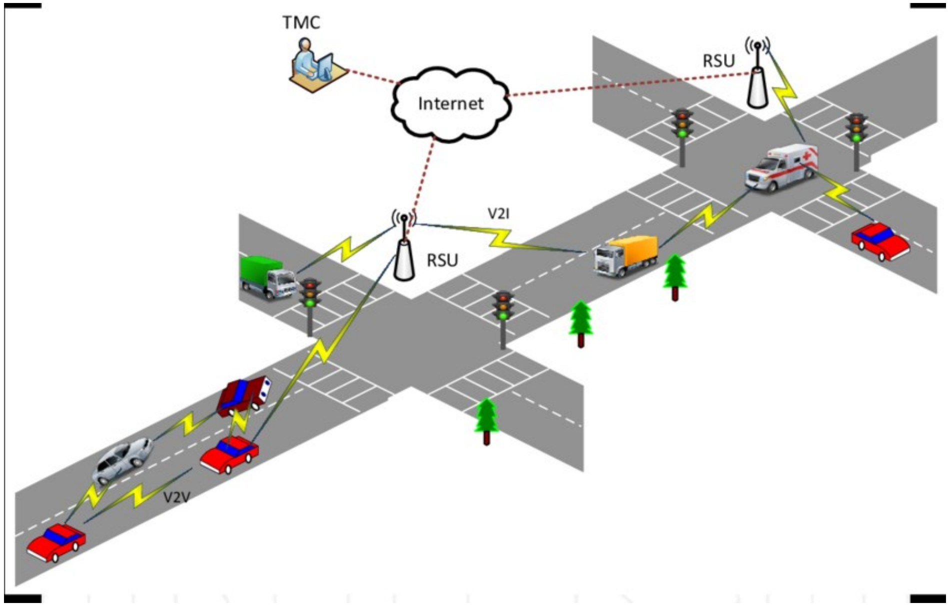
What Next?

- Vehicular networks
  - Requirements
  - Components
    - RSU (Roadside infrastructure units)
    - OBU (Onboard units in cars)
  - Vehicular network protocols
    - WAVE
    - 802.11p
    - 1609.x
  - Architectures & routing



Medium Access Control in VANETs: Requirements

- Supporting safety and non-safety applications
  - Safety applications: High reliability, low latency
  - Non-safety applications: Limiting bandwidth
- Implementation of point-to-point and point-to-multipoint communications
  - MAC protocol should sustain both types of communication
- Adaptation to single-hop or multi-hope delivery
  - MAC protocol for VANET is required to adapt to the single-hop or multi-hop traffic delivery

Medium Access Control for VANETs: Challenges

- Dynamic topology variation
  - Due to constant vehicle movement, the network topology changes rapidly and frequently
  - Channel quality and link reliability are drastically influenced
  - Mobile ad hoc networks (MANET) routing cannot be used
- Fast and reliable propagation
  - Vital emergency messages cannot tolerate a large delay
  - Accident information should be delivered across vehicles within 0.5 s
- Distributed communication
  - Centralized architecture doesn‘t work in VANETs with 802.11p
- Redundancy reduction
  - Broadcasting everything will clog the network
- QoS guarantee
  - Under the circumstance of high vehicle density, ensuring the QoS will be a challenge

Challenges in Numbers

Use-case	Type	Communication mode	Min. freq.	Max. latency
Emergency electronic brake lights	DEN/ V2X	Time limited, event-based periodic broadcast	10 Hz	100 ms
Abnormal condition warning	DEN/ V2X	Time limited, event-based periodic broadcast	1 Hz	100 ms
Slow vehicle warning	CAM/ V2X	Periodic broadcast, vehicle-mode dependent	2 Hz	100 ms
Wrong way driving warning	DEN/ V2X	Time limited, event-based periodic broadcast	10 Hz	100 ms
Signal violation warning	DEN/ I2X	Time limited, event-based periodic broadcast	10 Hz	100 ms
Pre-crash sensing warning	DEN/ V2X	Time limited, event-based periodic broadcast	10 Hz	50 ms

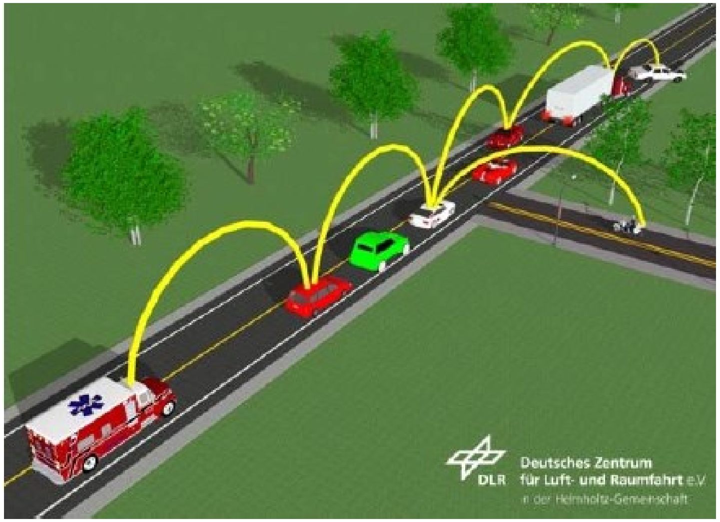
Source: “Ready to roll: why 802.11p beats LTE and 5G for V2X”

IEEE 802.11p Requirements

- Communication link between the vehicles and the roadside infrastructure exist for only a short time interval
  - Vehicle at 100 kph to an RSU
  - Vehicle 100 kph running in opposite directions
  - No time for authentication and association procedures prior to exchanging data
    - These sorts of functionality is moved to the upper layers

IEEE 802.11p Requirements

- Changes in baseline 802.11p standards are required to
  - Support longer ranges (up to 1 km)
  - High speed of vehicles (up to 500 kph relative velocities)
  - Extreme multipath environment (many reflections with long delays)
  - The need for multiple overlapping ad-hoc networks to operate with high quality of service
  - The nature of automotive applications to be supported (reliable broadcast of safety messages)



Source: DLR

Terms

- Roadside infrastructure units (RSU)
  - Provides wireless communication from roadside infrastructure to vehicles
  - Operates on 5.9 GHz direct short range communications (DSRC)
  - Ethernet connection to traffic signal controllers
  - GPS receiver for location and time
  - Local Wi-Fi hotspot
  - LTE cellular radio for long distance
  - Internal data storage for intersection map geometry
  - Software available for managing multiple roadside units from a central location

Source: Siemens (usa.siemens.com/intelligenttraffic

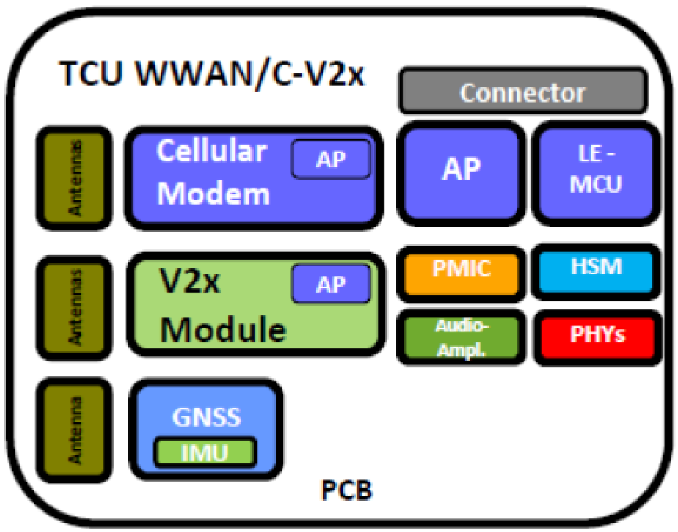
RSU Example

- Technical details
  - IEEE 802.11p 5.9 GHz DSRC
  - Receiver sensitivity of -97 dBm
  - IEEE 1609.4 security compliant
  - LTE for cellular backhaul (plan not included)
  - Sealed weatherproof enclosure
  - 2500 meter range, open-field, line-of-sight
  - CPU: Dual core at 800 Mhz for edge computing
  - 1 GB RAM
  - Power over Ethernet (PoE)

Source: Siemens

Terms

- Onboard units (OBU)
  - Network nodes on vehicles
  - Again, two different base technologies available
    - DSRC (802.11p)
    - Cellular vehicle network (LTE)



Source: P3, V2X Automotive On-board Unit Cost Analysis

Terms

- Pedestrian?

Source: DLR

Vehicular Ad Hoc Networks: Technologies

- Dedicated short-range communications (DSRC)
  - Also known as wireless access in vehicular environment (WAVE) in the US
- There are so many terms what is the relationship between them?
  - DSRC, IEEE 802.11p, IEEE 1609
  - IEEE 802.11p and IEEE 1609 standard define different parts of DSRC

Application	
Service/Presentation **IEEE 1609.1**	
Networking/Transport **IEEE 1609.3**	Security **IEEE 1609.2**
LLC/MAC upper **IEEE 1609.4**	
MAC lower/physical **IEEE 802.11p**	

IEEE 802.11p

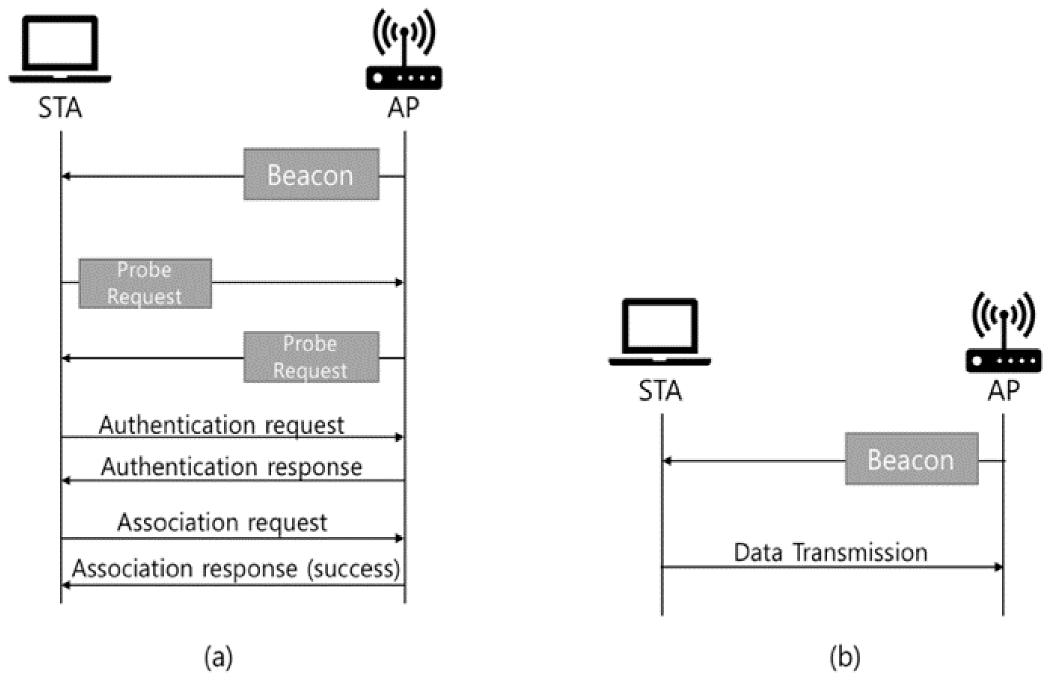
- IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add ***wireless access in vehicular environments*** (WAVE), published in 2010

- Data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure (RSUs in the Vein example!)

- Licensed ITS (Intelligent Transportation Systems) band of 5.9 GHz (5.85 GHz – 5.925 GHz)

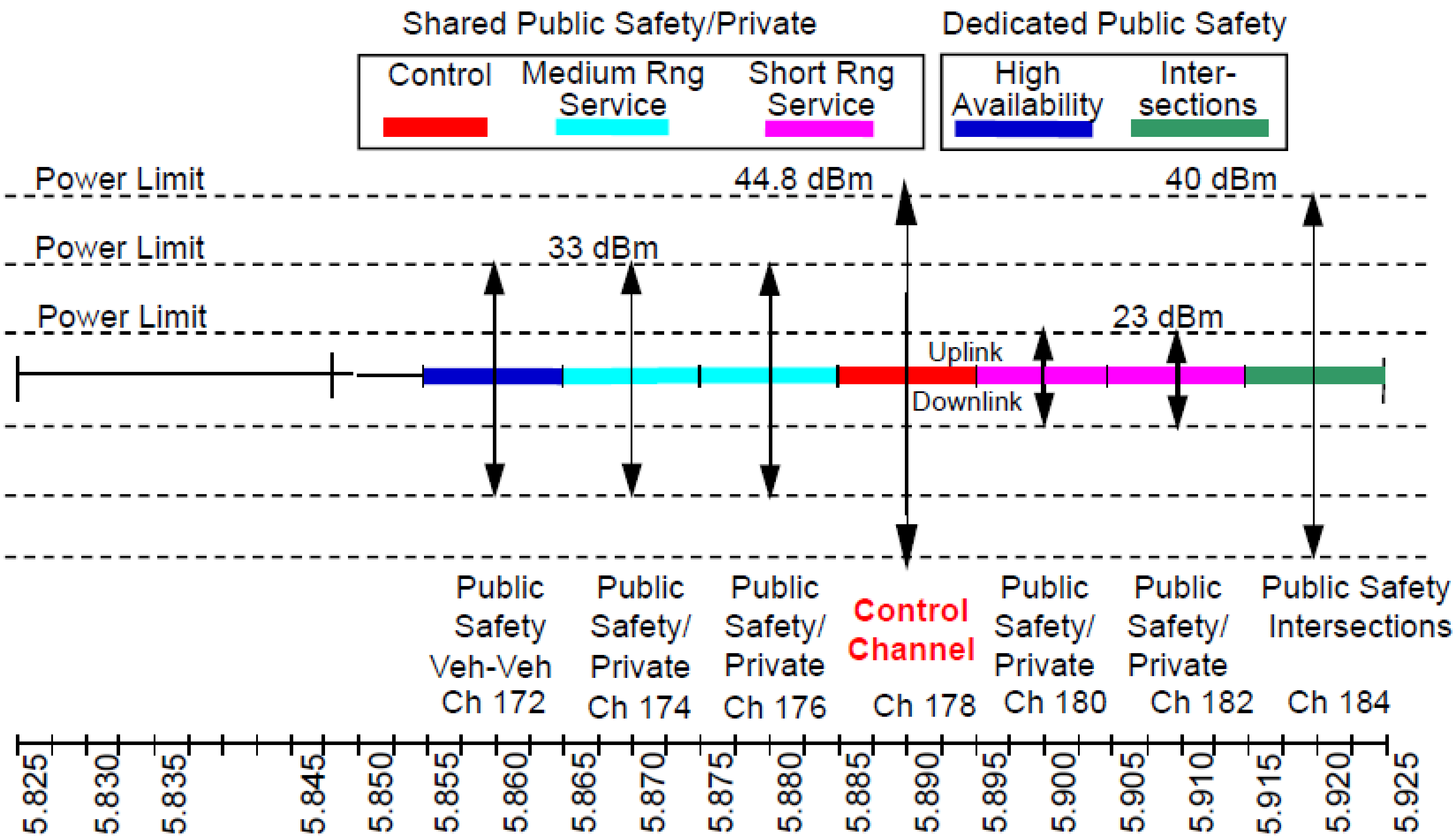
Vehicular Ad Hoc Networks: Technologies

- DSRC
  - Authentication and association takes several seconds in other 802.11 standards
  - 802.11p removes this process



Source: B. Lee., et al., „Extended IEEE 802.11p using distance-based grouping algorithm"

IEEE 802.11p Frequency Band



Source: Based on B. Cash (2008): North American 5.9 GHz DSRC Operational Concept / Band Plan

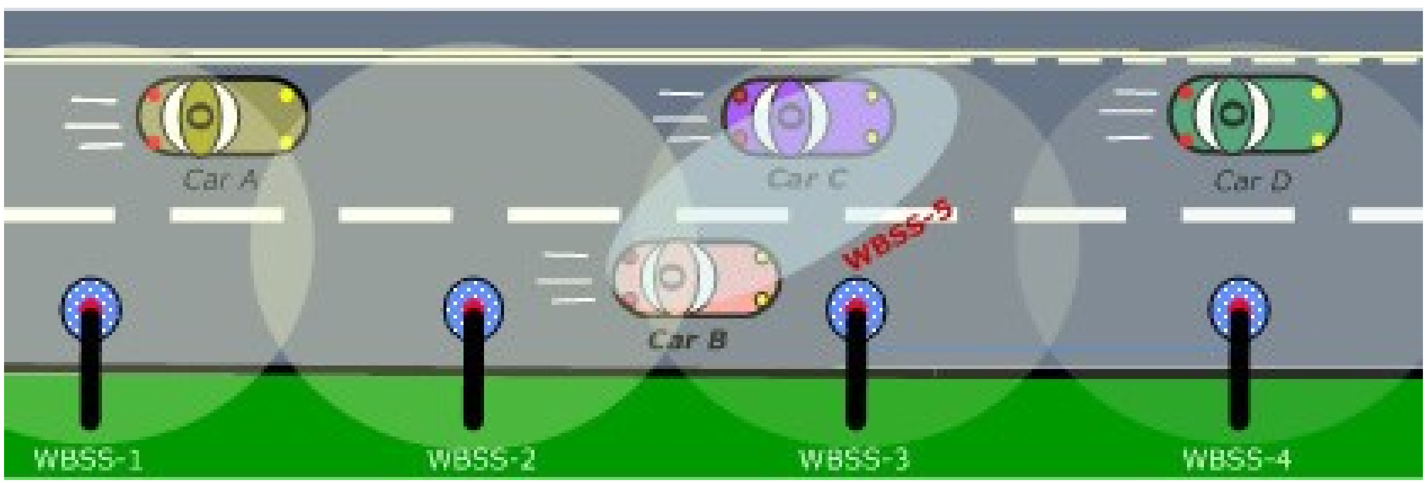
IEEE 802.11p Multi-Channel

- Control Channel
  - Broadcast communication
  - Dedicated to short, high-priority, data and management frames
    - Safety-critical communication with low latencies
    - Initialization of two-way communication on SCH

- Service Channel
  - Two way communication between RSU and OBU or between OBUs
  - For specific applications, e.g., tolling, internet access
  - Different kinds of applications can be executed in parallel on different service channels
  - Requires the setup of a WAVE Basic Service Set (WBSS – „ad-hoc group“) prior to usage of the SCH

WAVE Short Message Protocol (WSMP)

- WAVE Basic Service Set (WBSS)
  - Communication zone
  - Has a unique identifier
  - Vehicles must associate with only one WBSS at a time
  - Not only between RSU-vehicle, but also among vehicles
  - But this is not a must, non-WBSS communication can also be done



Source: Y. L. Morgan, „Notes on DSRC & WAVE Standards Suite: Its Architecture, Design, and Characteristics

IEEE 802.11p Operation Modes

- Without WAVE Basic Service Set (WBSS)
  - Safety-critical, low latency, messages and control messages
  - Mainly broadcast
  - Only on CCH

- With WAVE Basic Serbice Set (WBSS)
  - Two-way transactions (e.g., tolling, internet access)
  - Required to use SCH
  - Requires initiation of SCH
  - In contrast to normal WiFi, WBSS doesn‘t require authentication and association procedures

Comparison to IEEE 802.11a

- Data rate for 802.11p is half
- Time per symbol is twice: more reliable for multipath scenarios

	IEEE 802.11a	IEEE 802.11p
Data rate	6, 9, 12, 18, 24, 36, 48, 54 Mbps	3, 4.5, 6, 9, 12, 18, 24, 27 Mbps
Modulation	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM
Error Correction Coding	Convolutional Coding with K=7	Convolutional Coding with K=7
Coding Rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4
# of subcarriers	52 net	52 net
OFDM Symbol Duration	4.0 µs	8.0 µs
Guard Period	0.8 µs	1.6 µs
Occupied bandwidth	20 MHz	10 MHz
Frequency	5 GHz ISM band	5.850-5.925 GHz

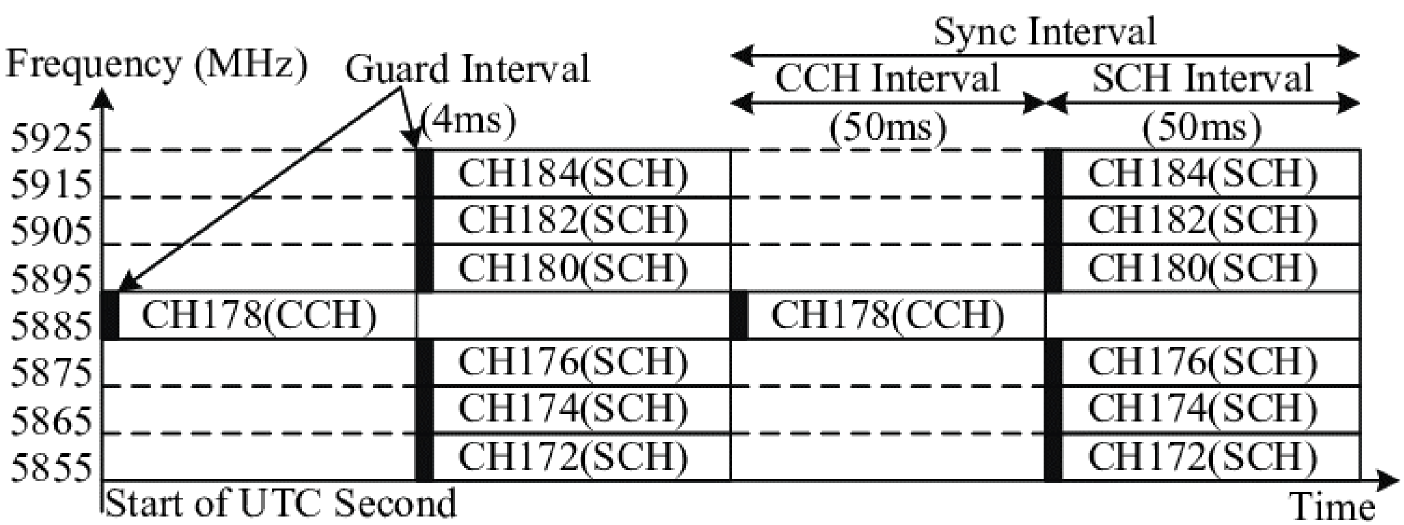
Longer guard period
→ Less Inter-symbol Interference
→ Better resistance against multipath error

Re-order of sub-carriers
→ Better multipath mitigation

Dedicated frequency band
→ Less Co-Channel Interference

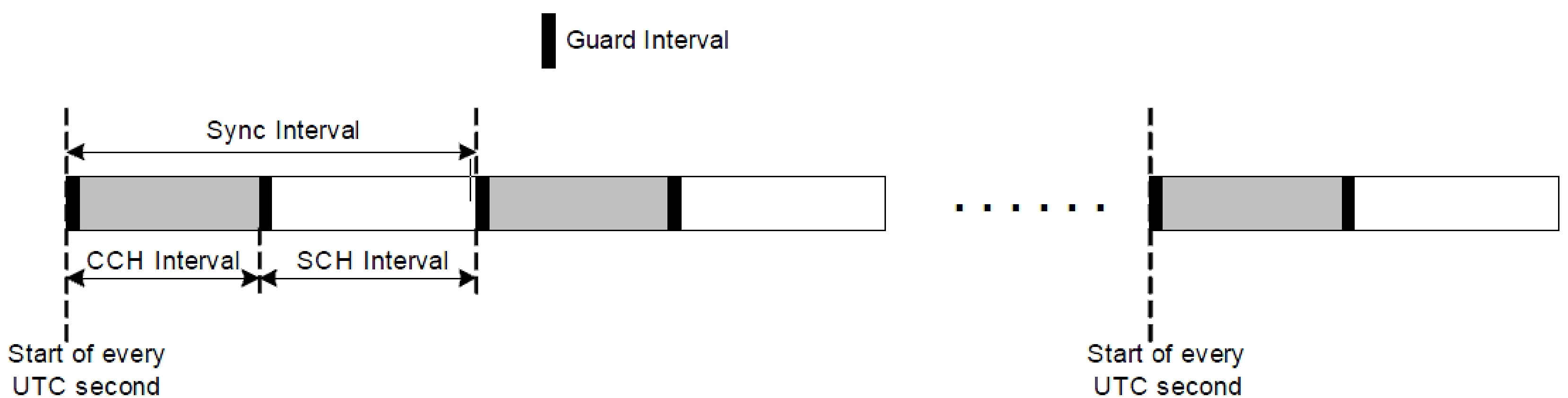
Multi-channel coordination

- Multi-channel coordination (IEEE 1609.4)
  - 7 OFDM channels separated by 10 MHz
  - ***Synchronized*** by UTC: more reliable!
  - Two types of phases
    - 1 control channel (CCH): Safety-related, reserved for short, high-priority msg.
    - 6 service channels (SCH): Non-safety-related,



Multi-channel coordination

- Channel coordination
  - Synchronized scheme based on coordinated universal time (UTC)
  - Assures that all DSRC devices will be monitoring the CCH during a common time interval (CCH interval)
  - Assures that members of a network will be using the corresponding SCH during a common time interval (SCH interval)
  - The sum of the CCH and SCH intervals comprises a Sync interval
  - At the start of a sync interval, all devices must monitor the CCH
  - There are 10 sync intervals per UTC second

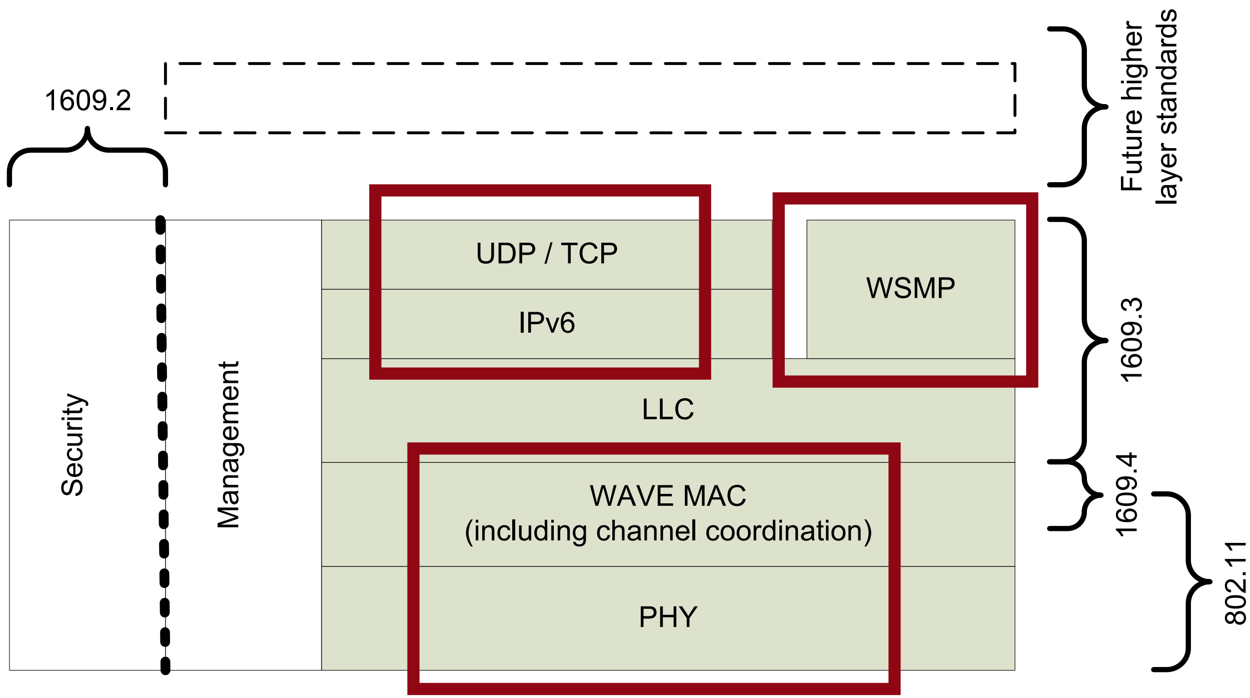


Vehicular Ad Hoc Networks: Technologies

- WAVE accommodates two protocol stacks
  - Standard Internet Protocol (IPv6)
  - WAVE Short Message Protocol (WSMP)
- WAVE short messages (WSMs) may be sent on any channel
- IP messages may be sent only on SCHs
- System management frames are sent on the CCH

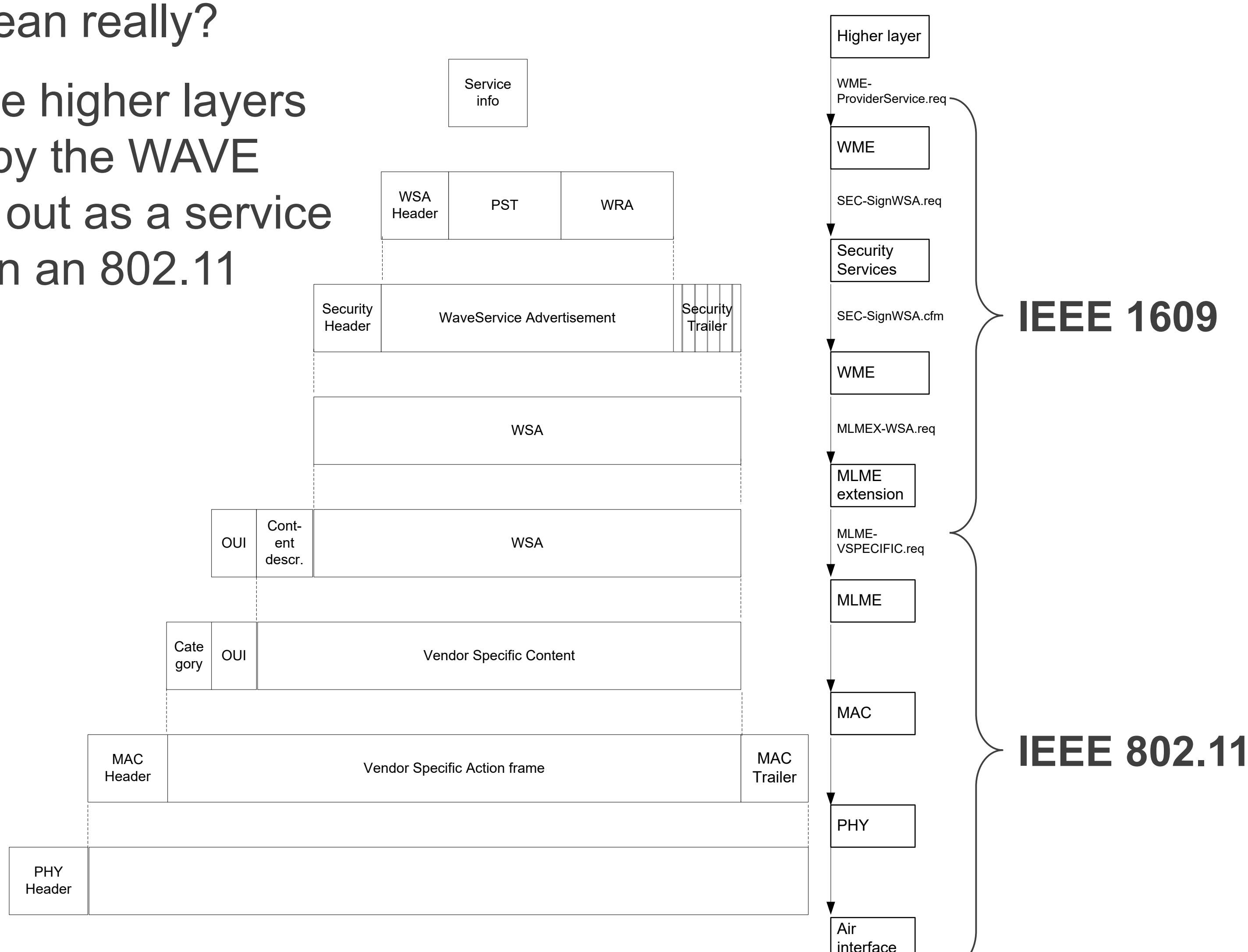
WAVE Short Message Protocol (WSMP)

- In reality, full-stack protocols are not often used
- Instead, minimalistic protocols such as WAVE Short Message Protocol (WSMP) are used



WAVE Short Message Protocol (WSMP)

- What does it mean really?
- Content from the higher layers are processed by the WAVE stack, and sent out as a service advertisement in an 802.11 frame



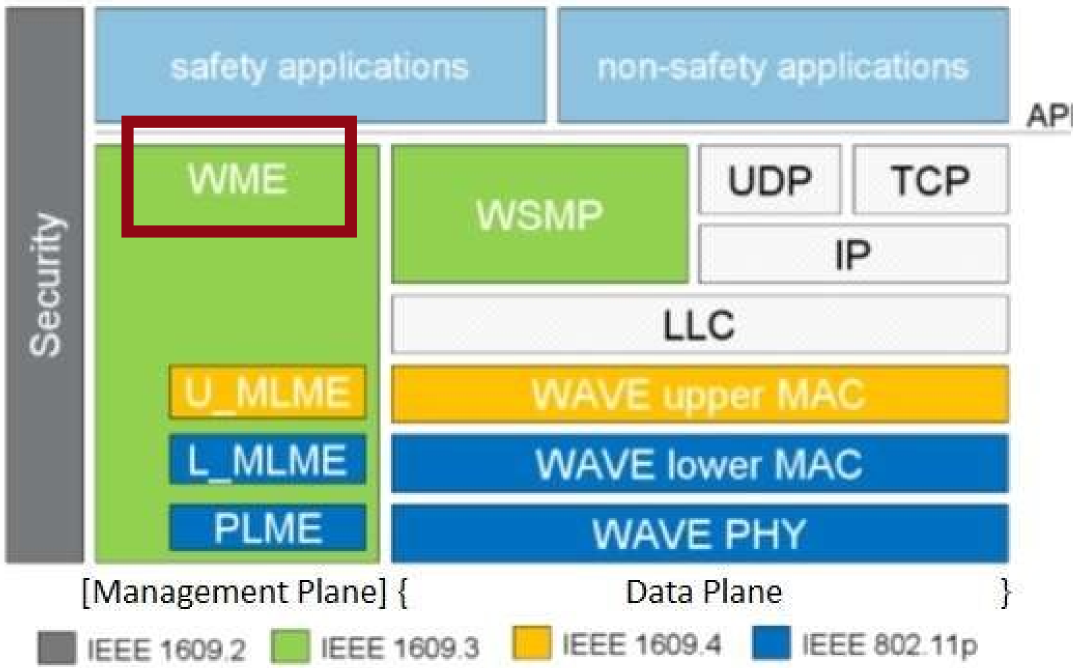
Source: J. Moring, „Overview 1609.0, 1609.3, 1609.4, 1609.5“, 2009

Types of WAVE Messages (SAE J2735)

- WAVE service advertisement (WSA)
  - WSA include information about one or more DSRC services that are offered in an area
  - A service can be any information exchange, e.g., tolling traffic alert, navigation, restaurant information, entertainment, etc.
  - Most services are provided by the RSU, but vehicles can also send WSA
  - Only sent in CCH interval
- WAVE short message (WSM)
  - Data messages being exchanged: Requires WSA before sending
- Basic safety message (BSM)
  - Conveys critical vehicle state information in support of V2V safety applications
  - It is not considered a service, and therefore, BSM doesn‘t require a WSA
  - If every vehicle starts broadcasting BSM, soon there will be a lot of collisions (active research field: how to adjust the sending rate)

WAVE Communication Stack Revisited

- WAVE Management Entity (WME)
  - Manages information related to advertising a service, maintaining a service, etc



802.11p DSRC/WAVE Protocol Stack

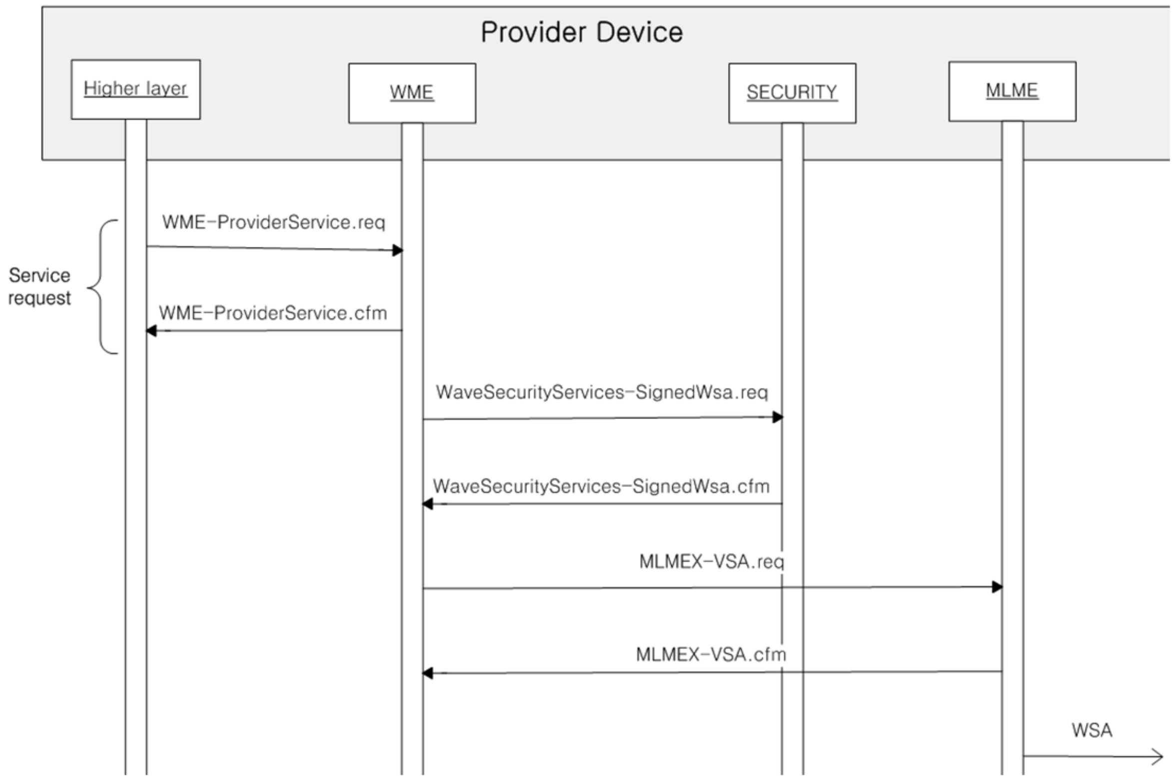
Source: http://www.rfwireless-world.com/Tutorials/802-11p-WAVE-tutorial.html

WAVE Short Message Protocol (WSMP)

- Provider vs User
  - In WSMP, nodes are divided in to providers and users
- Provider
  - Sends out WAVE Service Advertisements (WSA) on control channel (CCH)
    - Includes information on services and channels
    - May include IP configuration information (if IP is used)
  - Operates on identified service channels (SCH) at designated times for application data exchange
- User
  - Monitors WSAs for service of interest
  - May visit identified service channels at designated times for application data exchange

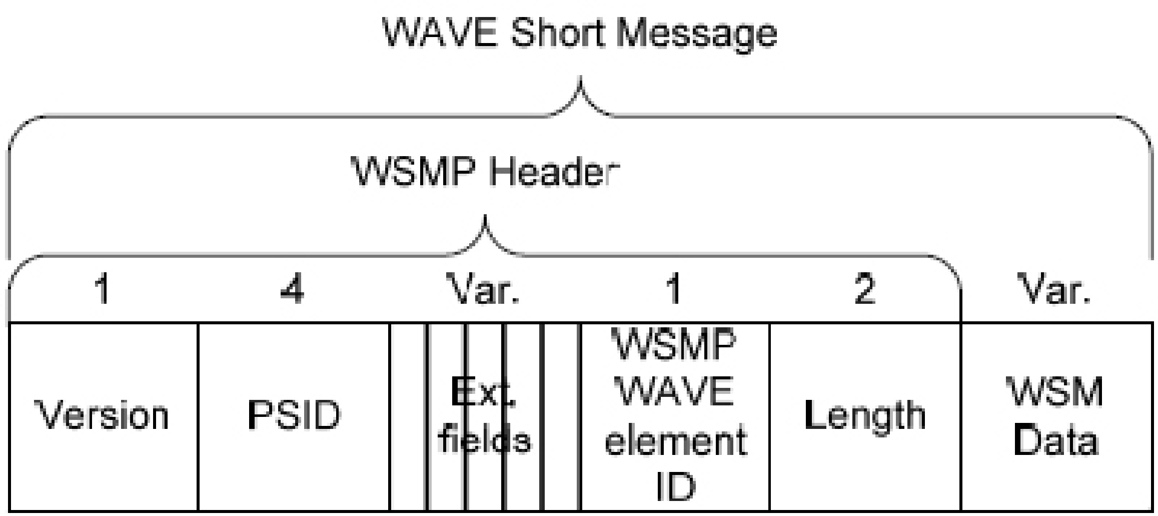
WAVE Short Message Protocol (WSMP)

- When a provider initiates a service,
  - Application makes a service request to the WME (running in local device)
  - WME checks the uniqueness of service and the security credentials
  - WME assigns a provider service ID (PSID) and advertises with WSA



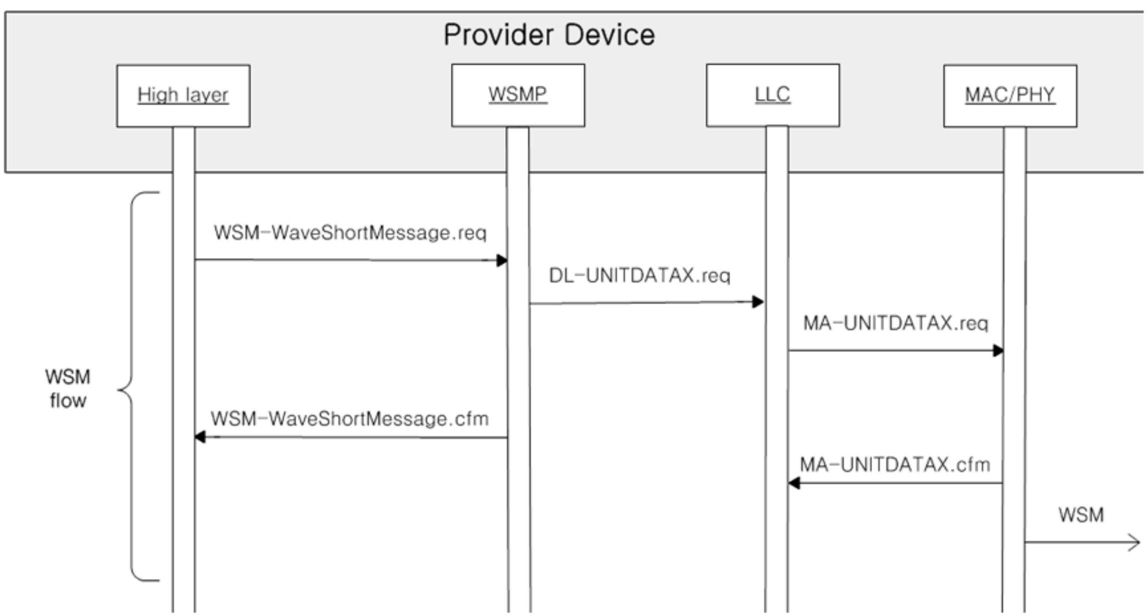
WAVE Short Message Protocol (WSMP)

- WAVE short message format
  - Protocol version
  - PSID
  - Var. (optional): Channel #, Transmission rate, transmit power
  - Length: Length of WSM data
  - Payload: WSM data



WAVE Short Message Protocol (WSMP)

- Wave short message (WSM) request
- Check the length of header
- Generate WSM header
- Append WSM data
- Send



WAVE Short Message Protocol (WSMP)

- WME keeps track of „applications“ on tables
  - Provider service table (PST)
  - User service table (UST)
- Applications must be registered in order to send WSM packets

Example in Veins

- Service subscription
- TraCIDemo11p.cc
  - When a node receives a WSA

```
void TraCIDemo11p::onWSA(WaveServiceAdvertisment* wsa) {
    if (currentSubscribedServiceId == -1) {
        mac->changeServiceChannel(wsa->getTargetChannel());
        currentSubscribedServiceId = wsa->getPsid();
        if  (currentOfferedServiceId != wsa->getPsid()) {
            stopService();
            startService((Channels::ChannelNumber) wsa->getTargetChannel(),
wsa->getPsid(), "Mirrored Traffic Service");
        }
    }
}
```

IP-Based Networks

- WSMP characteritstics
  - Supports communication of high-priority, time-sensitive safety data without the need for connection setup operations
- IP (internet protocol)
  - More traditional and less demanding exchanges
- Remote communication?
  - Reachable via RSUs connected to the internet
  - Or through cellular interface

Vehicular Ad Hoc Networks

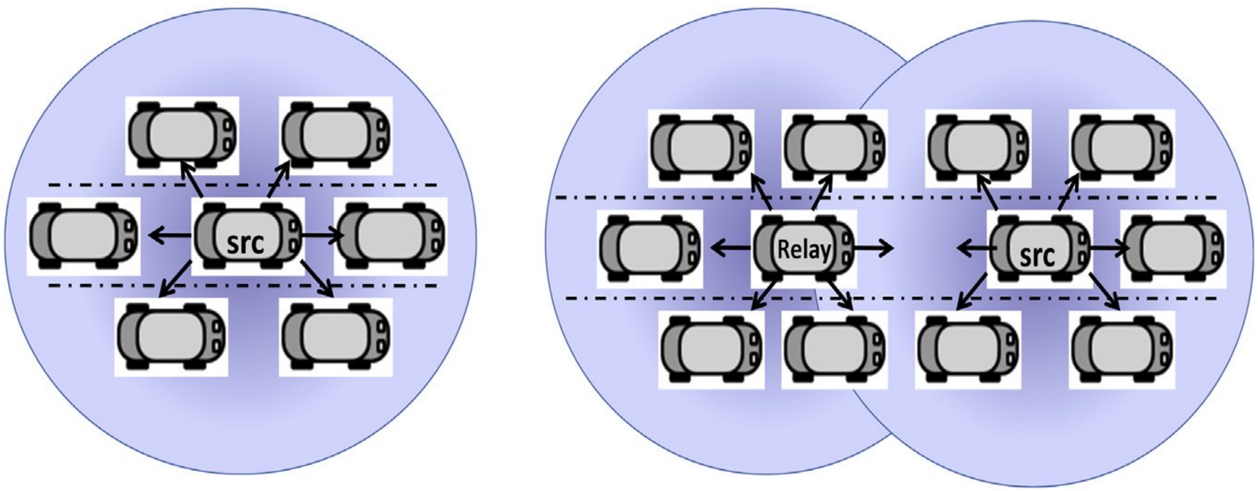
- Vehicular ad hoc networks (VANETs)
  - Operates with little or no permanent infrastructure
  - Characterized by
    - High mobility
    - Fixed road networks
    - Predictable speed and traffic patterns in congested situations
    - Very few power constraints or storage limitations
  - Not characterized by
    - High message throughput
  - Instead focuses on
    - Communication reliability and fast dissemination

Vehicular Ad Hoc Networks

- Types of connections
  - Vehicle-to-vehicle (V2V)
    - Messages are transmitted between neighboring vehicles
    - One-hop or multi-hop messaging scenarios in which vehicles communicate directly with other vehicles or through intermediary vehicles
  - Vehicle-to-infrastructure (V2I)
    - Messages are transmitted between vehicles and roadside units located on nearby arterial road intersections or high on-ramps
  - Vehicle-to-pedestrian (V2P)
    - Messages are transmitted between vehicles and pedestrians who send and receive messages via their phones or other wireless devices

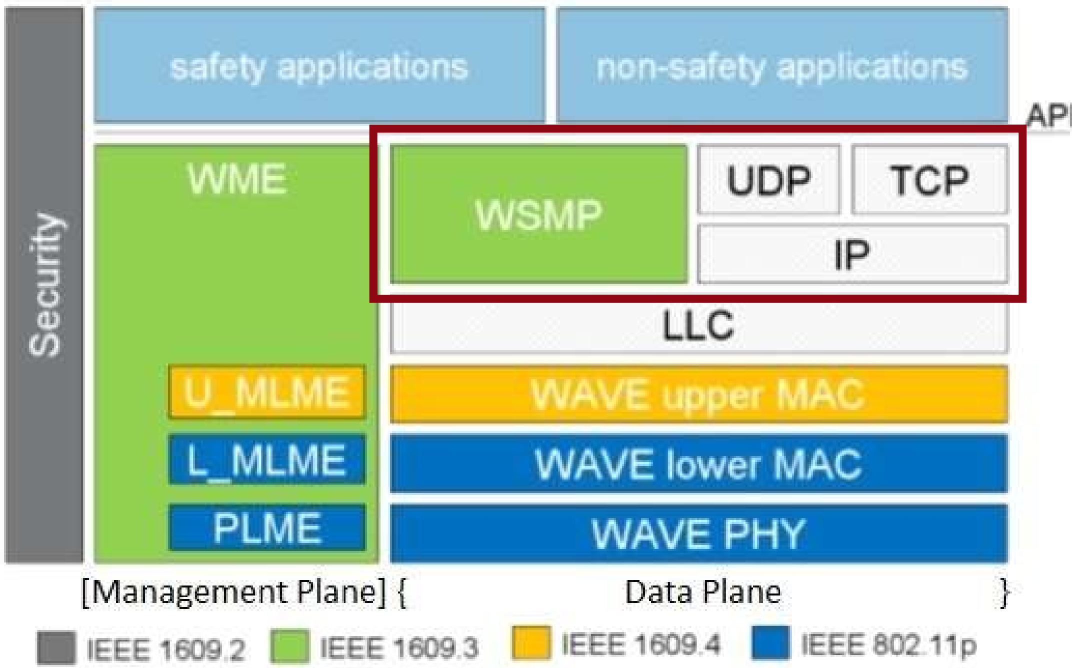
Vehicular Ad Hoc Networks

- Single-hop or multi-hop
  - „Relay“
  - OBUs act both as terminals and wireless routers in the VANET



Routing Schemes in VANET

- Routing is handled above the PHY/MAC layers: Network or transport layers => WSMP or TCP/IP
- Again, routing for MANETs do not work well
  - Frequent disconnects, highly dynamic topology changes

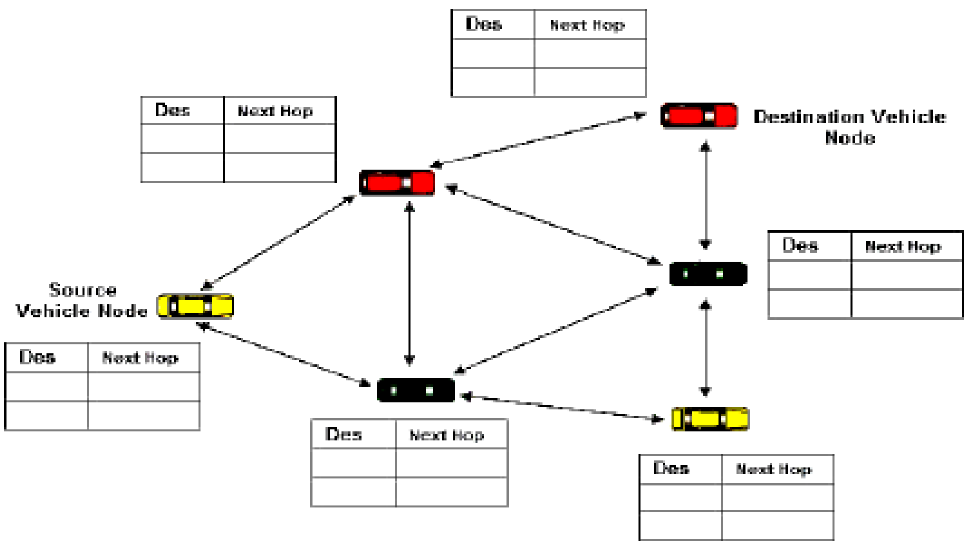


802.11p DSRC/WAVE Protocol Stack

Source: http://www.rfwireless-world.com/Tutorials/802-11p-WAVE-tutorial.html

Routing Schemes in VANET

- Categories of routing schemes
  - Topology-based routing
    - The choice of route from source to destination is based on links information previously collected by the vehicle (proactive schemes), or sought when needed (reactive schemes)
    - Step of searching or maintaining a route from source to destination is mandatory before sending data packets



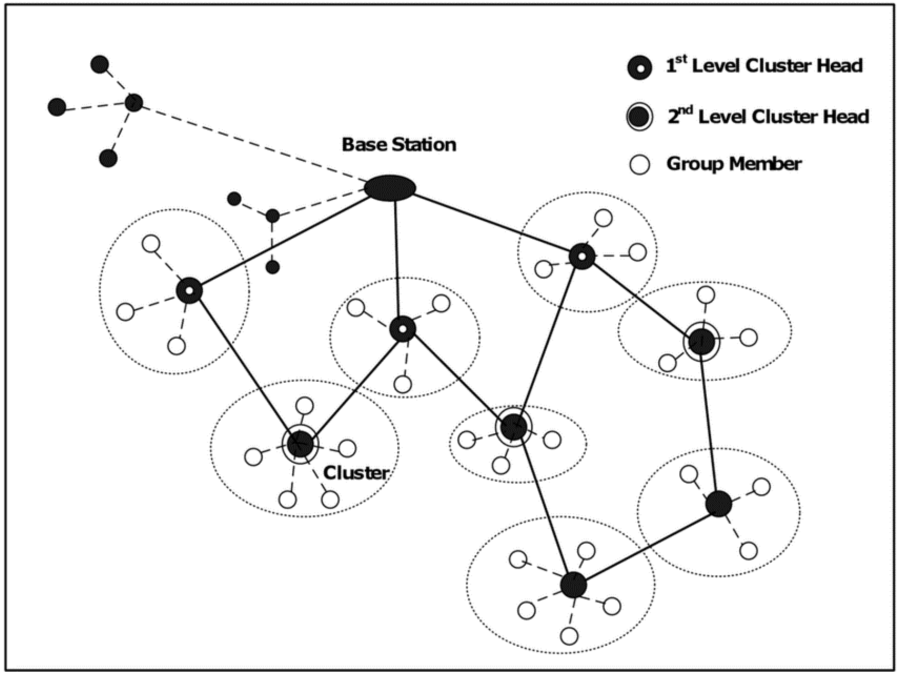
Source: K. N. Quareshi, et al., “VEHICULAR AD HOC NETWORKS ROUTING PROTOCOLS: SURVEY”, 2015

Routing Schemes in VANET

- Position-based routing protocols
  - Also called „geographic-based“ protocols
  - Uses vehicles geographical information in the relay selection process
  - Assumes that the nodes know their geographical locations (by GNSS)
  - Knowledge of the whole route is unnecessary

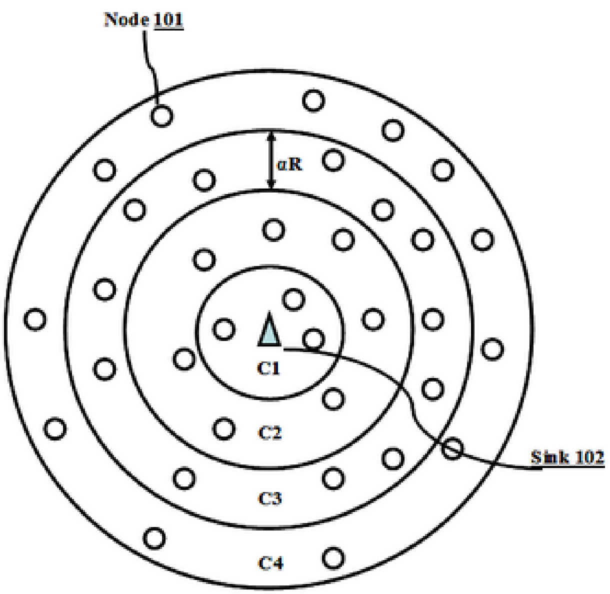
Routing Schemes in VANET

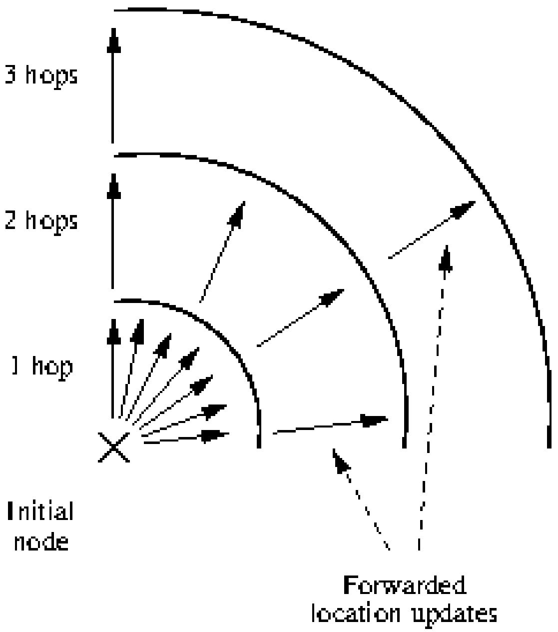
- Cluster-based routing
  - Vehicles sharing similar characteristics such as driving in the same direction with more or less the same velocity can form a cluster and elect a cluster-head which manages the cluster and is in charge of inter-cluster communications
  - Intra-cluster communication is performed using direct links



Routing Schemes in VANET

- Broadcast-based routing
  - Simple „flooding“ on the network in order to reach all vehicles
  - Problem of implosion
  - Overlap: Don‘t broadcast if you have already received the same packet

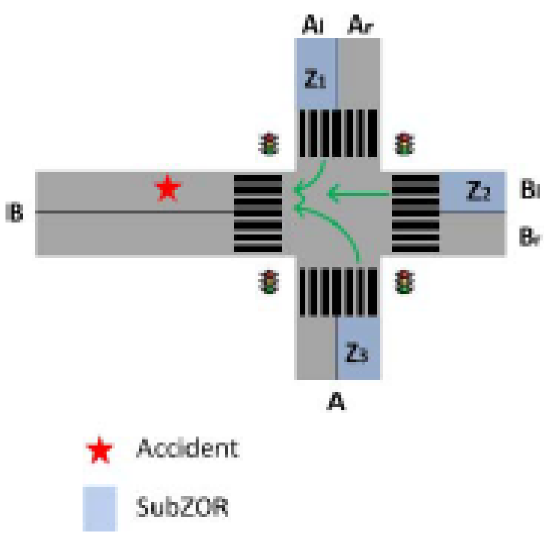




Source: S. Boumerdassi, et al., „A flooding-based solution to improve location services in VANETs, IEEE ICC 2016

Routing Schemes in VANET

- Geocast-based routing
  - Similar to broadcasting, but forwards packets to vehicles belonging to the destination area called zone of relevance (ZOR)
  - In order to prevent simple flooding, a forwarding area called zone of forwarding (ZOF) is used to confined the message
  - Also assumes that each node is aware of it‘s locations
  - Accident example:
    - When an accident happens, cars in z1, z2 and z3 want to be informed
    - The vehicles can re-route

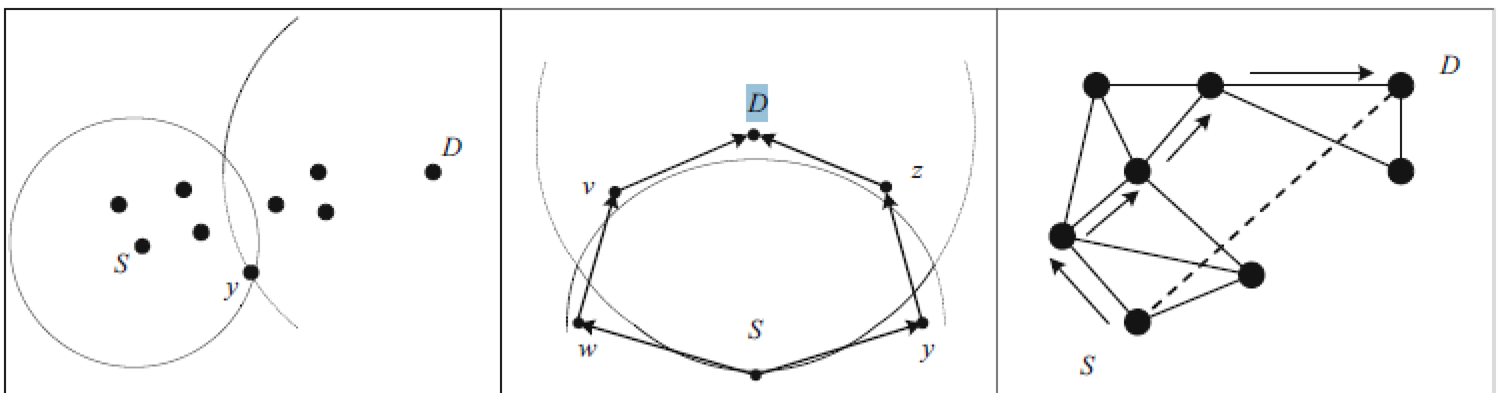


Routing Schemes in VANET

- Infrastructure-based routing
  - Uses infrastructure nodes (RSU) in junctions and along the roads as relays
  - Becomes similar to WiFi AP

Routing Schemes in VANET

- Geographic routing example
  - Greedy perimeter stateless routing (GPSR)
  - Classical position-based routing
  - Makes routing decisions using only information about their immediate neighbors in the network topology
  - Objective: S -> D
  - Fig b fails to deliver packet because no immediate neighbor is closer to D than itself

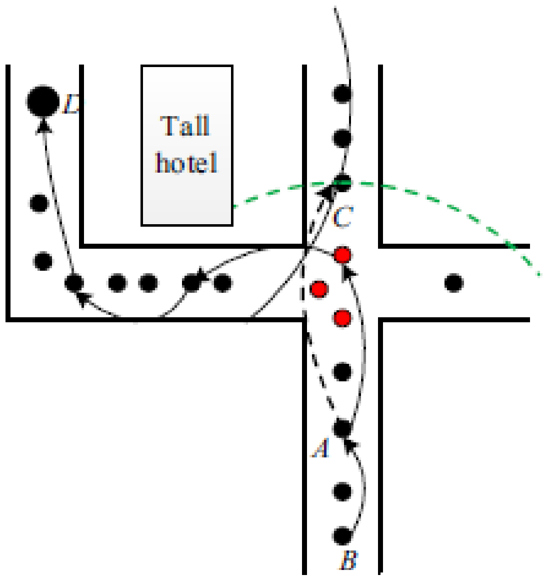


a Greedy forwarding   b Greedy forwarding failure   c Perimeter forwarding

Source: J. Liu, et al., „A survey on position-based routing for vehicular ad hoc networks, Telecomm. Syst. 2016

Routing Schemes in VANET

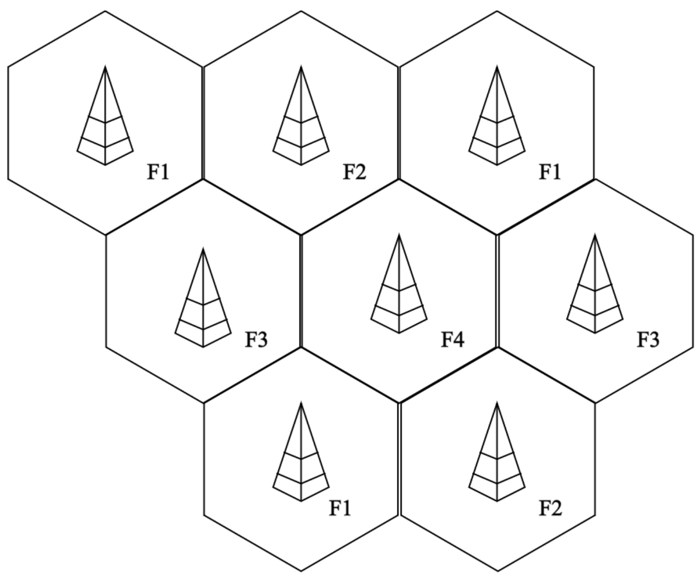
- You could also try to make use of the road topology in addition because there will not be obstacles along it
- Sending from C to D directly is difficult due to the hotel, so take a detour along the road



Source: J. Liu, et al., „A survey on position-based routing for vehicular ad hoc networks, Telecomm. Syst. 2016

Cellular Network

- ***Cellular*** network
  - The network is distributed over land areas called cells each served by at least one ***fixed-location transceiver***
  - A cell typically uses different set of frequencies from neighboring cells to avoid inteference and provide guaranteed service quality within each cell



Cellular Network

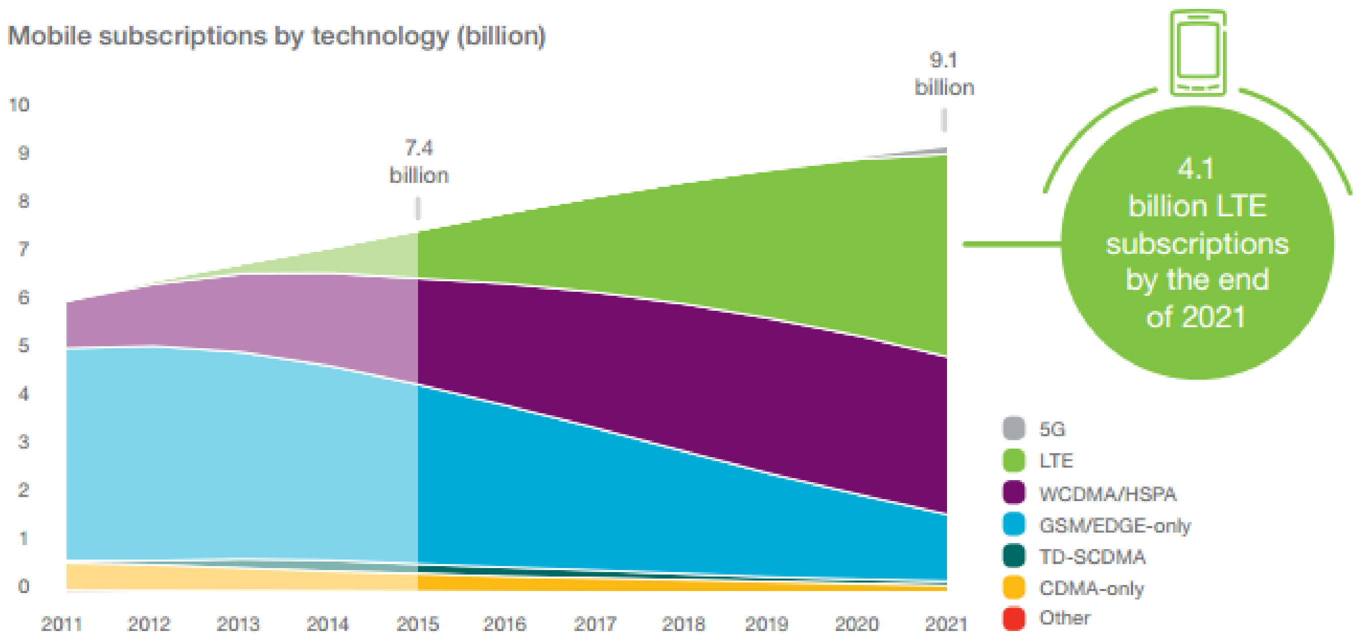
- How large are the cells?
  - Femto cells could be as small as tens of meters
  - Large cells could be up to 100 km
  - Typical radius is around 5 km/cell
- Handover
  - Movement from cell to cell results in handover
  - Switch over from one radio base station to another one

Acceptance Status of 802.11p

- De-facto standard for V2X is direct short range communication (DSRC) wireless technology, based on IEEE 802.11p
- In the US
  - Wireless Access in Vehicular Environment (WAVE)
  - “is expected to mandate the use of 802.11p for safety-related use-cases in the second quarter of 2016”
- In Europe
  - European Telecommunications Standards Institute (ETSI) TC-ITS European standards
  - “Dutch, German, and Austrian infrastructure organizations assessed the maturity of 802.11p for V2I and the C-ITS central systems technologies”

Acceptance Status of Cellular Tech.

- C-ITS (cooperative ITS) systems are typically defined by their application requirements and don't specify a particular technology
- LTE has been extremely successful in handheld devices
- Yet, less accepted than 802.11p based methods



Source: Ericsson Mobility Report, Nov 2015

Acceptance Status of Cellular Tech.

- Cellular technology is suited for non-safety-related use-cases as it stand today
  - Latency of the cellular technology is higher and there is more uncertainty
  - How does *handovers* work between mobile network operators? – unclear
- If the cellular modems were to be used for safety-related applications
  - They will have to meet the Automotive Safety Integrity Level (ASIL) standards making the modems more expensive
- LTE cellular networks are *centralized*
  - Each node communicates with the transceivers not direct with other nodes

802.11p vs LTE

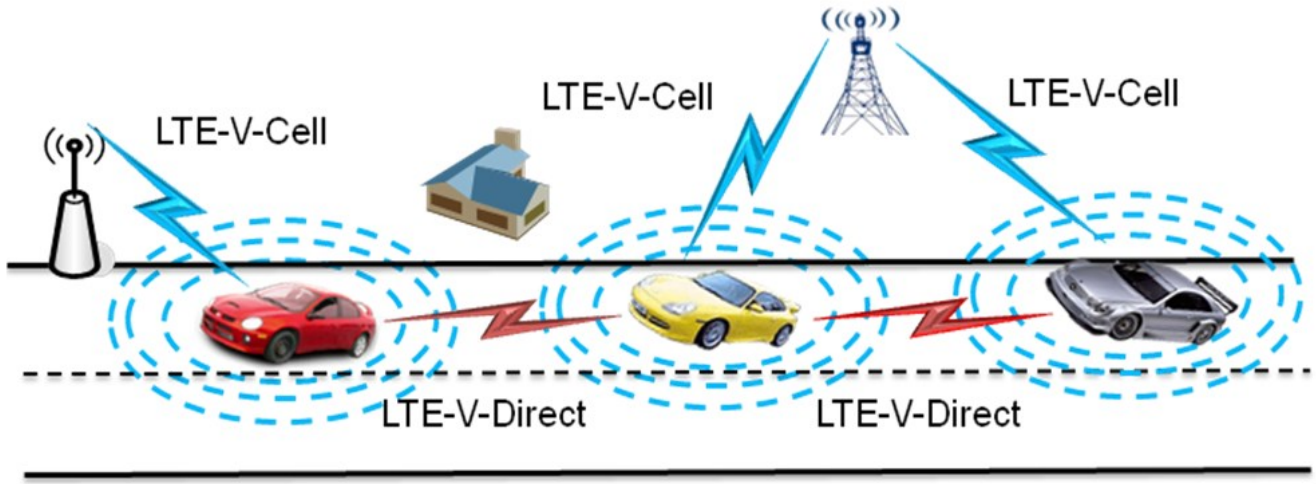
- IEEE 802.11p is the standard that support ITS applications in vehicular ad hoc networks (VANET)
  - Easy deployment, low cost, mature technology
  - Scalability issues
  - Unbounded delays
  - Lack of deterministic quality of service (QoS) – simply best effort
  - Limited range – it‘s still Wi-FI (200 m to several hundred meters)
  - Response times typically lower than a few milliseconds
- Long Term Evolution (LTE)
  - Cellular communication
  - Range up to several kilometers
  - No need to communicate in a multi-hop fashion – lower latency
  - Reliability is lower - more devices connected in a single network
  - Response time could be lower than 200 ms
  - Datarate is nowadays similar to WiFi (~ 1GBit/s)

802.11p vs LTE

- Latency
  - 802.11p (better) > cellular (base station)
  - But it is context dependent (multi-hop scenario)
- Coverage
  - Cellular > 802.11p
  - 5 km vs max. 1km
- Reliability
  - 802.11p > cellular
  - More nodes connected to a single network means larger uncertainty
- Communication costs
  - 802.11p > cellular
  - Need maintenance of the cellular network, and a separate plan
- Date rate
  - 802.11p = cellular

LTE V2V Communications

- Cellular networks have restricted usage in V2V communication
- 3GPP has recently developed Long Term Evolution Vehicle-to-Vehicle (LTE V2V) communication technology
- Details of LTE V2V to be covered later



Source: https://vtsociety.org/2018/02/vehicles-february-2018/

LTE V2V

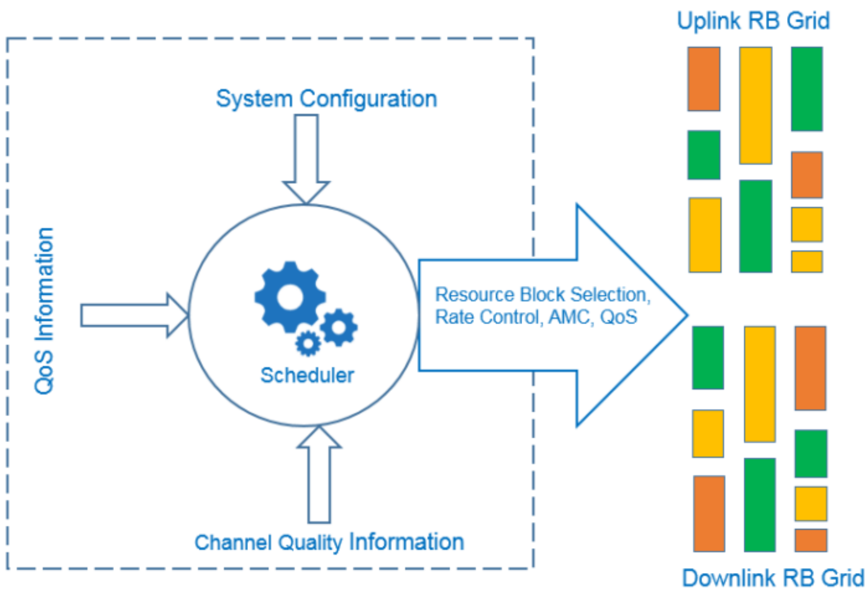
- 3GPP (3rd generation partnership project): standards organization
  - GSM and related 2G and 2.5G standards
  - UMTS and related 3G standards including HSPA
  - LTE and related 4G standards, including LTE Advanced and LTE Advanced Pro
  - Next generation and related 5G standards
- 3GPP has recently (2016) published a standard supproting V2V communications using LTE sidelink communications
  - Referred to as LTE-V, LTE-V2X, LTE-V2V or Cellular V2X
- The standard includes a mode (mode 4) where vehicels autonomously select and manage the radio resources without any cellular infrastructure support

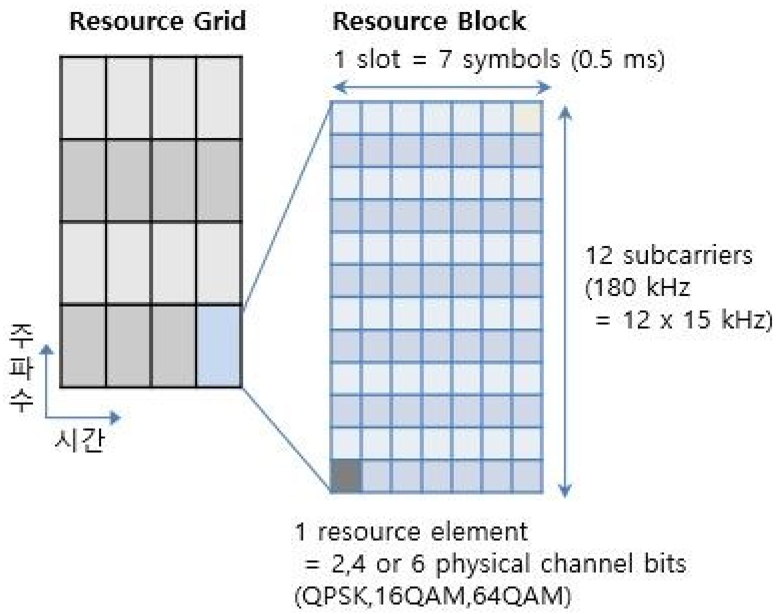
LTE V2V

- Release 12 (modes 1 and 2)
  - LTE sidelink was introduced for public safety D2D (device to device) communications
  - Focused on prolonging the lifetime of batteries
- Release 14: Mode 3 and mode 4 added
  - V2V communication
  - Focused on satisfying V2V requirements
  - High reliability, low latency, and network scalability
- Mode 3
  - Two vehicles directly communicate with each other, but the selection and management of resources is done by the cellular infrastructure
- Mode 4
  - Vehicles autonomously select and manage the resources without any cellular infrastructure support

Default LTE

- What is scheduling assignment?
  - The base station (eNodeB) performs scheduling of resources (time and frequency)
  - Assigns resource blocks to mobile devices
  - Link adaptation: Choice of symbols (such as QPSK, recall?) and code rate (redundancy for error checking) according to channel conditions





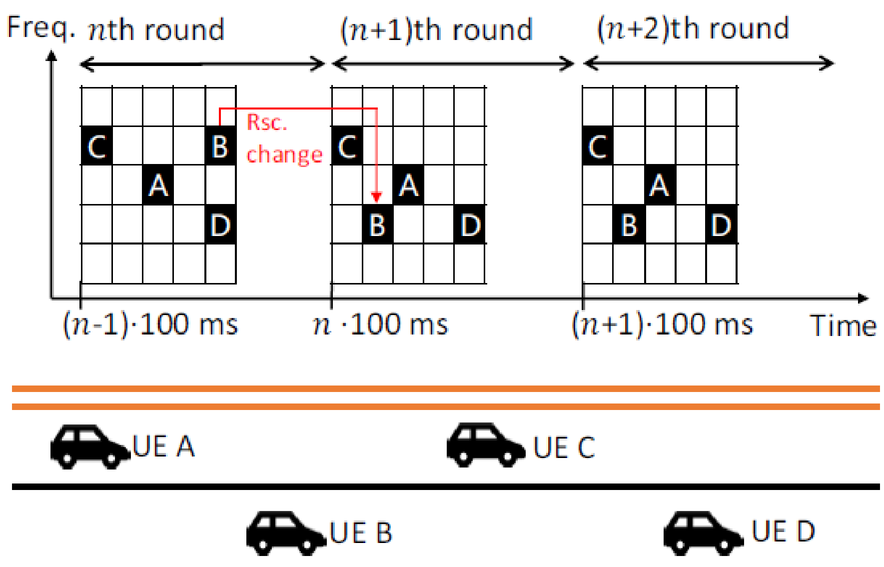
Source: http://www.techplayon.com/lte-enodeb-scheduler-and-different-scheduler-type/

LTE V2V

- LTE V2V
  - Eliminates the time division of resources
  - Vehicles can reserve a resource and transmit a packet at any point in time
    - Default LTE uses discontinuous reception, wakes up at pre-designated times and sleeps to save power
  - Reduces latency, but increases power consumption because the vehicles should be
  - Distributed scheduling
    - Vehicles autonomously select their radio resources when they cannot rely on the infrastructure
    - Then how do you ensure packet collisions don‘t happen?
    - Again, we should rely on „sensing-based“ schemes

LTE V2V

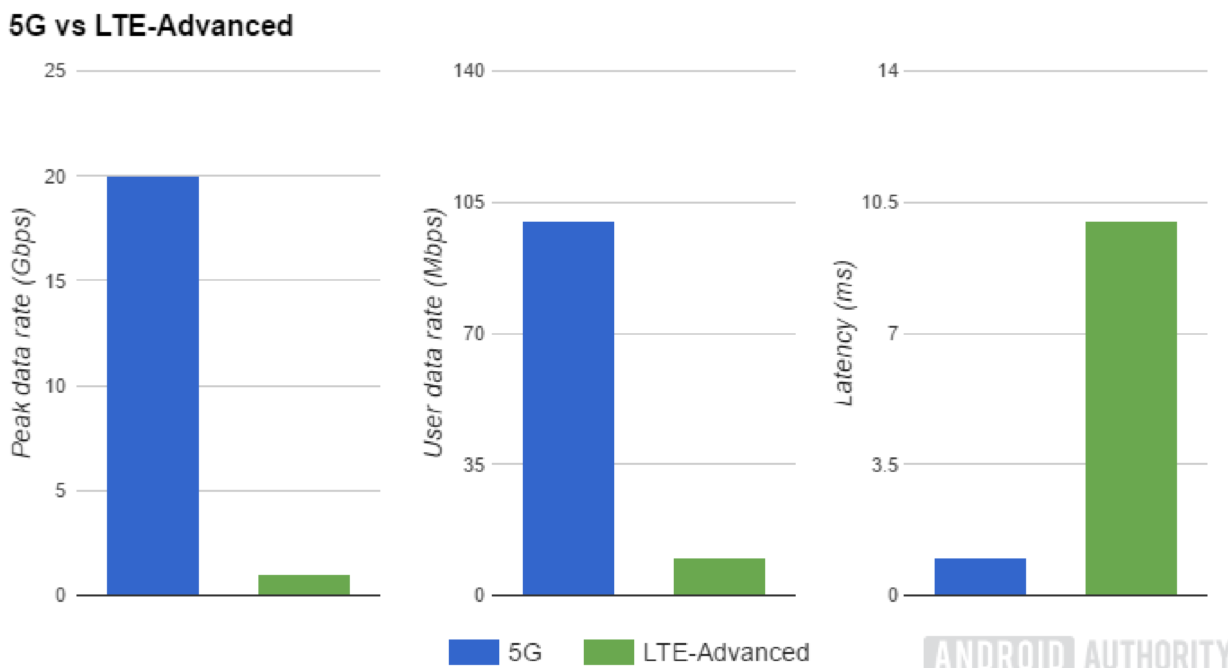
- Each vehicle determines the resource block to send their vehicle status
- It might take multiple rounds to find a suitable resource block



Source: S. Park, et al., „FAGA: Feedback-Aided Greedy Algorithm for Period Messages in LTE V2V Communications," IEEE TVT2017

And Beyond

- 5G
  - High throughput and low latency
  - Do we need to distinguish WiFi and cellular networks for VANETs?
  - Millimeter waves (30 Ghz ~) are planned to be used
  - Shorter range (few kilometers)
  - To be elaborated later



Source: https://www.androidauthority.com/what-is-5g-explained-944868/

References

- Wai Chen, „Vehicular Communications and Networks: Architectures, Protocols, Operation and Deployment“, Woodhead Publishing
- „A. Filippi, et al., „Ready to Roll: Why 802.11p beats LTE and 5G for V2X“, white paper by NXP, Cohda, and Siemens
- G. Acosta, „The WAVE Solution – Coming Soon to a Car Near You: Wireless Access“
- John B. Kenny, „Dedicated Short-Range Communicatinos (DSRC) Standards in the United Statesm,“ Proceedings of the IEEE, 2011
- Thomas Strang, et al., „Vehicle Networks: V2X Communication Protocols“