

# **Vehicular Networks**

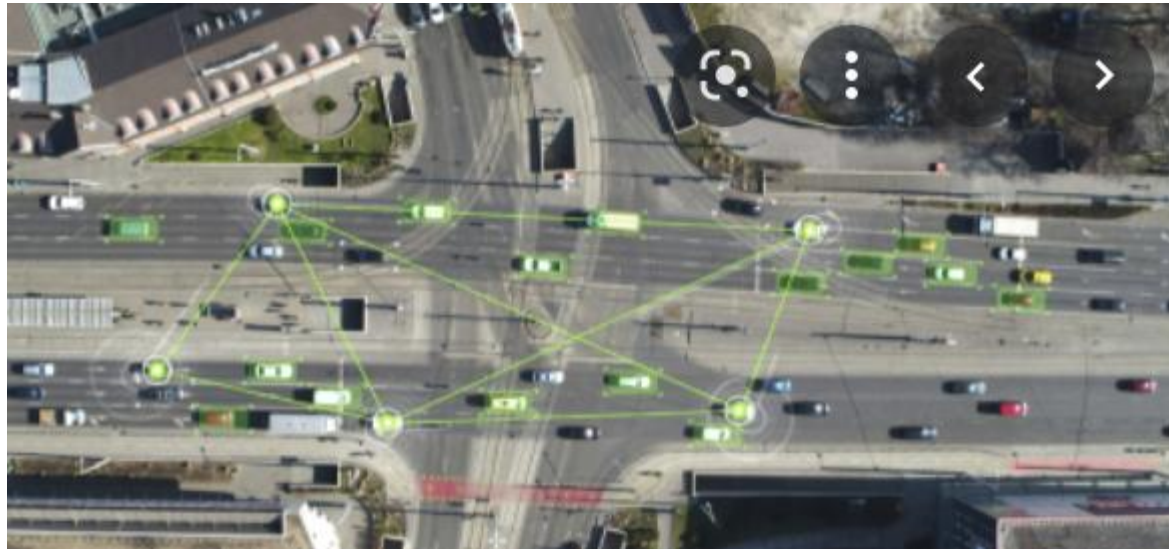
**Mestrado em Engenharia de  
Computadores e Telemática**

**2024/2025**

# Vehicular Networks

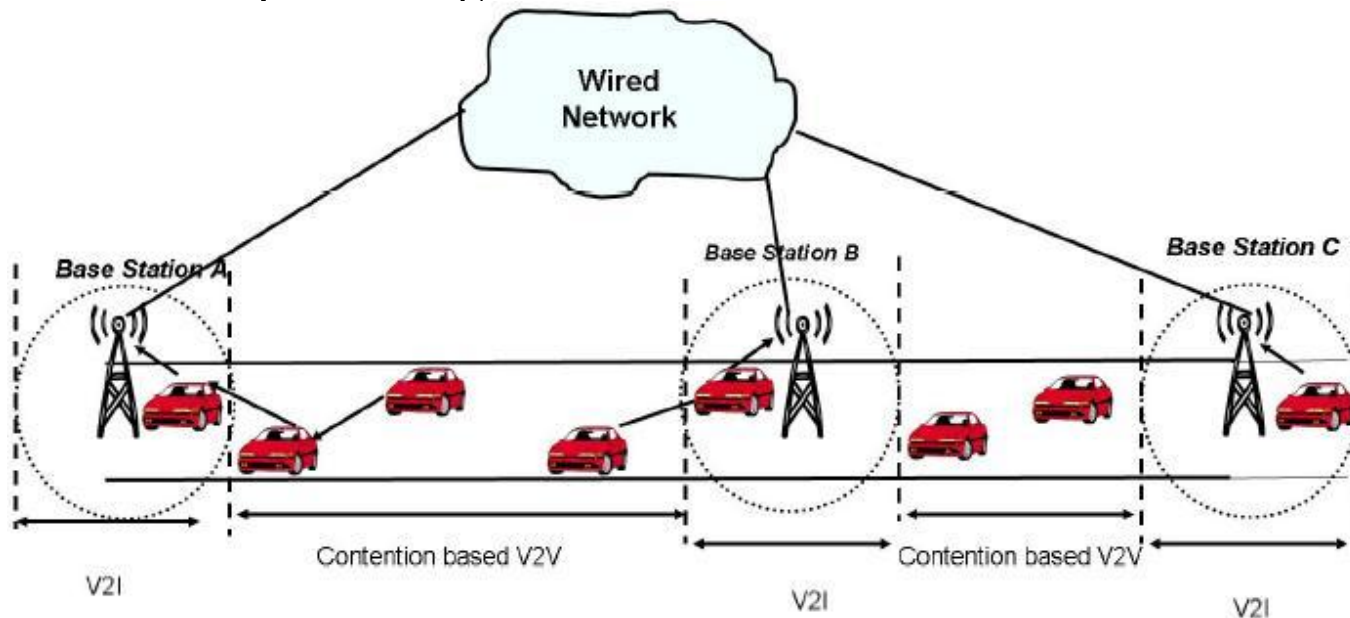
Vehicular networks can provide

- Safety
- Efficiency
- Traffic and road conditions
- Road signal alarm
- Local information



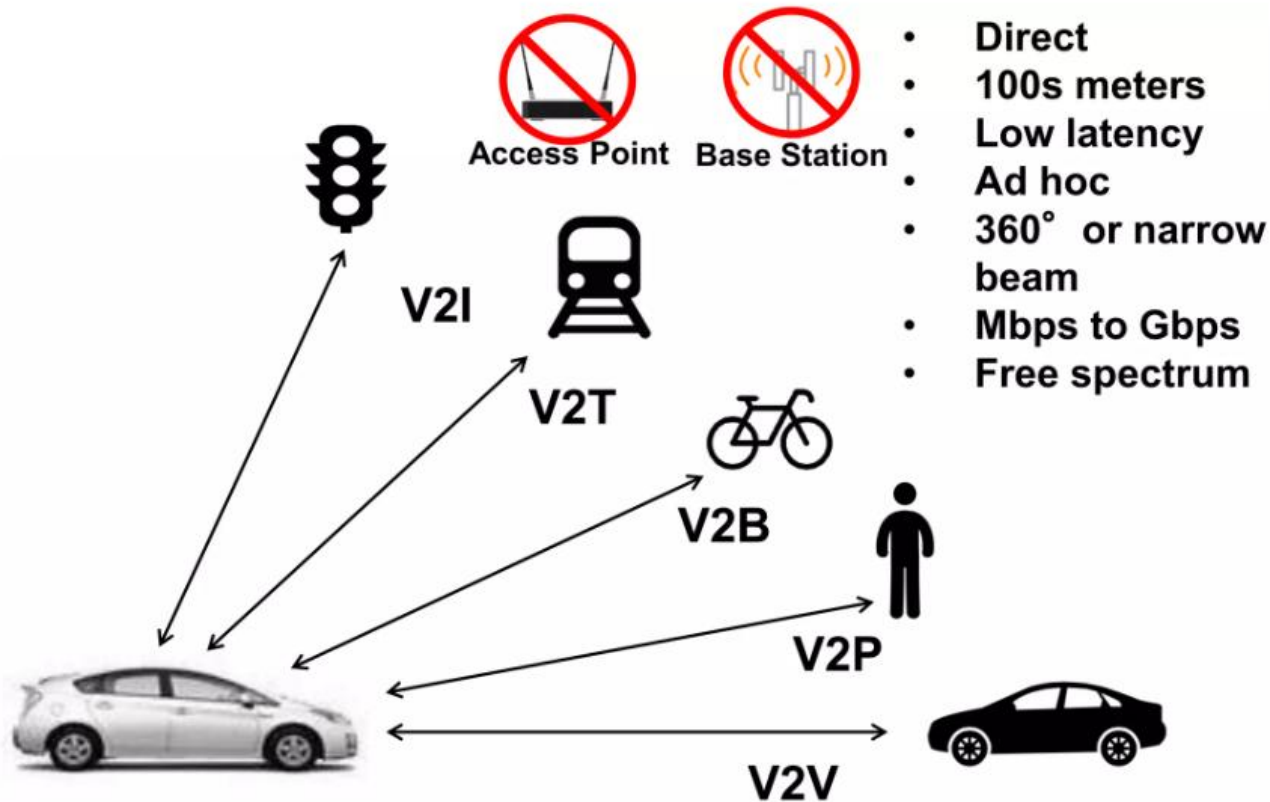
# Vehicular networks

- Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication will be possible
- On-board units in vehicles to perform communication, routing and application
- Road-side infrastructure units (RSUs), named network nodes, are equipped with on-board processing and wireless communication modules

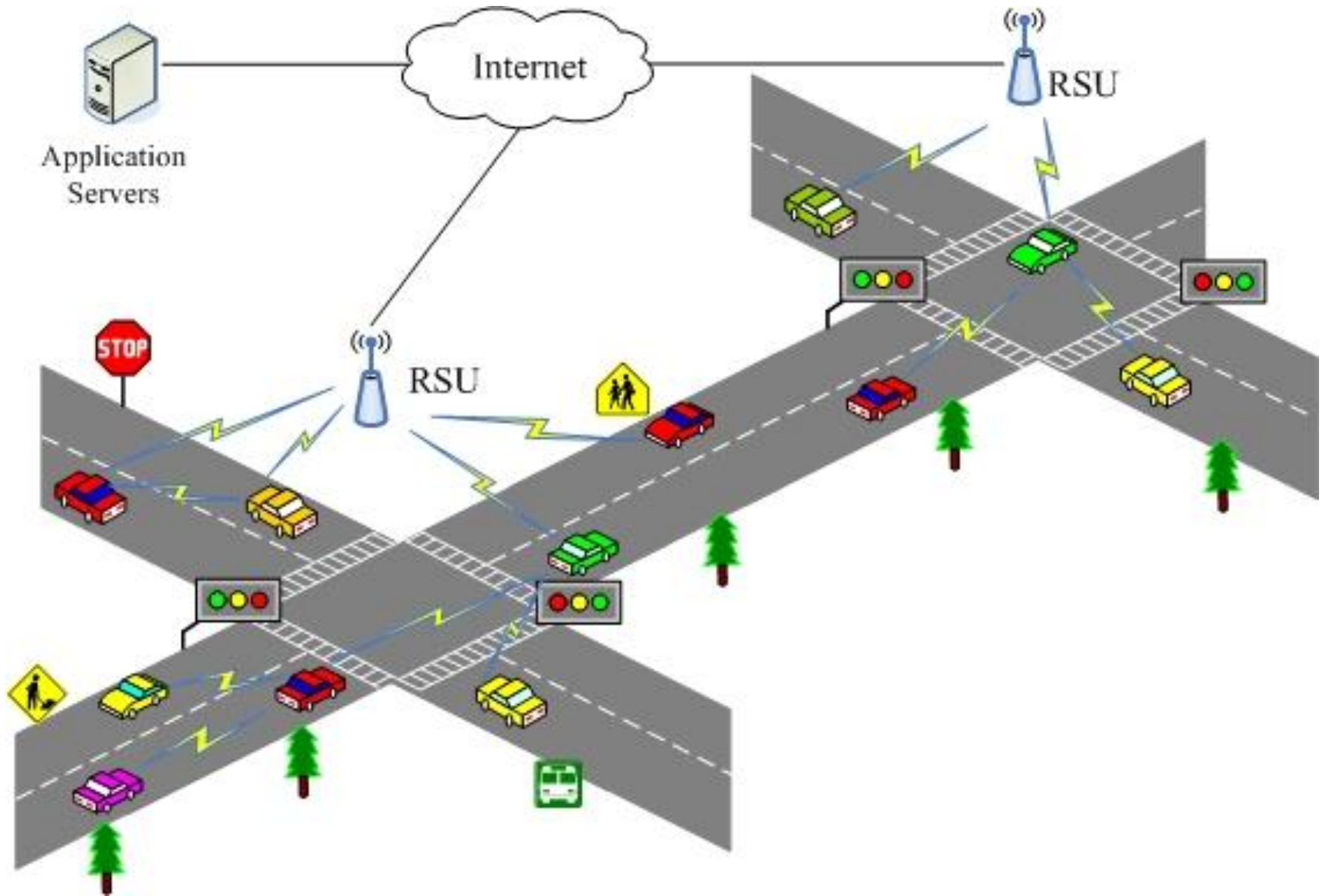


# Vehicle to Everything Communication

- Initially, before 5G

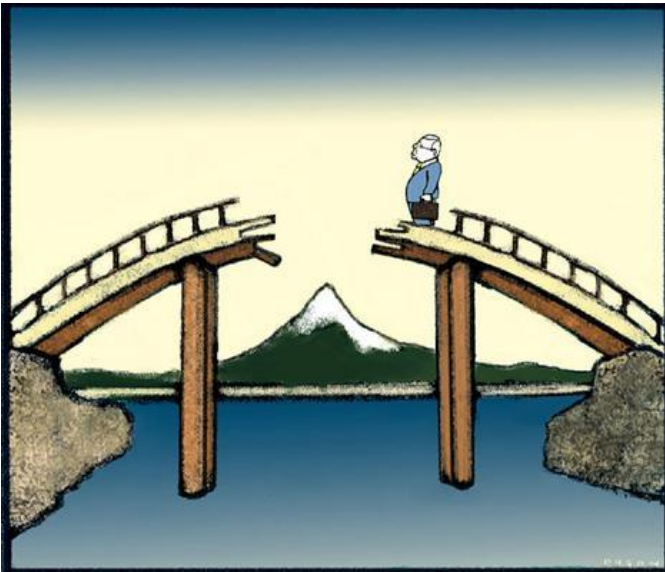
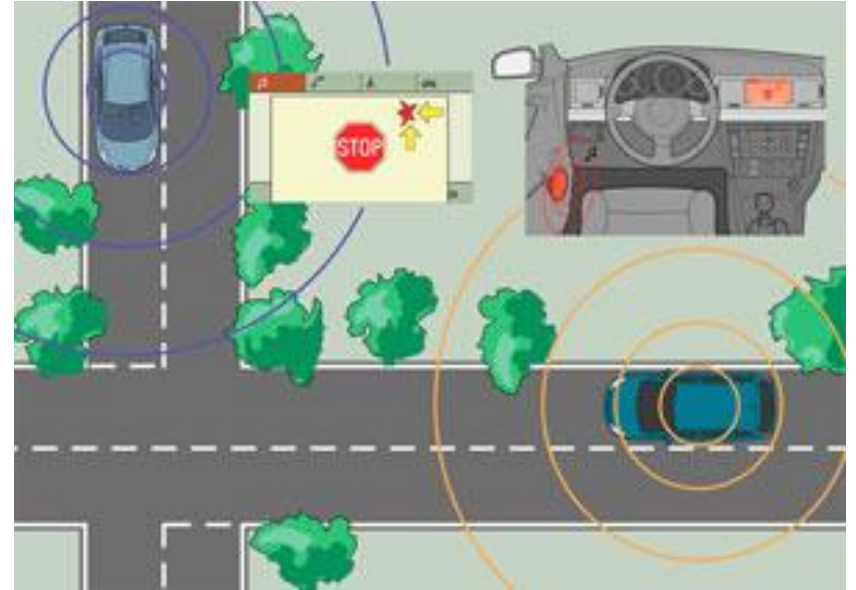
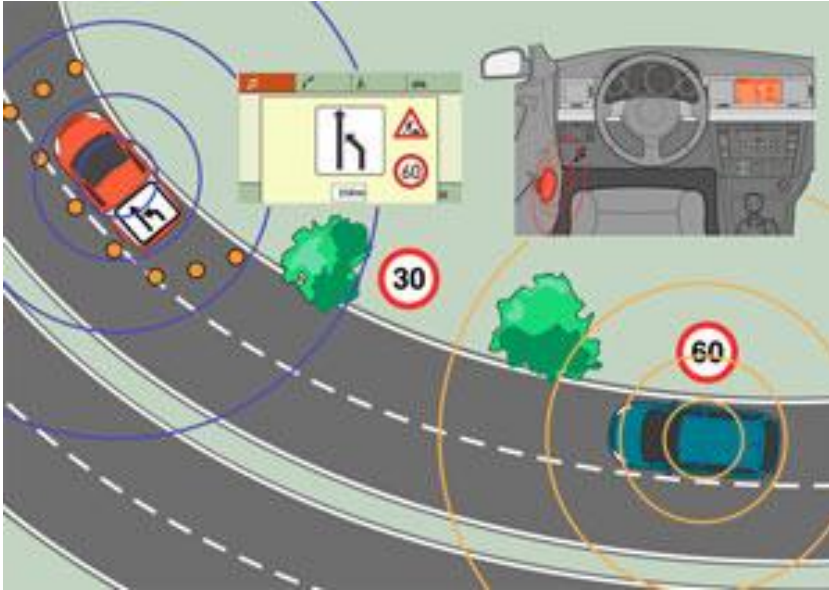


# Vehicular networks





# Warnings

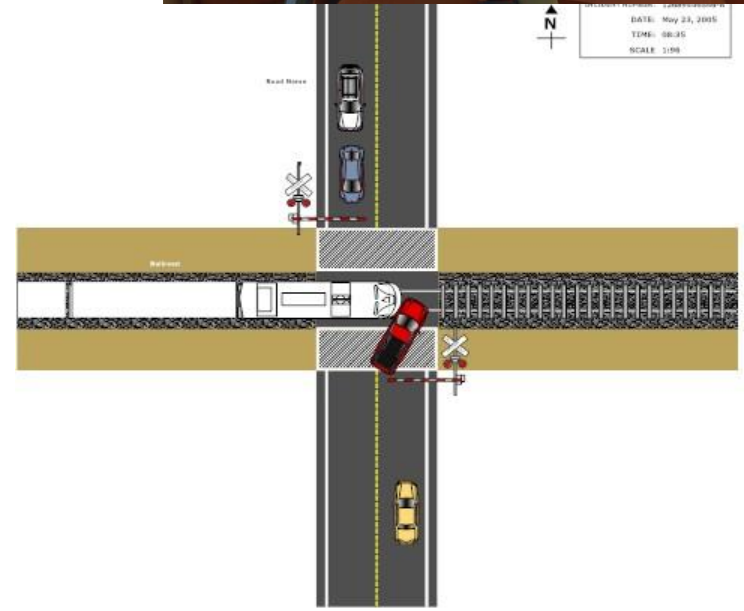
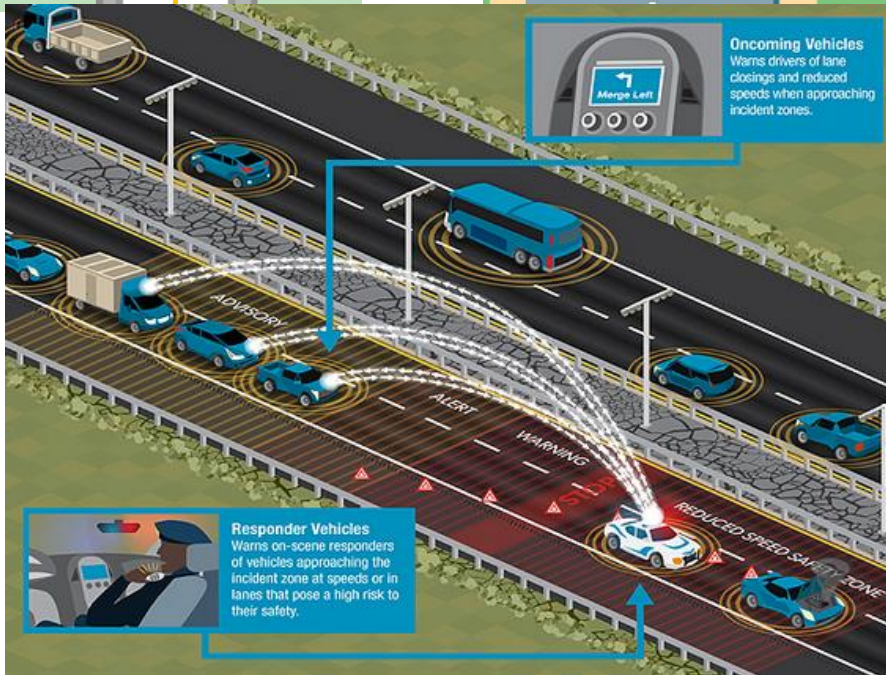
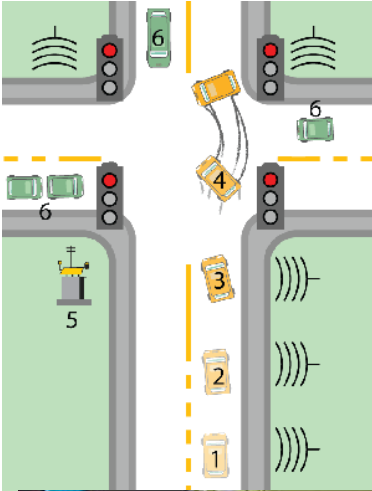


# Traffic and road conditions



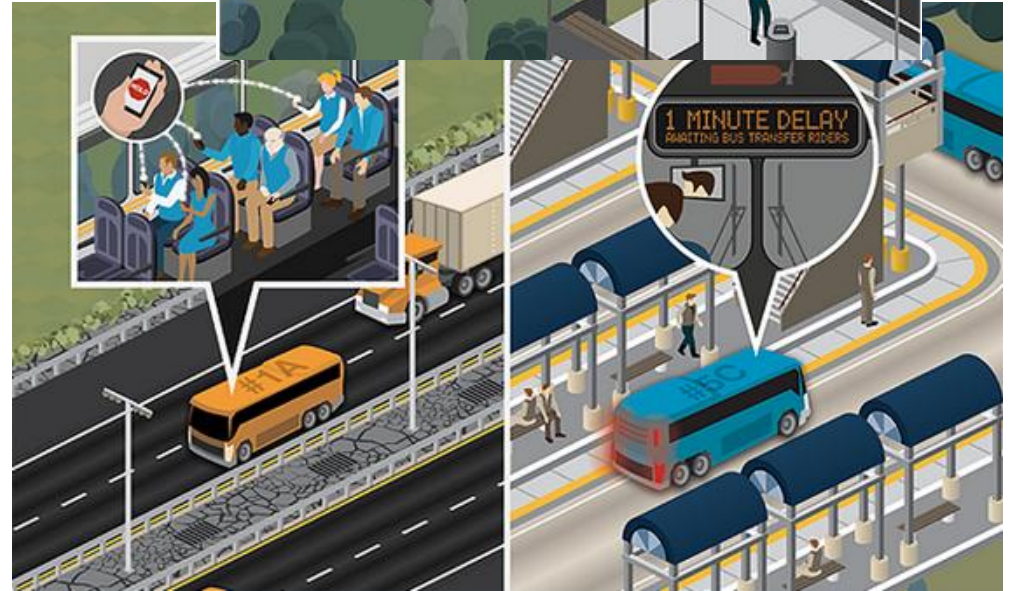
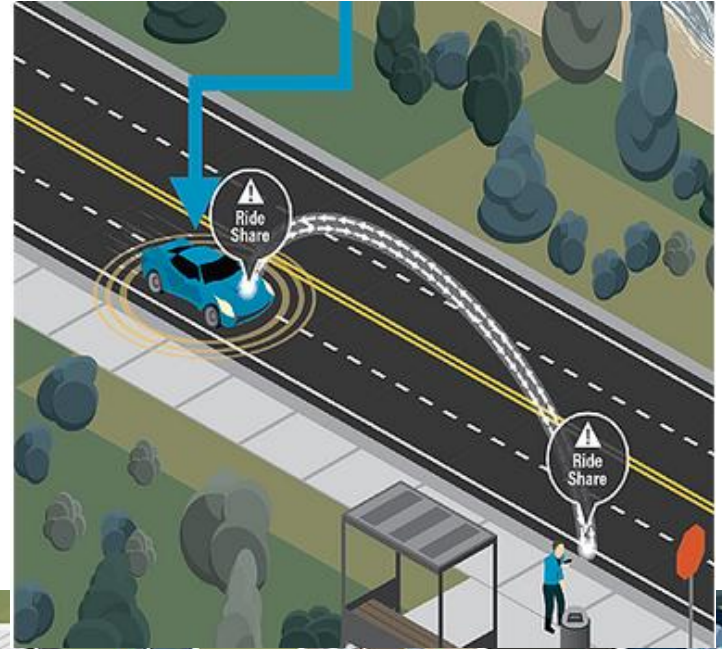


# Safety





# Efficiency

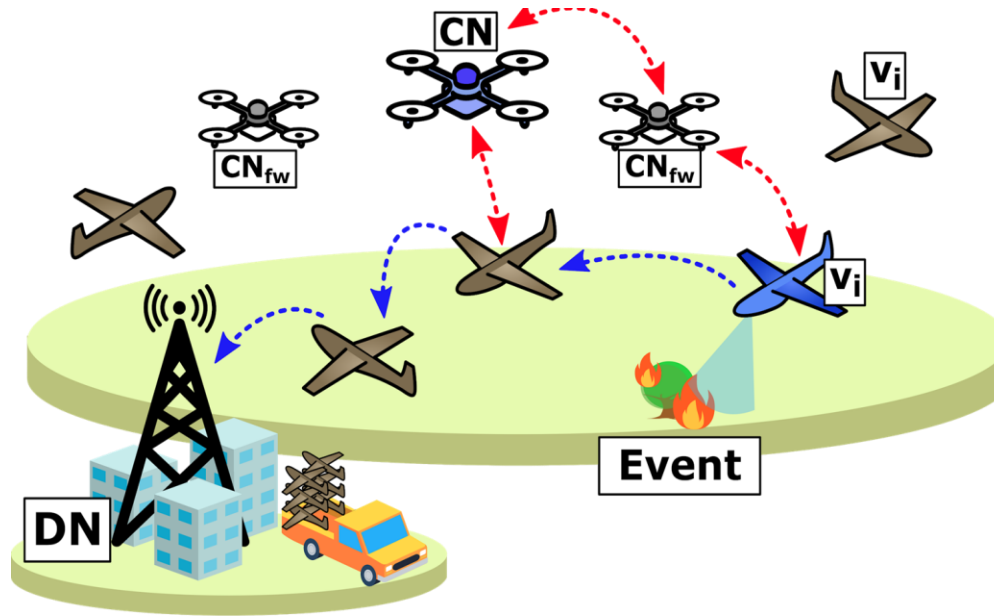




# SelfDriving

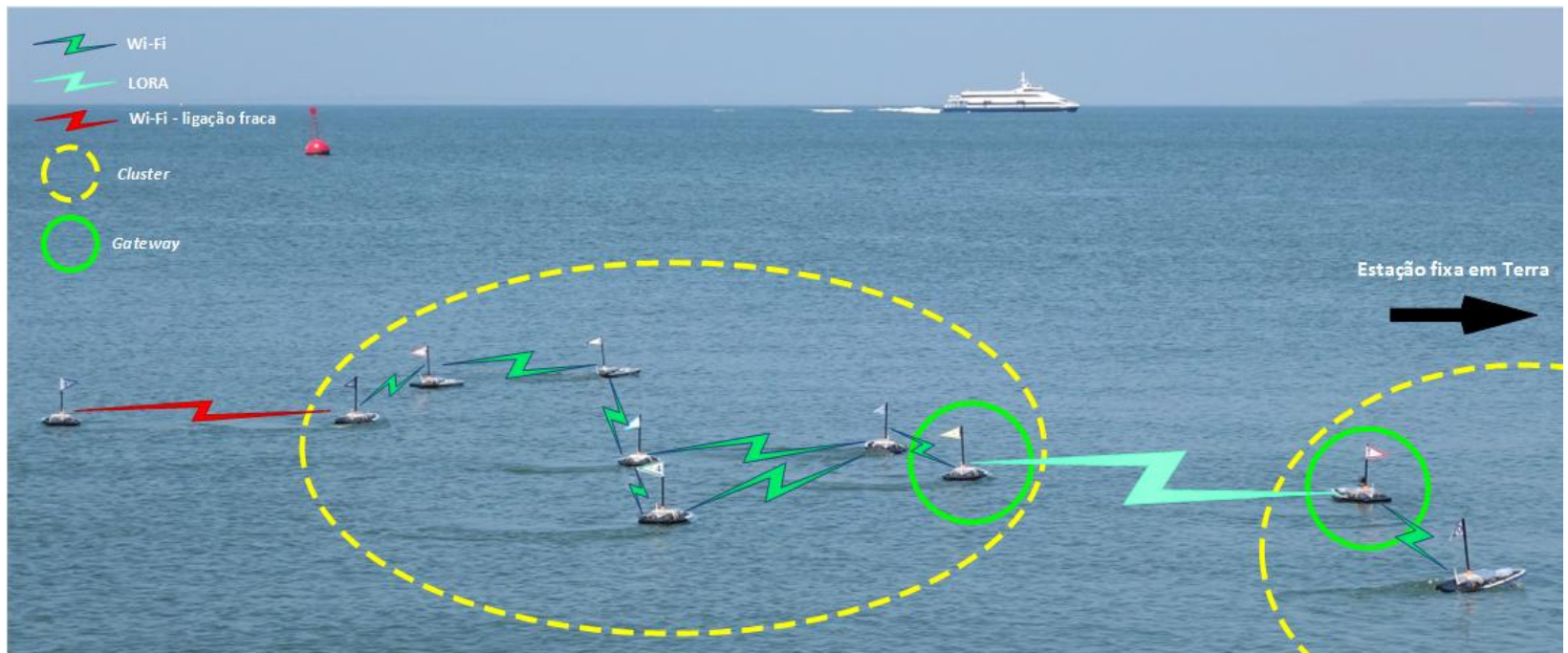


# Other types of vehicular networks





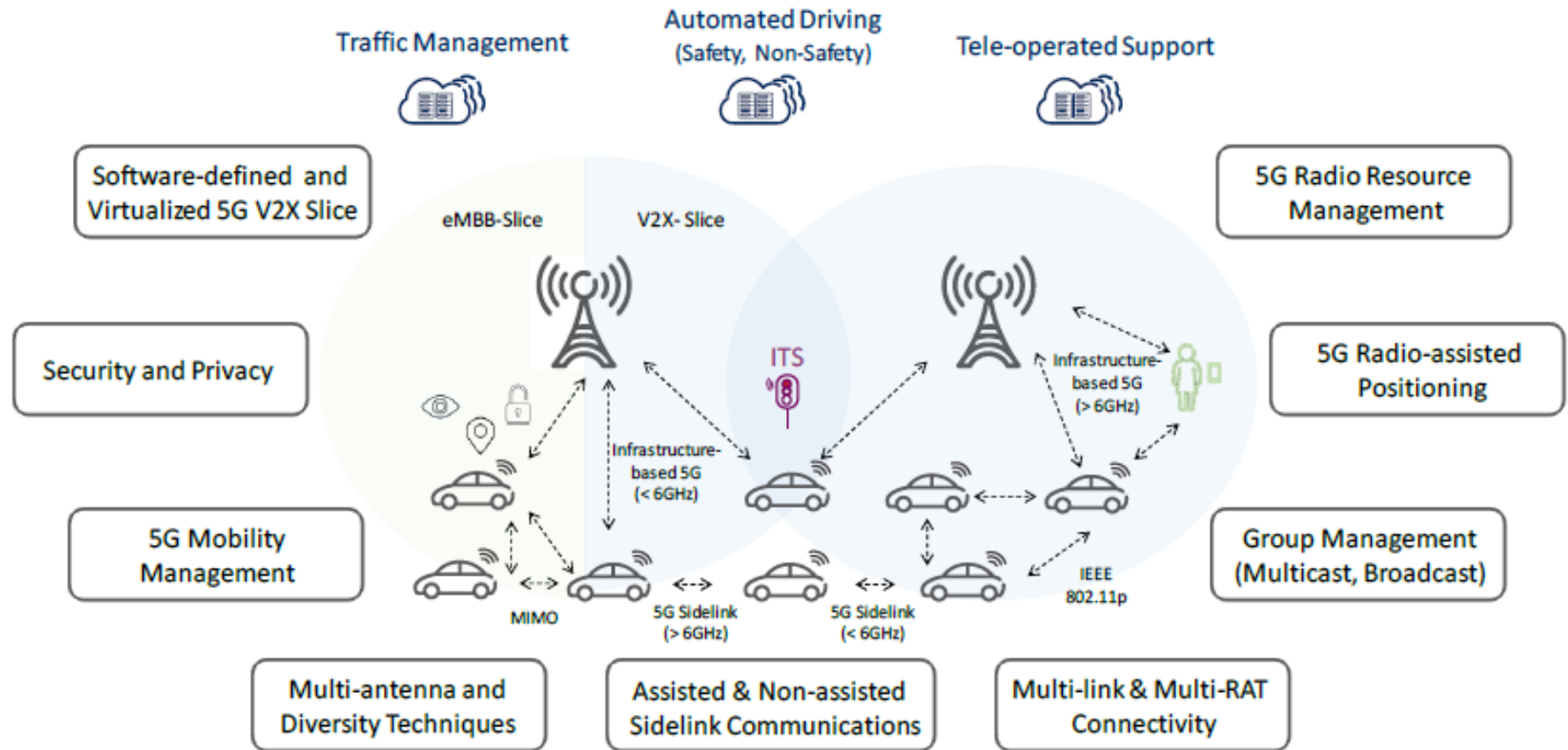
# Other types of vehicular networks





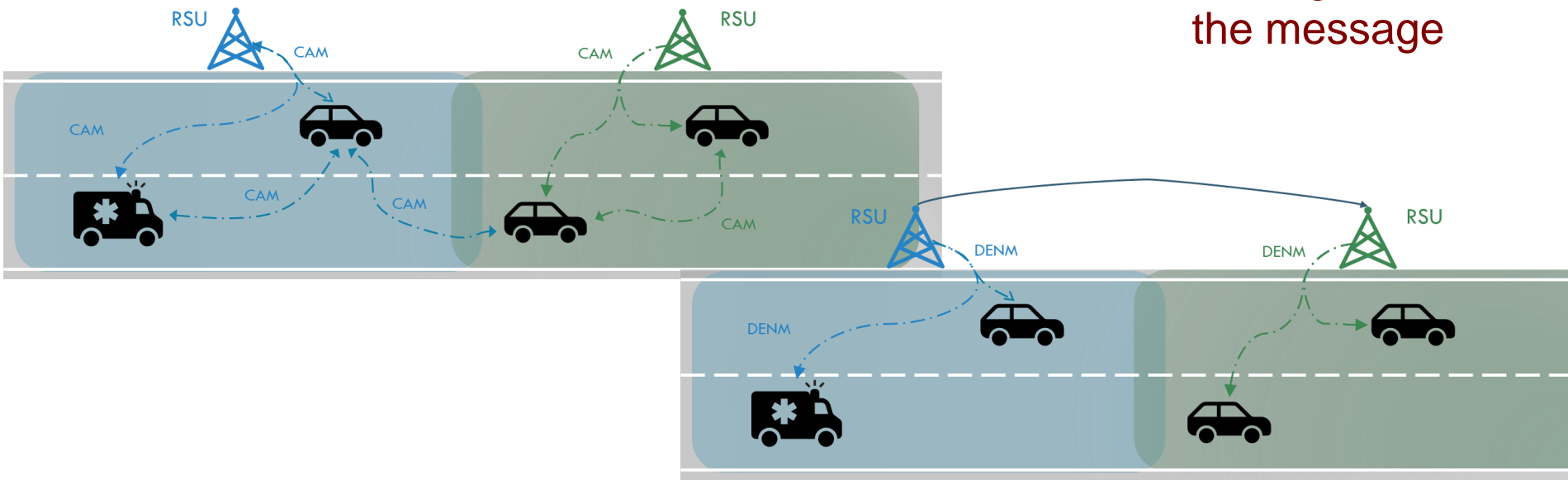
# How do they work?

## Intelligent Transportation Systems

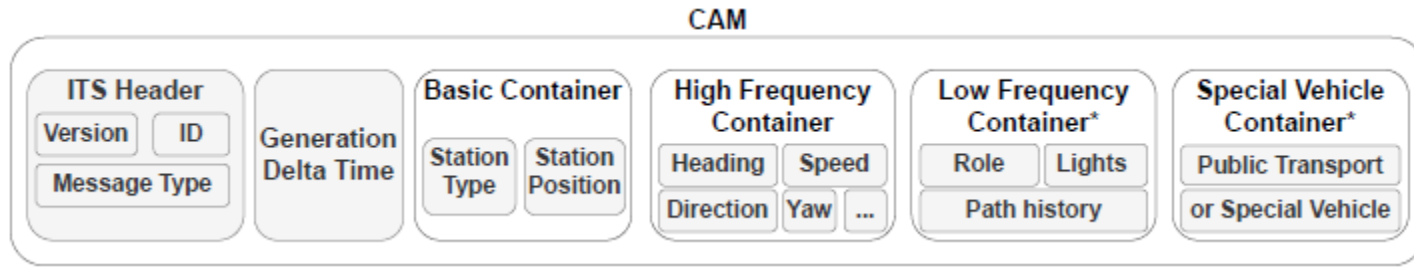


# Awareness and warning information

- Cooperative Awareness Messages (CAM)
  - Periodic
  - Contain information about the station such as the position and speed
- Decentralized Environmental Notification Messages (DENM)
  - Asynchronous
  - Contain information about the event and the station that generated the message



# Cooperative awareness messages



- Create and maintain awareness of vehicles using the road network or RSUs.
- The content varies depending on the type of ITS-S (Intelligent Transportation System – Station):
  - **Vehicles:** time, position, motion state, activated systems (*e.g.*, cruise control, pedals, and others), and the attribute information includes data about the dimensions, vehicle type, and role in the road traffic;
  - **RSUs:** station type and location.
- HF (High-Frequency) container with the fast-changing vehicle data (such as location, heading, or speed)
- LF (Low-Frequency) container with static or slow-changing data (such as the status of the exterior lights or pedals).

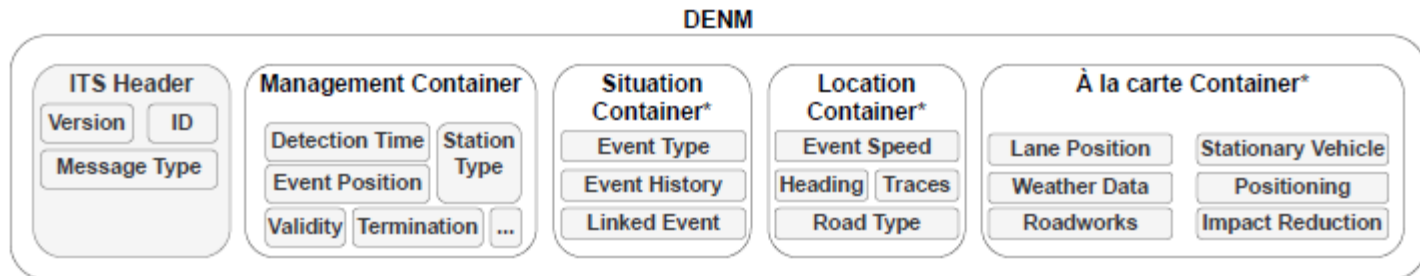
# Cooperative awareness messages

- CAMs have generation requirements, with the generation frequency between 1 Hz and 10 Hz.
- The HF container must be in every CAM message, while the low-frequency container can be updated at a maximum of 5 Hz frequency.
- The generation process must be effective, since the difference between CAM generation time and the time at which the CAM is delivered to networking transport layer shall be less than 50 ms.

CAM Information	Basis Container	ITS-Station Type
		Last Geographic Position
	High Frequency Container	Speed
		Driving Direction
		Longitudinal Acceleration
		Curvature
		Vehicle Length
		Vehicle Width
		Steering Angle
		Lane Number
		...
	Low Frequency Container	Vehicle Role
		Lights
		Trajectory
	Special Container	Emergency
		Police
		Fire Service
		Road Works
		Dangerous Goods
		Safety Car
		...



# Decentralized environmental notification messages

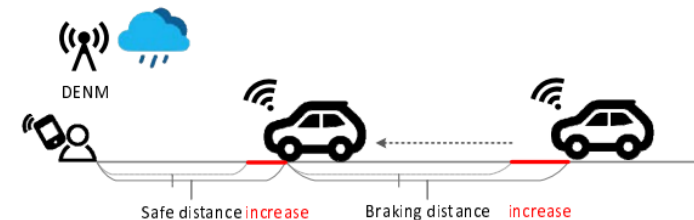
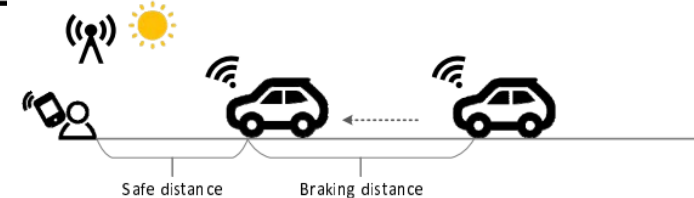


- Asynchronous messages to create and maintain awareness about a road event - *e.g.* road hazard or an abnormal traffic condition - such as its type, position, validity, timestamp and the history of the event.
- While the content varies depending on the type of event, it is expected that at least the detection time, the position of the event, the type of the related station and a set of cause codes identifying the type of event are present.
- Containers for certain types of events - such as the Road Works
- Stationary Vehicle Containers.

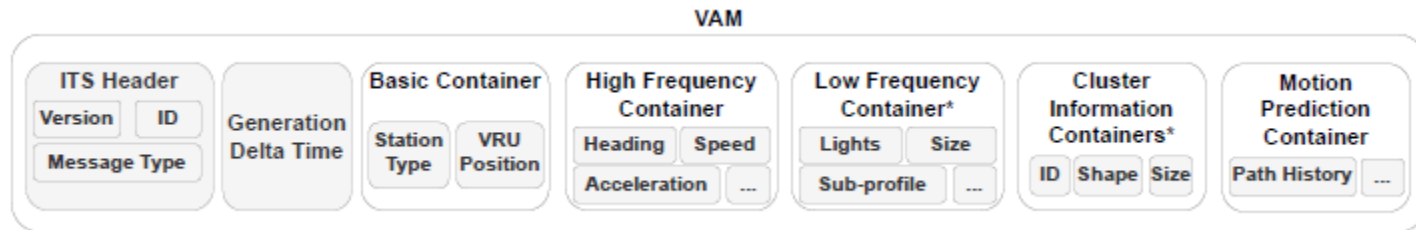
# Decentralized environmental notification messages

- Unlike CAMs, DENMs are generated as events occur, and thus, they are not generated periodically.
- They have a validity period, which after ending, means the DENM can no longer be considered up-to-date.
- When an event is no longer occurring, a particular type of DENM, a termination DENM, can be used to signal the end of the event - *e.g.* the end of the road hazard or of adverse weather conditions.

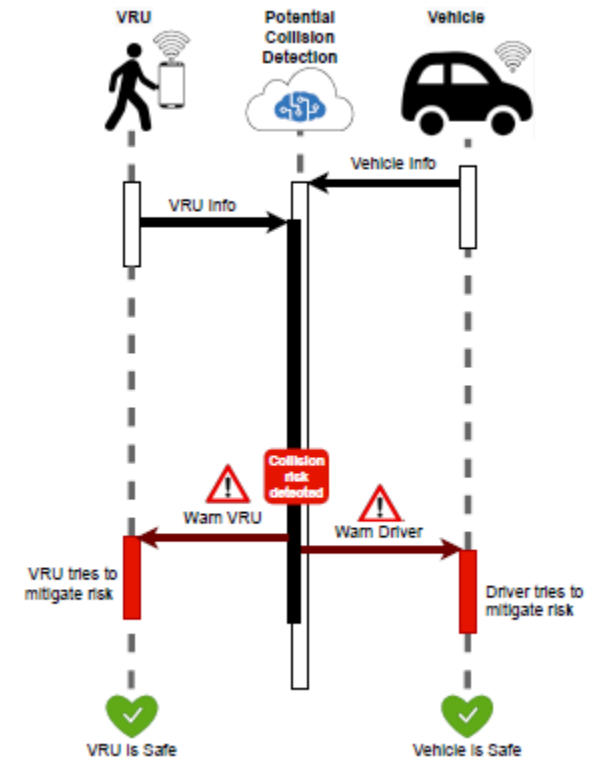
DENM Information	Management Container	Last Vehicle Position (GPS)
		Event Identifier
		Time of Detection
		Time of Message Transmission
		Event Position (GPS)
		Validity Period
		Station Type (Motor Cycle, Vehicle, Truck)
		Message Update / Removal
		Relevant Local Message Area (geographic)
		Traffic Direction (forward, backwards, both)
		Transmission Interval
		....
	Situation Container	Information Quality (low -high, tbd)
		Event Type (Number)
		Linked Events
	Location Container	Event Route (geographical)
		Event Path
		Event Speed
		Event Direction
	A la carte Container	Road Type
		Road Works (Speed Limit, Lane Blockage....)
		....



# Vulnerable Road User Awareness Message



- Periodic messages exchanged in the ITS network between stations to create and maintain awareness on VRUs, and support the risk assessment
- Basic status: time, position, speed, heading, yaw rate and acceleration, orientation, lane position, dimensions and VRU type.
- Advantages of a VAM standard message over the usage of a CAM
  - flexibility in terms of fully specifying the VRU type and situation, which is not possible without changing the CAM standard (therefore defeating the purpose of using a standard).

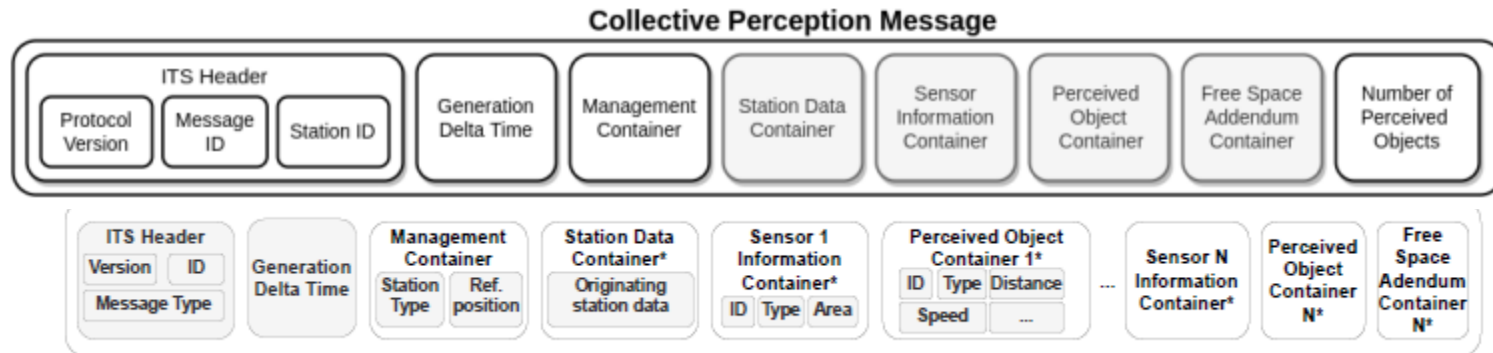


# Vulnerable Road User Awareness Message

- VAMs can distinguish between several types of VRUs - pedestrian, cyclist, motorcyclist, animal
- Within each category, they can distinguish several possible roles (*e.g.* for a cyclist VRU, between bicyclist, a wheelchair user, a horse rider, a roller skater, an e-scooter, and others).
- This distinction is crucial: several different VRUs - for example, a child pedestrian or a disabled pedestrian - have different dynamics from a typical pedestrian. That information can be used, for example, by safety services to fine-tune an accident prediction algorithm.

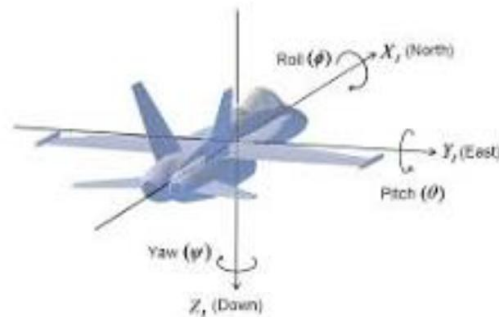
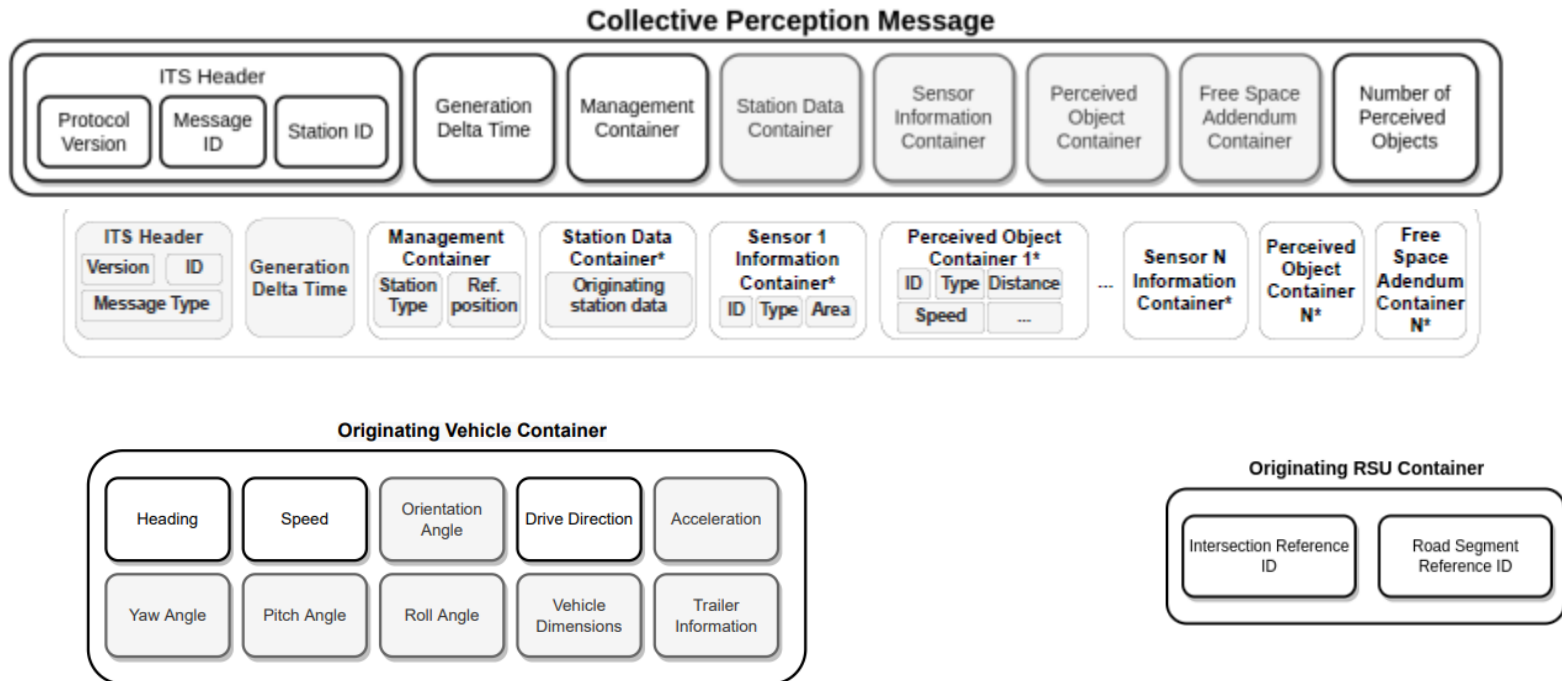


# Cooperative Perception Message

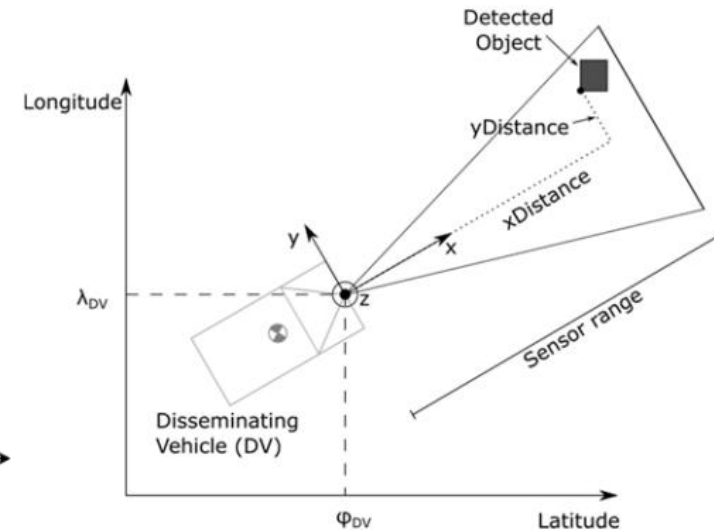
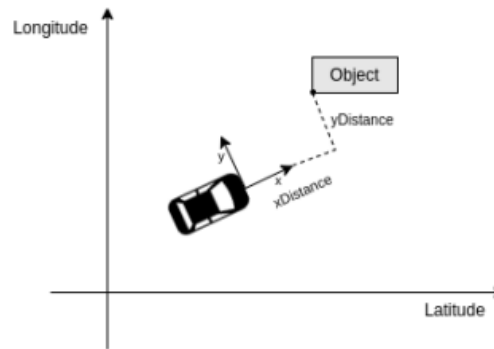
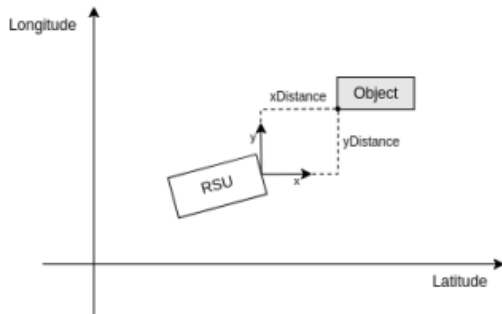
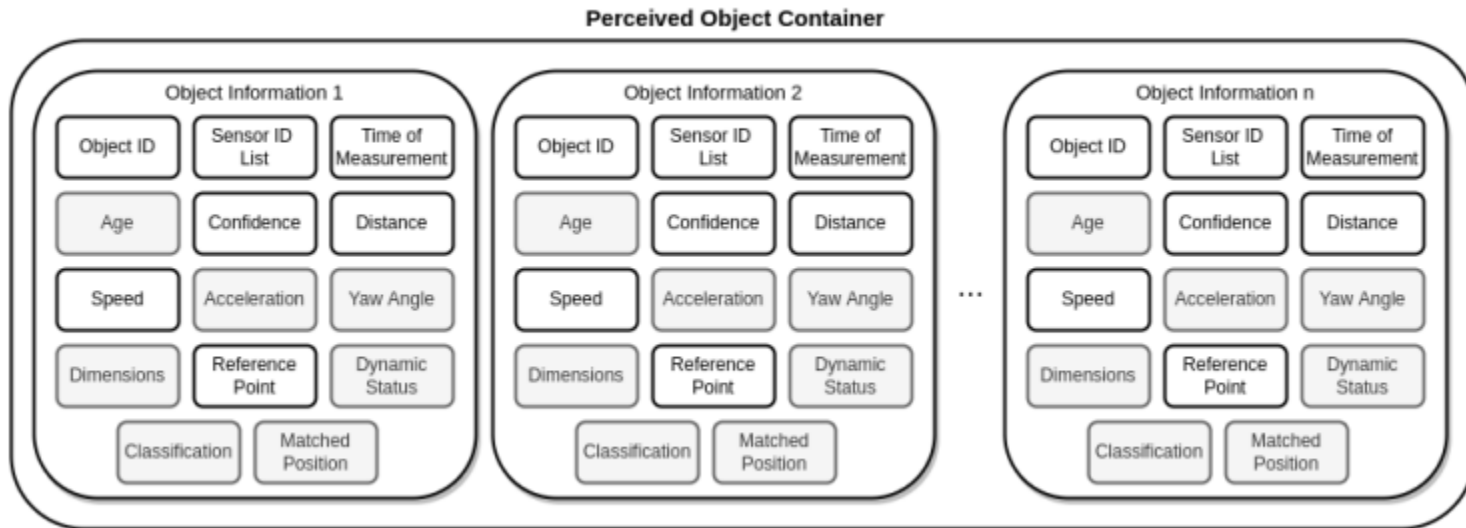


- Periodic messages between stations to broadcast information about the current environment perceived by 1 or more sensors.
- Sensors from a vehicle; a VRU and infrastructure can use CPMs to exchange the information obtained from their surroundings, improving the awareness of the situation.
- Sensor Information Container: sensor type - *e.g.* Radar, Lidar, video cameras or fusion algorithms, and the area the sensor covers.
- Perceived Object Container: object perceived by the sensor, the classification, the confidence of the classification, and several data about its dynamics, such as distance, speed, acceleration and angle.

# Cooperative Perception Message



# Objects information in CPMs



Coordinate System for detected object for vehicle

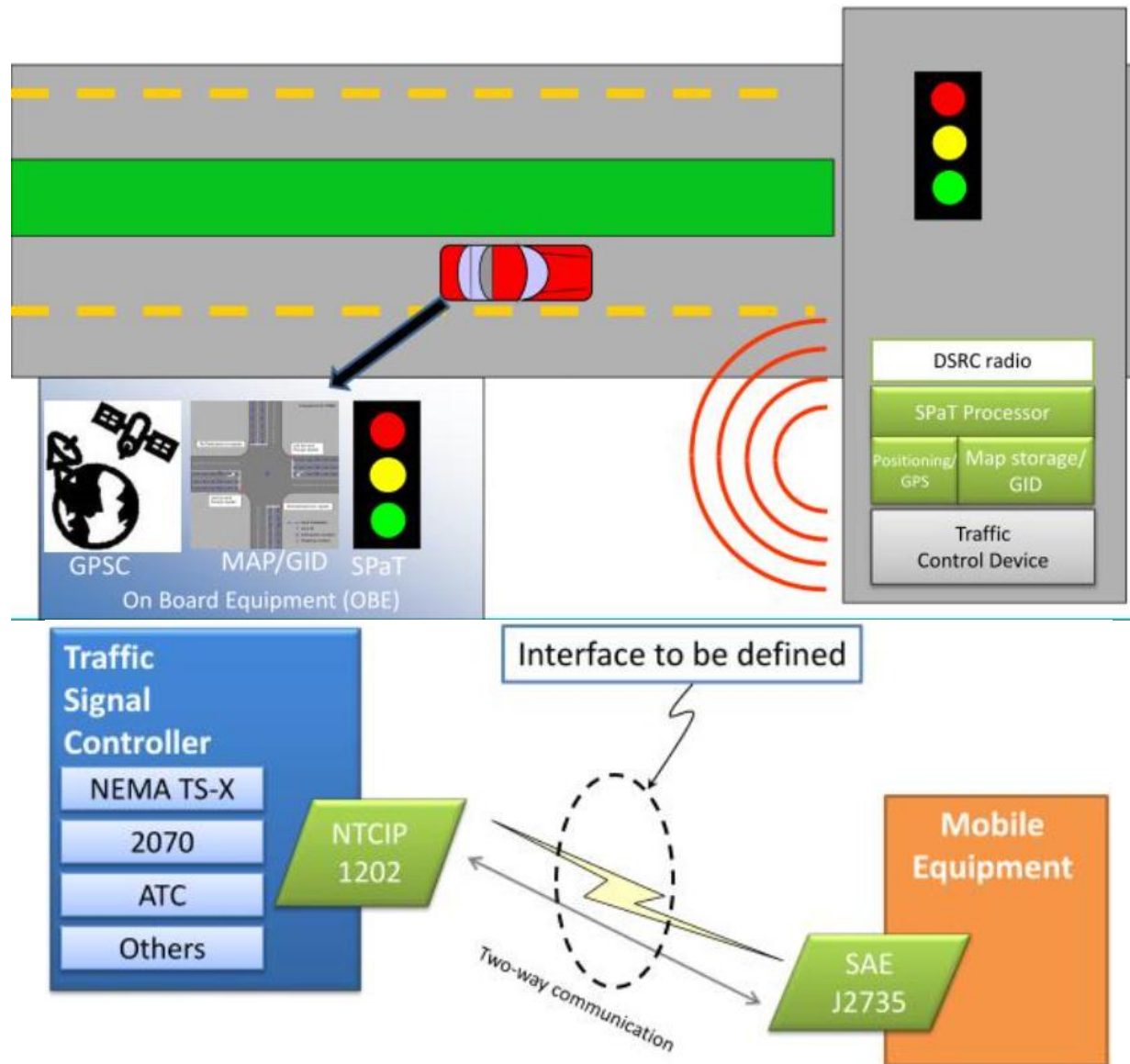
# SPAT: Signal Phase And Timing

- Defines an open interface for two-way communication between traffic signal controller and mobile devices
- Current movement state of each active phase
  - Safety applications, such as warnings and alerts for crash avoidance, red light violations
  - Mobility applications to enable dynamic and efficient traffic management
  - Environment applications that allow savings in fuel consumption and reduction in CO<sub>2</sub> emissions
- Current state of all lanes at the intersection are provided, as well as any active preemption or priority



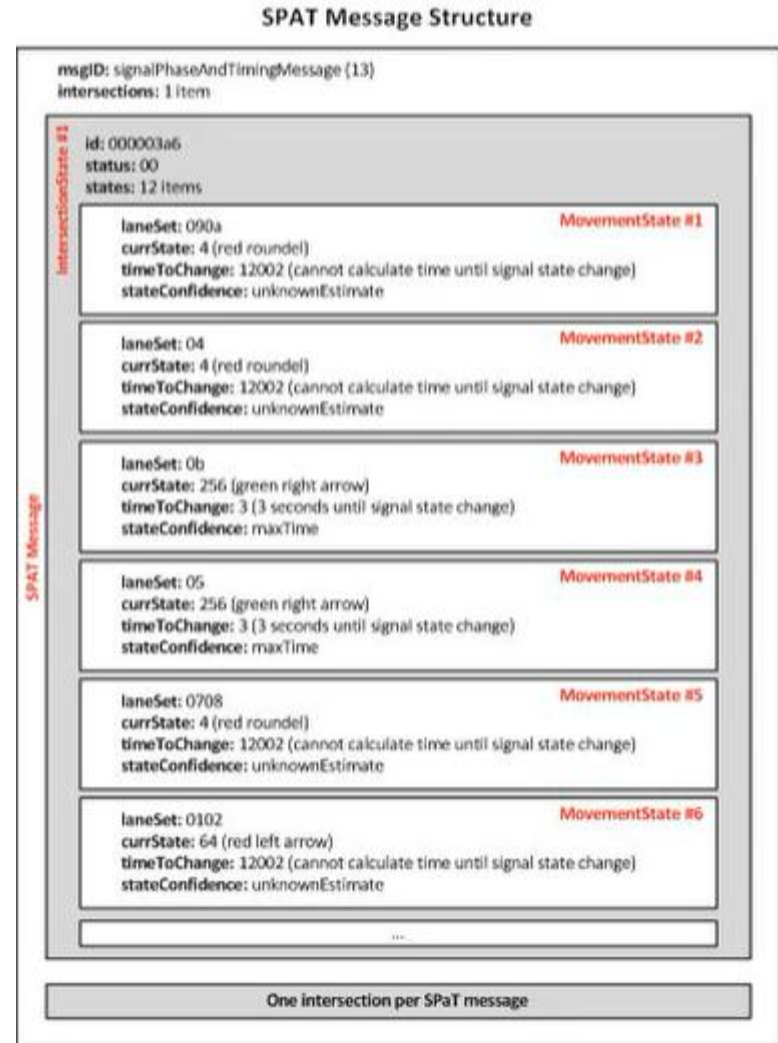


# SPaT: Signal Phase And Timing

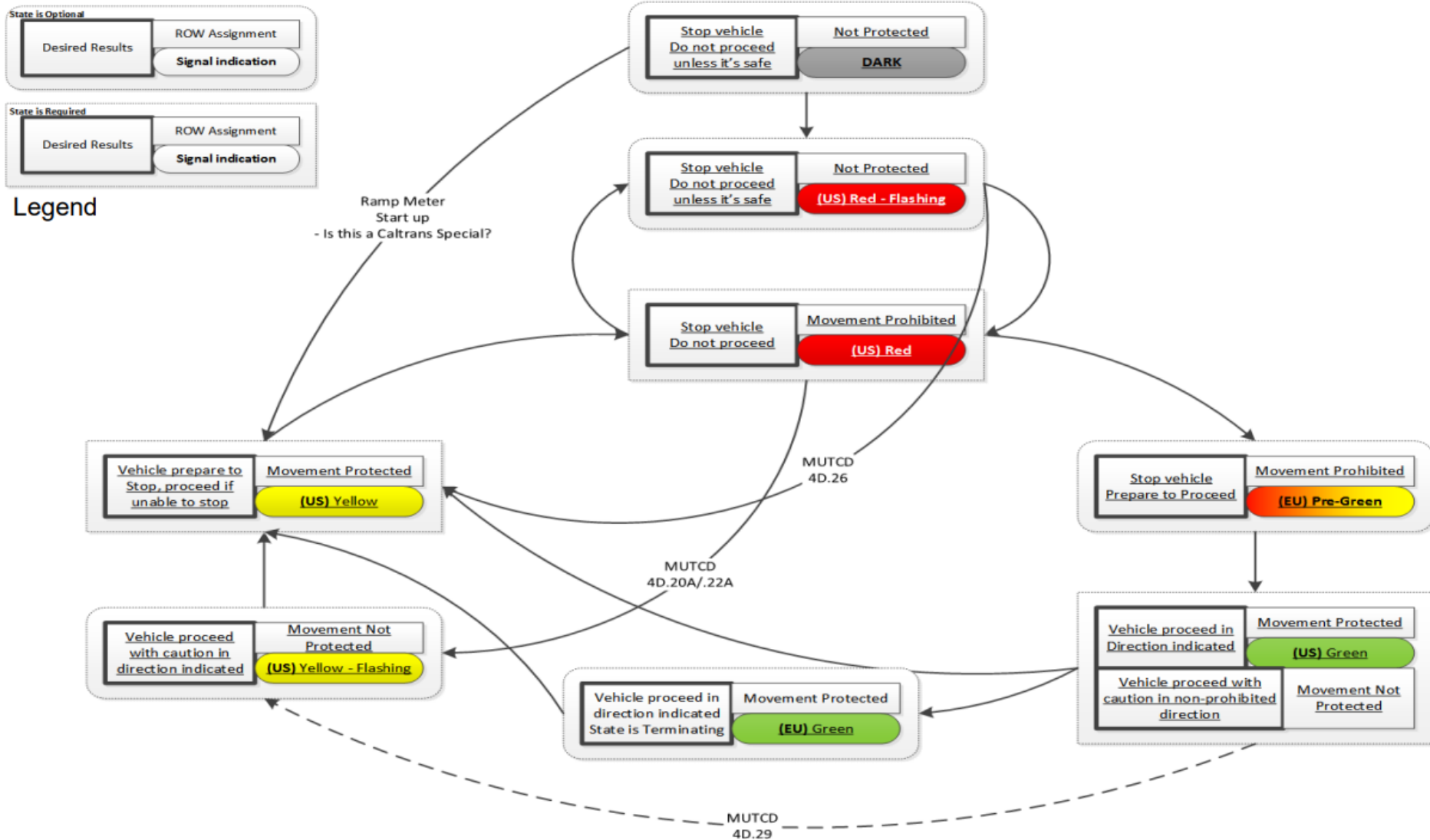


# SPaT: Signal Phase And Timing

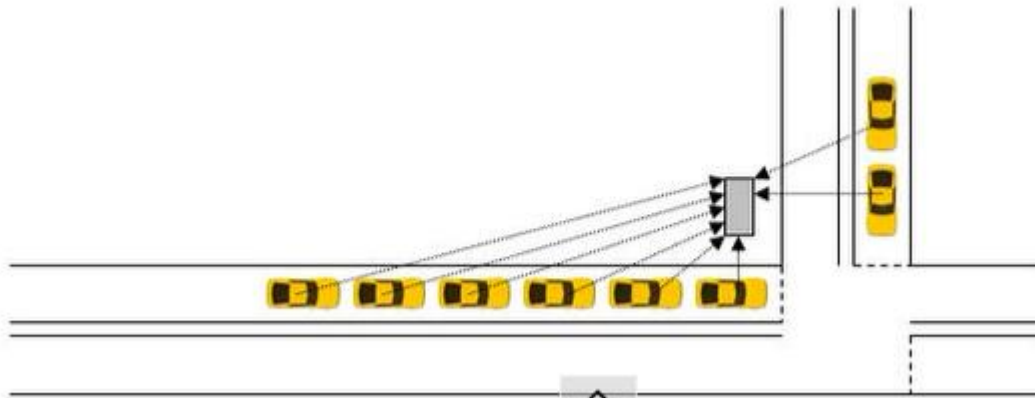
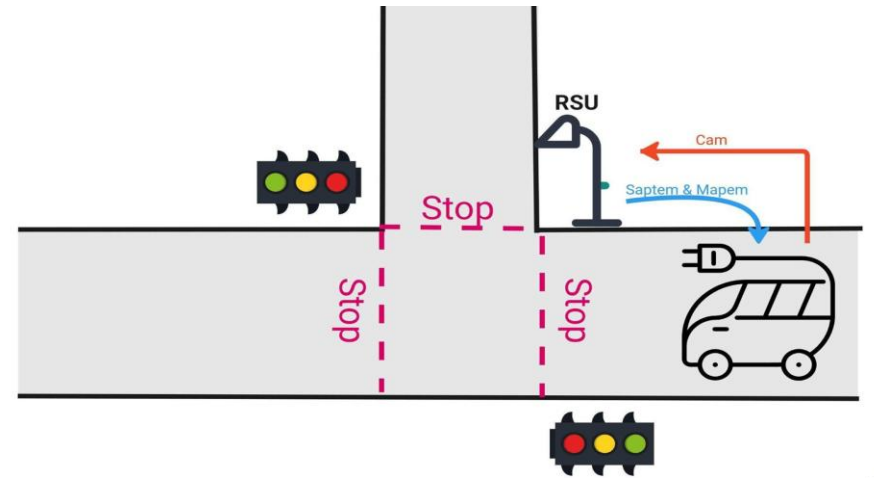
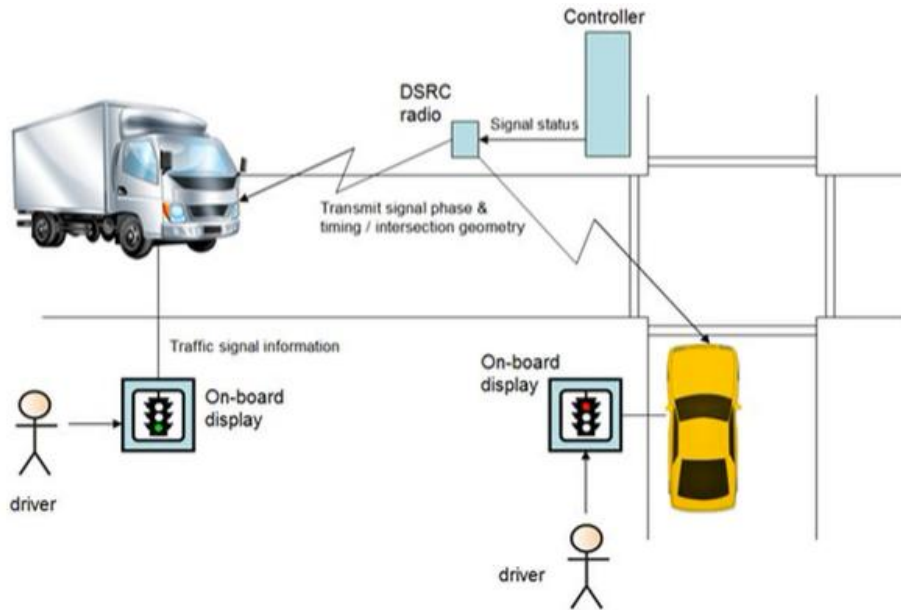
- Intersection state
- Movement state
  - Lane set (lanes 9-10 are for movement state 1)
  - Current state (green, yellow, red)
  - Time until current signal state changes
- Used in cooperation with a **map**



# SPAT: State diagram

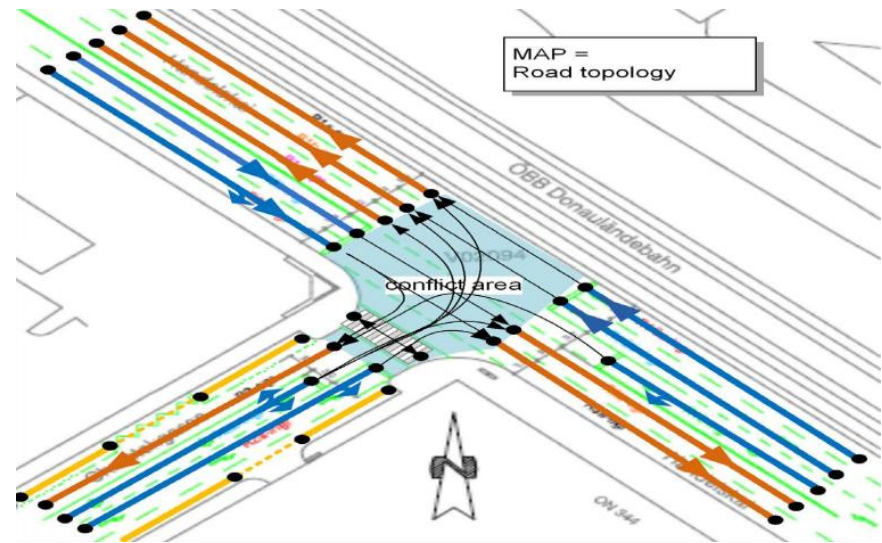


# They can be used virtually



# MAP: MAP

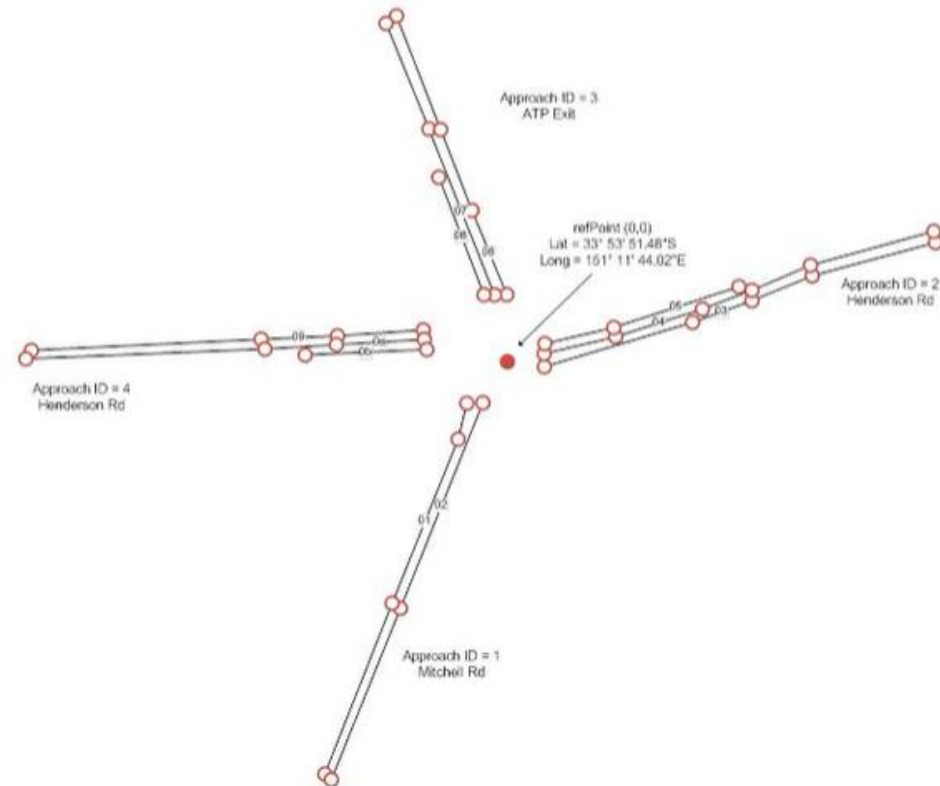
- Geometric layout of intersection
- Message data
  - Reference point (intersection center)
  - Number of approaches
  - Lane number
  - Lane width
  - Lane attributes
    - Straight, left, right, turn on red, speed limit, bus, etc...
  - Offsets
    - Points along each lane – used to detect vehicle position





# Example of a MAP information

<b>refPoint</b> <b>[Position3D]</b>	The Position3D data frame provides a precise location in the WGS-84 coordinate system, from which short offsets may be used to create additional data using a flat earth projection centred on this location.	
<b>laneWidth</b> <b>[LaneWidth]</b>	The LaneWidth data element conveys the width of a lane in units of 1 cm.	
<b>speedLimits</b> <b>[SpeedLimitList]</b> <b>(1..9)</b>	The SpeedLimitList data frame consists of a list of SpeedLimit entries.	RegulatorySpeedLimit  The RegulatorySpeedLimit data frame is used to convey a regulatory speed about a lane, lanes, or roadway segment.
<b>[laneSet]</b> <b>LaneList</b> <b>(1..255)</b>	The LaneList data frame consists of a list of GenericLane entries.	GenericLane  The GenericLane data frame is used for all types of lanes, e.g. motorized vehicle lanes, crosswalks, medians. The GenericLane describes the basic attribute information of the lane.
<b>preemptPriorityData</b> <b>[PreemptPriorityList]</b> <b>(1..32)</b>	The PreemptPriorityList data frame consists of a list of RegionalSignalControl-Zone entries.	SignalControlZone

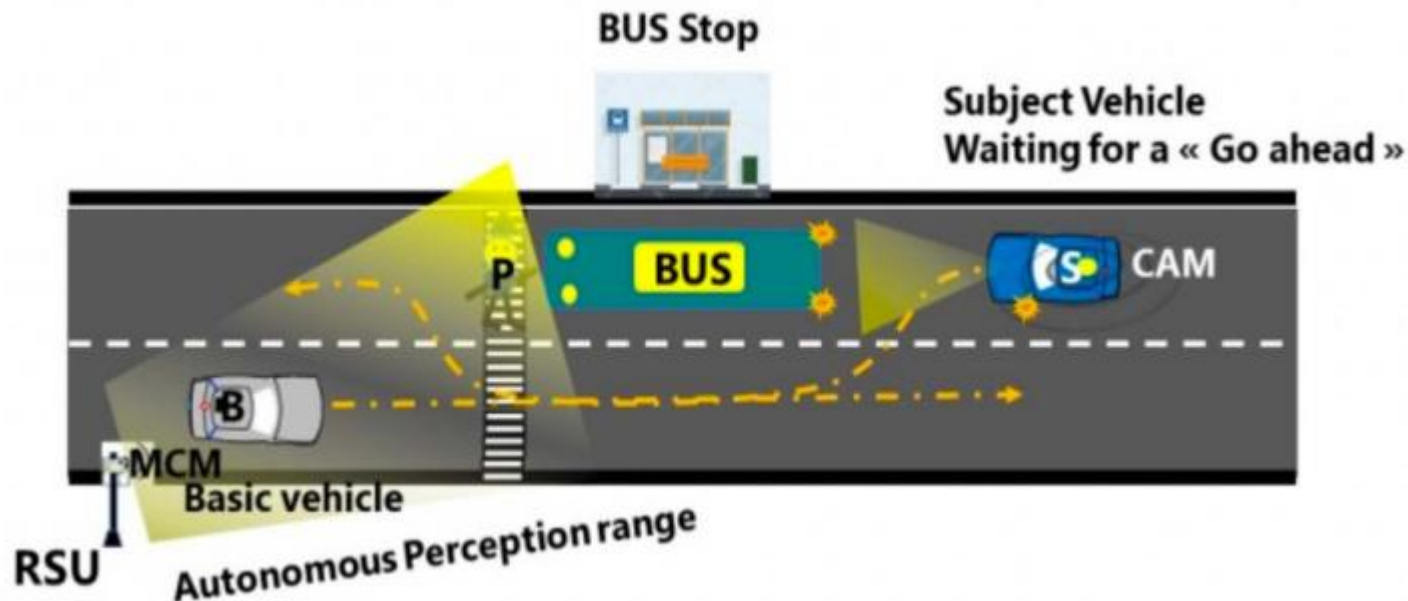


# Manoeuvre Coordination Message (MCM)

- Includes the intended (or planned) Maneuvers and one or more desired (or alternative) trajectories
  - Each trajectory is a spatial-temporal description of the vehicle trajectory in the next 5 to 10 seconds.
  - Planned trajectories are used by applications to improve the prediction of future locations of nearby vehicles and to detect conflicts
  - Desired trajectories are used to request a coordination between vehicles.
- It is expected that MCMs are generated continuously at a rate between 1 Hz and 10 Hz depending on the context
  - Early detection of the need of a Maneuver coordination.
  - The MC service can include triggering conditions while also having the possibility of being triggered by an application.
- For roadside applications, the MCMs are expected to include specific advices for specific vehicles, to e.g. suggest a given speed or a lane change
- MCMs transmitted by roadside units are expected to be smaller in size (although they can include advices for multiple vehicles) and transmitted less frequently than those transmitted by vehicles

# Manoeuvre Coordination Message (MCM)

- Vehicle S wants to overtake the stationary Bus.
- Any road user or other equipped road safety stakeholder could analyse the road traffic situation based on received information combined with other sensor data
- Advice or manage the road users how to act to realize an efficient and safe resolution of the situation.

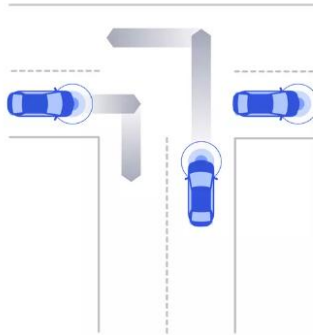


# Manoeuvre Coordination Message (MCM) - examples

- Goto Maneuver
- Idle Maneuver
- Follow Path Maneuver
- Follow Trajectory
- Scheduled Goto
- Stop Maneuver
- Maneuver Done
- Teleoperation Maneuver
- Teleoperation Done
- ...

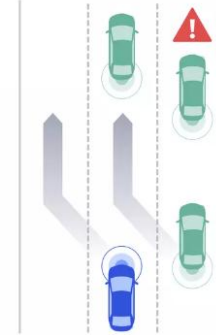
## Efficient maneuvers

Autonomous vehicles are able to make quicker, yet safe maneuvers by knowing the planned movements of surrounding vehicles



## Advanced path planning

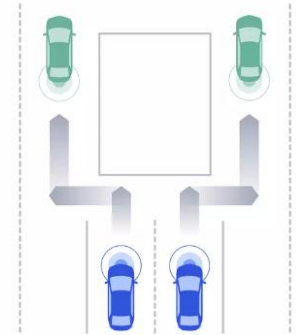
Supporting the level of predictability needed for advanced path planning for autonomous driving



Sudden braking  
and lane change  
on a freeway

## Coordinated driving

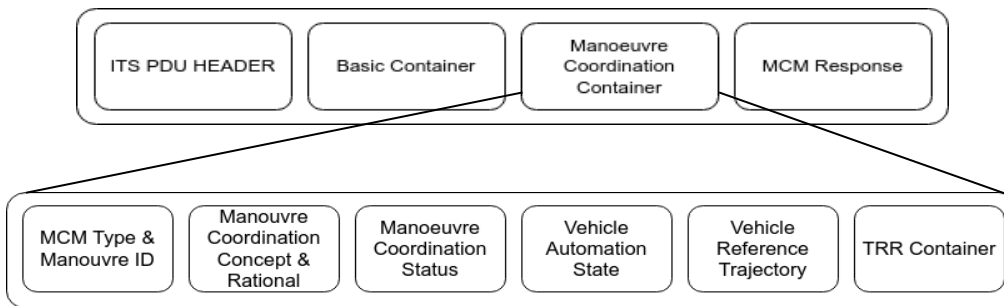
Autonomous vehicles are able to choose time-efficient paths toward their given destinations as they know the planned movements of other vehicles



- <https://lists.pt/docs/imc/master/Maneuvering.html>

# MCM Messages

## Structure



**MCM : Message that can be transmitted by the vehicles and/or infrastructure nodes to coordinate a maneuver.**

**MCM Type: Manoeuvre Type(offer, request..)**

**MCM Concept & Rational: Cooperation cost or the prescriptive goal of the manoeuvre.**

**MCM Coordination Status: Data element which indicates the current execution status.**

**Vehicle Automation State: Longitudinal or/and Lateral**

**Vehicle Reference Trajectory: Contains the trajectory that the vehicles intend to execute**

**TRR Container: Vehicle Reference Trajectory for reservation of a roadresource**

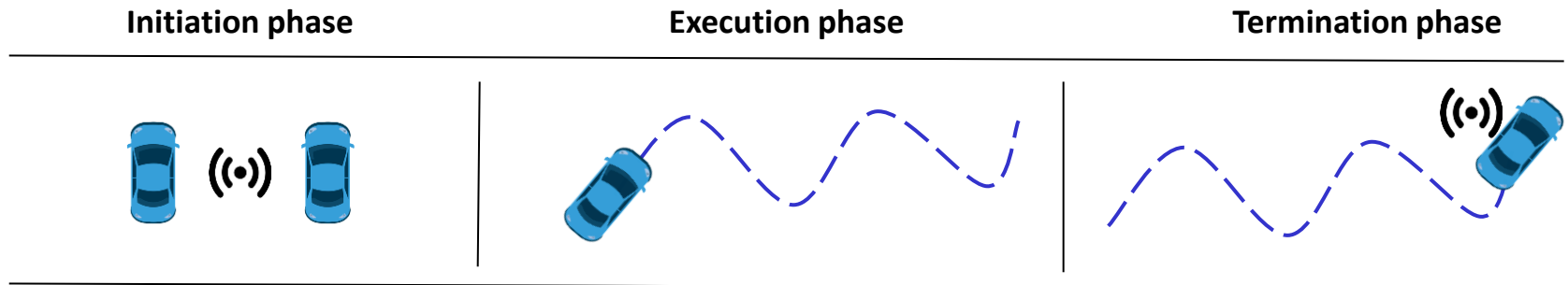


# Maneuver Cooperation Service

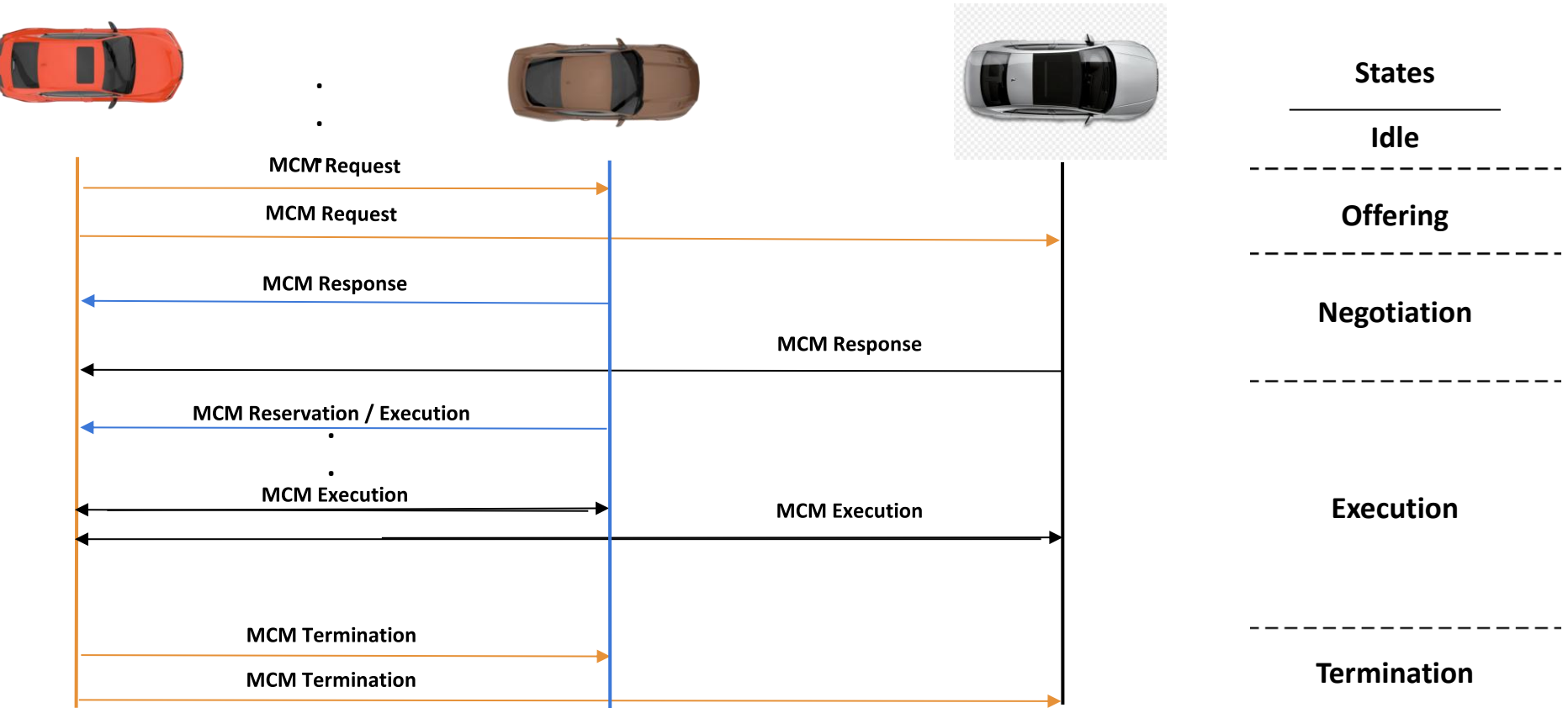
## Service

- The Manoeuvre Cooperation Service (MCS) serves as the orchestrator and facilitator, responsible for producing and managing the distribution of MCMs.
- It aims to support the driving automation functions of connected cooperative automated vehicles (CCAV) by fostering information exchange and cooperation between ITS-S nearby or remotely

## Manoeuvre coordination process



# Maneuver Cooperation Service



# **Communication Technologies**

# Requirements for the Communication Technologies

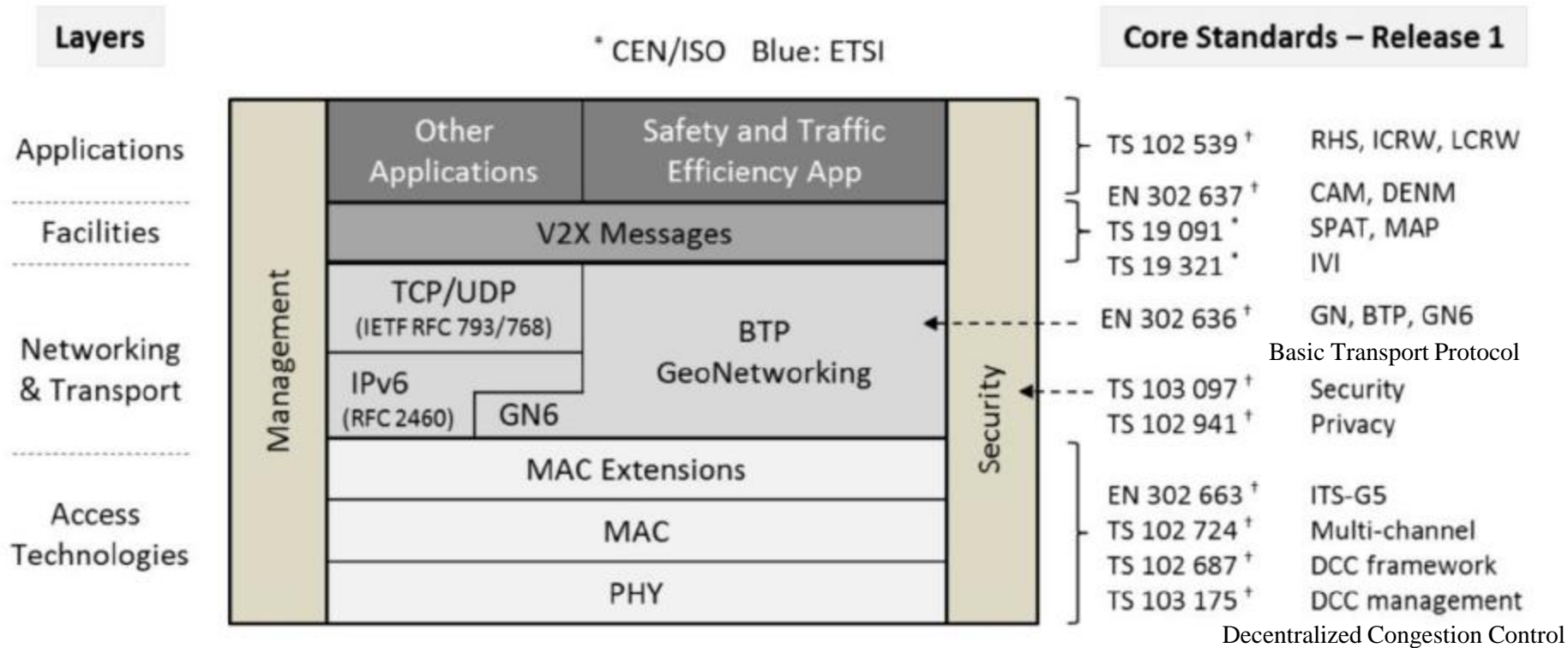
- Range ( $>200\text{-}400\text{m}$ )
- Delays ( $<10\text{msec}$ )
- Time for communication when in range ( $<10\text{-}20\text{msec}$ )
- Bandwidth ( $>>10\text{Mb/sec....} \rightarrow$  as much as possible)



# ITS-G5 (DSRC, IEEE 802.11p)

- Developed for vehicle-to-vehicle communication (it also supports vehicle-to-infrastructure communication)
- Based on IEEE 802.11a with PHY and MAC extensions (based on CSMA/CA: Carrier Sense Multiple Access/Collision Avoidance)
- Adapted for latency-critical V2X communications in the 5.9 GHz band
- Frequency: Operates in the 75 MHz band of 5.9 GHz spectrum
- Range: in LoS it can go up to 1Km
  - Prone to obstructions: buildings, trees, cars
- Delay: < 10msec
- Time for communication when in range (10-20msec)
- Rate up to 27Mb/sec in the largest mode (usual it is 12Mb/sec)

# ITS-G5



# ITS-G5 Challenges

- Vehicle safety communication applications rely heavily on periodic broadcast of basic safety messages (BSM) which contain the positions, velocities, and other information about the vehicles.
- These messages with the PHY layer overheads typically measure around 300 bytes with the full security certificate header, and are expected to be transmitted up to once every 100 ms. The periodicity is chosen to meet latency and accuracy requirements of vehicle safety applications.
- Channel congestion in dense vehicular environments (packet collisions)
- Lack of handshake/ACK in delivering broadcast frames
- No QoS support
- Next generation of the specification, namely 802.11bd, just released (<https://standards.ieee.org/ieee/802.11bd/7451/>)

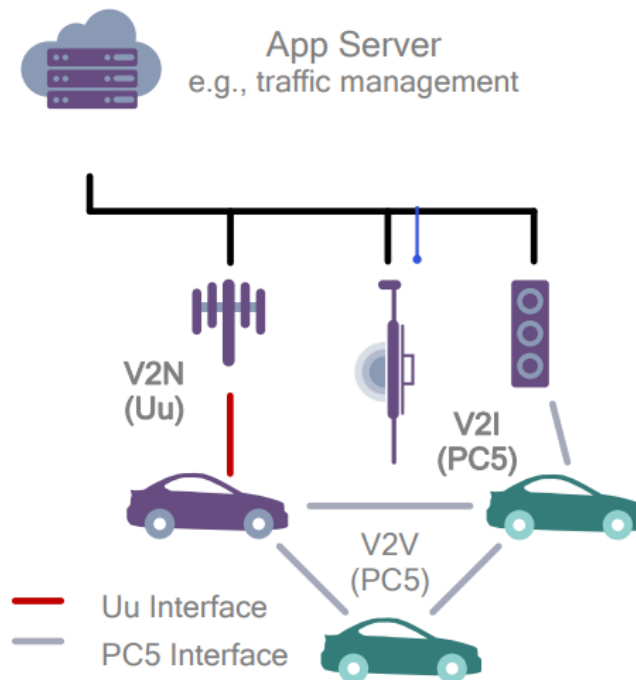
# <sup>42</sup>Cellular-V2X (LTE-based 3GPP Rel 14)

- Based on 3GPP Rel 14
- Frequency: 5.9GHz
- Range: in LoS, it can go up to 1Km
  - Prone to obstructions: buildings, trees, cars
- Delay: < 20msec
- Time for communication when in range (~100msec?)
- Rate up to 150Mb/sec in the largest mode



# <sup>43</sup>Cellular-V2X (LTE-based 3GPP Rel 14)

- Cellular-V2X defines a new air interface called PC5 for V2V, V2I communication.
- V2N is still over the legacy LTE Uu air interface and provides over the top cloud services.



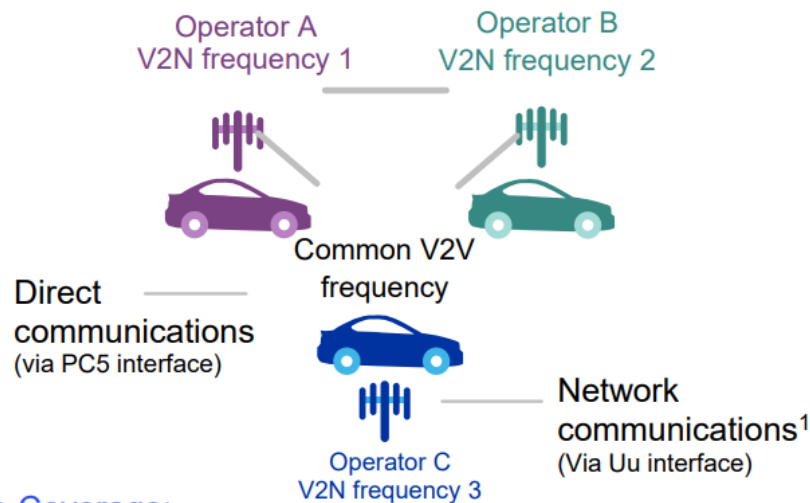
# 44 Cellular-V2X (LTE-based 3GPP Rel 14)

- C-V2X defines two Complementary Transmission Modes:
- 1) Direct safety communication independent of cellular network
  - Low latency Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Person (V2P) operating in ITS bands (e.g., 5.9 GHz)
- 2) Network communications for complementary services
  - Vehicle-to-Network (V2N) operates in the mobile operator's licensed spectrum
- Direct communications (V2V) via PC5 interface
  - Building upon LTE Direct device-to-device design with enhancements for high speeds / high Doppler, high density, improved synchronization, and low latency
    - Proximal direct communications (100s of meters)
    - Operates both in- and out-of-coverage
    - Latency-sensitive use cases, e.g., V2V safety
- Network communications (V2N) via Uu interface
  - Using LTE to broadcast messages from a V2X server to vehicles and beyond. Vehicles can send messages to the server via unicast
    - Wide area networks communications
    - Leverages existing LTE networks
    - More latency tolerant use cases, e.g., V2N situational awareness

# 45 Cellular-V2X (LTE-based 3GPP Rel 14)

## Transmission Mode 3

### In-coverage

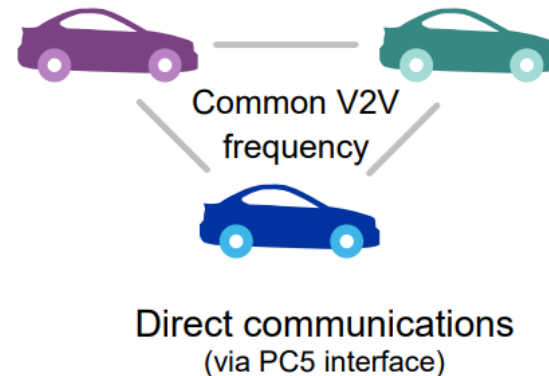


#### In-Coverage:

- eNode B (Cellular Base Station) schedules UEs (User Equipment)

## Transmission Mode 4



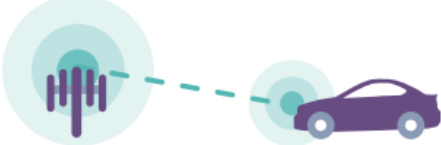
### Out-of-coverage



#### Out-of-Coverage:

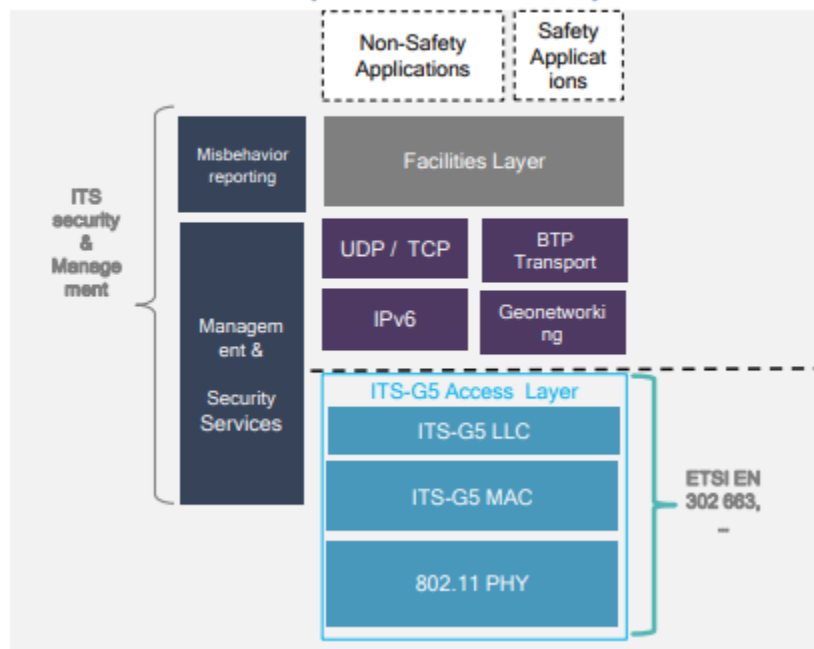
- No eNode B scheduling (aka Distributed Scheduling)
- Autonomous Resource Selection
  - Distributed Congestion Control

# 46 Cellular-V2X (LTE-based 3GPP Rel 14)

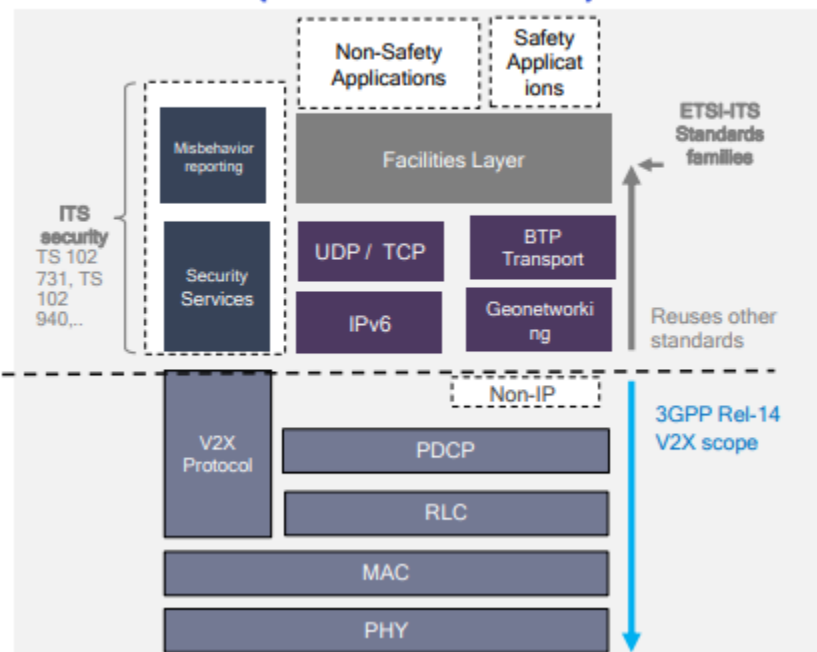
	Connected Vehicle Challenges	C-V2X Solutions
	High relative speeds Leads to significant Doppler shift / frequency offset	<b>Improved signal design</b> E.g. increasing # of ref signal symbols to improve synchronization and channel estimation
	High node densities Random resource allocation results in excessive resource collisions	<b>Improved transmission structure</b> Transmit control and data on the same sub-frame to reduce in-band emissions  <b>More efficient resource allocation</b> New methods using sensing and semi-persistent resource selection
	Time synchronization Lack of synchronization source when out-of-coverage	<b>Allow utilization of GPS timing</b> Enhancements to use satellite (e.g., GNSS) when out-of-coverage

# ITS-G5 vs C-V2X

## ITS (ITS-G5 based)



## C-V2X (D2D/PC5 based)

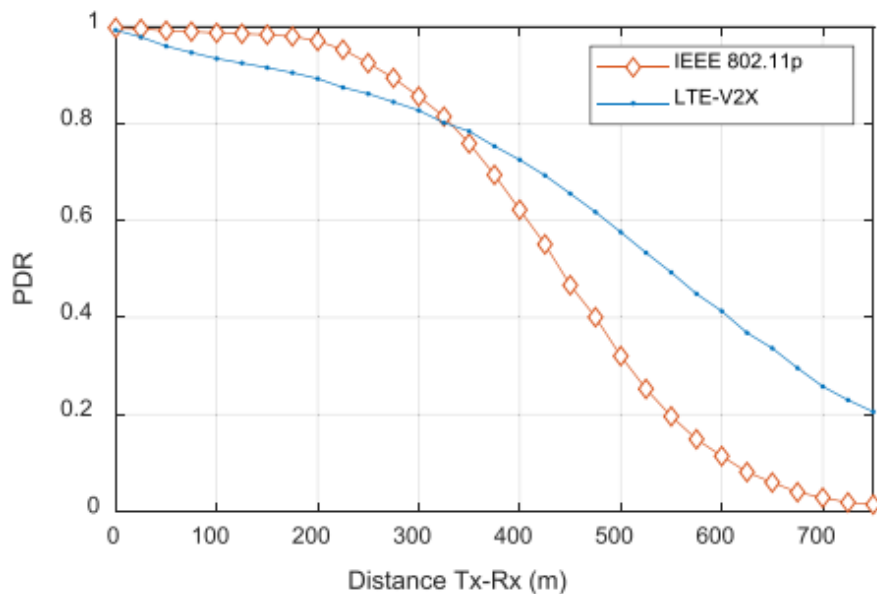




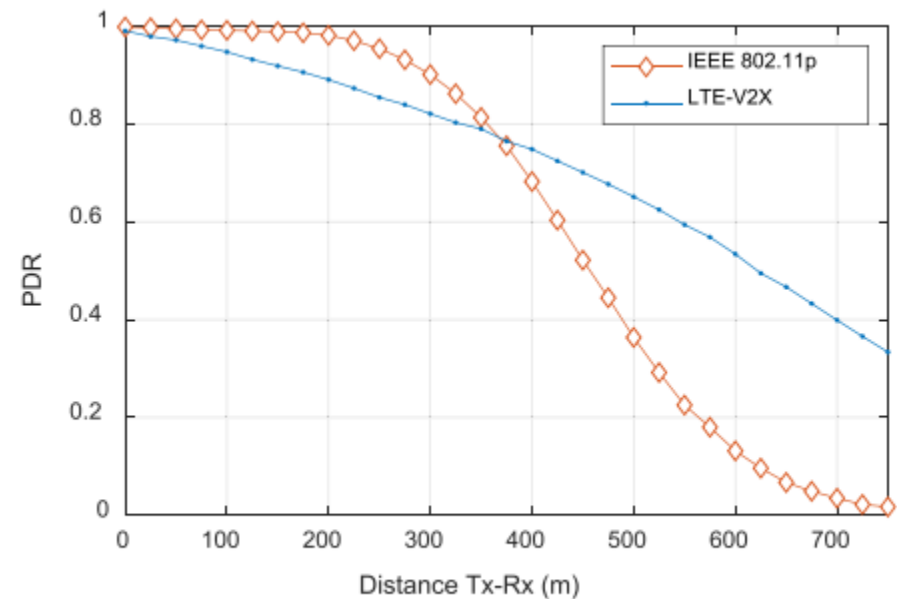
# ITS-G5, C-V2X, 5G (Standalone)

<b>Parameters</b>	<b>ITS-G5</b>	<b>C-V2X (LTE Rel. 14)</b>	<b>Future 5G SA</b>
<b>Currently available technology</b>	Yes	Yes	No
<b>Field trials (+10 years)</b>	Yes	No	No
<b>Applications</b>	V2V, V2I	V2V, V2I, V2N	V2V, V2I, V2N
<b>Latency</b>	5 ms	20 ms	<5 ms
<b>Data rate</b>	3-27 Mbps	150 Mbps	10 Gbps
<b>Multimedia and cloud services support</b>	No	Yes	Yes

# ITS-G5 vs C-V2X (Simulation)



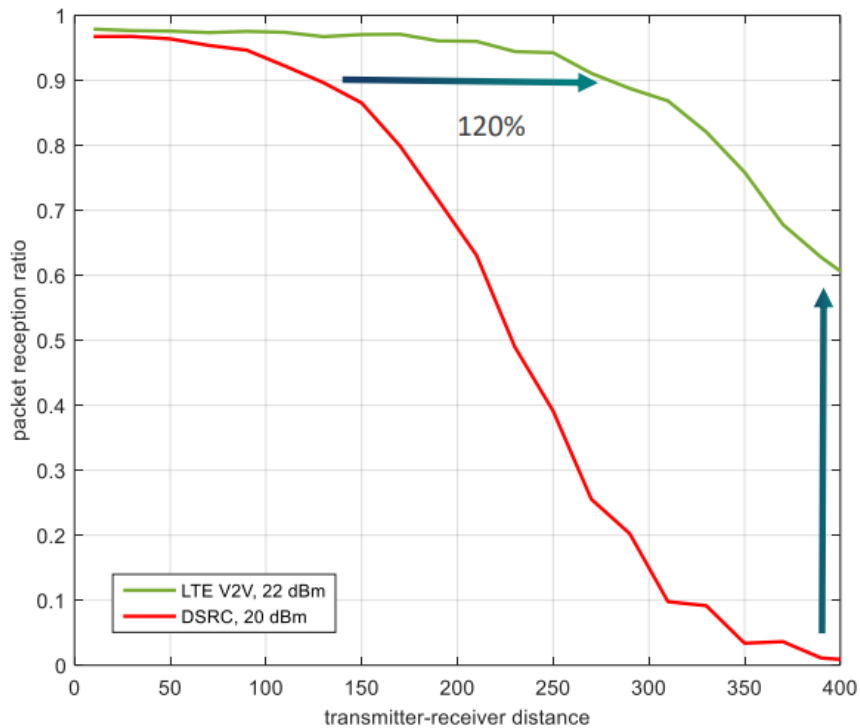
(a) Empirical-size model. 120 veh/km (CBR~0.33)



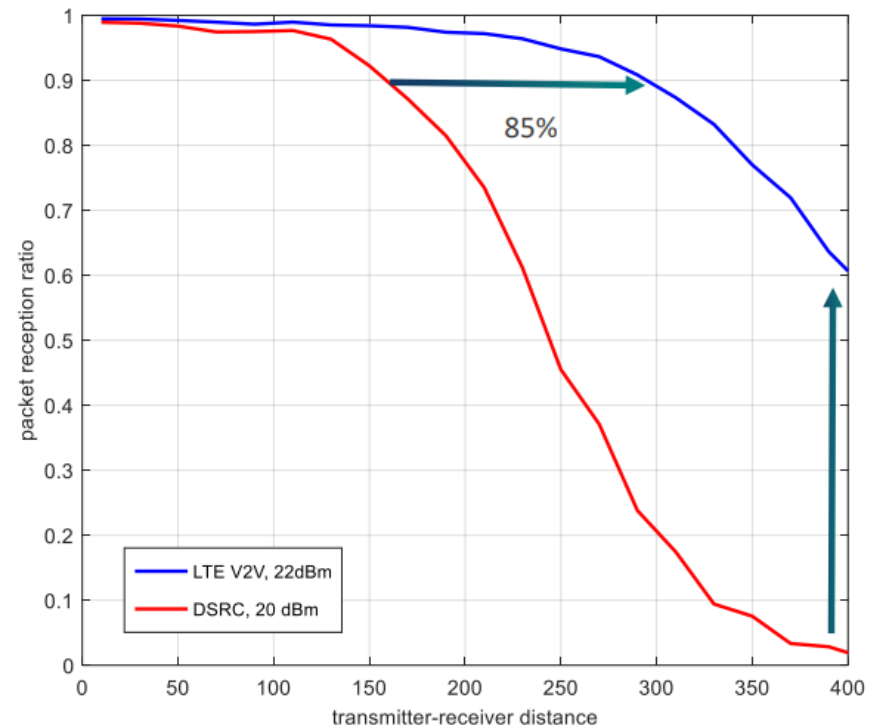
(b) Empirical-time model. 200 veh/km (CBR~0.23)

# ITS-G5 vs C-V2X (Qualcomm)

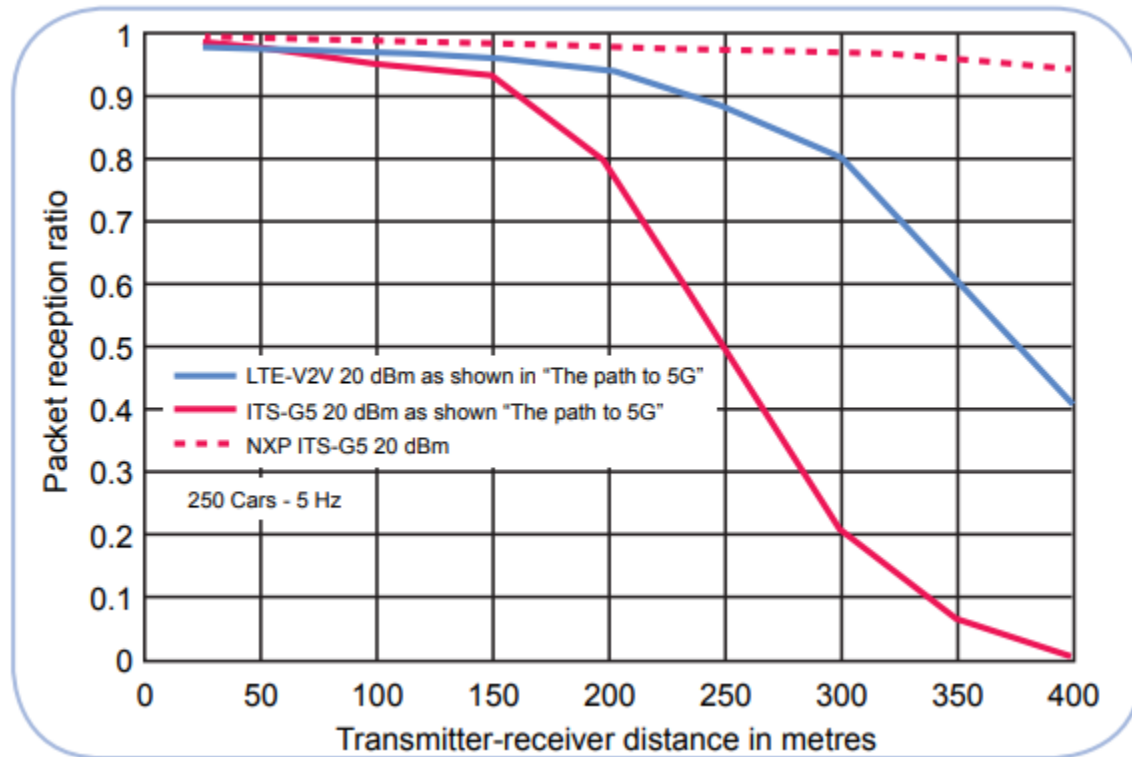
Freeway 250 km/hr, 69 cars



Freeway 140 km/hr, 123 cars



# ITS-G5 vs C-V2X (NXP)



# New radio Cellular-V2X (Rel 16)

## NR Design

## 5G NR C-V2X capabilities for autonomous driving

Scalable OFDM-based air interface



5G C-V2X is expected to efficiently address diverse spectrum bands for different use cases  
Leveraging wideband carrier support and OFDMA to deliver **higher data rates**

Self-contained slot structure



Smaller slot structure with immediate feedback to enable **ultra reliable low latency communications**

Advanced channel coding



State of the art LDPC/polar coding to deliver **higher reliability** with low complexity

Wideband carrier support



Wideband carrier based **higher data rates and system capacity**

Larger number of antenna



Efficiently utilize larger number of antennas than Rel-14 to deliver **higher data rate** and long range

LDPC: Low-Density Parity Check



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