U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

CISTER – Research Centre in
Real-Time & Embedded Computing Systems

Designing Vehicular Applications as Networked Multi-Agent Systems

Saeid Sabominiri / Pedro Santos

PDEEC - Special Topics / FEUP - U.Porto

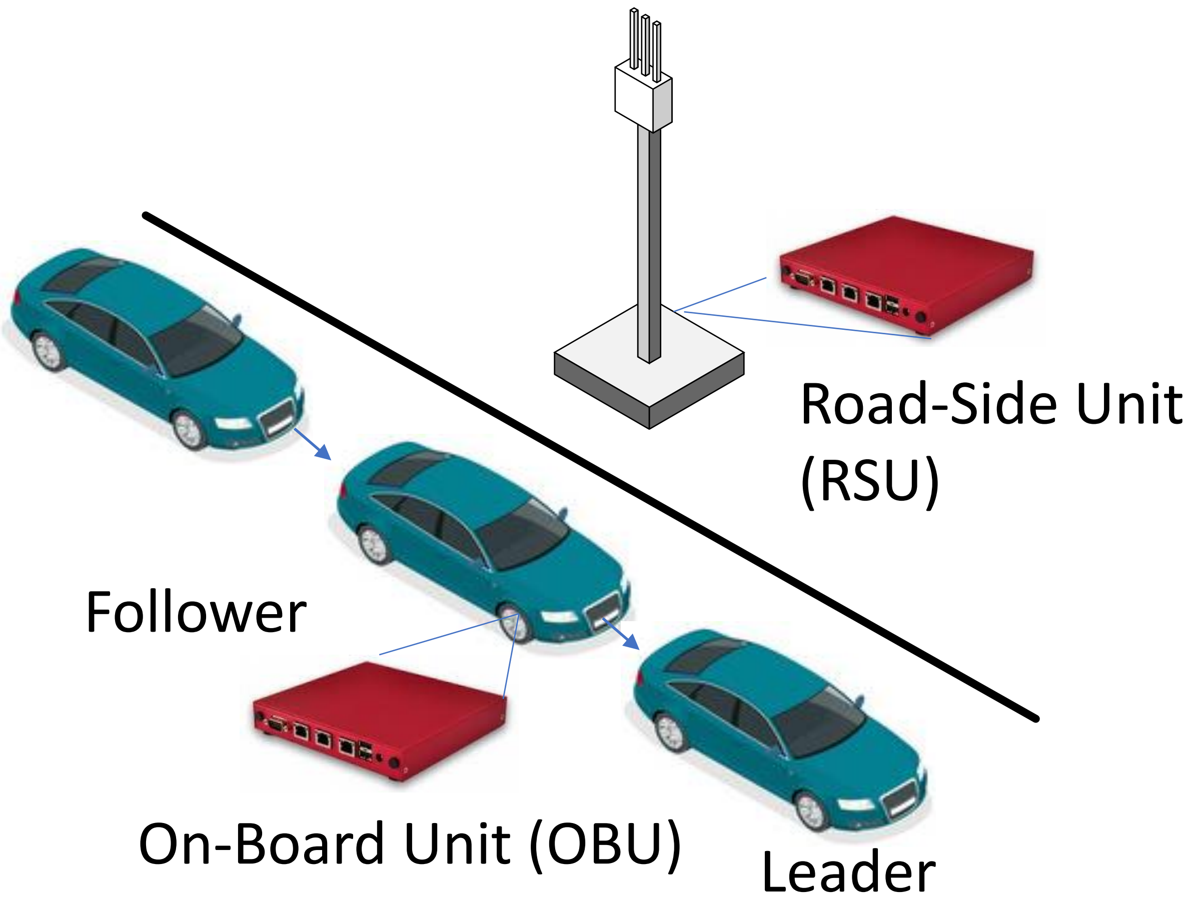
2020/2021

Special Topics & Proposed Topic

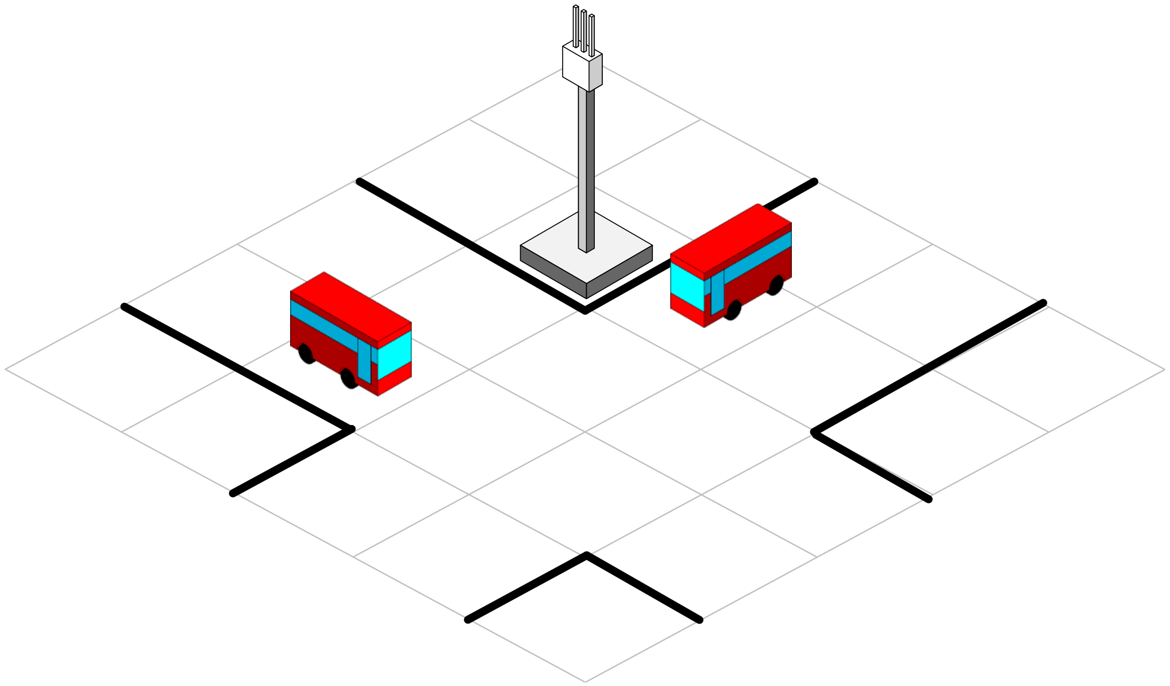
- Special Topics:
  - Planned Individual Study (PIS) on a scientific topic not addressed in courses offered by PDEEC but considered relevant for the student's thesis. PIS must be supervised by a professor or a PhD researcher. **The final deliverable for PIS is a document reporting the original work** developed by the student during this study. Co-authorship in the context of this study in not allowed.
- Proposed topic:
  - **Designing Vehicular Applications as Networked Multi-Agent Systems**
  - Communication and MAS approaches are relevant in vehicular scenarios
  - Examples:
    - Platooning
    - Intersection
    - Lane merging

Examples

Platooning Application



Intersection Scenario



Course Structure

- 12 ECTS; 1 ECTS = 28 hours → Total: 336 hours (over 10-16 weeks ? → 12 weeks)
- Report: due by June 20
- Proposed Components:
  - Literature review (120 hours)
  - Project (180 hours)

- Two evaluation elements
  - Report on technological landscape of vehicular communications and MAS
  - Report of the developed project on simulation of MAS in a platooning context
- Interaction
  - Weekly contact hours to discuss articles and project progression

Calendar

Week	Date	Lectures Content		Literature Review (120 hours)	Project steps (180 hours)
		Topic			
0			Introduction		
1	31/03/2021	T1	Building Blocks for Vehicular Applications	Paper review	
2	08/04/2021	T2	Wireless Propagation	Paper review (to include in report)	Define scenario and simulation tools
3	15/04/2021	T3	Communication Arch. and Open V2X Standards	Paper review (to include in report)	Define scenario and simulation tools
4	22/04/2021	-	Discussion on literature and project		Setup of simulation scenario
5	29/04/2021	T4	Cellular Technological Ecosystem	Paper review (to include in report)	Setup of simulation scenario
6	06/05/2021	T5	Simulation Tools	Paper review	Agent modelling
7	13/05/2021	T6	Co-existence & Other Technologies	Paper review	Agent modelling
8	20/05/2021		Project Discussion	Discussion	Communication protocols
9	27/05/2021		Project Discussion	Discussion	Communication protocols
10	02/06/2021 (Wed)		Project Discussion	Discussion	Application performance metrics
11	10/06/2021		Project Discussion	Discussion	Application performance metrics
12	17/06/2021		Review report	Discussion	Report

Background & Logistics

- Recommended Literature
  - Networking
    - Andrew S. Tanenbaum and David J. Wetherall. 2010. **Computer Networks** (5th. ed.). Prentice Hall Press, USA.
    - Slides by I. Radovanovic
  - Multi-agents
    - Michael Wooldridge; An introduction to multiagent systems. ISBN: 978-0-470-51946-2 (2nd Edition, 2009).
  - Machine Learning
    - Christopher M. Bishop. 2006. Pattern Recognition and Machine Learning (Information Science and Statistics). Springer-Verlag, Berlin, Heidelberg.
- Logistics
  - Conference tool - Zoom
  - Shared folder – Gdrive
  - Meeting time : Thursday 2:30pm Tehran time / 11am Lisbon time

Literature Review

Report on Literature

- Components
  - Wireless Technologies – Literature review
  - Multi-Agent Systems – Slide set – Due by 26/05/2021
- Literature Review
  - Describe each paper you read on the topic – 1 to 2 paragraphs
  - Write your view on the selected topics – 3 to 5 paragraphs
  - Topics to address
    - Wireless Propagation
    - Open V2X Standards
    - Cellular Technological Ecosystem
  - Structure of document
    - Introduction
    - Section per topic
    - Conclusion
- Slide set

Project

Outline for Project

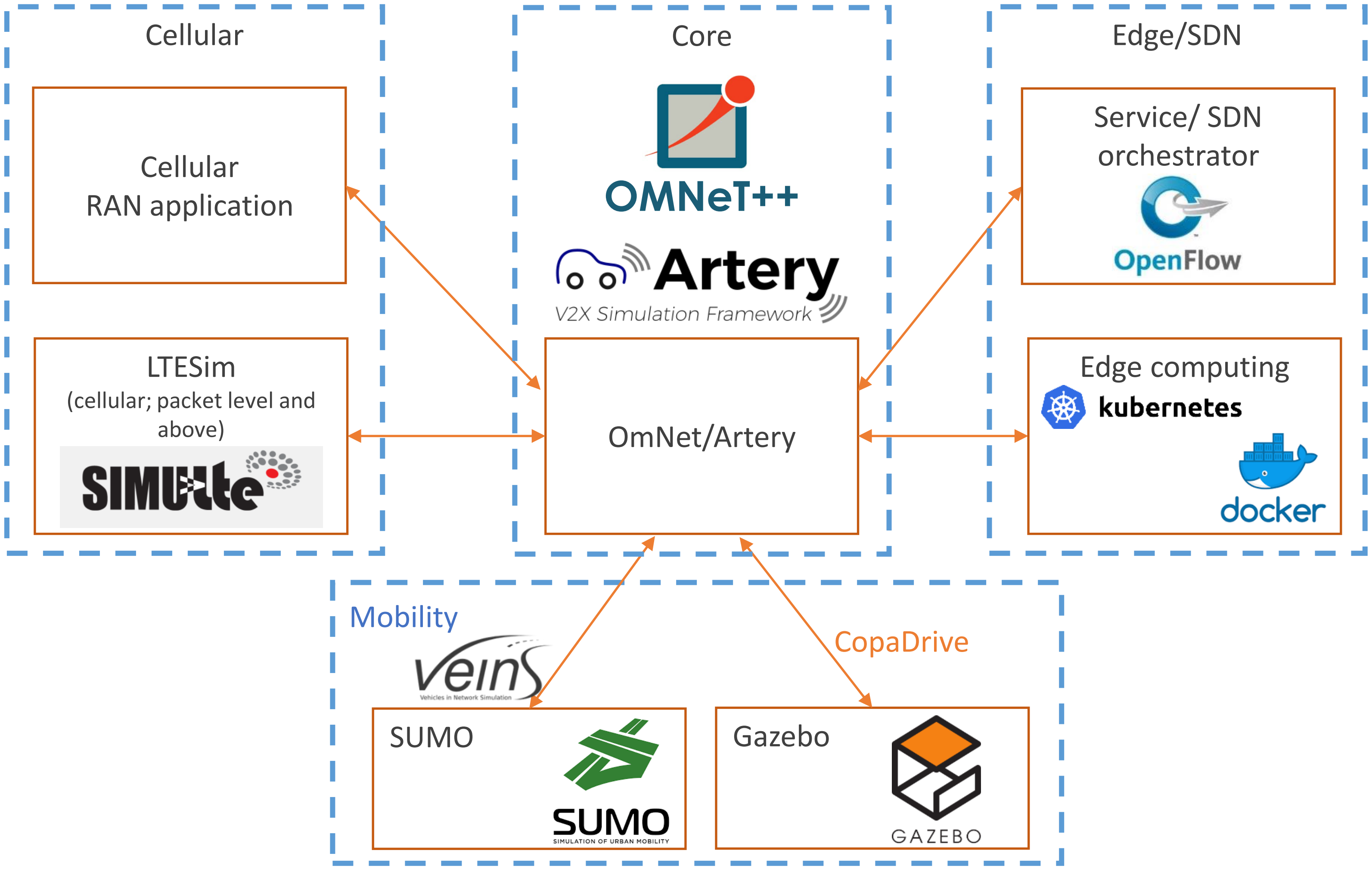
- Goal
  - Develop simulation of vehicular scenario with vehicle-to-vehicle and to-infrastructure (V2V/V2I) communication
  - Vehicles and infrastructure modelled as agents
  - Implement and evaluate vehicular application involving infrastructure
- Steps:
  1. Define scenario and simulation tools
  2. Setup of simulation scenario
  3. Agent modelling
  4. Communication protocols
  5. Application performance metrics
  6. Report

Detailed Workplan for Project

Stages:

1. Define scenario and simulation tools
    1. Identify vehicular application, design scenario and describe multi-agent behaviour
    2. Identify technologies – IEEE 802.11p and/or cellular – and simulation technologies to use – OMNeT++, SUMO or Gazebo, Artery)
2. Setup of simulation scenario (2-3)
    - Setup simulation environment
    - Set up mobility or control model of vehicles
    1. Test sending/reception of messages
3. Agent modelling (1-2)
    - Code agent behaviour (C++)
4. Communication protocols (1-2)
    - Map information to be conveyed between agents into communication protocol format
5. Performance metrics (2-4)
    - Identify performance metrics of application or communication
    - Design experiments
    - Collect logs & plot metrics
6. Write report (1-2)

Simulation Tools



Stage 1: Scenario Description

Setting	Intersection, highway, etc.
Vehicular application	Emergency breaking, traffic light coordination, etc.
Requirements on communication layer	End-to-end transmission time
Agents and their behaviour	Mobility of individual vehicles; decision-making processes
Metrics of performance of application or communications	How often
…	

Project Report

- Structure
  - Introduction
  - Scenario and Proposed Application
  - Implementation
  - Evaluation
  - Conclusion

T1. Building Blocks for Vehicular Applications

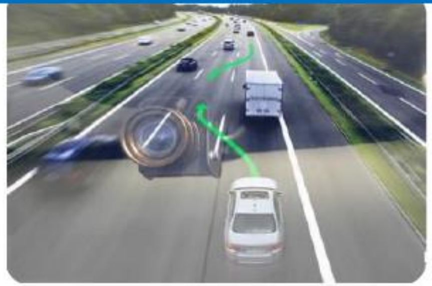
1. Building Blocks for Vehicular Applications

- Building Blocks:
  - Sensorization
  - Intelligence
  - Communication
- Relevant organizations in the area:
  - 5GAA – https://5gaa.org/
  - 5G-ACIA – https://www.5g-acia.org/
  - Projects – https://platooningensemble.eu/

Use-Cases & Requirements for Applications

Uses cases for autonomous driving applications (SA1 TR22.886)

Vehicle Platooning


Cooperative Operation, Sensor sharing


Remote Driving


Advanced Driving

NR-V2X requirements for autonomous driving (SA1 TS22.186)

Use Cases	E2E latency (ms)	Reliability (%)	Data rate (Mbps)
Vehicle Platooning	10	99.99	65
Advanced Driving	3	99.999	53
Extended Sensors	3	99.999	1000
Remote Driving	5	99.999	UL:25, DL:1

	Lateral (m)	Longitudinal (m)
Positioning Accuracy	0.1	0.5

Note: 5GAA may adjust the above requirements according to inputs from car OEMs.

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To Read & Discuss

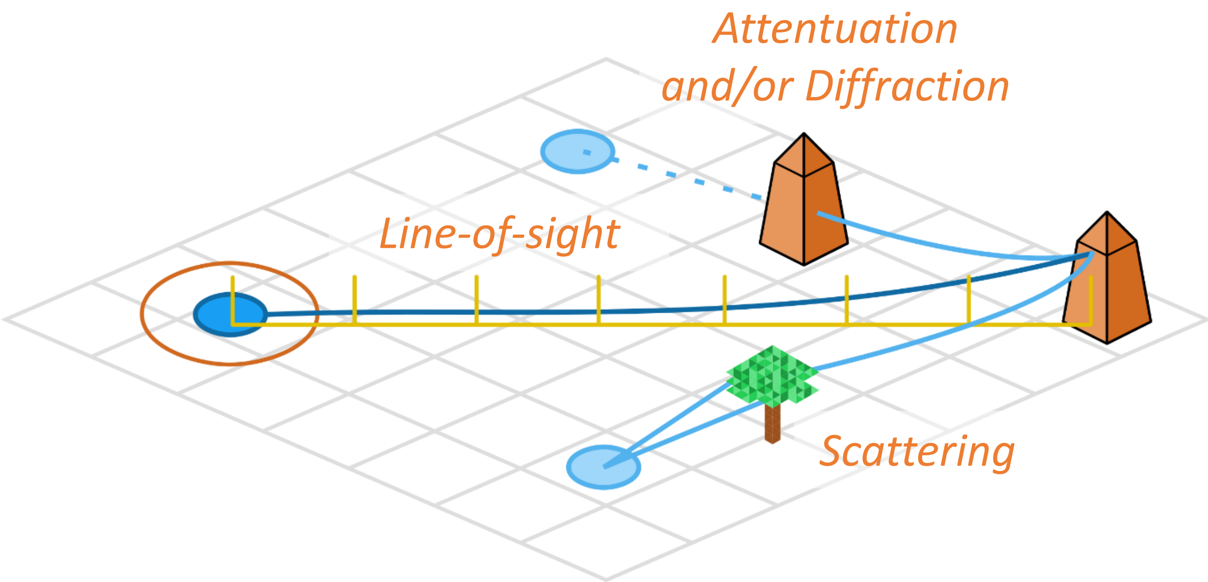
- E. V. Filho et al., “Towards a Cooperative Robotic Platooning Testbed”
- B. Vieira et al. “COPADRIVe - A Realistic Simulation Framework for Cooperative Autonomous Driving Applications”
- 5GAA, “C-V2X Use Cases Volume II: Examples and Service Level Requirements”
- 5G-PPP, “5G Automotive Vision”

T2. Wireless Propagation

Propagation Modelling

$$\rho_{[\text{dBm}]}(d) = \underbrace{\rho_0 - 10\,\alpha\,\log\left(\frac{d}{d_0}\right)}_{\text{Deterministic component}} + \underbrace{X_\rho, \qquad X_\rho \sim N_{\sigma_\rho}}_{\text{Stochastic component}}$$

- Components of a propagation model
  - **Large-scale Propagation**
    - Typically deterministic
  - **Small-scale Fading**
    - Typically stochastic
- Classes of Propagation Models
  - **Parametric:** parameter values already available
    - Free-space path loss (FSPL)
    - Two-ray ground reflection model
    - …
  - **Empirical:** drawn from measurements
    - Empirical log-distance path loss



Propagation Modelling

$$\mathrm{FSPL} = \left(\frac{4\pi d f}{c}\right)^2$$

$$\mathrm{FSPL(dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)$$

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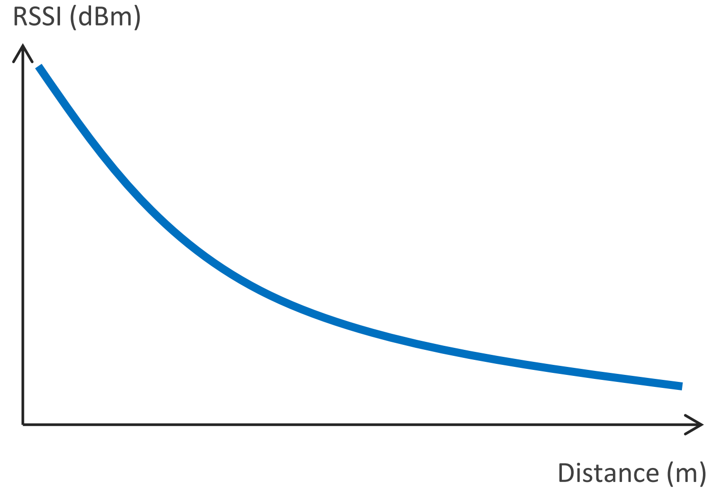

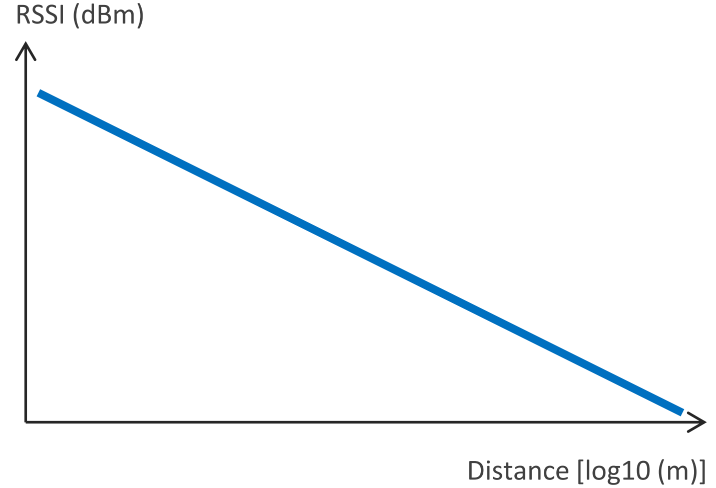

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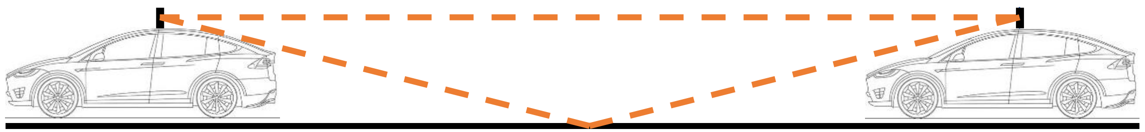

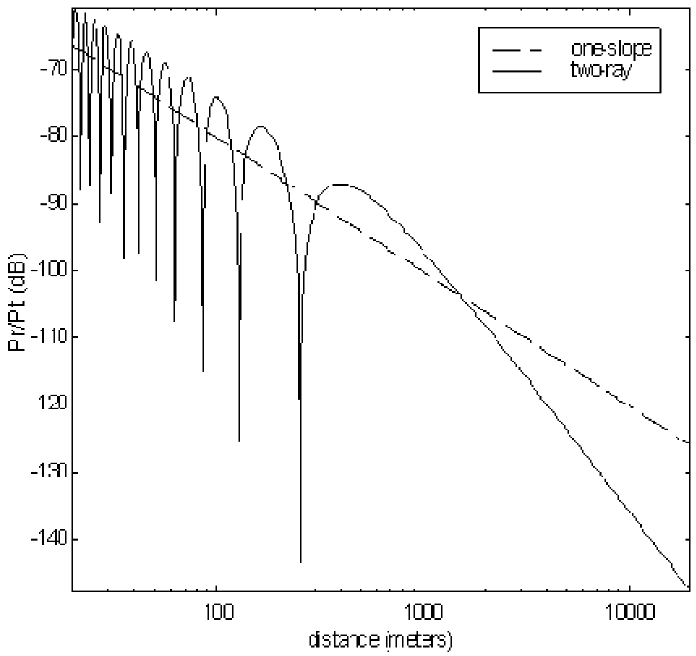

Thomas Schwengler. Wireless and Cellular Communications. http://morse.colorado.edu/~tlen5510/text/classwebch3.html

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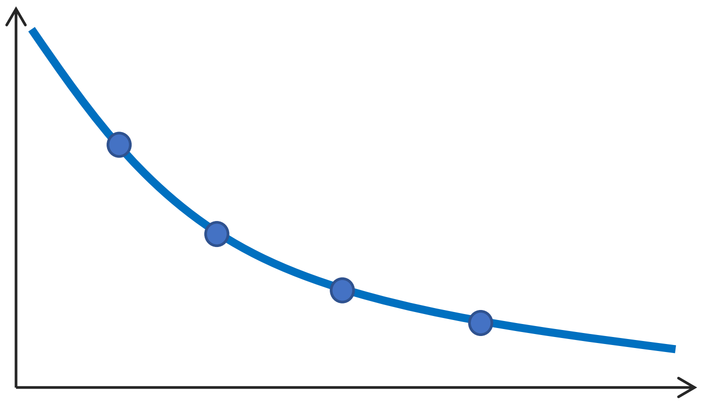
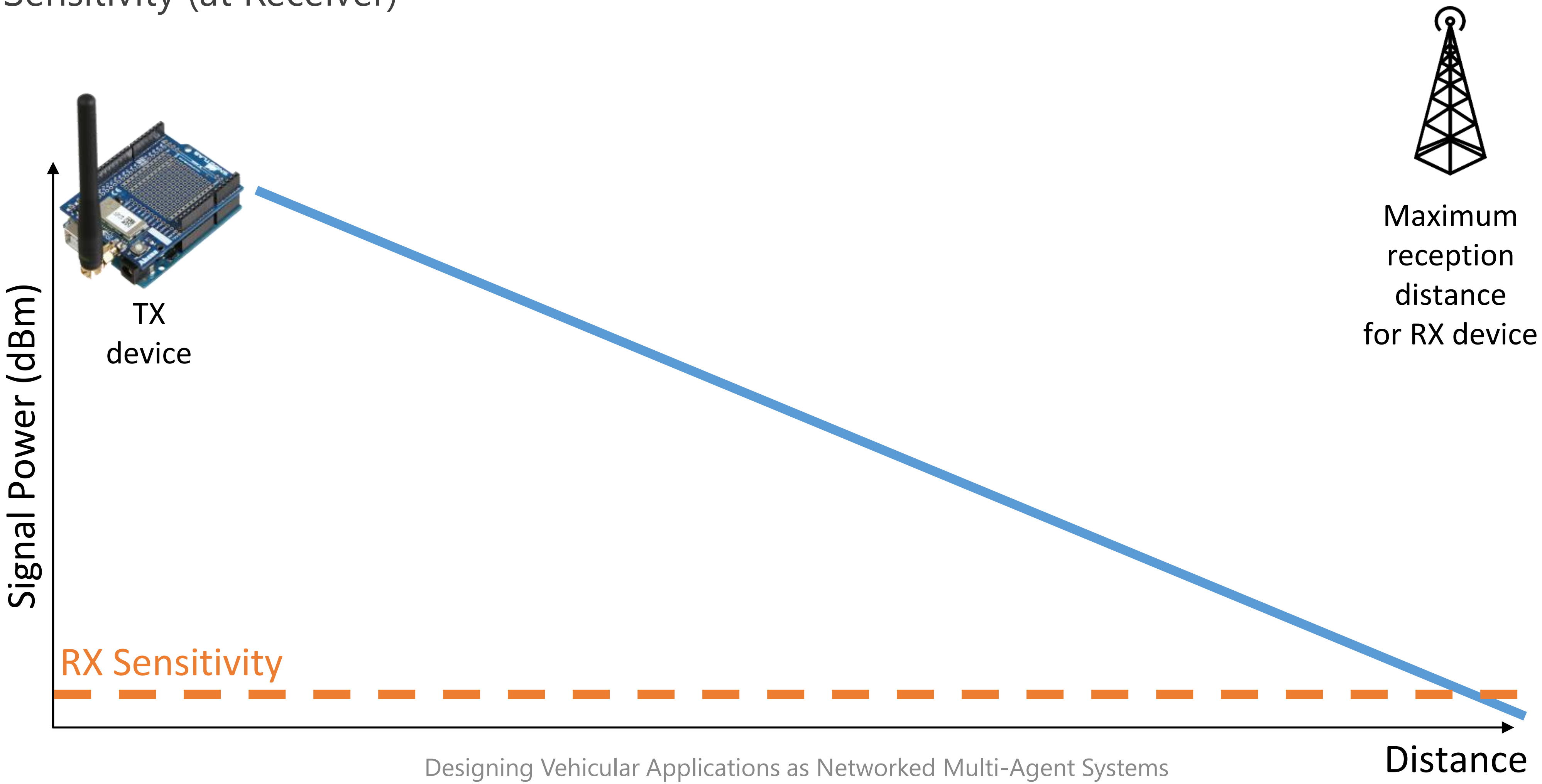


Link Budget

- Transmit power (Transmitter)
- Sensitivity (at Receiver)



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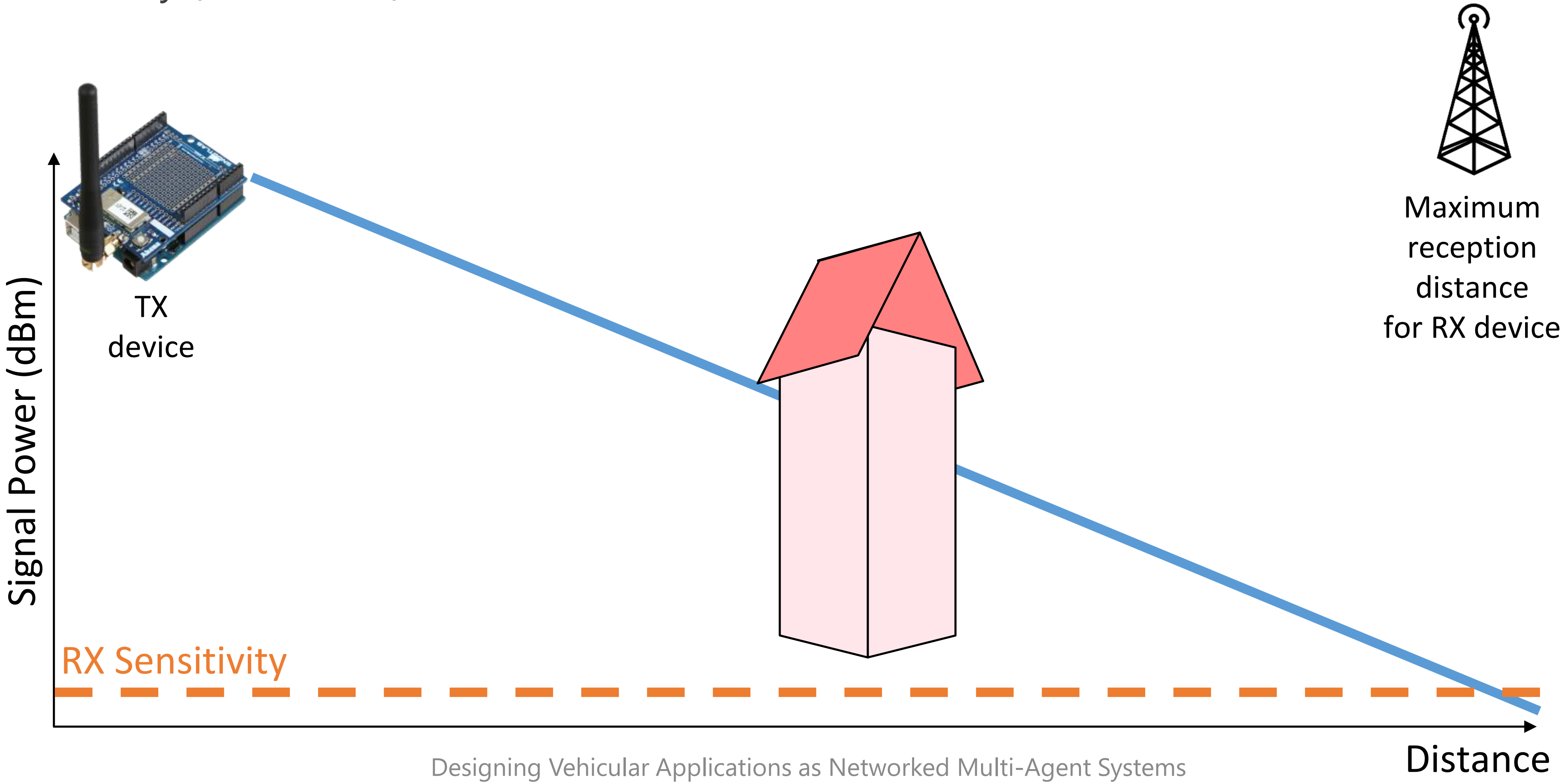

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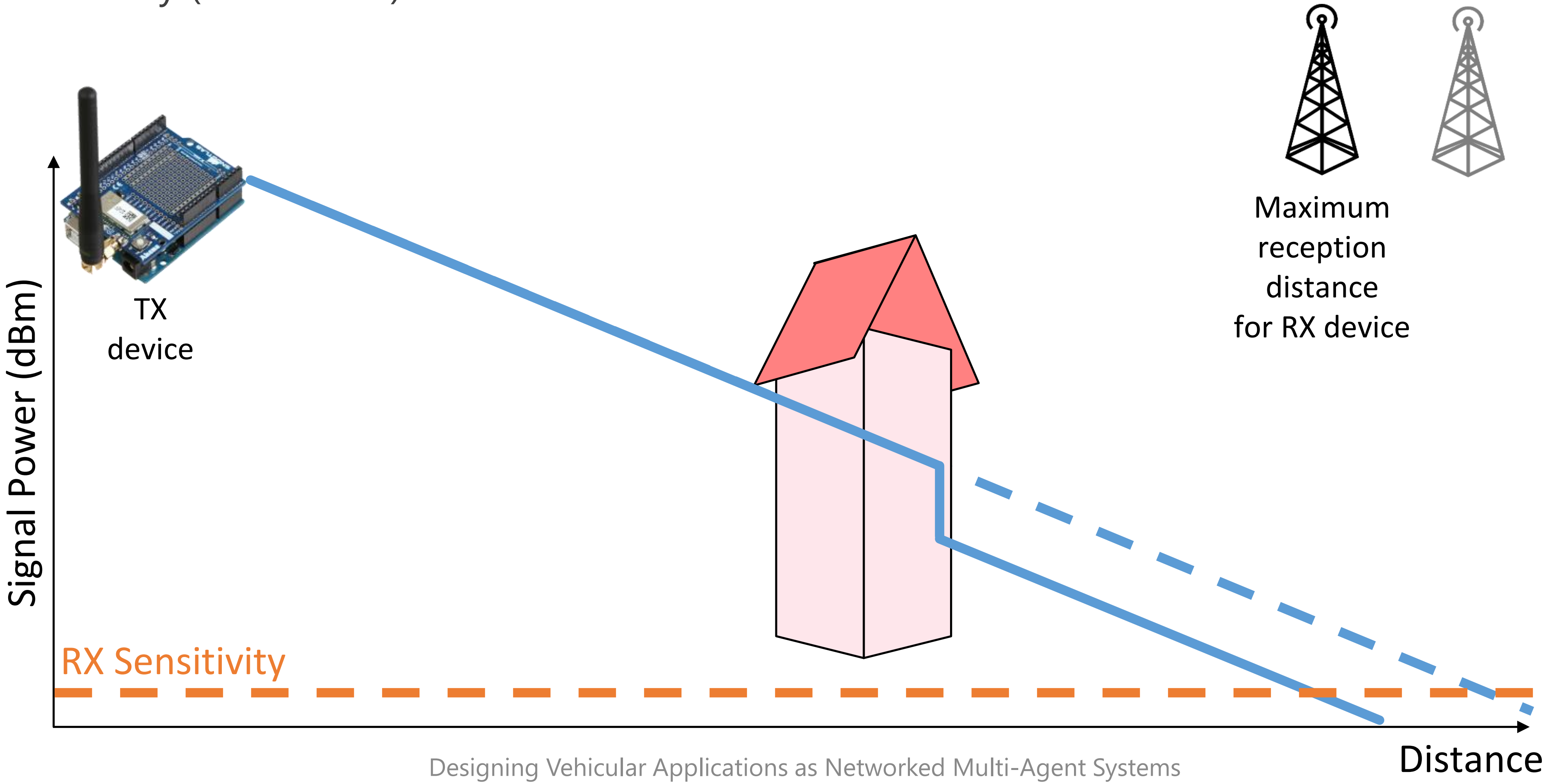

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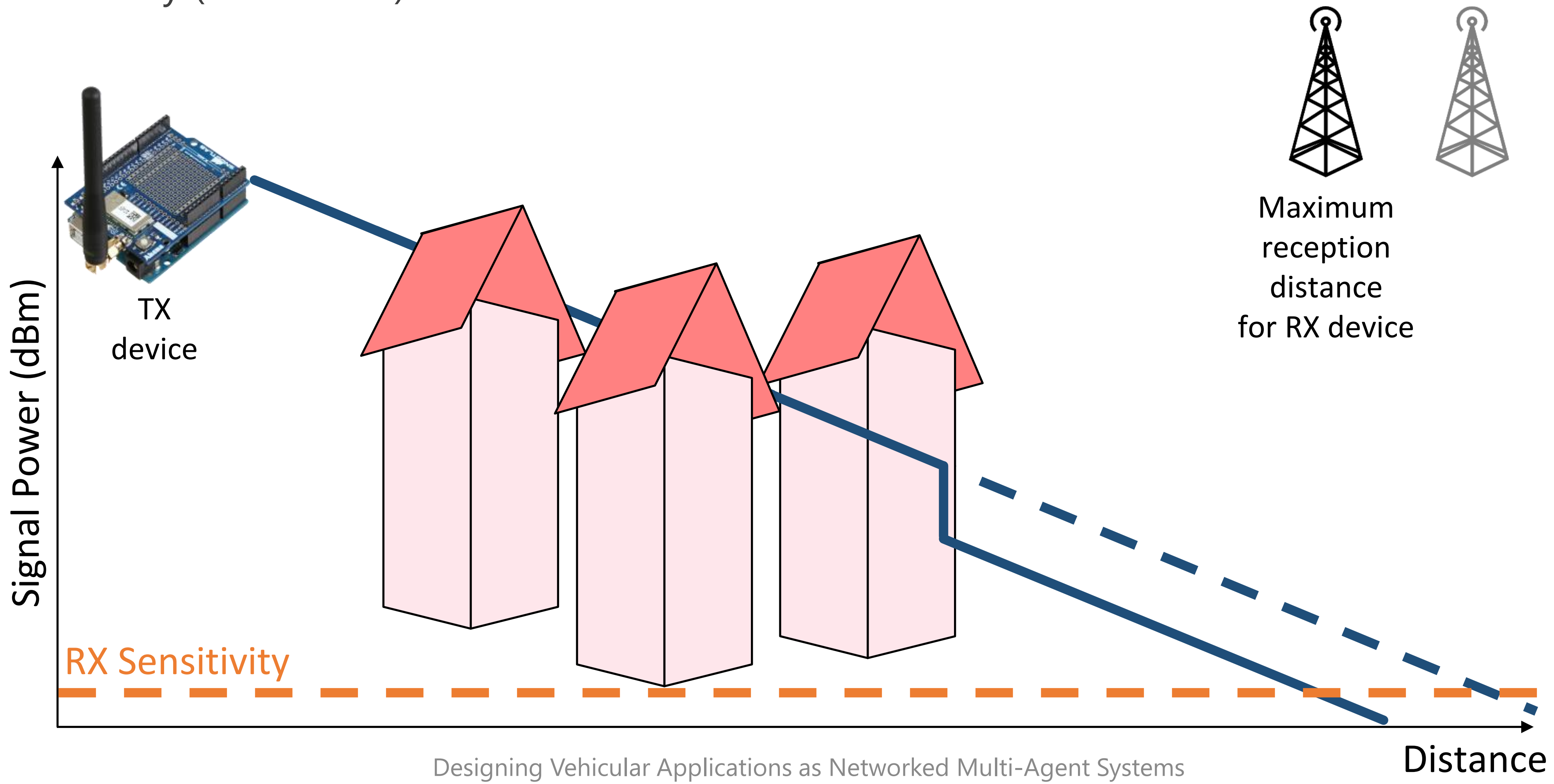

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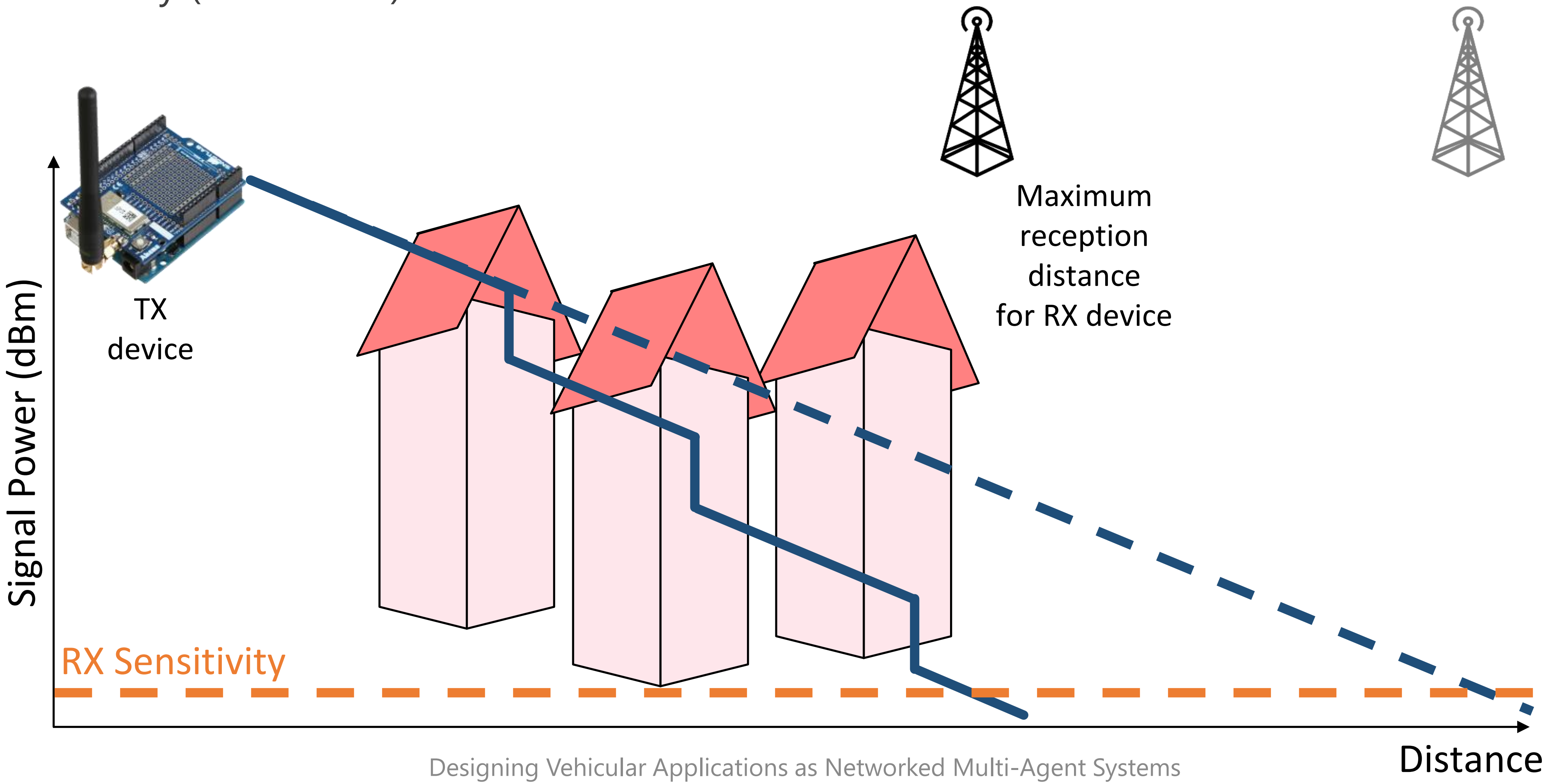


To Read & Discuss

- W.Viriyasitavat et al., “Vehicular Communications Survey and Challenges of Channel and Propagation Models”
- R.Meireles et al., “Experimental study on the impact of vehicular obstructions in VANETs”

T3. Communication Architectures & Open V2X Standards

15/04/2021

Network Scale and Communication Architecture

- Depending on the communication technology, networks can operate at various scales

2 meters	Up to 300 meters to 1km	>1km
Body Area Networks (BAN) Personal Area Networks (PAN) Bluetooth *Ad hoc or Master-Slave*	Local Area Networks (LAN) IEEE 802.11g/n/ac/ax (WiFi) **– 20dBm=100mW** IEEE 802.11p (DSRC) **– 23dBm = 200mW** *Typically Master-Slave, also Ad hoc*	Wide Area Networks (WAN) LTE, SigFox, LoRa, NB-IoT, WiMax *Asymmetric*

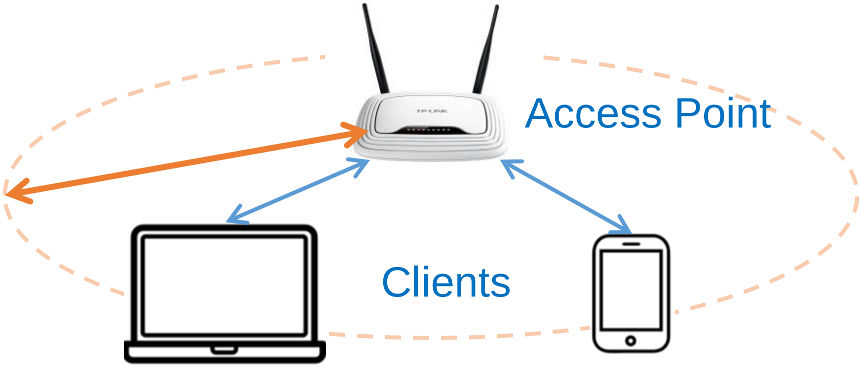
- Communication architectures can take typically one of shapes
  - **Symmetric**: both transmitter and receiver have similar capabilities (similar transmit power and sensitivity)
    - Typically found in small-to medium scale networks (BAN, LAN)
  - **Assymmetric**: one of the transceivers is more powerful than the other (higher transmit power and higher sensitivity)
    - Typical of cellular architectures (WAN)

Technologies of LAN and WAN

LAN

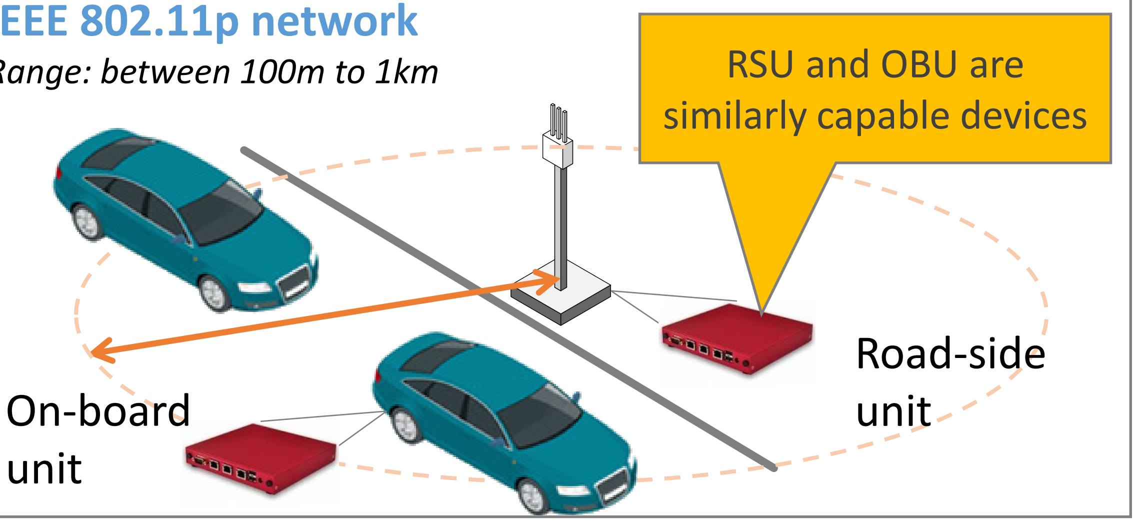
IEEE 802.11n/ac/ax network

Range: between 1m to 300m



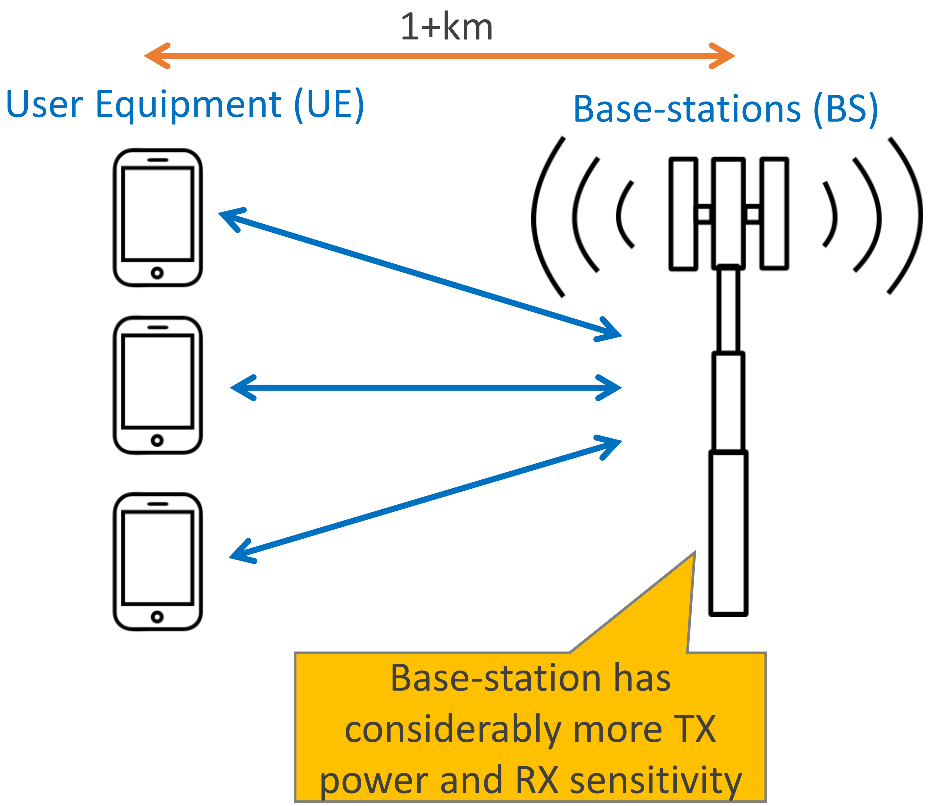
IEEE 802.11p network

Range: between 100m to 1km



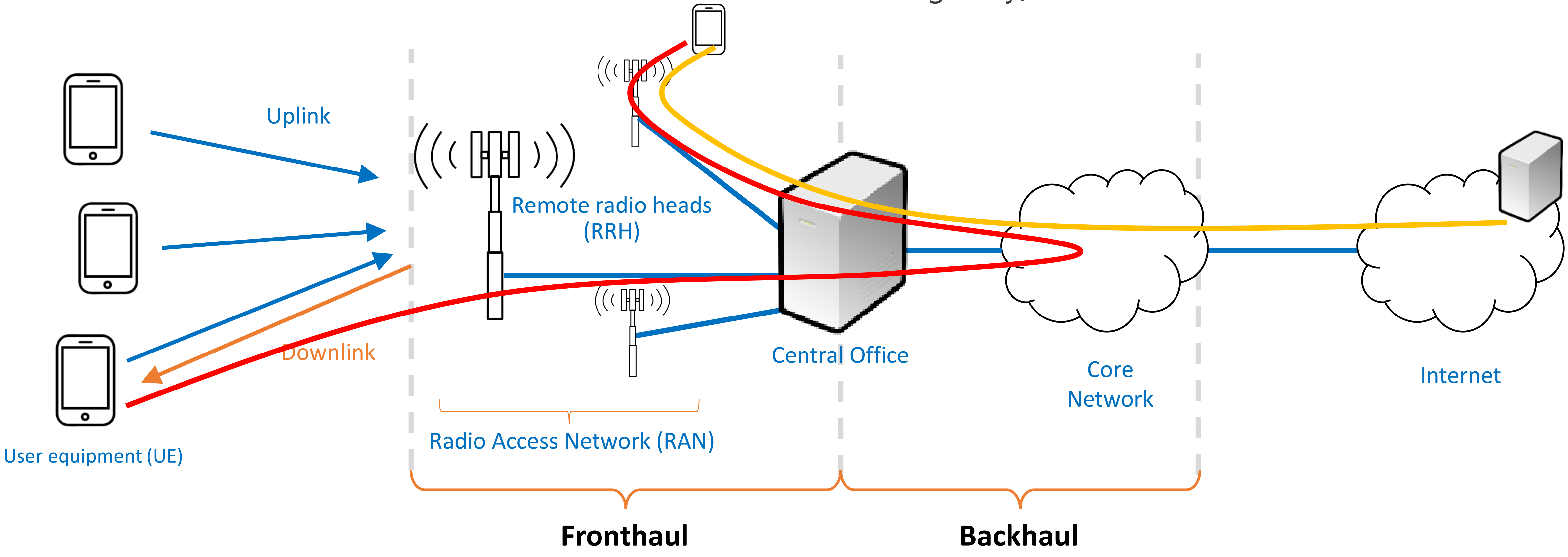
WAN

- **Cellular Technologies:** 2G/GSM, 3G/UMTS, 4G/LTE, 5G/NR, NB-IoT, LoRa, SigFox
- **WiMax** (IEEE 802.16)



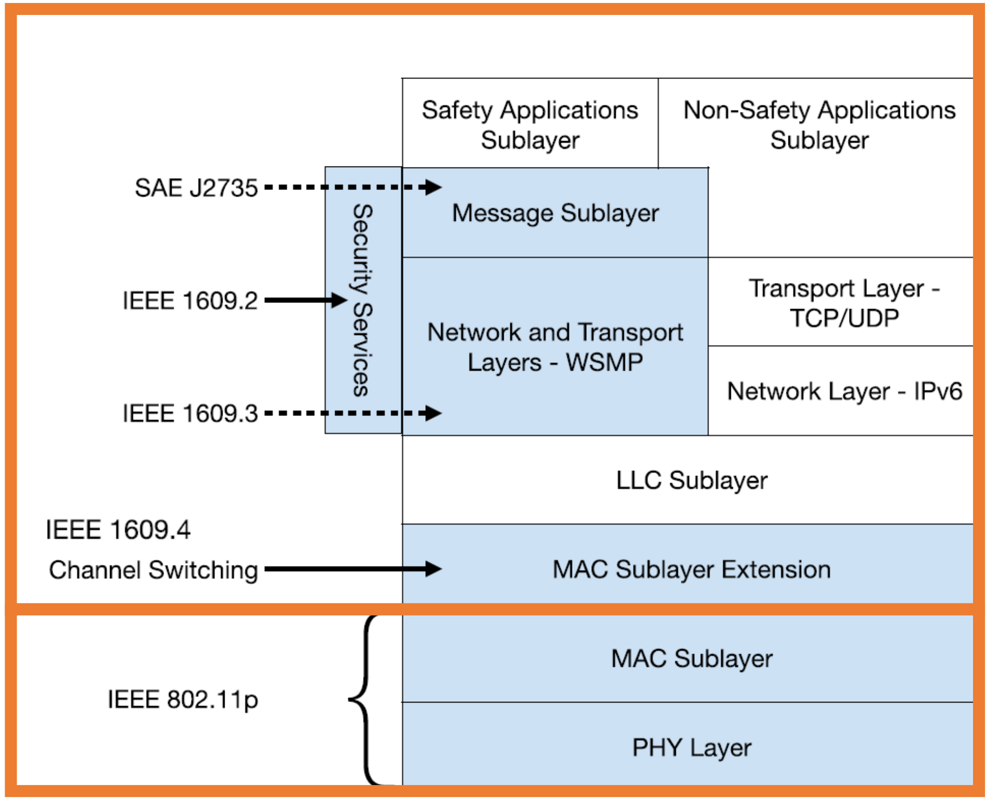
Cellular Architectures and Asymmetric

- The most prominent example of Wide-Area Networks (WAN) are **cellular** networks (and thus sometimes the terms WAN and cellular are used interchangeably)



Open V2X Standards (Symmetric)

- PHY/MAC layer
  - **IEEE 802.11p:** A variant of the IEEE 802.11 wireless for vehicular communications
  - Dedicated Short-Range Communication (DSRC)
- Upper and Service Layers
  - Several service stacks have been developed on top of the PHY/MAC layers specified by IEEE 802.11p
  - An example of such services are beacon messages broadcast periodically to all neighbours
- There are regional variants of the service stacks:
  - **ETSI ITS G5:** A service stack devised at Europe that builds on top of IEEE 802.11p
    - Periodic messages: Cooperative Awareness Messages (CAM)
  - **WAVE Wireless Access in Vehicular Environments (USA):** U.S. service stack the U.S. that builds on top of 802.11p
    - Periodic messages: Basic Safety Messages (BSM)
  - **ARIB T-101 (Japan):** Japanese service stack; operates on 700MHz



S. Gao, A. Lim, and D. Bevly, "An empirical study of DSRC V2V performance in truck platooning scenarios," *Digital Communications and Networks*, vol. 2, no. 4, pp. 233–244, Nov. 2016, doi: 10.1016/j.dcan.2016.10.003.

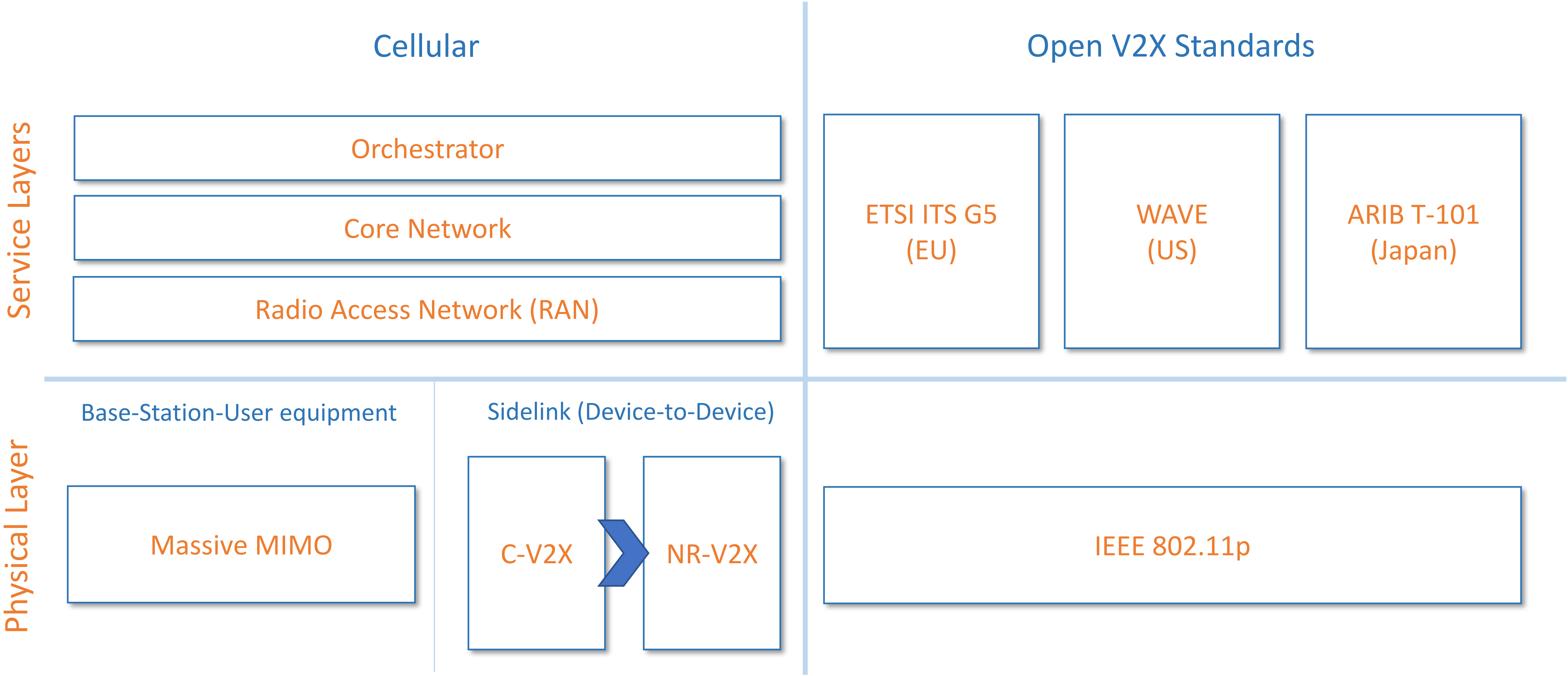
To Read & Discuss

- F. Arena et al., “A Review on IEEE 802.11p for Intelligent Transportation Systems”
- F.Bai et al., "Toward Understanding Characteristics of Dedicated Short Range Communications (DSRC) From a Perspective of Vehicular Network Engineers“
- S. Gao et al., "An-empirical-study-of-DSRC-V2V-performance-in-truck-platooning"

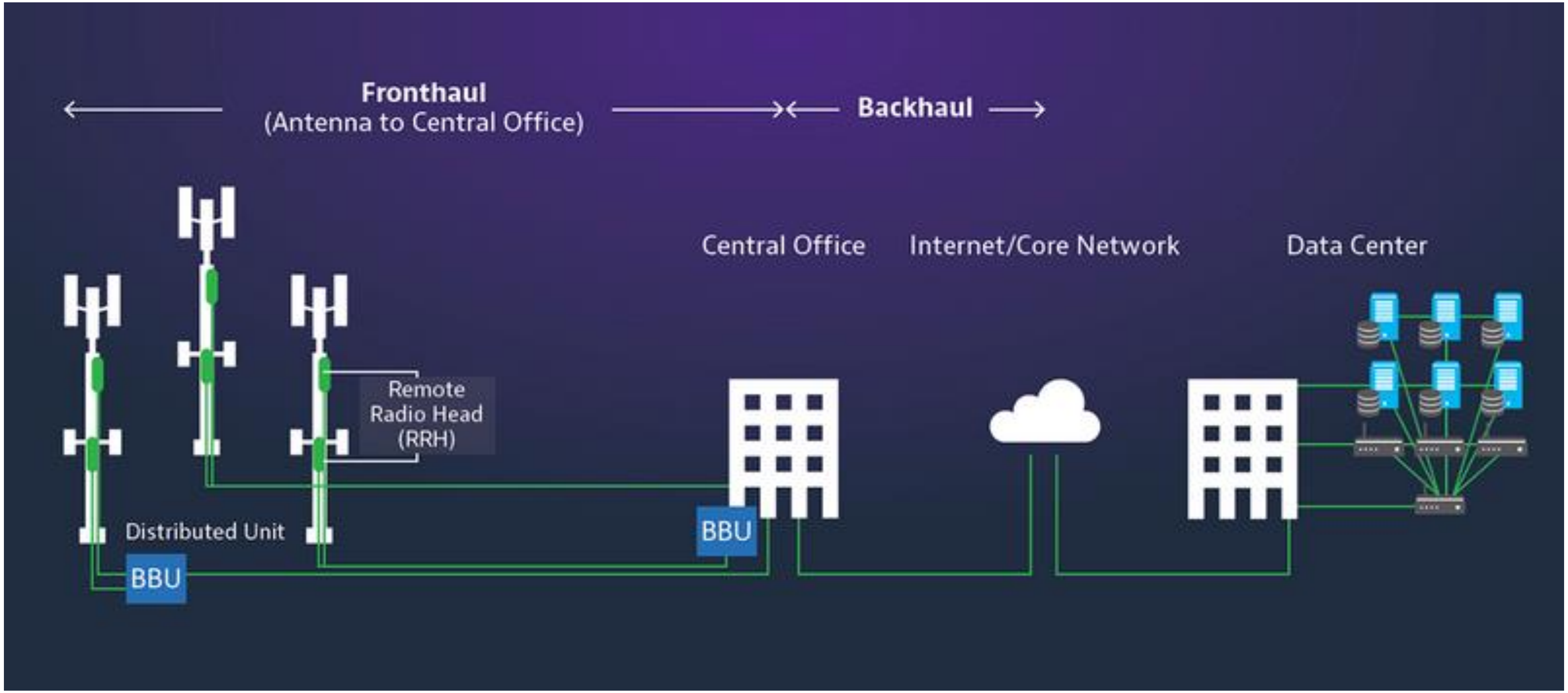
T4. Cellular Technologies Ecosystem

02/05/2021

Technological landscape on vehicular communications



Cellular Architectures



5. Cellular Technologies

- Technology development for cellular systems
  - Driven by 3GPP – a standardization body that includes most OEMs and operators
  - Cellular specifications are formalized in Releases – currently Release 16
- Massive MIMO
  - Emerging technology
- C-V2X / NR-V2X
  - In cellular terminology, a 'sidelink' that complements
- Cellular Service Stack

A GLOBAL INITIATIVE

OEMs: HUAWEI, NOKIA, ERICSSON

Telcos: altice, NOS, vodafone

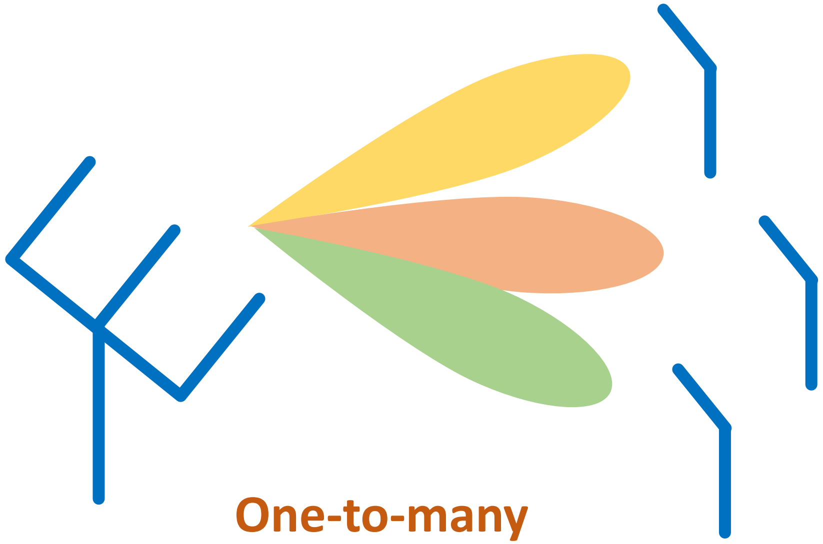
Commercial brand	Name of technical specification	Stand. Body	Time-frame
1G	N/A	N/A	1980
2G	Global System for Mobile Communications **(GSM)**	ETSI	1990
3G	Universal Media Telecom-munications System **(UMTS)**	3GPP	2000
4G	Long-Term Evolution **(LTE)**	3GPP	2010
5G	New Radio **(NR)**	3GPP	2020

MIMO & Massive MIMO

- **Multiple-Input Multiple-Output** is a well-established communication technology, used by both by open LAN standards and cellular specification
- Parameters in the system
  - Number of antennas per device – **N**
  - Number of users either RX or TX) – **M**
- There can be various combinations:
  - 1 TX with N antennas, 1 RX with N antennas (device-to-device)
  - 1 TX with N antennas, M RX with 1 antenna each (one-to-many)
  - M TX with 1 antennas; 1 RX with N antennas (many-to-one)
  - M TX with N antennas; M RX with N antennas (many-to-many)

A few examples of MIMO application:

One-to-one



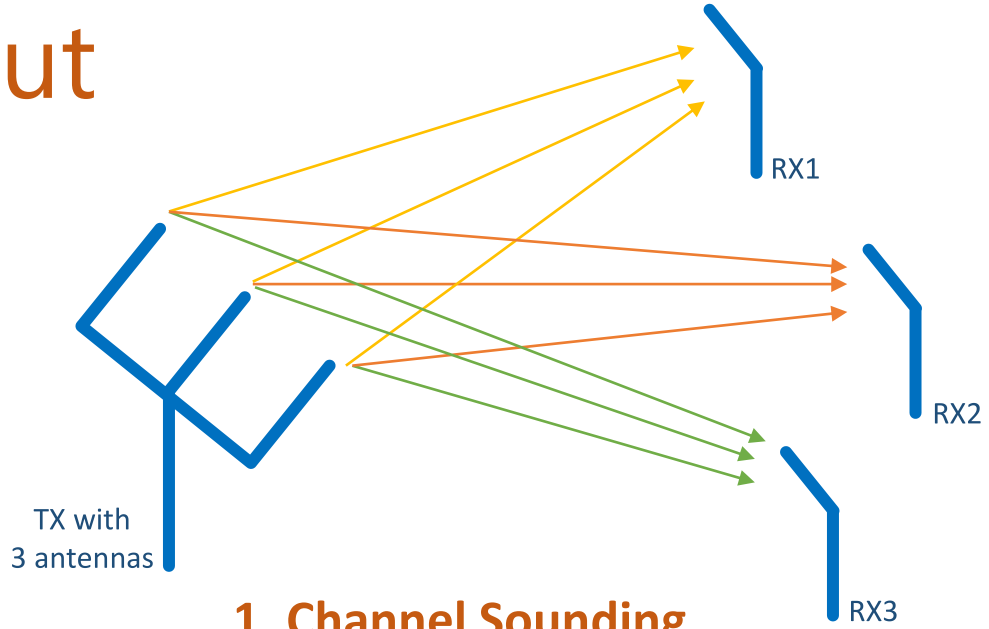
One-to-many

Multiple-Input Multiple Output

- Let's take the situation of 1 TX with 3 antennas, M RX with 1 antenna each (one-to-many)
- Channels between each TX antenna and each one of RX antennas are independent, i.e., it affects the transmitted signal in a different way.
- This leads to a matrix system that can be solved: $\boldsymbol{y} = \boldsymbol{Hx}$

$$\underbrace{\begin{bmatrix} Y_{1,3} \\ Y_{2,3} \\ Y_{3,3} \end{bmatrix}}_{\textit{Signal Received}} = \underbrace{\begin{bmatrix} H_{1,1} H_{1,2} H_{1,3} \\ H_{2,1} H_{2,2} H_{2,3} \\ H_{3,1} H_{3,2} H_{3,3} \end{bmatrix}}_{\textit{Channel matrix}} \underbrace{\begin{bmatrix} X_{1,3} \\ X_{2,3} \\ X_{3,3} \end{bmatrix}}_{\textit{Signal Transmitted}}$$

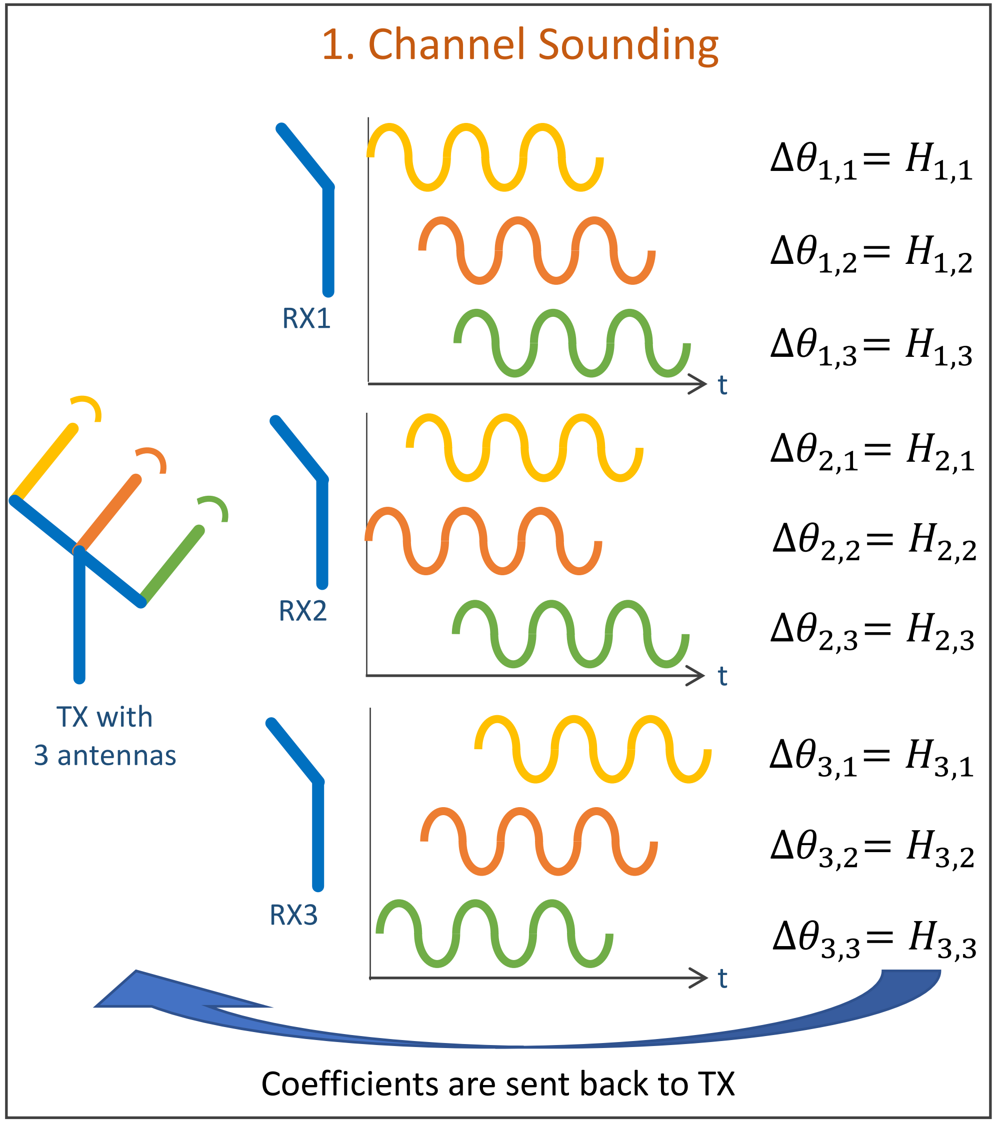
- Although counter-intuitive, it is in fact IMPERATIVE that the channels are very different! Otherwise, the channel matrix may not be invertible, and then the system is not solvable!
- The TX can learn the channels to each RX through a mechanism named Channel Sounding. Knowing the channel matrix , the TX can transmit to all receivers simultaneously. $\boldsymbol{m} = \boldsymbol{H}^{(-1)}\boldsymbol{H}\ \boldsymbol{m}$

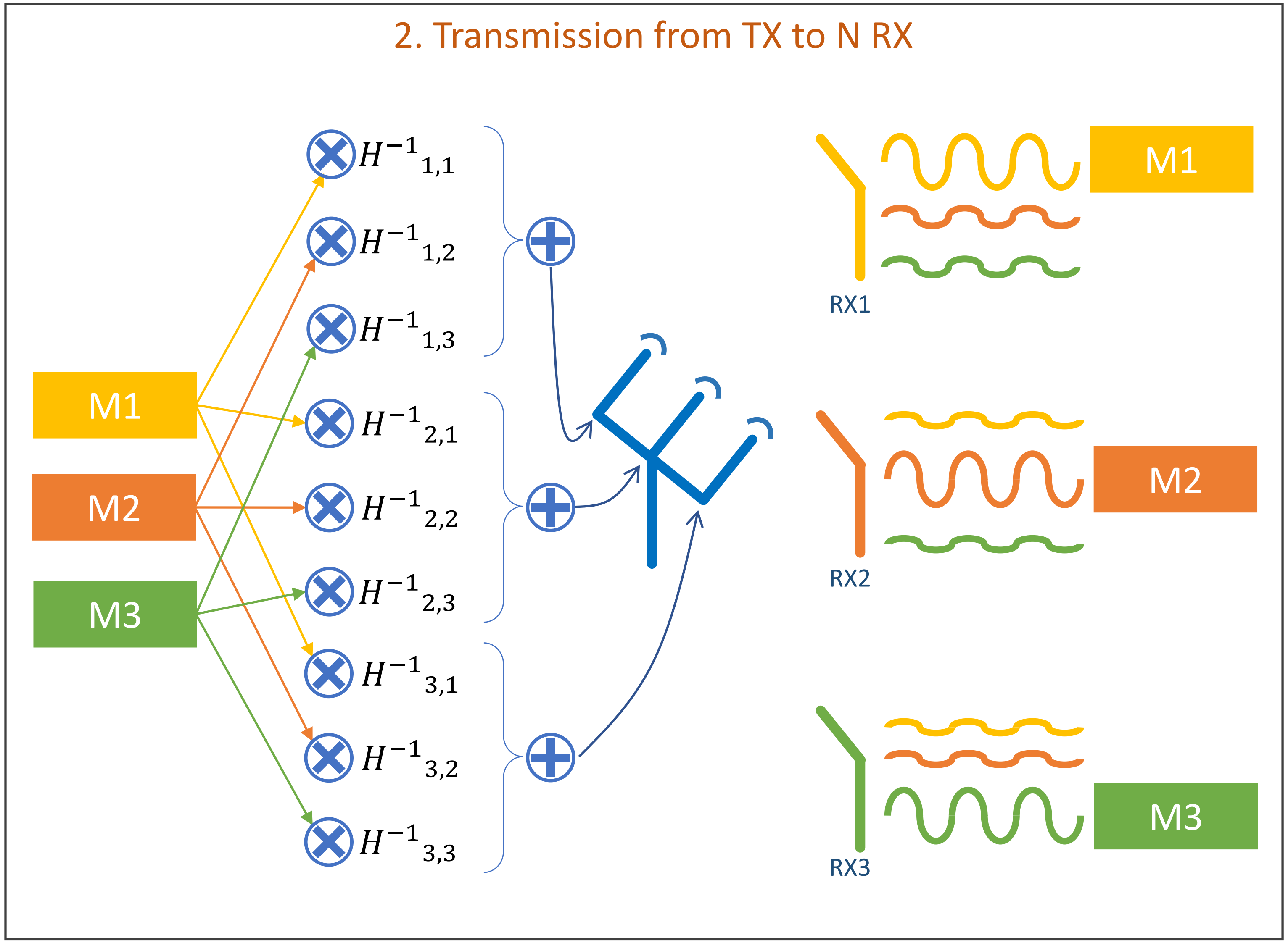


1. Channel Sounding

2. Transmission from TX to N RX

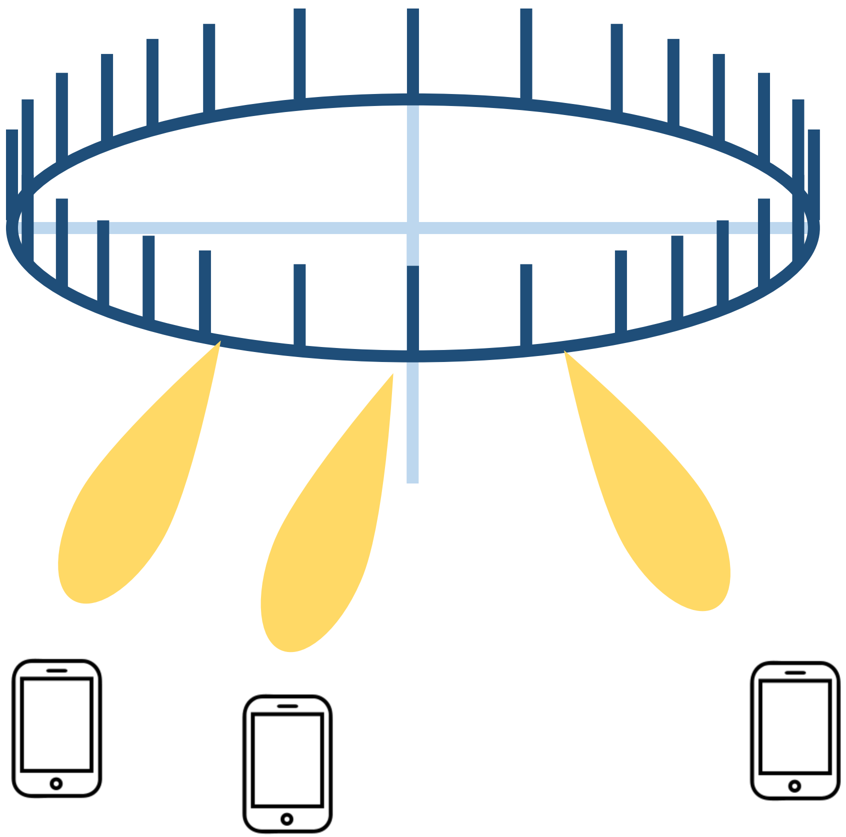
MIMO Transmission Example: 1-to-many





Massive MIMO

- Massive MIMO is performing MIMO with a N-antenna TX (base-station) to M users with a single antenna (for simplicity), at a larger scale (e.g., N > 50)
- It applies to having the base-station being both TX or RX



C-V2X

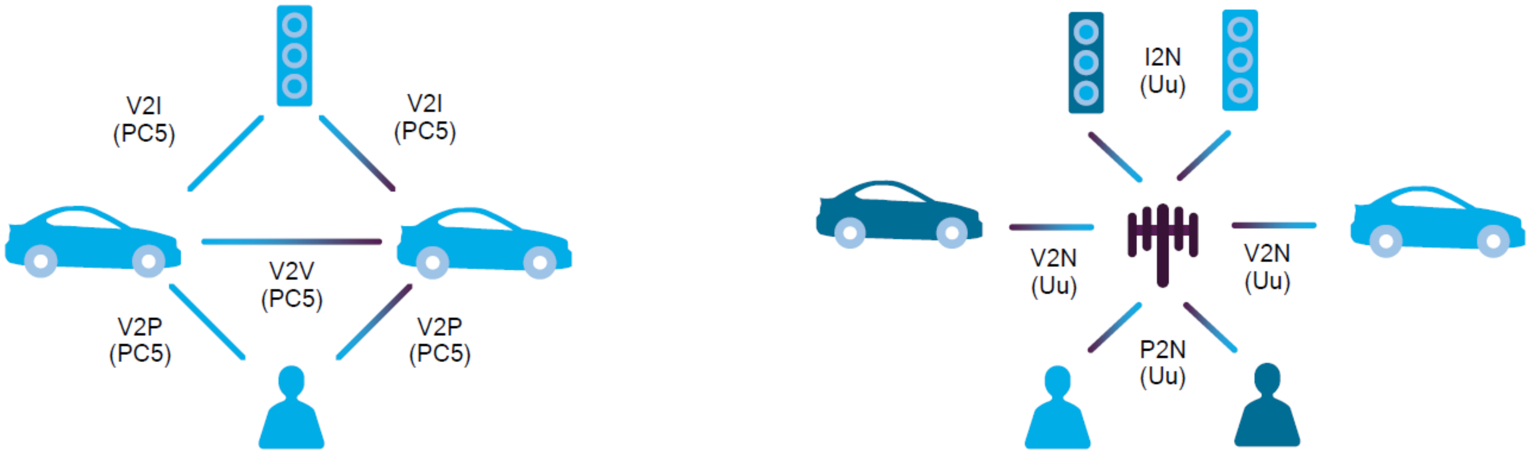
C-V2X has two complementary communication modes

Direct (= Sidelink)

V2V, **V2I**, and **V2P** operating in ITS bands (e.g. ITS 5.9 GHz) independent of cellular network

Network (= Up/Downlink)

V2N operates in traditional mobile broadband licensed spectrum



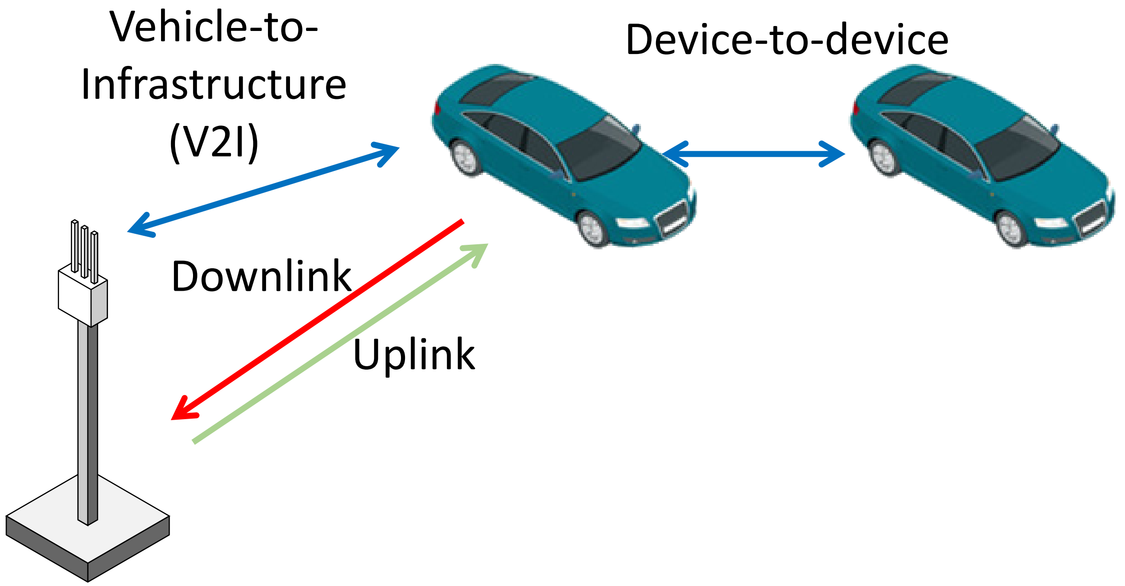
Short range (<1 kilometer), location, speed
Implemented over "PC5 interface"

Long range (>1 kilometers). e.g. accident ahead
Implemented over "Uu interface"

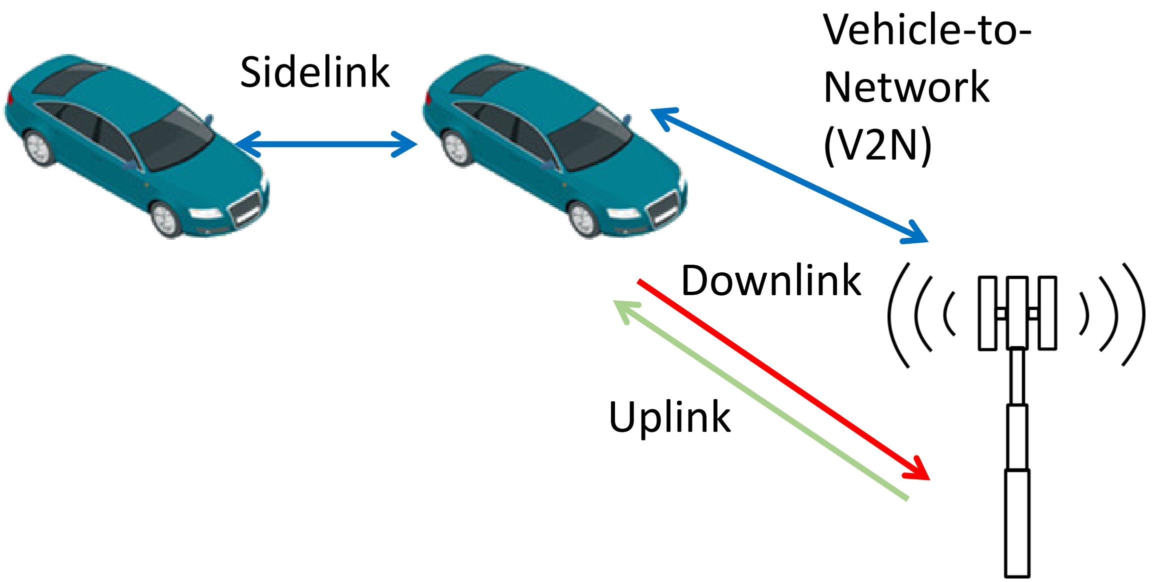
Maxime Flament (CTO, 5GAA), "**Path towards 5G for the automotive sector (slides)",** 17 Oct 2018.

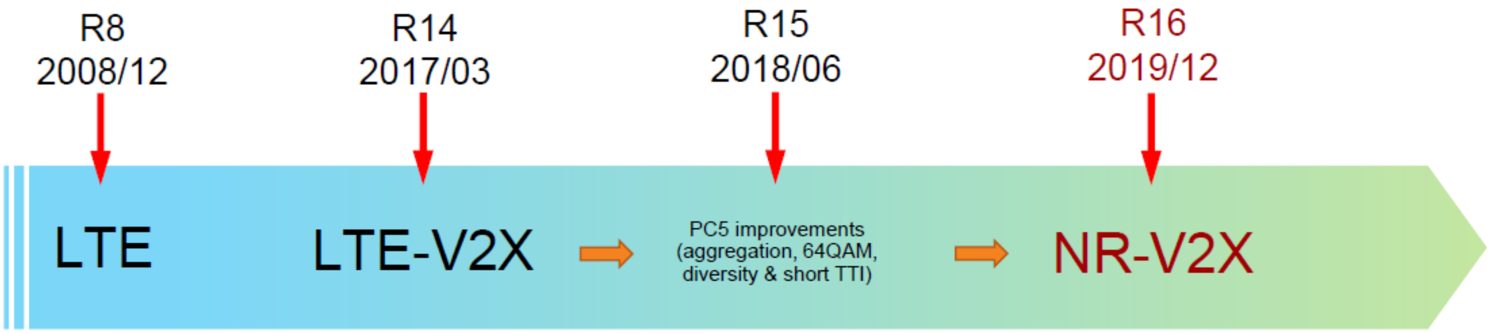
Terminology in Different Contexts

Open Standards
(prevalent in Local Area Networks)



Cellular
(Prevalent in Wide Area Networks)



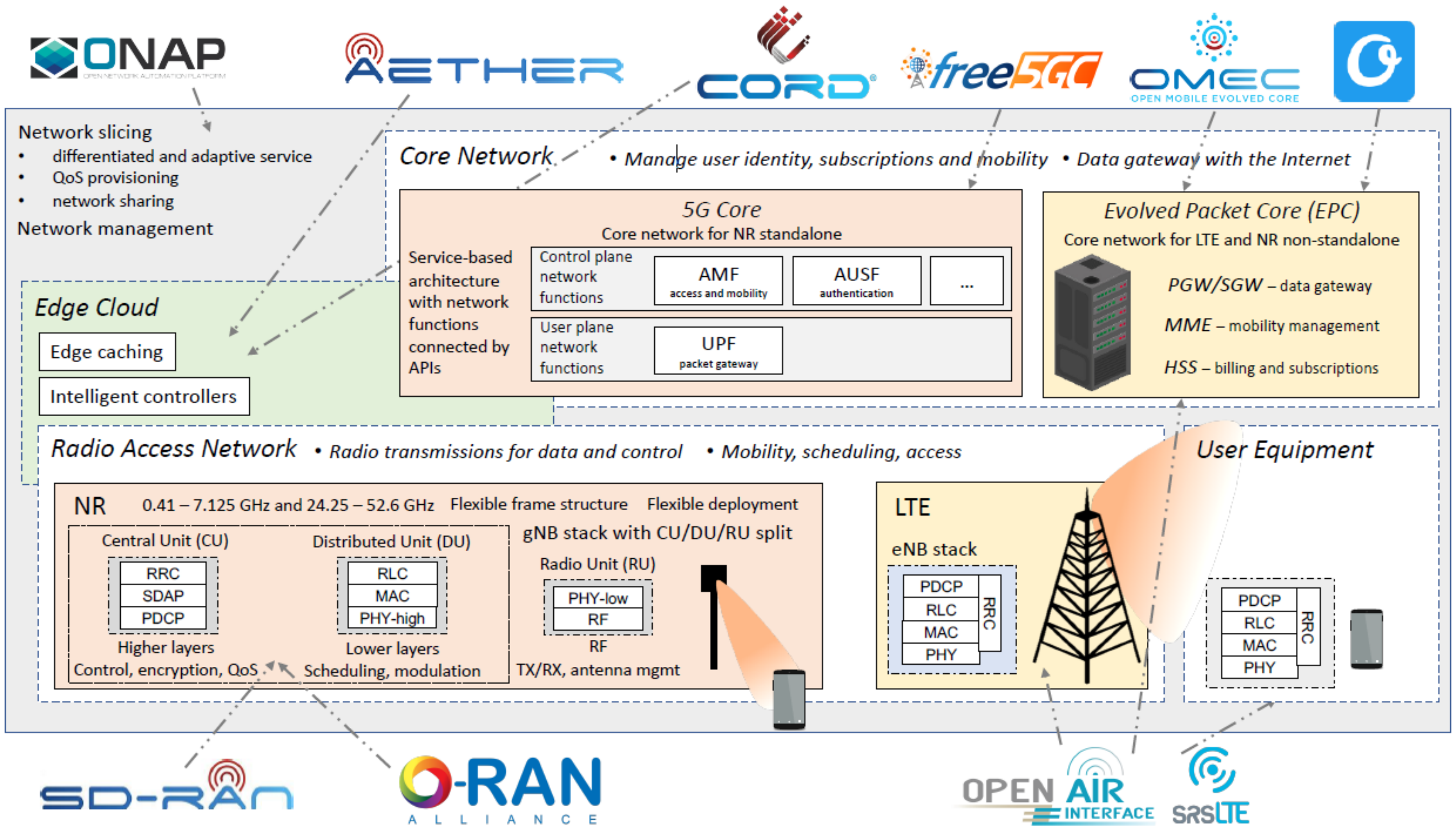


- NR-V2X study item started in June 2018.
- Subsequent NR-V2X work item by December 2019.

Maxime Flament (CTO, 5GAA), “**Path towards 5G for the automotive sector (slides)”,** 17 Oct 2018.

Commercial brand	Name of technical specification	Stand. Body	Time-frame
1G	N/A	N/A	1980
2G	Global System for Mobile Communications **(GSM)**	ETSI	1990
3G	Universal Media Telecom-munications System **(UMTS)**	3GPP	2000
4G	Long-Term Evolution **(LTE)**	3GPP	2010
5G	New Radio **(NR)**	3GPP	2020

Cellular Technological Ecosystem



To Read & Discuss

- E.Larsson et al., "Massive MIMO for Next Generation Wireless Systems"
- T.Marzetta, "Massive MIMO: An Introduction"
- 5GAA, "5GAA-v2x-technology-benchmark-testing-dsrc-and-c-v2x"
- M.Garcia et al., "A Tutorial on 5G NR V2X Communications“
- L.Bonati et al., "Open Programmable and Virtualized 5G Networks State-of-the-Art and the Road Ahead"

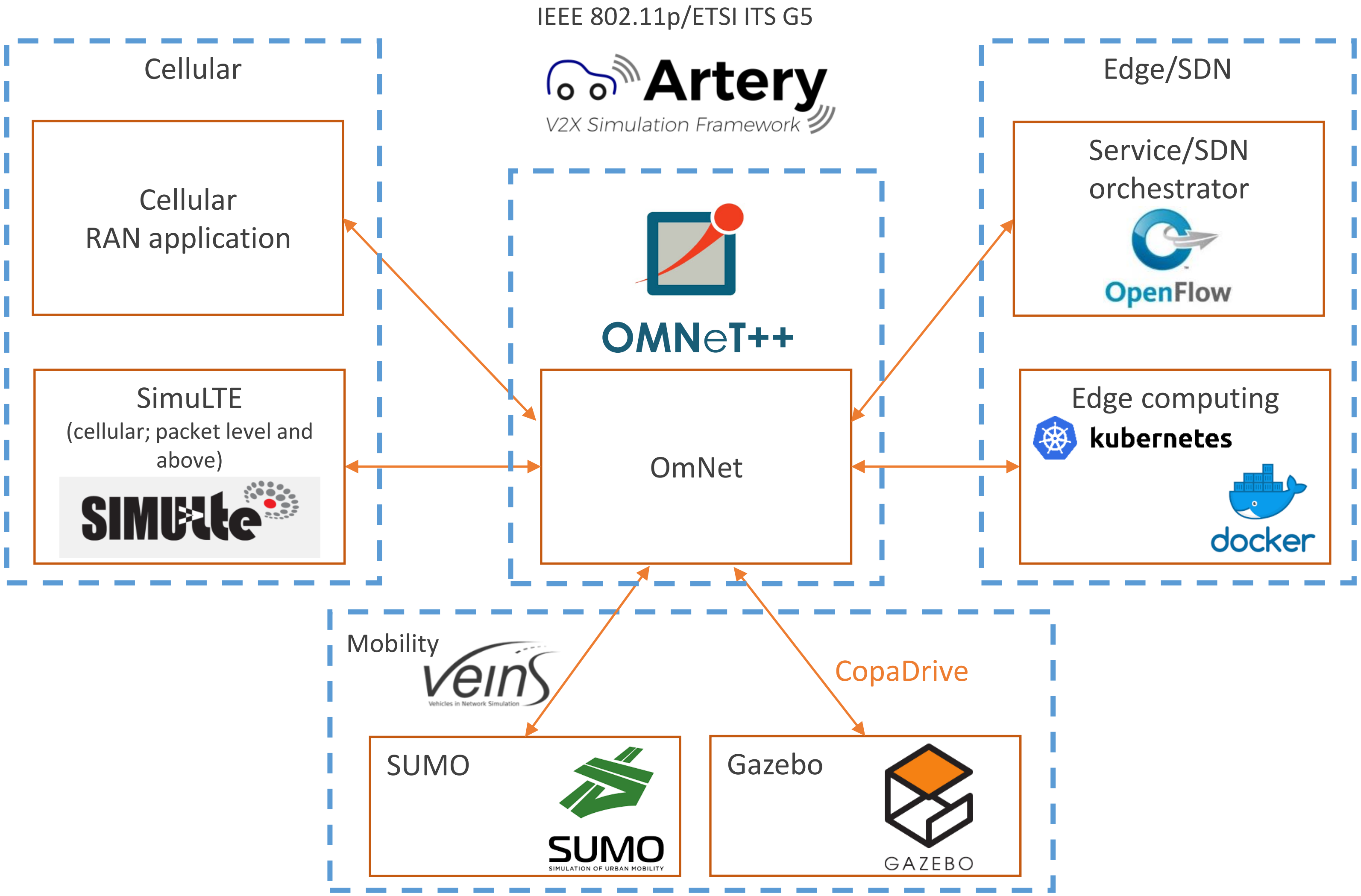
T5. Simulation Tools

31/03/2021

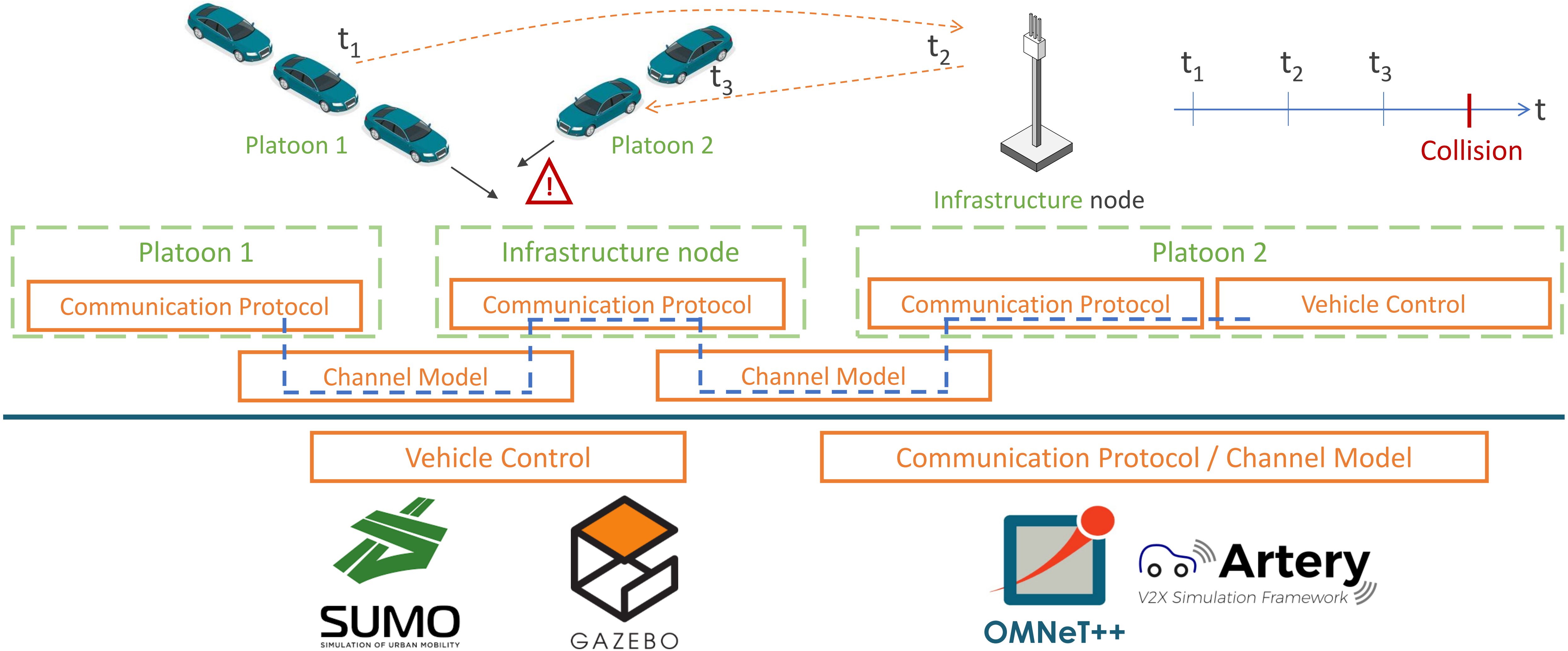
Simulation Tools

- OmNet: Discrete Event Simulator; focus on networking when paired with networking libraries (INET)
- Veins: VANET framework extension to OmNet++ (https://veins.car2x.org/)
- Artery: Extension to Veins that provides the ETSI ITS G5 stack
- SimuLTE: Extension to Veins and Artery for cellular communications
- Eclipse SUMO: Mobility simulator (Macroscopic vehicular mobility)
  - PLEXE: A platooning simulator (now integrated with SUMO)
- Gazebo: Robotic control simulator (Microscopic vehicular mobility)

Simulation Tools

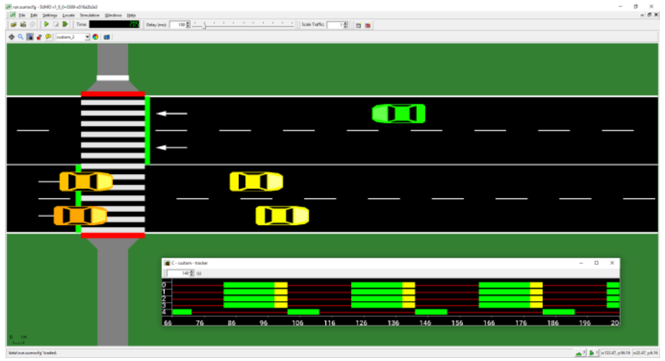


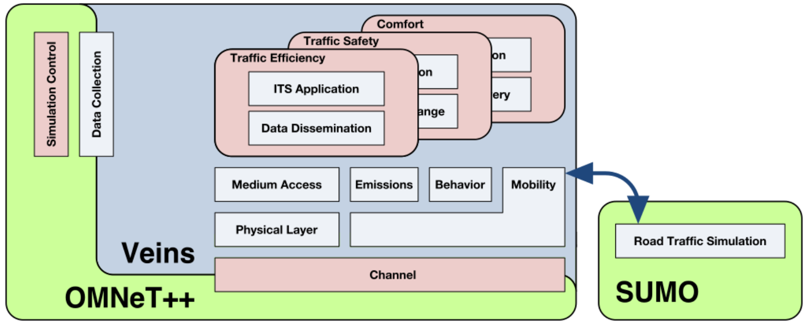
Simulation Example



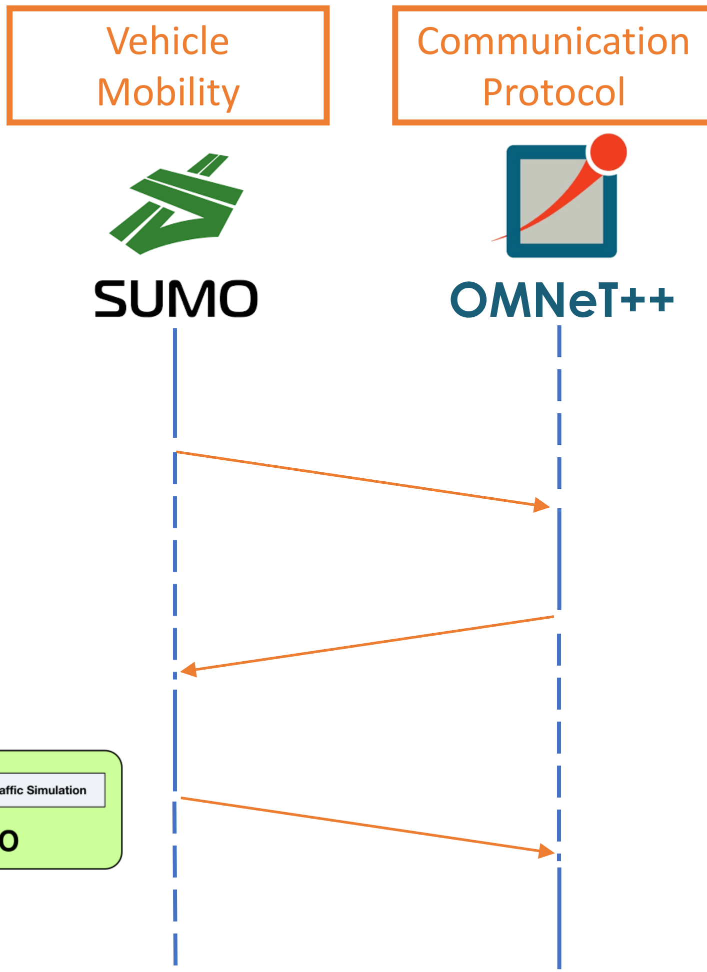
VEINS & SUMO

- SUMO is a large-scale mobility simulator
  - Contains (simple) mobility models that allow to model hundreds of vehicles.
  - It provides routing of vehicles, car following models, among other things
- Veins is an OMNeT library that links with SUMO
  - Inputs from the OMNeT (network) can affect vehicle mobility in SUMO.
- VEINS and SUMO operate in lockstep.
  - After an update from SUMO, OMNeT carries out the networking exchanges while SUMO waits.
  - Once OMNeT is over, relevant information is sent to SUMO, that will then run.





Lockstep Operation

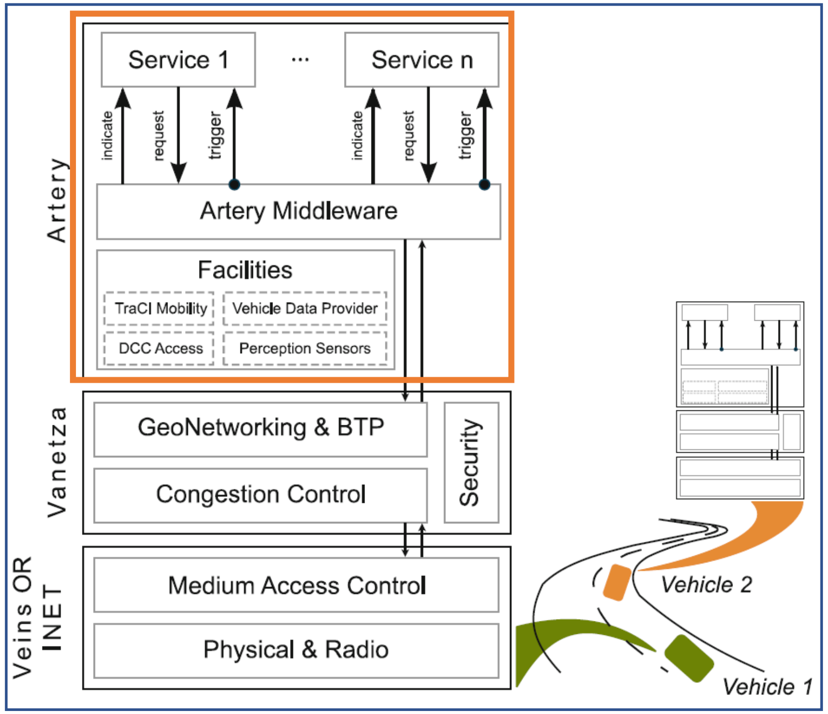


Artery & SimuLTE

- Two relevant additional libraries:
  - Artery provides the ETSI ITS G5 service stack
  - SimuLTE provides the PHY/MAC layers of cellular communications

Artery
V2X Simulation Framework

802.11p



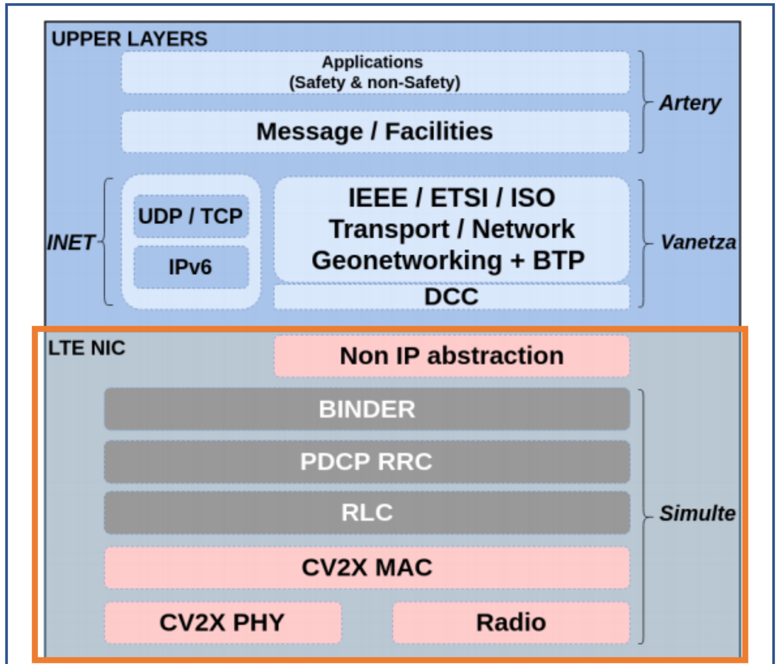


Fig. 1: OMNeT++ C-V2X Mode 4 Architecture

SIMUlte

5G

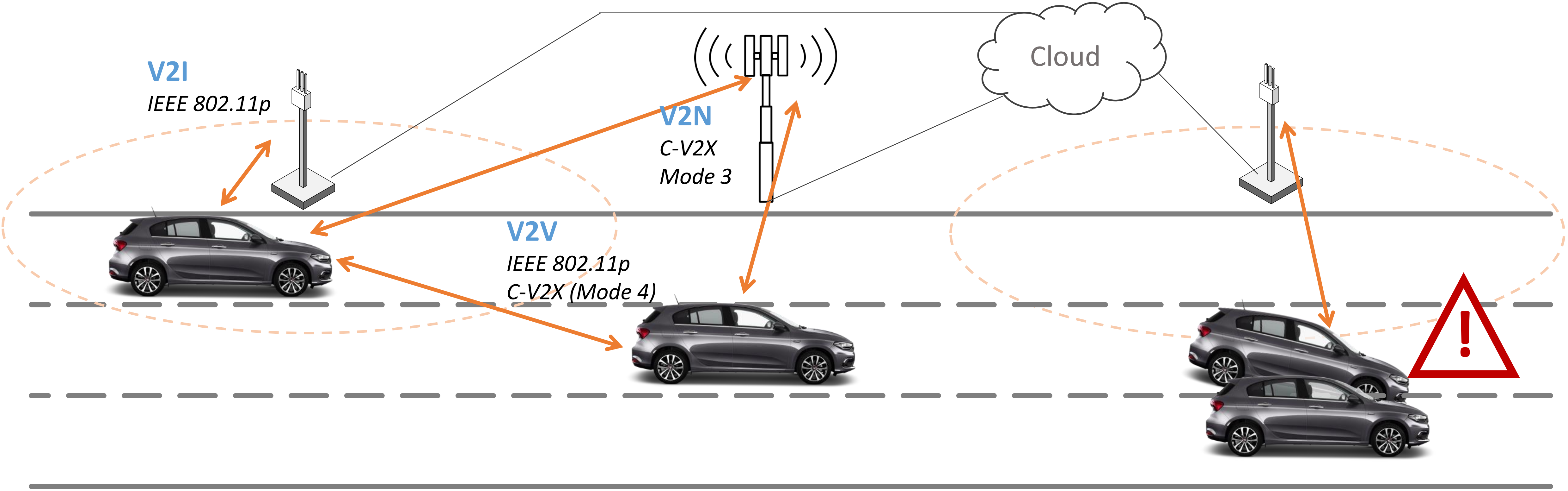
5. To Read & Discuss

- C.Sommer et al., “Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis”
- M.Segata et al., “PLEXE A Platooning Extension for Veins”
- R.Riebl et al., “Artery Large Scale Simulation Environment for ITS”
- R.Riebl et al., “Simulating LTE-Enabled Vehicular Communications”

T6. Co-existence & Other IEEE Technologies

Co-existence of 3GPP and IEEE 802.11

- Cellular and IEEE 802.11 technologies can be complementary
  - IEEE 802.11p operates as a local area network, being mostly useful for V2I and V2V low-latency messages
  - Cellular can complement with long-distance V2N links in areas where infrastructure coverage is limited
  - C-V2X can compete with IEEE 802.11p for V2V links, but there is no concept of Road-Side Unit (RSU)



Noteworthy Versions of IEEE 802.11 standard

- Original – 1/2 Mbit/s, CSMA/CA
- **IEEE 802.11a** (1999) – Band: **5Ghz;** rates: up to 54 Mbit/s. Mod: OFDM w/[BPSK, QPSK, 16-QAM, 64QAM]
- **IEEE 802.11b** (1999) – Band: 2.4GHz, rates: up to 11Mbit/s. Mod.: DSSS
- **IEEE 802.11g** (2003) – Same physical layer as 802.11a but now on **2.4GHz band**
- **IEEE 802.11n** (2007) – Band: 2.4 & 5 GHz; rates: up to 600Mbit/s (if both devices support it). Multi-Input Multiple-Output (MIMO), up to 4 spatial streams.
- **IEEE 802.11ac (WiFi 5)** (2013) – Based on 11n. Band: 2.4 & 5 GHz; rates: up to 6.77Gbit/s . Downlink Multi-User (MU)-MIMO, 160 MHz channels (vs. 80MHz), higher modulation 256-QAM (vs. 64-QAM), 8 spatial streams (vs. 4)
- **IEEE 802.11ax (WiFi 6)** (2018) - Based on 11ac. Band: 2.4 & 5 GHz; rates: up to 11Gbit/s. OFDMA, MU-MIMO, on the uplink (as well as downlink), 1024-QAM.
- **IEEE 802.11be (WiFi 7)** – *in the works…*

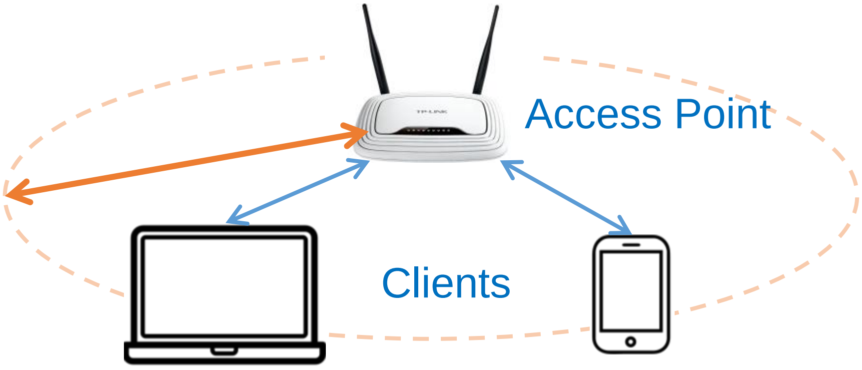
- ***IEEE 802.11ad** – 60GHz (mmWave) - WiGig – implements beamforming*
- ***IEEE 802.11ay** - 60 GHz - Enhancements for ultra High Throughput in and around the 60 GHz Band*

Technologies of LAN and WAN

LAN

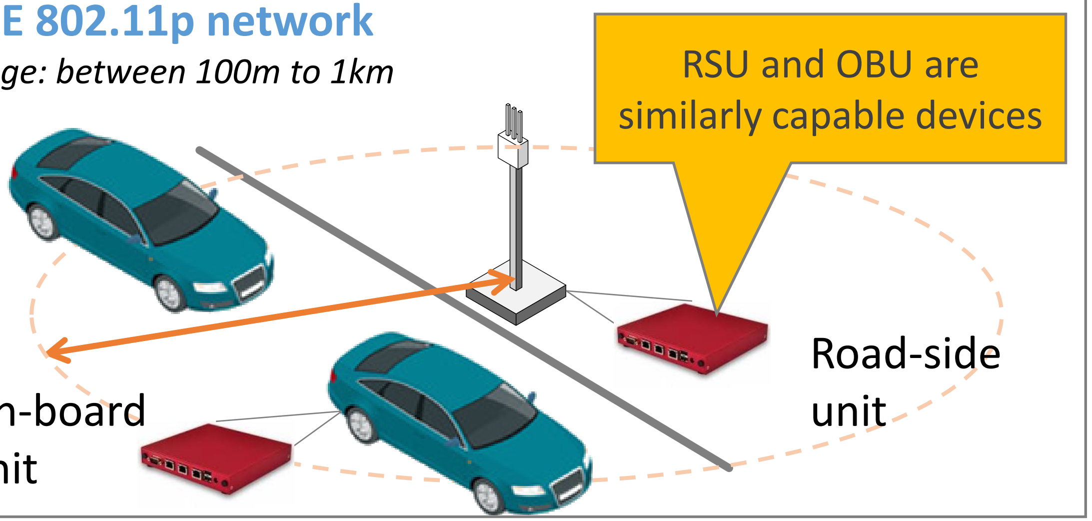
IEEE 802.11n/ac/ax network

Range: between 1m to 300m



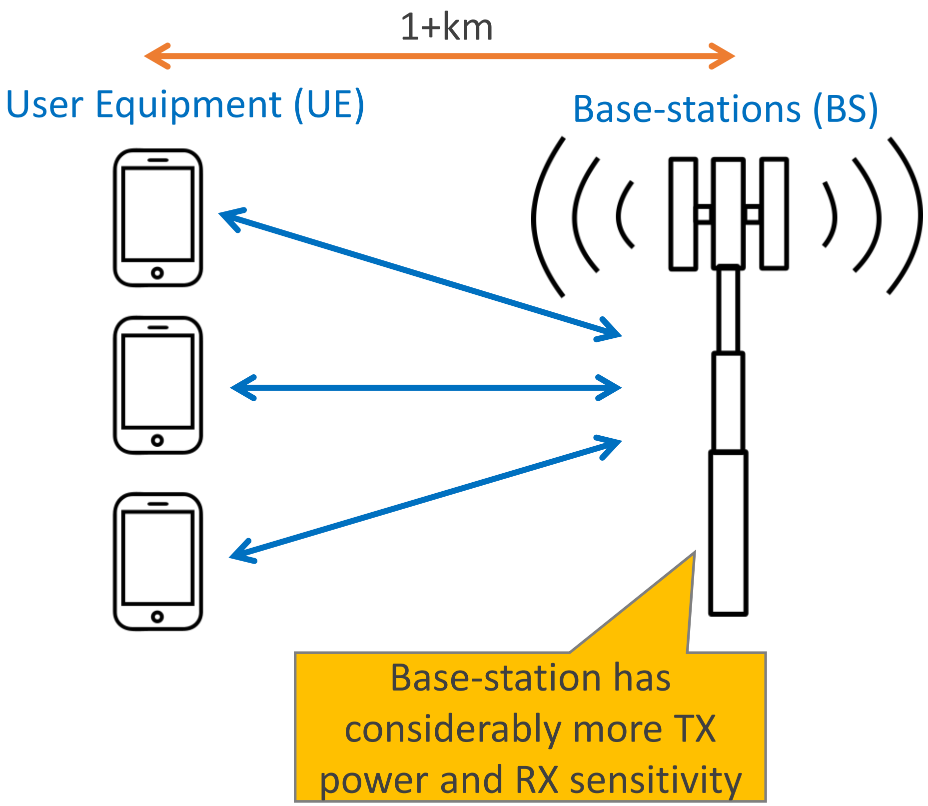
IEEE 802.11p network

Range: between 100m to 1km

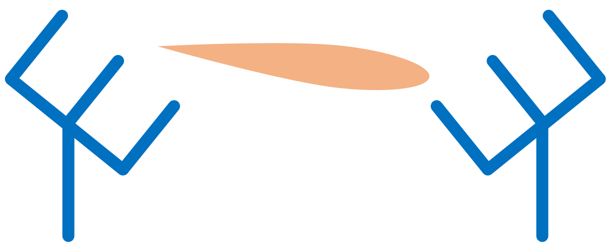


WAN

- **Cellular Technologies:** 2G/GSM, 3G/UMTS, 4G/LTE, 5G/NR, NB-IoT, LoRa, SigFox
- **WiMax** (IEEE 802.16)

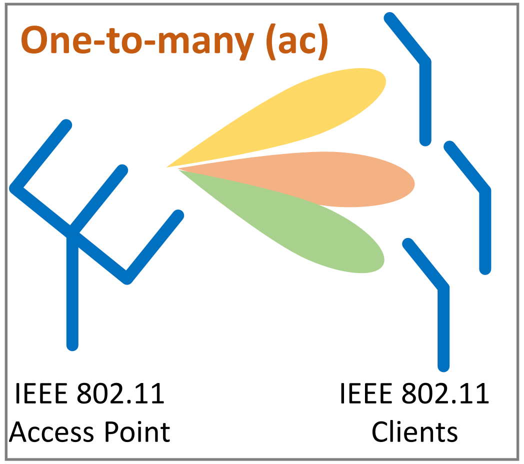


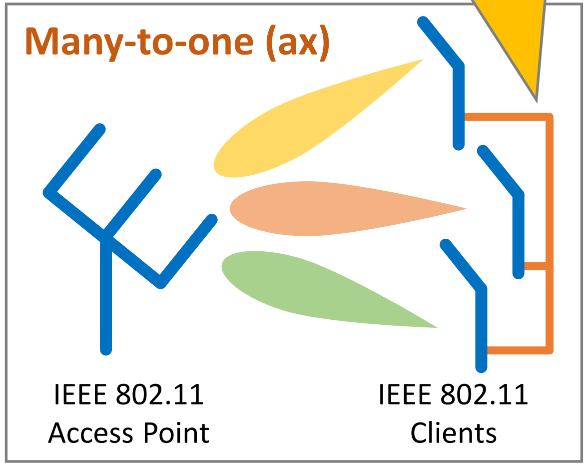
IEEE 802.11ad and 11ax

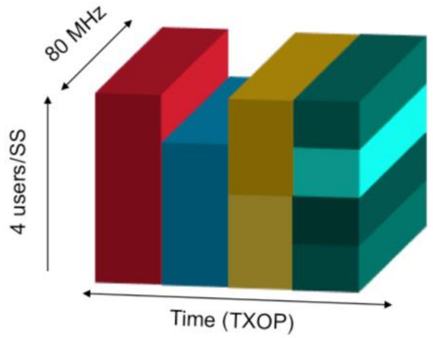


- IEEE 802.11ad
  - Beamforming at millimeter wavelengths (mmWave) – 60GHz –, requiring highly directional (narrow) beams
- IEEE 802.11ax
  - IEEE 802.11ac supported MU-MIMO in the *Downlink* – from IEEE 802.11 AP to clients – **one-to-many**
  - The *Uplink* – **many-to-one** – is more challenging because all client devices need to be **synchronized!**
  - IEEE 802.11ax defines a new period of **synchronized transmissions triggered by specific AP packets**
  - This is a ground-breaking change: so far IEEE 802.11 always relied on probabilistic medium access.

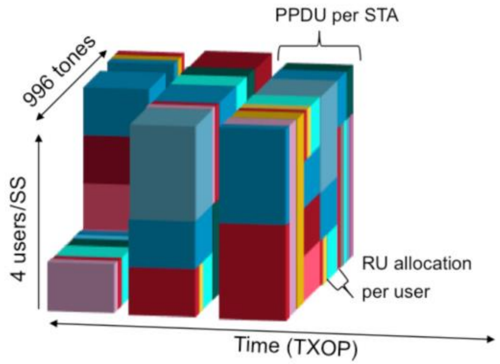
How to synchronize multiple wireless clients?







OFDM (11ac MU-MIMO)



OFDMA (11ax MU-MIMO)

OFDMA is also used in cellular specification. This show that the same wireless technologies end up finding use in both cellular and WLAN standards

To Read & Discuss

- “3GPP C-V2X and IEEE 802.11p for Vehicle-to-Vehicle communications in highway platooning scenarios”
- “A Tutorial on IEEE 802.11ax High Efficiency WLANs”
- “Exploratory Study of 802.11ad Vehicular Links”