Vehicular Networks

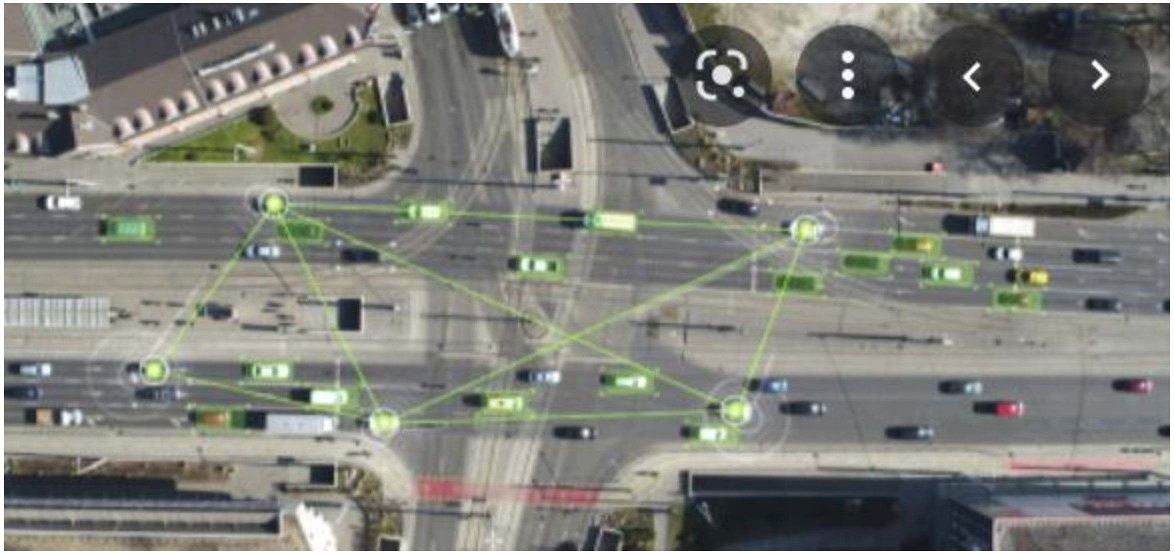
Mestrado em Engenharia de Computadores e Telemática

2023/2024

Vehicular Networks

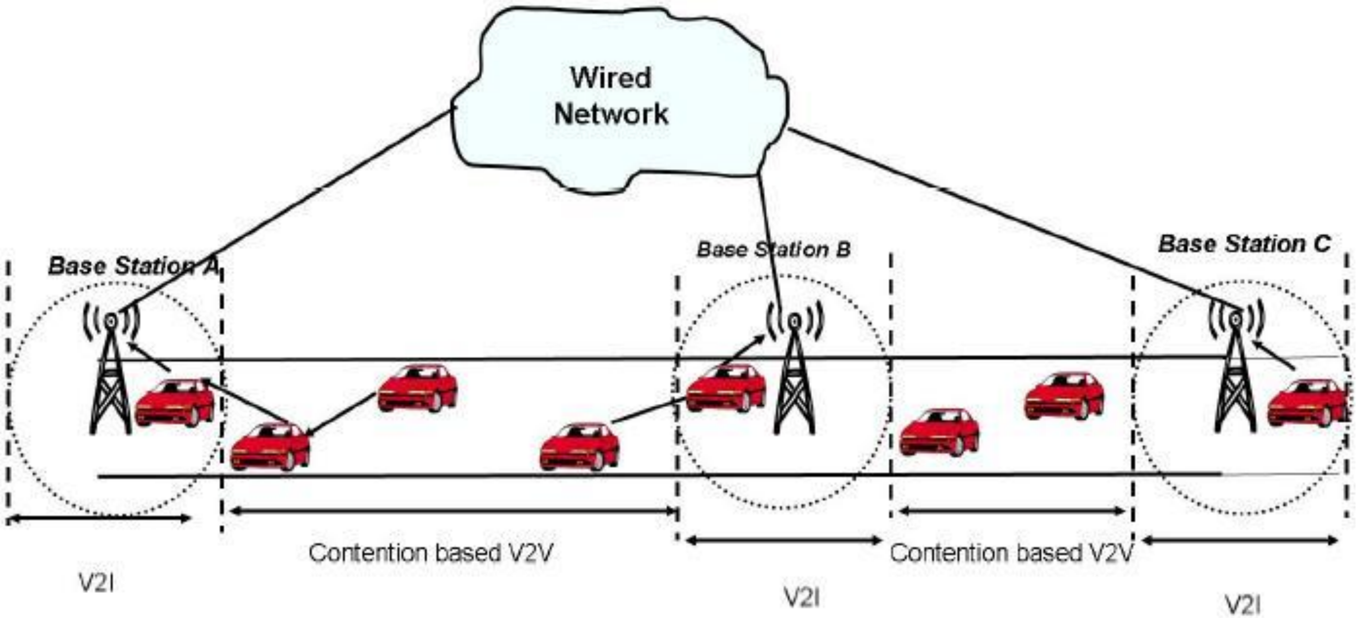
Vehicular networks can provide

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



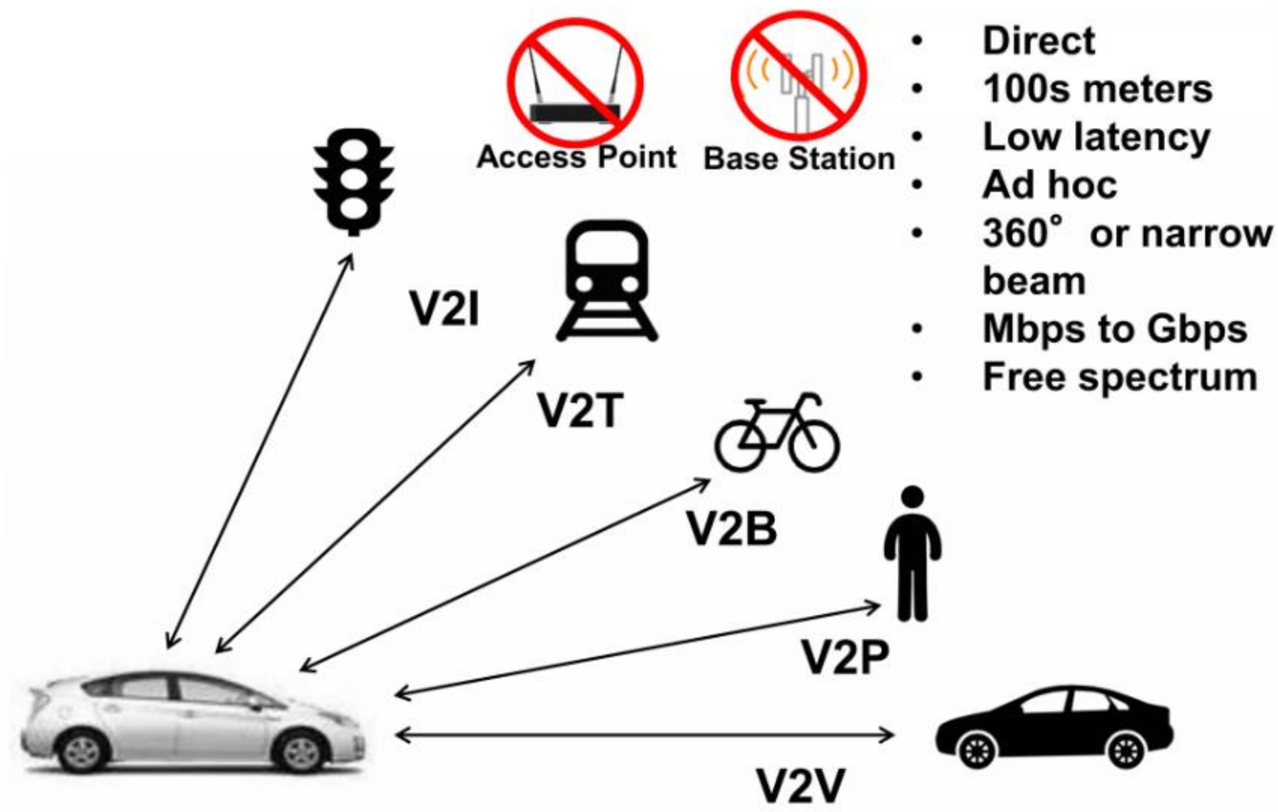
Vehicular networks

- 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

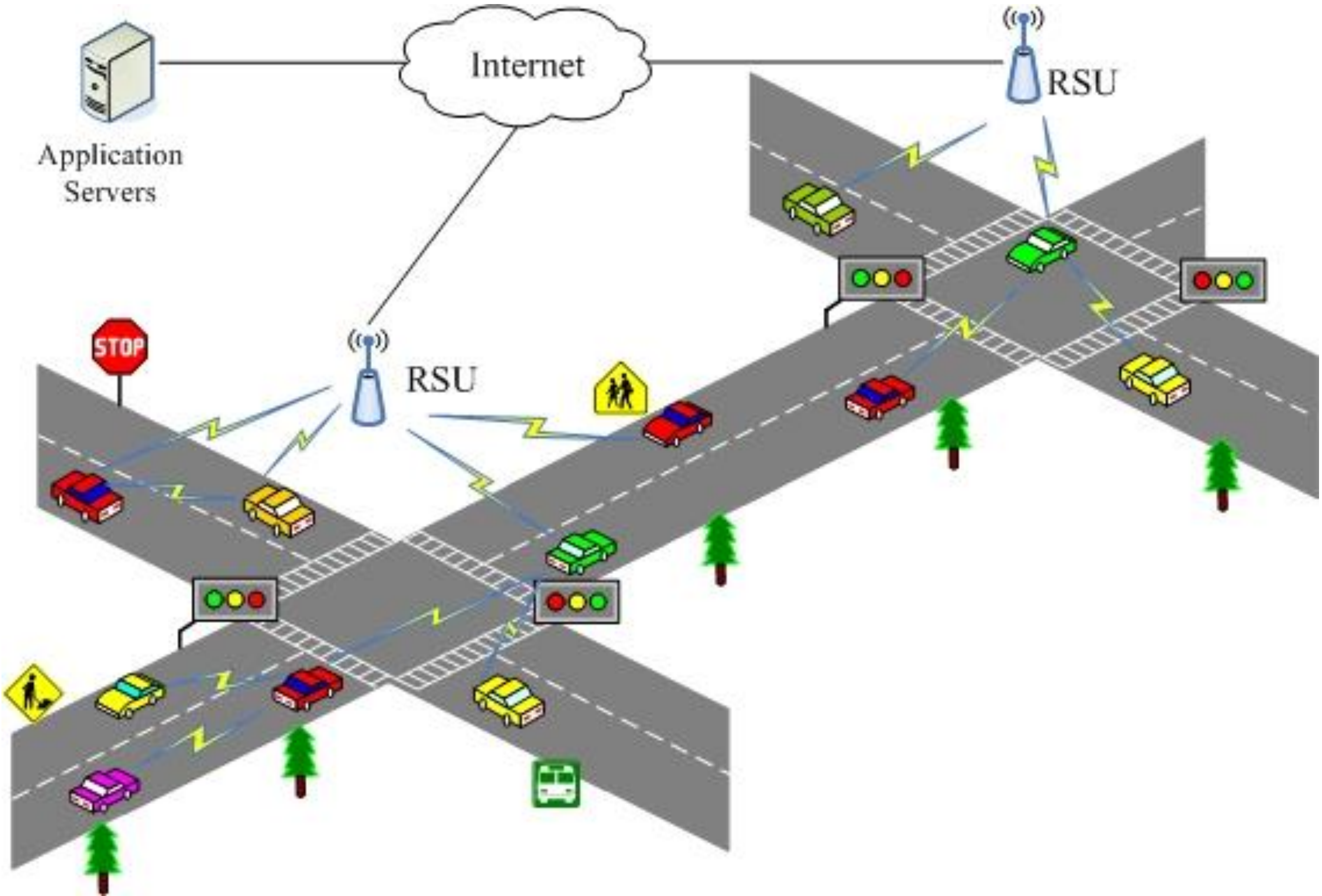


Vehicle to Everything Communication

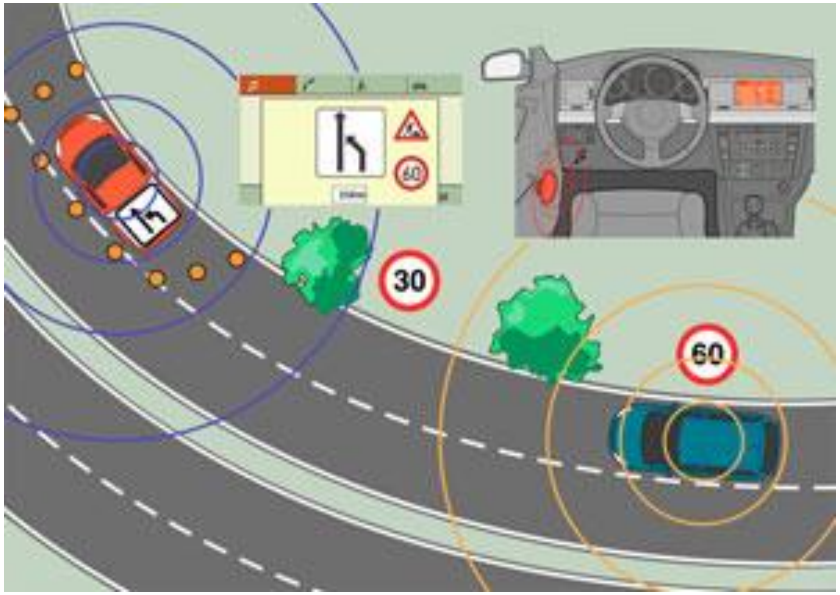
- **Initially, before 5G**

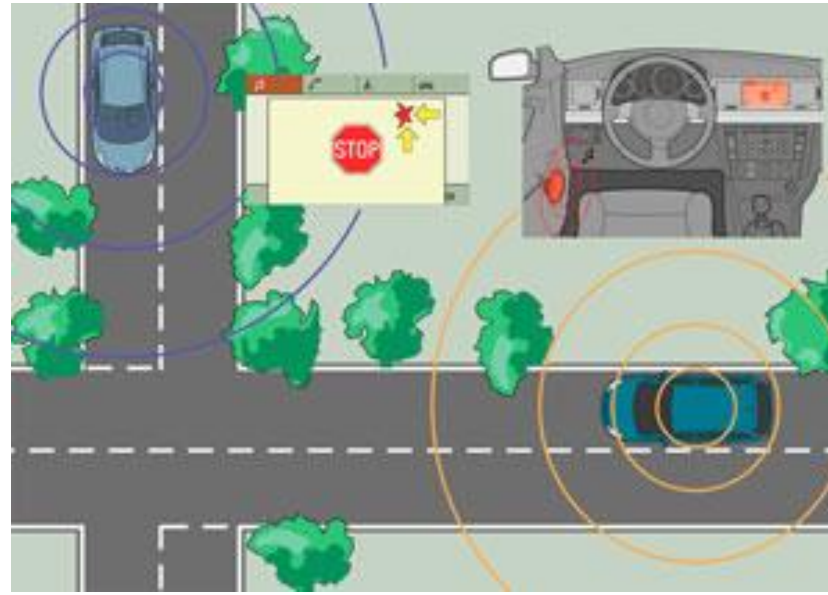


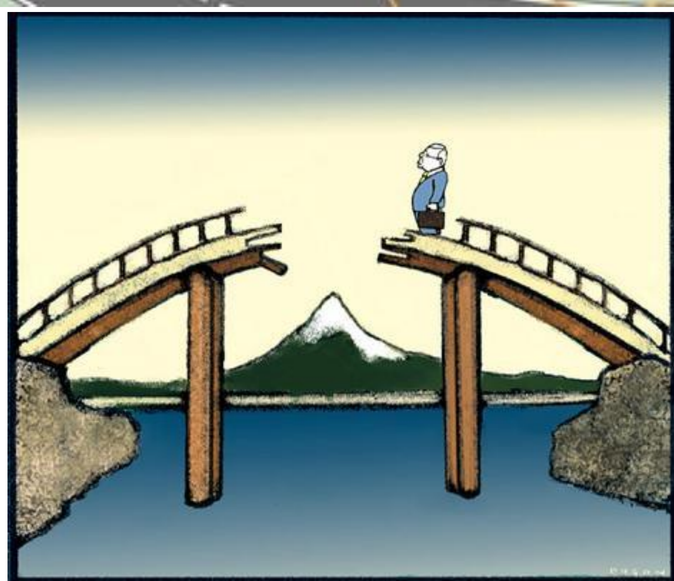
Vehicular networks



Warnings

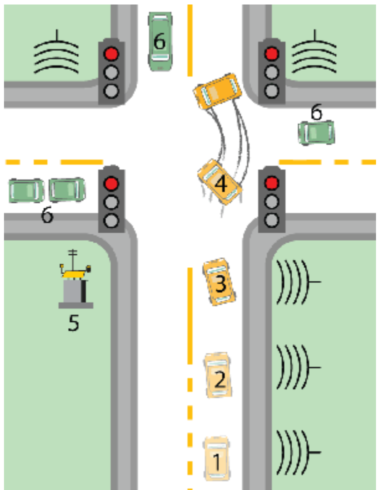


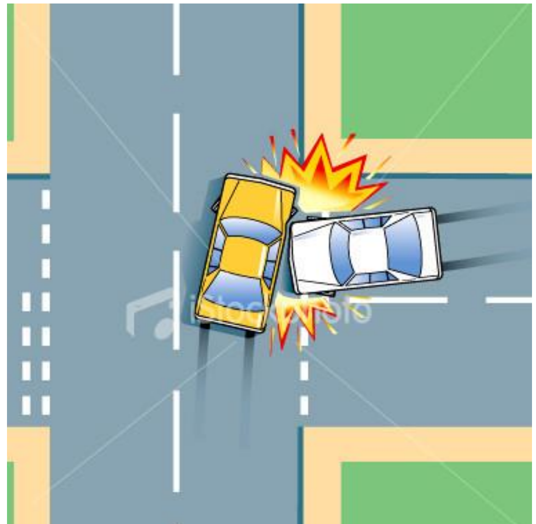


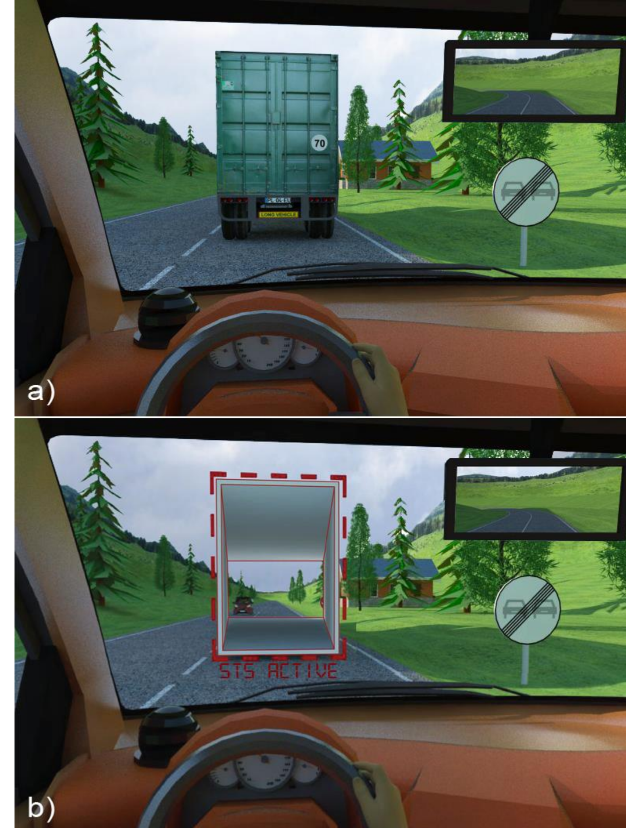


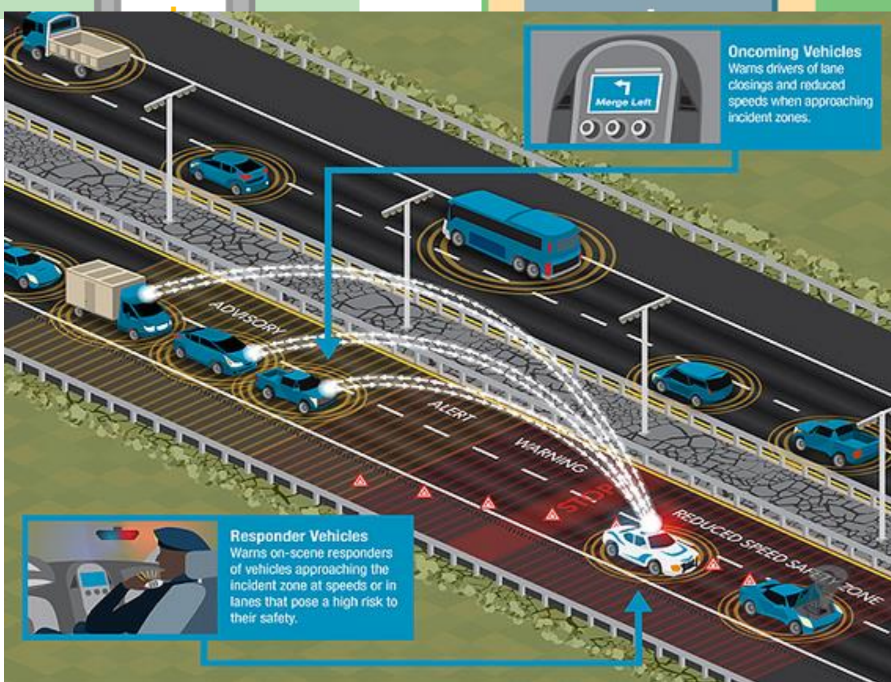
Traffic and road conditions

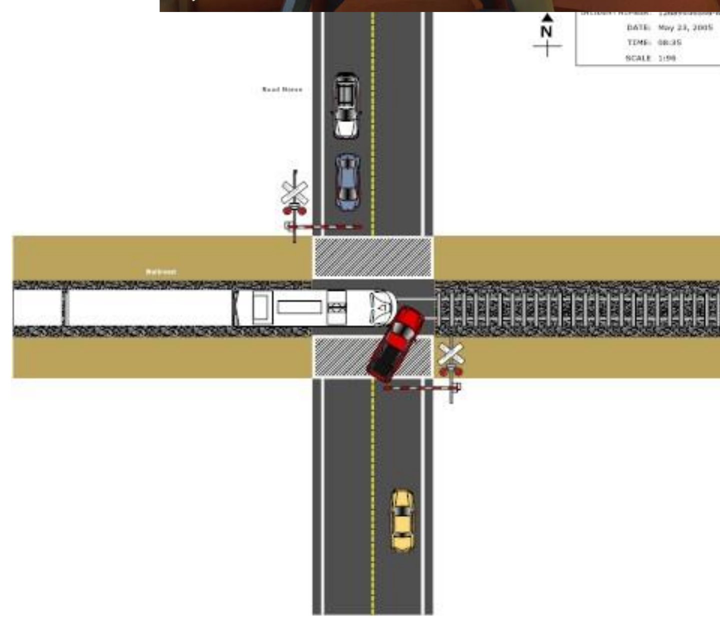
Safety


6
6
6
4
3
5
2
1

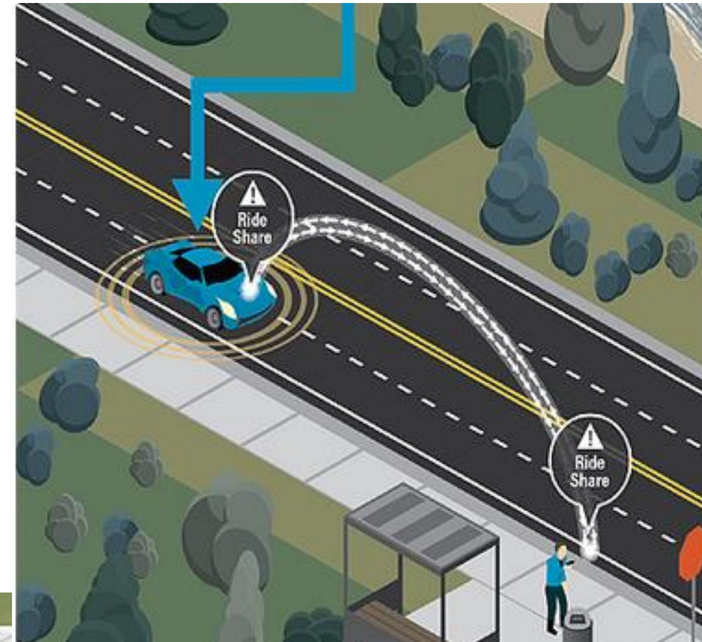



a)
STS ACTIVE
b)

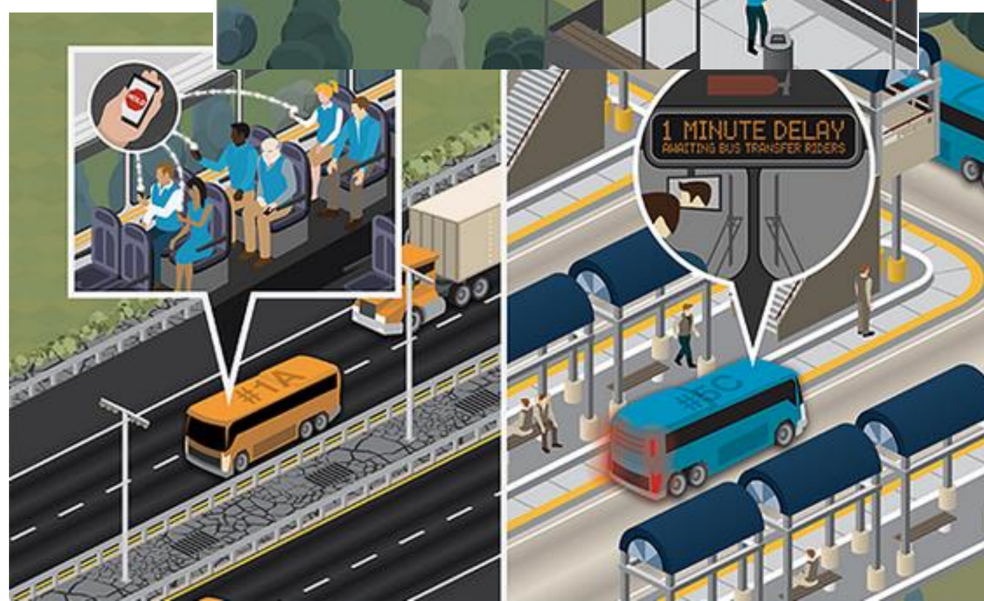

Merge Left
Oncoming Vehicles
Warns drivers of lane closings and reduced speeds when approaching incident zones.
ADVISORY
ALERT
WARNING
STOP
REDUCED SPEED SAFETY ZONE
Responder Vehicles
Warns on-scene responders of vehicles approaching the incident zone at speeds or in lanes that pose a high risk to their safety.


N

Efficiency

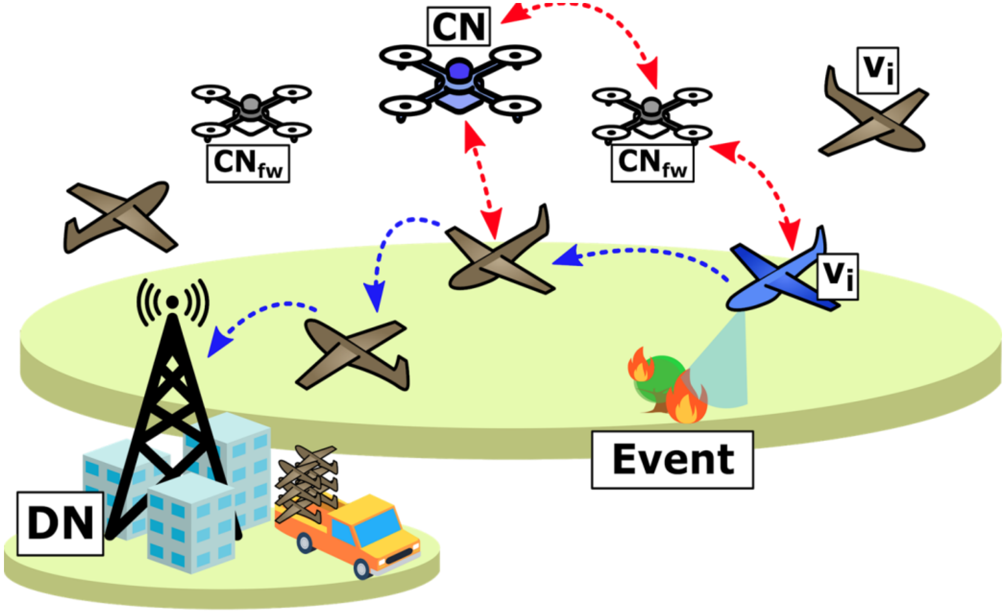

Ride Share
Ride Share


LIACC

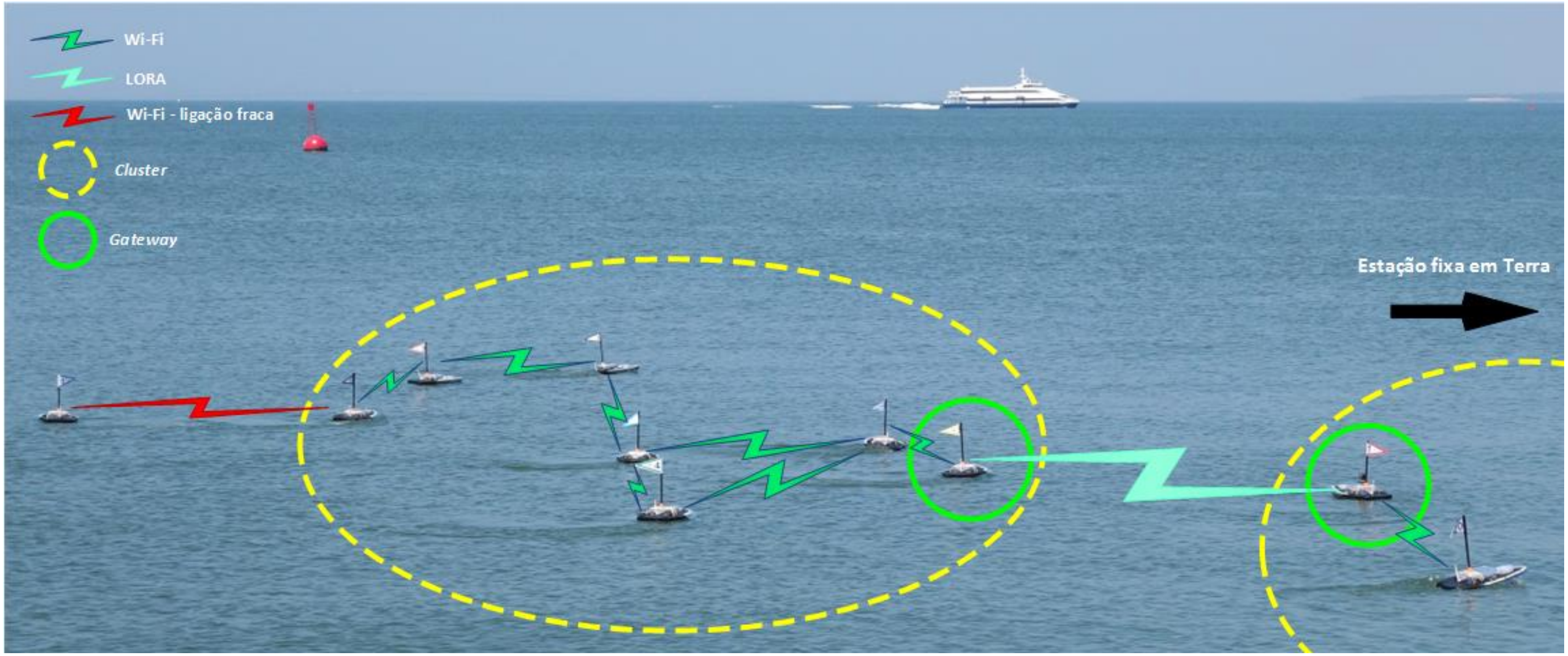

1 MINUTE DELAY
AWAITING BUS TRANSFER RIDERS
#1A
#5C

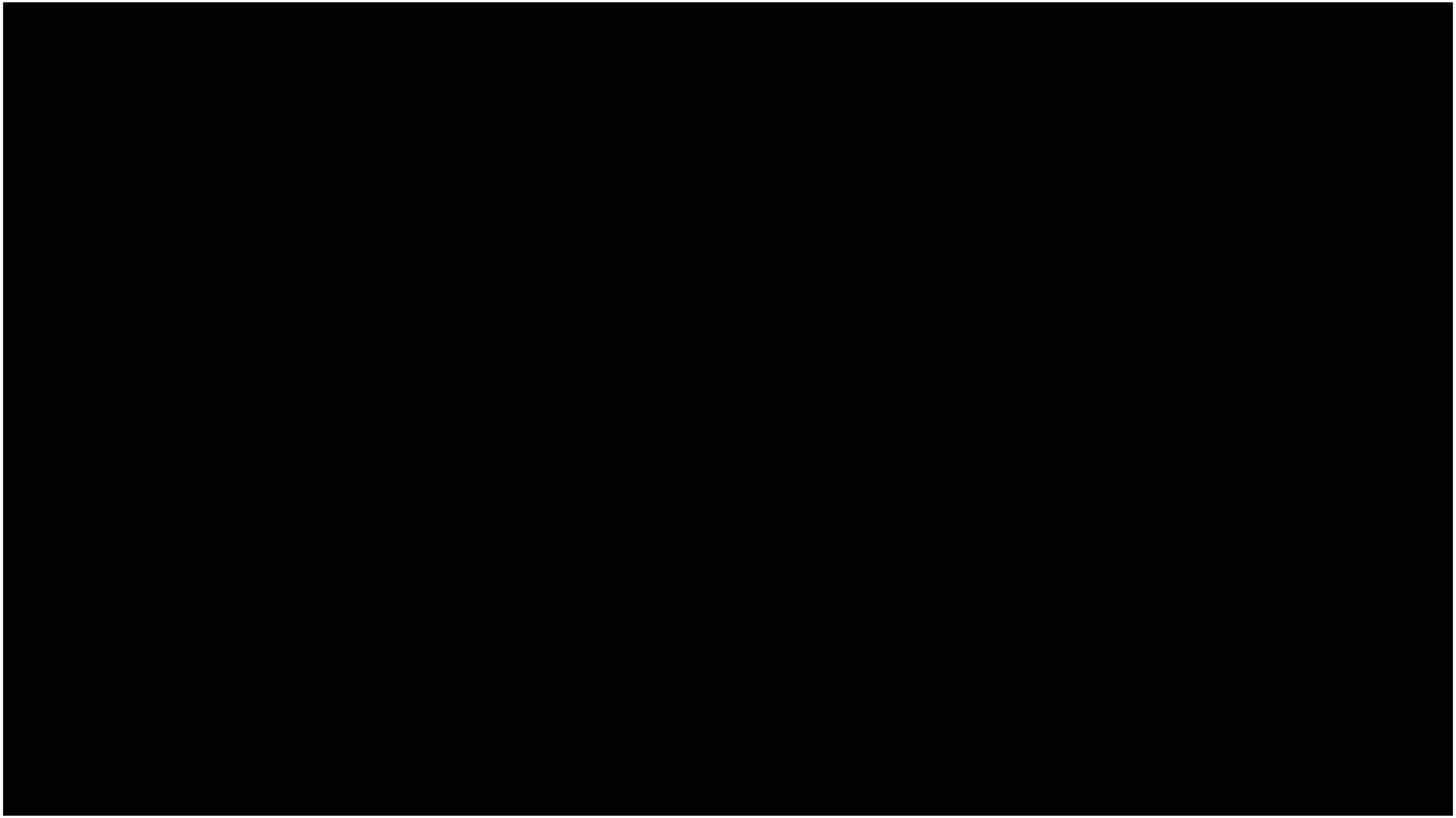
SelfDriving

Other types of vehicular networks

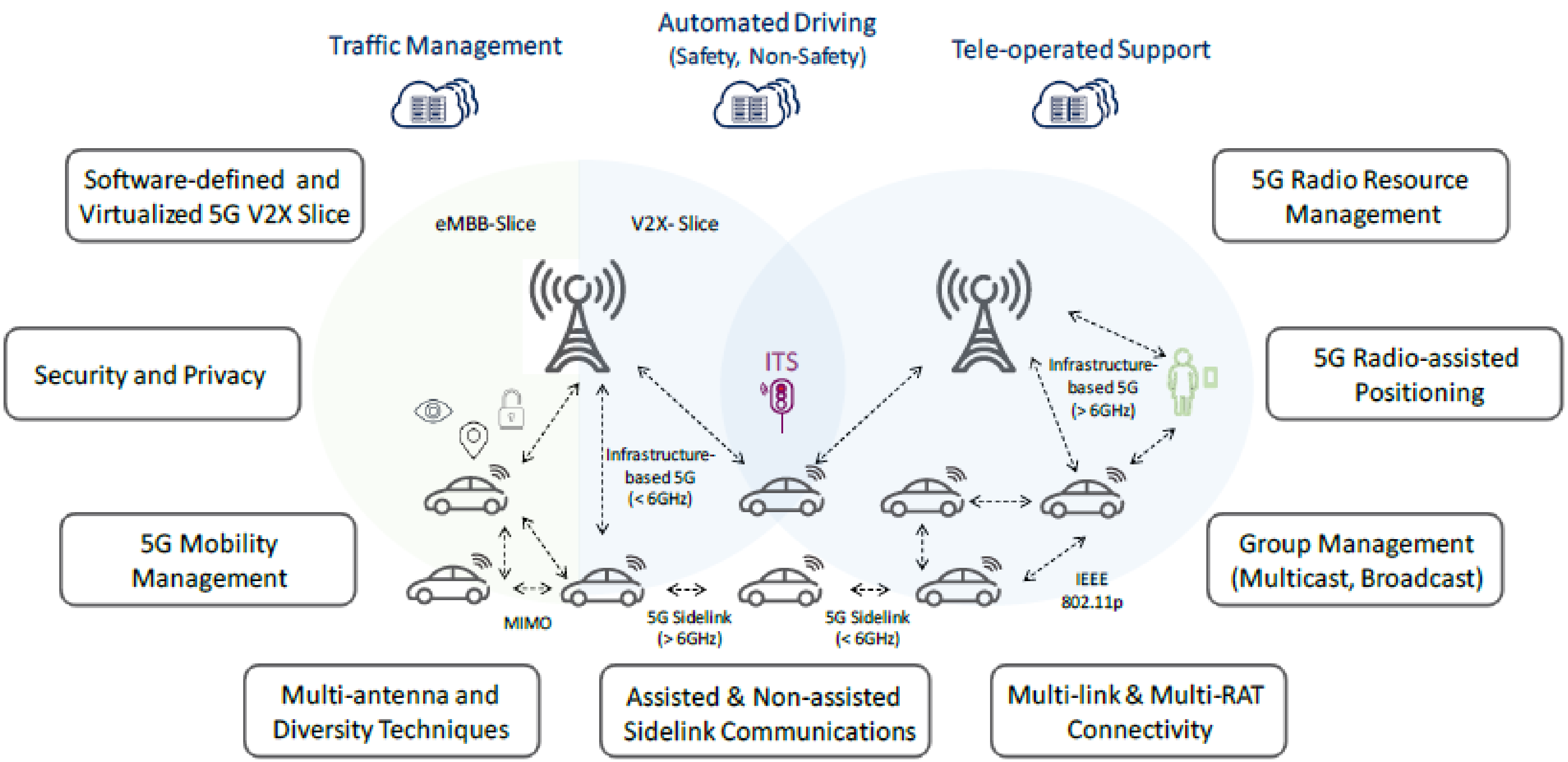


Other types of vehicular networks



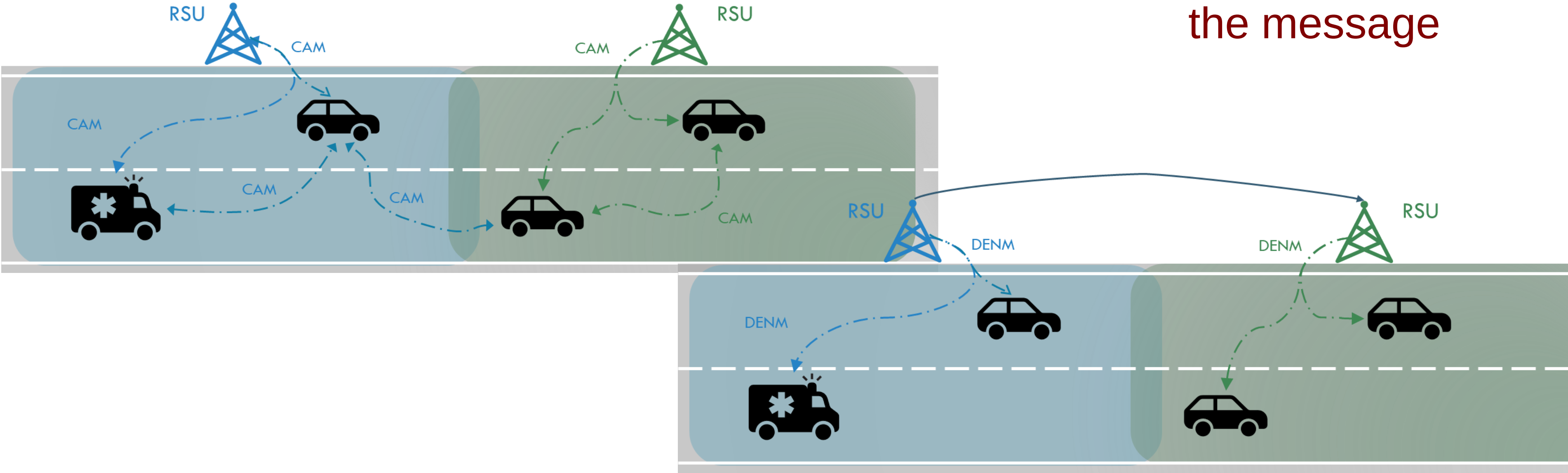


How do they work?
Intelligent Transportation Systems

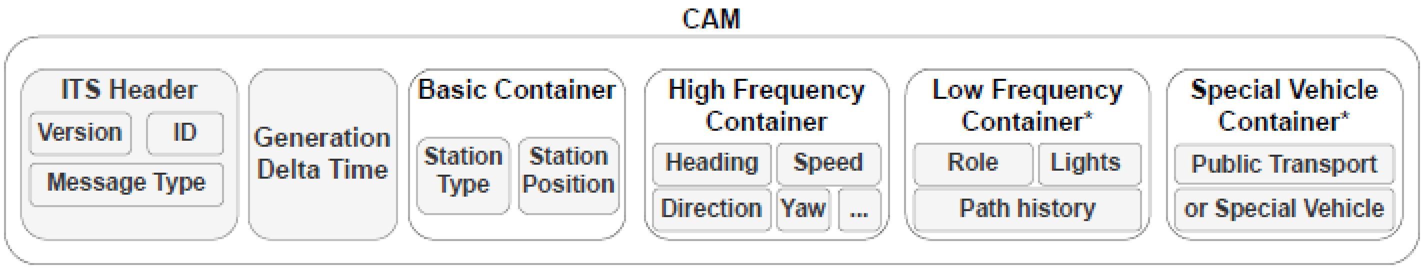


Awareness and warning information

- 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



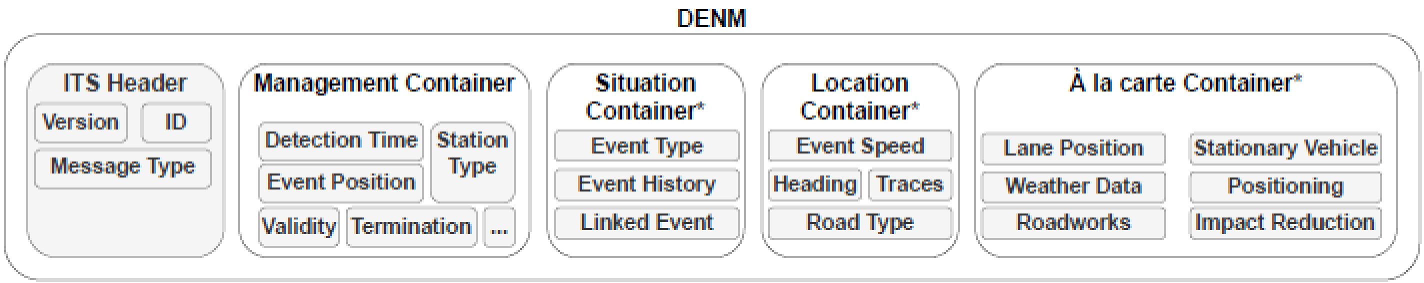
- Create and maintain awareness of vehicles using the road network or RSUs.
- The content varies depending on the type of ITS-S:
  - Vehicles: time, position, motion state, activated systems (*e.g.*, cruise control, pedals, and others), and the attribute information includes data about the dimensions, 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

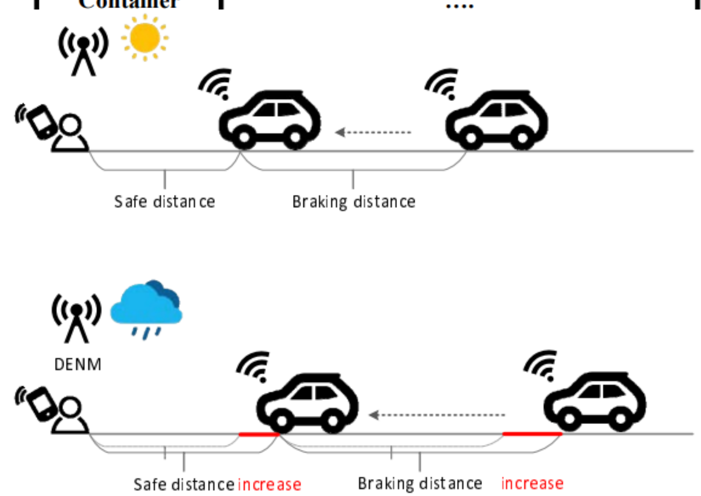


- Asynchronous messages to create and maintain awareness about a road event - *e.g.* road hazard or an abnormal traffic condition - such as its type, position, validity, timestamp and the history of the event.
- While the content varies depending on the type of event, it is expected that at least the 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.

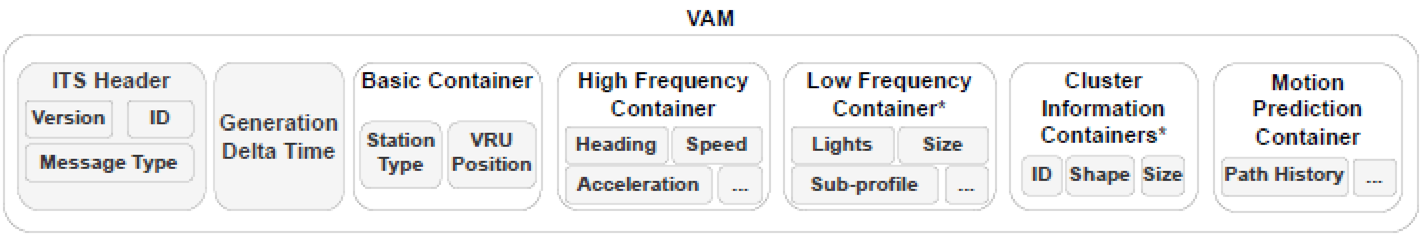
Decentralized environmental notification messages

- 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.

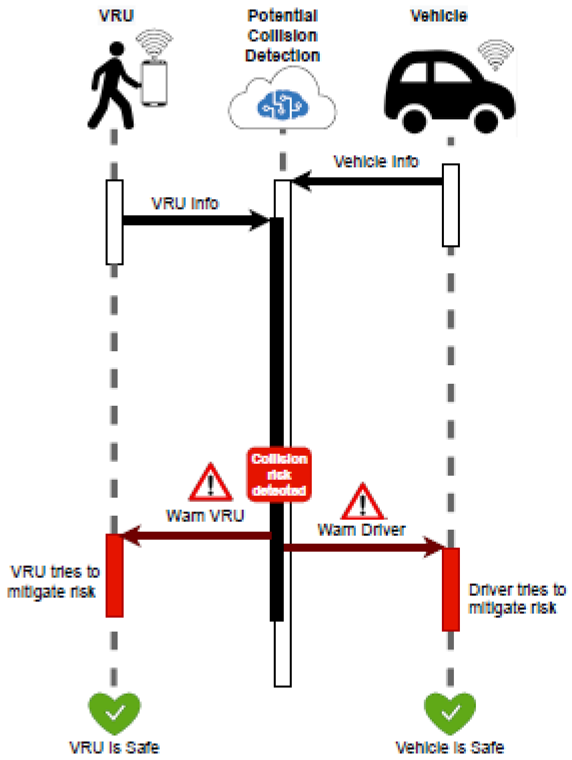
DENM Information	Management Container	Last Vehicle Position (GPS)
		Event Identifier
		Time of Detection
		Time of Message Transmission
		Event Position (GPS)
		Validity Period
		Station Type (Motor Cycle, Vehicle, Truck)
		Message Update / Removal
		Relevant Local Message Area (geographic)
		Traffic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



Vulnerable Road User Awareness Message



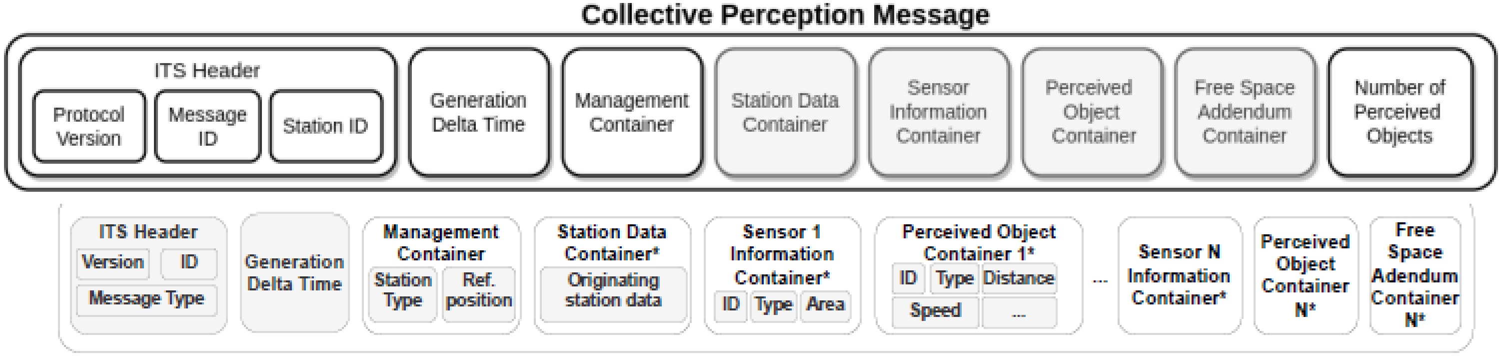
- Periodic messages exchanged in the ITS network between stations to create and maintain awareness on VRUs, and support the risk assessment
- Basic status: time, position, speed, heading, yaw rate and accelleration, orientation, lane position, dimensions and VRU type.
- Advantages of a VAM standard message 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 VRU - 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.

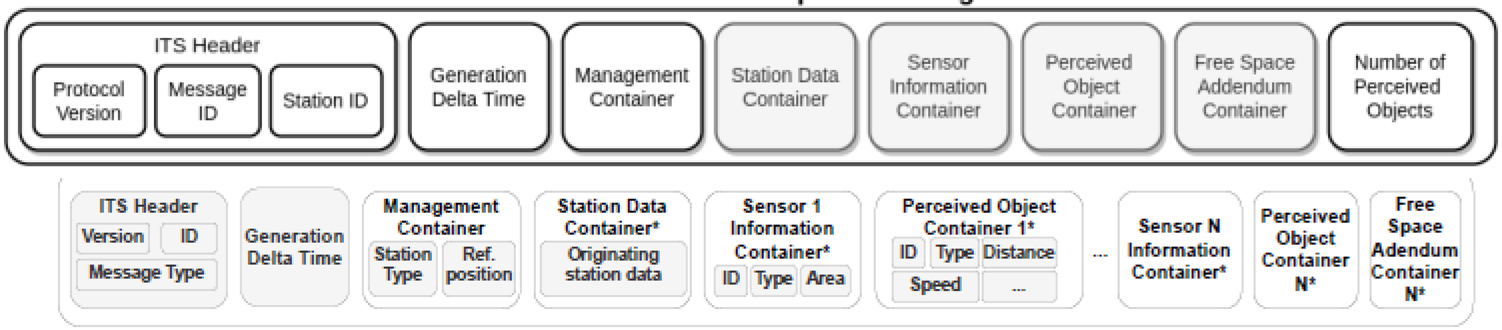
Cooperative Perception Message



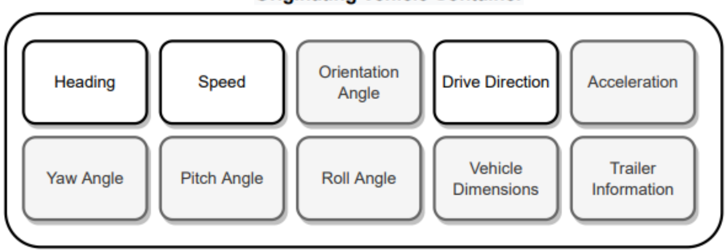
- Periodic messages between stations to broadcast information about the current environment perceived by 1 or more sensors.
- Sensors from a vehicle, a VRU and infrastructure can use CPMs to exchange the information obtained from their surroundings, improving the awareness of the situation.
- Sensor Information Container: sensor type - *e.g.* Radar, Lidar, video cameras or fusion algorithms, and the area the sensor covers.
- Perceived Object Container: objected 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

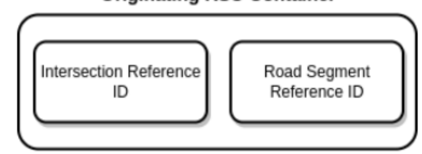
Collective Perception Message

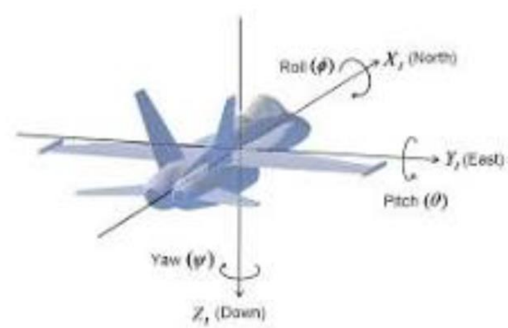


Originating Vehicle Container

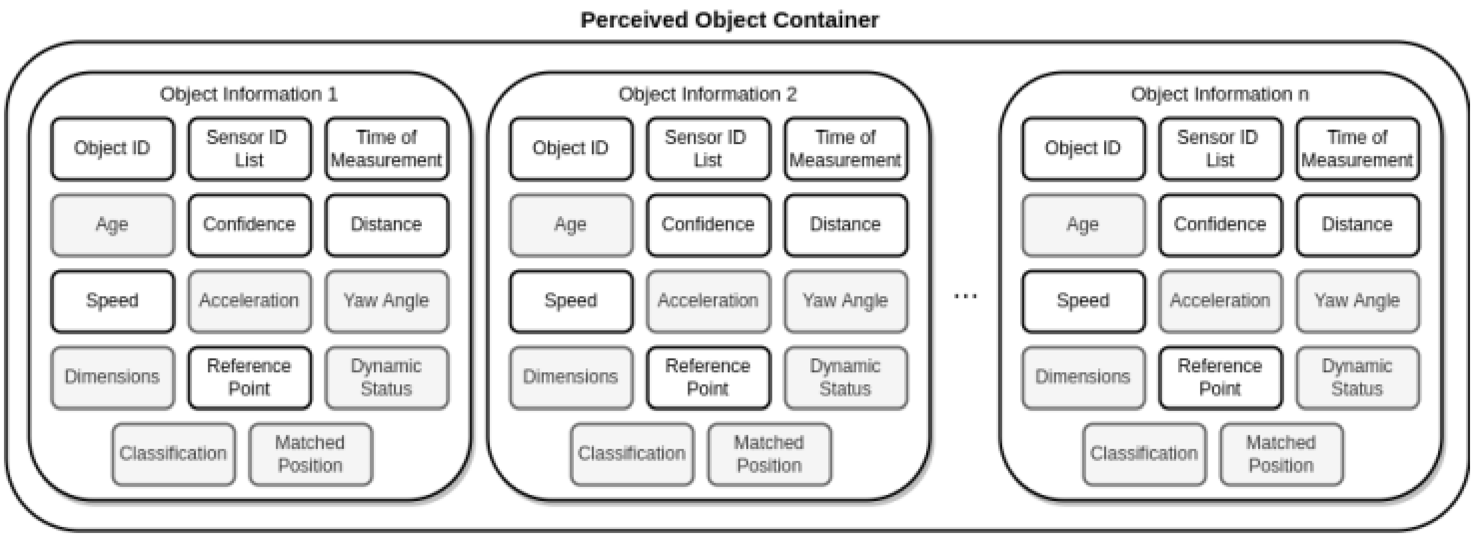


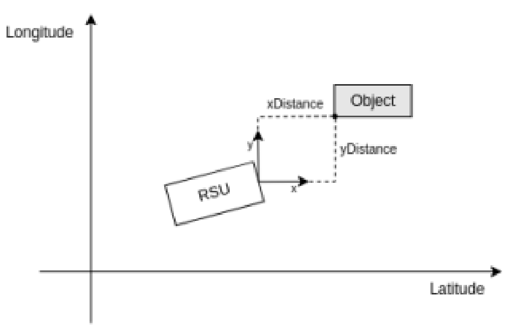
Originating RSU Container

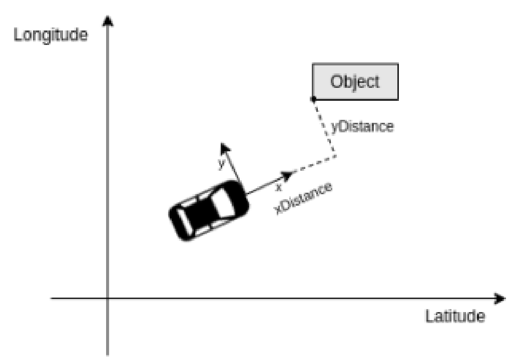


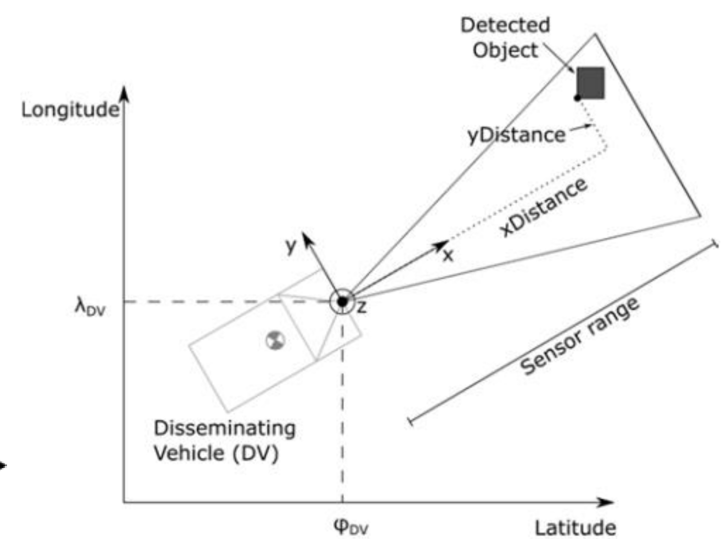


Objects information in CPMs







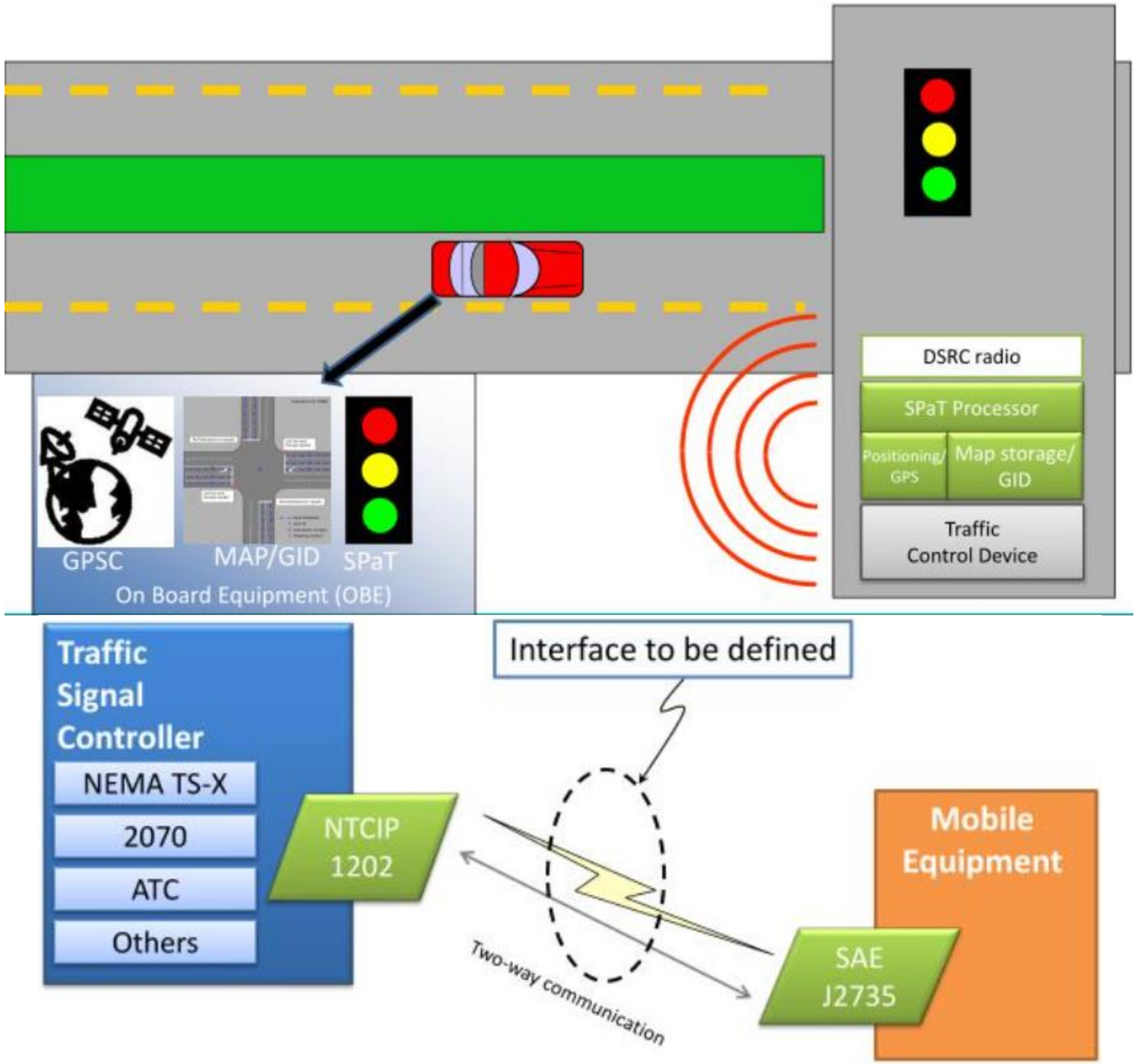


Coordinate System for detected object for vehicle

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 $CO2$ emissions
- Current state of all lanes at the intersection are provided, as well as any active preemption or priority

SPAT: Signal Phase And Timing

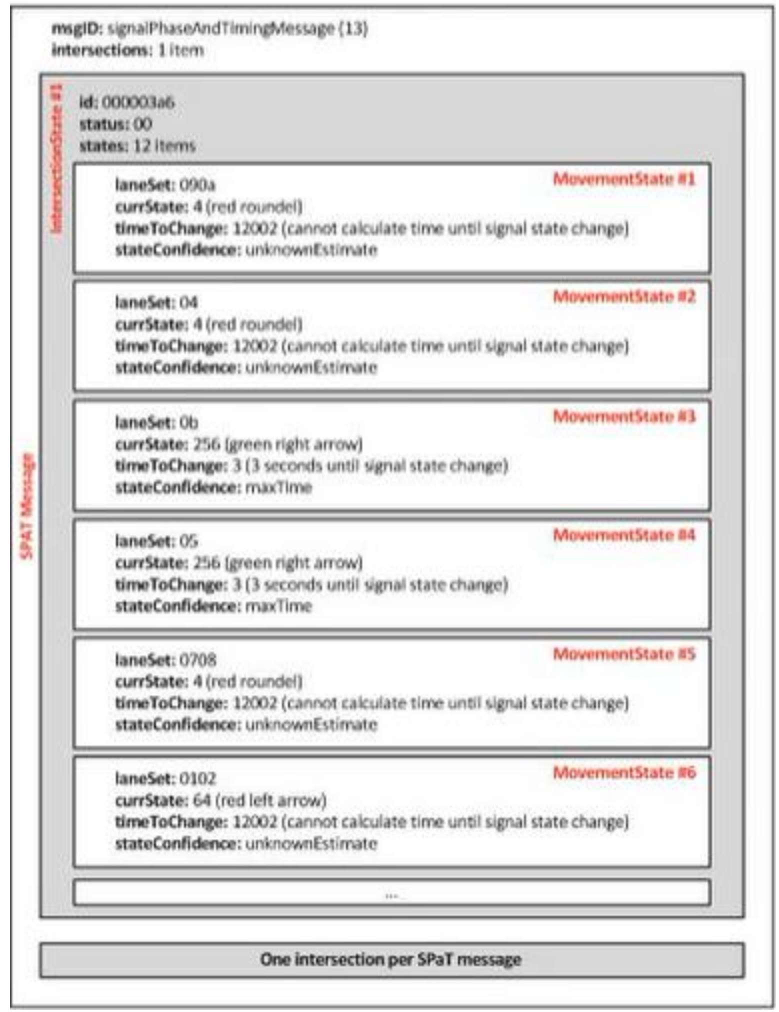


SPAT: Signal Phase And Timing

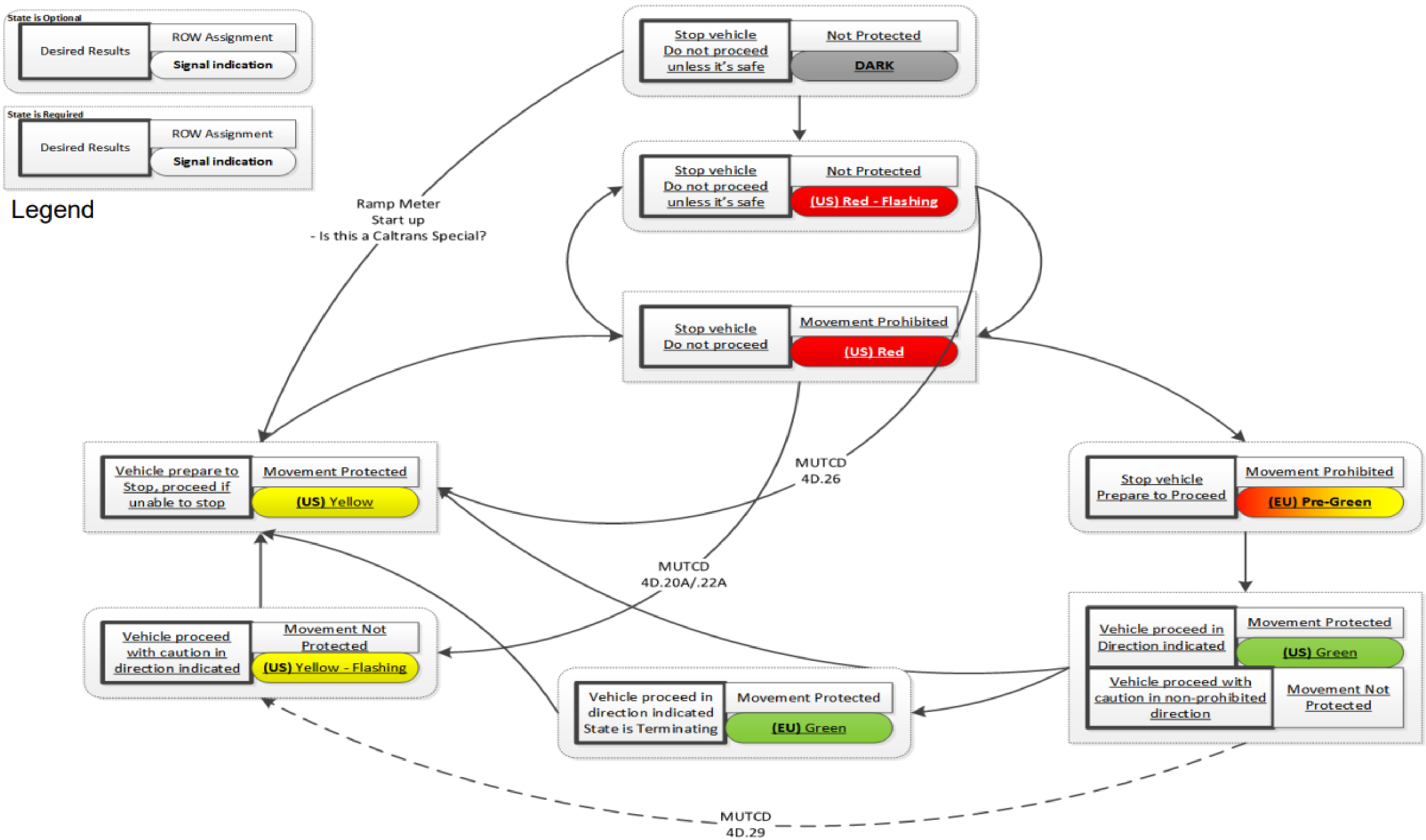
- Intersection state
- Movement state
  - Lane set (lanes 9-10 are for movement state 1)
  - Current state (green, yellow, red)
  - Time until current signal state changes

- Used in cooperation with a **map**

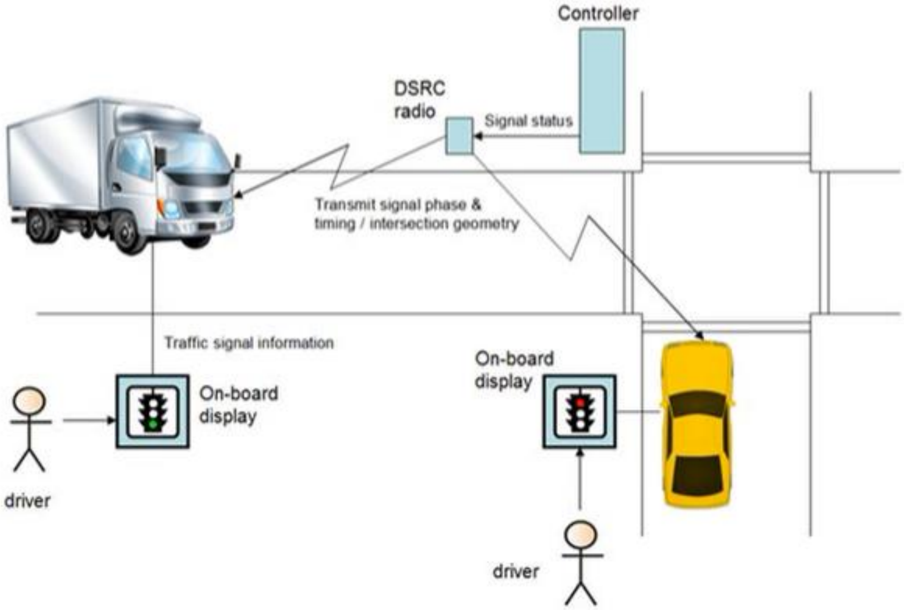
SPAT Message Structure

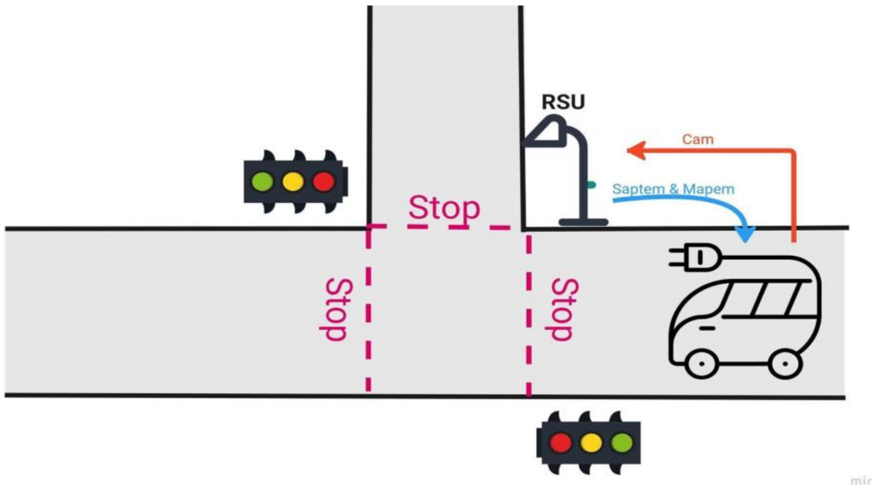


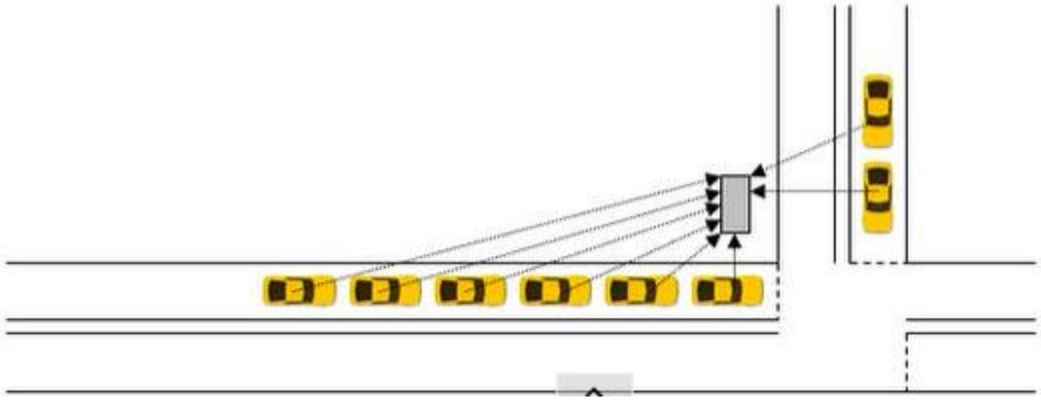
SPAT: State diagram



They can be used virtually

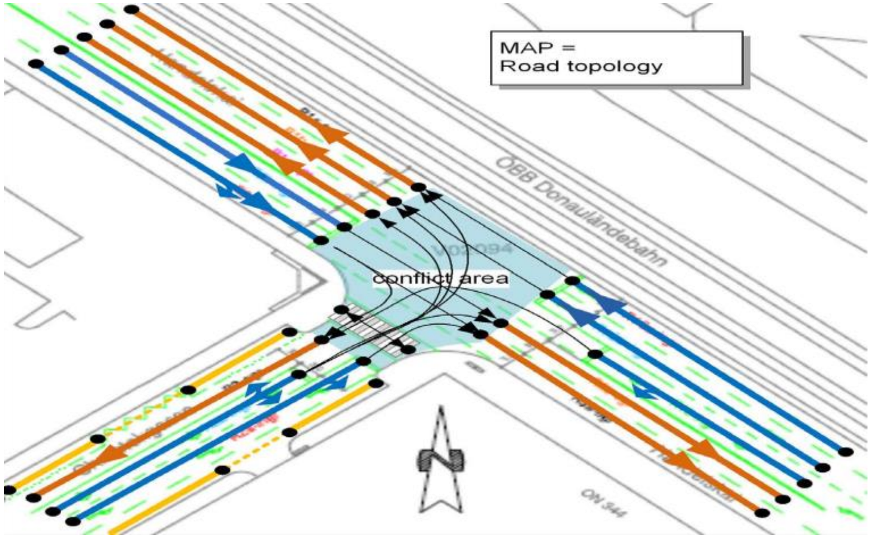






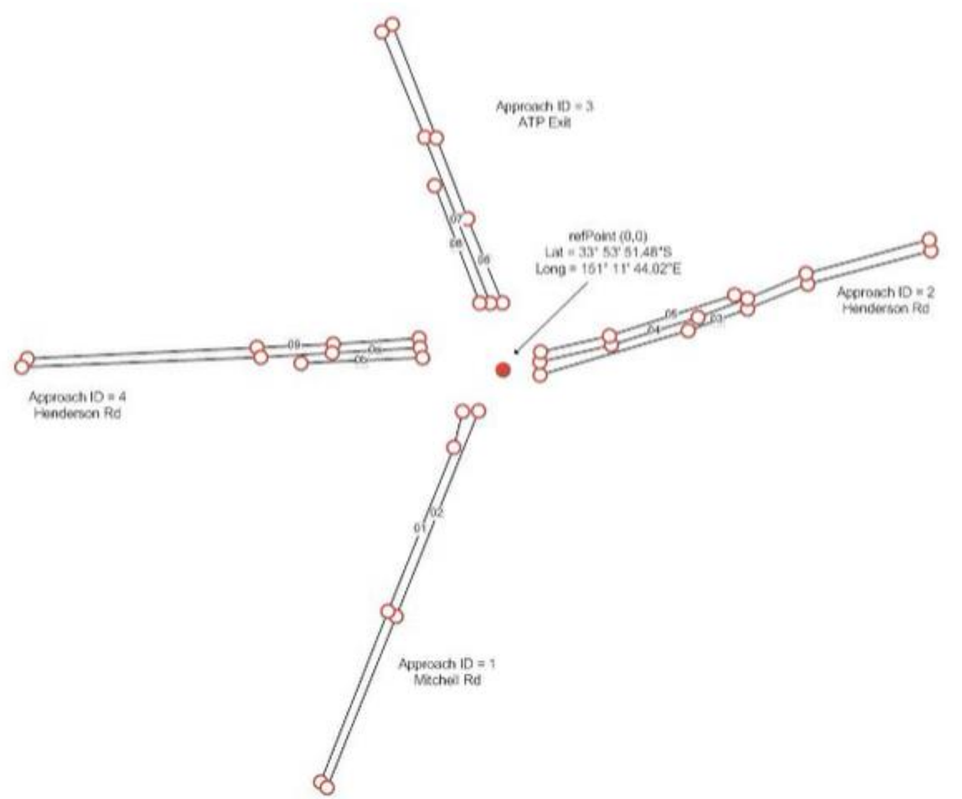
MAP: MAP

- 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

refPoint [Position3D]	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.	
laneWidth [LaneWidth]	The LaneWidth data element conveys the width of a lane in units of 1 cm.	
speedLimits [SpeedLimitList] (1..9)	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.
[laneSet] LaneList (1..255)	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.
preemptPriorityData [PreemptPriorityList] (1..32)	The PreemptPriorityList data frame consists of a list of RegionalSignalControl-Zone entries.	SignalControlZone

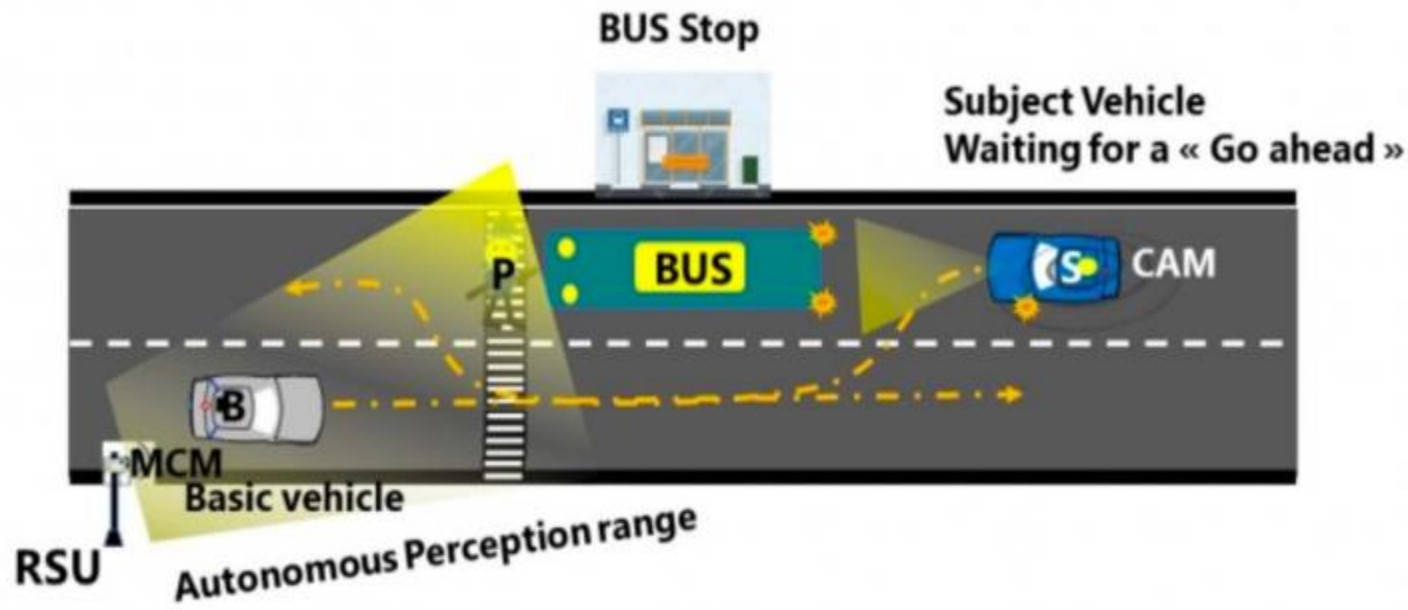


Manoeuvre Coordination Message (MCM)

- 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)

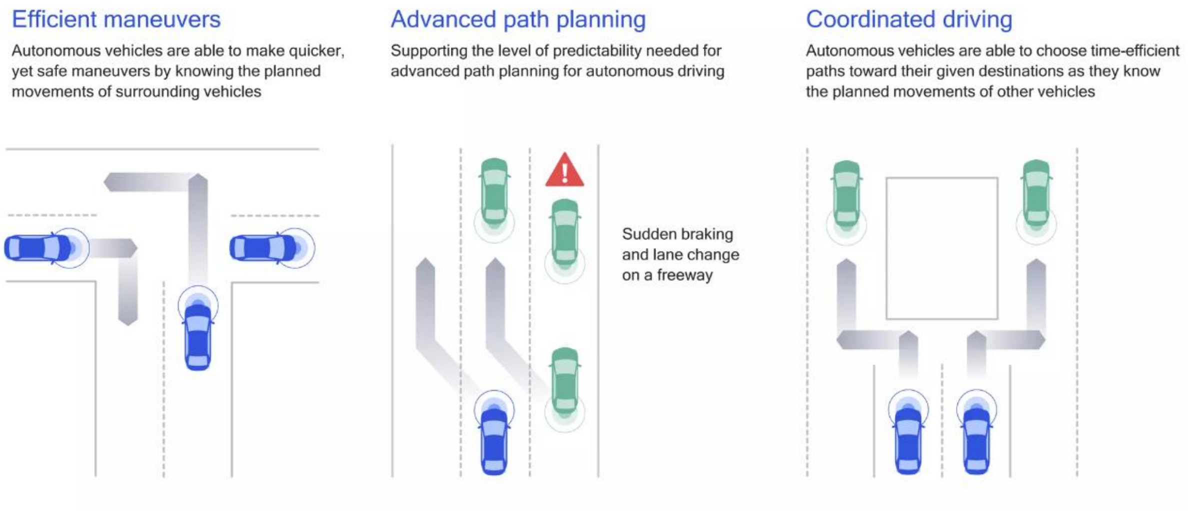
- Vehicle S wants to overtake the stationary Bus.
- Any road user or other equipped road safety stakeholder could analyse the road traffic situation based on received information combined with other sensor data
- Advice or manage the road users how to act to realize an efficient and safe resolution of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



TR 103 439 - V2.1.1 - Intelligent Transport Systems (ITS); Multi-Channel Operation study; Release 2 (etsi.org)

Manoeuvre Coordination Message (MCM) - examples

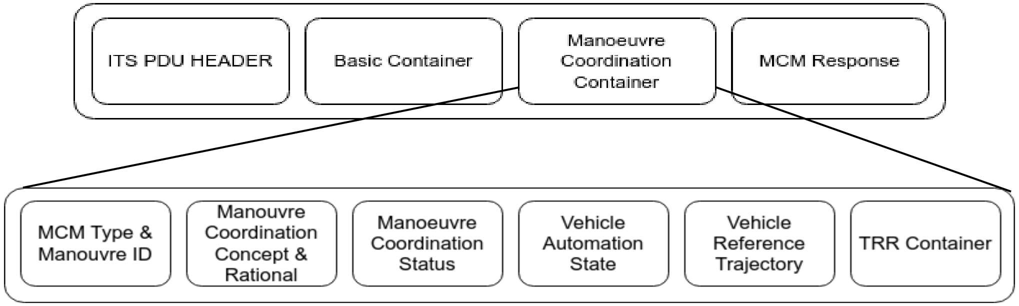
- Goto Maneuver
- Idle Maneuver
- Follow Path Maneuver
- Follow Trajectory
- Scheduled Goto
- Stop Maneuver
- Maneuver Done
- Teleoperation Maneuver
- Teleoperation Done
- …



- https://lsts.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

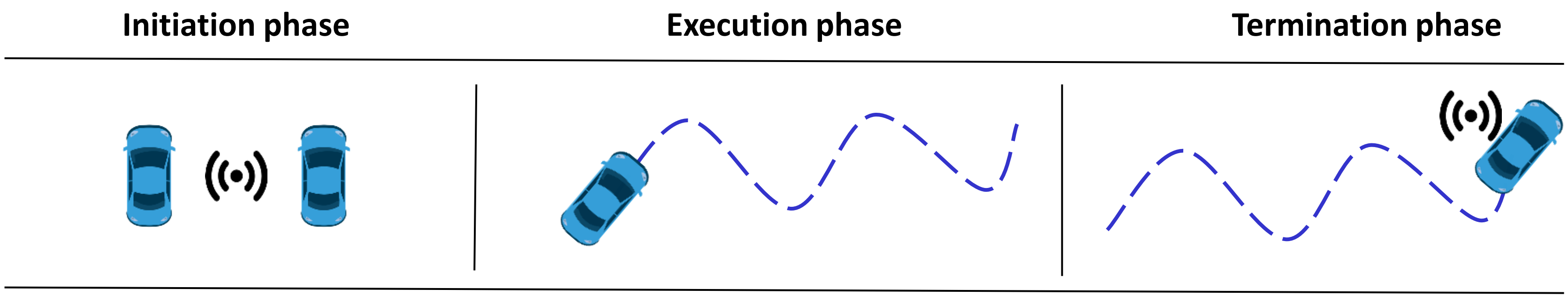
TRR Container: Vehicle Reference Trajectory for reservation of a roadresource

Maneuver Cooperation Service

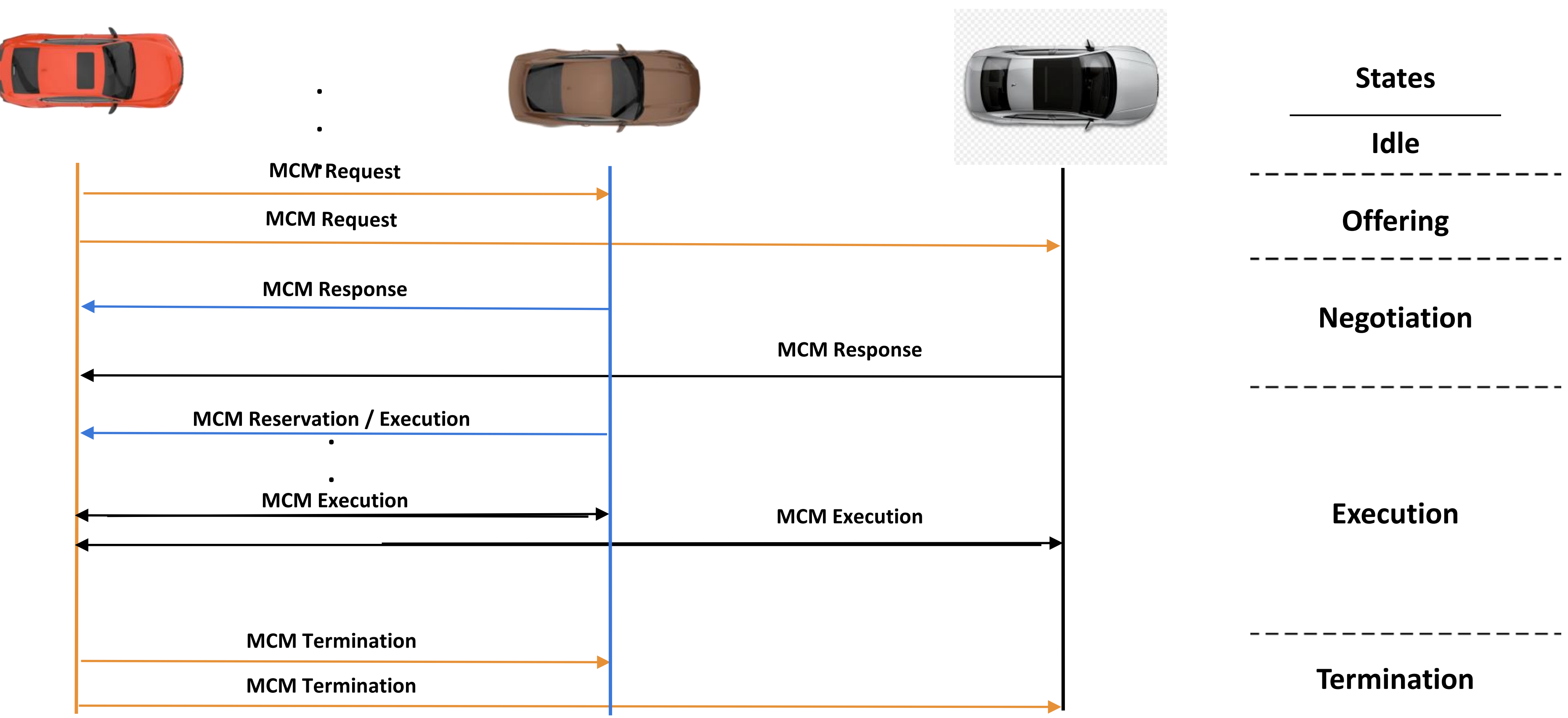
Service

- The Manoeuvre Cooperation Service (MCS) serves as the orchestrator and facilitator, responsible for producing and managing the distribution of MCM.
- 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

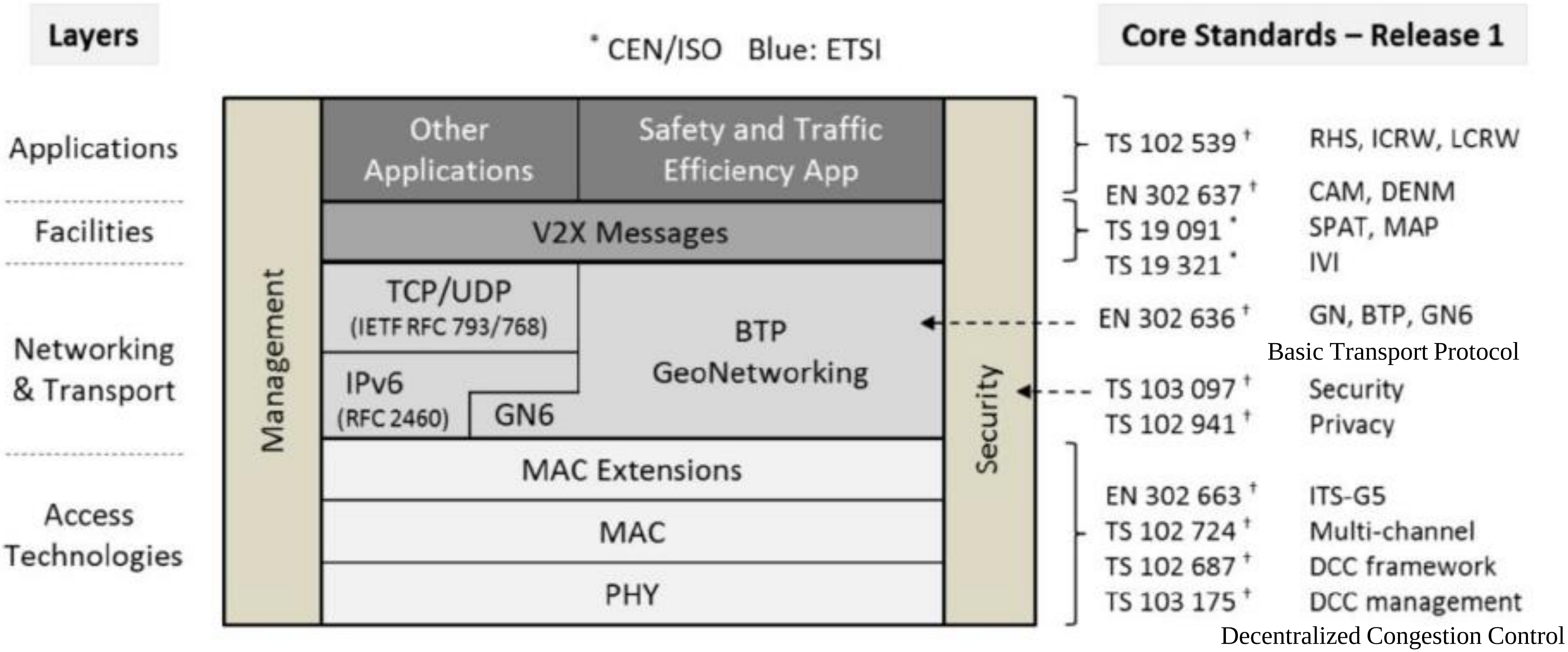
Requirements for the Communication Technologies

- Range (>200-400m)
- Delays (<10msec)
- Time for communication when in range (<10-20msec)
- Bandwidth (>>10Mb/sec.... → 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


Layers
* CEN/ISO Blue: ETSI
Core Standards – Release 1
Applications
Facilities
Networking & Transport
Access Technologies
Management
Other Applications
Safety and Traffic Efficiency App
V2X Messages
TCP/UDP
(IETF RFC 793/768)
BTP
GeoNetworking
IPv6
(RFC 2460)
GN6
MAC Extensions
MAC
PHY
Security
TS 102 539 † RHS, ICRW, LCRW
EN 302 637 † CAM, DENM
TS 19 091 * SPAT, MAP
TS 19 321 * IVI
EN 302 636 † GN, BTP, GN6
Basic Transport Protocol
TS 103 097 † Security
TS 102 941 † Privacy
EN 302 663 † ITS-G5
TS 102 724 † Multi-channel
TS 102 687 † DCC framework
TS 103 175 † DCC management
Decentralized Congestion Control

ITS-G5 Challenges

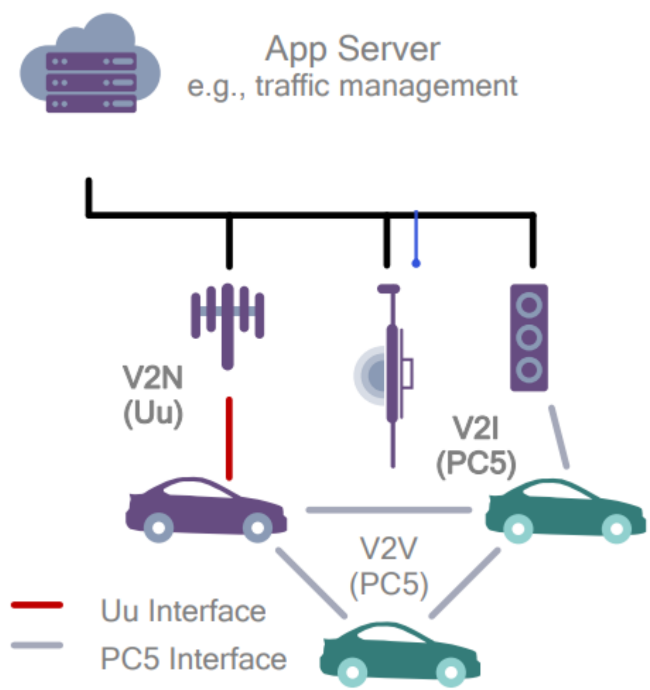
- Vehicle safety communication applications rely heavily on periodic broadcast of basic safety messages (BSM) which contain the positions, velocities, and other information about the vehicles.
- These messages with the PHY layer overheads typically have around 300 bytes with the full security certificate 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 (https://standards.ieee.org/ieee/802.11bd/7451/)

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

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

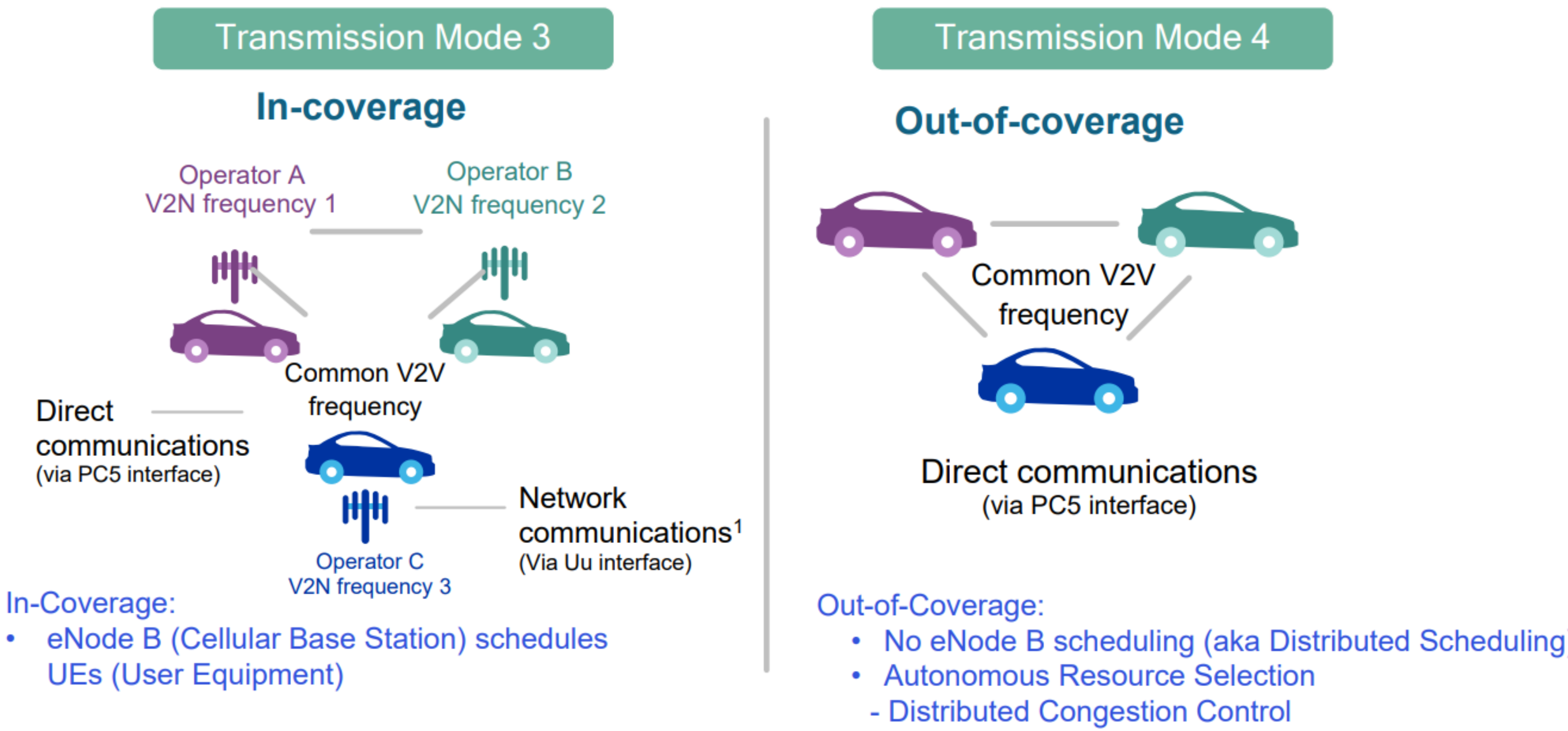
- Cellular-V2X defines a new air interface called PC5 for V2V, V2I communication.
- V2N is still over the legacy LTE Uu air interface and provides over the top cloud services.



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

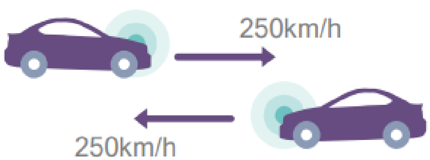
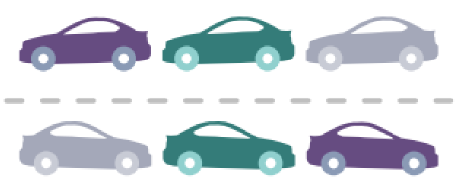
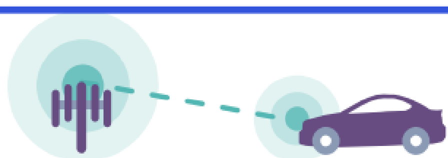
- C-V2X defines two Complementary Transmission Modes:
- 1) Direct safety communication independent of cellular network
  - Low latency Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Person (V2P) operating in ITS bands (e.g., 5.9 GHz)
- 2) Network communications for complementary 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

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

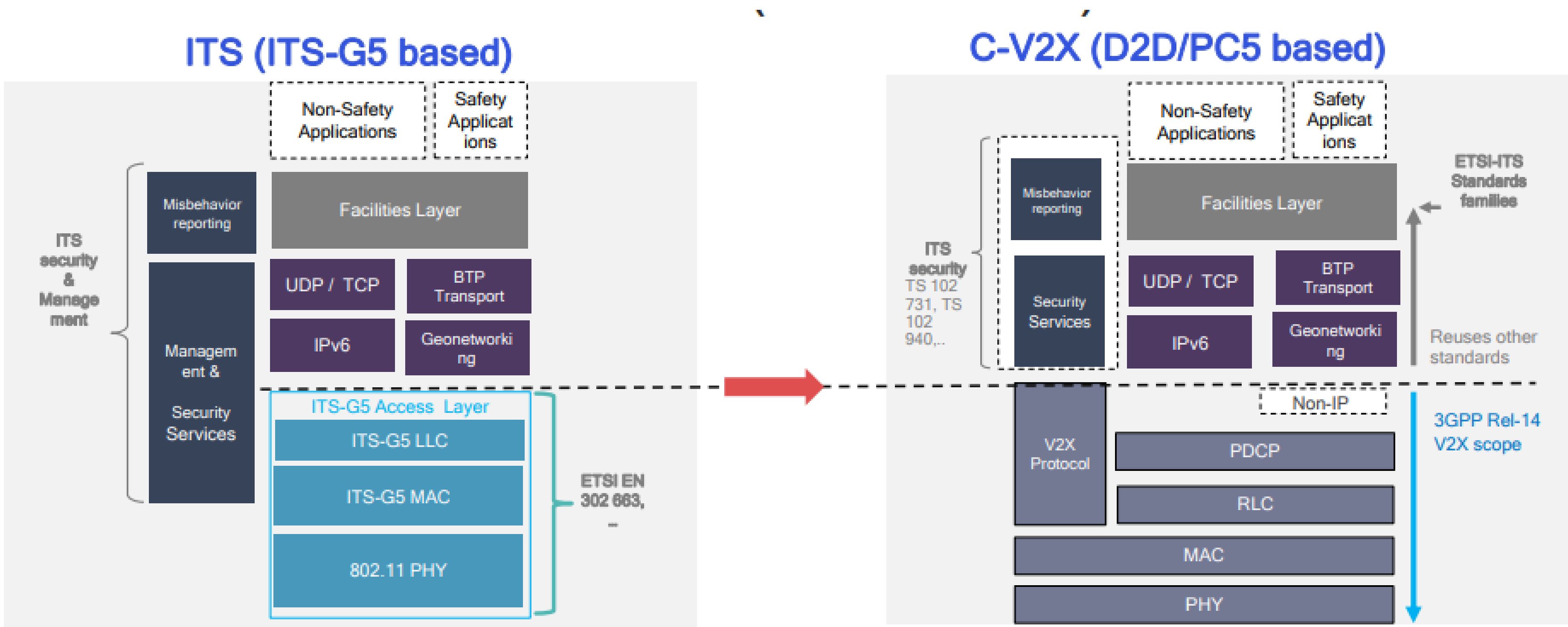


https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/c-v2x_intro.pdf

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

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

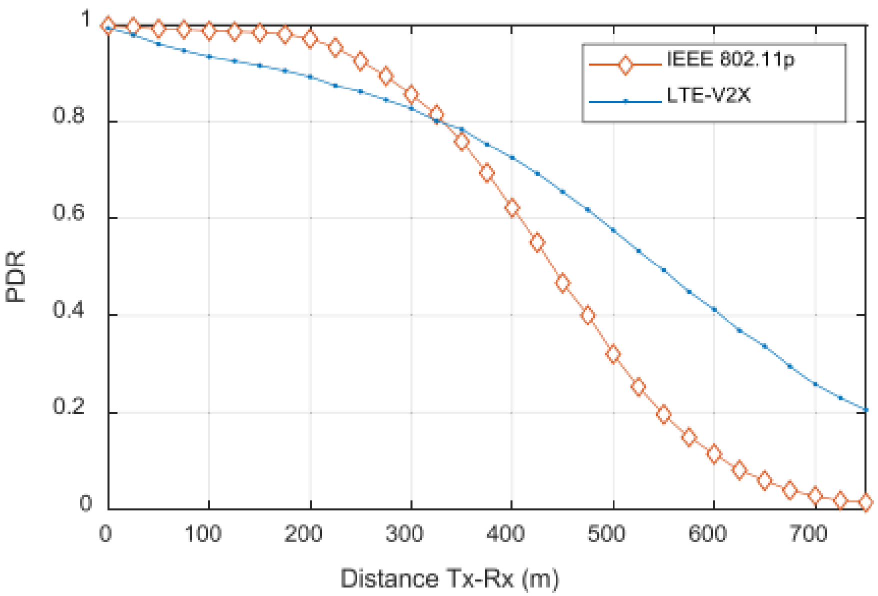
ITS-G5 vs C-V2X



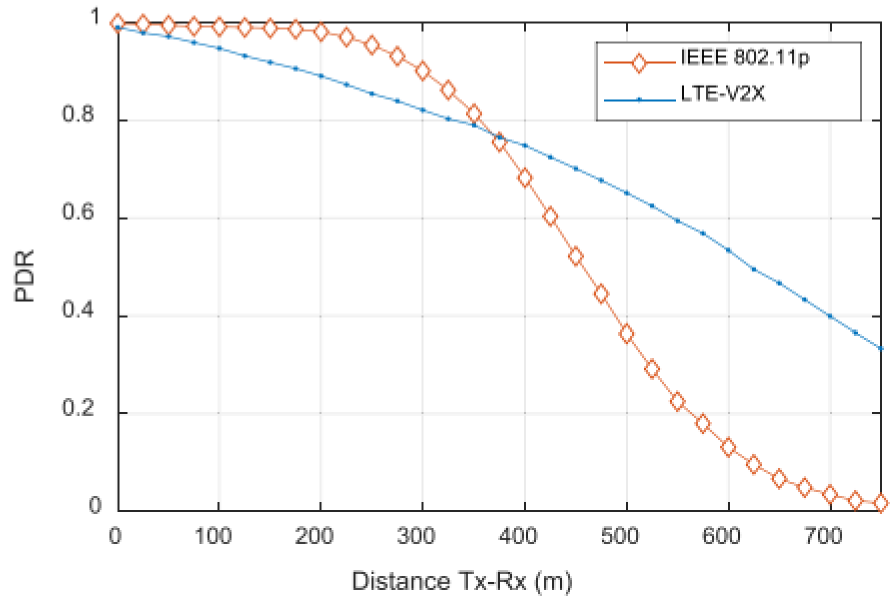
ITS-G5, C-V2X, 5G (Standalone)

Parameters	ITS-G5	C-V2X (LTE Rel. 14)	Future 5G SA
Currently available technology	Yes	Yes	No Yes, private networks
Field trials (+10 years)	Yes	No	No
Applications	V2V, V21	V2V, V2I, V2N	V2V, V2I, V2N
Latency	5 ms	20 ms	<5 ms
Data rate	3-27 Mbps	150 Mbps	10 Gbps
Multimedia and cloud services support	No	Yes	Yes

ITS-G5 vs C-V2X (Simulation)

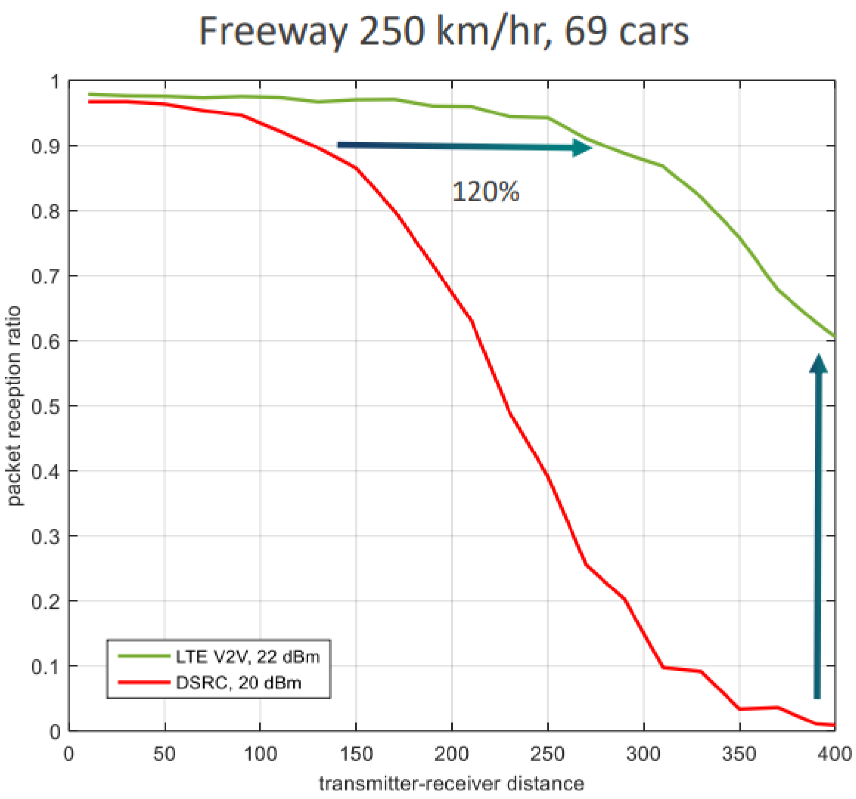


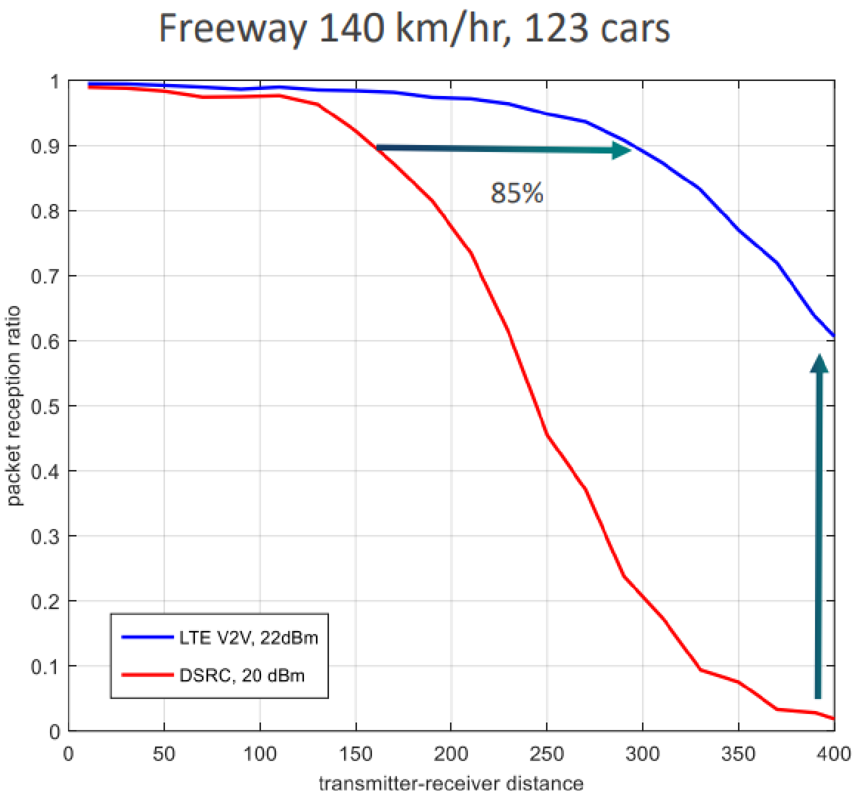
(a) *Empirical-size model*. 120 veh/km (CBR~0.33)



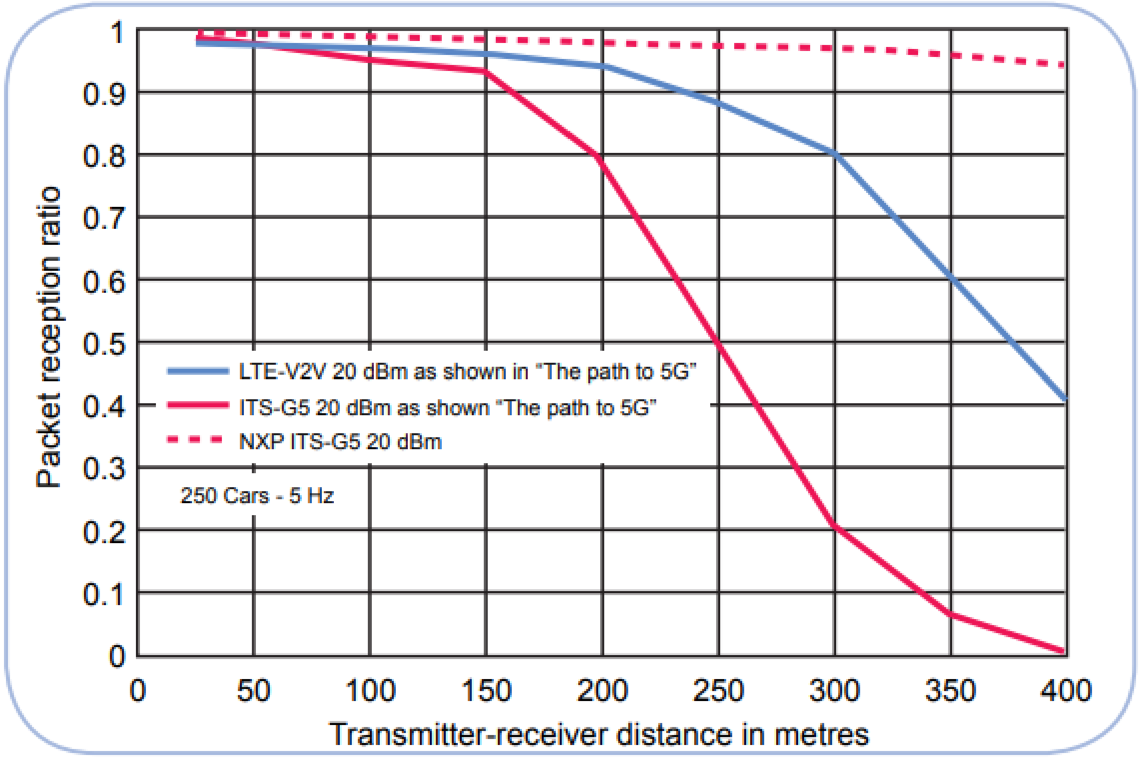
(b) *Empirical-time model*. 200 veh/km (CBR~0.23)

ITS-G5 vs C-V2X (Qualcomm)





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

https://www.etsi.org/deliver/etsi_ts/102600_102699/10263702/01.02.01_60/ts_10263702v010201p.pdf

https://www.etsi.org/deliver/etsi_ts/102600_102699/10263703/01.01.01_60/ts_10263703v010101p.pdf

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