Introduction to Intelligent Vehicles
[7. Connectivity]

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Outline

- Dedicated Short-Range Communications (DSRC)
  - **Basics**
  - Protocol Stack
  - Applications
  - Pilot Deployments
  - Challenges
- Cellular Vehicle-to-Everything (C-V2X)
- From ACC to CACC

DSRC

- Dedicated Short-Range Communications (DSRC)
  - Ad hoc networking technology that allows vehicles to communicate with
    - Each other
    - Roadside unit
    - Bicycle
    - Pedestrian
    - Train
  - Commonly referred to as V2X
  - IEEE portions: Wireless Access in Vehicular Environments (WAVE)
- Now in some deployment after years of research

Communication Advantages

- Advantages
  - Much more precise data exchanged
  - Longer range = a few hundred meters
  - Communication with non-nearest neighbors
  - Some non-line-of-sight capability
  - 360 degrees with one device
- Disadvantages
  - Dependent on other vehicles
- DSRC and sensors are complementary

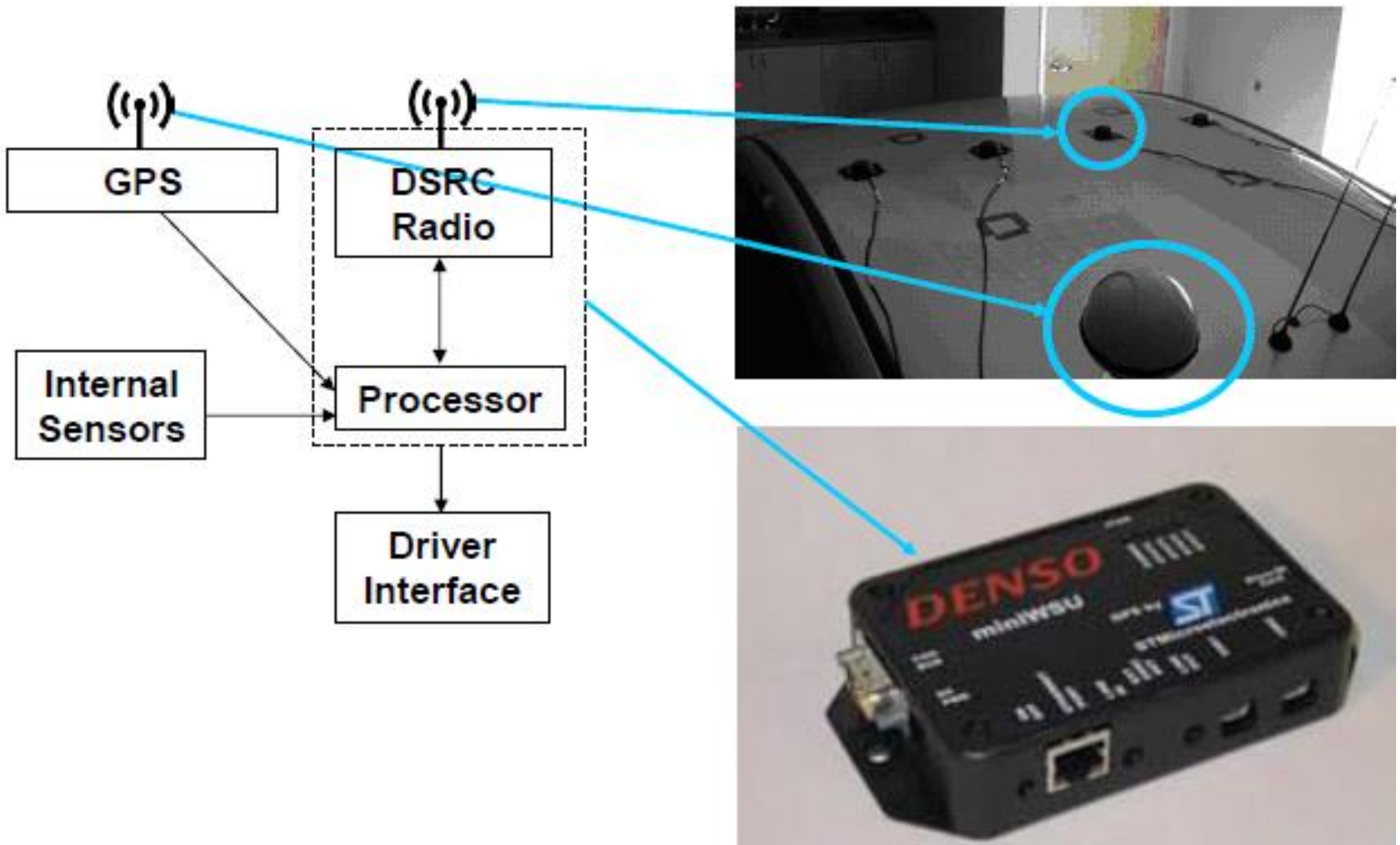
DSRC-Based ACC?

- What is Adaptive Cruise Control?
  - Adjust vehicle speed to maintain a safe distance from the vehicle ahead
- How does ACC work?
  - **Sense** (?) the distance from the vehicle ahead (also consider the speed itself)
  - Decide if it is safe
  - Maintain a safe distance from the vehicle ahead or brake if needed
- How do you think?

Current Deployment

- Toyota and Lexus (several models)
  - Japan, since October 2015
- General Motors and Cadillac CTS
  - US and Canada, since March 2017
- Volkswagen announced deployment in EU starting 2019
- EU Car2Car Communications Consortium, representing many automakers, sets broad deployment target for 2019
- US National Highway Traffic Safety Administration (NHTSA) is pursuing a regulation to require DSRC in new vehicles
- In November 2020, US Federal Communications Commission reallocates all DSRC's spectrum for other uses

Prototype



Example of DSRC Prototype System
Many suppliers are in this space

http://comsocscv.org/docs/20140611-Toyota-Kenney.pdf

V2V Safety Concept

Concept

- Each vehicle sends Basic Safety Messages (BSM) frequently in all directions
- Receiving vehicles assess collision threats
- If there is a threat, warn driver or take control of the vehicle

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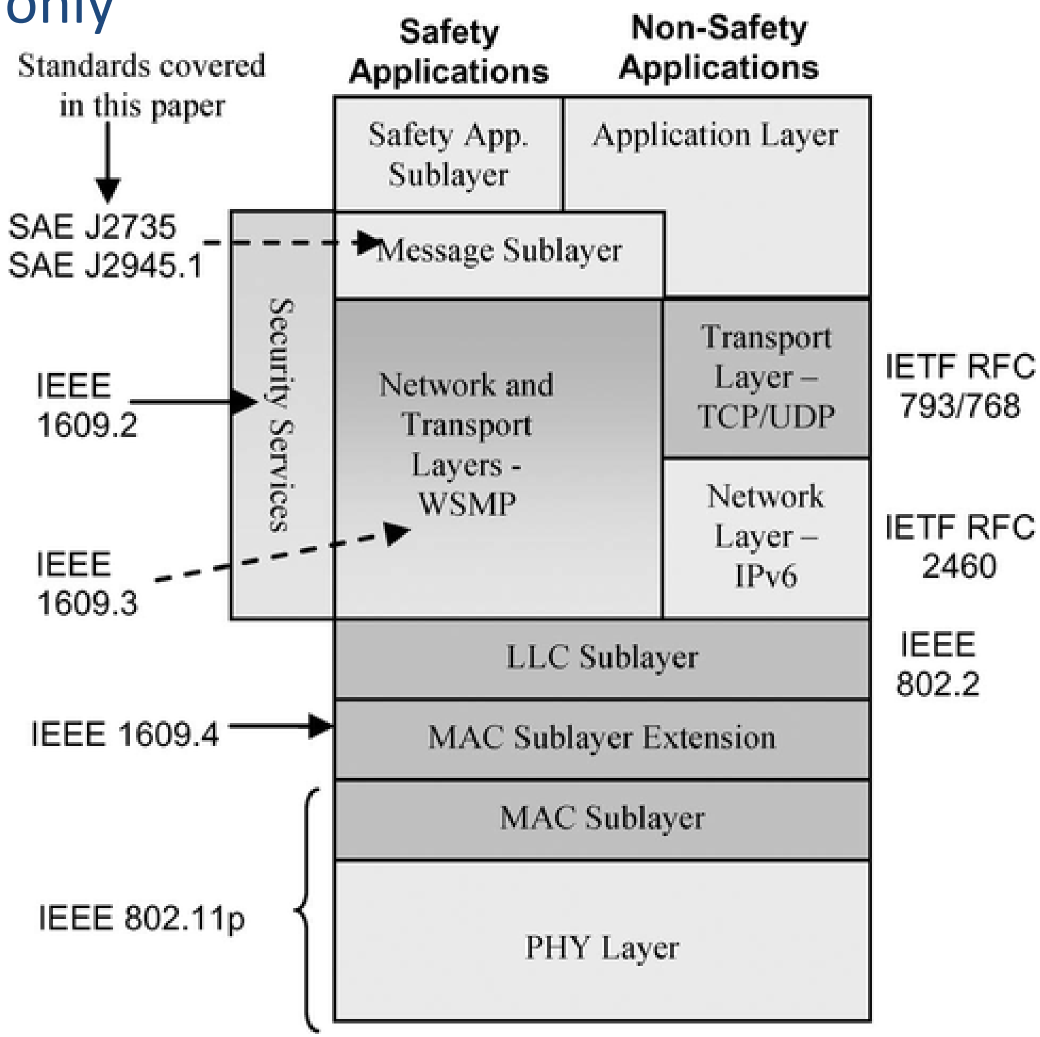
Protocol Stack

- This is US only



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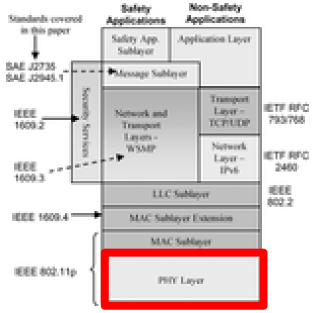
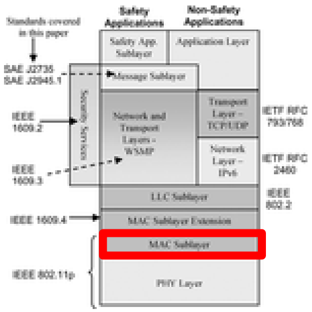
Physical Layer



- ❑ Standardized within IEEE 802.11 (802.11p)
  - ➢ Somewhat dated standard, but feasibility for high speed/mobility is proven
  - ➢ 5.9 GHz band in US and EU
  - ➢ 10 MHz channels
- ❑ Similar to IEEE 802.11a (OFDM) PHY
  - ➢ Tighter transmit "spectral mask" than 802.11a
- ❑ Used in US, EU, and Japan
  - ➢ Under consideration in many other countries
- ❑ 3GPP is developing competing "LTE V2X" standard
  - ➢ Not interoperable with DSRC
  - ➢ China seems to be interested
  - ➢ Direct device-to-device link (not normal LTE)

MAC Sublayer

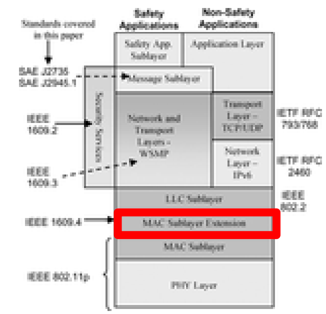


- ❑ Also standardized within IEEE 802.11
- ❑ Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)
  - ➢ "Listen before talk"
  - ➢ Random wait after busy period
- ❑ Main differences from normal Wi-Fi
  - ➢ Wi-Fi LAN uses Access Point (AP) structure
  - ➢ DSRC operates "outside the context of a Basic Service Set (BSS)"
    - No AP
  - ➢ MAC is ad hoc
  - ➢ Less delay in establishing communication

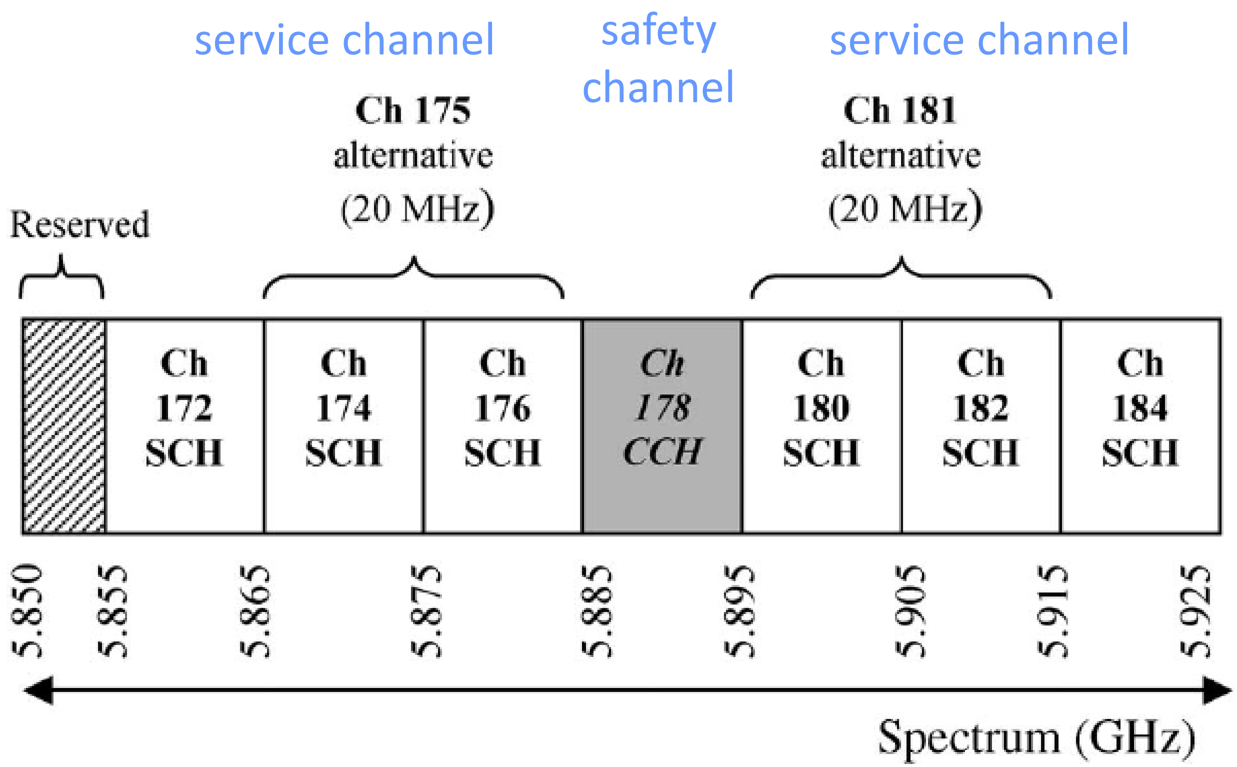
Business Implication of PHY and MAC

- One objective of IEEE 802.11p amendment was to change as little as possible
  - Encourage Wi-Fi silicon vendors to support 802.11p WAVE in standard products

MAC Sublayer Extension (IEEE 1609.4)



- **Objective**
  - Multiplex one radio effectively among multiple channels



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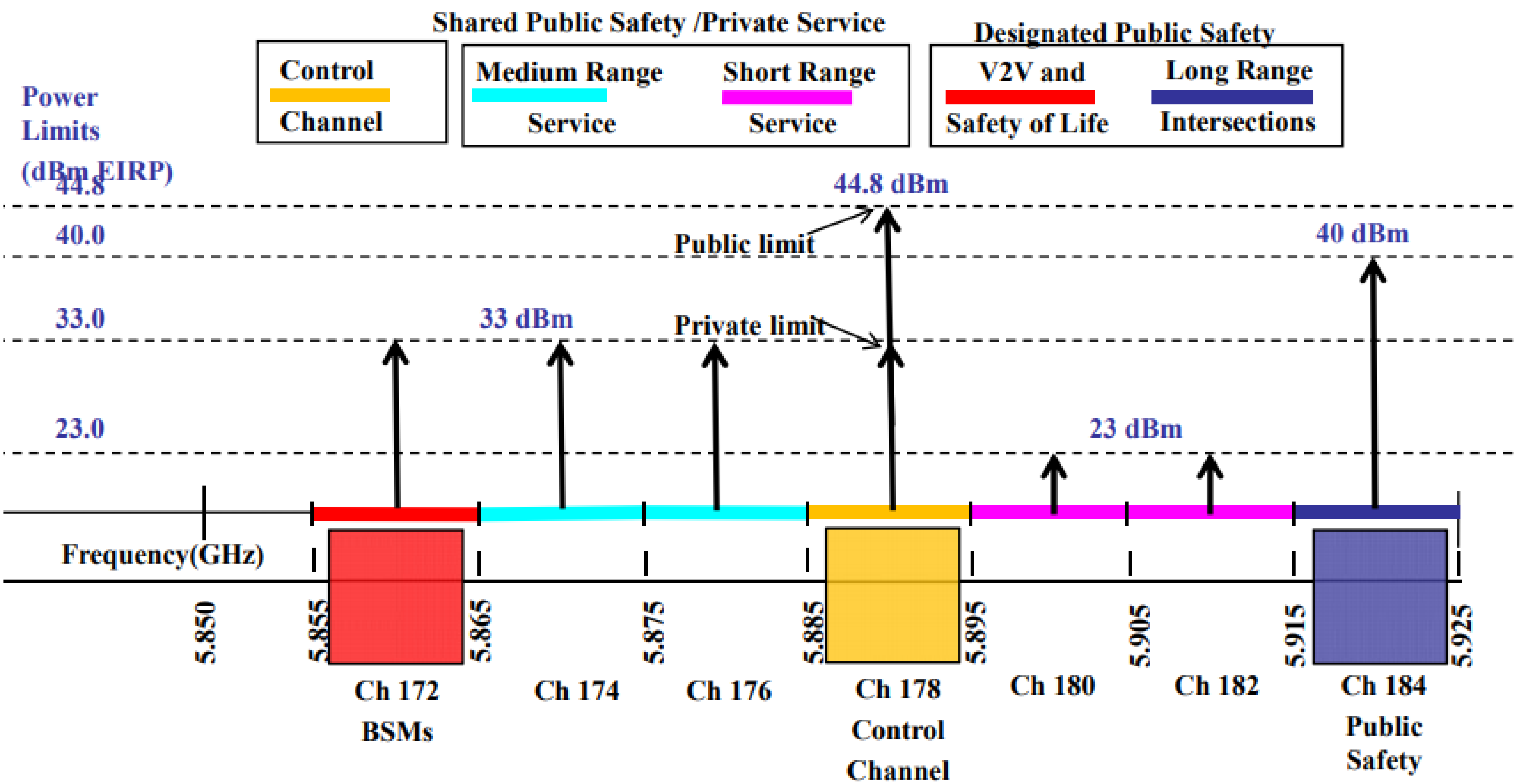
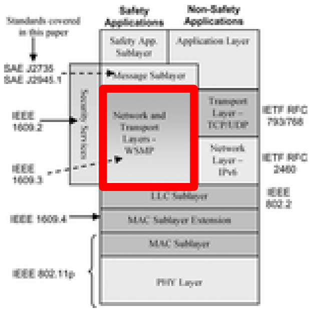
Updated DSRC Spectrum



Networking Services (IEEE 1609.3)

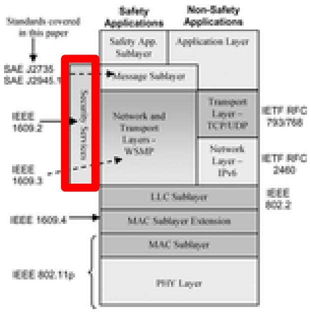


- Two protocols
  - WAVE Short Message Protocol (WSMP)
    - Packets of WSMP are referred to WAVE Short Messages (WSMs)
  - WAVE Service Advertisement (WSA)
    - Sent on Control Channel to indicate services available on Service Channels
- Key parameter: Provider Service ID (PSID)
  - In WSMP, identify the service that the WSM payload is associated with
    - A device creates a list of PSIDs that have active receive processes at higher layers
    - When a WSM arrives, if the PSID matches one of those on the list, the WSM payload is forwarded to that process
  - In WSA, indicate the type of service being advertised
  - In security certificate, demonstrate authority to send a given message

Why Not IP?

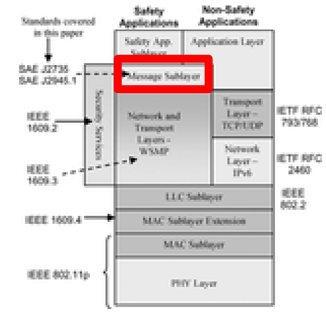
- The Internet Protocol (IP) has become the default Layer 3 protocol in many networks
  - Connect to the public Internet
  - Find a path to a node anywhere, based only on its public IP address
  - Achieve connectivity via a set of highly successful IP routing protocols
  - A minimum of 52 bytes for a UDP/IPv6 packet
- In the vehicular environment, many packets are sent directly over the air from the source to the destination
  - Routing is less of an issue for 1-hop transmissions
  - The minimum WSM overhead is 5 bytes
    - Even with options and extensions, it will rarely exceed 20 bytes

Security (IEEE 1609.2)



- **Authentication**
  - Shows sender is authorized, and data is not altered
    - Used in broadcasts like safety messages
    - Elliptic Curve Digital Signature Algorithm (ECDSA) and Public Key Infrastructure (PKI)
- **Encryption**
  - Keeps data secret
    - Not used in broadcasts like safety messages
    - Combination of asymmetric and symmetric crypto (very common approach)
- **Security requires backend infrastructure to generate and manage certificates**
  - Security Certificate Management System (SCMS)

SAE Standards



- SAE J2735 Message Set Dictionary
  - Define syntax and semantics of messages and component elements
- SAE J2945/x Application Requirements
  - J2945/0: common application requirements
  - J2945/1: **Basic Safety Message (BSM)** application requirements
  - J2945/9: Personal Safety Message application requirements
  - Other J2945/x will follow
  - Note: application requirements are primarily for message senders
    - Power, message frequency, data accuracy, etc.

DSRC Message Types

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Message Type	Purpose
A La Carte Message	Generic message with flexible content
Basic Safety Message	Conveys vehicle state information necessary to support V2V safety applications
Common Safety Request	A vehicle uses this to request specific state information from another vehicle
Emergency Vehicle Alert Message	Alerts drivers that an emergency vehicle is active in an area
Intersection Collision Avoidance	Provides vehicle location information relative to a specific intersection
Map Data	Sent by RSU to convey the geographic description of an intersection
NMEA Corrections	Encapsulates one style of GPS corrections – NMEA style 183
Probe Data Management	Sent by RSU to manage the collection of probe data from vehicles
Probe Vehicle Data	Vehicles report their status over a given section of road; aggregated to derive road conditions
Roadside Alert	Sent by RSU to alert passing vehicles to hazardous conditions
RTCM Corrections	Encapsulates a second style of GPS corrections – RTCM
Signal Phase and Timing Message	Sent by RSU at a signalized intersection to convey the signal's phase and timing state.
Signal Request Message	A vehicle uses this to request either a priority signal or a signal preemption.
Signal Status Message	Sent by RSU to convey the status of signal requests.
Traveler Information	Sent by RSU to convey advisory and road sign types of information

DSRC BSM Part I

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Data item name, Element/Frame, and length	Description
DSRC_MessageID element, 1 byte	The first element in every message, used by the parser to determine how to parse the rest of the message
MsgCount element, 1 byte	A sequence number, incremented with each successive transmission of a **BSM** by a given vehicle, used primarily to estimate packet error statistics.
TemporaryID element, 4 bytes	A value chosen randomly and held constant for a few minutes, it helps a receiver correlate a stream of **BSMs** from a given sender.
DSecond element, 2 bytes	The current time, modulo one minute, with resolution 1 millisecond.
Latitude, Longitude 2 elements, 4 bytes each	Geographic latitude and longitude, with resolution 1/10 microdegree.
Elevation element, 2 bytes	Position above or below sea level, resolution 0.1 meter.
PositionalAccuracy frame, 4 bytes	Conveys the one-standard-deviation position error along both semi-major and semi-minor axes, and the heading of the semi-major axis.
TransmisionAndSpeed frame, 2 bytes	3 bits encode vehicle transmission (gear) setting. 13 bits convey unsigned vehicle speed, resolution 1 cm/second.
Heading element, 2 bytes	Compass heading of vehicle's motion, resolution 1/80 degree.
SteeringWheelAngle element, 1 byte	Current position of the steering wheel, resolution 1.5 degree. Clockwise rotation is a positive angle.
AccelerationSet4Way frame, 7 bytes	Provides longitudinal acceleration, lateral acceleration, vertical acceleration, and yaw rate.
BrakeSystemStatus frame, 2 bytes	Conveys whether or not braking is active on each of four wheels, also conveys the status of the following control systems: Traction Control, Anti-Lock Brakes, Stability Control, Brake Boost, and Auxiliary Brakes.
VehicleSize frame, 3 bytes	Vehicle length and width, resolution 1 cm.

DSRC BSM Part II

Data item name, Element/Frame, and length	Description
EventFlags element, 2 bytes	An optional set of bit flags, each of which can convey the occurrence of a given "event." A given event may be flagged only if a set of minimum activation criteria are met. Examples include: Hard Brake, Hazard Lights, Emergency Response Vehicle, Stop Line Violation
PathHistory frame, variable length (typically on the order of 20 bytes for a straight path and less than 100 bytes for a curved path)	Used to convey where a vehicle has been, in the form of individual data structures sometimes called "Bread Crumbs." Each bread crumb includes a prior position, and optionally time and position accuracy. **PathHistory** is useful in identifying lane level information in the absence of map data. The number of bread crumbs in a frame is a function of the degree to which the actual path can be represented in piecewise linear fashion.
PathPrediction frame, 3 bytes	Indicates the path that a sender expects to traverse. 2-byte radius of curvature and 1-byte prediction confidence.
RTCMPackage frame, variable	Conveys GPS correction data in the RTCM style. Variable length depends on number of satellites in view.

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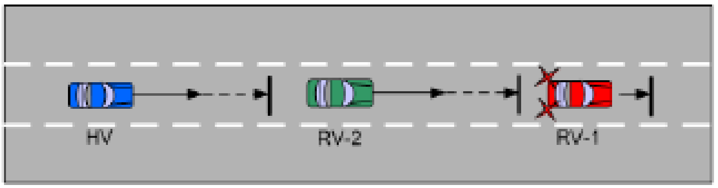
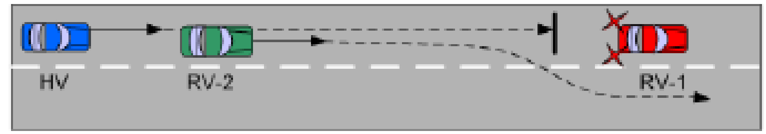
- From ACC to CACC

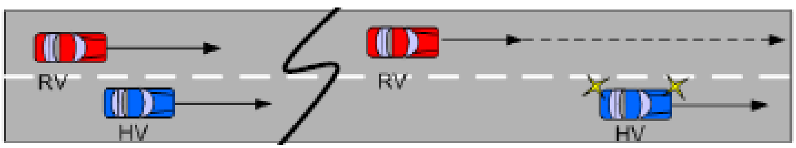
V2V Applications



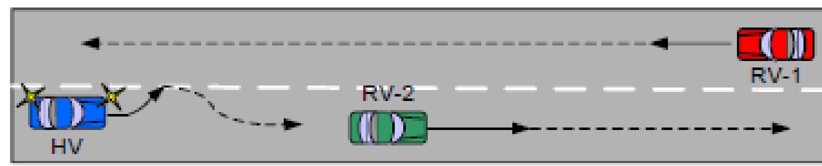
Emergency Electronic Brake Lights (EEBL)



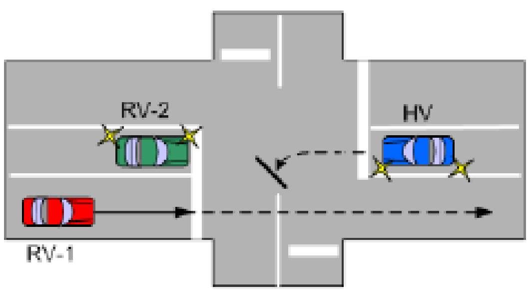
Forward Collision Warning (FCW)



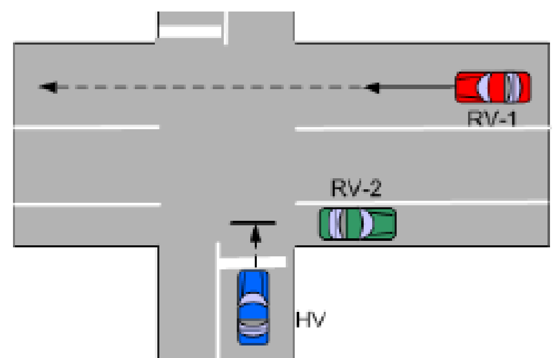
Blind Spot / Lane Change Warning (BSW / LCW)



Do Not Pass Warning (DNPW)



Left Turn Assist (LTA)



Intersection Movement Assist (IMA)

Applications from USDOT

V2I Safety

Red Light Violation Warning
Curve Speed Warning
Stop Sign Gap Assist
Spot Weather Impact Warning
Reduced Speed/Work Zone Warning
Pedestrian in Signalized Crosswalk Warning (Transit)

V2V Safety

Emergency Electronic Brake Lights (EEBL)
Forward Collision Warning (FCW)
Intersection Movement Assist (IMA)
Left Turn Assist (LTA)
Blind Spot/Lane Change Warning (BSW/LCW)
Do Not Pass Warning (DNPW)
Vehicle Turning Right in Front of Bus Warning (Transit)

Agency Data

Probe-based Pavement Maintenance
Probe-enabled Traffic Monitoring
Vehicle Classification-based Traffic Studies
CV-enabled Turning Movement & Intersection Analysis
CV-enabled Origin-Destination Studies
Work Zone Traveler Information

Environment

Eco-Approach and Departure at Signalized Intersections
Eco-Traffic Signal Timing
Eco-Traffic Signal Priority
Connected Eco-Driving
Wireless Inductive/Resonance Charging
Eco-Lanes Management
Eco-Speed Harmonization
Eco-Cooperative Adaptive Cruise Control
Eco-Traveler Information
Eco-Ramp Metering
Low Emissions Zone Management
AFV Charging / Fueling Information
Eco-Smart Parking
Dynamic Eco-Routing (light vehicle, transit, freight)
Eco-ICM Decision Support System

Road Weather

Motorist Advisories and Warnings (MAW)
Enhanced MDSS
Vehicle Data Translator (VDT)
Weather Response Traffic Information (WxTINFO)

Mobility

Advanced Traveler Information System
Intelligent Traffic Signal System (I-SIG)
Signal Priority (transit, freight)
Mobile Accessible Pedestrian Signal System (PED-SIG)
Emergency Vehicle Preemption (PREEMPT)
Dynamic Speed Harmonization (SPD-HARM)
Queue Warning (Q-WARN)
Cooperative Adaptive Cruise Control (CACC)
Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
Emergency Communications and Evacuation (EVAC)
Connection Protection (T-CONNECT)
Dynamic Transit Operations (T-DISP)
Dynamic Ridesharing (D-RIDE)
Freight-Specific Dynamic Travel Planning and Performance
Drayage Optimization

Smart Roadside

Wireless Inspection
Smart Truck Parking

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Pilot Deployment

- USDOT Connected Vehicle Safety Pilot (~2015)
  - Safety Pilot Driver Clinics
    - Assess user acceptance of the connected vehicle technology
    - Test in-vehicle wireless technology in a **controlled environment**
    - Determine how motorists respond to and benefit from the alerts and warnings
  - Safety Pilot Model Deployment
    - Install DSRC devices on 3,000 vehicles to test safety applications
    - Operate on **public streets** in an area highly concentrated with equipped vehicles
    - Include a mix of cars, trucks, and transit vehicles
    - Is led by the University of Michigan Transportation Research Institute (UMTRI)

Pilot Deployment: New York City

USDOT Connected Vehicle Pilot Deployment Program

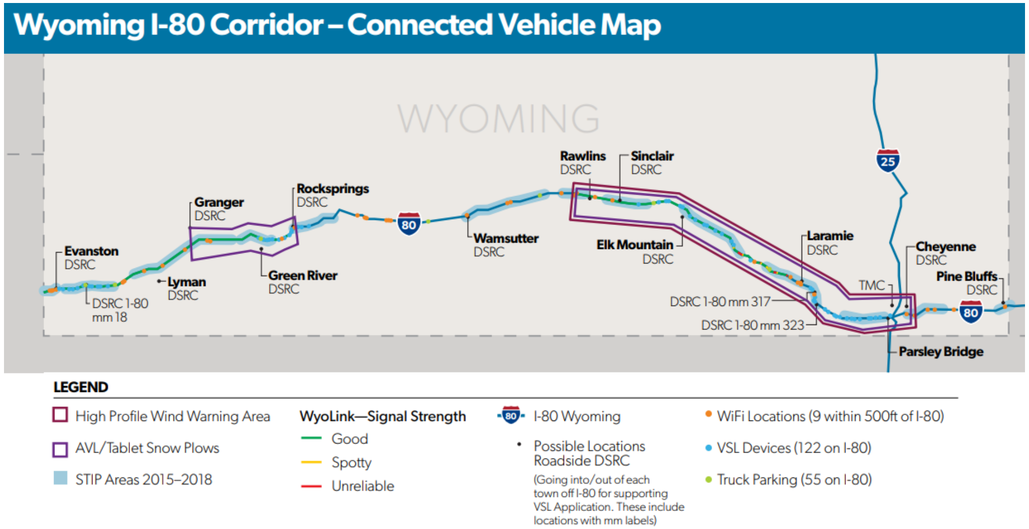
- New York City DOT Pilot
  - V2V safety applications
    - (1) Forward crash warning, (2) emergency electronic brake lights, (3) blind spot warning, (4) lane change warning, (5) intersection movement assist, and (6) vehicle turning right in front of bus warning
  - V2I safety applications
    - (1) Speed compliance, (2) curve speed compliance, (3) speed compliance in work zone, (4) red light violation warning, (5) oversize vehicle compliance, and (6) emergency communications and evacuation information
  - Deployment by numbers
    - 5,850 taxis, 1,250 MTA buses, 400 UPS vehicles, 250 NYCDOT vehicles, 250 DSNY vehicles
    - 353 roadside units at ~310 signaled intersections (Manhattan and Brooklyn)
  - Videos
    - https://www.youtube.com/watch?v=Bxu29Qbs-zI&t=45s
    - https://www.youtube.com/watch?v=_xL8vlJ5IcY&t=6s
    - https://www.youtube.com/watch?v=TWPn-Tyd3sw

Pilot Deployment: Tampa

- USDOT Connected Vehicle Pilot Deployment Program
  - Tampa-Hillsborough Expressway Authority Pilot
    - Morning backups
      - (1) End of ramp deceleration warning, (2) forward collision warning, and (3) emergency electronic brake light warning
    - Wrong-way drivers
      - (1) Wrong-way entry and (2) intersection movement assist (IMA)
    - Pedestrian safety
      - (1) Mobile accessible pedestrian signal system and (2) pedestrian in a signalized crosswalk vehicle warning
    - Transit delays
      - (1) Transit signal priority and (2) IMA
    - Streetcar conflicts
      - (1) Vehicle turning right in front of transit vehicle and (2) pedestrian in a signalized crosswalk vehicle warning
    - Traffic progression
      - (1) intelligent signal system, (2) probe data enabled traffic monitoring, and (3) IMA
    - Deployment by numbers
      - 1,600 private vehicles, 10 buses, 10 streetcars, 500+ pedestrians, and 40 roadside units
    - Video
      - https://www.youtube.com/watch?v=q1ewENzPgLo

Pilot Deployment: Wyoming

- USDOT Connected Vehicle Pilot Deployment Program
  - Wyoming DOT Pilot
    - Applications
      - (1) Forward collision warning, (2) infrastructure-to-vehicle situational awareness, (3) work zone warning, (4) spot weather impact warning, and (5) distress notification
    - Deployment by numbers
      - 75 roadside units, 400 vehicles including fleet vehicles and commercial trucks
    - Video
      - https://www.youtube.com/watch?v=9TPluh2dm20



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Challenges: Spectrum Sharing

- Wi-Fi and cellular networks need more spectrum
- Licensed users are "primary"
  - No "harmful interference" from unlicensed users
  - Licensed: defense, aviation, weather, satellite
  - Unlicensed National Information Infrastructure (U-NII): mostly Wi-Fi
- US Congress and Federal Communications Commission (FCC) want to open 5 GHz spectrum for U-NII
  - Main goal, open 80 and 160 MHz channels for IEEE 802.11ac
  - Two proposals from Wi-Fi industry
    - One is favored by DSRC community
    - The other is unacceptable

Challenges: Scalability

- ❑ Will it work?

- ❑ Aspects of scalability
  - ➢ Processing resource: collision threat assessment and per-message security
  - ➢ Wireless channel resource
  - ➢ Security infrastructure

Challenges: Security and Privacy

- Goals
  - Receivers need to trust information they get
  - We need to preserve privacy of drivers
  - Costs need to be controlled
- Two principal areas
  - Per-message security
    - Attach digital signature and certificate to each BSM
      - Signature: 32 bytes
      - Certificate: ~70-80 bytes
      - BSM itself: ~60-70 bytes
      - Lower layer: ~80 bytes
  - Security infrastructure

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- ❑ **Cellular Vehicle-to-Everything (C-V2X)**
- ❑ From ACC to CACC

5G Automotive Association

- **Working groups**
  - Use cases and technical requirements
  - System architecture and solution development
  - Evaluation, testbeds, and pilots
  - Standards and spectrum
  - Business models and go-to-market strategies

Technology

- C-V2X is initially defined as LTE V2X in 3GPP Release 14
  - Device-to-device is direct communication without necessarily relying on network involvement for scheduling
    - Vehicle-to-Vehicle (V2V)
    - Vehicle-to-Infrastructure (V2I)
    - Vehicle-to-Pedestrian (V2P)
  - Device-to-cell tower is another communication link
    - Enable network resources and scheduling
    - Utilize existing infrastructures
  - Device-to-network uses traditional cellular links to enable cloud services
    - Vehicle-to-Network-based communication (V2N)
- It can operate without a SIM and without network assistance

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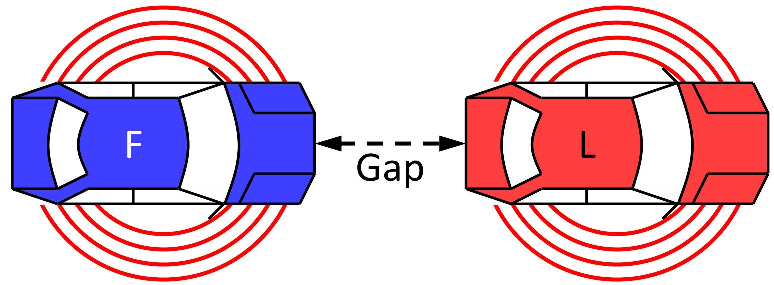
Adaptive Cruise Control (ACC)

- What is ACC?
  - Adjust vehicle speed to maintain a safe distance from the vehicle ahead
- Why is ACC helpful?
  - Maintain a safe distance and avoid a collision
- When is ACC working?
- Where is ACC working?
- Who develops ACC?
- How does ACC work?
  - Sense the distance from the vehicle ahead (also consider the speed itself)
  - Decide if it is safe
  - Maintain a safe distance from the vehicle ahead or brake if needed

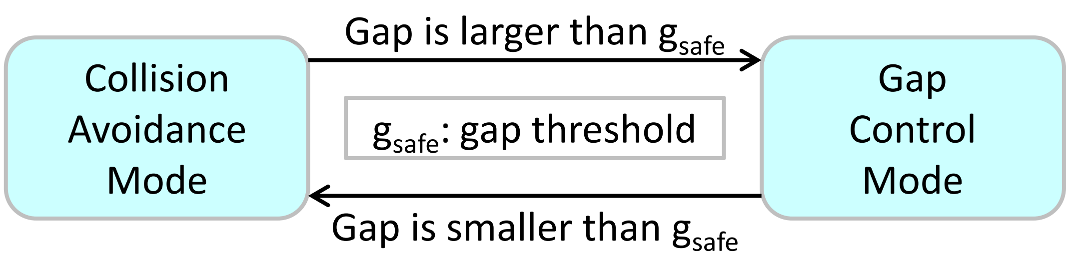
Cooperative Adaptive Cruise Control (CACC)

❑ Two simplified CACC modes

- Gap control mode
  - The following vehicle (F) decides acceleration based on the gap, speeds, and accelerations of the two vehicles



- Collision avoidance mode
  - The following vehicle (F) decelerates with its maximum deceleration



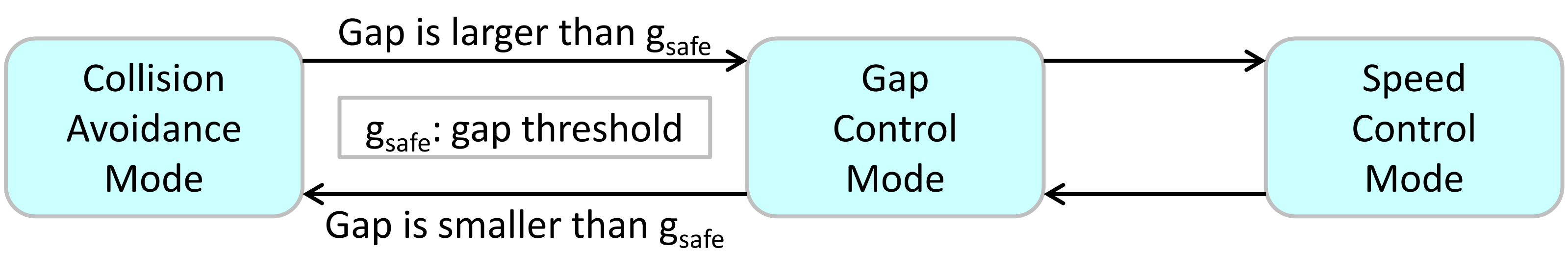
❑ Information and its sources

- Gap, speeds, and accelerations
- Camera, radar, lidar, and communication messages (e.g., 10Hz)

Random Stuff

❑ A more complicated model

- One more mode: speed control mode



❑ Math behind it

- $g_{safe} = 0.1\,v + (v^2 / 2D) - (v'^2 / 2D') + 1.0$
  - 0.1: CACC message/task period
  - v: velocity of the following vehicle
  - v': velocity of the leading vehicle
  - D: maximum deceleration of the following vehicle
  - D': maximum deceleration of the leading vehicle
  - 1.0: minimum gap requirement

Benefits

- ACC systems, like human drivers, may not exhibit string stability [Wikipedia]

- With more information, CACC can perform vehicle-following better
  - CACC may also consider multiple leading vehicles

Q&A