CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING

DEPARTMENT OF TELECOMMUNICATION ENGINEERING

B2M32BTSA - Bezdrátové technologie

BE2M32BTSA - Wireless Technologies and Sensor Networks

Communications of autonomous systems

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6G mobile RESEARCH LAB

Overview

Autonomous systems

- Overview of use-cases

Requirements on communication protocols

- Key performance indicators (latency, reliability, etc.)
- Tradeoffs in wireless communications
- Service requirements
- Ultra-reliable low latency commutations

Communication protocols for V2X

- IEEE 802.11p & IEEE 802.11bd
- LTE V2X & NR V2X
- Comparison

Autonomous systems

Autonomous communication systems

What kind of systems?

- Systems operating with a high or complete autonomy
- Minimal or no intervention from user required

Use-cases

- Automated factory (autonomous mobile robots, swarm production)
- Autonomous train control systems
- Autonomous aerial systems
- Autonomous marine systems
- **Vehicular communication (autonomous driving)**

Automated factory

Roadmap to swarm production:

Step	Focus area	Actions
(1)	Wireless production	Remove cables between manufacturing line modules. Cloud-based production control. • Manufacturing target: Flexibility, reconfiguration. • Communication needs: robust low-throughput delay-tolerant wireless communication links to static units.
(2)	PLC	Remove hardware, use cloud-based soft PLCs instead. • Manufacturing target: Faster and cheaper adaptation of new functionalities. • Communication needs: reliable high-throughput low-latency wireless communication links to static units.
(3)	AMR	Move functionality (localization and navigation) to the cloud. Investigate new localization techniques. • Manufacturing target: more efficient fleet management/cheaper robots and shared world model (cloud robotics). • Communication needs: ultra-reliable high-throughput low-latency wireless communication links to mobile units.
(4)	Swarm production	Remove conveyor belts, make product carriers into small mobile robots. • Manufacturing target: More flexible and robust automation. • Communication needs: ultra-reliable high-throughput low-latency wireless communication links to both static and mobile units.

PLC: Programmable logic controllers   AMR: Autonomous mobile robots

I. Rodriguez, et. al., “5G Swarm Production: Advanced Industrial Manufacturing Concepts Enabled by Wireless Automation.”, *IEEE Communications Magazine*, 2021.
https://www.designnews.com/automation-motion-control/automated-mobile-robots-are-delivering-efficiencies-manufacturing

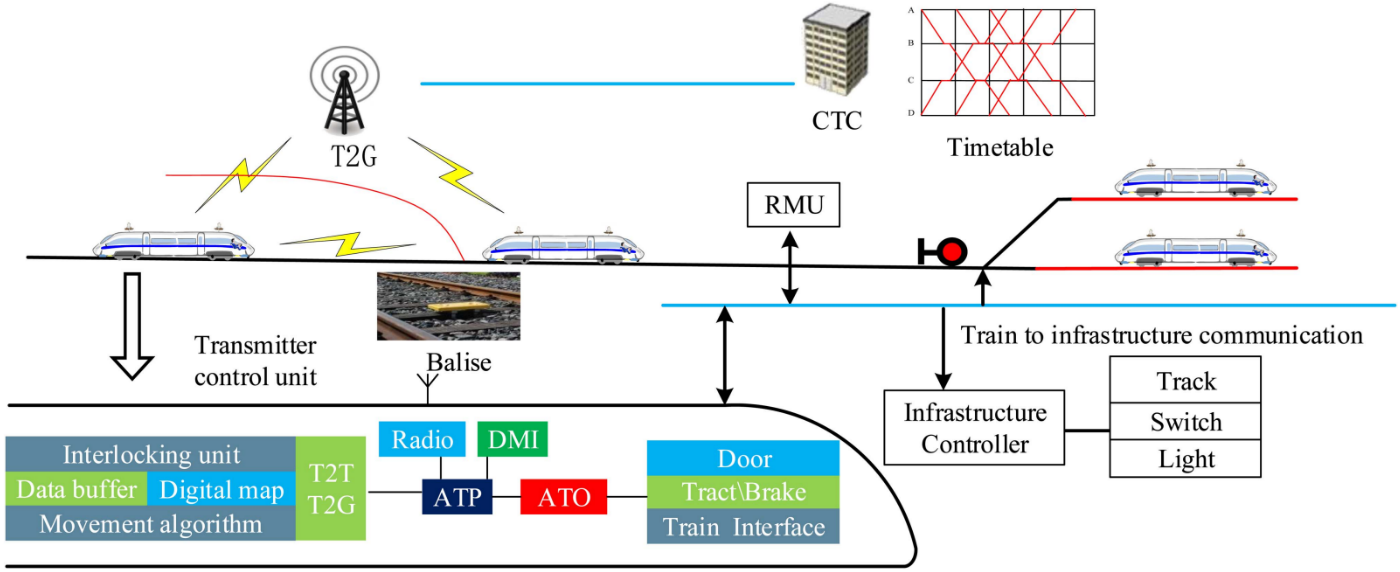
Autonomous train control system

Types of communications

- Train-to-Ground (T2G)
- Train-to-Train (T2T)

Main concepts in autonomous train control

- Automatic Train Protection (ATP)
  - Controls velocity of train => automatically decelerates if current velocity is above limit
- Automatic Train Operation (ATO)
  - Onboard subsystem managing train operation



Haifeng Song, et al., “Train-Centric Communication Based Autonomous Train Control System,” IEEE TRANSACTIONS ON INTELLIGENT VEHICLES, VOL. 8, NO. 1, JANUARY 2023

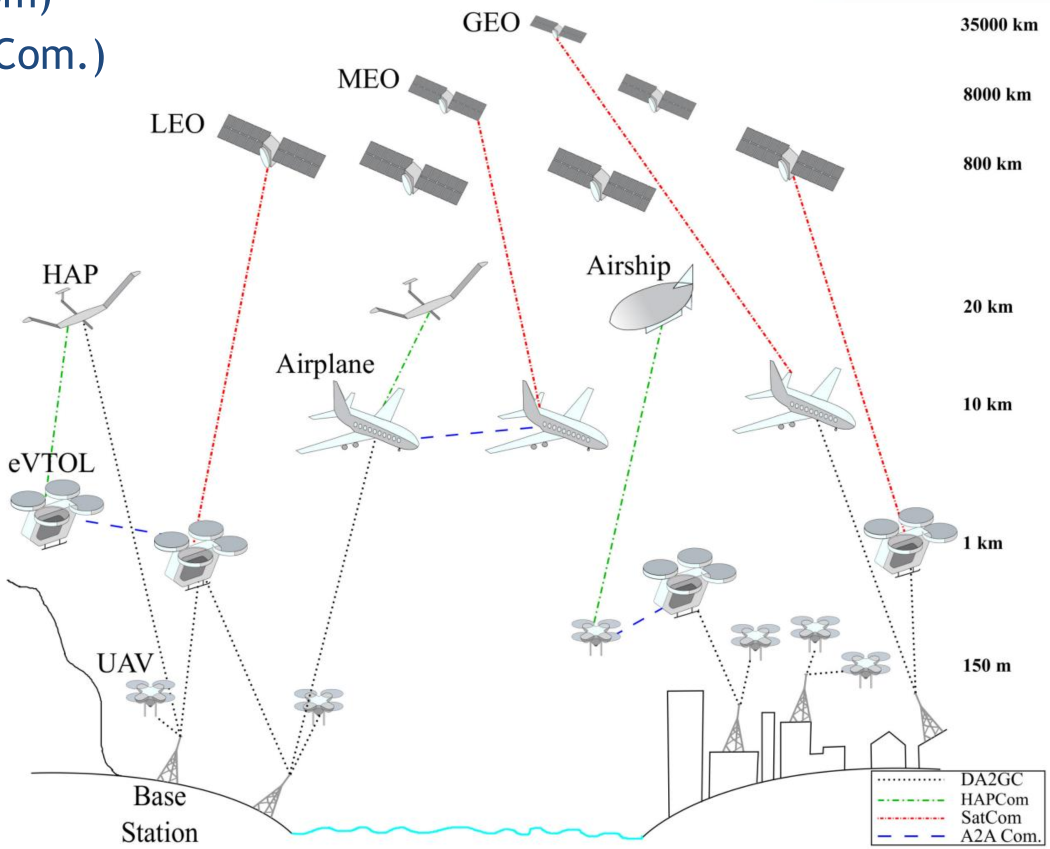
Autonomous Aerial Systems

Types of communications

- Direct Air-to-Ground communication (DA2GC)
- High Altitude Platform Communications (HAPCom)
- Satellite Communication (SatCom)
- Air-to-Air communication (A2A Com.)

Fully autonomous operation (FAO)

- Operation w/o (remote) pilot
- Ground supervisor can still be present to monitor the flight

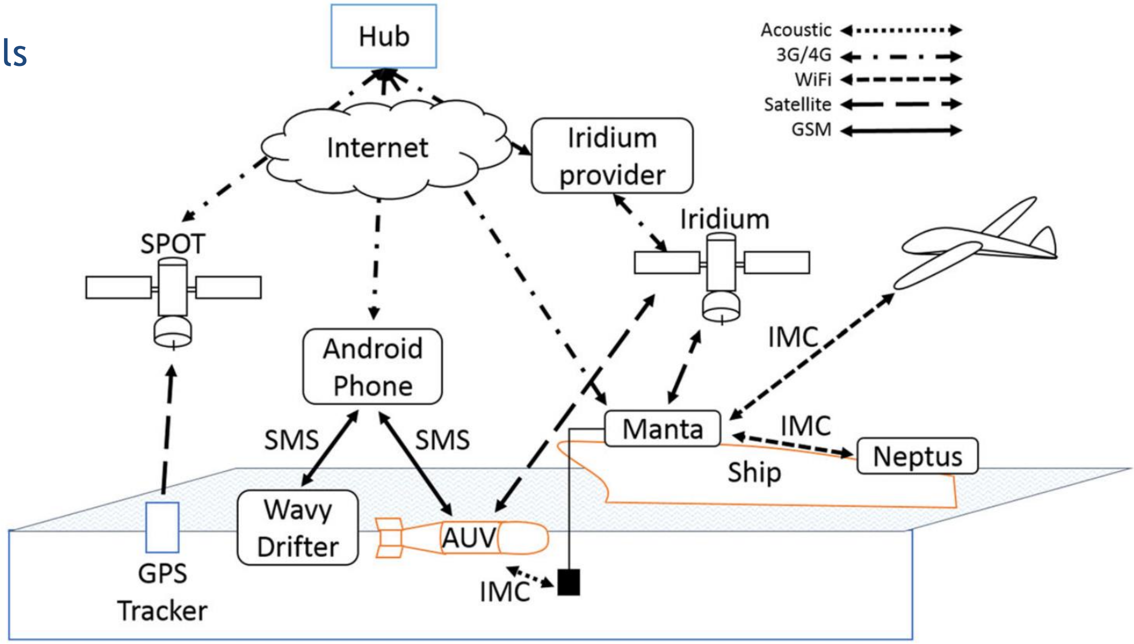


Aygün Baltaci, et al., “A Survey of Wireless Networks for Future Aerial Communications (FACOM),” IEEE Communications Surveys & Tutorials, 2021.

Autonomous marine systems

Types of communications

- Over Air
  - 5G NR
- Satellite
  - LEO/GEO satellites
  - Inmarsat, Iridium, Globalstar, …
- Underwater
  - Optical and acoustic signals

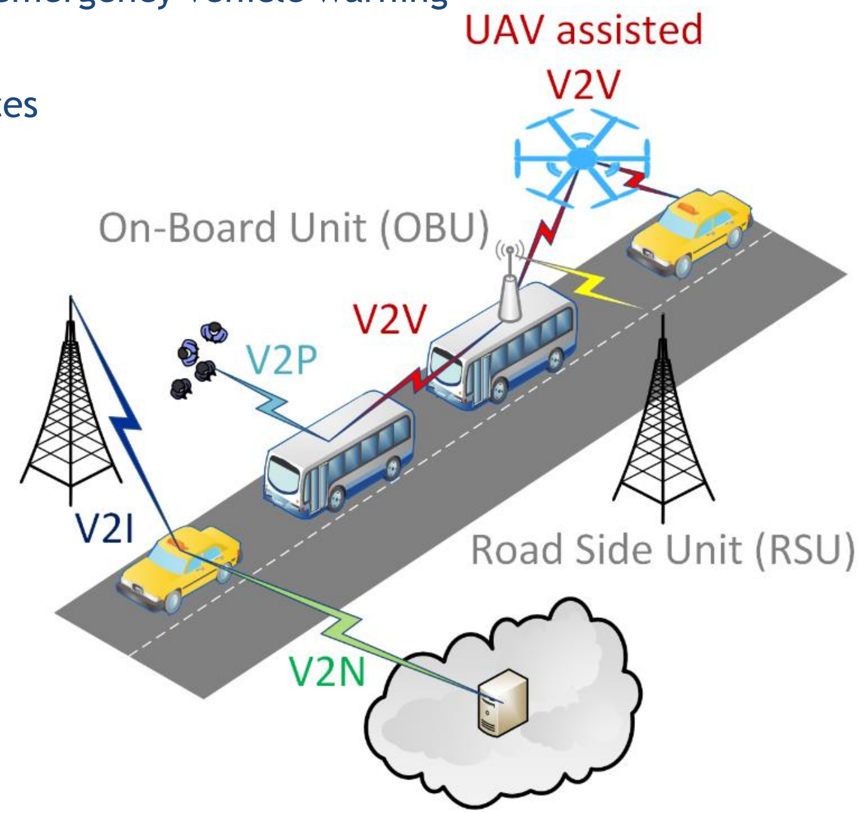


Zolich,et. al., “Survey on communication and networks for autonomous marine systems.”, *Journal of Intelligent & Robotic Systems*, *2019*.
https://www.3gpp.org/news-events/2006-maritime2

Vehicular communication

Types of communications

- Vehicle-to-Vehicle (V2V)
  - Collision avoidance, braking information, blind spot warning
- Vehicle-to-Infrastructure (V2I)
  - Providing traffic signal/light priority, emergency vehicle warning
- Vehicle-to-Network (V2N)
  - Real-time traffic/routing, cloud services
- Vehicle-to-Pedestrian (V2P)
  - Safety alerts to pedestrians, cyclists
- **Vehicular-to-everything (V2X)**



Autonomous driving: automation levels

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE) AUTOMATION LEVELS

Full Automation

0
No Automation

Zero autonomy; the driver performs all driving tasks.

1
Driver Assistance

Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design.

2
Partial Automation

Vehicle has combined automated functions, like acceleration and steering, but the driver must remain engaged with the driving task and monitor the environment at all times.

3
Conditional Automation

Driver is a necessity, but is not required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice.

4
High Automation

The vehicle is capable of performing all driving functions under certain conditions. The driver may have the option to control the vehicle.

5
Full Automation

The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

https://www.acmwillowrun.org/smart-car-road-testing-101/

Requirements on communication protocols

Key performance indicators

Latency

- End-to-end (E2E) latency to deliver data
  - **millisecond or lower**

Reliability

- Probability that a data of size D is successfully transferred within a time period T
  - **Reliability of 99.99% or higher**

Availability

- Defined as the probability that a given service is available (coverage)
  - For instance, **99.99%** availability means that one user among 10000 does not receive proper coverage

Mobility

- Ensure latency, reliability, and availability for high mobility scenarios
  - Speeds up to **500** km/h

Latency and reliability of wireless communication

Latency

- $t = t_{que} + t_{req} + t_{grant} + t_{data} + t_{ack} + N * t_{retransmission} + t_{comp}$
  - t_{que} = Queuing
  - t_{req} = Transmission of request to send data (usually in uplink)
  - t_{grant} = Transmission of grant to send data (usually in uplink)
  - t_{data} = Transmission of data
  - t_{ack} = Transmission of acknowledgement
  - $t_{retransmission}$ = Retransmission incorporating $t_{data} + t_{ack}$
  - N = Number of retransmissions
  - t_{comp} = Computing/processing of data (e.g., computing in cloud)

Reliability

- $R = (1 - \epsilon_{sync})(1 - \epsilon_{req})(1 - \epsilon_{grant})(1 - \epsilon_{data})(1 - \epsilon_{ack})$
  - ϵ_{sync} = Probability of error in synchronization
  - ϵ_{req} = Probability of transmission request error (usually only uplink)
  - ϵ_{grant} = Probability of access grant reception error (usually only uplink)
  - ϵ_{data} = Probability of data transmission error
  - ϵ_{ack} = Probability of acknowledgement error

Tradeoffs in wireless communications (1/2)

Access and data transmissions

- **Four-step access**
  - 1. step: Request -> 2. step: Grant -> 3. step: Data transmission -> 4. step: Data ACK
  - High latency and high reliability

- **Three-step access**
  - 1. step omitted (no t_{req} and ϵ_{req})
  - Device **requirements have to be predicted** -> incorrect prediction wasted transmission time
  - Lower latency than four-step access

- **Grant-free access**
  - 1. and 2. steps omitted (no t_{req}, t_{grant}, ϵ_{req}, ϵ_{grant})
  - Low latency but low reliability in highly loaded scenarios

Tradeoffs in wireless communications (2/2)

Code rate $\mathrm{R} = k/n$

- Useful *k* (bits) vs redundant data in packet of size *n*
  - high *R* (e.g., 5/6, 3/4) => low latency, low reliability
  - low *R* (e.g., 1/2) => high reliability, high latency

Modulation

- Selection depending on channel quality and service requirements
  - Robust modulation (BPSK, QPSK) => High reliability but high latency due to low spectral efficiency => low data rates
  - Efficient modulation (64QAM or higher) => low reliability but low latency due to high spectral efficiency => high data rates

Energy consumption aspect

- High transmission power
  - Reliable communication at high energy consumption
- Frequency of transmissions
  - Frequent short transmissions => low latency & high energy consumption

Transmission Time Interval (TTI)

- Short TTI (less than 1 ms) => low latency and high reliability but high overhead
- long TTI (1 ms) => high latency (especially in case of retransmissions due to longer HARQ) but low overhead

Service requirements

	Service	E2E latency [ms]	Reliability $1-10^{-x}$ [-]
Driving[1]	Assisted	5	5
	Co-operative	10	5
	Tele-operated	20	5
Industry 4.0	Machine control	1	5
	Factory automation	10	4
	Extremely reliable factory automation	1	9
	Process automation	50	6
Tactile Internet		1	9

x	Reliability $1-10^{-x}$ [-]	Reliability [%]
4	0,9999	99,99
5	0,99999	99,999
6	0,999999	99,9999
9	0,999999999	99,9999999

Industry 4.0 => 4th industrial revolution => increasing automation and the employment of smart machines and smart factories

Tactile internet => very low latency communication systems while ensuring high reliability and availability

[1] Study on Enhancement of 3GPP Support for 5G V2X Services (Release 16), document 3GPP TR 22.886 v16.0.0, Jun. 2018

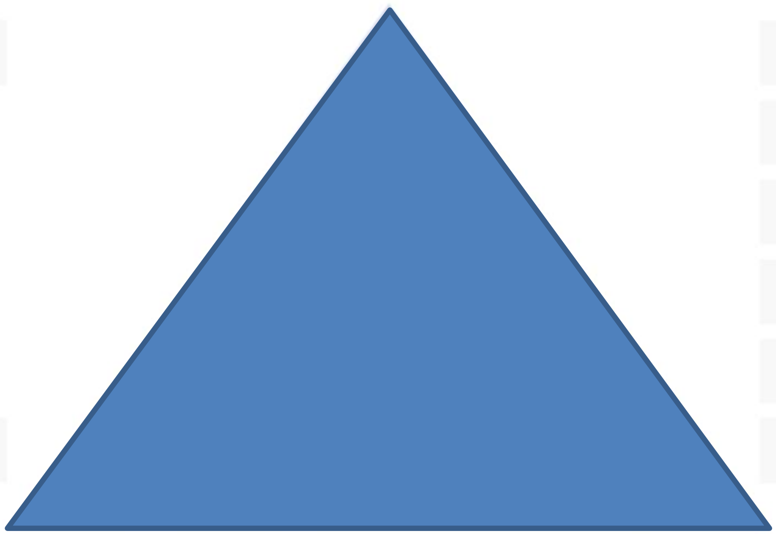
Key building blocks of 5G

eMBB

- Peak download speeds of over 10 Gbps
- Real-life (average) speeds higher than 4G LTE

Smart home / building

Smart city



Ultra HD and 3D videos

B2B and B2C cloud-based apps

AR/VR (Augmented / Virtual Reality)

Industrial automation

Mission-critical applications

Self-driving vehicles

mMTC

- 1 million devices per square kilometre
- Long battery life (up to ten years)
- Mass deployment of low-powered, low-cost, low complexity IoT devices

uRLLC

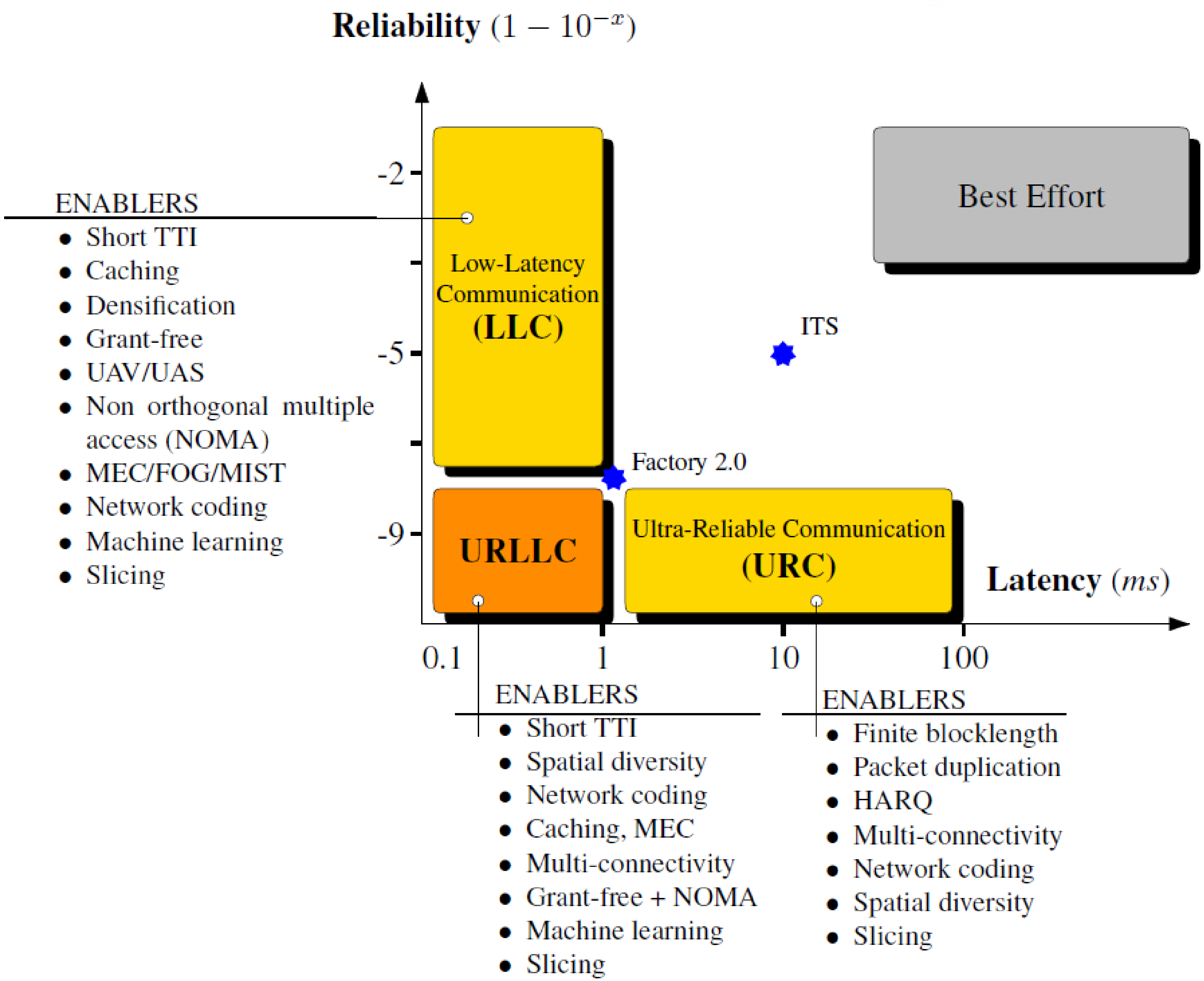
- 99.99% reliability
- Low latencies of below 1 millisecond
- Low data rates (in bits per second or kilo bits per second)

eMBB = enhanced Mobille BroadBand
mMTC = massive Machine Type Communication

uRLLC = ultra-Reliable low latency communication

https://commsbrief.com/what-do-embb-mmtc-and-urllc-mean-in-5g/

Enablers of services



M. Bennis, M. Debbah, and H.V. Poor, “Ultra-reliable and low-latency wireless communication: Tail, risk, and scale.”, *Proceedings of the IEEE*, 2018.

Ultra-reliable low latency communication

Requirements and enablers

- End-to-end latency below 1ms
  - Short **Transmission Time Interval (TTI)**
  - **Edge caching**
    - Resources cached at the network edge
  - **Multi-access edge computing (MEC)**
    - Computational resources close to the device
  - **Grant-free access**
    - For uplink communication => saves times as there is no need to request/waits for grant allowing to transmit
  - **Non-Orthogonal Multiple Access (NOMA)**
    - Access the same resources by multiple users at the same time
  - On-device (distributed) **machine learning** and **artificial intelligence**
- Reliability $1\text{-}10^{-5}$ (99.999 %)
  - **Multi-connectivity**
- Availability of service (coverage) 99.99 %
  - **Dense deployment** of Access Points (APs)/Base Stations (BSs)

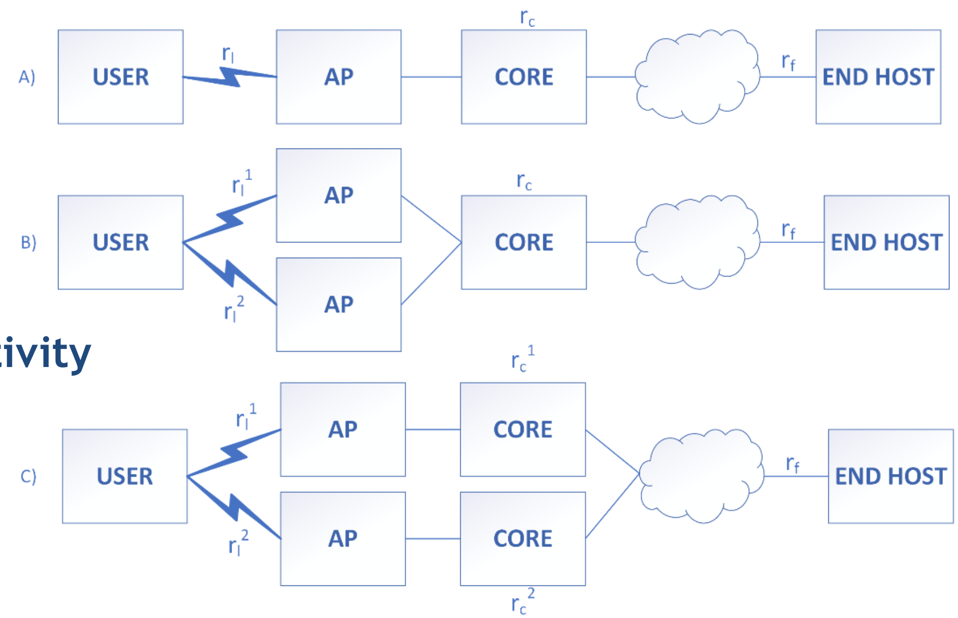
Reliability of multi-connectivity

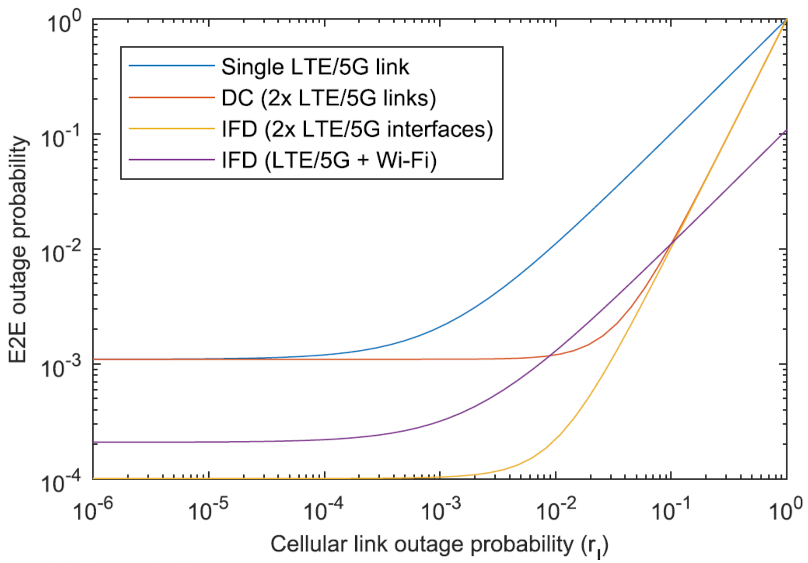
Multi-connection approach

A. Reliability of **single protocol/link**
   - $R_{single} = r_l r_c r_f$

B. Reliability of **N-link connectivity**
   - $R_{link} = \left(1 - \prod_{i=1}^{N}\left(1 - r_l^i\right)\right) r_c r_f$

C. Reliability of **N-interfaces connectivity**
   - $R_{interface} = \left(1 - \prod_{i=1}^{N}\left(1 - r_l^i r_c^i\right)\right) r_f$





- DC always superior or equal to single
- IFD is always superior or equal to DC
- If cellular outage probability is high IFD combining LTE/5G and WiFi outperforms IFD with 2x LTE/5G interfaces

DC = Dual connectivity IFD = Interface diversity

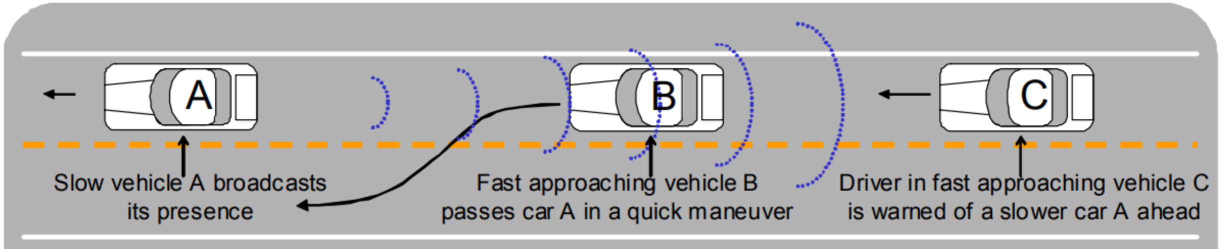
P. Popovski, et. al., “Wireless access in ultra-reliable low-latency communication (URLLC).”, *IEEE Transactions on Communications*, 2019.

Communication protocols for V2X

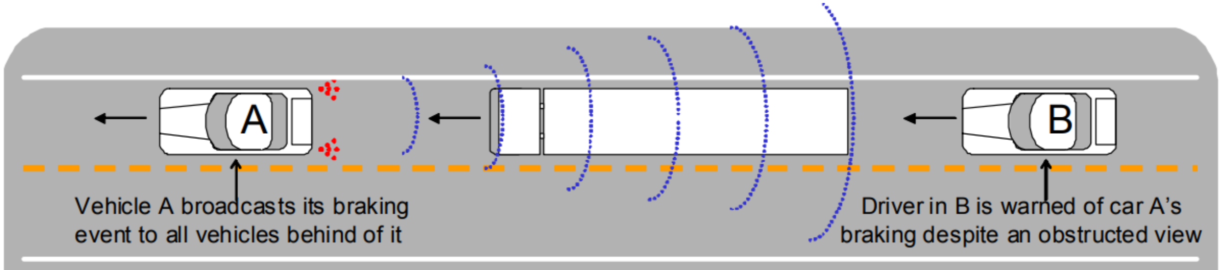
IEEE 802.11p

Standard for vehicular communication

- Build on top of IEEE 802.11 series
  - Modified IEEE 802.11 towards low overhead and low latency
- Enabling safety vehicular communication



(a) Rear-end Collision Avoidance



(b) Extended Emergency Brake Light

D. Jiang, and L. Delgrossi, "IEEE 802.11 p: Towards an international standard for wireless access in vehicular environments.", IEEE *VTC Spring 2008*.

IEEE 802.11p PHY & MAC

Physical layer (PHY)

- Based on **IEEE 802.11a OFDM**
  - Operates on licensed ITS band 5.9 GHz (5.85 – 5.925 GHz)
- Bandwidth 10 MHz but OFDM timings are doubled (e.g., symbol duration, CP)
  - Addressing increased root mean square (RMS) delay spread in vehicular communication – inter-symbol interference
- Improved transmission mask to reduce cross-channel interference (i.e., interference between channels)
- 52 subcarriers modulated via BPSK, QPSK, 16QAM and 64QAM
  - Data rates between 3 Mbit/s (CR 1/2, BPSK) and 23 Mbit/s (CR ¾, 64 QAM)

CH 172 5 860 MHz	CH 174 5 870 MHz	CH 176 5 880 MHz	CH 178 5 890 MHz	CH 180 5 900 MHz	CH 182 5 910 MHz	CH 184 5 920 MHz
Accident avoidance safety of life	Service channels		Control channel	Service channels		High power long range

Medium Access Control (MAC)

- Communication **without need to establish Basic Service Set** (BSS)
  - Disabling of managing procedures (channel sensing, association, etc.) => exchange data faster between vehicles
- Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)
- Enhanced Distributed Channel Access method (EDCF)

D. Jiang, and L. Delgrossi, “IEEE 802.11 p: Towards an international standard for wireless access in vehicular environments.”, IEEE *VTC Spring 2008*.

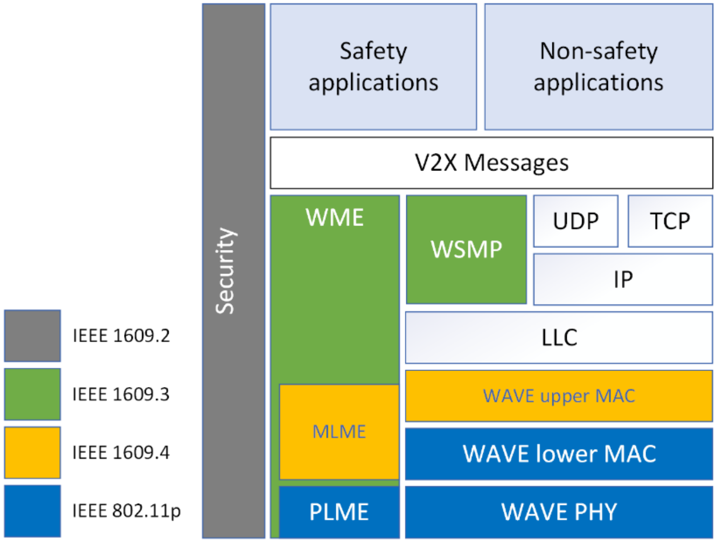
DSRC communication stack

Dedicated Short-Range Communications (DSRC)

- Standardized by Federal Communications Commission (FCC) in USA
- Based on 802.11p
- Often known as IEEE 802.11p WAVE (Wireless Access in Vehicular Environment)

DSRC Communication stack

- **IEEE 802.11p**
  - Physical layer management entity (PLME)
- **IEEE 1609**
  - 1609.2 - security
  - 1609.3 – connection setup and management
    - Wave Short Message Protocol (WSMP)
    - WAVE Management Entity (WME)
      - Frame queueing, priority channels, …
  - 1609.4 – multi channel support
    - switching among channels
- Vehicular to everything (V2X) messages
  - Basic Safety Messages (BSM) format



A. Festag, “Standards for vehicular communication—from IEEE 802.11 p to 5G.”, *Elektrotechnik und Informationstechnik, 2015.*

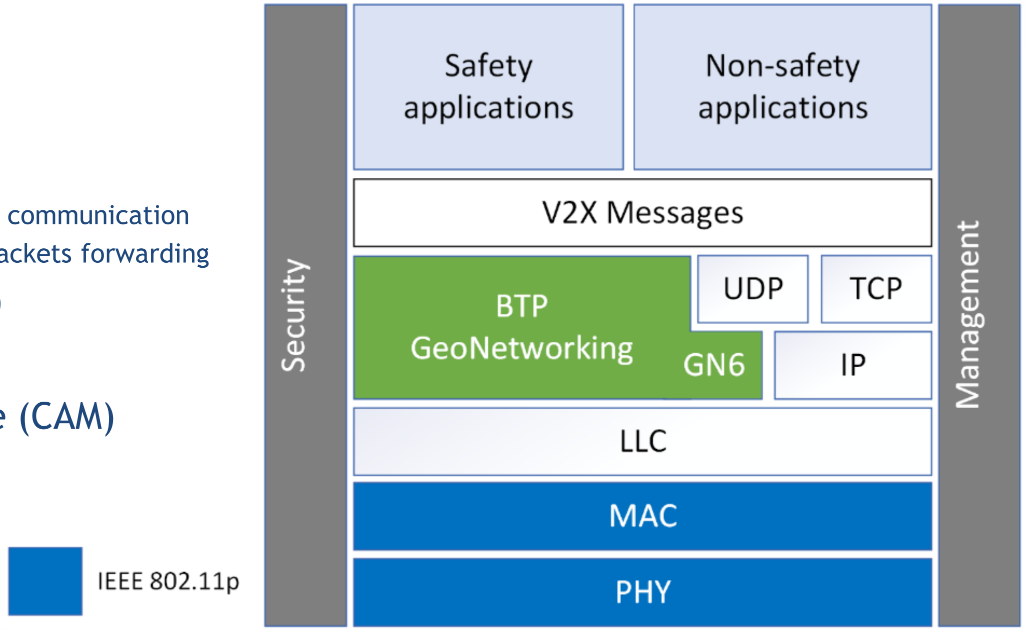
C-ITS communication stack

Cooperative - Intelligent Transportation System (C-ITS)

- Developed by European Telecommunications Standards Institute (ETSI)
- Based on 802.11p
- Often labeled as Intelligent Transportation System - G5 (ITS-G5)

C-ITS communication stack

- **IEEE 802.11p**
- **ETSI EN 302 636**
  - Basic Transport Protocol (BTP)
  - GeoNetworking
    - Ad-hoc routing protocol for multi-hop communication
    - Use of geographical coordinates for packets forwarding
  - IPv6 over GeoNetworking (GN6)
- **ETSI EN 302 637**
  - Cooperative Awareness Message (CAM)



A. Festag, “Standards for vehicular communication—from IEEE 802.11 p to 5G.”, *Elektrotechnik und Informationstechnik, 2015.*

IEEE 802.11bd

Evolution of IEEE 802.11p

- First approval in 2018
- Higher spectral efficiency, enhanced reliability
- **Doubles the range of IEEE 802.11p**
- **Up to 500 km/h** compared to 200 km/h (IEEE 802.11p)
- **Full backward compatibility** with IEEE 802.11p
- Dual carrier modulation
  - Range extension

PHY & MAC

- **Based on IEEE 802.11ac** with half subcarrier spacing
- Up to 256 QAM
- Low Density Parity Check (LDPC) coding
- mmWaves based on IEEE 802.11ad(ay)
- Adaptive re-transmissions
- Two 10 MHz channels (Primary and secondary)

G. Naik, B. Choudhury, and J.M. Park, “IEEE 802.11 bd & 5G NR V2X: Evolution of radio access technologies for V2X communications.”, *IEEE Access, 2019*.

IEEE 802.11p vs IEEE 802.11bd

	IEEE 802.11p						IEEE 802.11bd					
			100 bytes		1500 bytes				100 bytes		1500 bytes	
MCS index	Modulation	Code Rate	Data rate [Mbit/s]	Transmission latency [ms]	Data rate [Mbit/s]	Transmission latency [ms]	Modulation	Code Rate	Data rate [Mbit/s]	Transmission latency [ms]	Data rate [Mbit/s]	Transmission latency [ms]
0	BPSK	1/2	2,32	0,34	2,94	4,08	BPSK	1/2	2,38/1,33*	0,34/0,60*	3,02/1,52*	3,98/7,88*
1	BPSK	3/4	3,12	0,26	4,37	2,74	QPSK	1/2	3,85/2,35*	0,21/0,34*	5,93/3,02*	2,02/3,98*
2	QPSK	1/2	3,50	0,21	5,77	2,08	QPSK	3/4	4,76	0,17	8,72	1,38
3	QPSK	3/4	4,76	0,17	8,52	1,41	16-QAM	1/2	5,71/3,77*	0,14/0,21*	11,41/5,92 *	1,05/2,03*
4	16-QAM	1/2	5,55	0,14	11,19	1,07	16-QAM	3/4	6,45	0,12	16,57	0,73
5	16-QAM	3/4	6,67	0,12	16,13	0,744	64-QAM	2/3	7,41	0,11	20,13	0,60
6	64-QAM	2/3	7,14	0,11	20,83	0,576	64-QAM	3/4	7,41	0,11	22,22	0,54
7	64-QAM	3/4	7,69	0,10	23,08	0,52	64-QAM	5/6	7,41	0,11	24,19	0,50
8	-	-	-	-	-	-	256-QAM	3/4	8,00	0,10	28,30	0,42
9	-	-	-	-	-	-	256-QAM	5/6	8,00	0,10	30,92	0,39

*dual carrier (DC) modulation

W. Anwar, N. Franchi, N. and G. Fettweis, “Physical layer evaluation of V2X communications technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11 bd, and IEEE 802.11 p.”, *IEEE Vehicular Technology Conference (VTC2019-Fall)*, IEEE, 2019.

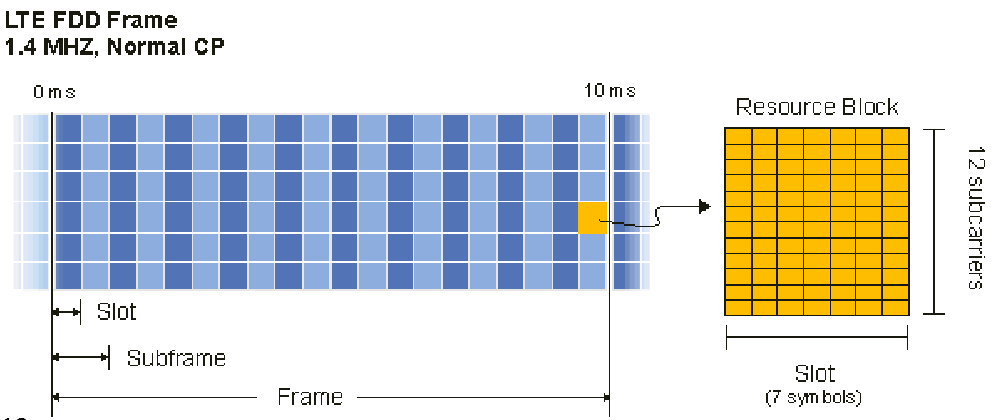
LTE (Cellular) V2X

Cellular based communication (Details in MKSA course)

- Pushed by 3GPP
- From Release 14 (2017) and onward
- Based on **Device-to-Device communication** (Proximity Services) 3GPP Release 12
- Exploits dedicated interface PC5 addressing high speed (**up to 250 km/h**) and high vehicle density
- Operates in **ITS 5.9 GHz band**
  - Short range <1km
- Communication with network in mobile **broadband licensed spectrum**
  - Long range >1 km

Physical layer

- OFDM
  - 1 ms (14 OFDM symbols)
  - 12 subcarriers (each 15 kHz)
- QPSK, 16 QAM



J. Springer, “Connectivity Standards in the Automotive Industry”, 5GAA, 2019.
3GPP TR 37.985. Overall Description of Radio Access Network (RAN) Aspects for Vehicle-to-Everything(V2X) Based on LTE and NR. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network.
http://rfmw.em.keysight.com/wireless/helpfiles/89600b/webhelp/subsystems/lte/content/lte_overview.htm

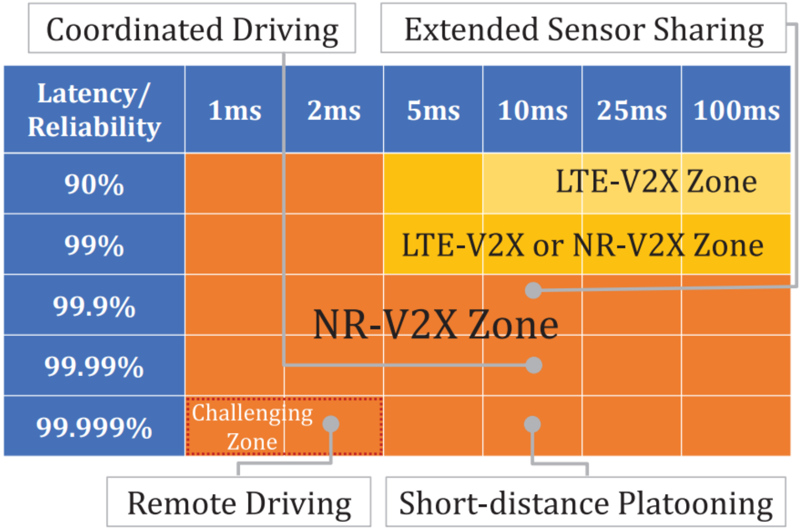
New Radio (NR) V2X

Cellular based communication (Details in MKSA course)

- 3GPP Release 16 (2020)
- Complements and supports internetworking with LTE V2X
- Enhanced URLLC
- 256QAM, network slicing, **short TTI**
- Precise positioning

PHY layer

- Up to 400 MHz bandwidth
- Numerology 15/30/60/120/240 kHz spacing
- LDPC => high reliability
- Polar codes (ultra-low decoding latency)
- mmWaves

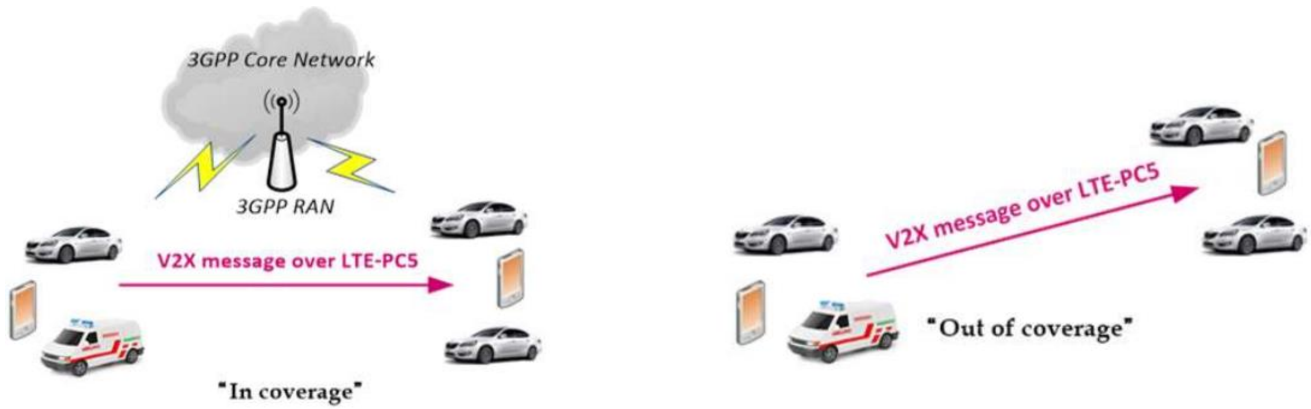


H. Bagheri, et. al., “5G NR-V2X: Towards connected and cooperative autonomous driving.”, *IEEE Communications Standards Magazine*, 2021.
3GPP TR 37.985. Overall Description of Radio Access Network (RAN) Aspects for Vehicle-to-Everything(V2X) Based on LTE and NR. 3rd Generation Partnership Project: Technical Specification Group Radio Access Network.

NR V2X sidelink

Sidelink channel

- Physical sidelink feedback channel (PSFCH)
  - New feedback channel for retransmissions and acquisition of channel state information
  - High reliability and low latency
- Aggregation of up to 16 carriers
- **Unicast and multicast support**
- Communication Modes
  - Mode 1 (**vehicle under BS coverage**) – configured and dynamic scheduling
    - Base station is informed about vehicle channel quality
  - Mode 2 (**vehicle without BS coverage**) – dynamic scheduling
    - Channel sensing by the vehicles



H. Bagheri, et. al., "5G NR-V2X: Towards connected and cooperative autonomous driving.", *arXiv preprint arXiv:2009.03638.*, 2020.

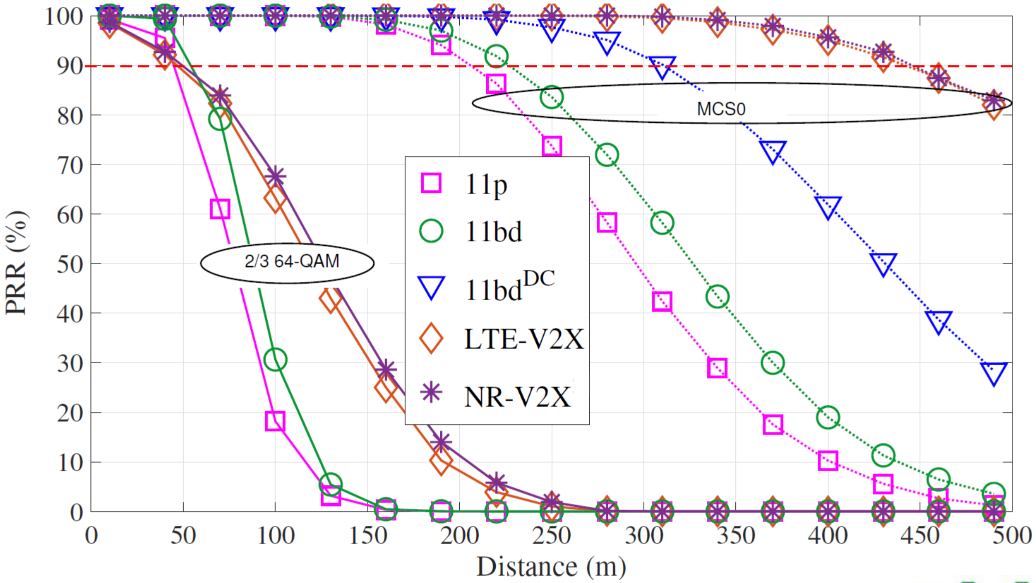
LTE V2X vs NR V2X

	MCS index	Modulation	Code Rate	100 bytes: Number of Resource Blocks	100 bytes: Data rate [Mbit/s]	100 bytes: Transmission latency [ms]	1500 bytes: Number of Resource Blocks	1500 bytes: Data rate [Mbit/s]	1500 bytes: Transmission latency [ms]
LTE V2X	0	QPSK	0,13	30	1,09	1	434	1,13	11
	6	QPSK	0,47	8	4,08	1	116	4,22	3
	7	QPSK	0,55	7	4,66	1	99	1,94	3
	10	QPSK	0,81	5	6,53	1	69	7,09	2
	13	16-QAM	0,52	4	8,16	1	53	9,24	2
	17	16-QAM	0,75	3	10,88	1	38	12,88	1
	21	64-QAM	0,65	2	16,32	1	28	17,49	1
	27	64-QAM	0,93	2	16,32	1	19	25,77	1

	MCS index	Modulation	Code Rate	100 bytes@NR 15 kHz: Number of Resource Blocks	100 bytes@NR 15 kHz: Data rate [Mbit/s]	100 bytes@NR 15 kHz: Transmission latency [ms]	1500 bytes@NR 60 kHz: Number of Resource Blocks	1500 bytes@NR 60 kHz: Data rate [Mbit/s]	1500 bytes@NR 60 kHz: Transmission latency [ms]
NR V2X	0	QPSK	0,12	23	1,41	0,75	337	1,70	8
	6	QPSK	0,44	7	4,63	0,25	91	6,31	2
	7	QPSK	0,51	6	5,40	0,25	78	7,36	2
	10	16-QAM	0,33	4	8,10	0,25	60	9,57	2
	13	16-QAM	0,48	3	10,79	0,25	42	13,67	1
	17	64-QAM	0,45	2	16,19	0,25	29	19,80	1
	21	64-QAM	0,65	2	16,19	0,25	21	27,34	1
	27	64-QAM	0,92	1	32,38	0,25	15	38,27	1

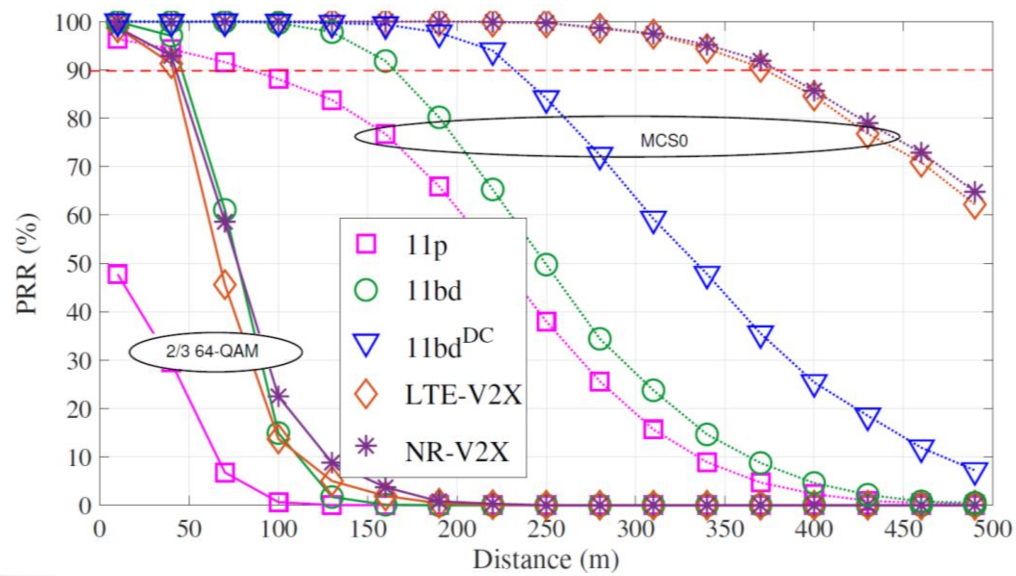
W. Anwar, N. Franchi, N. and G. Fettweis, "Physical layer evaluation of V2X communications technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11 bd, and IEEE 802.11 p.", *IEEE Vehicular Technology Conference (VTC2019-Fall),* IEEE, 2019.

Packet Reception Ratio (PRR)



Packet of 100 bytes

Packet of 1500 bytes



PRR – Packet Reception Ratio

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Questions?

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