



Lecture 4: Vehicular Communication Architecture Architectures, Protocols, Operation and Deployment

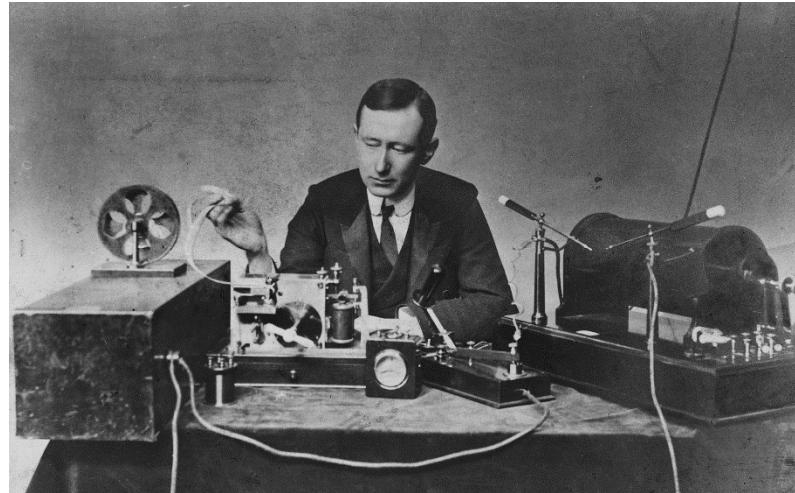
Prof. Sangyoung Park
Module "Vehicle-2-X: Communication and Control"



Contents

- Communication basics
- Protocols for vehicular communication architectures
- Architectures for vehicular communication architectures

- What is wireless communication?
 - Transfer of information or power between two or more points that are not connected by an electrical conductor
 - Most common wireless common wireless technologies use radio waves



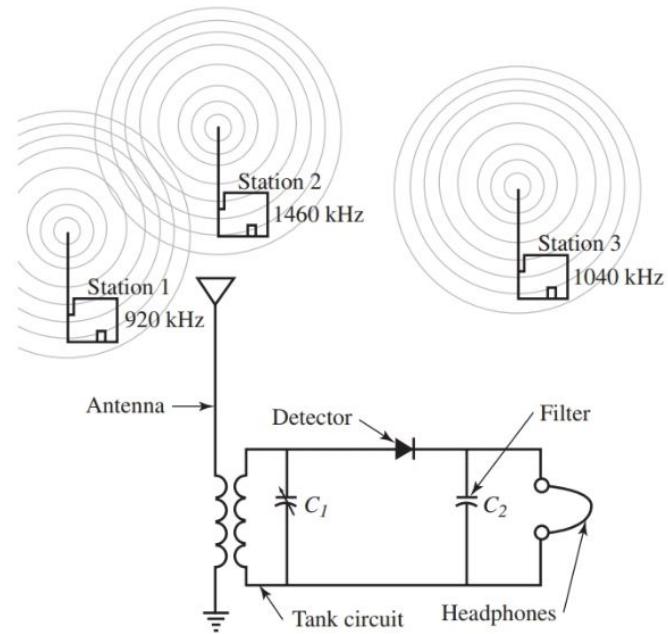
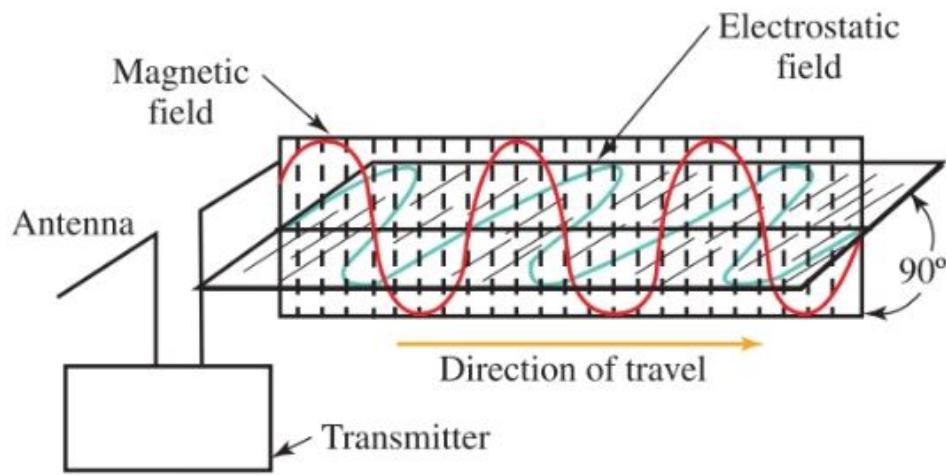
Marconi sending the first radio signal across the Atlantic

Source: Wikipedia

Basics of Wireless Communication

■ Basics of Wireless Communication

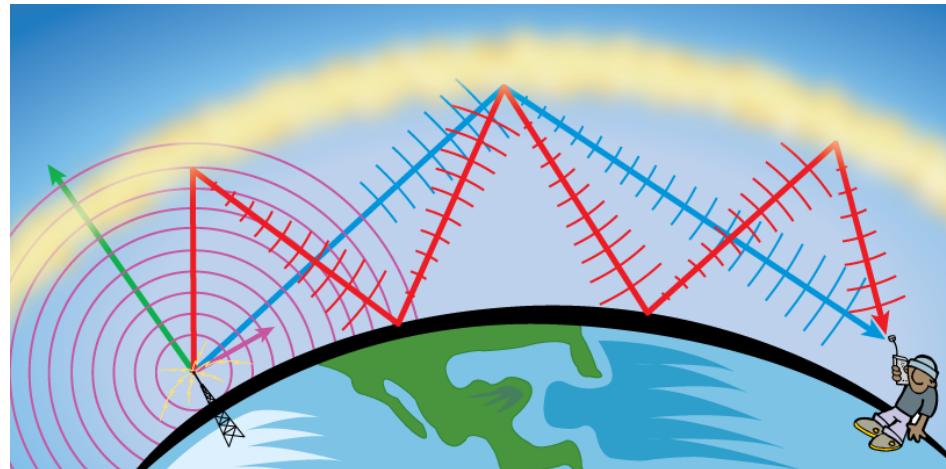
- Electromagnetic waves are generated around alternating currents (transmitter)
- Electrical currents are generated when electromagnetic waves reach the antenna (receiver)



Source: <http://electricalacademia.com/electronics/radio-transmitter-and-receiver-working-block-diagram/>

Basics of Wireless Communication

- How could Marconi send signals across such a distance? (England – New Foundland)
 - Ionosphere: Electrically charged gas particles (ionized) formed by radiation from the sun
 - Reflected or refracted at around 100 km altitude



Source: US National Weather Service

Basics of Wireless Communication

- But what about the signal attenuation?
 - You send a **powerful signal!**
 - Signals transmitted by new high-power station in England
 - 150 m, kite-supported antenna for reception



Transmitter Antenna

Source: Wikipedia



- How is range determined?
 - A transmitter should put **enough energy** into a **symbol** for the receiver to be able to **hear** it
- Symbol?
 - A radio signal that represents information
 - FSK (frequency shift keying)
 - Radio transmitting at frequency X: 1
 - Radio transmitting at frequency Y: 0
- Hearing
 - Receiver could hear and comprehend the message if „energy per symbol“ is large enough



- What lowers the „energy per symbol“?

- Propagation loss

- Spreading out of RF energy as the signal dissipates
 - Square of the distance in free-space

- $$\frac{P_r}{P_t} = D_t D_r \left(\frac{\lambda}{4\pi d} \right)^2$$
, D_t , and D_r are parameters related to the direction of antenna, λ is the wavelength, and d is the distance

- Attenuation loss

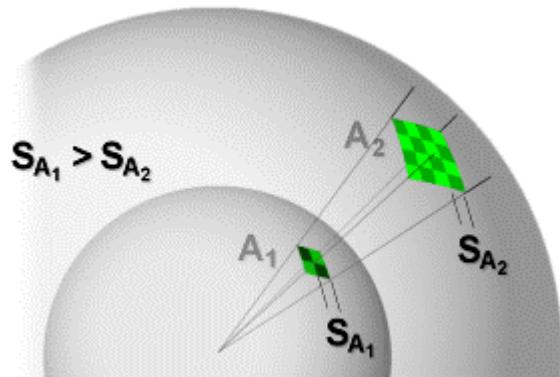
- Propagation through material other than air walls, etc.

- Connector loss

- Transmit antenna loss

- Receiver antenna loss

- Small antennas, etc.



Source: <http://www.radartutorial.eu/01.basics/Free-Space%20Path%20Loss.en.html>

- One easy thing to forget
 - One easy way to increase the energy per symbol is to reduce the data rate
 - If you use constant power consumption on the transmission side, half the data rate, then the energy per symbol will be twice
 - Hence, decreasing the data rate also effectively increases the range of wireless communication

Mode	Outdoor Range		Indoor Range	
	Meters	Feet	Meters	Feet
1 Mbps DSSS	550	1804	50	164
2 Mbps DSSS	388	1275	40	133
5.5 Mbps CCK	235	769	30	98
11 Mbps CCK	166	544	24	79
5.5 Mbps PBCC	351	1151	38	125
11 Mbps PBCC	248	814	31	101
6 Mbps OFDM	300	984	35	114
12 Mbps OFDM	211	693	28	92
18 Mbps OFDM	155	508	23	76
24 Mbps OFDM	103	339	18	60
36 Mbps OFDM	72	237	15	48
48 Mbps OFDM	45	146	11	36
54 Mbps OFDM	36	119	10	32

https://www.eetimes.com/document.asp?doc_id=1271995

- What other factors play a role in successful hearing?

- Interference
 - Signal to noise ratio (SNR)

$$SNR = \frac{P_{signal}}{P_{noise}}$$

- If noise is too large compared to the signal, the original signal cannot be reconstructed
- Decibels (dB)
 - Because many signals have a very wide dynamic range, signals are often expressed using the logarithmic decibel scale
 - $P_{signal,dB} = 10 \log_{10}(P_{signal})$, $P_{noise,dB} = 10 \log_{10}(P_{noise})$
 - Similarly signal to noise ratio can be defined,

$$\begin{aligned} SNR_{dB} &= 10 \log_{10}(SNR) = 10 \log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \\ &= P_{signal,dB} - P_{noise,dB} \end{aligned}$$



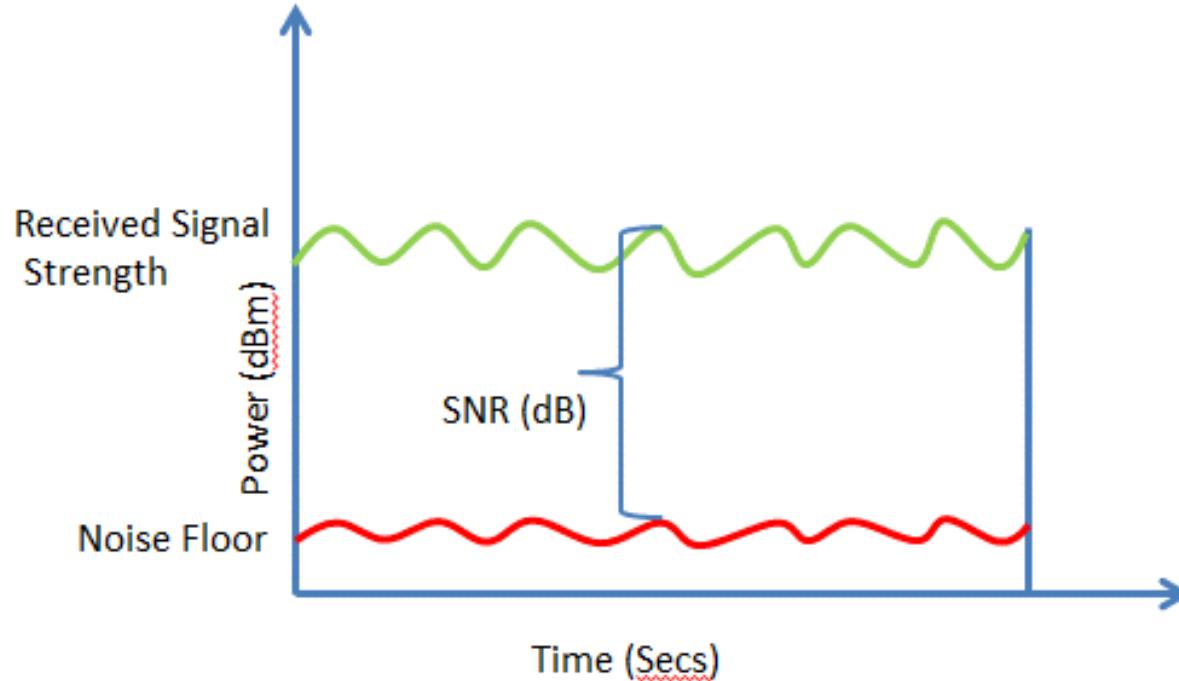
Basics of Wireless Communication

- What are the typical signal strengths?
 - Often described in terms of dB with reference to milliwatt (mW): dBm

Power level	Power	Notes
80 dBm	100 kW	Transmission power of FM radio station (50 km range)
62 dBm	1,588 W	Maximum legal power of US HAM
60 dBm	?? W	Microwave RF power
27 dBm	500 mW	Typical cellular phone transmission power
23 dBm	200 mW	IEEE 802.11n wireless LAN 40 MHz-wide in 5 GHz
15 dBm	32 mW	Typical wireless LAN transmission in laptops
4 dBm	2.5 mW	Bluetooth class 2 radio, 10 m range
-174 dBm	0.178 fW	Typical received signal power from a GPS satellite
$-\infty$ dBm	0 W	Zero power

Basics of Wireless Communication

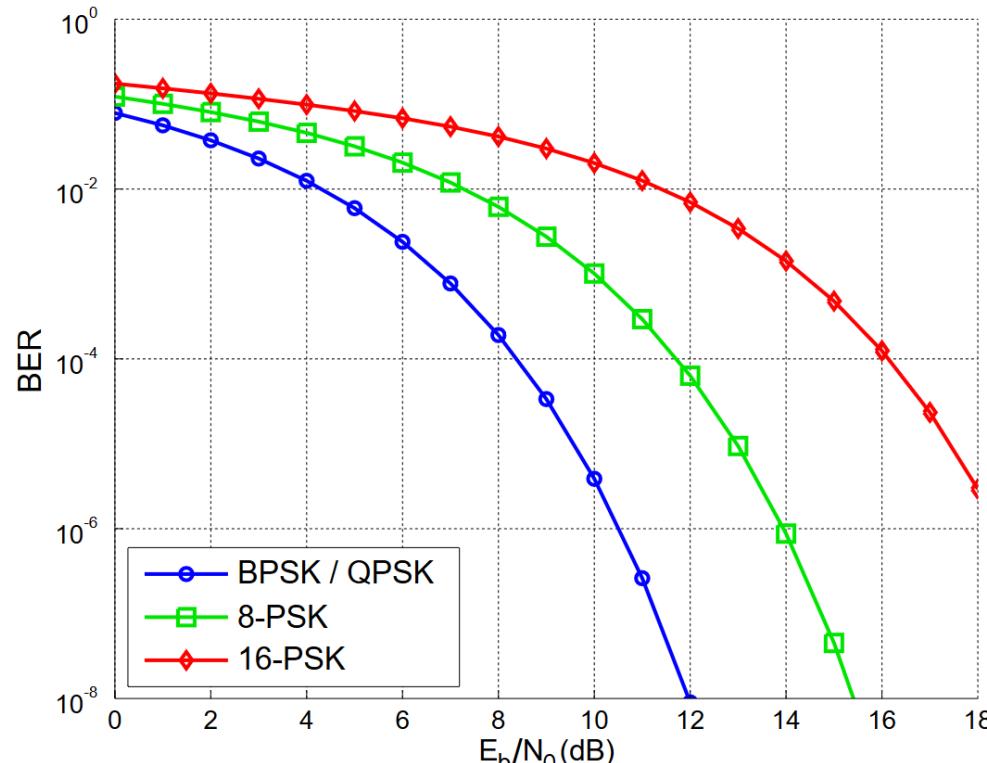
- What is the SNR in dB if a receiver gets a signal of -75 dB and the noise floor is measured at -90 dBm?



Source: [https://documentation.meraki.com/MR/WiFi_Basics_and_Best_Practices/Signal-to-Noise_Ratio_\(SNR\)_and_Wireless_Signal_Strength](https://documentation.meraki.com/MR/WiFi_Basics_and_Best_Practices/Signal-to-Noise_Ratio_(SNR)_and_Wireless_Signal_Strength)

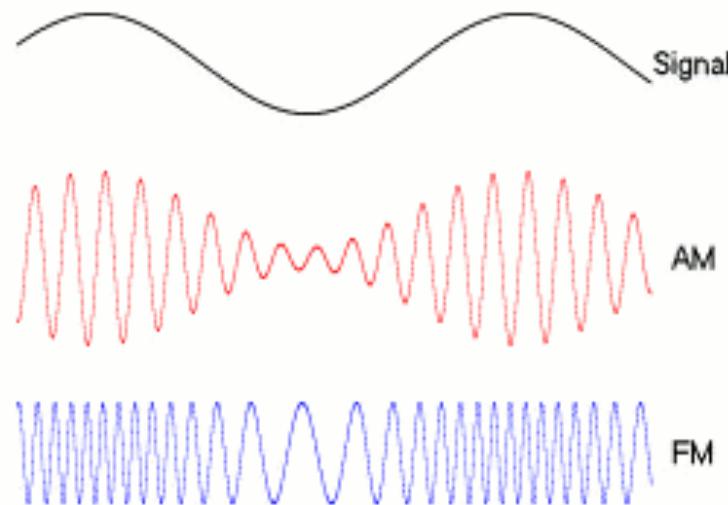
- SNR impacts performance
- SNR of an access point (AP) signal, measured at the user device, decreases as range to the user increases
- SNR decreases when there are RF interference from microwave ovens and cordless phones increases the noise level
- Laptop access to a 802.11b/g access point
 - > 40 dB SNR: excellent signal 5 bars: very fast
 - 25 dB to 40 dB SNR: very good signal (3-4 bars): very fast
 - 15 dB to 25 dB SNR: low signal (2 bars): usually fast
 - 10 dB to 15 dB SNR: very low signal (1 bar): mostly slow
 - 5 dB to 10 dB SNR: no signal

- Why is the data rate slower for lower SNR?
 - E_b/N_o : Energy per bit to noise power spectral density ratio
 - Signal power divided by the user bit rate
 - Bit error rate (BER) increases according to decreasing E_b/N_o
 - You have to retransmit if there is a bit error



Source: wikipedia

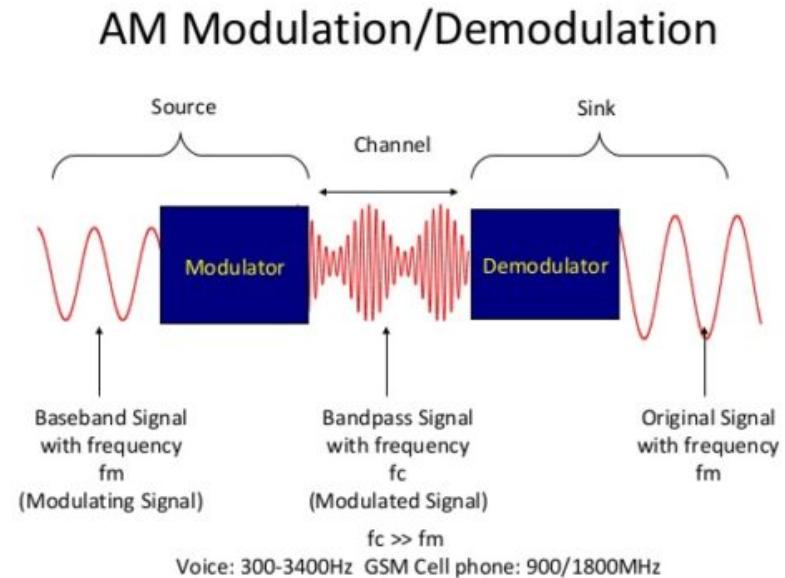
- What is modulation?
 - Process of varying one or more properties of a periodic waveform, called the *carrier signal* with a modulating signal that typically contains information to be transmitted
- Analog Modulation
 - Amplitude modulation (AM)
 - Frequency modulation (FM)



Source: wikipedia

- Why do you need a carrier signal?
 - You need oscillation to send something over the wireless channel
 - How would you send a flat signal over a wireless channel?
 - Several carrier waves of different frequencies can transmit at the same time without interference

- Modulation and demodulation?

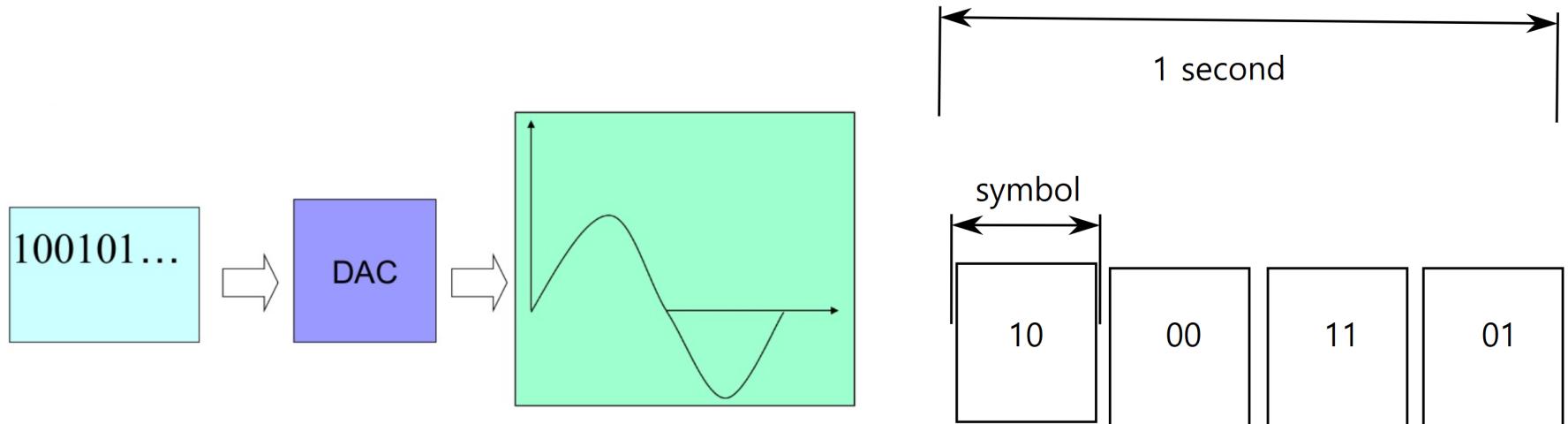


Source: <http://hamradioindia.com/articles/modulation-demodulation/>

Basics of Wireless Communication

■ Digital modulation

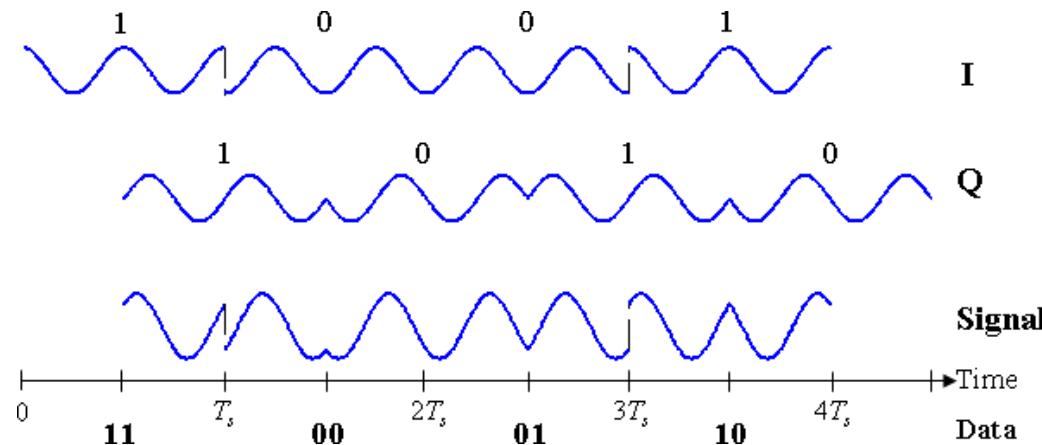
- Modulation: digital-to-analog conversion
- Demodulation: analog-to-digital conversion
- Analog “symbols” are assigned to each digital bits
 - Four symbols are representing 10, 00, 11, 01
 - For example, musical tones can be a “symbol”
 - 4 symbols/sec = 8 bits/sec



Source: S. Nazin, "Digital to Analog Conversion"

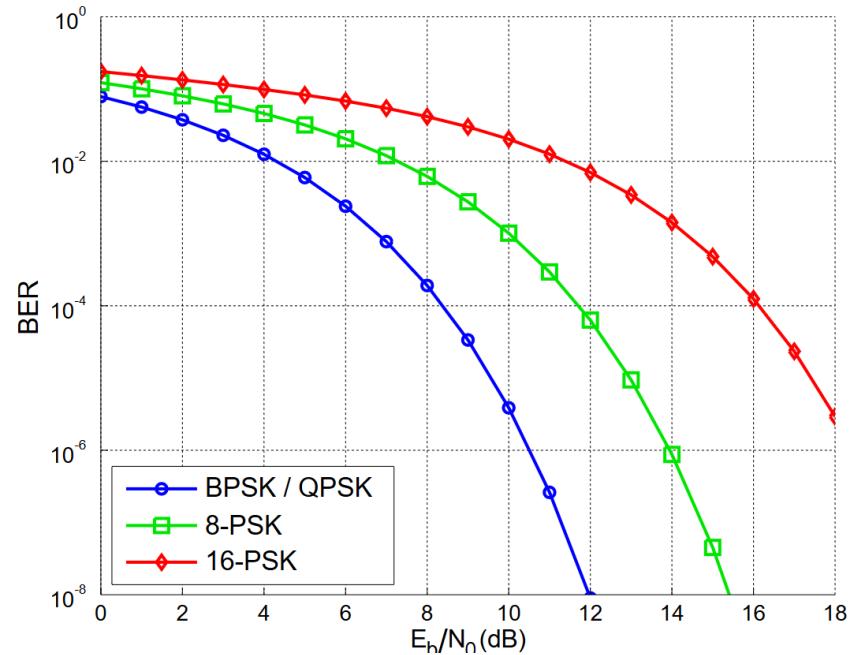
Basics of Wireless Communication

- Digital modulation types
 - PSK (phase shift keying)
 - different phases are used
 - FSK (frequency shift keying)
 - different frequencies are used
 - ASK (amplitude shift keying)
 - different amplitudes are used
 - QAM (quadrature amplitude modulation)
 - at least two phases and two amplitudes are used



Basics of Wireless Communication

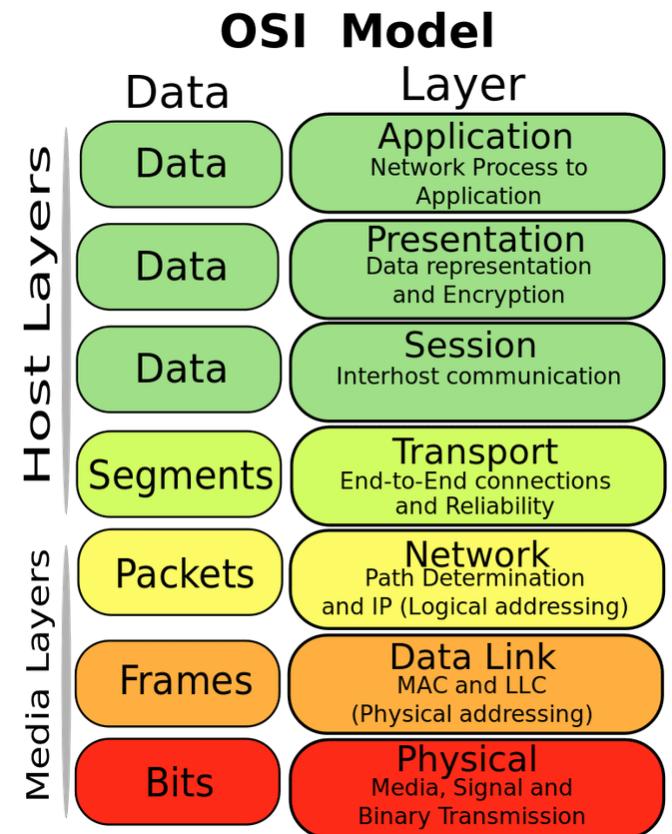
- So what were BPSK and QPSK?
- BPSK with binary (two) symbols
- QPSK with four symbols, etc
- Why is the BER lower for BPSK?
 - The more elaborated manner you divide the phases, the error of detecting symbols in a wrong way increases



- What happens if there is a bit error?
- You can apply error coding and trying to figure out what the original bit was
- You can retransmit the data bits
- But these sorts of tasks maybe be handled at different abstraction layers

OSI Model

- Open Systems Interconnection Model (OSI Model)
 - Conceptual model that characterizes and standardizes the communication functions of a telecommunication or computing system
 - Lower layers are closer to physical world and hardware
 - Upper layers are closer to software
- Physical layer: Everything we discussed
- Data link layer: MAC, Ethernet
- Network layer: IP
- Transport layer: TCP, UDP
- Session layer
- Presentation layer: SSL, SSH, IMAP, FTP
- Application layer: HTTP, DNS



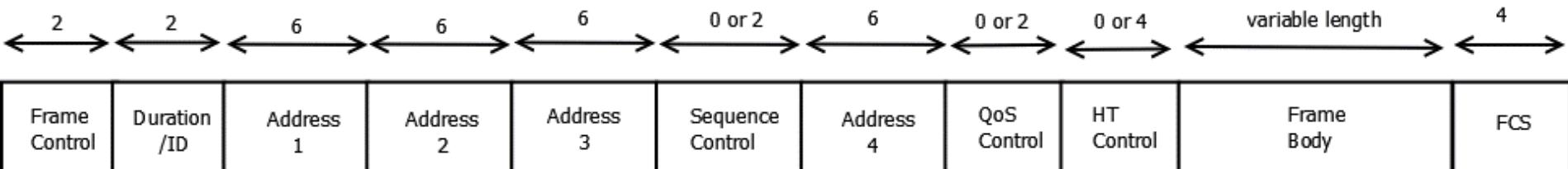
- IEEE802.11
 - WLAN computer communication in various frequencies
 - Created and maintained by IEEE
 - Set of media access control (MAC) and physical layer



- 802.11 physical layer (PHY)
 - Interface between the MAC and the wireless media where frames are transmitted and received
- PHY provides an interface to exchange frames with the upper MAC layer for transmission and reception of data
- PHY uses signal carrier and spread spectrum modulation to transmit data frames over the media
- PHY provides a carrier sense indication back to the MAC to verify activity on the media

Wireless Network Protocols

- 802.11 – Frame formats (layer 2)
 - MAC header: contains control information including „retry“ bits
 - Retry bits ensure duplicate packets are handled
 - Payload (actual data)
 - Frame check sequence (FCS): error detecting codes – adds redundancy



- 802.11 Media Access Control
 - How is access to the media controlled?
- Asynchronous, best-effort, connectionless delivery of MAC layer data
- There is no guarantee that the frames will be delivered successfully

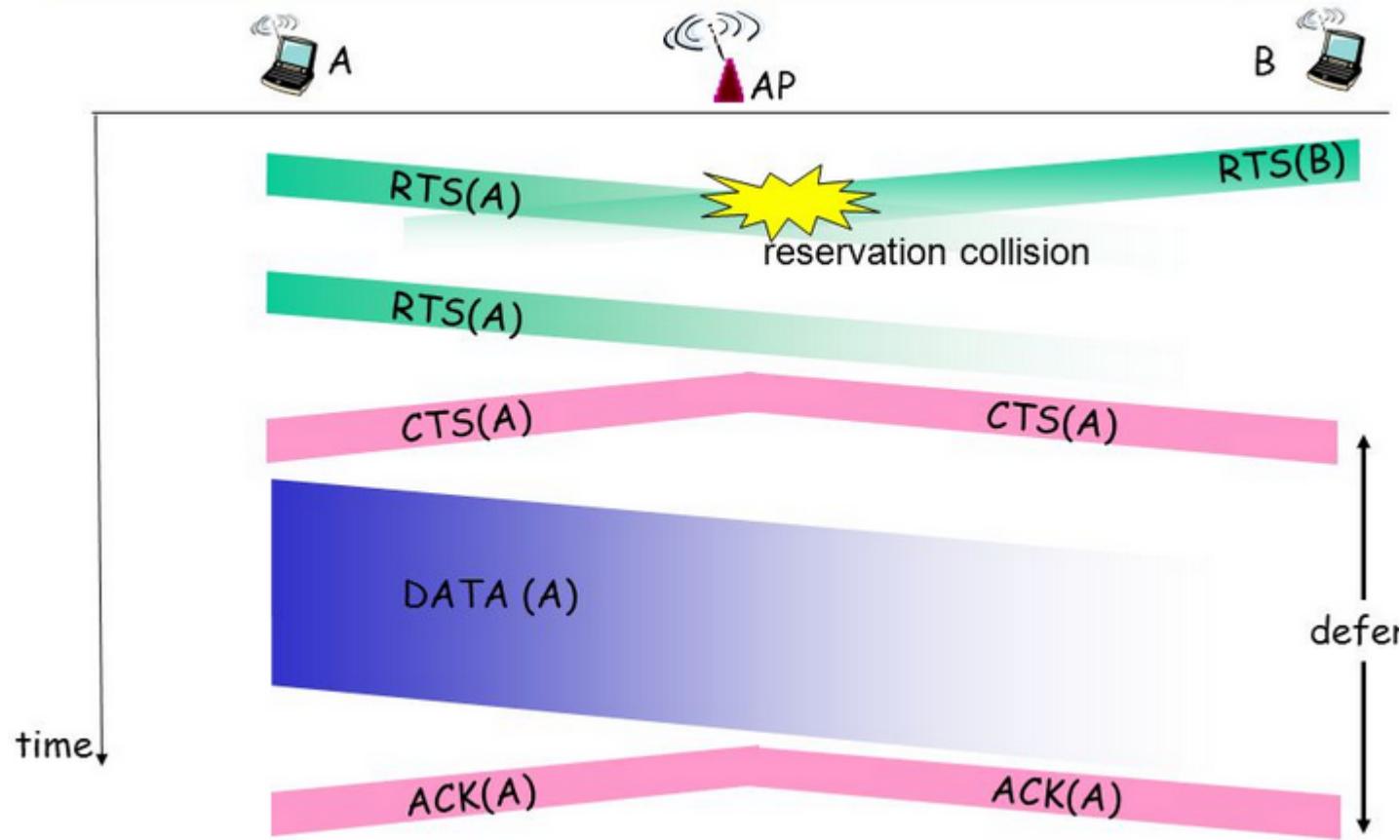
- 802.11 MAC utilizes carrier-sense multiple access with collision avoidance (CSMA/CA)

- Security is provided by wireless equivalent privacy (WEP), which is an encryption service for data delivered on WLAN

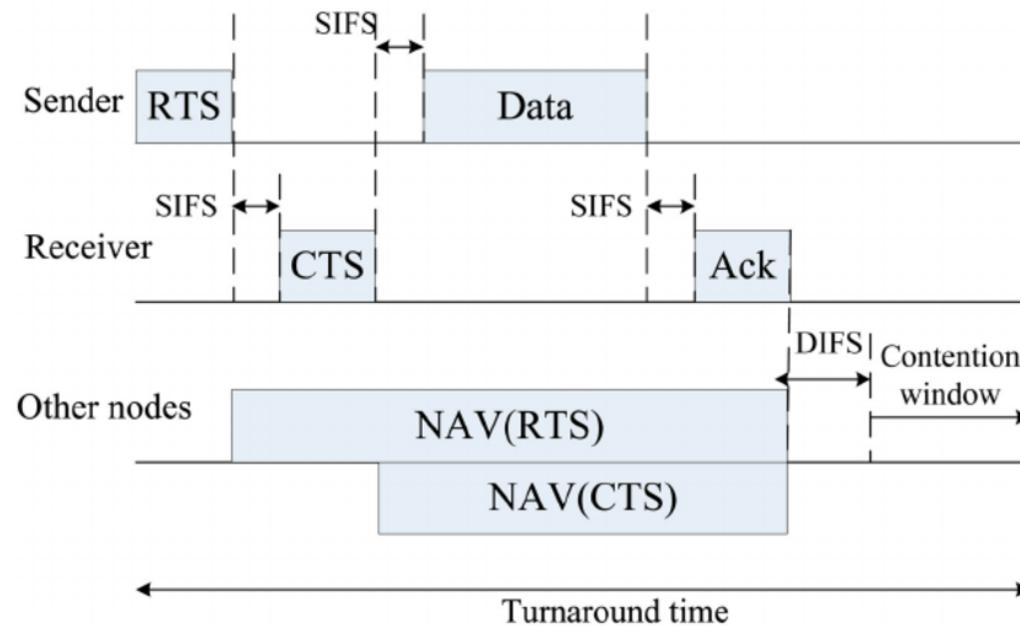
- Carrier-sense multiple access with collision avoidance (CSMA/CA)
- CSMA/CA is a protocol that operates in the data link layer
- Steps
 - **Carrier sense:** Prior to transmitting, a node first listens to the shared medium
 - **Collision avoidance:** if another node was heard, the node waits for a period of time (usually random) for the node to stop transmitting before listening again for a free communications channel
 - **RTS/CTS Handshake (optional):** request to send (RTS) packet is sent to the receiver, and the receiver responds with a clear to send (CTS) packet
 - **Transmission:** the node awaits receipt of an acknowledgement packet from the access point to indicate the packet was received and error-checked correctly

Collisions

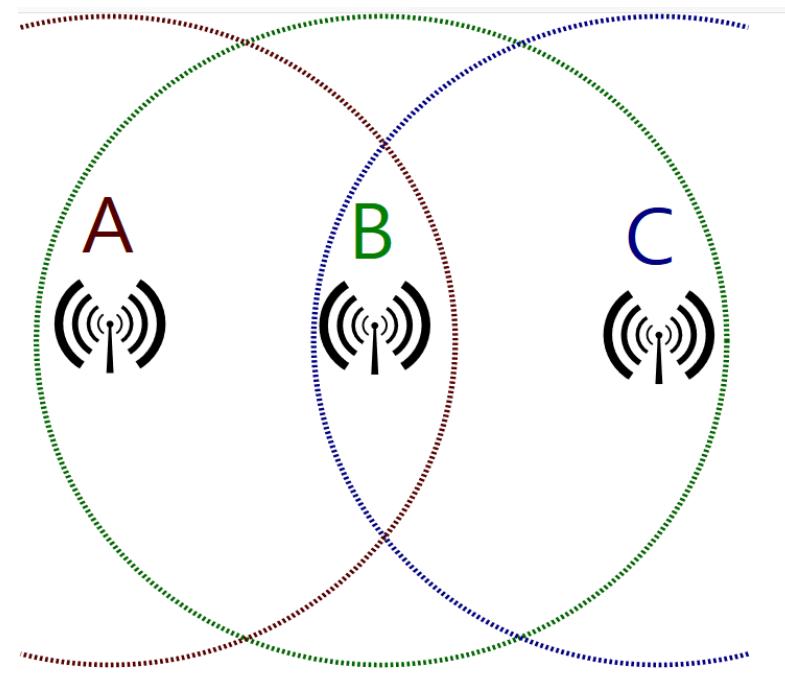
- Collision occurs when two nodes tries to access the same medium at the same time



- CSMA/CA time graphs

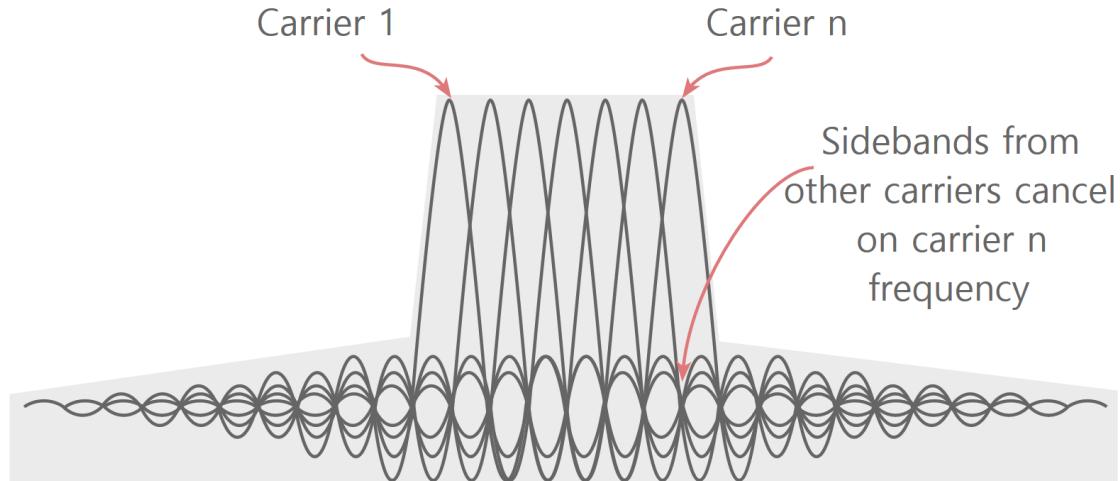


- But why doesn't it guarantee successful delivery?
- Hidden node problem
 - If node A wants to send something to node B while node C is sending something, it cannot be sensed and there will be collision at node B



- Amendments have been made
 - 802.11 legacy
 - Released in June 1997
 - Bitrate of 2 or 2 Mbit/sec
 - 802.11a (OFDM waveform)
 - Released in June 1999
 - Datarates of 1.5 to 54 Mbit/sec
 - Operates at 5 GHz frequency band and has less range
 - 802.11b (2000)
 - First widely accepted protocol
 - 11 Mbit/sec
 - 2.4 GHz range used – overlaps with microwave ovens, cordless phones, bluetooth – interference issues
 - 802.11g(2003)
 - OFDM based transmission scheme, 2.4 GHz band
 - 22 Mbit/sec or 54 Mbit/sec

- Orthogonal frequency division multiplexing (OFDM)
 - Encoding of digital data on ***multiple carrier frequencies***
 - Used in wireless networks and 4G mobile communications
 - Why is it called ***orthogonal?***
 - Because their channels are placed adjacent to each other with carefully set band gaps
 - Cancellation (see the common x-axis crossings) – no band gaps required to reduce interference



List of WLAN Channels

- Around 2.4 GHz (802.11b/g/n/ax)
 - Fourteen channels are designated in the 2.4 GHz range
 - Spaced 5 MHz apart
 - Does it mean only 14 devices can connect to an AP?
 - No
 - Multiple devices share single channel by dividing time

Channel	F ₀ (MHz)	North America ^[6]	Japan ^[6]	Most of world ^{[6][7][8][9][10][11][12][13]}
1	2412	Yes	Yes	Yes
2	2417	Yes	Yes	Yes
3	2422	Yes	Yes	Yes
4	2427	Yes	Yes	Yes
5	2432	Yes	Yes	Yes
6	2437	Yes	Yes	Yes
7	2442	Yes	Yes	Yes
8	2447	Yes	Yes	Yes
9	2452	Yes	Yes	Yes
10	2457	Yes	Yes	Yes
11	2462	Yes	Yes	Yes
12	2467	No ^B except CAN	Yes	Yes
13	2472	No ^B	Yes	Yes
14	2484	No	11b Only ^C	No

Source: wikipedia

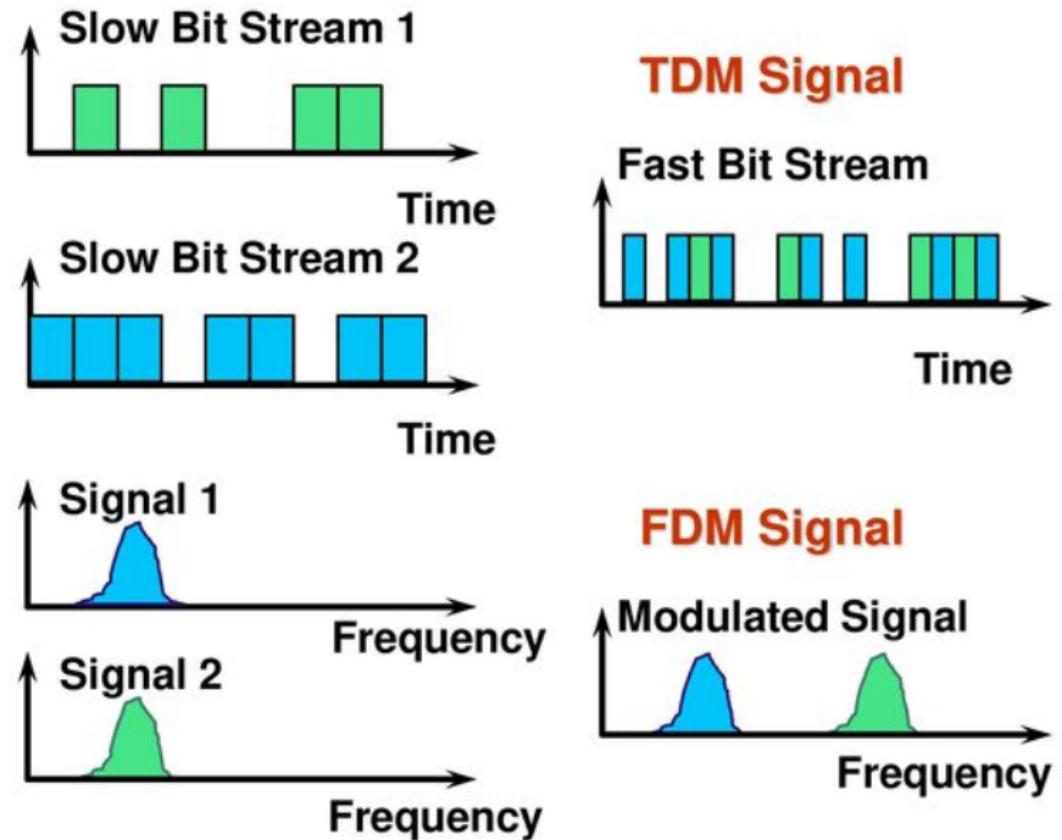
TDM vs FDM

- Time division multiplexing (TDM)

- Sharing time on the same media
- Need sync pulse
- Interference is small

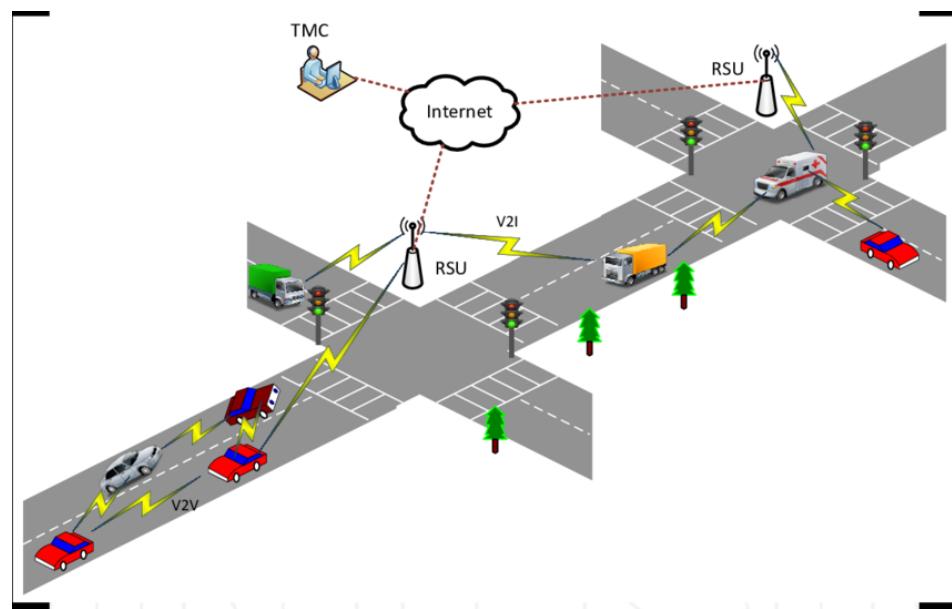
- Frequency division multiplexing (FDM)

- Sharing frequency on the same media
- Guard band needed to reduce interference
- More complex circuit



Source: Sajid Awan, „Data over cable networks“

- 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-hop delivery
 - MAC protocol for VANET is required to adapt to the single-hop or multi-hop traffic delivery

- 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

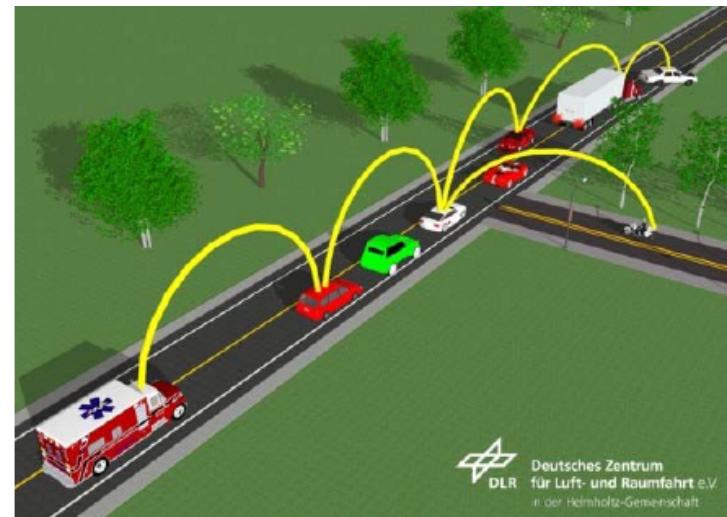
Challenges in Numbers

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"

- 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

- 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)



 Deutsches Zentrum
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in der Helmholtz-Gemeinschaft

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)

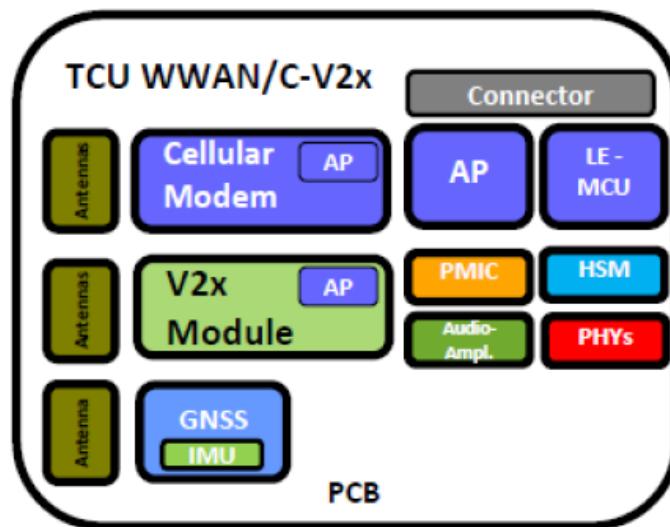
RSU Example

- 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)



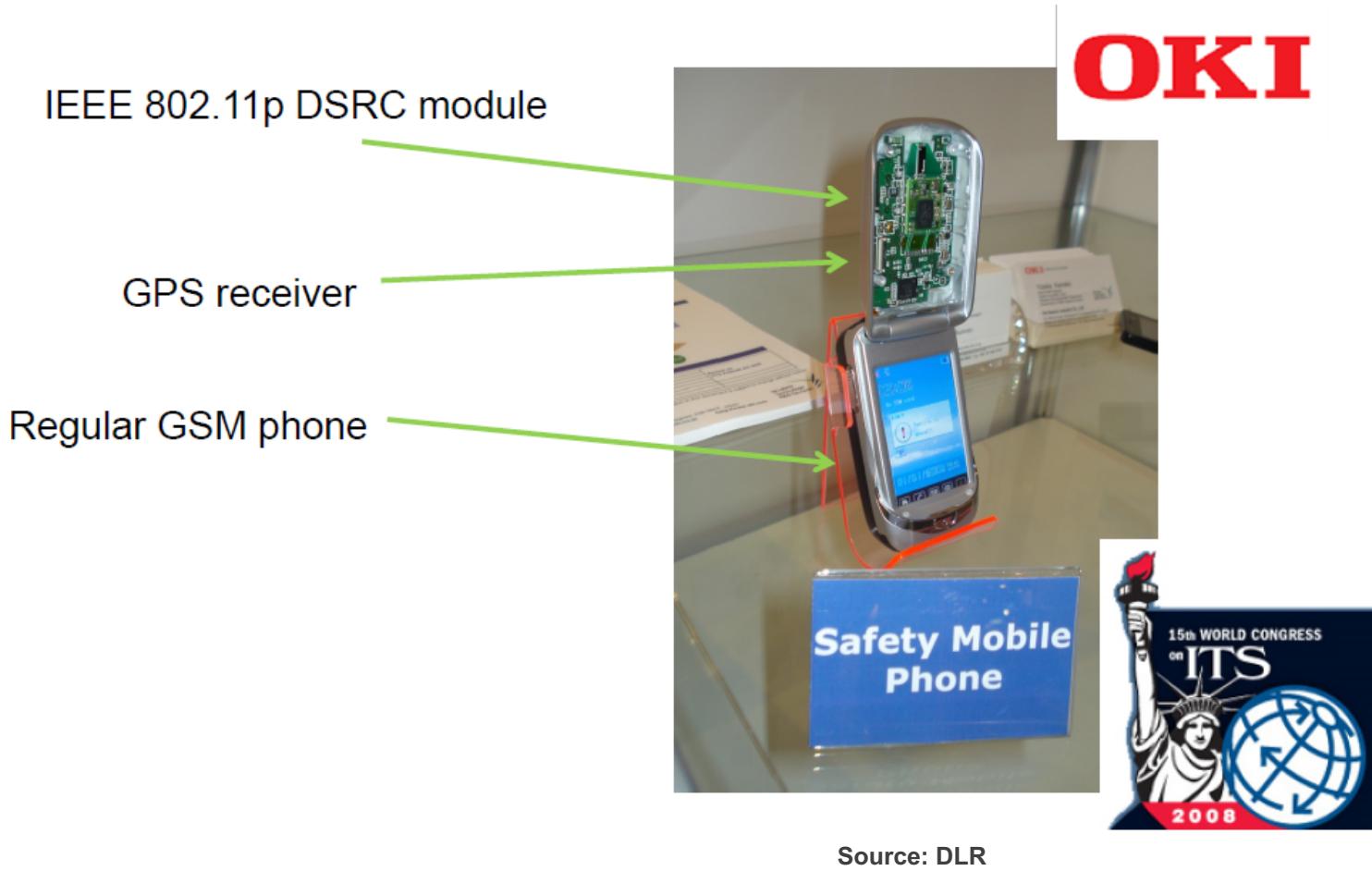
Source: Siemens

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



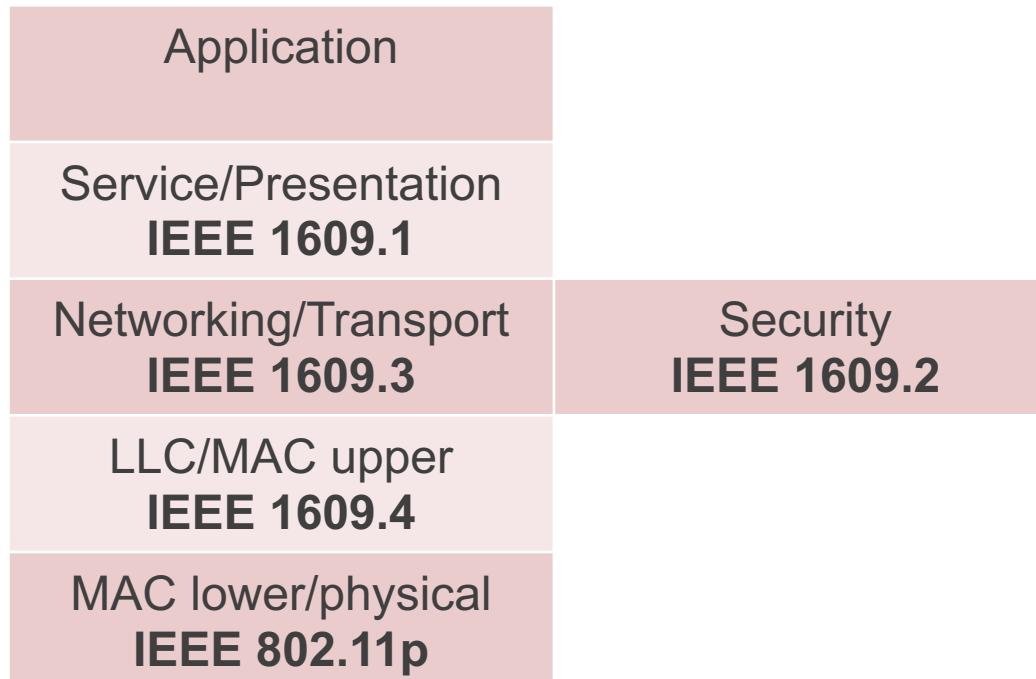
Source: P3, V2X Automotive On-board Unit Cost Analysis

- Pedestrian?



Source: DLR

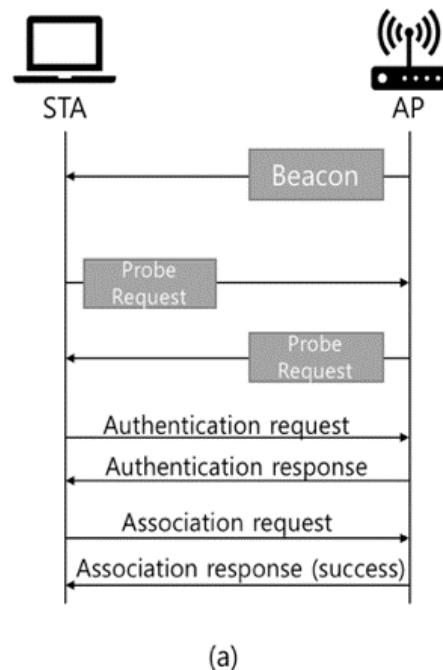
- Dedicated short-range communications (DSRC)
 - Also known as wireless access in vehicular environment (WAVE) in the US
- There are so many terms what is the relationship between them?
 - DSRC, IEEE 802.11p, IEEE 1609
 - IEEE 802.11p and IEEE 1609 standard define different parts of DSRC



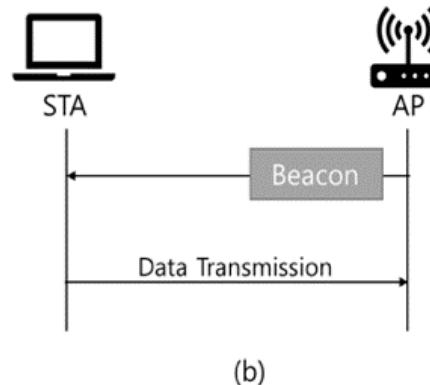
- IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add ***wireless access in vehicular environments*** (WAVE), published in 2010
- Data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure (RSUs in the Vein example!)
- Licensed ITS (Intelligent Transportation Systems) band of 5.9 GHz (5.85 GHz – 5.925 GHz)

■ DSRC

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



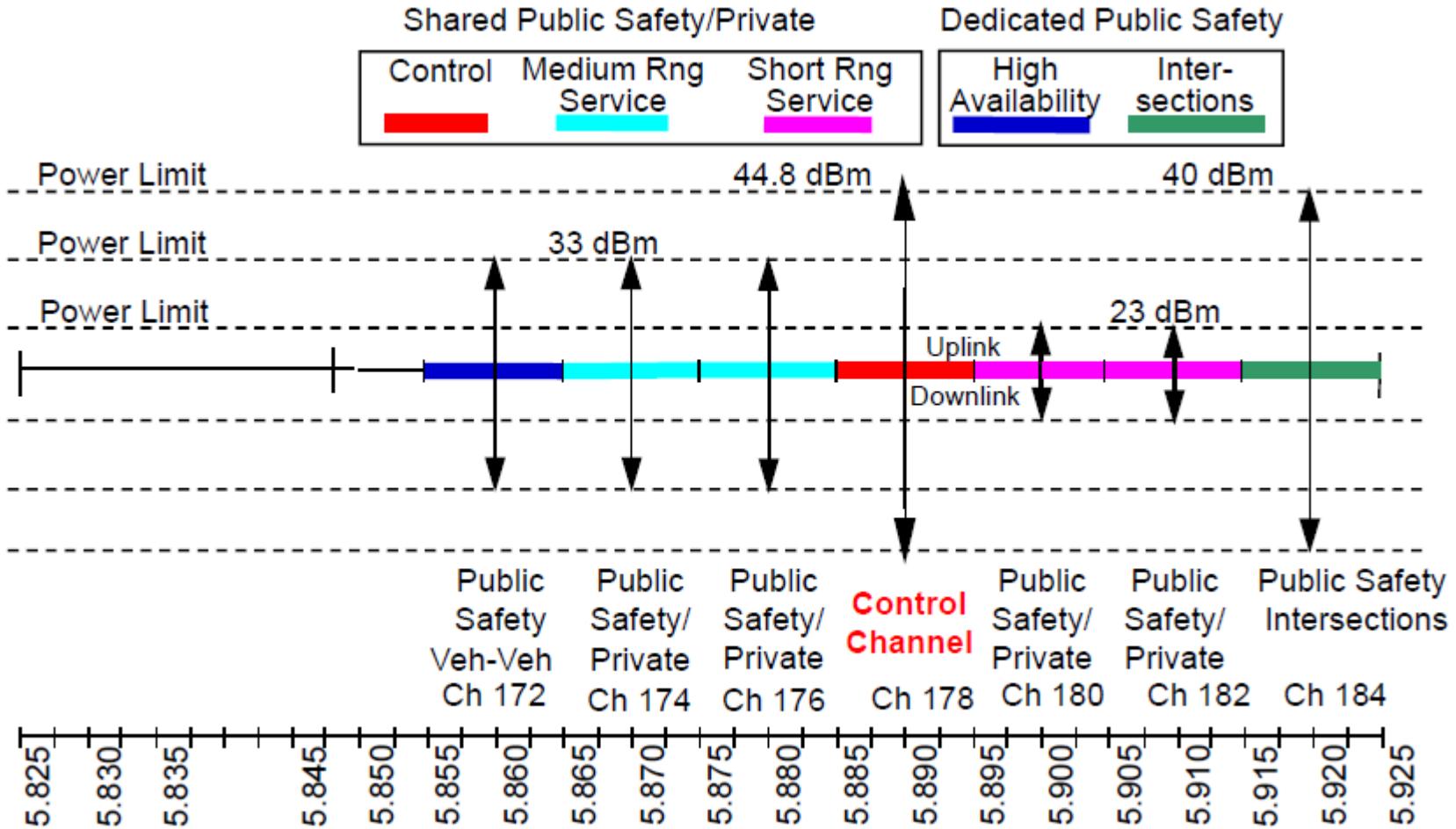
(a)



(b)

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

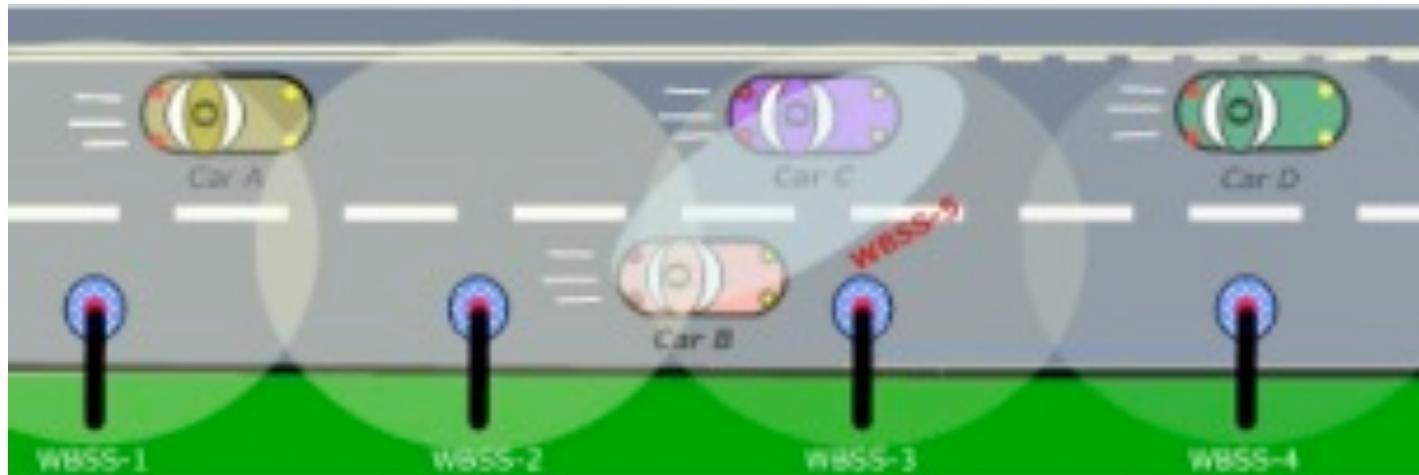
IEEE 802.11p Frequency Band



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

- 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 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

- Without WAVE Basic Service Set (WBSS)
 - Safety-critical, low latency, messages and control messages
 - Mainly broadcast
 - Only on CCH
- With WAVE Basic Service 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 μ s	8.0 μ s
Guard Period	0.8 μ s	1.6 μ s
Occupied bandwidth	20 MHz	10 MHz
Frequency	5 GHz ISM band	5.850-5.925 GHz

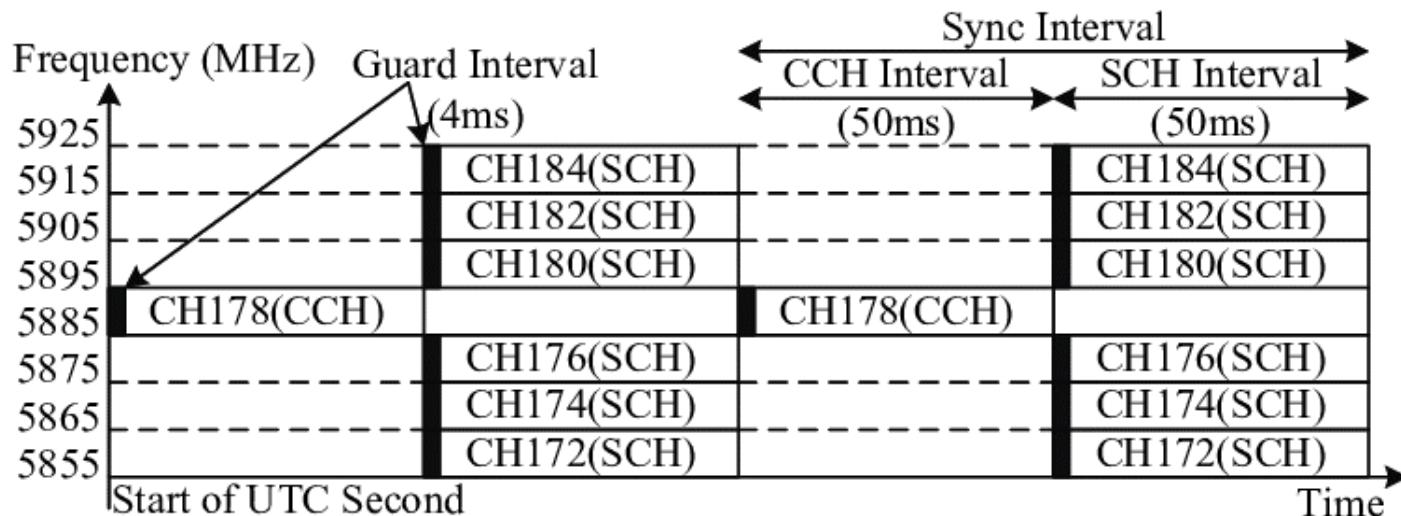
Longer guard period
 → Less Inter-symbol Interference
 → Better resistance against multipath error

Re-order of sub-carriers
 → Better multipath mitigation

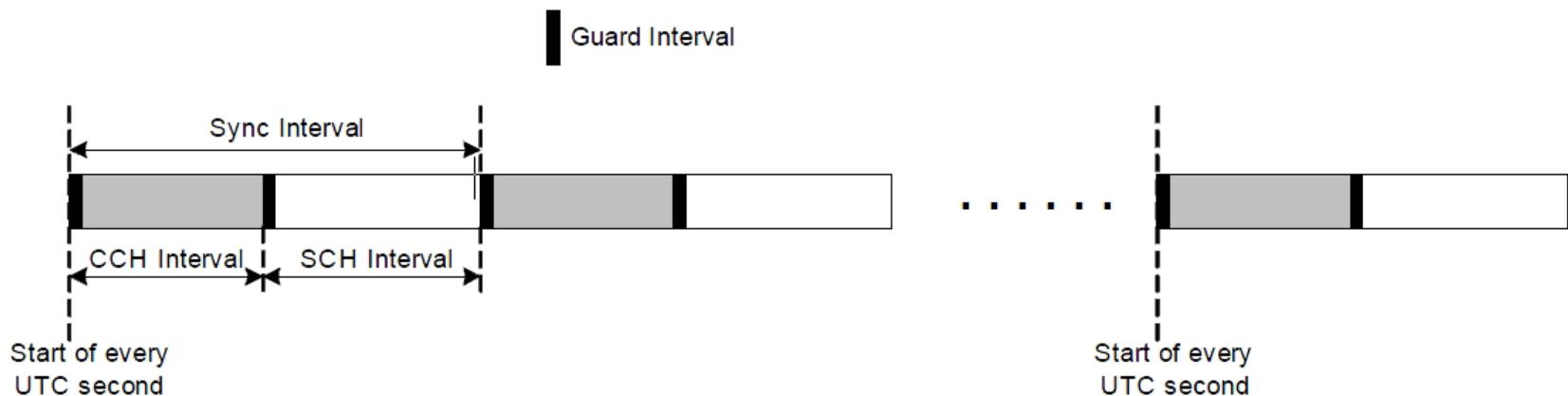
Dedicated frequency band
 → Less Co-Channel Interference

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,



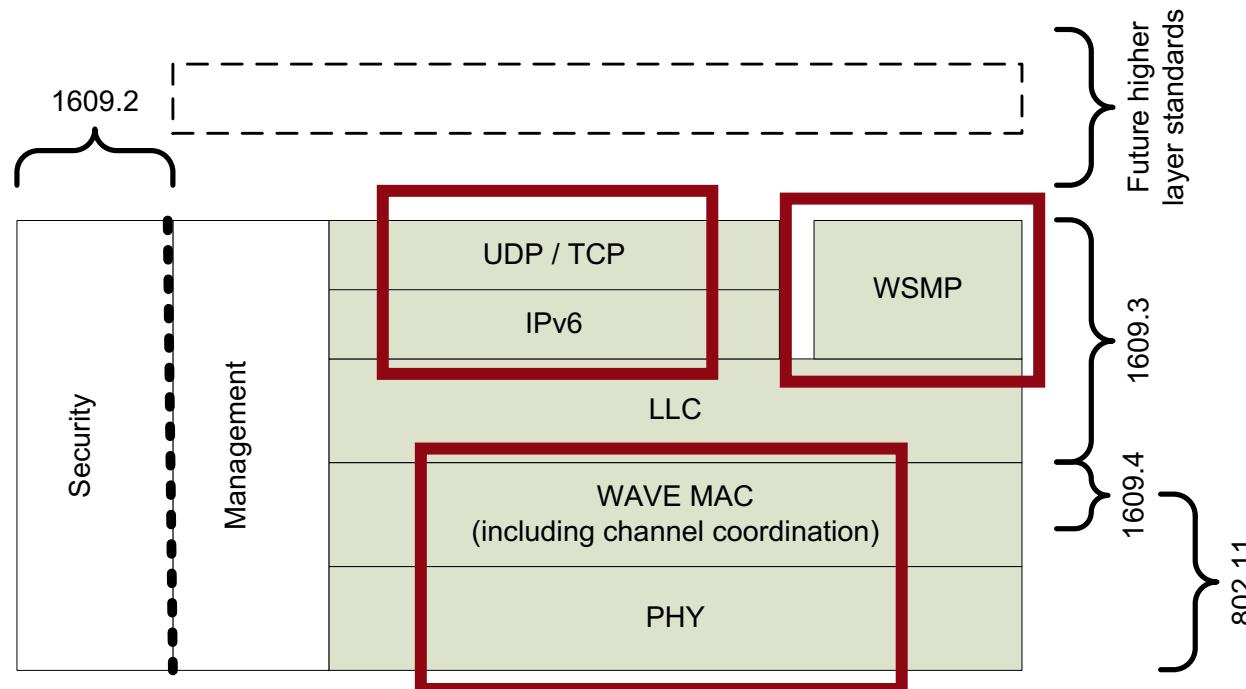
- Channel coordination
 - Synchronized scheme based on coordinated universal time (UTC)
 - Assures that all DSRC devices will be monitoring the CCH during a common time interval (CCH interval)
 - Assures that members of a network will be using the corresponding SCH during a common time interval (SCH 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



- 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

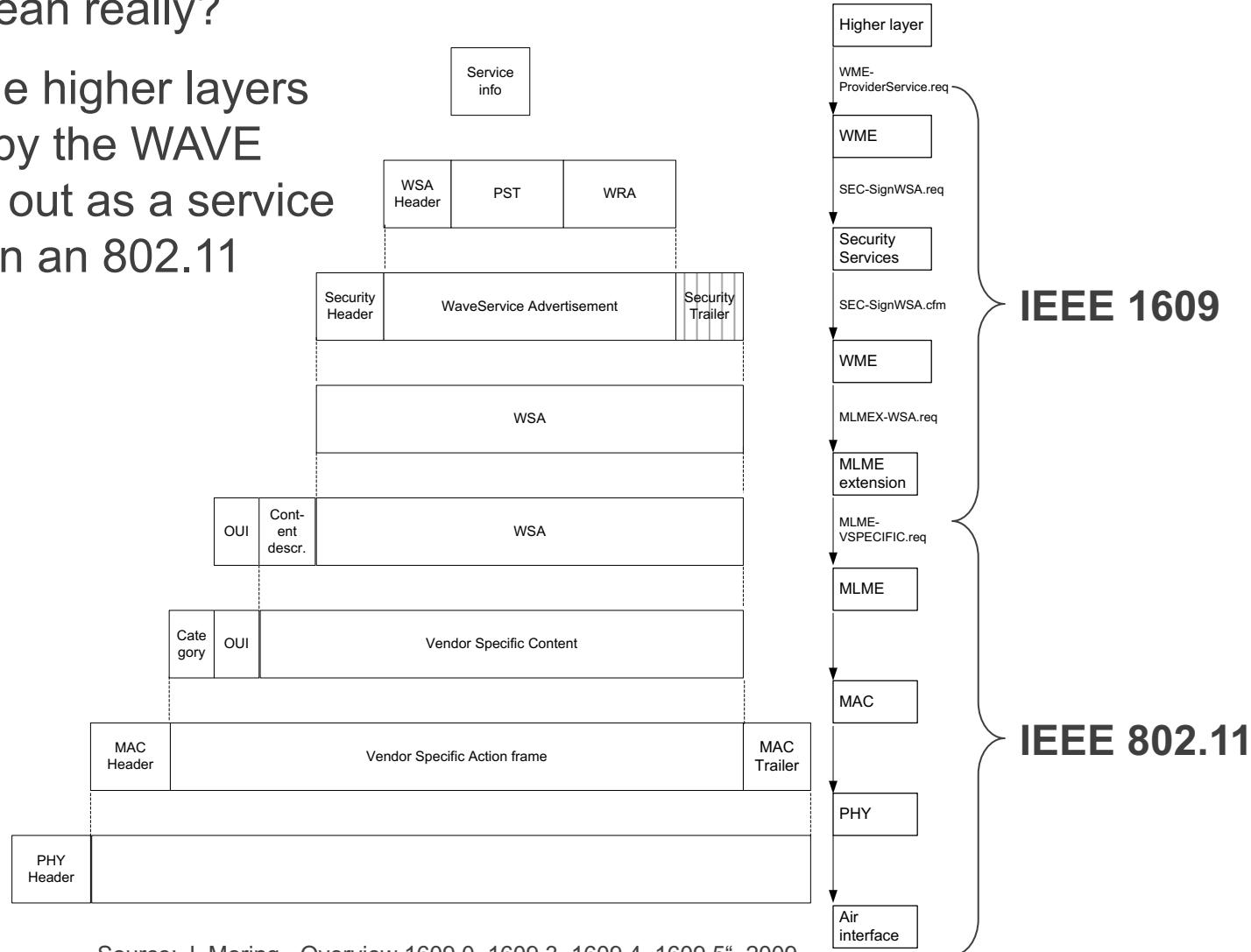
WAVE Short Message Protocol (WSMP)

- 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



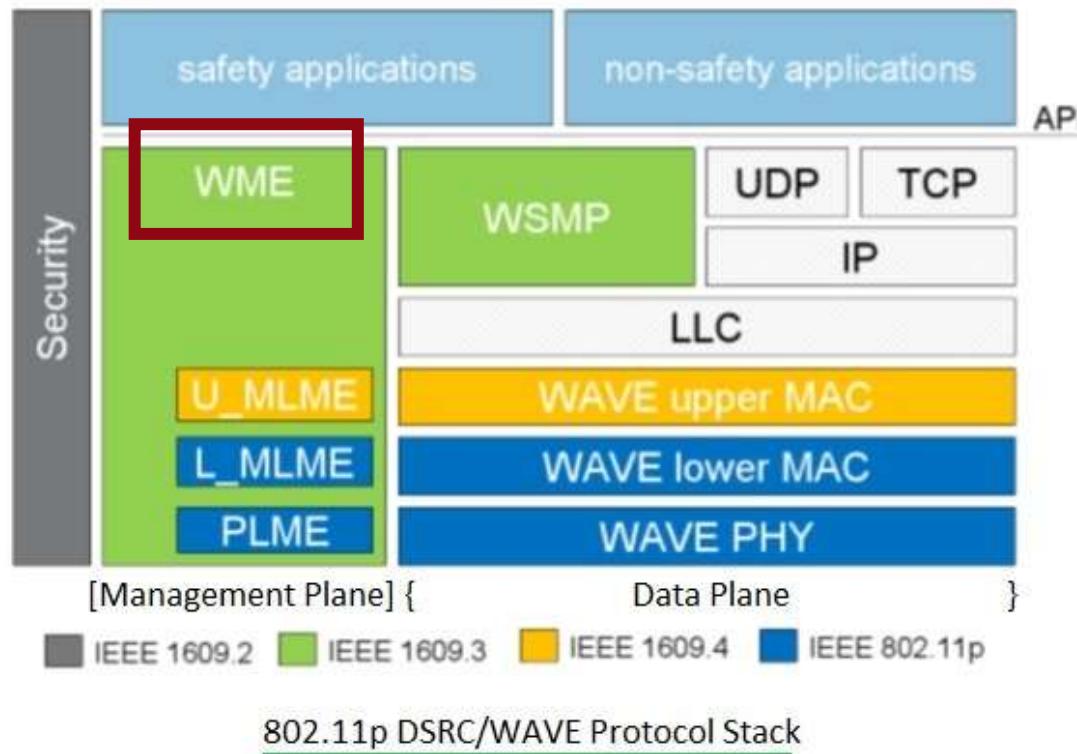
Source: J. Moring, „Overview 1609.0, 1609.3, 1609.4, 1609.5“, 2009

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

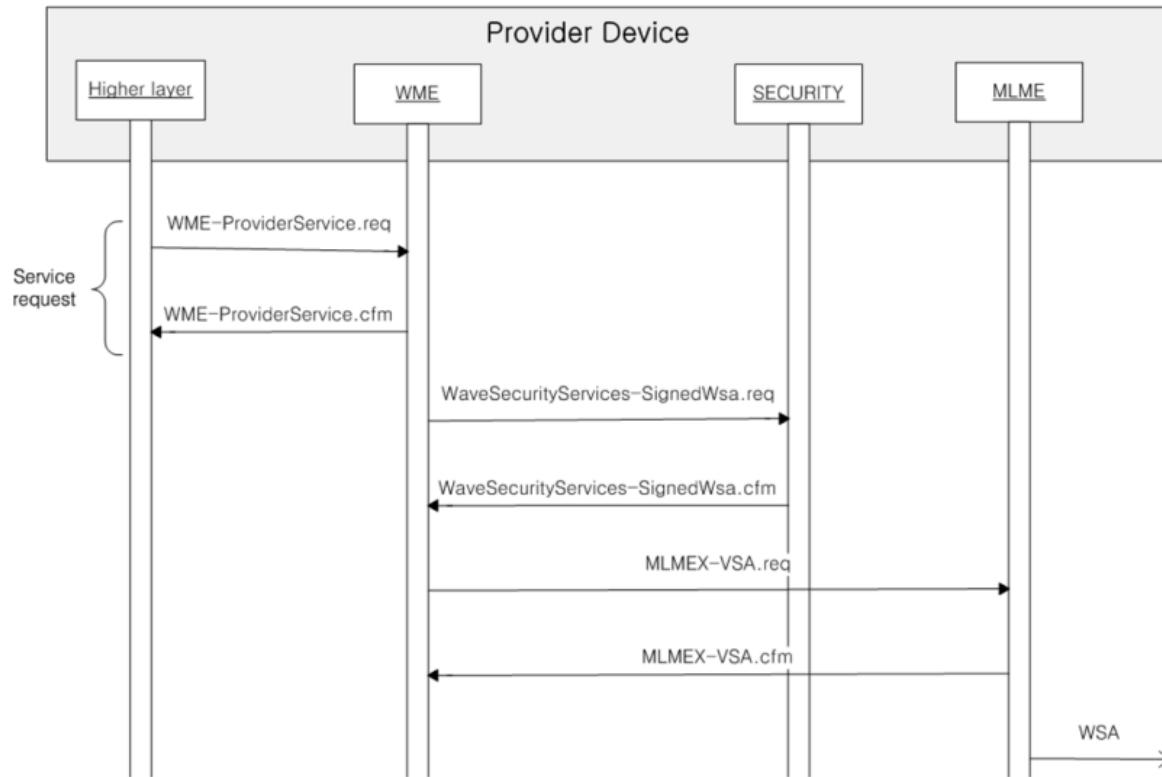


Source: <http://www.rfwireless-world.com/Tutorials/802-11p-WAVE-tutorial.html>

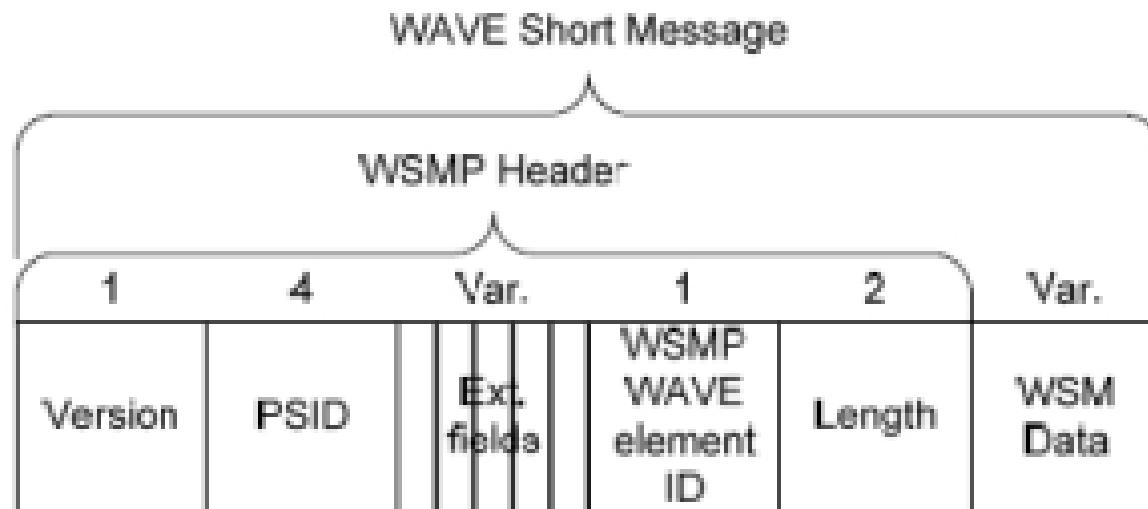
- Provider vs User
 - In WSMP, nodes are divided into providers and users
- Provider
 - Sends out WAVE Service Advertisements (WSA) on control channel (CCH)
 - Includes information on services and channels
 - May include IP configuration information (if IP is used)
 - Operates on identified service channels (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

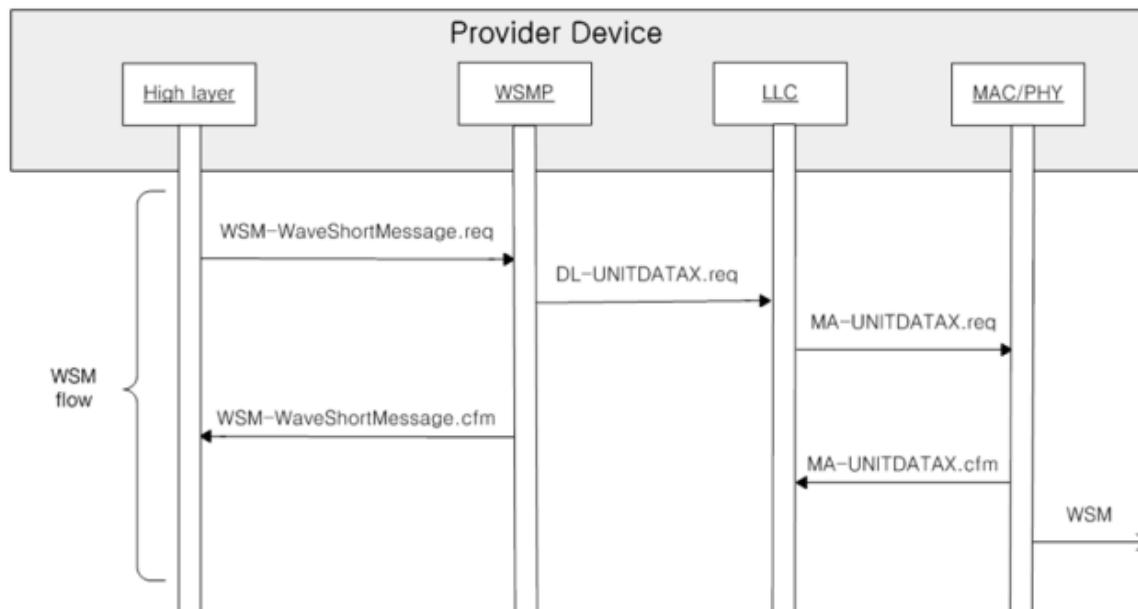


- WAVE short message format
 - Protocol version
 - PSID
 - Var. (optional): Channel #, Transmission rate, transmit power
 - Length: Length of WSM data
 - Payload: WSM data



WAVE Short Message Protocol (WSMP)

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



- 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

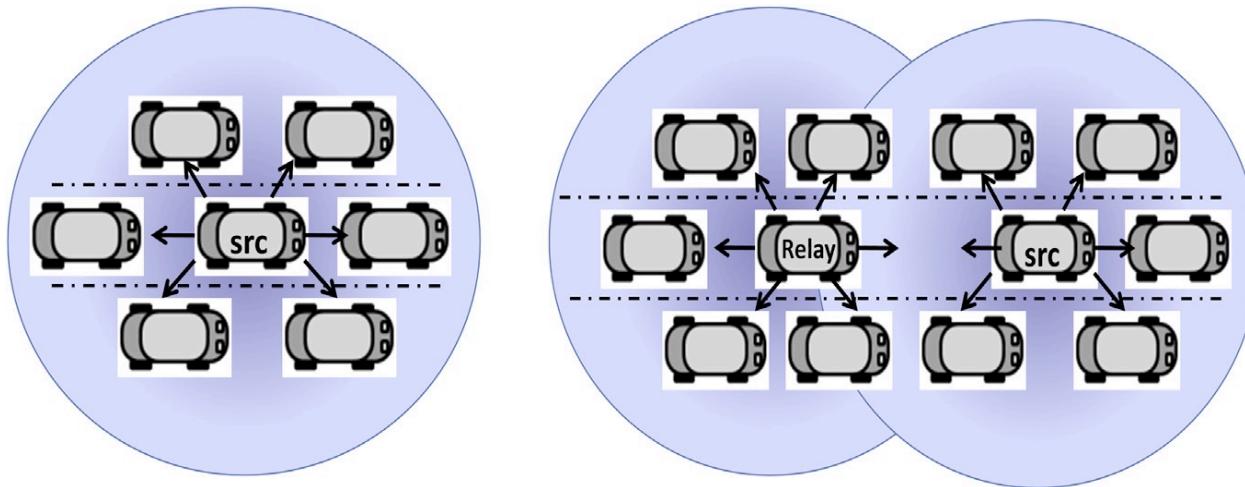
```
void TraCIDemo11p::onWSA(WaveServiceAdvertisement* wsa) {  
    if (currentSubscribedServiceId == -1) {  
        mac->changeServiceChannel(wsa->getTargetChannel());  
        currentSubscribedServiceId = wsa->getPsid();  
        if (currentOfferedServiceId != wsa->getPsid()) {  
            stopService();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

- WSMP characteristics
 - 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 (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

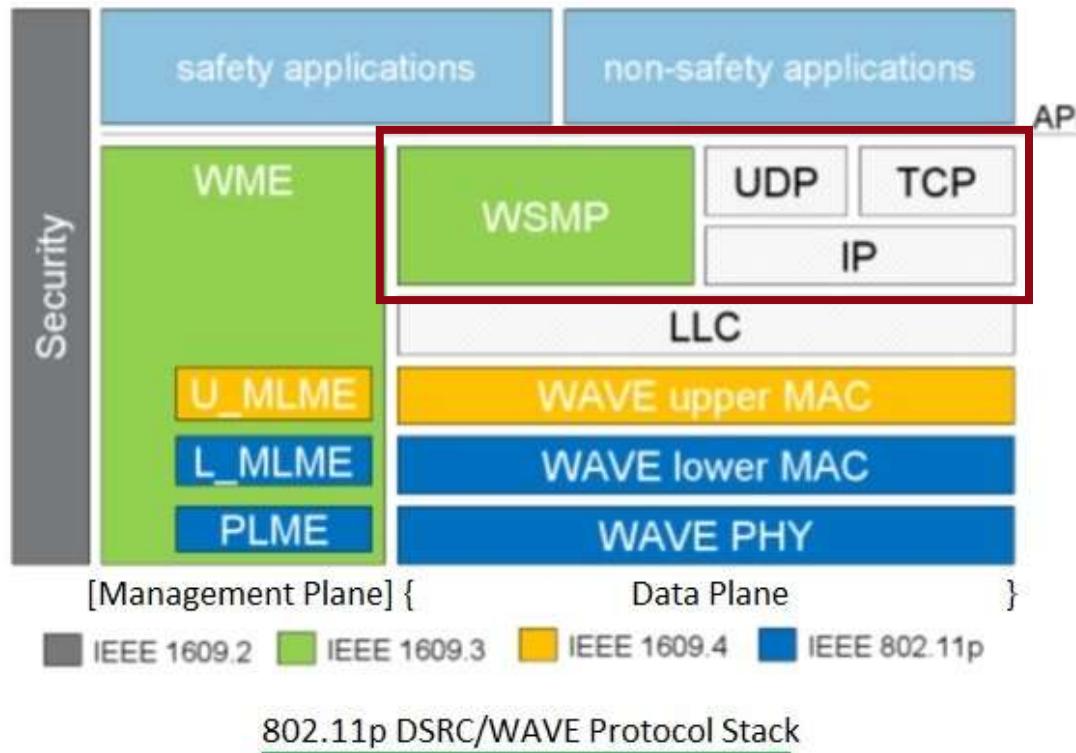
- Types of connections
 - Vehicle-to-vehicle (V2V)
 - Messages are transmitted between neighboring vehicles
 - One-hop or multi-hop messaging scenarios in which vehicles communicate directly with other vehicles or through intermediary vehicles
 - Vehicle-to-infrastructure (V2I)
 - Messages are transmitted 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

- 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



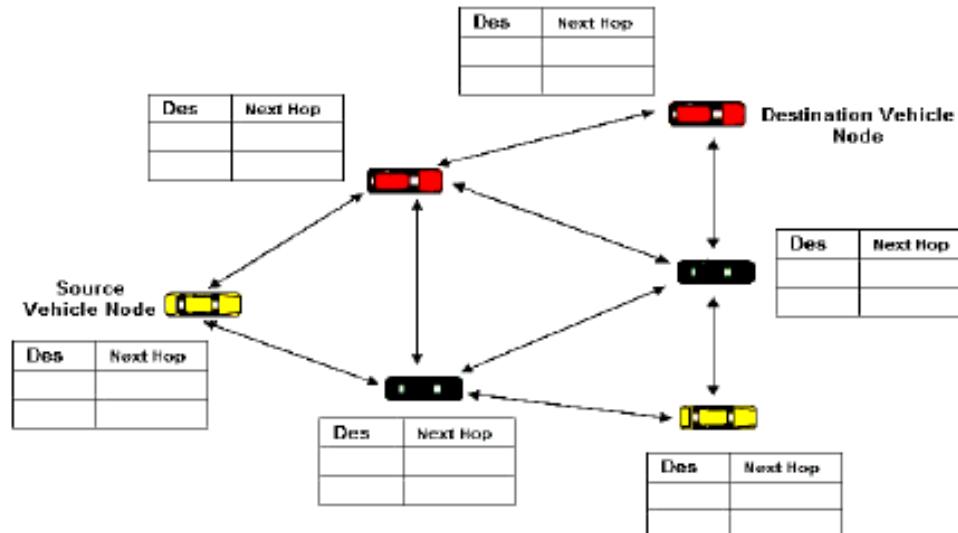
Source: <http://www.rfwireless-world.com/Tutorials/802-11p-WAVE-tutorial.html>

Routing Schemes in VANET

- Categories of routing schemes

- Topology-based routing

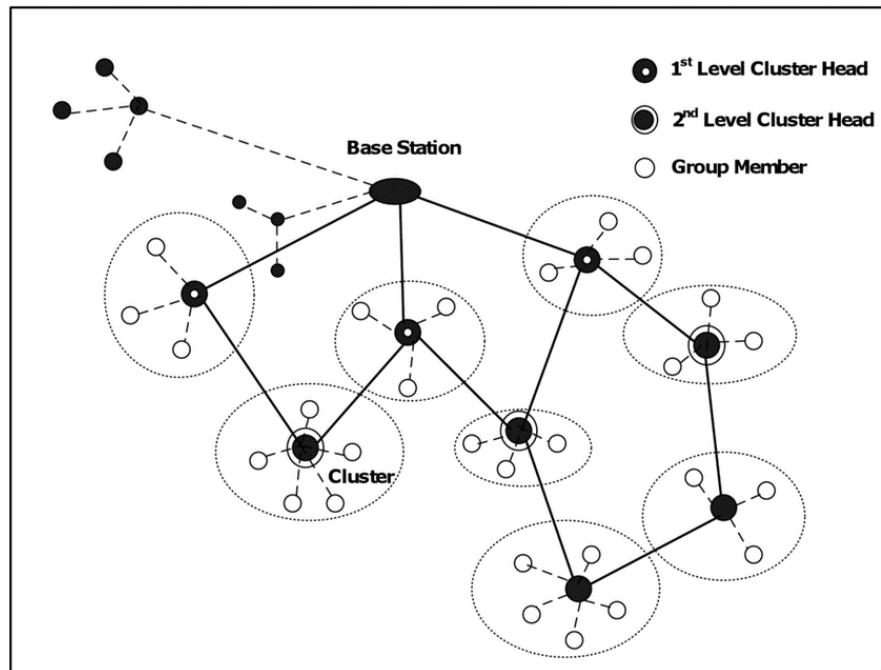
- The choice of route from source to destination is based on links information previously collected by the vehicle (proactive schemes), or sought when needed (reactive schemes)
 - Step of searching or maintaining a route from source to destination is mandatory before sending data packets



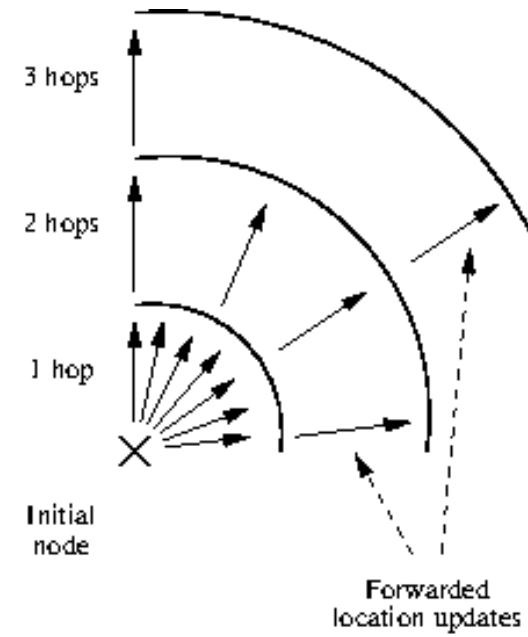
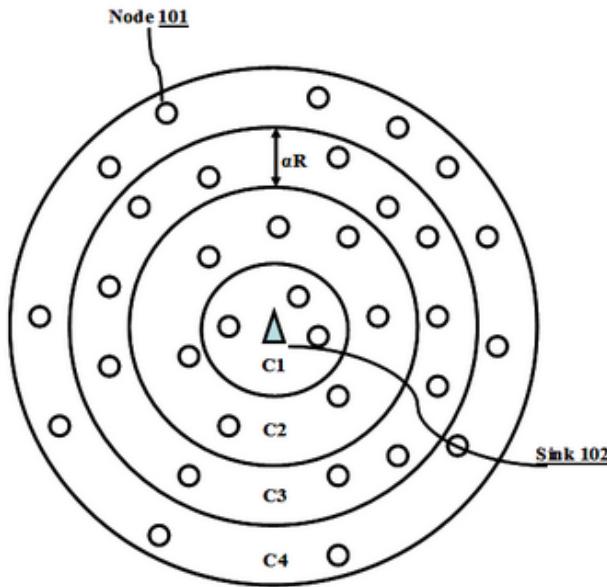
Source: K. N. Quareshi, et al., "VEHICULAR AD HOC NETWORKS ROUTING PROTOCOLS: SURVEY", 2015

- 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

- 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



- 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

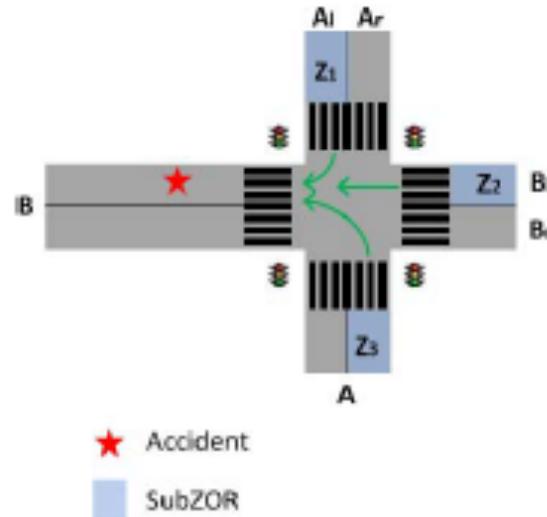


Source: S. Boumerdassi, et al., „A flooding-based solution to improve location services in VANETs, IEEE ICC 2016

Routing Schemes in VANET

- Geocast-based routing

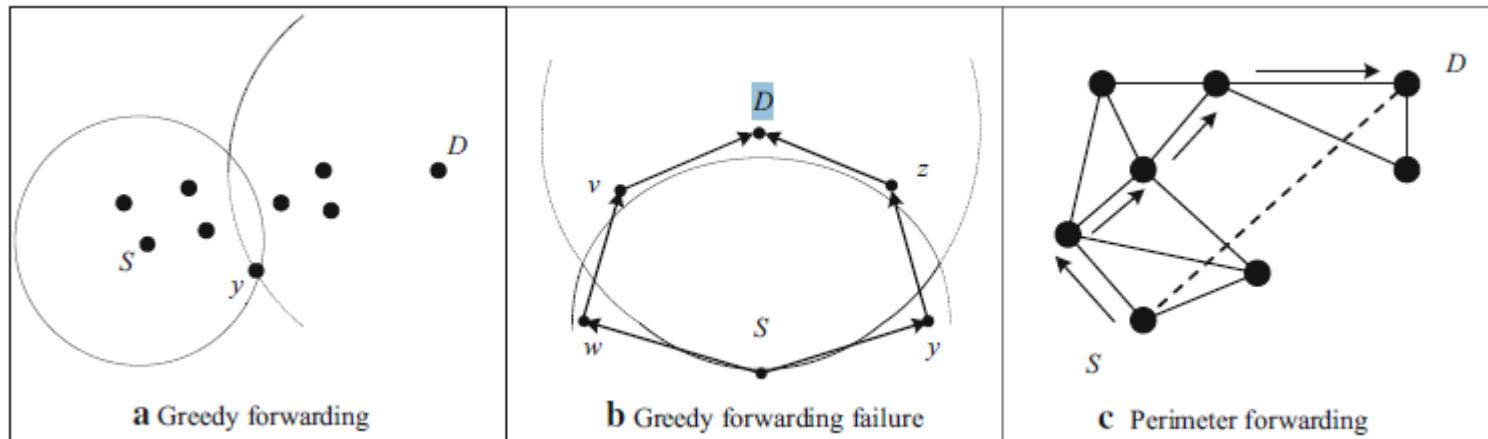
- Similar to broadcasting, but forwards packets to vehicles belonging to the destination area called zone of relevance (ZOR)
- In order to prevent simple flooding, a forwarding area called zone of forwarding (ZOF) is used to confine the message
- Also assumes that each node is aware of its locations
- Accident example:
 - When an accident happens, cars in z_1 , z_2 and z_3 want to be informed
 - The vehicles can re-route



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

■ Geographic routing example

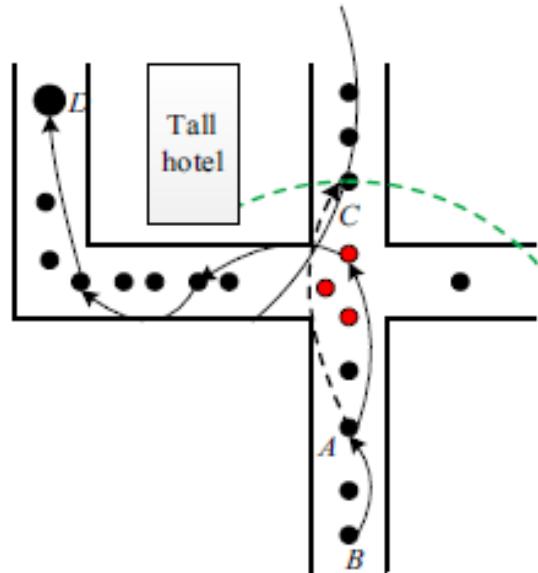
- Greedy perimeter stateless routing (GPSR)
- Classical position-based routing
- Makes routing decisions using only information about their immediate neighbors in the network topology
- Objective: $S \rightarrow D$
- Fig b fails to deliver packet because no immediate neighbor is closer to D than itself



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

Routing Schemes in VANET

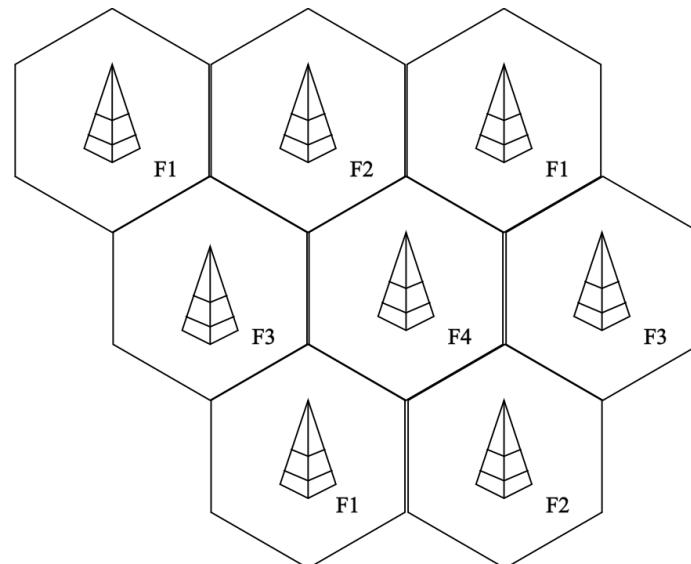
- You could also try to make use of the road topology in addition because there will not be obstacles along it
- Sending from C to D directly is difficult due to the hotel, so take a detour along the road



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

■ **Cellular** network

- 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 interference and provide guaranteed service quality within each cell

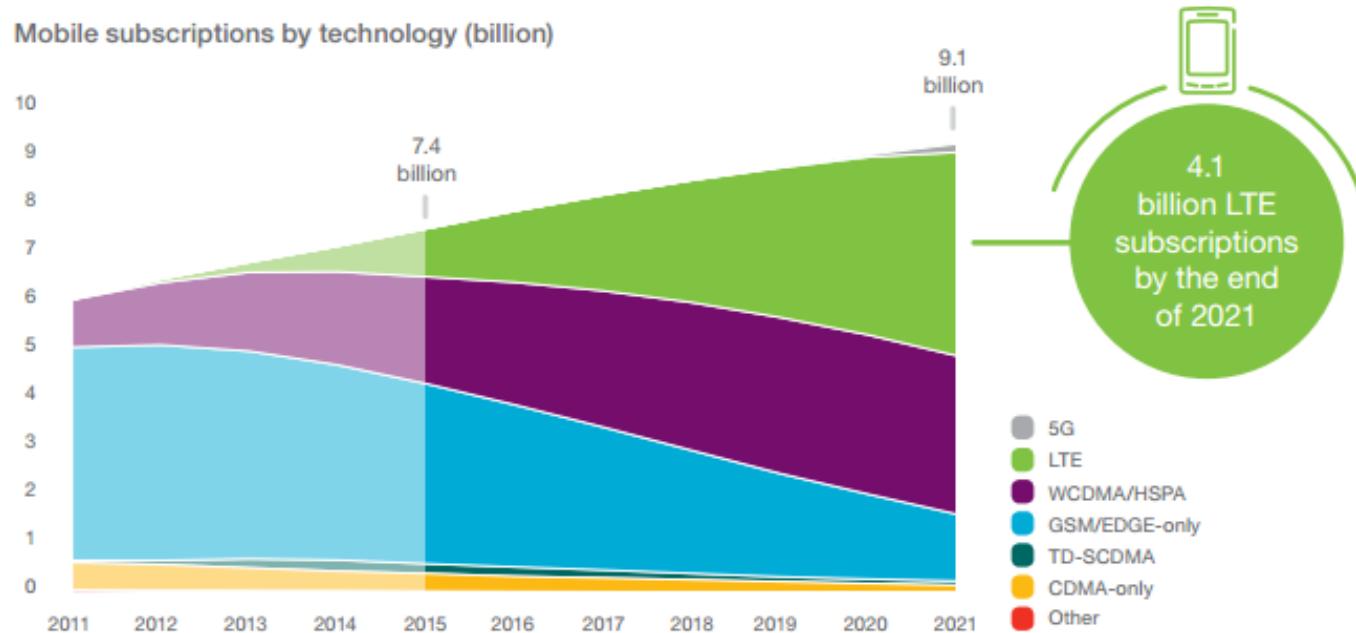


- How large are the cells?
 - Femto cells could be as small as tens of meters
 - Large cells could be up to 100 km
 - Typical radius is around 5 km/cell
- Handover
 - Movement from cell to cell results in handover
 - Switch over from one radio base station to another one

- 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

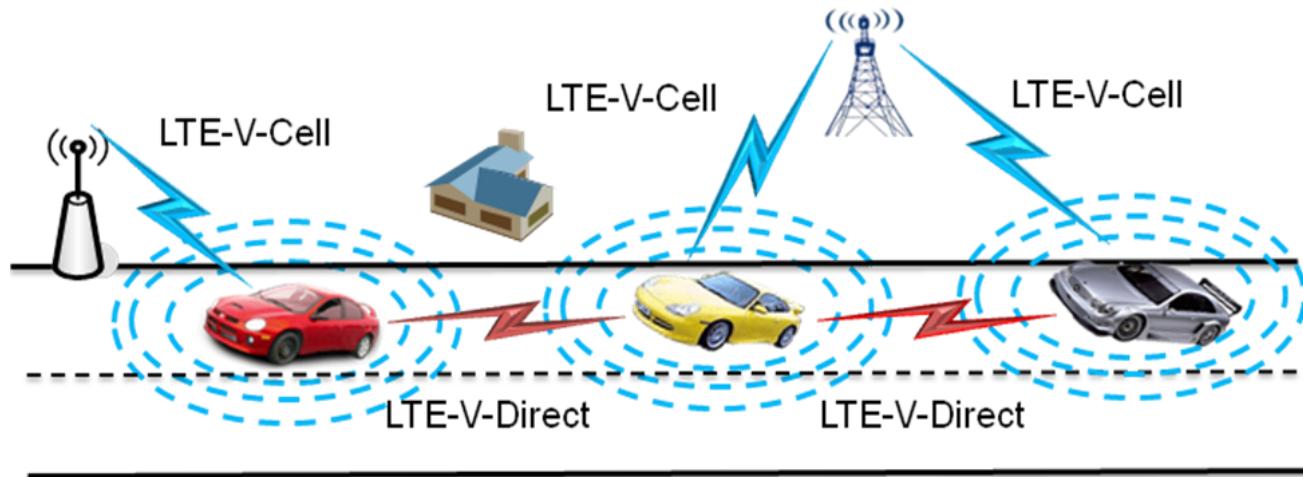
Acceptance Status of Cellular Tech.

- Cellular technology is suited for non-safety-related use-cases as it stands 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

- 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)

- 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

- 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



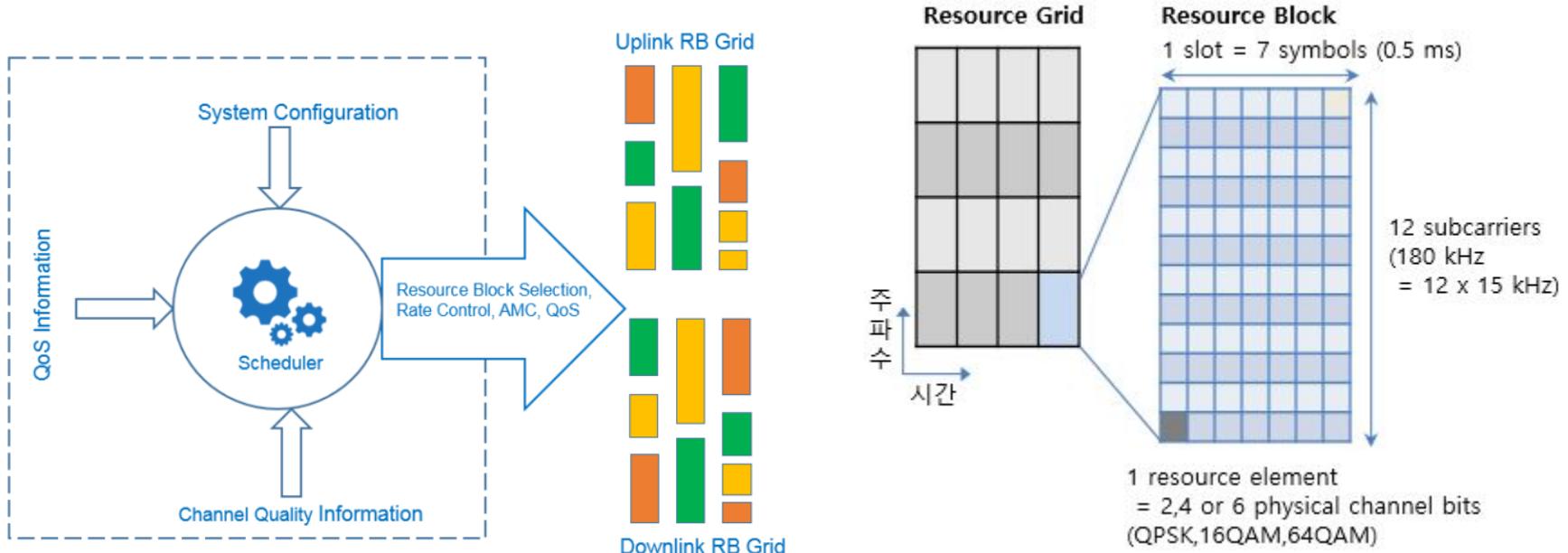
Source: <https://vtsociety.org/2018/02/vehicles-february-2018/>

- 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 supporting 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 vehicles autonomously select and manage the radio resources without any cellular infrastructure support

- 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

■ 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

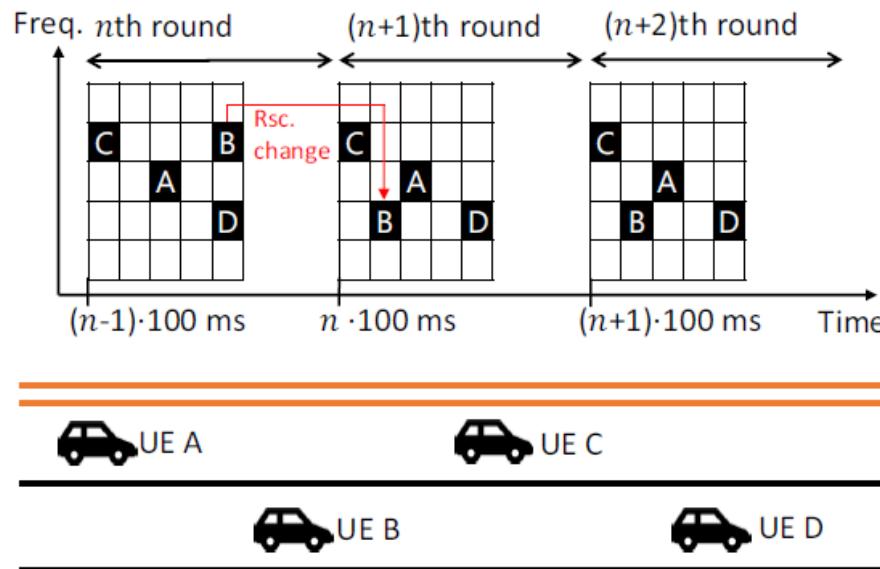


Source: <http://www.techplayon.com/lte-enodeb-scheduler-and-different-scheduler-type/>

■ LTE V2V

- 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

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

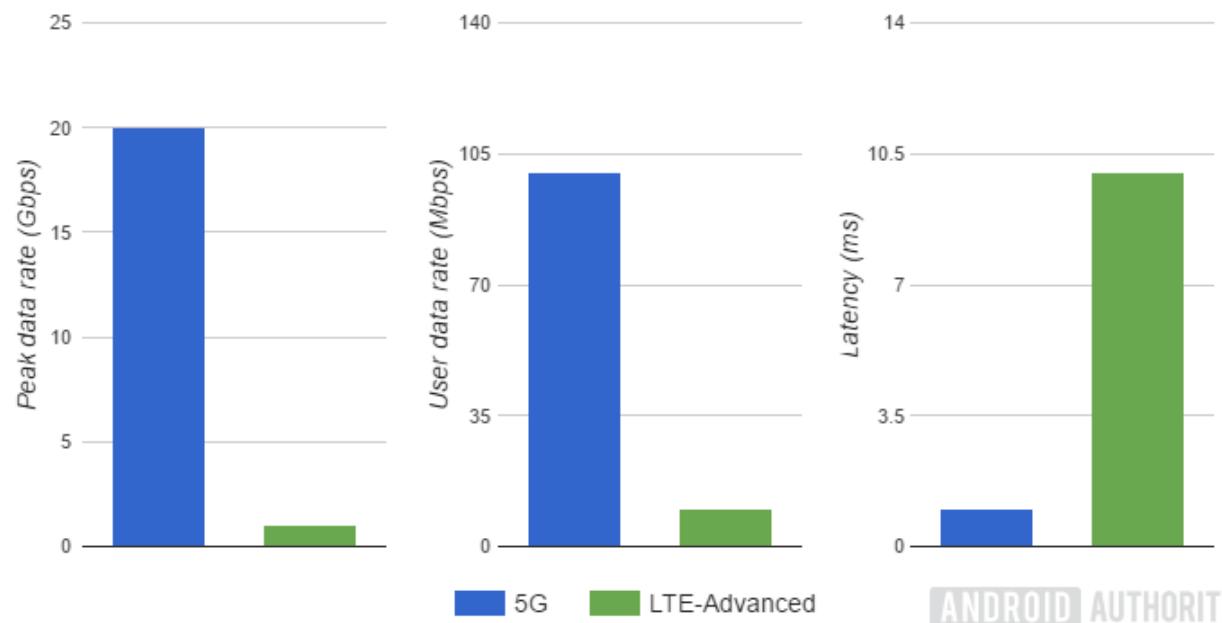


Source: S. Park, et al., „FAGA: Feedback-Aided Greedy Algorithm for Periodic Messages in LTE V2V Communications,“ IEEE TVT2017

■ 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)

5G vs LTE-Advanced



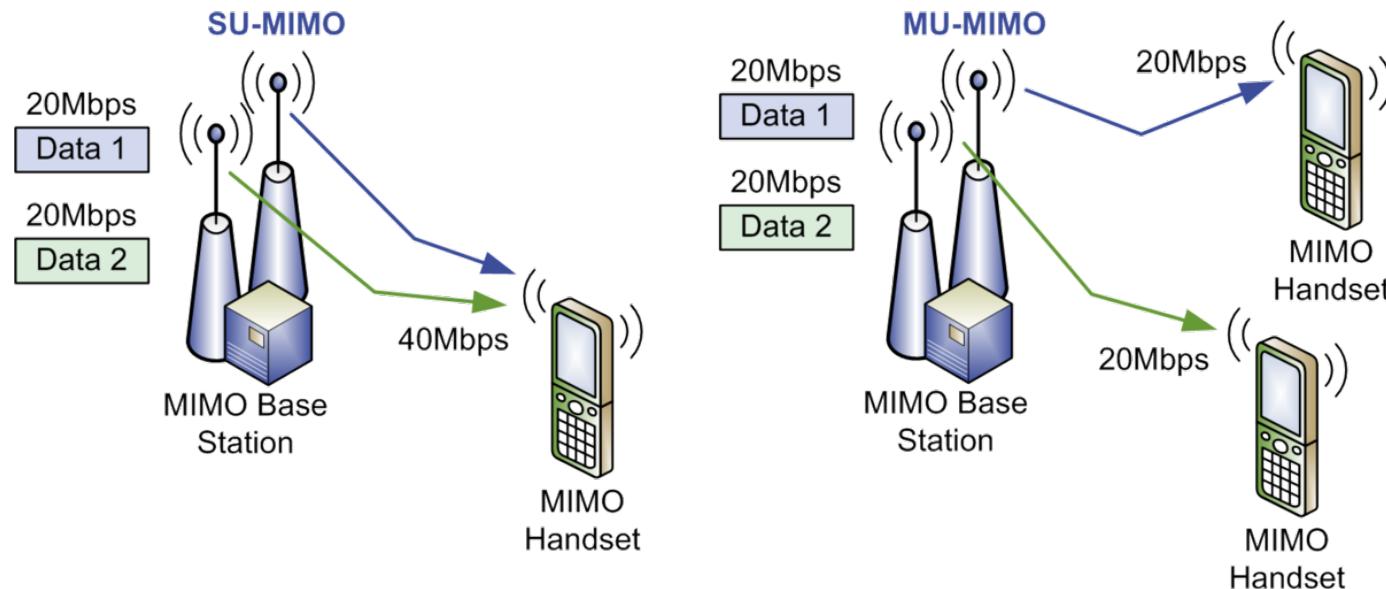
- „An advanced wireless technology that has begun wide deployment in 2019
- Bandwidth
 - The reach is short so more cells are required
 - $\lambda = \frac{c}{f}$
 - Higher the frequency, shorter the wavelength
 - Difficulty traversing many walls and windows, so indoor coverage is limited
 - Verizon's 28 GHz
 - Sprint, China Mobile: 2.5 GHz, and others mostly 3.3 and 4.2 GHz
 - Upgrading existing towers -> lowers cost
- Latency
 - Air latency (phone - tower): 8-12 ms
 - To server (phone – server): ~30 ms (25-40% lower than typical 4G)
 - 1 ms latency is still years away



- Frequency range 1 (<6 GHz)
 - Maximum channel bandwidth is 100 MHz (crowded frequency range)
- Frequency range 2 (>24 GHz)
 - Minimum channel bandwidth is 50 MHz and the maximum is 400 MHz
- FR2 coverage
 - Due to higher frequencies, some 5G signals are not capable of traveling large distances (over a hundred meters)
 - 5G base stations every few hundred meters!

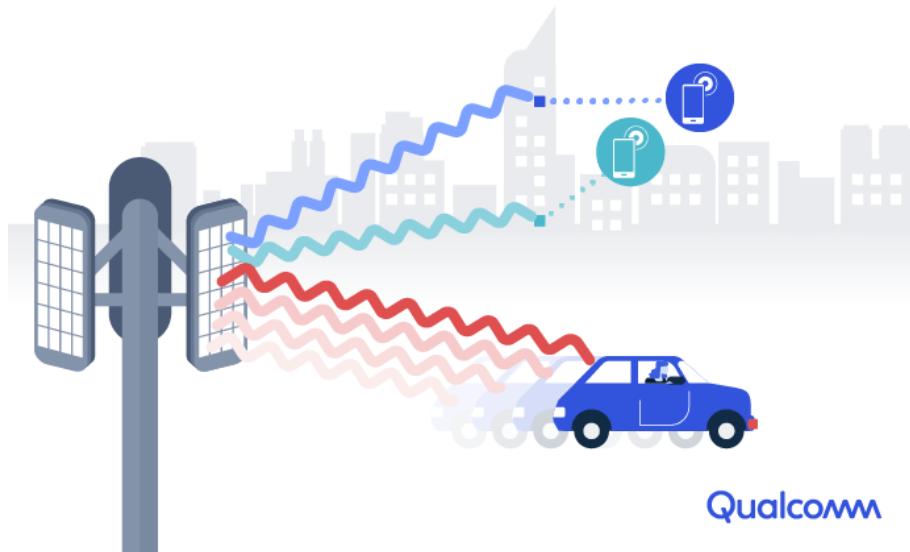
Massive MIMO

- Massive MIMO (multiple input and multiple output) antennas increase throughput



Beamforming

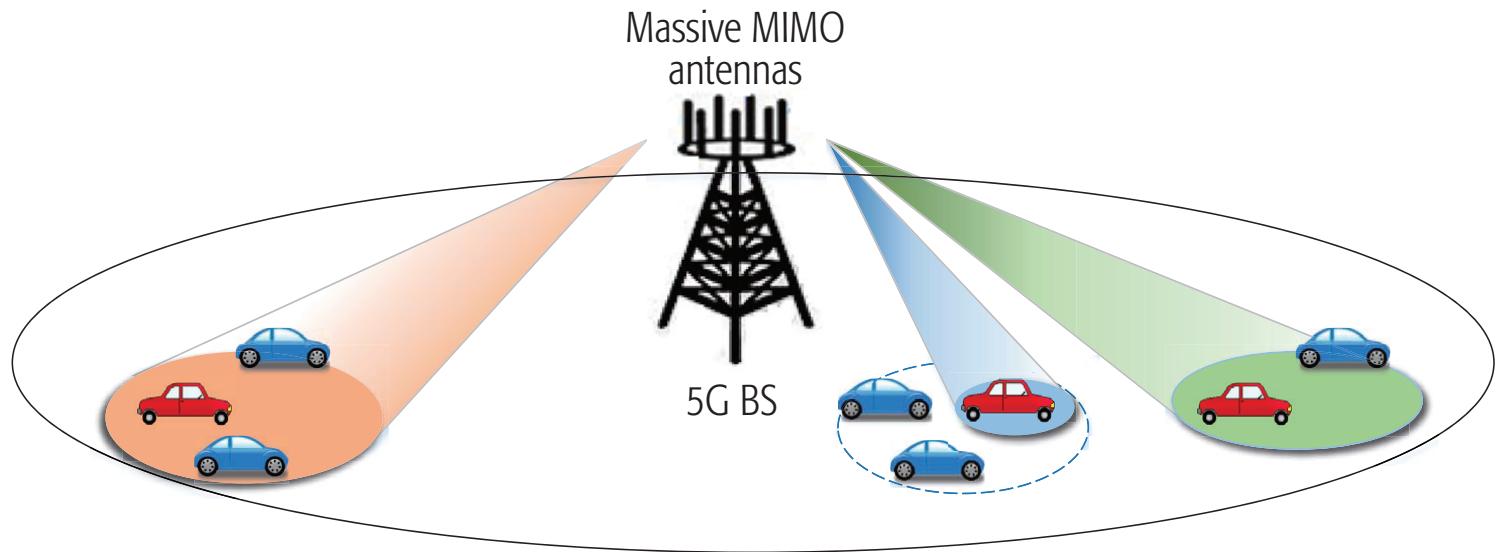
- Direct radio waves to a target
- Achieved by combining elements in an antenna array in such a way that signals particular angles experience constructive interference
- Improves signal quality and data transfer speeds



<https://www.qualcomm.com/news/onq/2019/06/20/how-5g-massive-mimo-transforms-your-mobile-experiences>

For Vehicular Networks?

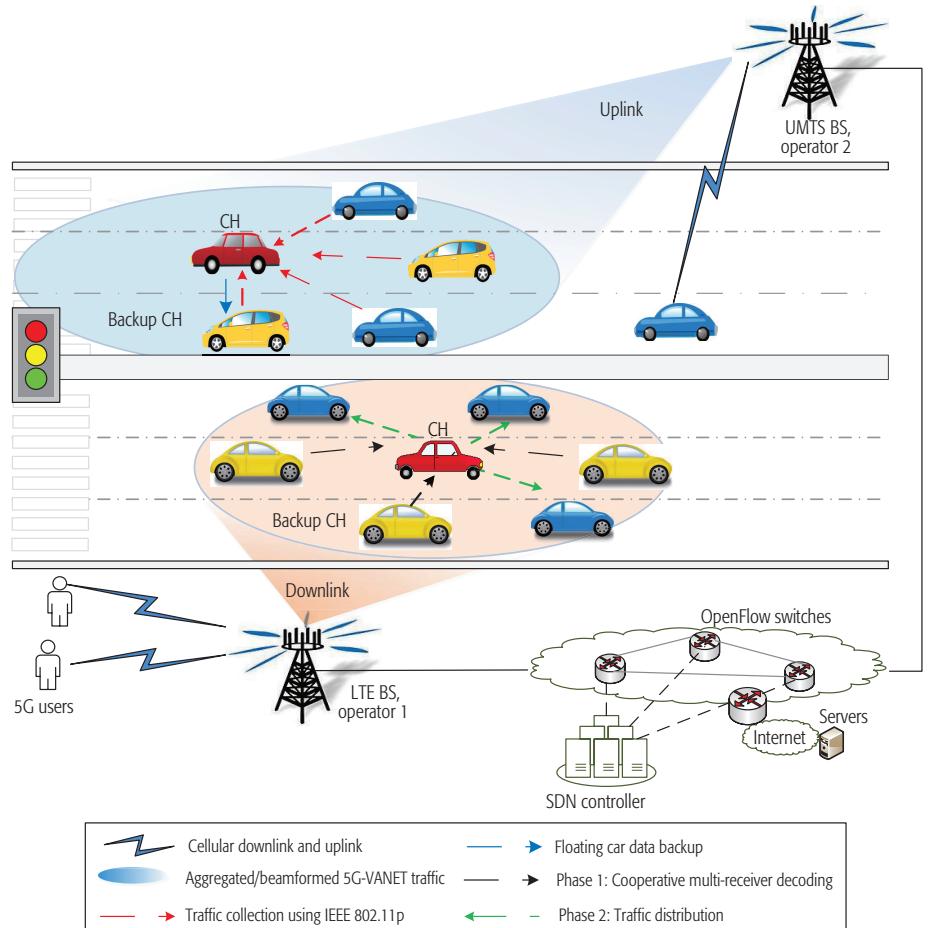
- Cluster-based communication
- Cluster head (CH)
- Beamforming



Software Defined Networks (SDN)

■ SDN

- Centralized control of network architecture
- Differs from IP (general internet)



References

- Wai Chen, „Vehicular Communications and Networks: Architectures, Protocols, Operation and Deployment“, Woodhead Publishing
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- 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
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