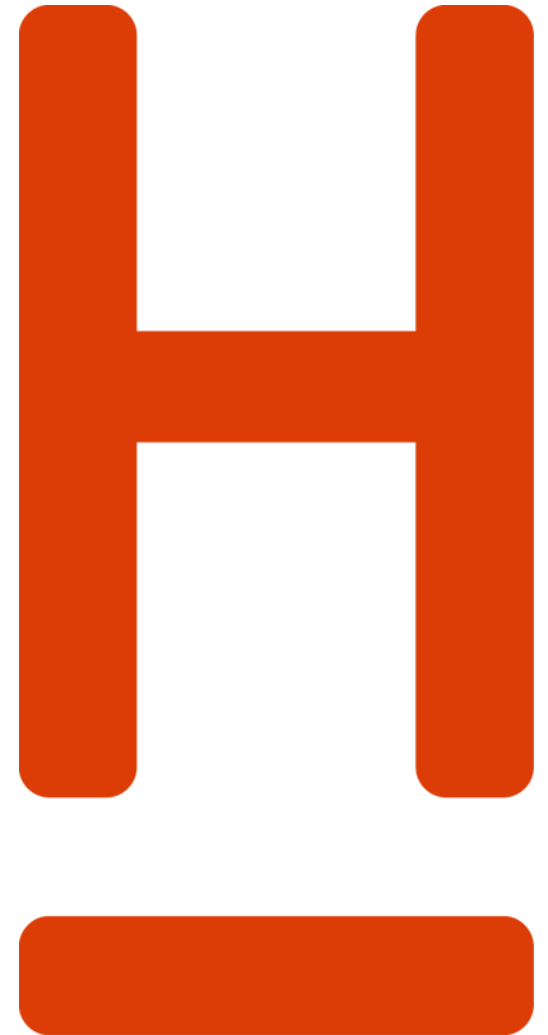


**HOCHSCHULE  
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UNIVERSITY OF  
APPLIED SCIENCES  
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–  
*Fakultät IV  
Wirtschaft und  
Informatik*

# Fahrzeugvernetzung – V2X

*Lecture 8: Cellular V2X*



# Lecture 8

## *Previous Lecture*

- ▶ Control Theory Approach
- ▶ Congestion/Awareness Control
- ▶ Transmission Control Protocol
- ▶ Channel Load Measures
- ▶ Decentralized Congestion Control
- ▶ Transmit Rate Control Mechanism



# Lecture 8

## *Outline*

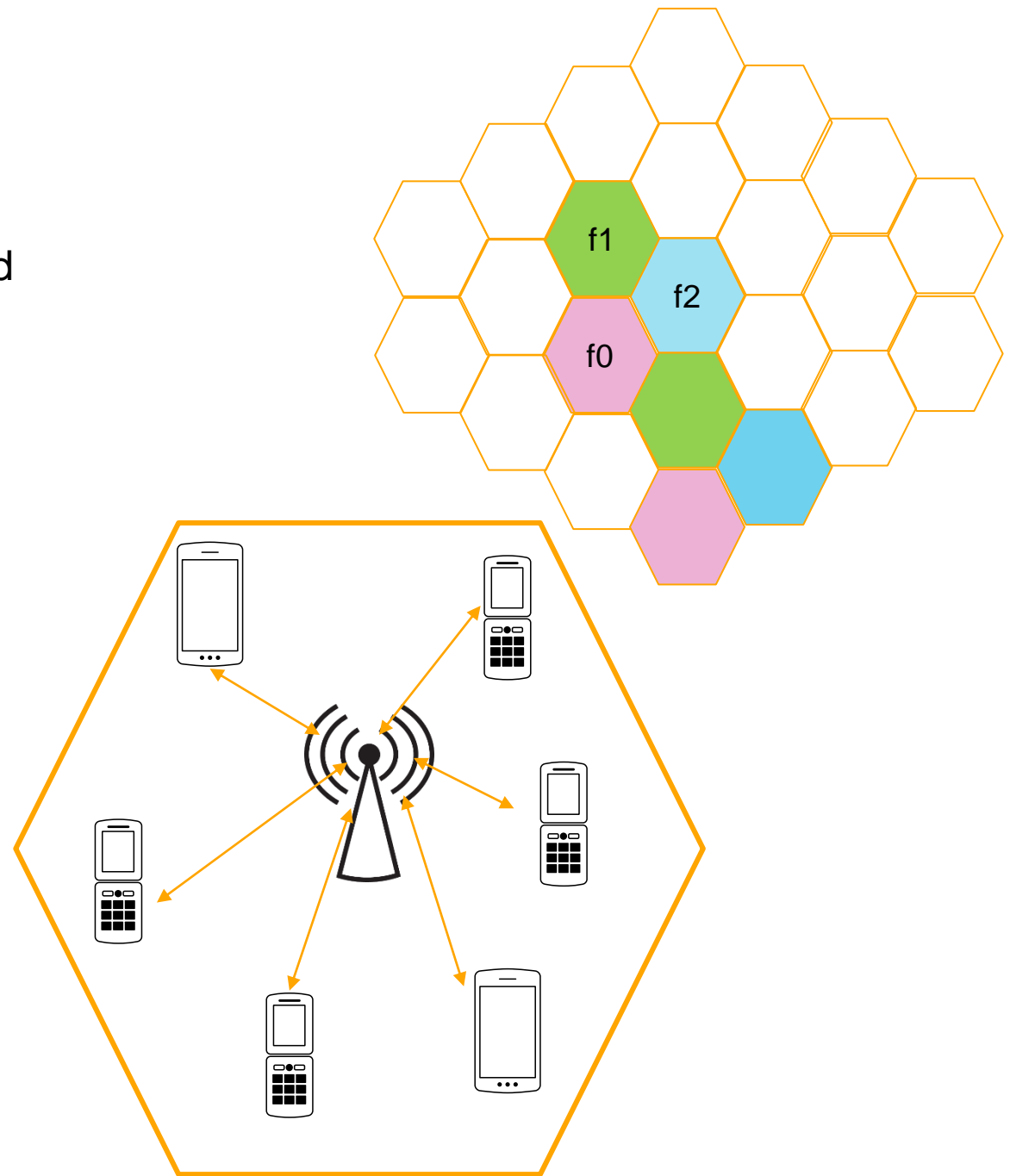
- ▶ Cellular Network Basics
- ▶ Device-to-Device Communication
- ▶ C-V2X Communication
- ▶ C-V2X Communication Modes
- ▶ Sensing-based Semi-Persistent Scheduling
- ▶ C-V2X Decentralized Congestion Control



# Lecture 8

## Cellular Networks - Basics

- ▶ Divide the **world into cells**, each served by a **base station**
- ▶ Allow frequency reuse in frequency-division multiple access (FDMA) protocols
  - ▶ Exploit **spatial diversity** of the carrier used



# Lecture 8

## Cellular Networks – Radio Access Technology

### ► Duplexing

- Refers to how **uplink** and **downlink** communication are sharing available resources

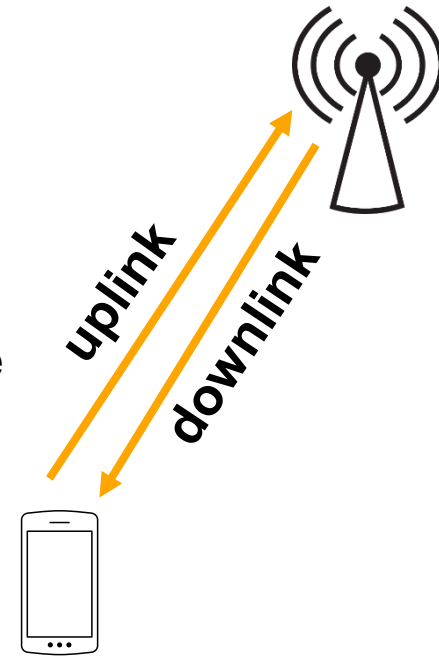
### ► Frequency Division Duplex (FDD): Two separate frequencies are used

- One frequency for **uplink**: From UE to base station
- One frequency for **downlink**: From base station to UE

### ► Time Division Duplex (TDD): Same frequency is used alternating between uplink and downlink

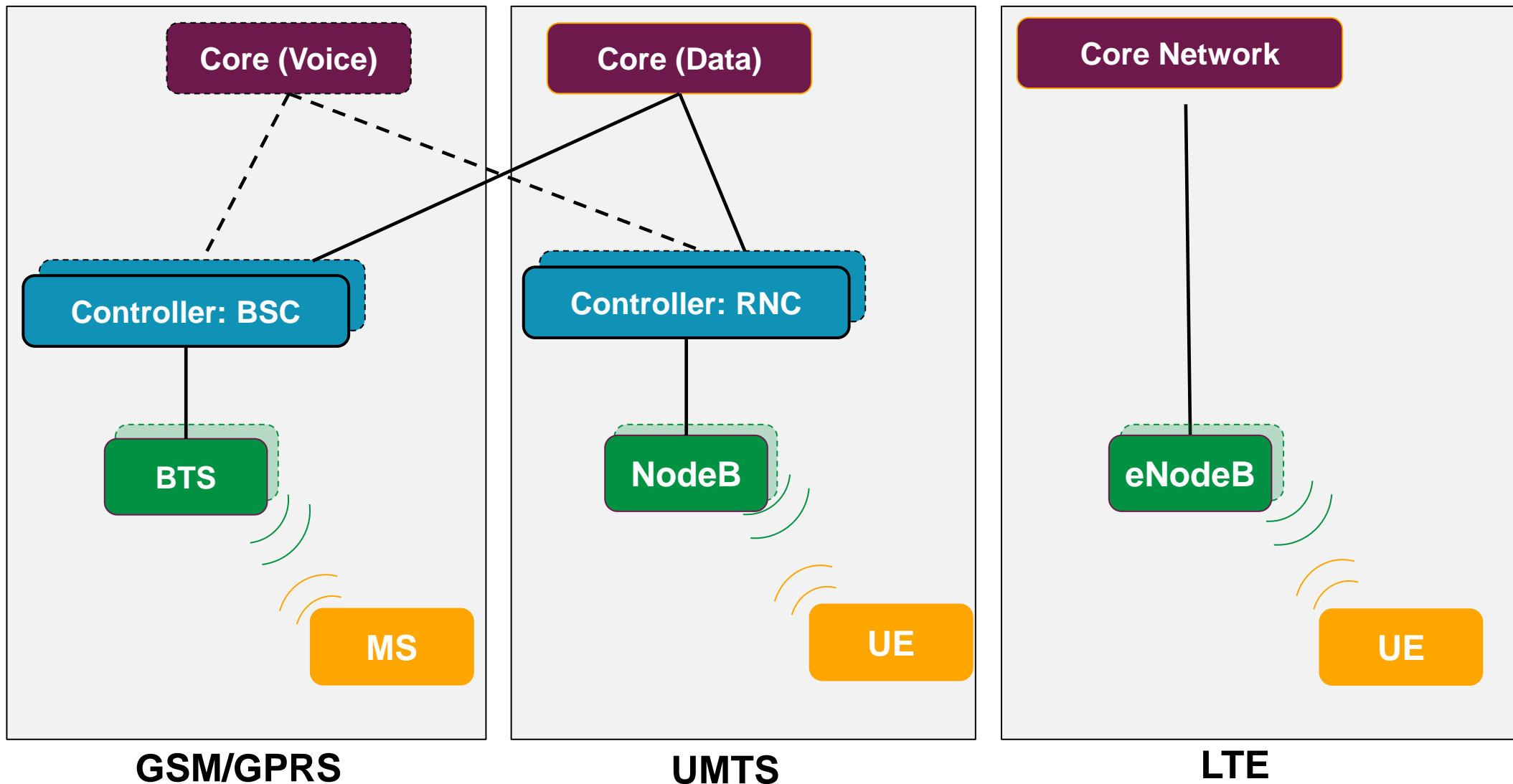
### ► Multiple access scheme further **subdivide available resources** into independent channels (e.g. for serving multiple users):

- TDMA, FDMA, CDMA



# Lecture 8

## Cellular Networks – Architecture of three Generations



# Lecture 8

## Cellular Networks – Architecture of three Generations

### ► Base Station Controller (BSC):

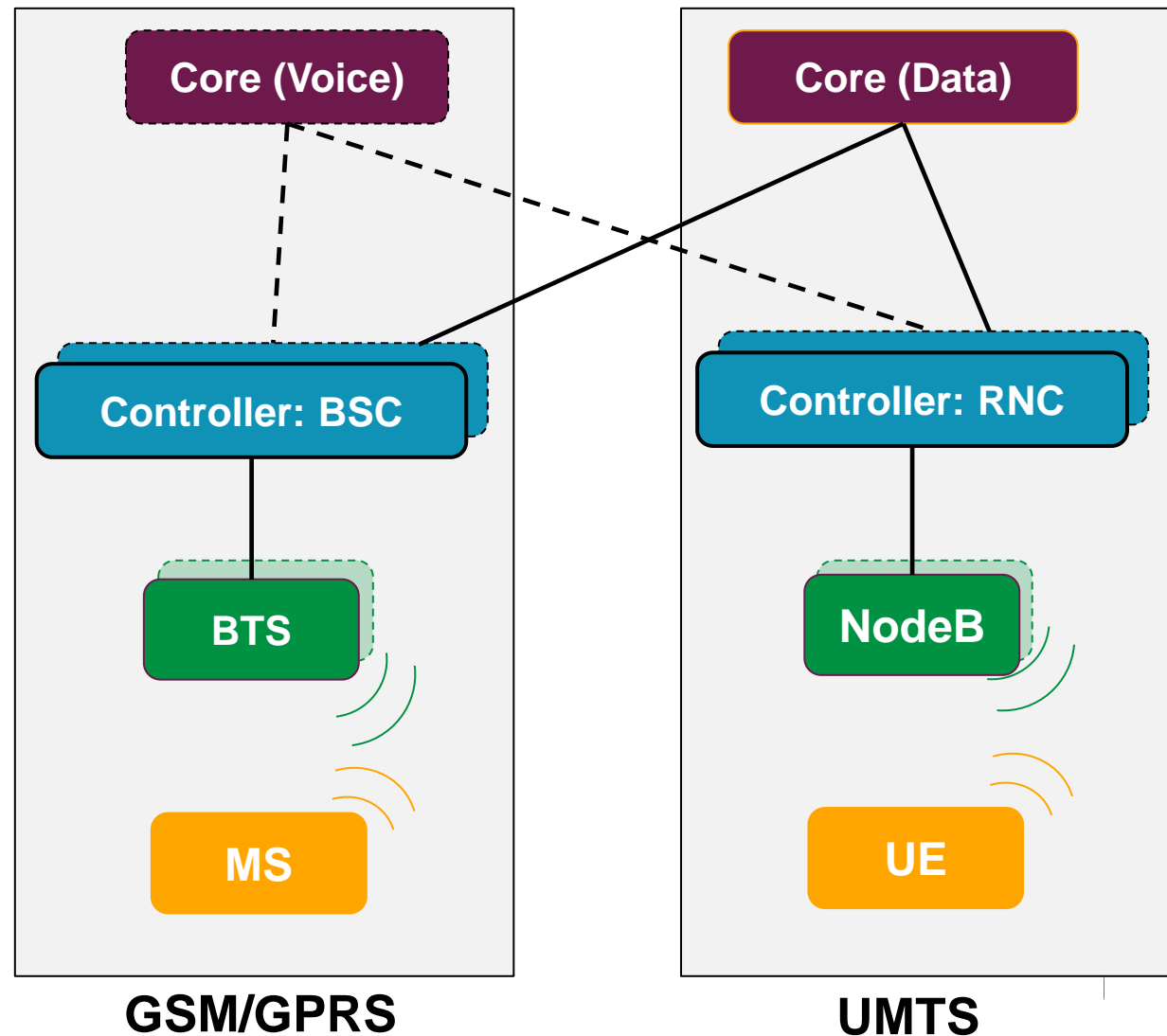
- Serves all higher functions such as channel allocation
- Connected to one and several hundred BTSs

### ► Base Transceiver Station (BTS):

- Implements the physical layer of the air interface

### ► Radio Network Controller (RNC):

- Responsible for scheduling decisions



# Lecture 8

## *Cellular Networks – Global System for Mobile Communication (GSM)*

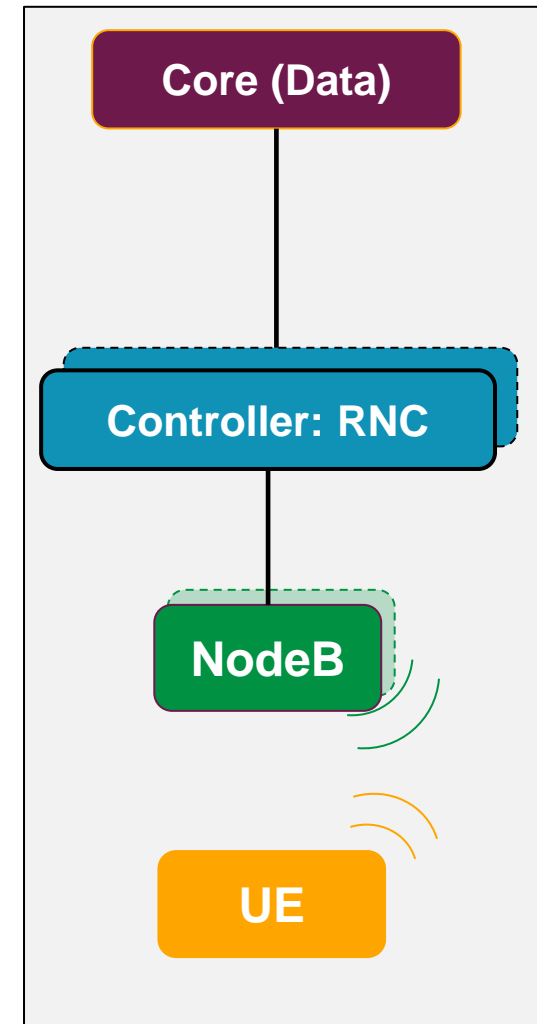
- ▶ Connect **mobile telephones wirelessly** to each **other** and to regular **landline telephones** - Conceived in the early 1980s
- ▶ On the physical layer GSM employs **FDD** – **separate** frequencies for **uplink** and **downlink**, **FDMA** and **TDMA** for providing multiple channels
  - ▶ For GSM-900 standard
    - ▶ **124 frequency bands** per direction, each 100 kHz wide in 900 MHz band
    - ▶ Each frequency band is subdivided into **eight time slots** → A total of **992 channels**
- ▶ **GPRS (General Packet Radio Service)** allows packet-oriented data transport over flexibly allocated channel on the air (In 1997)
  - ▶ **No circuit** is needed to be established in the core network
    - ▶ Inefficient use of resources with **circuit-switched data technology** as data connection would **tie up resources** by allocating a **circuit** irrespective of **whether it is being used or not**



# Lecture 8

## Cellular Networks – Universal Mobile Telecommunication System (UMTS)

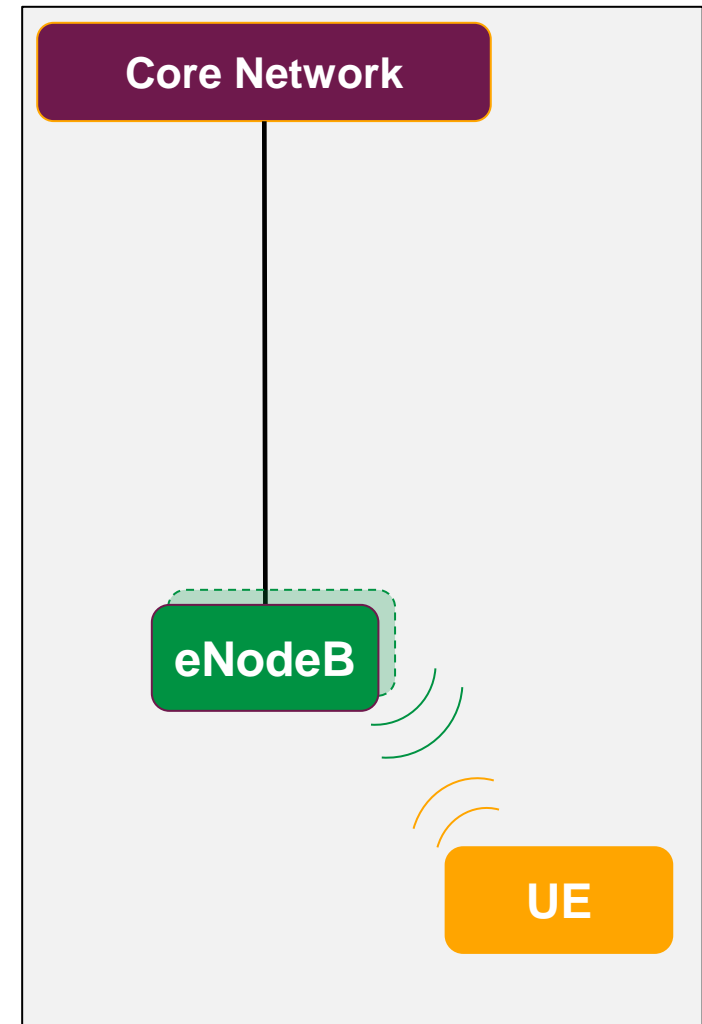
- ▶ Developed to meet the **growing resource demands** of mobile **data connections**
- ▶ First commercial deployments operates on a new set of frequencies in parallel with established GSM networks (in 2002)
  - ▶ UMTS uses different technology in the **access network** but shares the same **core network** as GSM
- ▶ It uses **pure CDMA** dedicating the **whole frequency band** to all users simultaneously
  - ▶ Static FDD or flexible TDD for uplink and downlink
- ▶ **Scheduling decisions** from the radio network controller (**RNC**) into the base station (NodeB)
  - ▶ To **reduce delays** and allow data transmission on multiple logical channels in the downlink
- ▶ Data speeds pushed to **7.2 Mbit/s**



# Lecture 8

## Cellular Networks – Long Term Evolution (LTE) (1/3)

- ▶ Launched commercially in 2009
- ▶ Based on a **redesigned air interface, radio access network and core network**
- ▶ The underlying technology of all network components in LTE is **IP**
  - ▶ Unlike UMTS, LTE does **not use most of existing** infrastructure
  - ▶ There is **no a simple way** to provide **voice services** to mobile phones
- ▶ Three possibilities to provide voice services
  - ▶ **Voice over LTE** that encapsulated such traffic for transport to new core network component
  - ▶ **Voice over IP** applications on the mobile device
  - ▶ **Legacy fallback network** like GSM or UMTS that a device may connect to for performing voice calls



# Lecture 8

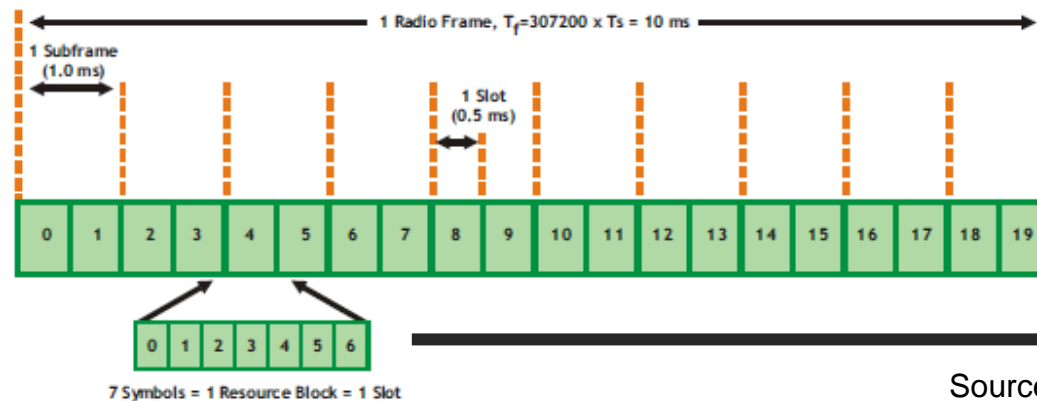
## *Cellular Networks – Long Term Evolution (LTE) (2/3)*

- ▶ LTE integrates all **radio access** into a single entity called evolved NodeB (**eNodeB**)
  - ▶ eNodeB is **directly** networked with other eNodeB as well as connected to the **core network**
  - ▶ Less signaling across different entities → **smaller round trip times** and **connection setup delays**
- ▶ LTE air interface make flexible use of wide variety of different bandwidths and frequencies
  - ▶ Bandwidth from **1.4 MHz** to **20 MHz**
  - ▶ Frequency band as low as **700 MHz** and as high as **2.7 GHz**
    - ▶ Can be split between uplink and downlink in either **FDD** or a **TDD** fashion
- ▶ Data modulation of up to 64-QAM and **spatial multiplexing (MIMO)** of up to 4x4 for the downlink
  - ▶ Theoretical peak download rate of **300 Mbit/s** and a latency of **5 ms**
    - ▶ Assuming best channel conditions and no load on 20MHz-wide-band

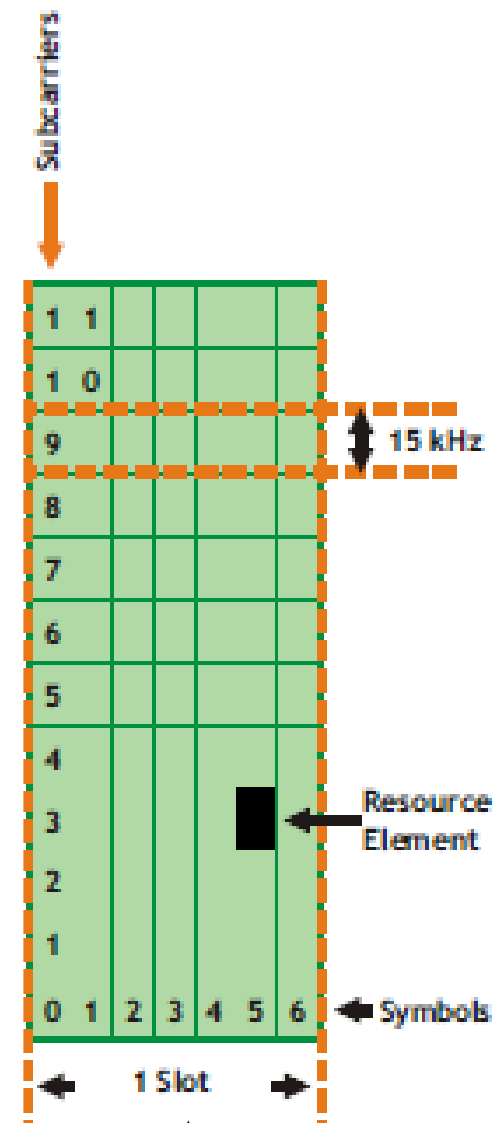
# Lecture 8

## Cellular Networks – Long Term Evolution (LTE) (3/3)

- ▶ For scheduling the available frequency band is split into 0.5-ms slot
- ▶ **Resource block (RB):** Combination of 12 subcarriers and 6 or 7 slots
  - ▶ RB occupies 180 KHz in the frequency domain and 0.5 ms in the time domain
  - ▶ One or multiple RBs are allocated per direction and user used to transport frames of length 10ms
- ▶ A radio frames are further subdivided into 10 sub-frames
- ▶ Each sub-frame carries 1 transport block which contains the payload data



Source: Aritsu



# Lecture 8

## *Evolution of C-V2X (Cellular-Vehicle-to-Everything-Communication)*

### D2D

- ▶ LTE Release 12/13
- ▶ Device-to-device communication
- ▶ Foundation for direct V2X communication over cellular

### C-V2X

- ▶ C-V2X Release 14/15
- ▶ Enhance communication performance
  - ▶ Low latency
  - ▶ High reliability for V2X safety applications
  - ▶ Extended communication range

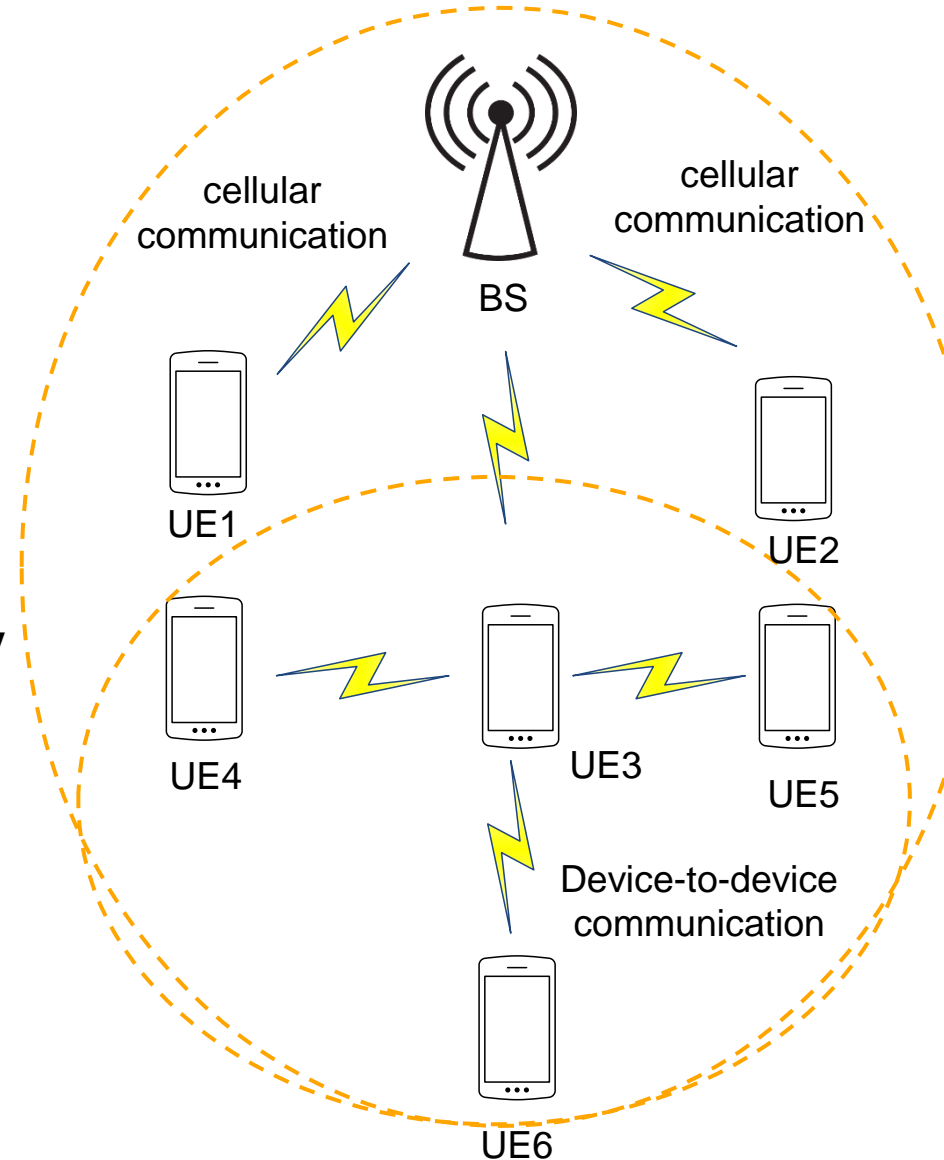
### 5G for V2X

- ▶ C-V2X Release 16
- ▶ Ultra-high throughput
- ▶ Ultra-low latency
- ▶ Ultra-high reliability
- ▶ Foundation for autonomous driving

# Lecture 8

## *Device-to-Device Communication*

- ▶ New **cellular-based** communication technology
- ▶ Allow **user equipments (UEs)** in close proximity to communicate using a **direct link**
  - ▶ Without having their radio signal **travel all the way through** the base station (BS) or the core network
  - ▶ Leading to **low latency** in communication due to a **shorter signal** traversal path
- ▶ Support **local data services** very efficiently through unicast, groupcast and broadcast transmissions



# Lecture 8

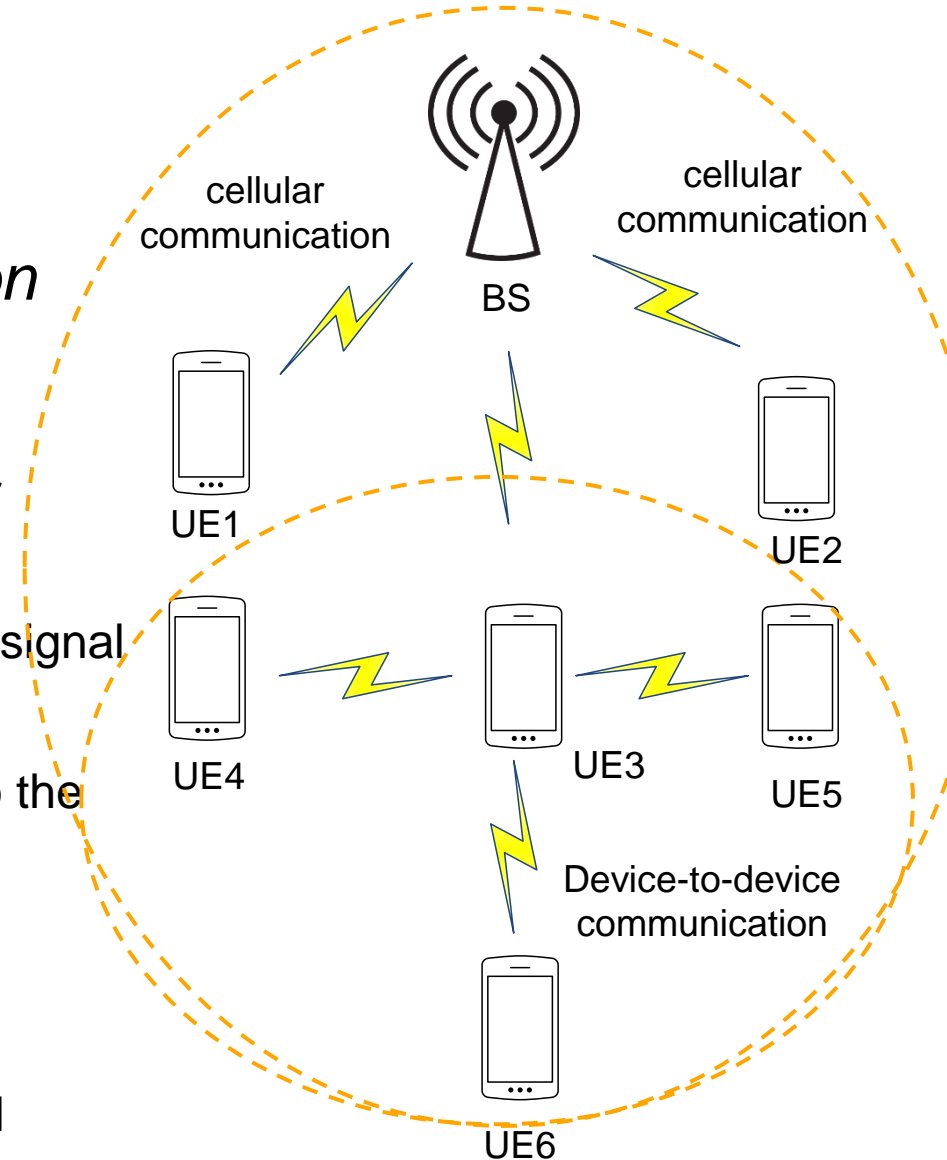
## D2D Communication - Coverage Extension

### ► Relaying

- **Relays** are used to extend the coverage of cellular service and enable **multi-hop communication**
  - **UE** (e.g., at the cell edge) may encounter poor signal quality while connecting to the BS
  - UE close to it that has, however, a better link to the BS may act as a *relay*
  - **UE3** acts as a relay between the **BS** and **UE6**

### ► Cooperative diversity techniques

- Relay it via **multiple parallel paths** to boost signal strength at a receiver



# Lecture 8

## *D2D Spectrum Allocation*

### ▶ Inband D2D communication

- ▶ Cellular and D2D communication use the same licensed spectrum
- ▶ Spectrum either divided into non-overlapping portions (**overlay**) or not (**underlay**)
  - ▶ **Overlay** scheme easier to implement
  - ▶ **Underlay** scheme leads to opportunistic and more efficient spectrum use

### ▶ Outband D2D communication

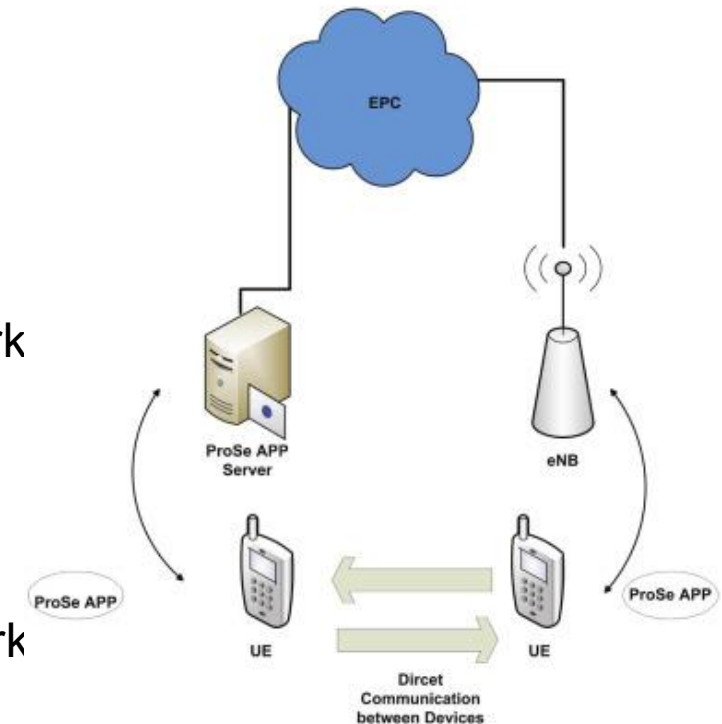
- ▶ D2D communication uses unlicensed spectrum e.g., 2.4 GHz ISM band or 38 GHz mm Wave band
- ▶ **Controlled Outband D2D**
  - ▶ D2D communication is controlled by the cellular network
- ▶ **Autonomous Outband D2D**
  - ▶ Cellular network controls only the cellular communication leaving the control of D2D communication to the users



# Lecture 8

## *D2D Proximity-based Services (ProSe)*

- ▶ Allows physically close devices to **discover themselves** and communicate via direct links
- ▶ **Three scenarios** for D2D communication are considered:
  - 1) **All** UEs involved in D2D communication are within network coverage
  - 2) Only **some** of the UEs in D2D communication are within network coverage
  - 3) **None** of the UEs in D2D communication are within network coverage
- ▶ When a UE wants to communicate with its peer UE, the **ProSe APP** in it requests for expression codes of its target peer from the server
- ▶ Alternatively, a UE can obtain the expression codes from the Proximity Function in the **eNB**



# Lecture 8

## *D2D Challenges – Device Synchronization*

- ▶ **Synchronization among UEs** helps a UE to use the **right time slot** and **frequency** for **discovering** and **communicating** with its peer
- ▶ **Global synchronization** among all UEs in a network may not be required for D2D communication
  - ▶ **Local synchronization** among neighboring devices is sufficient
- ▶ **Challenging situations:**
  - ▶ UEs belong to **different BSs** that may not be **themselves synchronized**
  - ▶ Some of the UEs are **in the coverage** of the network and some **outside the coverage**
  - ▶ All UEs lie outside network coverage

# Lecture 8

## *D2D Challenges – Peer Discovery*

- ▶ A UE should **be able to discover** other nearby UEs **quickly** and with low power consumption
  
- ▶ Two types of peer discovery techniques
  - ▶ **Restricted**
    - ▶ Devices cannot be discovered by the end users without their permissions
  
  - ▶ **Open**
    - ▶ Devices can be discovered whenever they are in the proximity of other users

# Lecture 8

## *D2D Challenges – Mode Selection*

- ▶ Mode selection is concerned with choosing the **right mode**
  - ▶ **Cellular** or **D2D** for communication between two UEs
  
- ▶ Mode selection can be done by the **network** or by the **UEs**
  
- ▶ Decision based on some **performance objectives**
  - ▶ High spectral efficiency
  - ▶ Low latency
  - ▶ Low transmit power

# Lecture 8

## *D2D Challenges – Ressource Allocation*

- ▶ Important step in creating and maintaining **direct links** between D2D pairs in a cellular network
- ▶ Resource allocation framework for inband multicell architecture
  - ▶ **Overlay**: Uplink spectrum is divided into two orthogonal portions with  **$f$  fraction** assigned to D2D communication and  **$1-f$**  to cellular communication
  - ▶ **Underlay**: Spectrum is divided into bands and D2D UEs can randomly and independently access of  $\beta B$  of them
- ▶ Choosing optimal value of  $f$  and  $\beta$  is challenging

# Lecture 8

## *D2D Challenges – Interference Management*

### ▶ **Inband communication**

- ▶ Cellular and D2D links may interfere with each other based on how they share the frequencies

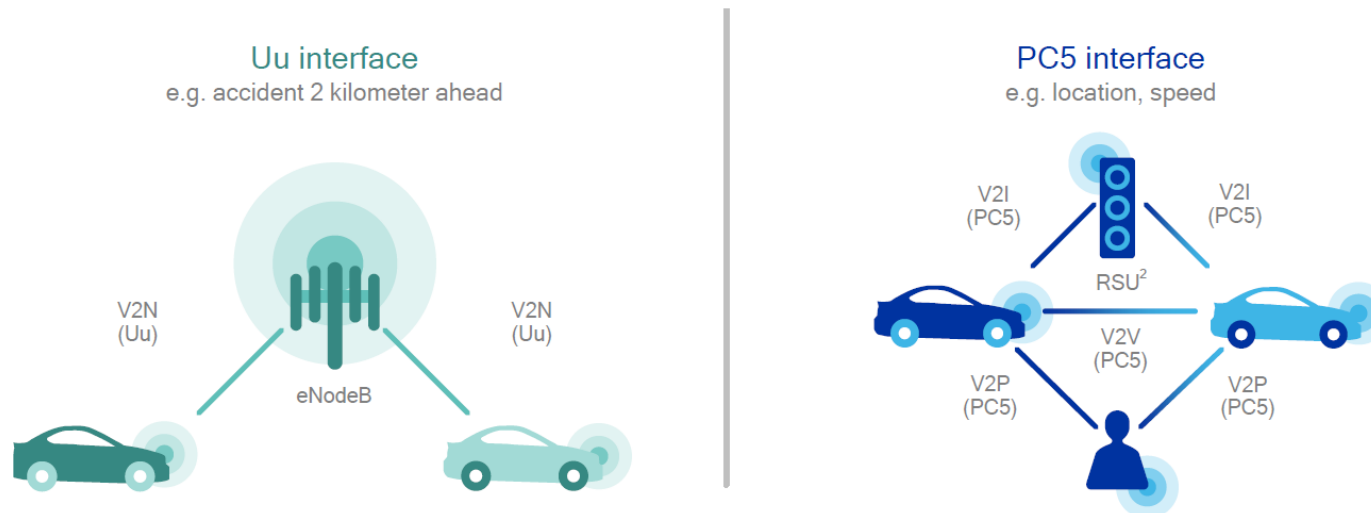
### ▶ **Outband communication**

- ▶ D2D links suffer interference from each other as well as from other devices operating in the same band
- ▶ Several centralized, distributed and hybrid algorithms proposed for interference management
  - ▶ **Power control** as interference can be reduced if UEs transmit at lower power levels
  - ▶ Careful **scheduling of transmissions**

# Lecture 8

## Cellular V2X (C-V2X)

- ▶ Created within **LTE Release 14 in 2016** and included a short-range interface that can be used also outside the cellular coverage
- ▶ LTE-V2X is **an evolution of D2D** functionalities
- ▶ Current version of C-V2X is called LTE-V2X as part of 3GPP Rel-14 & 15
- ▶ C-V2X is claimed as a unified technology platform which integrates:
  - ▶ Long-range cellular network communications → **LTE-V2X Uu**
  - ▶ Short-range, network-less, direct communications → **LTE-V2X PC5**

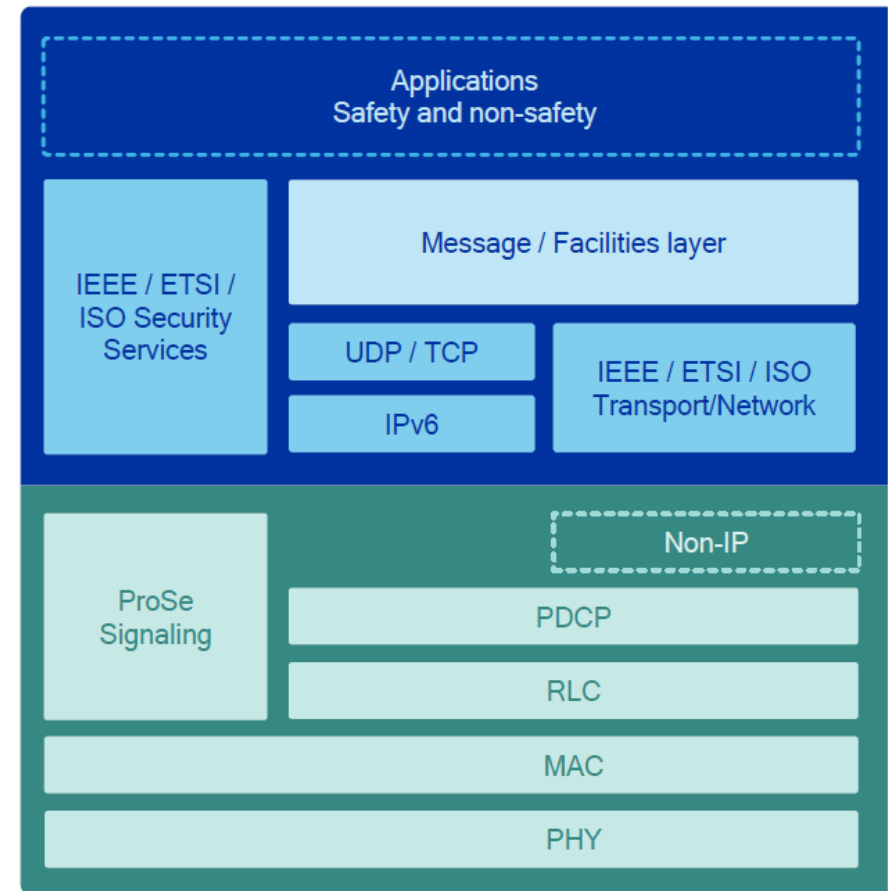


Source: Qualcomm

# Lecture 8

## Cellular V2X (C-V2X) Protocol Stack

- ▶ Reuse of **DSRC/ITS-G5** established service and app layers
  - ▶ Already defined by automotive and standards communities, e.g. ETSI, SAE
  - ▶ Developing abstraction layer to interface with 3GPP lower layers
- ▶ Reuse of existing **security** and **transport** layers



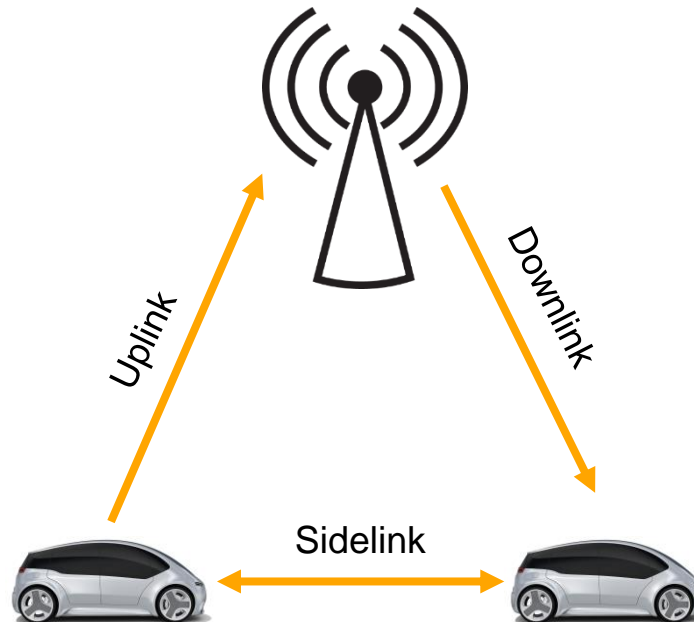
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# Lecture 8

## *C-V2X Radio Interfaces*

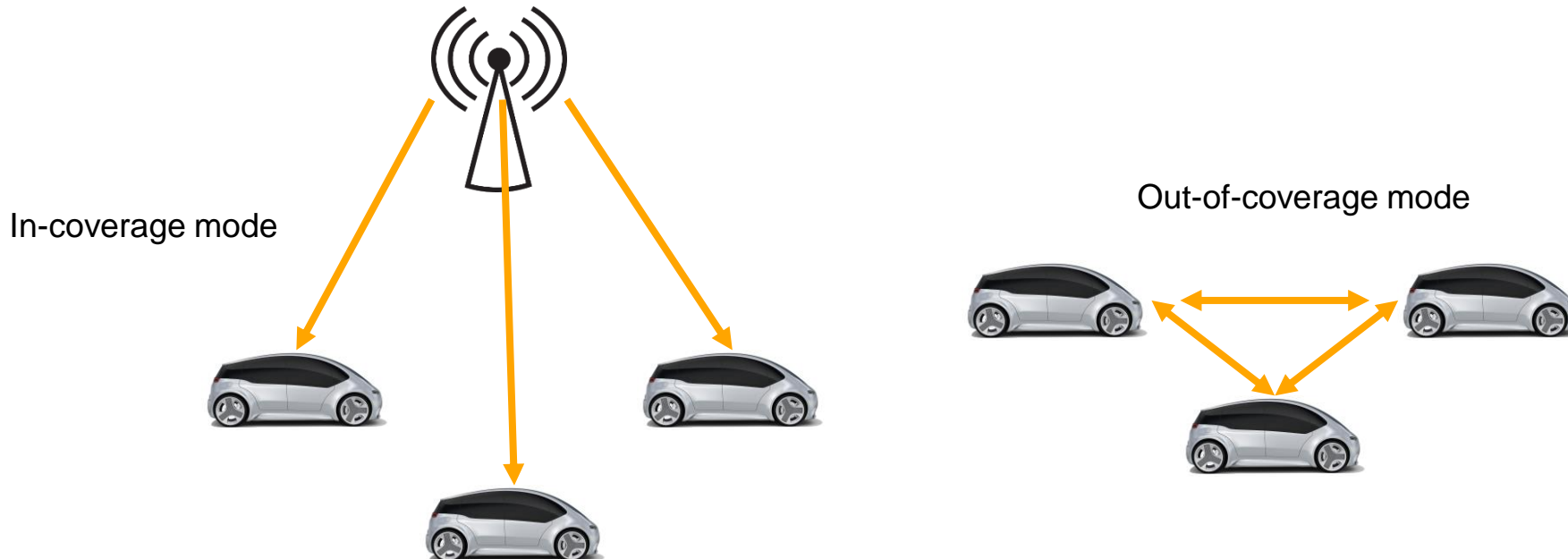
- ▶ LTE-V2X standard includes two radio interfaces:
  - ▶ **Uu interface** to support vehicle-to-infrastructure communications (uplink and downlink)
  - ▶ **PC5 interface** to support V2V communications based on direct LTE sidelink



# Lecture 8

## C-V2X Communication Mode

- ▶ **LTE sidelink or D2D communication** introduced for public safety has defined two modes of operation:
  - ▶ **Mode 1** and **mode 2** for **centralized** and **distributed scheduling** of UE transmissions
    - ▶ Centralized scheduling occurs at the eNB → **In-coverage mode**
    - ▶ Distributed scheduling is carried out by the D2D UEs themselves with no need to be in coverage area of the eNB → **Out-of-coverage mode**



# Lecture 8

## *C-V2X Communication Modes (1/2)*

- ▶ **Mode 1** and **2** were designed with the objective of **prolonging the battery lifetime** of mobile devices at the **cost of increasing the latency**
- ▶ V2X network requires **highly reliable** and **low-latency** communications
- ▶ Two new communication modes (modes 3 and 4) were specifically designed to satisfy the latency requirement and accommodate high density of vehicles
  - ▶ **Mode 3**: Cellular network selects and manages the radio resources used by vehicles for their direct V2V communications
  - ▶ **Mode 4**: Vehicles autonomously select the radio resources for their direct V2V communications

# Lecture 8

## *C-V2X Communication Modes (2/2)*

Mode	Scheduling method	Channel access	Use case	Release
Mode 1	eNB	eNB-controlled	Public safety VoIP	LTE Rel-12
Mode 2	Distributed	Random, with blind re-transmissions	Public safety VoIP	LTE Rel-12
Mode 3	eNB	eNB-controlled	V2X	LTE Rel-14
Mode 4	Distributed	Sensing, with semi-persistent transmission	V2X	LTE Rel-14

# Lecture 8

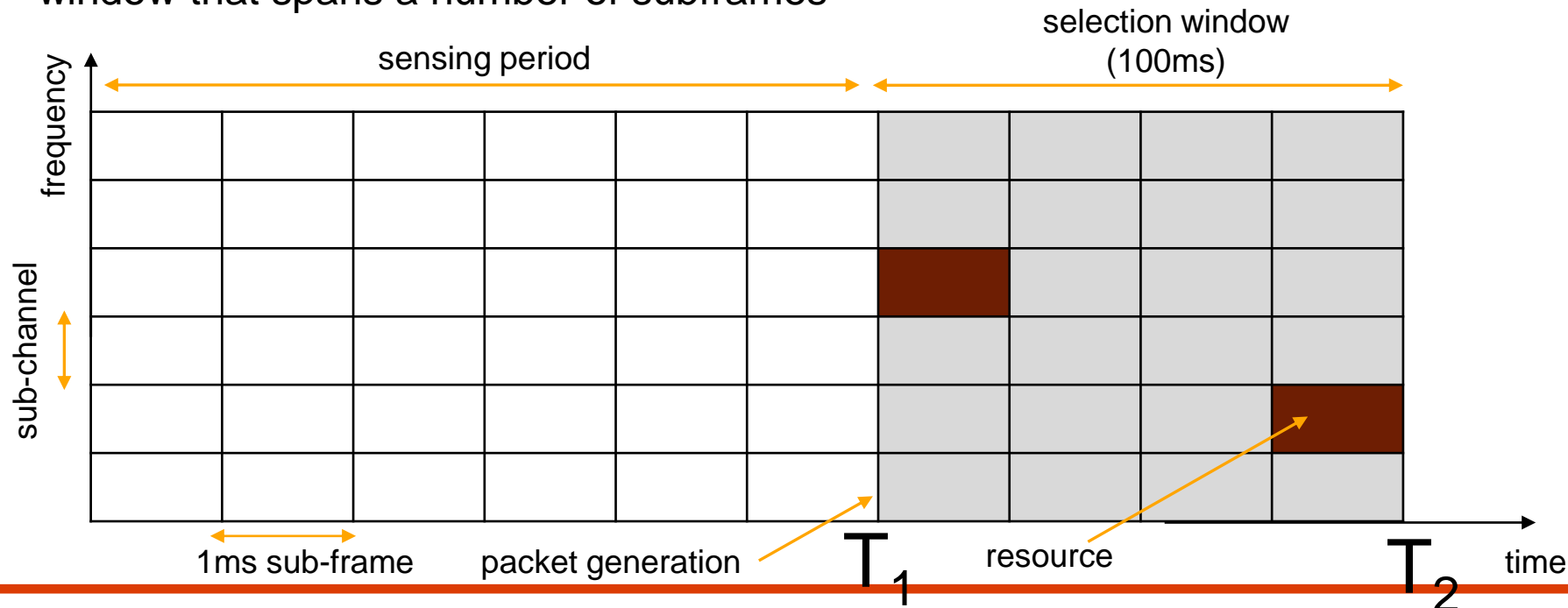
## *C-V2X Communication Mode 4*

- ▶ **Mode 4** offers an **alternative** technology to DSRC or ITS-G5 as resource is **self-allocated** for V2X transmissions
- ▶ It operates **without infrastructure** support although the UEs could be in eNB coverage
- ▶ It uses a specific **resource pool configuration** and **semi-persistent scheduling (SPS)** to select and reserve resource for transmissions
- ▶ V2X resource pool indicates which **subframes** of a channel are utilized for **V2X**
  - ▶ Rest of the **subframes** can be utilized by other services, including **cellular communications**

# Lecture 8

## *Sensing-based Semi-Persistent Scheduling (SPS)*

- ▶ Introduced to support services that require **deterministic latency**
- ▶ Mode 4 adopts this concept and uses **sensing** to determine **suitable semi-persistent transmission** opportunities
  - ▶ Set of **sub-frames** and **sub-channels** for transmission
- ▶ UE shall select a **set of candidate** single-subframe resources within the selection window that spans a number of subframes



# Lecture 8

## *Resource Reservation in SPS (1/4)*

- ▶ Whenever a vehicle needs to reserve new resources, it randomly selects a **reselection counter (RC)**
  - ▶ After each transmission, **RC** is decremented by **one**. When it is equal to **zero**, new resources must **be selected**
- ▶ **Steps**
  1. When a vehicle needs to transmit a new packet and the RC is zero, it has to reserve new resources within a **Selection Window (SW)**
    - ▶ **SW** is the **time window** between the time the packet has been **generated** and the defined **maximum latency** (e.g.  $T_2=100$  ms for 10Hz)
    - ▶ Vehicle **identifies** within **SW** the resources it could reserve
    - ▶ A **shorter window** provides a **shorter latency** but might **increase** the **probability of collisions**

# Lecture 8

## *Resource Reservation in SPS (2/4)*

2. Vehicle creates a list of **available resources** it could reserve

- ▶ This list includes all the resources **except** those that meet the following two conditions:
  - ▶ Resource will be utilized by **another vehicle** in the SW
  - ▶ **Reference Signal Received Power (RSRP)** over the resource is **higher** than a given **threshold**
- ▶ The list must contain at least **20%** of all the resources initially identified in the SW
  - ▶ Otherwise the process is iteratively executed until the **20% target** is met
  - ▶ In each iteration, the RSRP threshold is **increased by 3dB**



# Lecture 8

## *Resource Reservation in SPS (3/4)*

3. Vehicle creates a **list of candidate resources** that includes the resources previously identified that experienced the lowest **average RSSI (Received Signal Strength Indicator)**
  - ▶ Size of the **list must be equal to the 20%** of all the resources in the SW identified during the initial step
  - ▶ Vehicle then **randomly** chooses **one** of the candidate resources in the list, and **reserves it for the next n transmissions** where **n** is given by the re-selection counter

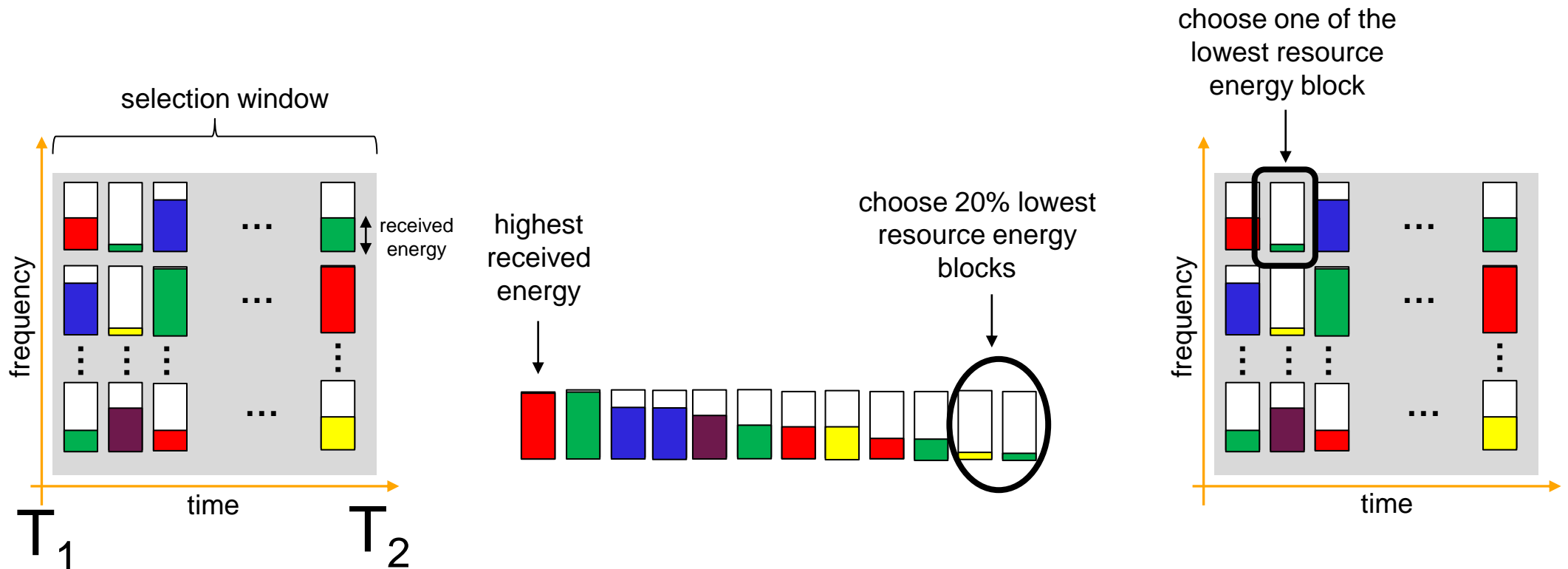
# Lecture 8

## Resource Reservation in SPS (4/4)

Measure resource energy on available resources

Rank resources based on received energy

Choose one of the lowest energy resources for transmission



# Lecture 8

## *Transmission Errors in Mode 4*

### ► **Errors due to half-duplex transmissions**

- A packet which cannot be received because the vehicle is transmitting its own packet in the same sub-frame → e.g. two vehicles selecting the same sub-frame

### ► **Error due to received signal power below the sensing power threshold**

- Depends on the **path loss** (distance between transmitter and receiver) and **sensing power threshold**

### ► **Error due to packet collisions**

- Occurs when at least two vehicles transmit on the same resource (i.e. the same sub-channel and sub-frame)
- Mainly depends on the traffic density

# Lecture 8

## *C-V2X Communication Mode 3 (1/2)*

- ▶ Each **operator** can implement its **own resource management algorithm** that should fall under one of these two categories:
  - ▶ **Dynamic scheduling**: Vehicles request sub-channels to the eNB for each packet transmission
    - ▶ Increased cellular **signaling overhead** and packet **latency**
  - ▶ **SPS**: eNB reserves sub-channels for the periodic transmissions like in mode 4
    - ▶ BUT in contrast with mode 4, it is up to the eNB to decide **how long** the reservation should be **maintained**
    - ▶ Mode 3 does **not define a reselection counter**
- ▶ Vehicles operating under mode 3 can be supported by different cellular operators
  - ▶ **Different operators** transmit in **different carriers** → Vehicle's ability to simultaneously receive in multiple carriers
  - ▶ **Different operators** share the **same carrier** → Coordination mechanism between operators is needed to avoid **packet collisions**

# Lecture 8

## *C-V2X Communication Mode 3 (2/2)*

- ▶ Vehicles also communicate using **sidelink** or **V2V communications** under mode 3
- ▶ But the selection of **sub-channels** is managed by the **eNB**
  - ▶ **Not** by each **vehicle** as in mode 4
- ▶ Mode 3 is **only** available when vehicles are under **cellular coverage**
- ▶ Mode 3 utilizes the **same sub-channel arrangements** as defined for mode 4

# Lecture 8

## *C-V2X Decentralized Congestion Control*

- ▶ In dense scenarios, all stations **shall cooperate** to keep the **channel unsaturated**
- ▶ Metrics to characterize the channel state:
  - ▶ **Channel busy ratio (CBR)**: Portion of sub-channels in the resource pool whose RSSI measured exceeds a pre-configured threshold
  - ▶ **Channel occupancy ratio (CR)**: Total number of sub-channels used for its transmissions divided by the total number of sub-channels in a predefined time window
- ▶ **Transmit adaptation mechanisms** → If measured CR is higher than the CR limit, the station has to decrease its CR below that limit by applying one of following technique
  - ▶ **Drop packet transmission**: Simply drops the packet transmission
  - ▶ **Adapt the data rate**: Reduce the number of sub-channels used for the transmission
  - ▶ **Adapt transmission power**: reduce transmission power → Overall CBR in the area will be reduced

# Lecture 8

## *Some Communication Challenges of C-V2X*

- ▶ **Synchronization:** To address the synchronization requirements leading to frequency errors and timing errors, C-V2X users rely on GPS → Problematic in locations such as tunnels, underground parking lots and urban canyon
- ▶ **Long packet latency:** Due to the delay selection window of 20-100ms in the PHY
- ▶ **Resource allocation:** Resources are reserved in a semi-persistent manner, i.e., before knowing the exact packet size → Reservation will result either in over-allocation (inefficient) or under-allocation of resource size
- ▶ **Half-duplex problem:** Due to the multiple-users access scheme, users will miss the safety messages that were transmitted concurrently to theirs. This does not occur in ITS-G5, which is based on a “listen-before-talk

# Lecture 8

## *Literature*

- ▶ C. Sommer et al.: “Simulation Tools and Techniques for Vehicular Communications and Applications”, 2015
- ▶ M. Gonzalez-Martín et al.: ”Analytical Models of the Performance of C-V2X Mode 4 Vehicular Communications”, 2018
- ▶ Amr Nabil et al.: “Performance Analysis of Sensing-Based Semi-Persistent Scheduling in C-V2X Networks”, 2018
- ▶ R. Molina-Masegosa and Javier Gozalvez: “A New 5G Technology for Short-Range Vehicle-to-Everything Communications”, 2017
- ▶ A. Mansouri et al.: “A First Investigation of Congestion Control for LTE-V2X Mode 4”, 2019

