of very diverse type ranging from temperature and humidity measuring type (to perceive information about road condition), to magnetic or acoustic data collecting type (to estimate number of vehicles and congestion). In this context, a roadside sensor is not considered to be just sensor electronics. Rather, it is a sensor device interfaced to a battery operated small scale low-power computer with wireless communication capability. Roadside sensor radios are DSRC compatible, and they support at least basic packet delivery service of DSRC. A possible roadside sensor might be the Intel Mote [7], an ARM processor based micro device with its own SRAM and Flash memory. Intel Mote runs TinyOS [8] operating system that can make DSRC implementation and application development on the sensor node possible.

Wireless communication capable signs can be considered of a special type of roadside sensors that are pre-programmed to announce certain warning information, such as stop sign or suggested curve speed. Also, they might have cellular system connections for easy remote updates (e.g. reduced speed limit under rain or snow). Such signs can also be deployed to act as variable message boards for a variety of advisory information. Since the information embedded into such signs are wirelessly emitted (in addition to being visual signs), they can be relayed among cars for increased road safety.

On-board and roadside equipment of the discussed vehicular safety network are illustrated in Figure 2, to provide a visualization of the concepts in action.

Backhaul network part of the vehicular safety network design can be seen as the gateway point to the outer world from the temporal network at the roadside. New generation cellular network terminal on-board lets the safety system send and receive regular IP packets from the rest of the world. Beyond being connected to the Internet for personal computing purposes, such connectivity enables the road authorities to immediately react to the road anomalies (e.g. accidents, congestions etc.) right after they are detected at roadside. This opportunity might even be used to stream live audio and video from an accident scene, given that the next generation cellular networks will support QoS requirements of the multimedia traffic from end user terminals.

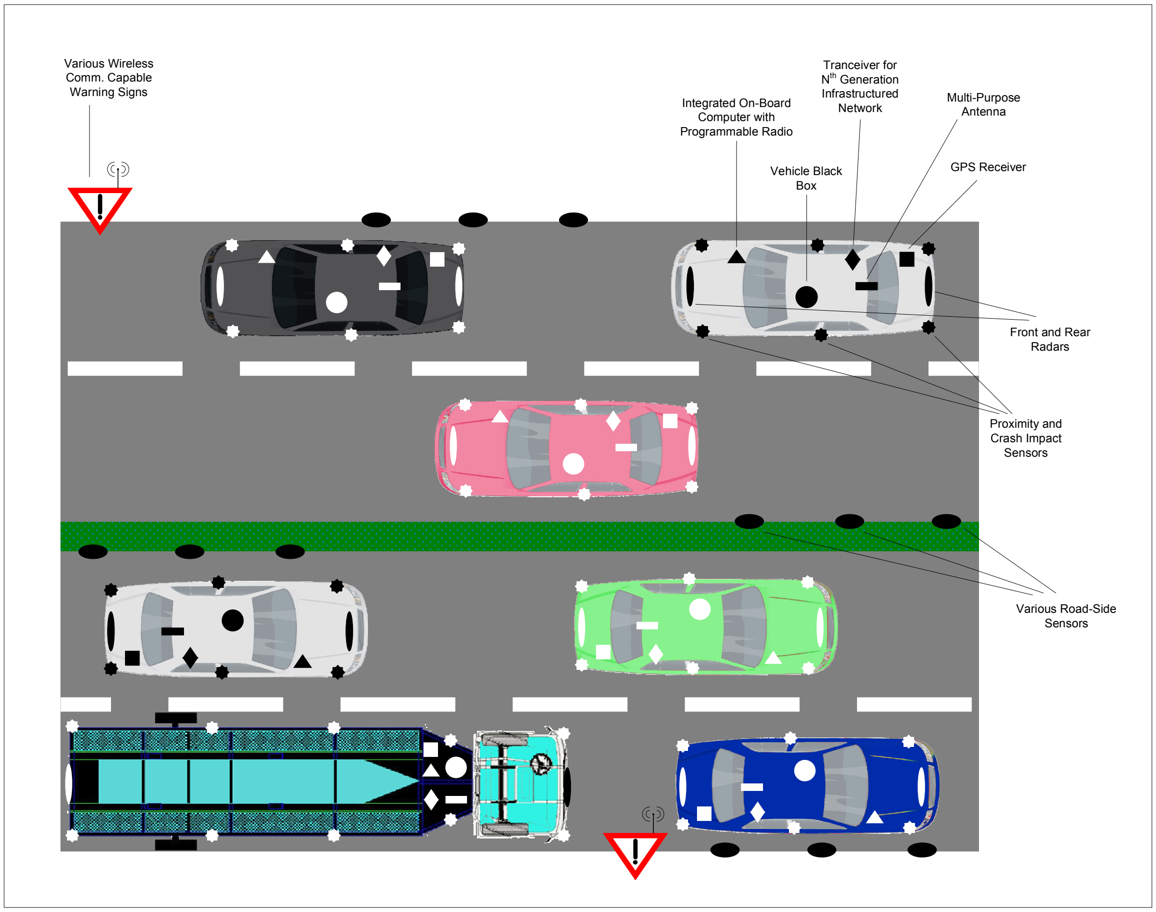

Figure 2. Major Components of the Vehicular Safety Network on the Road

4. Requirements of the Vehicular Safety Network

In this section, requirements of the vehicular safety network are investigated in three categories, namely, inter-vehicle communication requirements, roadside communication requirements and backhaul communication requirements.

Communication requirements of the on-board equipment within the vehicle are given in Table 1. This requirement analysis is based on a basic bus model. An advanced inter-vehicle communication network should provide optical and wireless on-board device connectivity together with the wired communication bus approach.

REQUIREMENT NAME	DETAIL
Supported Basic Service	Fault Tolerant Packet Delivery
Supported High Speed Service	Best Effort Multimedia Packet Delivery
Number of Devices	Up to 32 devices
Data Rate (Basic Services)	64 Kbps
Data Rate (Multimedia Services)	1Mbps
Maximum Permitted Propagation Latency	5ns per meter on bus
Assumed Average Bus Length	100 meters
Error Correction	At least CRC-16 equivalent
Media of Transmission	Paired Copper with Common Return
Bus Termination	Must be compliant to ISO 11898-2 and 3
Segmentation	Must be possible via bridging
Signal Voltage Levels	Max. 12V DC absolute
Reliability	Bus line breakage, short circuits and short to grounds must be detectable
Security	Left to applications. Not needed at physical layer.

Table 1. Inter-vehicle communication requirements of the vehicular safety network

Roadside communication requirements of the vehicular safety network are summarized in Table 2. Satisfying these requirements in the design is the most important factor leading to a successful vehicular safety network, because the majority of the safety related messaging will be flowing between roadside elements of the network. Also the need to implement some of the given requirements on limited resource roadside sensors implies a lot of challenges. Frequency and power related requirements are examined for North America as governed by FCC.

Backhaul network part of the design has the requirements that are listed in Table 3. Such requirements are important to come up with a complete vehicular safety network design, since an isolated safety network at the roadside will not benefit from the vast amount of services available through the global Internet.

REQUIREMENT NAME	DETAIL
Nominal Communication Range	300 meters in clear line-of-sight
Worst Packet Delivery Latency	100 ms
Data Rate (Basic Services)	1 Mbps
Data Rate (Multimedia Services)	16 Mbps
Number of Devices	Up to 100 devices in nominal communication range
Media of Transmission	Air (Microwave)
Error Correction	At least CRC-32 equivalent
Expected BER	$\sim 10^{-4}$
Operation Frequency	Dedicated 5.9 GHz
Operation Bandwidth	75 MHz (5.850 - 5.925 GHz)
Radio Output Power Requirements	Nominally less than 30 dBm
Typical Mobility Speeds	Up to 120 miles per hour worst case Up to 60 miles per hour on average
MAC Layer Requirements	Bounded delay guarantee. Power saving sleep/wakeups at basic service rates (for battery constrained roadside sensor nodes).
Routing/Application Layer Requirements	Multi-hop relaying capability with bounded delays. Quick adaptation to high speeds of mobility. Dynamic binding to services. Location and direction awareness.
Reliability	Resilience to strong multipath fading and Doppler shifts caused by high mobility. ACK based reliable packet delivery. Delay aware priority based channel access support in MAC layer. Dedicated control channel for immediate announcement and warnings.
Security	A small subset of IEEE 802.11i for latency insensitive applications

Table 2. Roadside communication requirements of the vehicular safety network

REQUIREMENT NAME	DETAIL
Data Rate to Vehicle Terminal (Basic)	384 Kbps
Data Rate to Vehicle Terminal (Multimedia)	Up to 10 Mbps
Network Layer Requirements	Basic IP packet delivery service. QoS supported IP packet delivery service for multimedia traffic.
Service Requirements	24/7 available road authority emergency contact IP service. 24/7 available commercial roadside assistance IP service.

Table 3. Backhaul communication requirements of the vehicular safety network

5. Selected Protocols for the Requirements

In this section, the selected protocols (to satisfy the requirements given in Section 4 as much as possible) are discussed. The view of the protocol stacks at the key elements in the network is illustrated in Figure 3.

For the inter-vehicle communications, CAN [5] is used between on-board equipment deployed in the vehicle. Although most of the requirements listed in Table 1 are satisfied by the CAN protocol at the physical layer, high speed communication at 1Mbps rate requires a relatively short distance cabling (<40m) between on-board equipment, as well as a very low rate background traffic. CAN protocol also works closely coupled with a higher level protocol CANopen. This protocol eases the application development for devices connected together via CAN physical layer.

For roadside communications, DSRC [6] is selected to be the underlying protocol. It is based on some modifications to IEEE 802.11a modulation and IEEE 802.11 MAC layer. Unfortunately, this protocol (in its current state) can not offer a bounded delivery latency guarantee under varying channel load and high mobility conditions. Therefore, additional precautions have to be deployed in software, at least to warn the user about the times when delay requirements are voided. This protocol will be running on both on-board equipment and roadside devices. However, roadside equipment might be implementing only the basic service portion of the DSRC, depending on their hardware limitations.

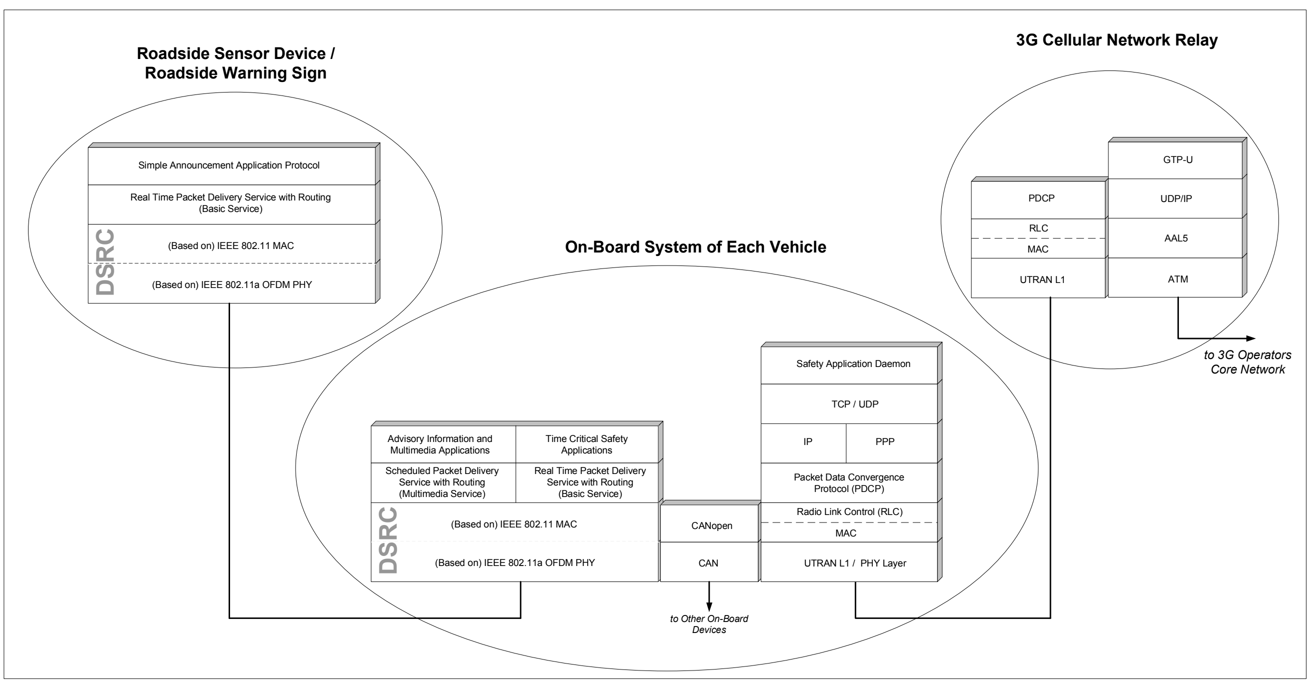

Figure 3. Protocol stacks at the key elements of the vehicular safety network

Backhaul network design is selected to have service from a UMTS network [9]. Therefore the UMTS terminal connected to the CAN bus introduces a new protocol stack to the on-board computer, which interfaces the on-board system to the Internet.

6. A Primitive Performance Evaluation

In this section, the proposed design is evaluated under a typical basic scenario to see if the requirements of the network are satisfied with the given protocol selections.

A typical roadside scenario is selected to be as follows. Let us consider a drawbridge with three-lanes in each direction. At some time, there happens to be approximately 10 vehicles in each direction within the 1000 meter vicinity of the bridge. This implies that the vehicles have to relay the messages approximately three hops away to let the far most vehicle to hear it. Right after an abrupt maneuver by a careless driver, a warning message has to be relayed to all 10 vehicles traveling on the same direction, as illustrated in Figure 4.

Let us further assume that DSRC can deliver the basic roadside channel rate of 1Mbps to the safety application with 50% efficiency. Also, relaying of this information at each hop will roughly halve the effective throughput of the wireless link. Therefore the rate at which the far most vehicle can hear the warning message is:

$$500\text{Kbps} \cdot \tfrac{1}{2} \cdot \tfrac{1}{2} = 125\text{Kbps}$$

Assuming such a warning message can be constructed in a 1Kbyte packet, it will take $125\text{Kbps}/8\text{Kbps} \cong 64\text{ms}$ to transmit this packet all the way back to the far most car. Assuming even a 10 ms additional delay for propagation and multipath fading will keep the latency (74ms) under 100ms requirement limit, as given in Section 4.

However, this rough calculation did not take into account the following two important factors:

- Collision delays due to multiple access.
- Doppler effects due to the vehicular mobility.

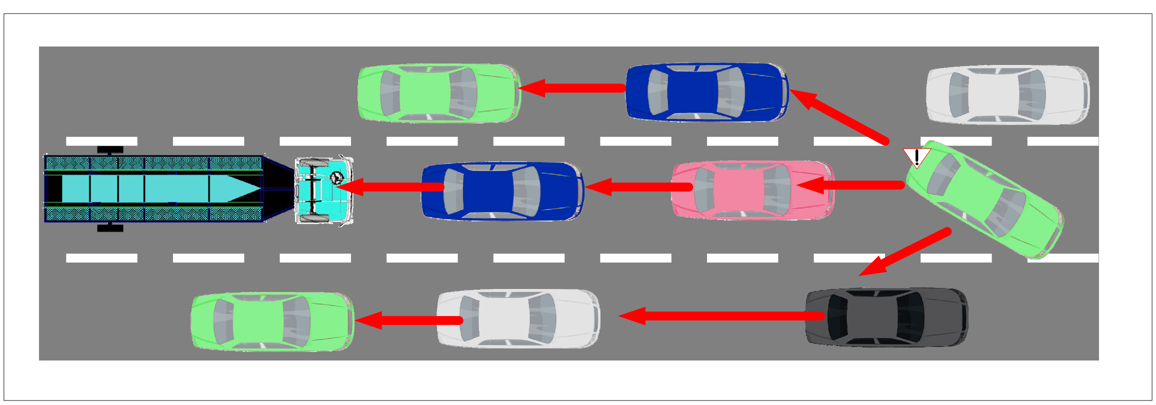

Figure 4. A typical roadside scenario for basic performance evaluation purposes

An early analysis of DSRC as given in [10], demonstrates that the performance degradation is significant when high mobility is observed. Also, in the same study throughput is observed to suffer more from high density of vehicles, as compared to the latency.

7. Conclusion and Future Work

In this paper, a high level design for vehicular safety networks is realized. During the design process, basic services that must be supported are first determined. Then, the conceptual network design is presented for those set of services. Following, the requirements of the vehicular safety networks are investigated, given the challenges of such a network. Finally, the protocol choices made to satisfy the requirements are explained and a primitive performance evaluation is given.

Field of the vehicular safety networks are slowly advancing with the increasing demand from the automotive industry. So far as the network requirements are concerned, a low latency link protocol supporting high speed vehicles is still needed before we can start seeing practical implementations of vehicular safety networks on roads.

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