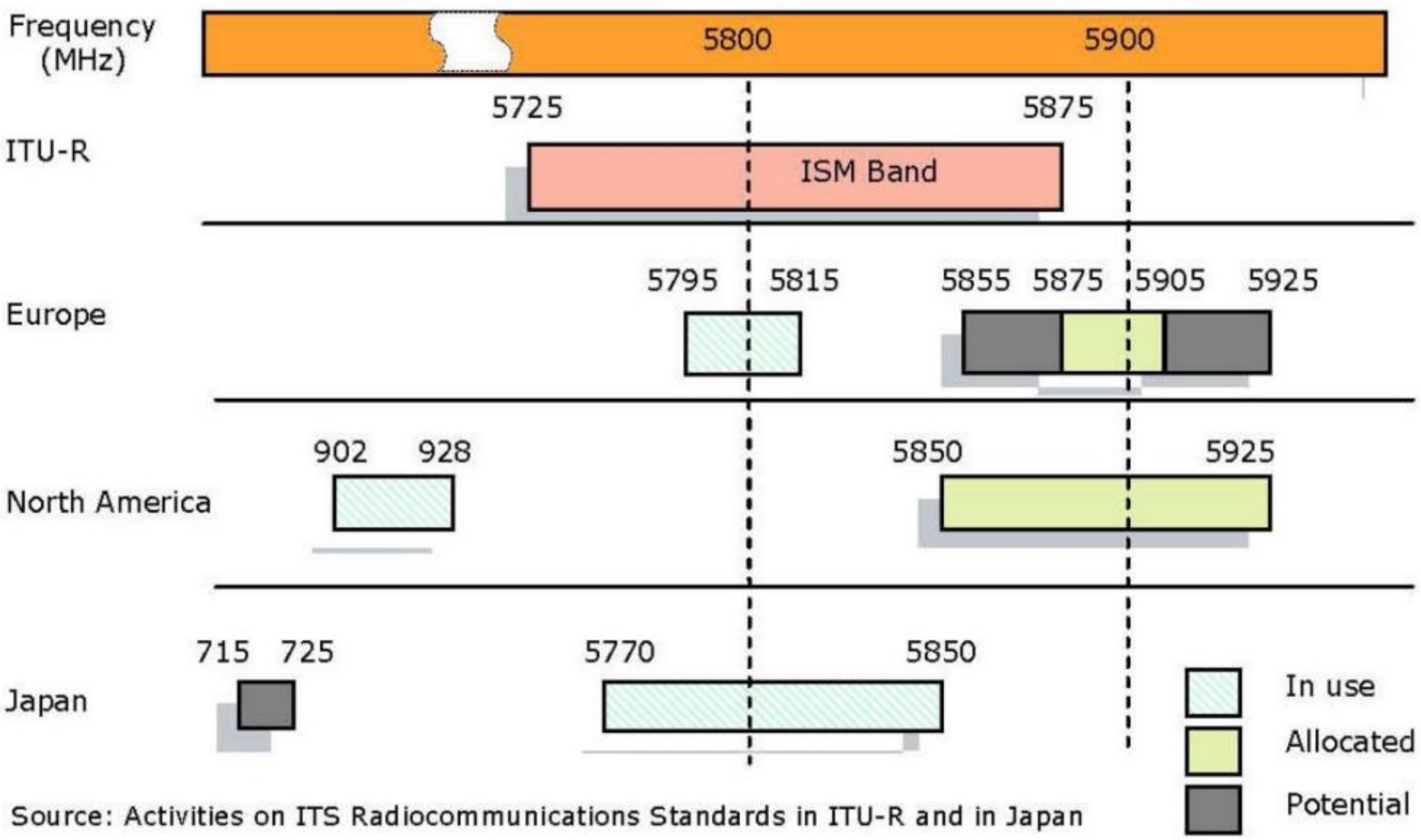
IEEE 802.11p
Intelligent Transportation Systems

Rolland Vida

DSRC – Dedicated Short Range Communications

- Dedicated in 1999 by the FCC (Federal Communications Commission) to vehicular communications
  - 75 MHz of spectrum in the 5.9 GHz band (5.850-5.925 GHz)
- In Europe, ETSI allocated in 2008 30 MHz in the 5.9 GHz band for ITS
- Systems in US, Europe, Japan not really compatible with each other



Source: Activities on ITS Radiocommunications Standards in ITU-R and in Japan

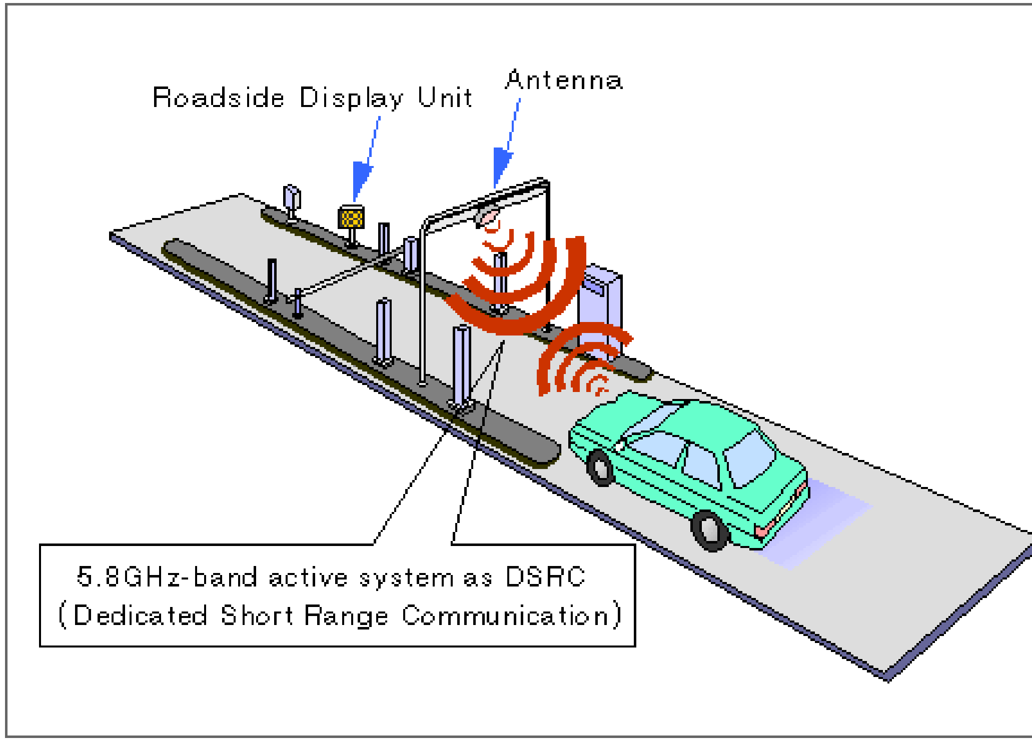
DSRC – Dedicated Short Range Communications

- Traditional ISM bands (Industry, Science, Medical) – 900 MHz, 2.4 GHz, 5 GHz
  - **Free, unlicenced bands**
  - Populated by many technologies – Wifi, Bluetooth, Zigbee
  - No restrictions other than some emmission and co-existance rules

- DSRC band
  - **Free but regulated spectrum**
  - Restrictions in terms of usage and technologies
  - All radios should be compliant to a standard

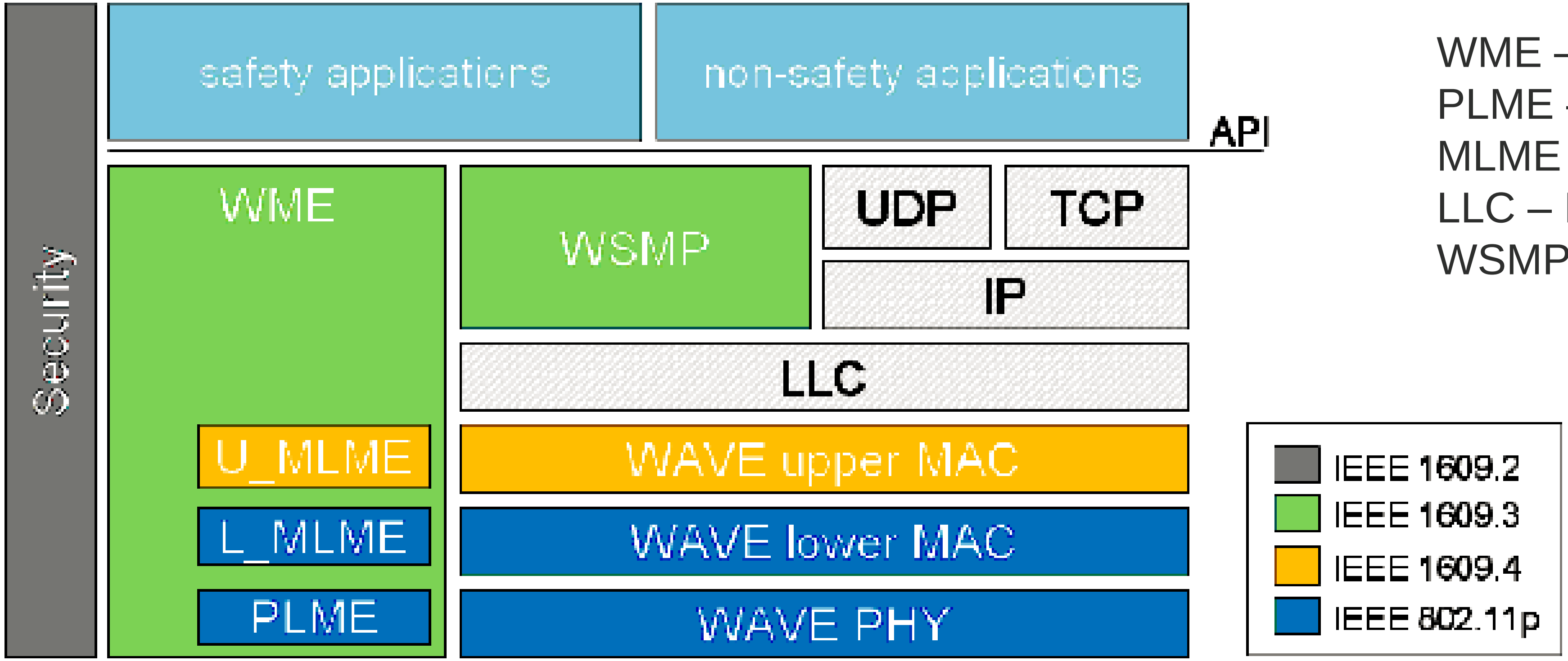
DSRC – Dedicated Short Range Communications

- **Basic goals of DSRC**
  - Support of low latency, secure transmissions
  - Fast network acquisition, rapid and frequent handover handling
  - Highly robust in adverse weather conditions
  - Tolerant to multi-path transmission
- **Mainly for public safety applications**, to save life and improve traffic flow
- Private services also permitted
  - Spread the deployment costs, encourage quick development and adoption
  - **Electronic Toll Collection (ETC)** was initially one of the main drivers



WAVE

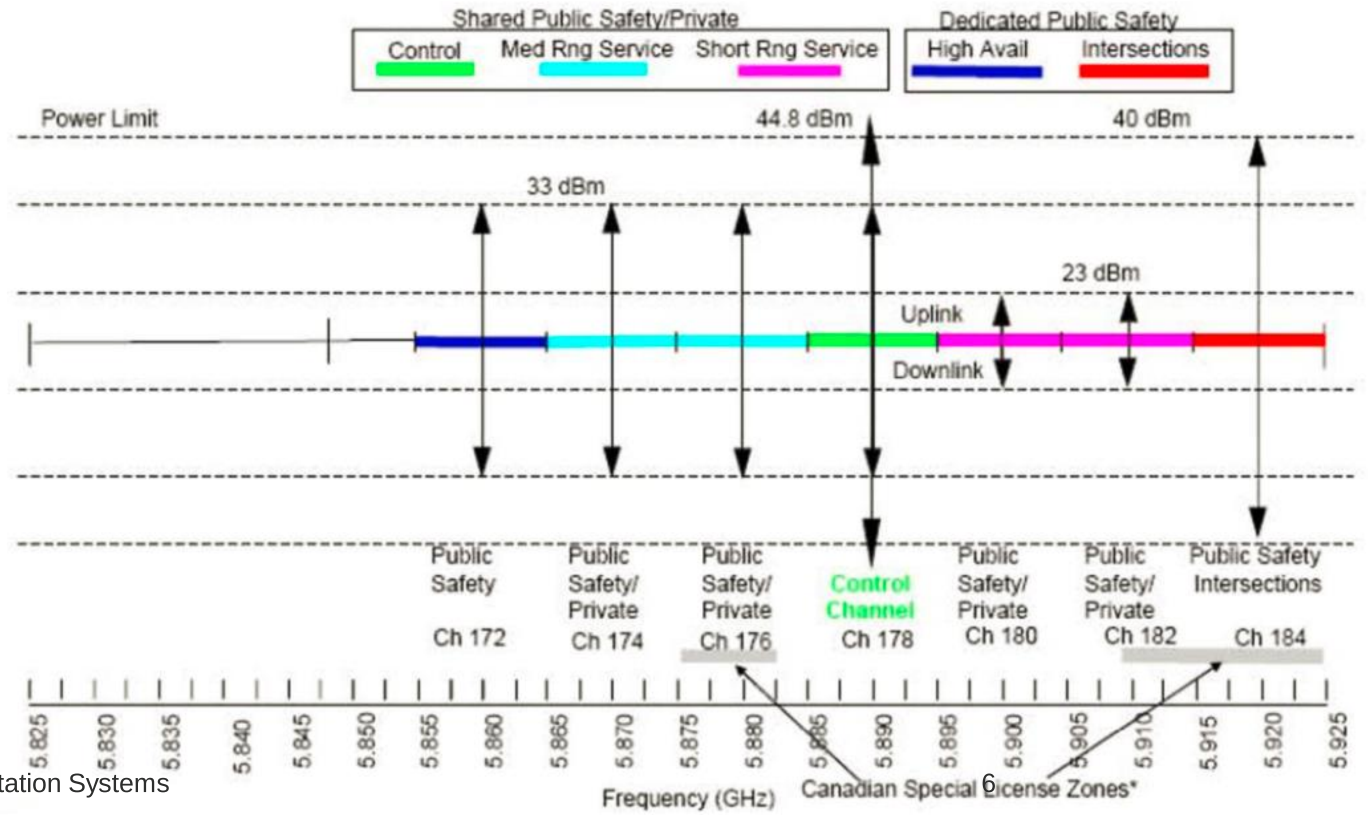
- IEEE 802.11
  - Collection of physical (PHY) and medium-access control (MAC) layer specifications for implementing WLAN
  - 802.11a (5 GHz, OFDM), 802.11b (2.4 GHz, DSSS), 802.11g (2.4 GHz, OFDM), 802.11n (2.4 and 5 GHz, MIMO-OFDM), 802.11ac (5 GHz, MIMO-OFDM)
  - **802.11p – part of WAVE (Wireless Access in Vehicular Environment)**



WME – WAVE Management Entity
PLME – Physical Layer Manag. Entity
MLME – MAC Layer Manag. Entity
LLC – Logical Link Control
WSMP – WAVE Short Message Prot.

WAVE spectrum bands

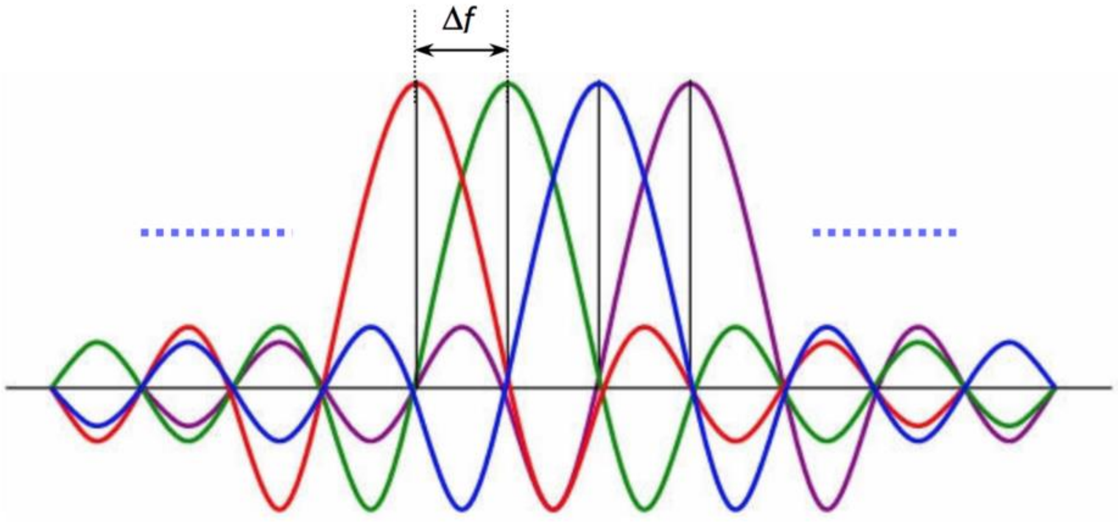
- 75 MHz wide spectrum divided into 7x10 MHz wide channels, 5 MHz guard band
  - Channel 178 the **control channel (CCH) -** transmit WAVE Short Messages (WSM), announce services
  - Channel 172 reserved for **high availability applications (future use)**
  - Channel 184 reserved for **intersections**
  - The other channels shared between public safety and private uses
    - Channels 174-176 and 180-182 can be combined to form a 20 MHz channel



- In Europe the **ITS-G5 standard**
  - **ITS-G5B band**: 5.855 – 5.875 GHz
    - 172, 174 SCH – ITS non-safety app
  - **ITS-G5A band**: 5.875 – 5.905 GHz
    - 176, 178 SCH – ITS traffic safety app
    - 180 CCH
  - **ITS-G5D band**: 5.905 – 5.925 GHz
    - 182, 184 SCH – for future use

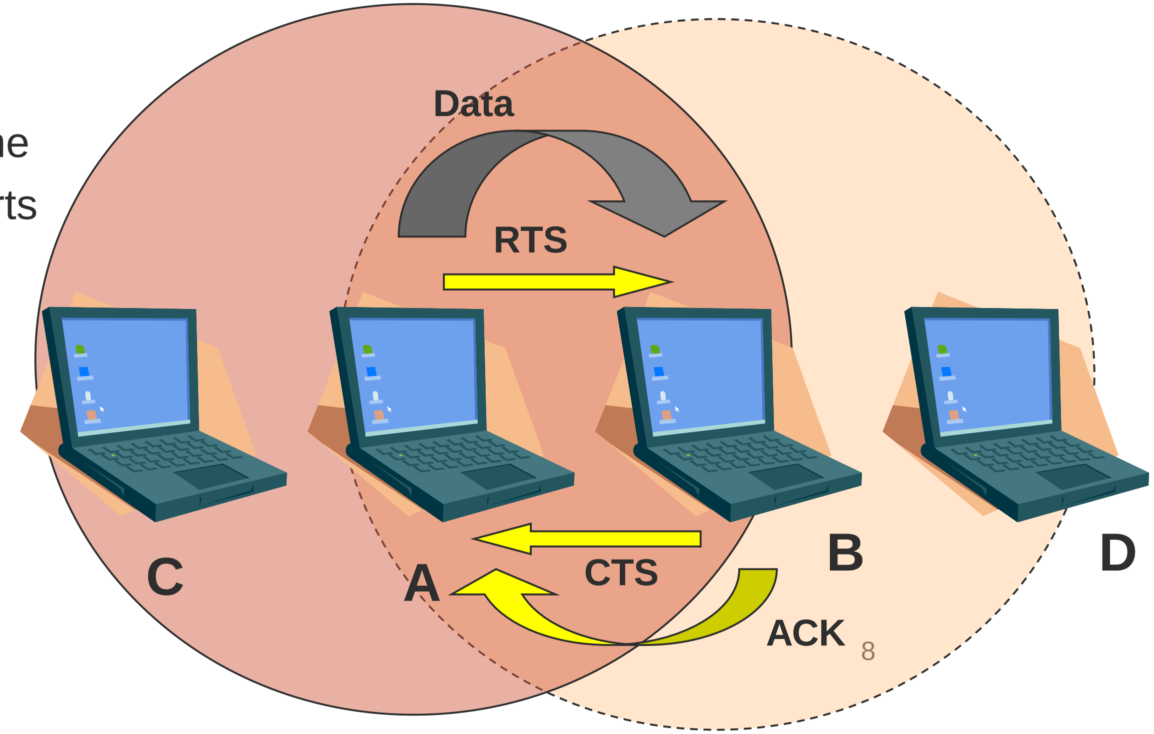
WAVE (802.11p) vs IEEE 802.11

- 10 MHz channels instead of 20 MHz
- 3-27 Mbps instead of 6-54 Mbps
- Same modulation schemes (BPSK, QPSK, 16QAM, 64QAM)
- Carrier spacing reduced to 0.15625 MHz from 0.3125 MHz
  - 48 data subcarriers for both



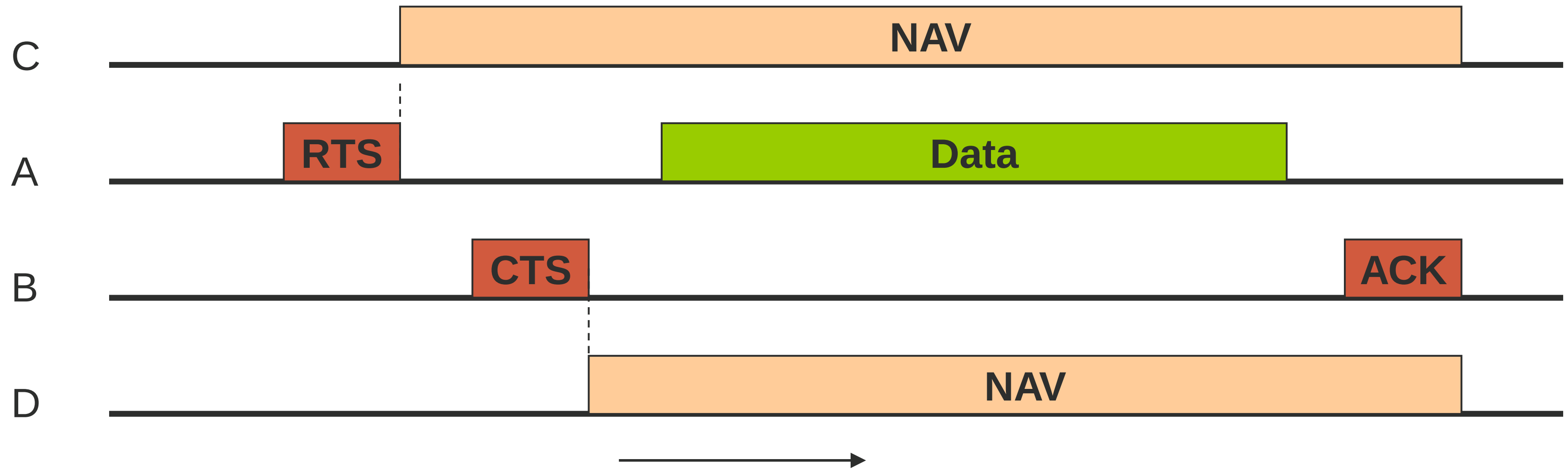
Traditional IEEE 802.11 MAC (DCF)

- **DCF – Distributed Coordination Function**
  - A sends an RTS frame to B, asking the permission to send a data frame
    - **Request To Send**
  - If B gives the permission, it sends back a CTS frame
    - **Clear To Send**
  - A sends the data frame, and starts an ACK timer
    - If B receives the packets in order, it replies with an ACK frame
    - If the timer expires without receiving an ACK, everything starts from scratch



Traditional IEEE 802.11 MAC (DCF)

- C hears A, receives the RTS frame
  - Deduces that in the next moments someone will start to send data
  - It stops its own transmission, while the other conversation is not finished
    - Knows when it ends from the ACK timer, included in the RTS frame
  - It sets an internal reminder to himself, saying that the channel is virtually occupied
    - NAV – Network Allocation Vector
- D does not hear about the RTS, but hears the CTS
  - Also sets a NAV for himself

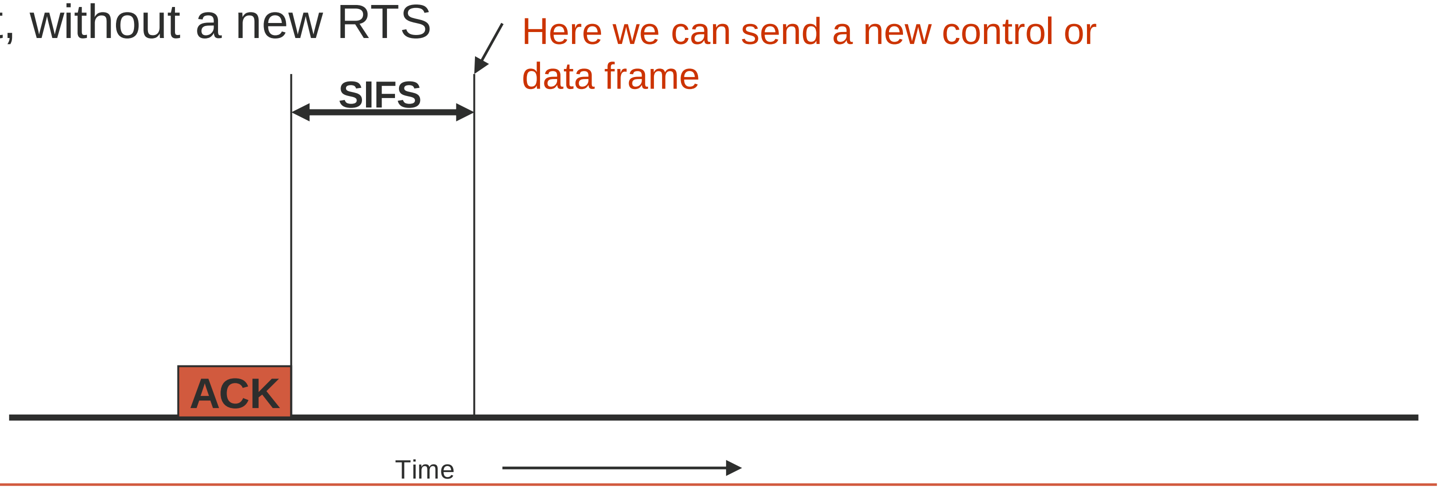


Traditional IEEE 802.11 MAC (PCF)

- **PCF – Point Coordination Function**
  - An Access Point controls the access to the wireless channel
    - No collisions
  - The AP polls the other stations, to find out who has data to send
    - The standard defines only some basic features of the poll
      - Does not define the frequency, or the order in which different stations are polled
      - Does not ask for equal treatment for all the stations
  - The AP periodically sends a **beacon frame**
    - 10-100 beacons / s
    - It contains system parameters
      - Hopping sequence and dwell times (for FHSS), clock synchronization, etc.
    - New stations are invited to participate in the polling

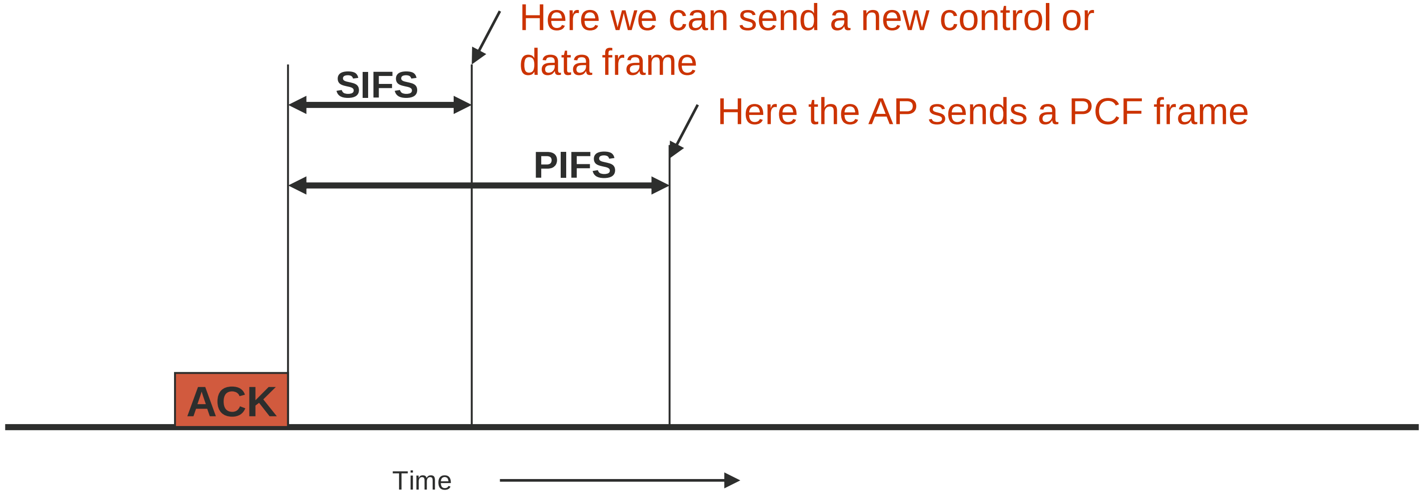
Traditional IEEE 802.11 MAC (DCF & PCF)

- PCF and DCF can operate in parallel inside the same cell
  - Distributed and centralized control in the same time?
    - Is possible, if carefully defined timers are used
    - After the sending of a frame, a certain guard time is required before any other transmission
- Four specific timers
  - **SIFS – Short Inter-Frame Spacing**
    - The shortest spacing, to support those devices that currently occupy the channel for a short conversation
    - After the SIFS, a receiver can send a CTS to an RTS
    - After the SIFS, a receiver can send an ACK for a given part of the data frame
    - A new part can be sent, without a new RTS



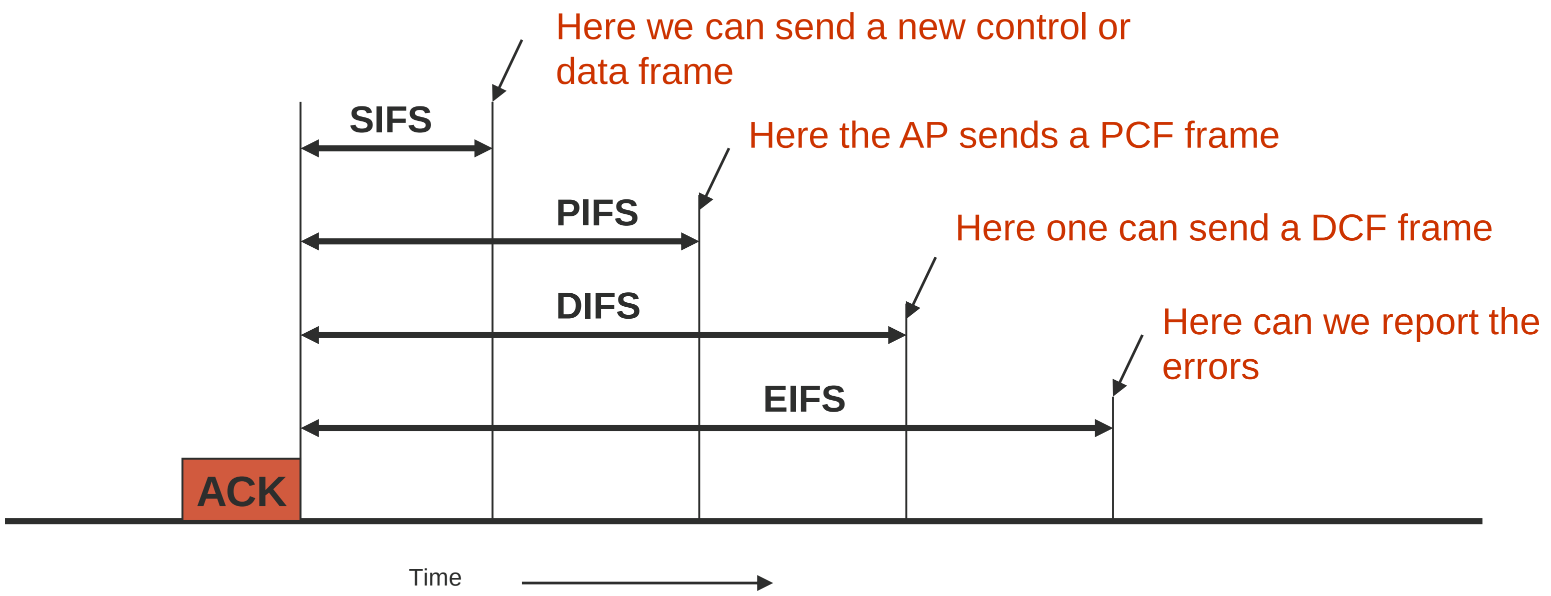
Traditional IEEE 802.11 MAC (DCF & PCF)

- **PIFS – PCF Inter-Frame Spacing**
  - After an SIFS, only one specific station can send
  - If nothing is sent until the end of the PIFS, the AP has the possibility to take over the channel, and send a new beacon or a polling frame
    - An ongoing conversation can be finished without disturbing it
    - The AP can access the channel without a contention
      - No contention with the greedy users



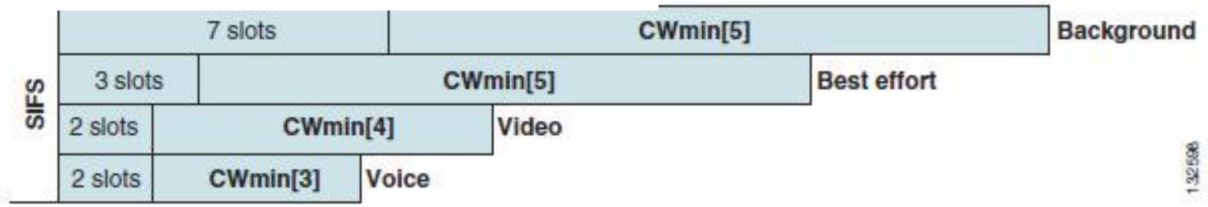
Traditional IEEE 802.11 MAC (DCF & PCF)

- **DIFS – DCF Inter-Frame Spacing**
  - If the AP does not have anything to send, after the DIFS anyone can try to gain access to the channel
    - Usual contention rules
    - Exponentially increasing back off interval, if collision
  - Same DIFS value for all traffic types
- **EIFS – Extended Inter-Frame Spacing**



802.11e MAC - Enhanced Distributed Coordination Access (EDCA)

- To support **Quality of Service differentiation**
- **Arbitration Inter-Frame Spacing** to replace the static DIFS
  - Different values for each **Access Category**
  - AIFS = 1 SIFS + AIFSN * slot time
  - By default…
    - Voice Queue (AIFSN=2) 1 SIFS + 2 * slot time
    - Video Queue (AIFSN=2) 1 SIFS + 2 * slot time
    - Best Effort Queue (AIFSN = 3) 1 SIFS + 3 * slot time
    - Background Queue (AIFSN = 7) 1 SIFS + 7 * slot time
  - When AIFS expires, choose a random value between 0 and **CWmin (minimum contention window)**
  - Start decrementing a backoff timer
  - If another node starts transmitting, access is deferred until the channel is free again
  - Then backoff timer decrementation is resumed from where it was stopped
  - If backoff = 0, transmission starts
  - If collision, no ACK received – CWmin is doubled until it reaches CWmax



802.11p MAC

- **Enhanced Distributed Coordination Access (EDCA)**
  - Defined in IEEE 802.11e, to support **Quality of Service differentiation**
    - In 802.11e four Access Categories (AC)
      - Voice, Video, Best Effort and Background
    - In 802.11p ACs to differentiate between:
      - **safety critical and non-safety applications**

802.11p beaconing

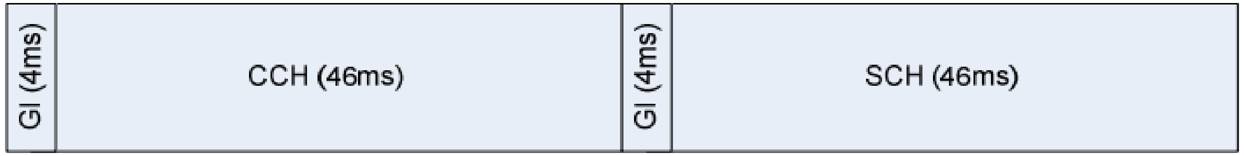
- Basic Service Set in traditional IEEE 802.11
  - Multiple handshakes to ensure distributed medium access
- **Wave Basic Service Set (WBSS)** in 802.11p
  - A node broadcasts a beacon, to advertise its WBSS
  - What kind of services it supports, how to join the WBSS
- Within the WBSS, nodes exchange beacons using the **Wave Short Message Protocol (WSMP)**
  - To create cooperative awareness
  - Information on speed, position, acceleration, direction
  - Sent at regular intervals (e.g., 10 Hz – 100 ms)
- Sent on the CCH, no ACK
  - After the channel is sensed free for AIFS
  - If not free, backoff for the size of a Contention Window, and try again
  - No doubling of the contention window
- As opposed to data sent on SCH, where ACK should be sent
  - If no ACK received, collision occured, contention window doubled

IEEE 1609.x

- IEEE 1609.2 – security services
- IEEE 1609.3 – management services
  - Channel usage monitoring
  - Received channel power indicator (RCPI)
  - Management parameters
- IEEE 1609.4 – QoS and multi-channel access
  - User Priorities mapped to Access Categories in EDCA
  - Multi-channel access for single radio 802.11p devices

IEEE 1609.4 channel swithcing

- 7 FDMA channel frequencies
- **Multi-channel radios** can send and receive over several channels simultaneously
  - Might have problems with interferences between channels
- **Single channel radios** to access both CCH and SCH
  - Either transmit or receive on a single 10 MHz channel
- **Alternating access**
  - Repetitive periods of 100 ms
    - 46 ms allocated to the CCH channel
    - 46 ms allocated to the SCH channels
    - 4 ms guard interval for switching between CCH and SCH
      - Nodes should wait for a random backoff after the end of the guard interval, before starting to transmit
  - Time synchronisation needed to an external time reference
    - Coordinated Universal Time (UTC) from GPS or other devices
      - **WAVE Time Advertisement (WTA)** frame

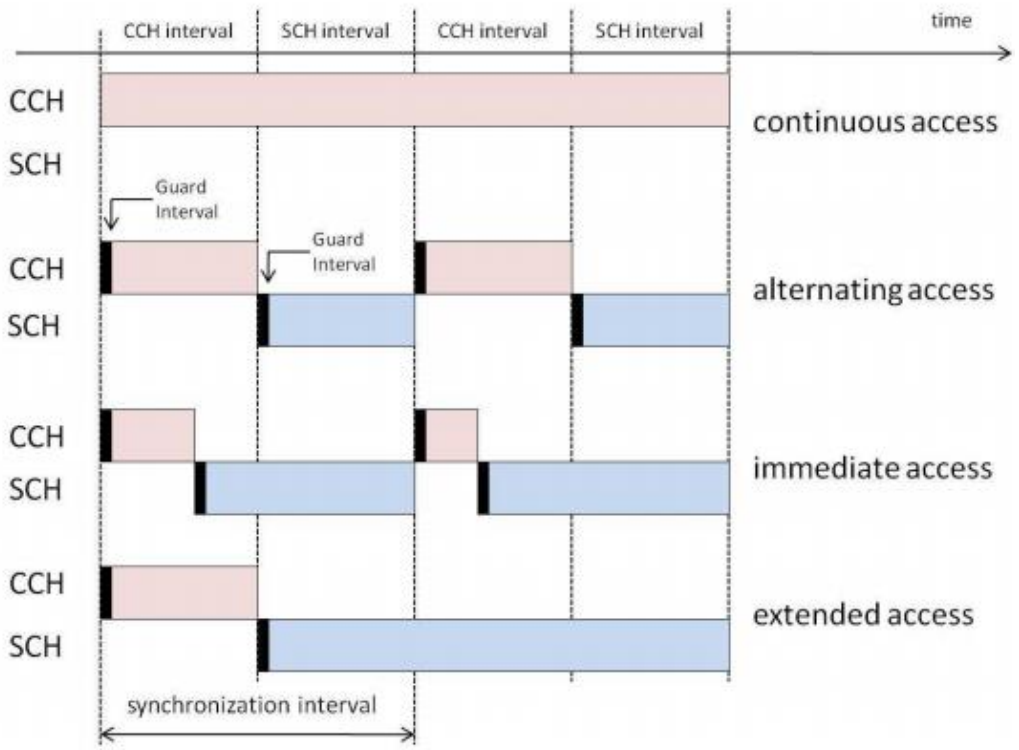


IEEE 1609.4 channel switching

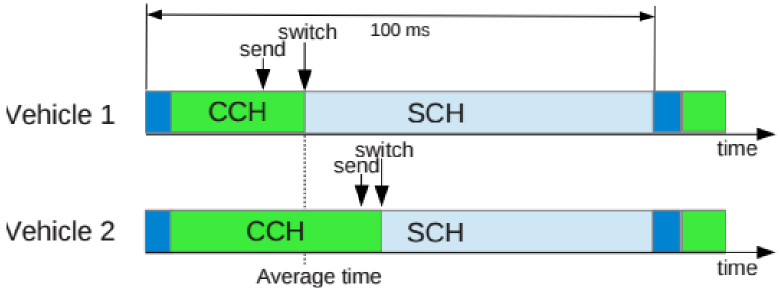
- **Continuous access**
  - Transmission can be continuous on the CCH and all SCHs
  - It cannot be guaranteed that all other stations will listen to the CCH outside the CCH slot
  - Safety messages sent over the CCH in the SCH slot might be ineffective
  - The usage of SCH not efficient if nodes listen to the CCH 50% of the time

- Alternative solutions to minimise the impact of channel switching?

IEEE 1609.4 channel switching



- **Immediate access**
  - The node does not have to wait until the CCH slot is over
  - After the CCH transmission is over, switch to SCH
  - Improve the performance of bandwidth-demanding non-safety applications in SCH, at the expense of the CCH
- **Extended access**
  - Transmission on the SCH without waiting for the CCH
- **Adaptive Independent Channel Switching**
  - If more vehicles, more beacons on the CCH
  - Nodes can change their average switching time based on vehicle density
    - Long SCH intervals if not many vehicles
    - Fewer collisions at the start of the SCH, as nodes switch independently of each other
  - Drawback is that not all nodes on the CCH in the same time
    - Vehicle 1 will miss the beacon of Vehicle 2



IEEE 1609.4 channel switching

- **Fragmentation**
  - To better utilise the residual time at the end of the SCH interval
  - An extra fragmentation header should be used, which is a drawback
  - Works for large packets (TCP)

- **Best-fit scheme**
  - Send the packet that best fits the residual time at the end of the SCH interval
    - Better than fragmentation only if packets of different sizes are present in the queue
  - Hard to know in advance the actual duration of transmission
    - Frequent changes in the channel congestion
    - Stochastic nature of backoff

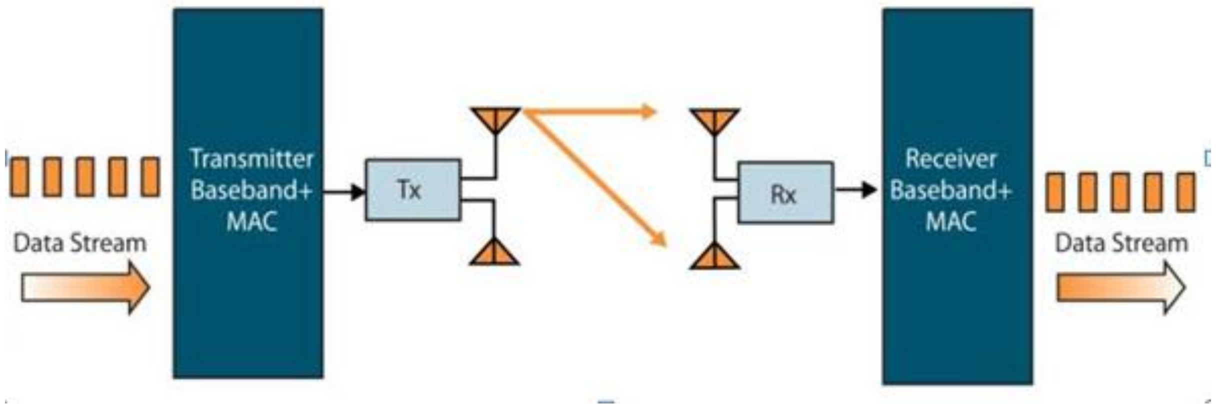
IEEE 802.11bd

- **IEEE 802.11p (2010)**
  - Based on IEEE 802.11a
  - Since then, new standards, more efficient, higher throughput, lower latency

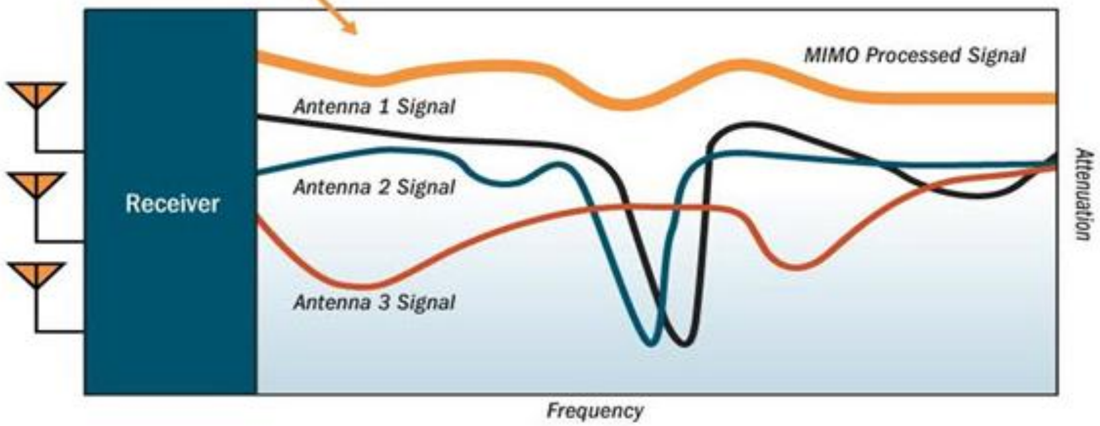
- **IEEE 802.11bd**
  - Working group established in 2019
  - Standardisation ongoing, expected to end in 2022 végére
  - Based on IEEE 802.11ac (WiFi 5)

MIMO – Multiple Input Multiple Output (WiFi 4, 2009*)

- More transmitting and receiving antennas (e.g.. 3 x 3)
- **Traditional sending:** 1 sender, 2 receiver antennas
  - The receiver processes only the best quality signal



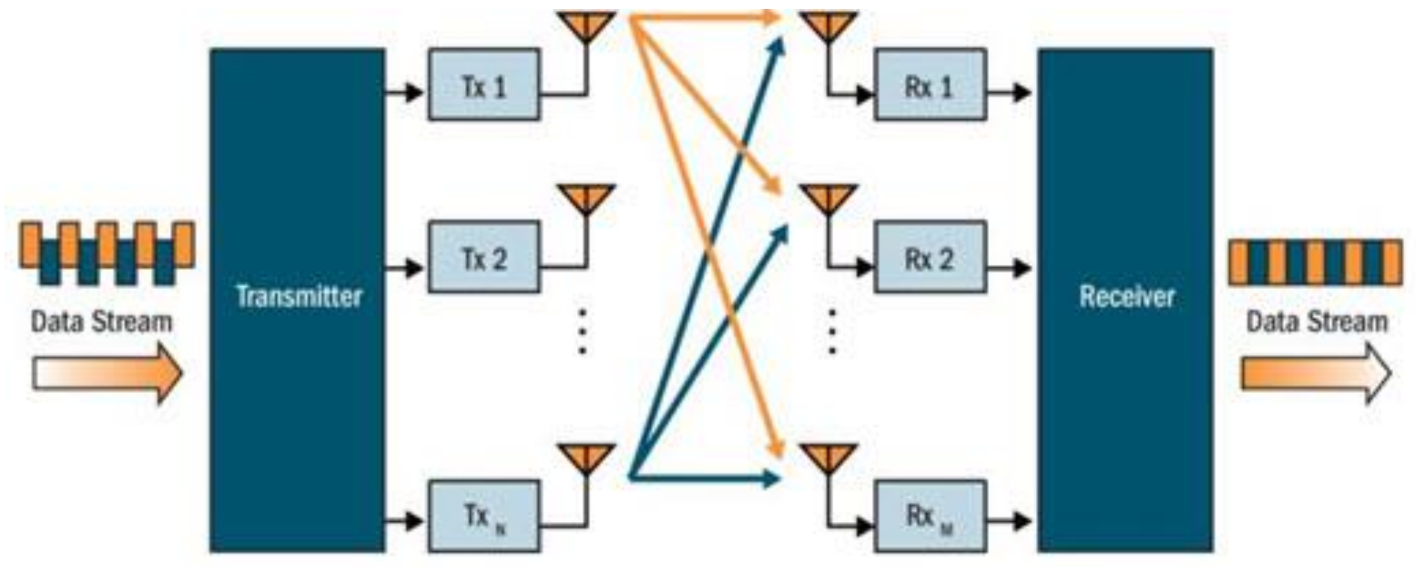
- **MIMO sending**: e.g., 3 sending, 3 receiver antenna
  - Each sender sends the same signal
  - Each receiver hears each sender
    - Different quality, antenna diversity
  - Each signal is processed

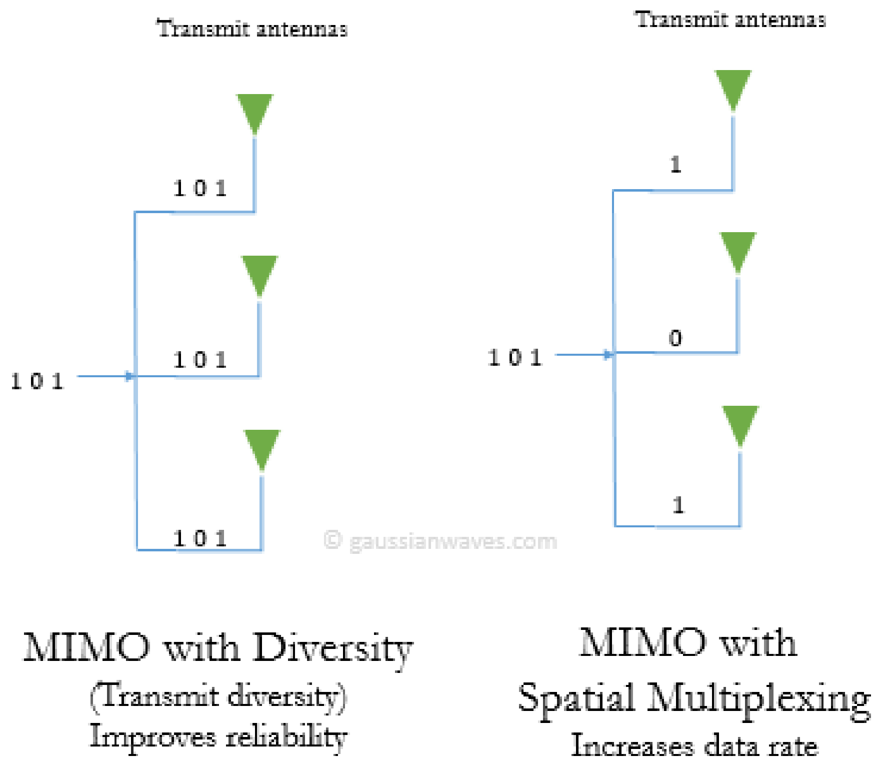


* The frst iPhone appears in 2007-ben, more and more WiFi enabled devices since then, need for higher data rates

Spatial multiplexing (WiFi 4)

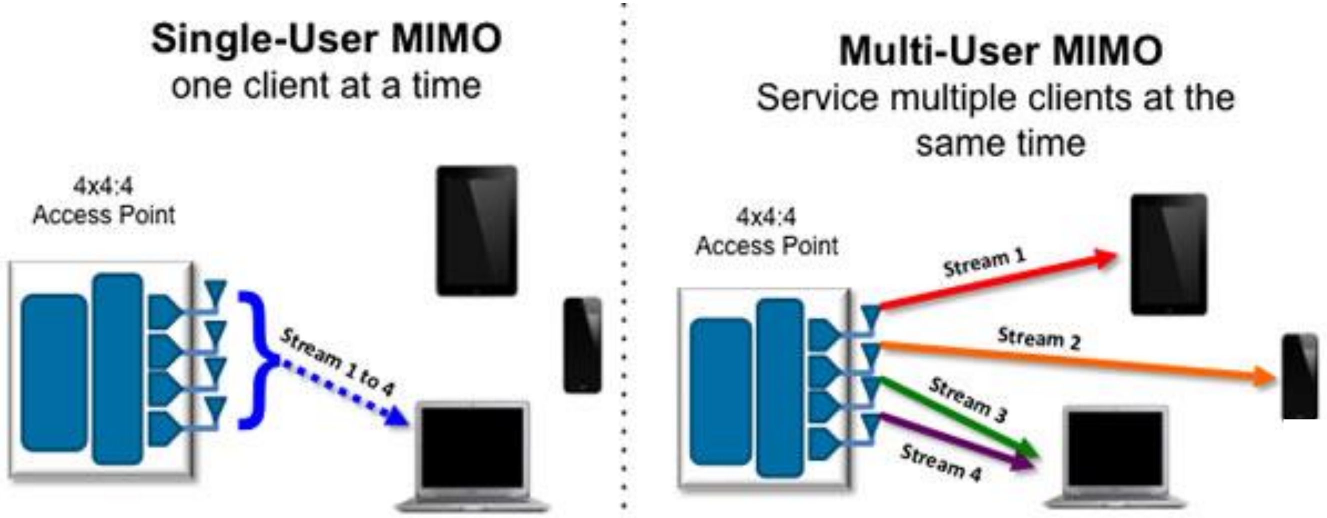
- Data is divided, each antenna sends a different data stream
  - Similarly to OFDM, where different data on each carrier
- Each receiver receives data from each sender, with different quality



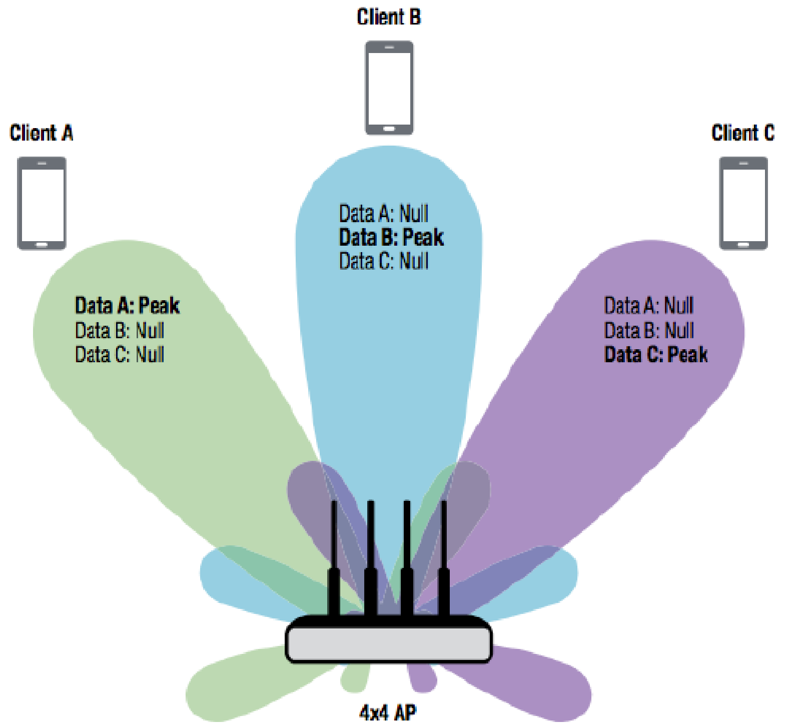


Multi-User MIMO (MU-MIMO) and Beamforming (WiFi 5, 2013)

- **MU-MIMO:** More receivers in parallel, streams divided among them



- **Beamforming:** data streams focused on different receivers
  - Needs accurate positioning of receivers



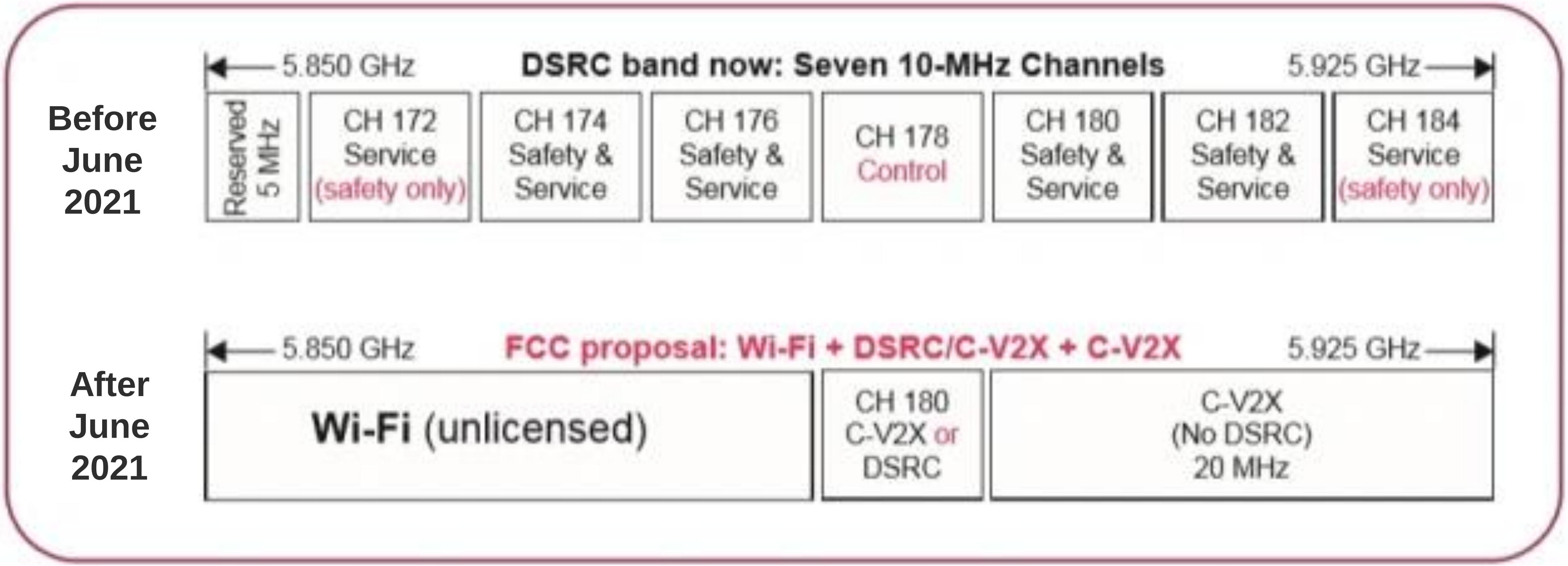
802.11bd (based on WiFi 5)

- 20 MHz channels instead of 10 MHz
- 256-QAM instead of 64-QAM modulation
- Support for MIMO and spatial streaming
- Twice as large transfer speeds as in 802.11p
- Twice as large communication distance as in 802.11p
- Works for larger vehicle speeds as well (max. 500 km/h, instead of max. 200 km/h)

IEEE 802.11bd^{DC}

- DC – Dual Carrier Modulation
  - On the 20 MHz channel, each signal is transmtted over two subcarriers in parallel
- More reliable transmission
- Based on the IEEE 802.11ax (WiFi 6) standard

New FCC rule (effective of June 2021)

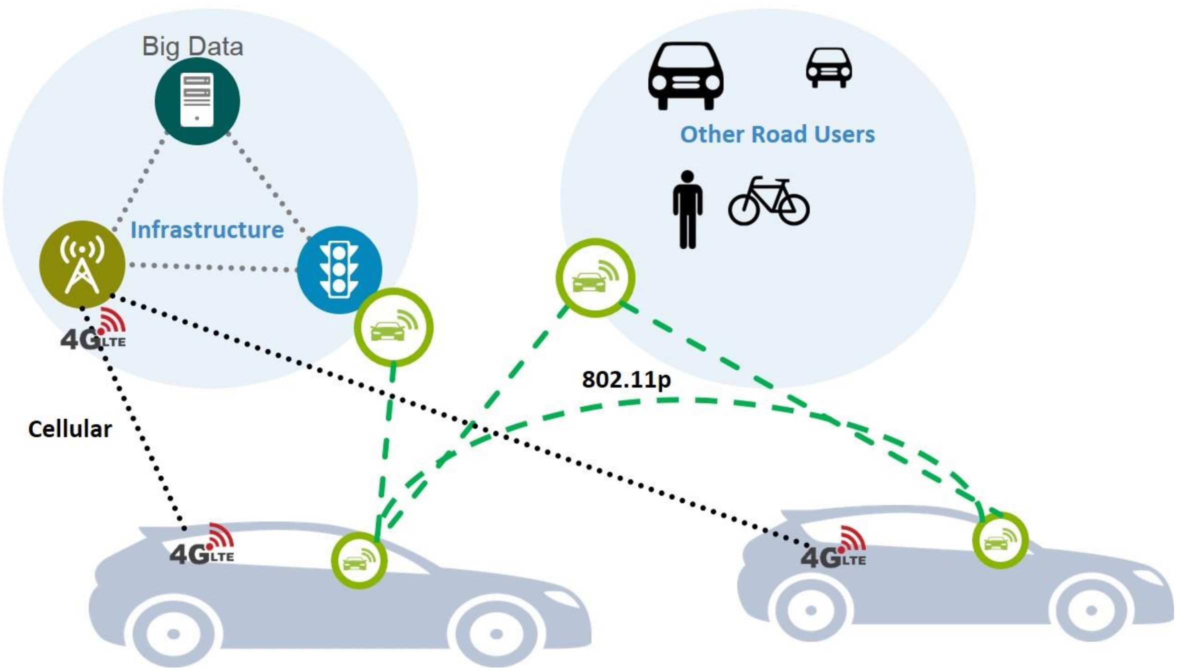


802.11p or C-V2x?

C-V2x: Cellular Vehicle to Everything

- Requirements for Cooperative ITS systems
  - High relative speeds between transmitters and receivers
  - Extremely low latency in safety-related applications (<50 ms)
  - Tolerate high load generated by periodic transmission of multiple messages, and high vehicle density
  - V2x messages are mostly local in nature, are important for nearby receivers

Cellular and IEEE 802.11p for C-ITS



802.11p or C-V2x

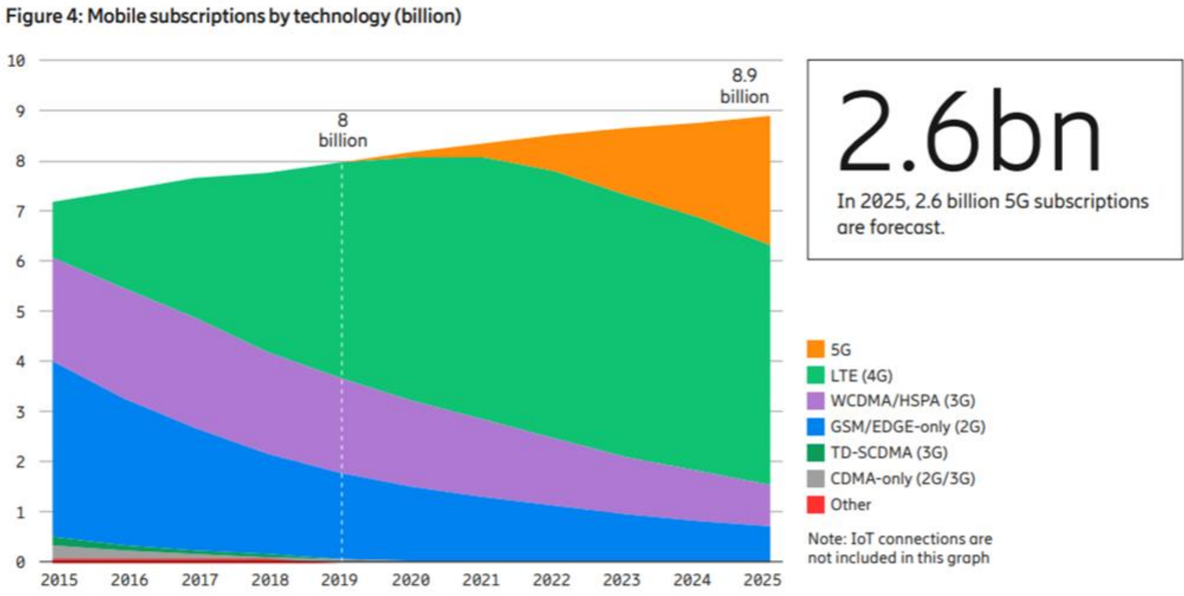
- **802.11p is here today**
  - Standard approved in 2009
  - Several ETSI ITS plug-test events
  - Extensive field trials
    - Safety Pilot, Drive C2X, Score@F, simTD, etc.

- Significant efforts in the last 10 years to validate 802.11p
  - This should be re-done for any other alternative technology

802.11p or C-V2x

- **Some argue that Cellular-V2x is still far out**
- Cellular technology is by far the most successful wireless standard
  - 5.5 billion mobile broadband subscriptions in Q2 2018
- LTE (Rel. 8) dates back to 2009, 5G under deployment in 2022
  - Extensive cellular infrastructure, it takes time to upgrade
  - ~ 5 billion LTE subscribers still in 2025, next to 2.6 billion 5G subscribers
- LTE Rel. 8. can only address basic ITS use cases
  - No support for low latency and high mobility use cases
  - 3GPP V2x study group established in 2015

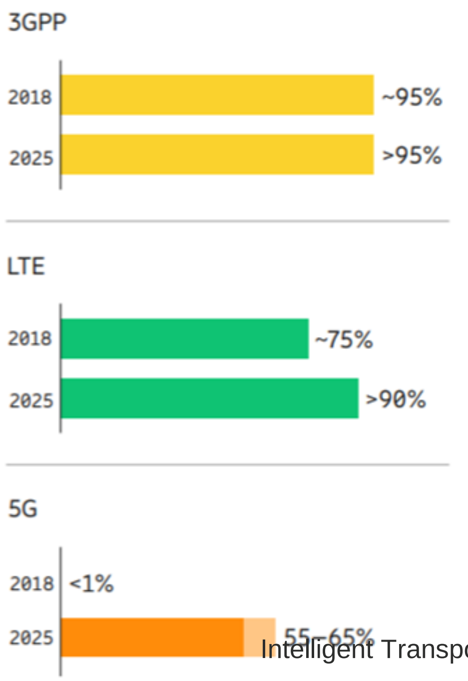
Mobile subscriptions worldwide.
Source: Ericsson Mobility Report, November 2019

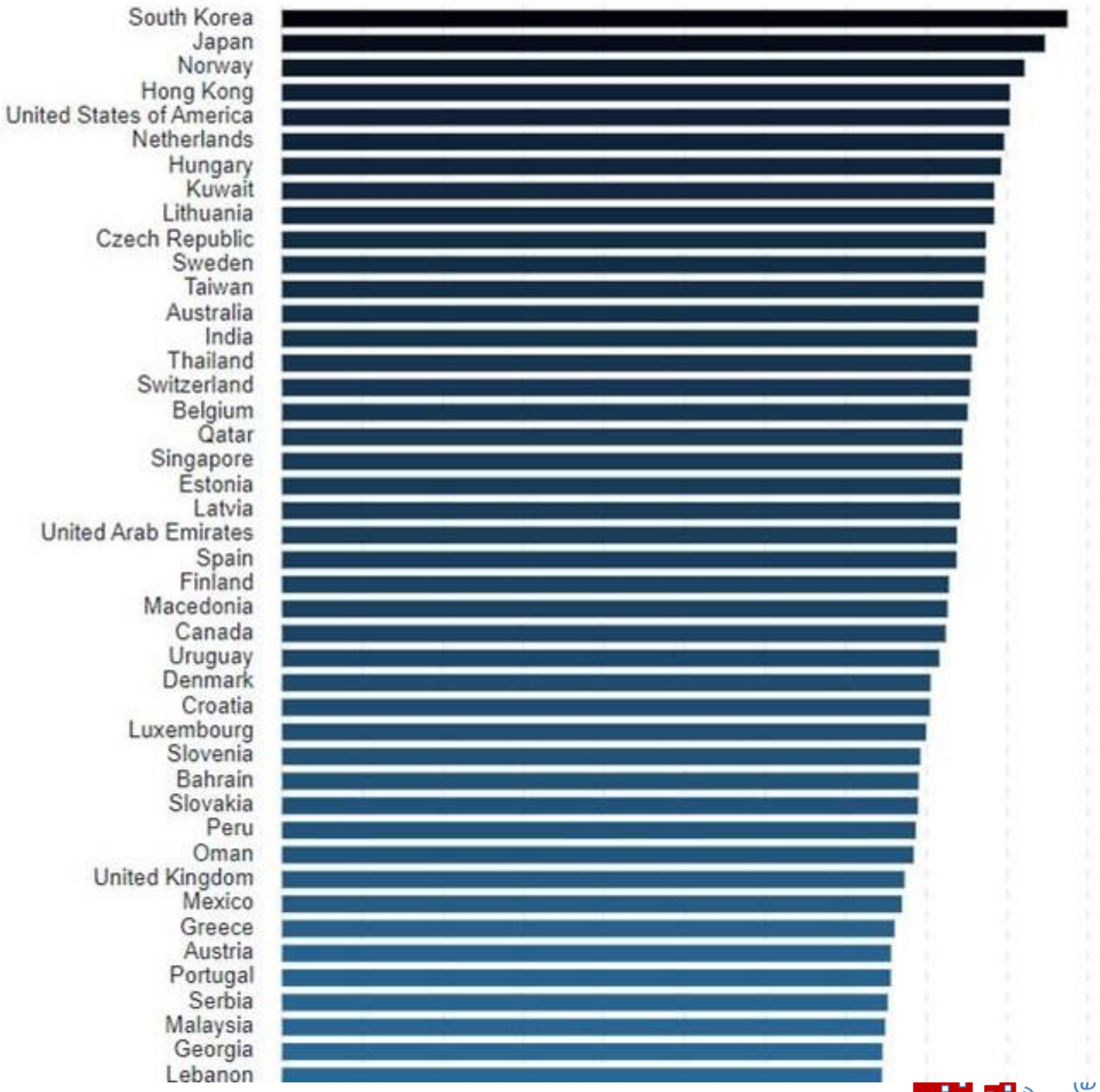


State of LTE in 2018

- LTE coverage still far from 100%
  - Not geographic coverage, but percentage of time when LTE signal available to users
  - Around 65-68% in Germany, France
  - Extensive 3G infrastructure

Figure 15: World population coverage by technology[2]





LTE support for V2x applications

- LTE Release 8 can cover most of the V2I – I2V non-safety use cases
- Problem with very congested scenarios
  - evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-A (Rel. 9)
    - Designed to support static scenarios – crowds in football stadiums
    - Not efficient when a large number of incoming and outgoing vehicles
- Problems with handovers between MNOs (mobile network operators) and cooperation between application service providers

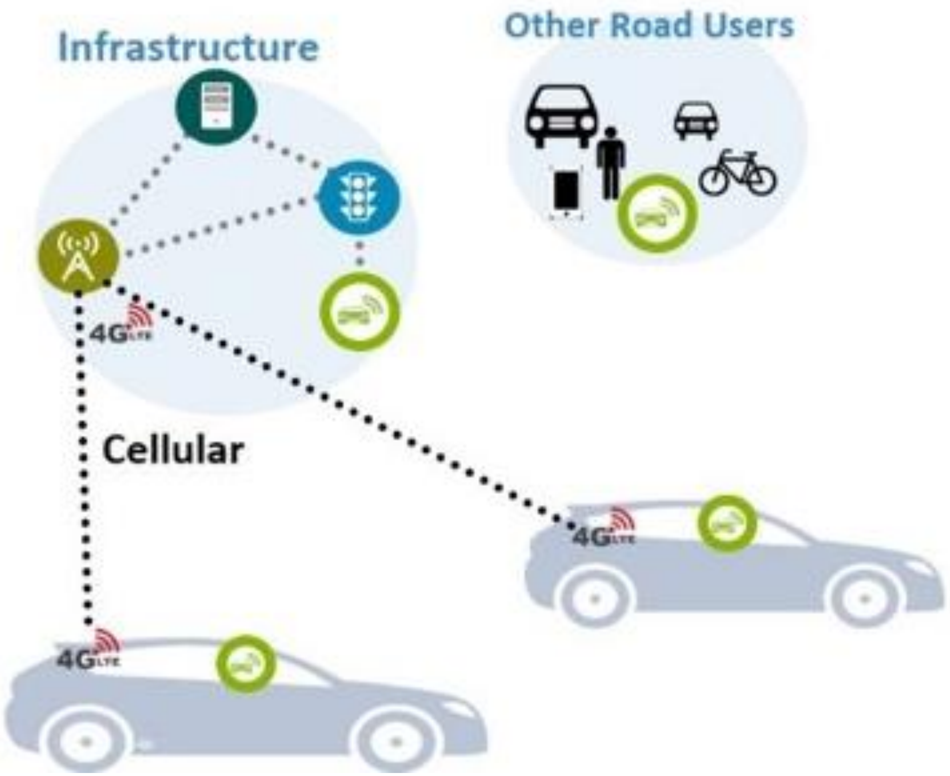
LTE support for V2x applications

- Safety-related use cases represent the real challenge
  - Need complete coverage along the roads (which is not yet the case)
  - Need to handle high bandwidth with very low latency
- Some V2V use-cases require **continuous information exchange** (1 – 20 Hz)
    - **Cooperative Awareness Messages (CAM) - autonomous cars**
  - Too much data for LTE networks to handle
    - **Example: 256 bytes/message, 10 Hz, 2 hours of driving/day = 0.5 Gbyte per month per car**
    - **At the receiver side, assuming 30 cars in the area of interest, roughly 15 Gbytes per month**
    - 1 autonomous car in 2020 – **4 Tbyte per day** **(generated inside the car, not transmitted entirely)**
- MNOs typically bill based on resources used ($ / bit / s), but V2V traffic should be free
  - Alternative business model to be developed to justify investments


THE COMING FLOOD OF DATA IN AUTONOMOUS VEHICLES
RADAR
~10-100 KB
PER SECOND
SONAR
~10-100 KB
PER SECOND
GPS
~50KB
PER SECOND
CAMERAS
~20-40 MB
PER SECOND
AUTONOMOUS VEHICLES
4,000 GB
PER DAY... EACH DAY
LIDAR
~10-70 MB
PER SECOND
intel

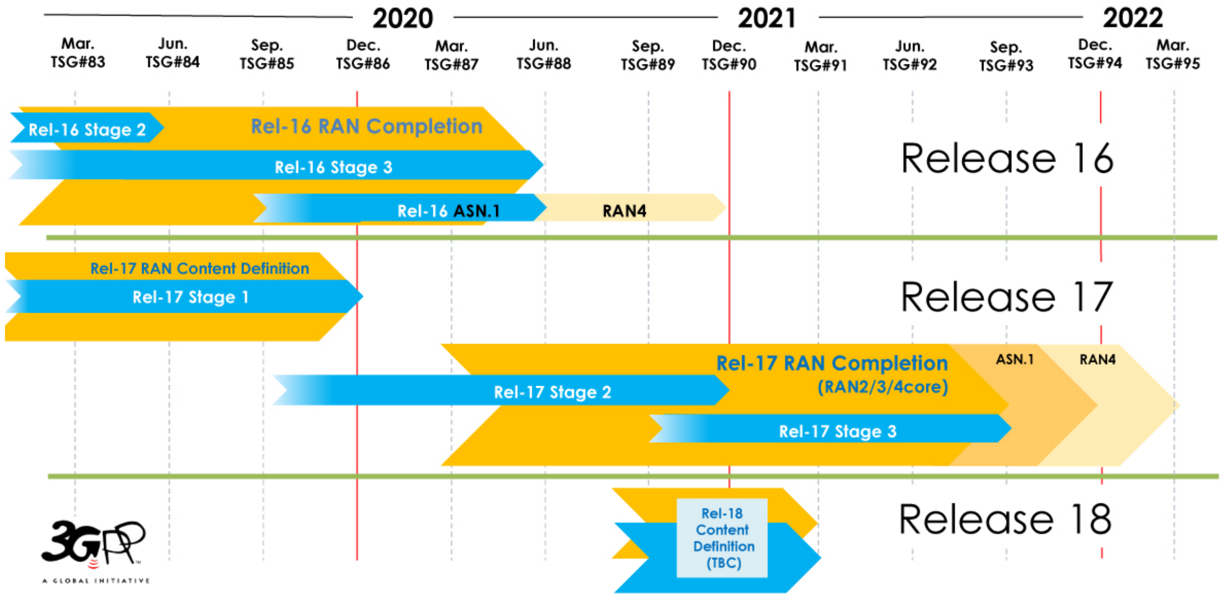
LTE support for V2x applications

- Some V2V use cases do not require high bandwidth, but **very low latency**
  - event-based broadcasting of Decentralized Environmental Notification messages (DENM) – e.g. fast braking
- Could work in the cellular network, but not always
  - Across multiple MNOs, across borders, across cells
- **Another solution: develop direct communication technology, as part of the cellular system**
  - **Device-to-Device** communication, part of Release 12, but not suitable for V2V
    - If two devices want to communicate directly, the network allocates the time / frequency resources
    - The network manages the interference generated by the D2D communication
    - Signalling/control via the eNodeB
    - Direct data sending between the UEs
  - D2D will not work if no continuous network coverage



C-V2x evolution

- LTE-D2D – Release 12 (2012)
- C-V2x Phase I– Release 14 (started in 2014, published in 2016)
  - V2V, V2I, V2N support
- C-V2x Phase II – Release 15 (published in 2018)
  - 5G support (called also 5G-V2x)
- C-V2x Phase III – Release 16 (2020)
  - Enhanced 5G support
  - Also called NR-V2X



Source: 3GPP TSG SA#87e, 17-20 March 2020, e-meeting document SP-200222

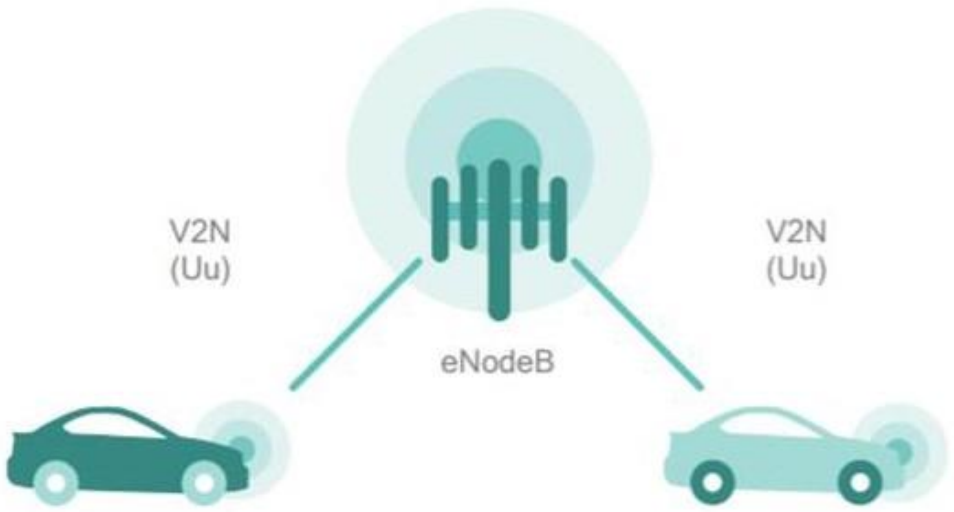
C-V2X defines two complementary transmission modes

Network communications

V2N on “Uu” interface operates in traditional mobile broadband licensed spectrum

Uu interface

e.g. accident 2 kilometer ahead



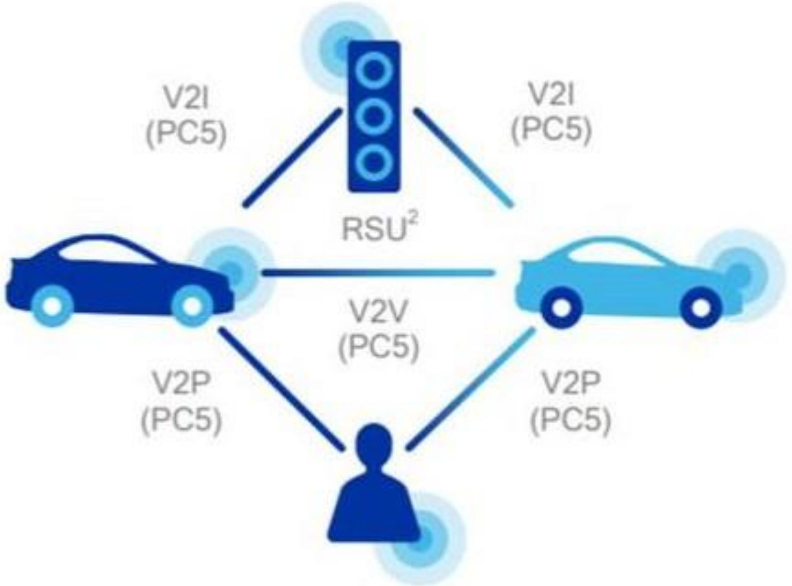
On the traditional cellular spectrum

Direct communications

V2V, V2I, and V2P on “PC5” interface[1], operating in ITS bands (e.g. ITS 5.9 GHz) independent of cellular network

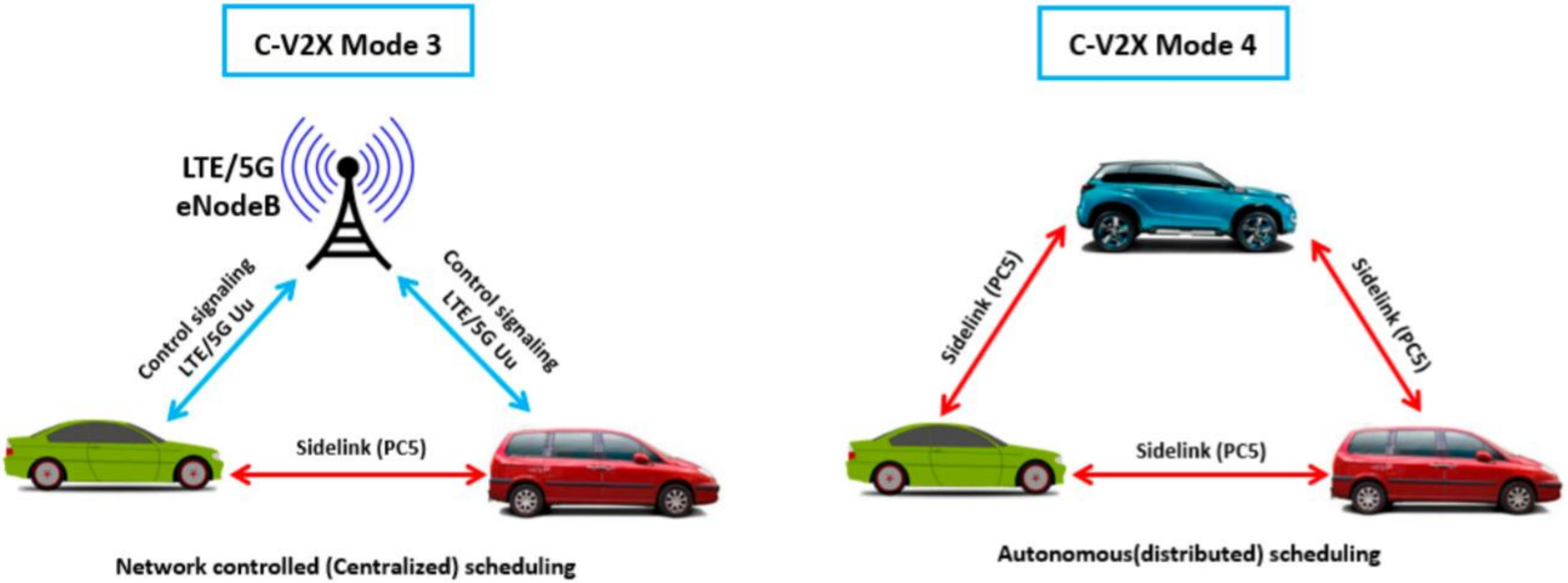
PC5 interface

e.g. location, speed



On 5,9 GHz

C-V2X Sidelink (PC5) Modes in Rel. 14/15

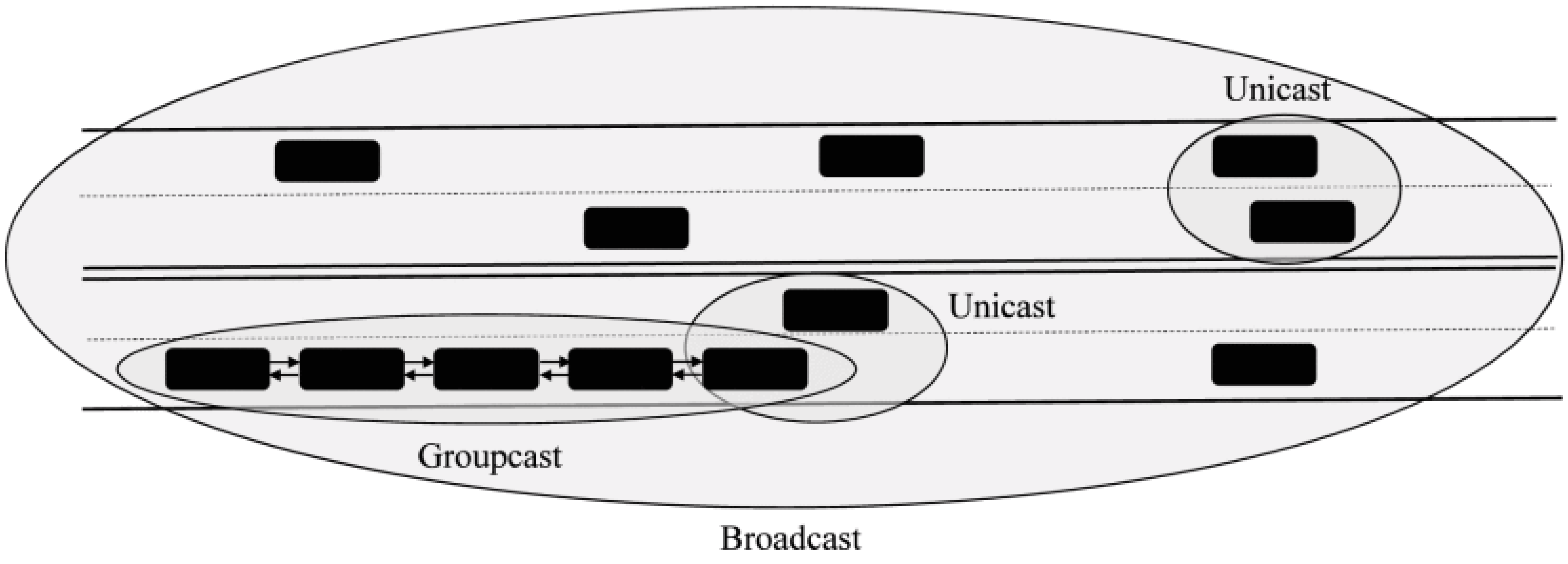


Communication modes

LTE-V2X – only broadcast communication

NR-V2X:

- Unicast – direct communication between two vehicles
- Broadcast – everyone within radio range
- Groupcast – e.g., platooning



OKOS VÁROS @ BME TMIT

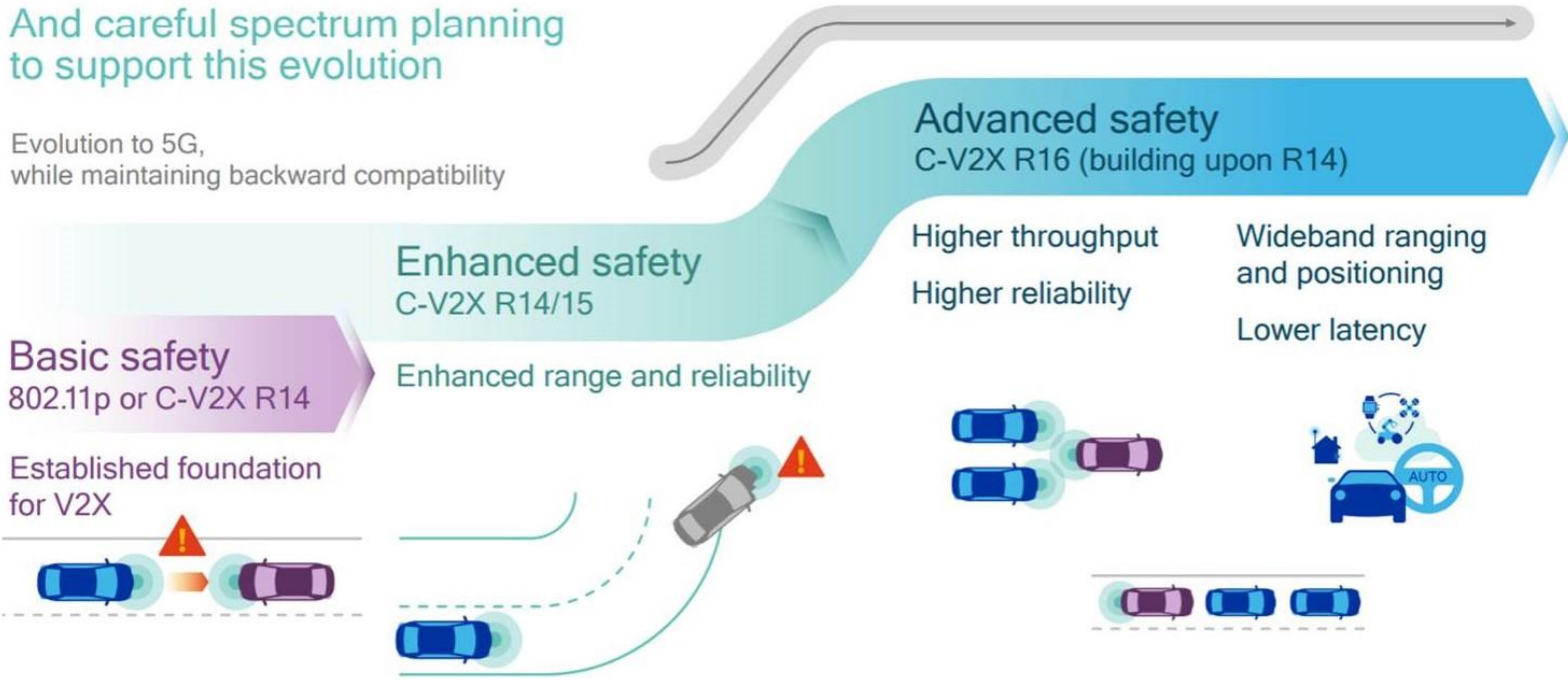
NR-V2X frequencies

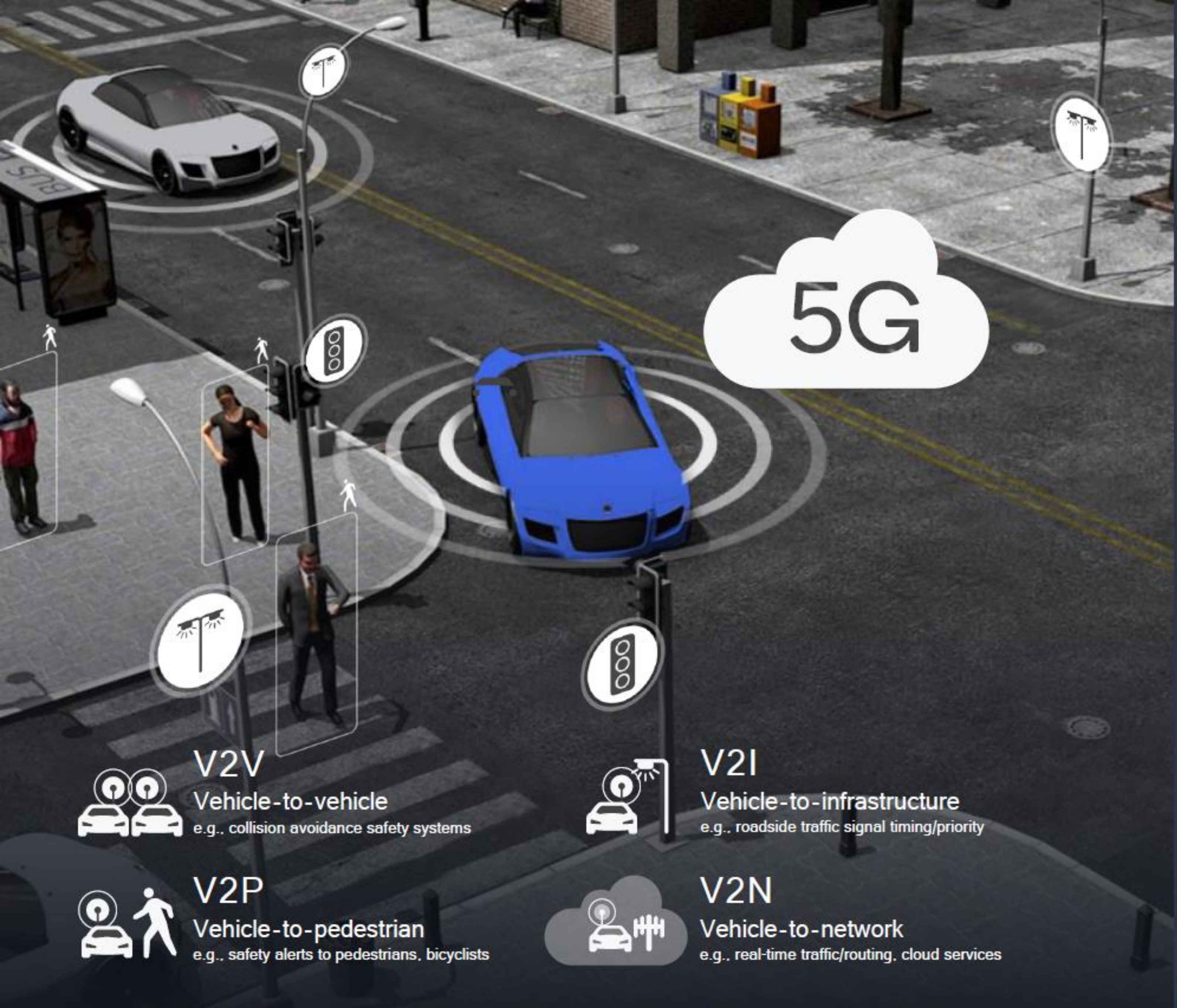
- NR-Sidelink (Rel. 16) frequencies
  - 5,9 Ghz – together with other technologies (pl. IEEE 802.11p/bd)
  - 2,5 Ghz – only NR-V2X
- Supported channel sizes – 10, 20, 30, 40 MHz
- **Carrier spacing**
  - For LTE-V2X fixed carrier-spacing (15 kHz)
  - For NR-V2X variable carrier spacing (15, 30, 60 kHz)
- **HARQ (Hybrid Automated Repeat Request)**
  - feedback from the receiving vehicle
  - ACK/NACK –based feedback in case of Unicast
  - NACK-only feedback in case of Groupcast

Sidelink optimization in Rel. 17

- **Power saving for Battery-powered UEs**
  - Typicaly for the NR-V2X devices carried by pedestrians, bikers
  - In Rel. 16 „always on” operation
- **Sidleink DRX mode (Discontinous Reception)**
  - Coordinating the sleeping cycles among UEs
- **Improving reliability and latency**
- **Sidelink Relaying**
  - UE-to-Network
  - UE-to-UE
    - In Rel. 16, only support for single-hop
    - Relay discovery, selection, authorization

Continuous V2X technology evolution required





C-V2X

Rel 14/15 C-V2X established basic safety

Rel 16 NR C-V2X saw continued evolution for advanced use cases

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- Release 14/15 C-V2X standards completed
- Broad industry support with 5GAA
- Global trials started in 2017; first commercial deployment expected in 2020
- Qualcomm® 9150 C-V2X chipset announced in September, 2017
- Integration of C-V2X into the Qualcomm® Snapdragon™ Automotive 4G and 5G Platforms announced in February, 2019

Qualcomm 9150 C-V2X and Qualcomm Snapdragon Automotive 4G/5G Platforms are products of Qualcomm Technologies, Inc. and/or its subsidiaries.

Driving C-V2X global presence with trials and demos

Gaining traction across numerous regions and industry sectors

From standards completion to independent field testing to initial deployments

1. CAMP = Crash Avoidance Metrics Partnership LLC and this project includes the listed OEMs and Qualcomm.

Collaborating with key ecosystem players

CAMP	Ford	Quectel	Kapsch
PSA	Lear	SWARCO	Neusoft Reach
BMW	Valeo	Commsignia	Simcom
Daimler	WNC	Genvict	Sasken,
SAIC	CMCC	Nebulalink	Thundersoft
Continental	AT&T	R&S	Telit
Bosch	NTT DoCoMo	Datang	Lacroix
LG	CMRI	Ficosa	And more…
ZTE	McCain	Savari	

5GAA Automotive Association

- 8 of the top 9 global automakers
- Top automotive Tier 1 suppliers
- 9 of the top 10 global telecommunications companies
- Top 3 global smartphone manufacturers
- Top global semiconductor companies
- Top 5 global wireless infrastructure companies
- Top global test and measurement companies and certification entities
- Global representation from Europe, China, US, Japan, Korea, and elsewhere

Strong C-V2X momentum globally

Sep. 2016
5GAA founded

Jan. 2017
ConVeX trial in Germany announced

Feb. 2017
Towards 5G trial in France announced

Mar. 2017
Rel-14 C-V2X spec finalized

Sep. 2017
MDM 9150
First C-V2X chipset introduced

Oct. 2017
San Diego Regional C-V2X trial
AT&T, NOKIA, Ford, McCain

Apr. 2018
First multi-OEM demo in D.C.

Jun. 2018
1st US deployment in Denver
FICOSA, WNC, kapsch, SAVARI, CDOT, Panasonic, Ford

Jul. 2018
Europe's first multi-OEM demonstration in Paris

Oct. 2018
Multi-OEM performance evaluation of C-V2X

Oct. 2018
C-V2X functional and performance test report published

Nov. 2018
Reaches 100 members

Nov. 2018
China-SAE ITS Stack Compatibility

Jan. 2019
Cooperative driving live interactive demos in Las Vegas
DUCATI, Ford

Jan. 2019
Announcing C-V2X implementation in Las Vegas
commsignia, RTC

Feb. 2019
C-V2X integrated with Qualcomm® Snapdragon™ Automotive 4G/5G platforms

Feb. 2019
TELEFÓNICA/ SEAT's live C-V2X/ 5G demo at MWC Barcelona

Mar. 2019
SAIC project complete

Mar. 2019
Cross border demo
conVex

May 2019
C-V2X ecosystem demos

Nov. 2019
Live demos show C-V2X as a market reality

Nov. 2019
CAMP congestion control scenario testing by OEM consortium

Jan. 2020
ETSI European specifications and standards for C-V2X completed

Jan. 2020
C-V2X deployment in Virginia with VaDoT

Feb. 2020
C-V2X devices passed European Radio Equipment Directive (RED)