HOCHSCHULE
HANNOVER
UNIVERSITY OF
APPLIED SCIENCES
AND ARTS
–
Fakultät IV
Wirtschaft und
Informatik

Fahrzeugvernetzung – V2X

Lecture 8: Cellular V2X

Hugues Tchouankem, 17.11.2021

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

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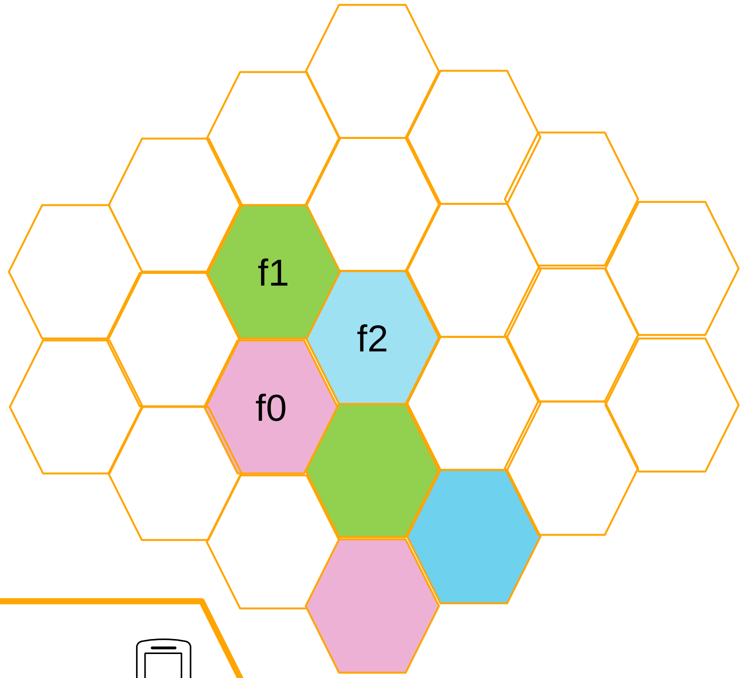
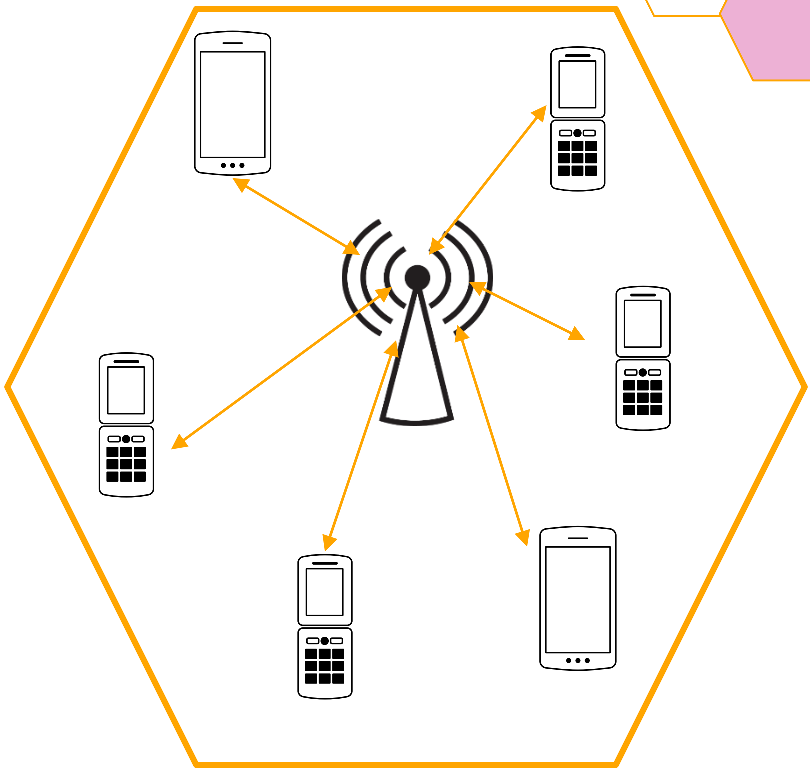
Cellular Networks - Basics

- ► 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





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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

BSC: Base Station Controller

BTS: Base Transceiver Station

RNC: Radio Network Controller

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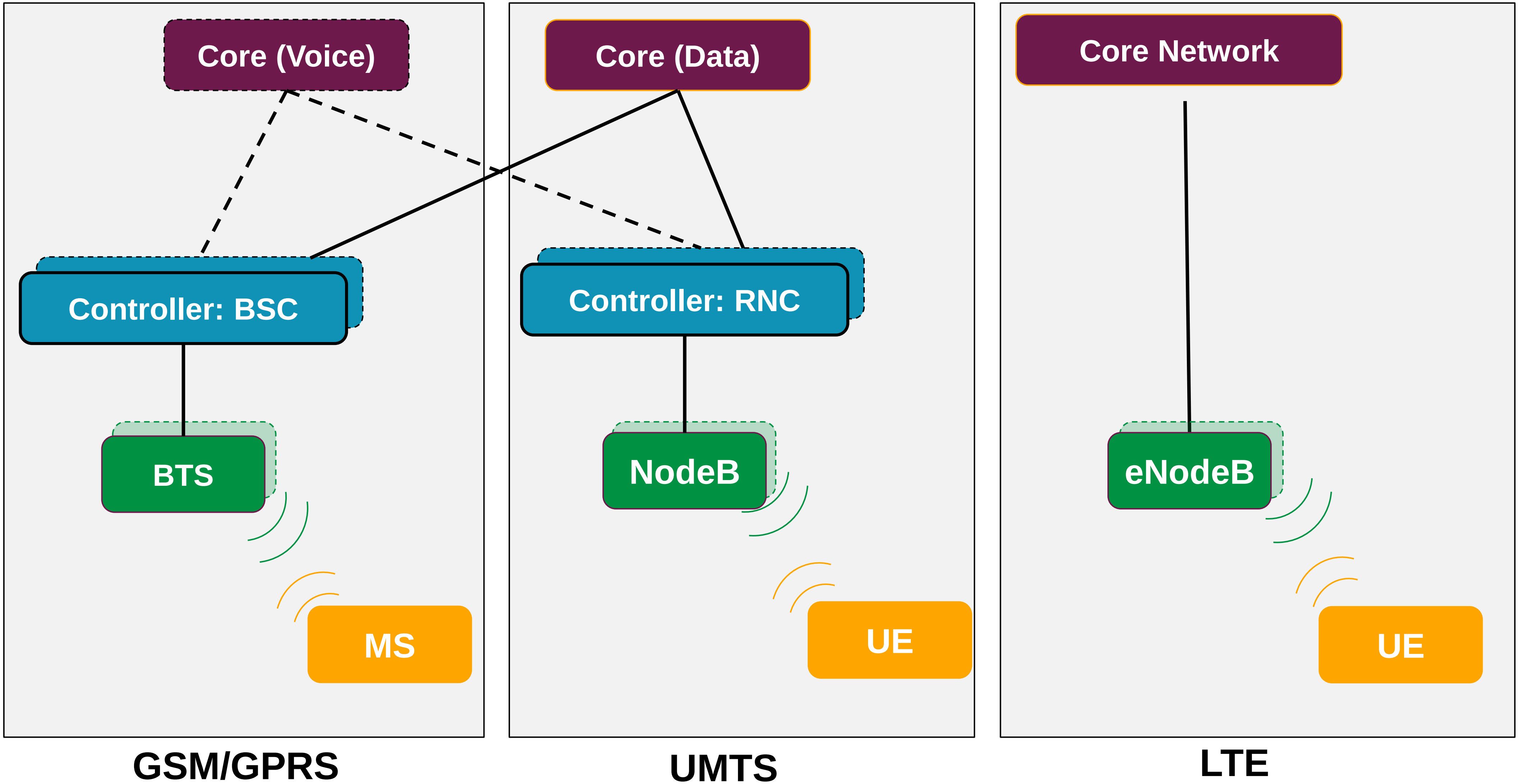
Cellular Networks – Architecture of three Generations



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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

BTS: Base Transceiver Station   BSC: Base Station Controller   RNC: Radio Network Controller

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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**

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Cellular Networks – Universal Mobile Telecomunication 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 GMS networks
  - ► 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
- ► **High speed downlink packet access** (**HSDPA**) - as an extension of UMTS - moves **scheduling decisions** from the radio network controller (**RNC**) into the base station (called **eNodeB**)
  - ► To **reduce delays** and allow data transmission on multiple logical channels in the downlink
- ► **High speed uplink packet access** (**HSUPA**) allows more efficient coding in the uplink
- ► Data speeds pushed to **7.2 Mbit/s**

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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

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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

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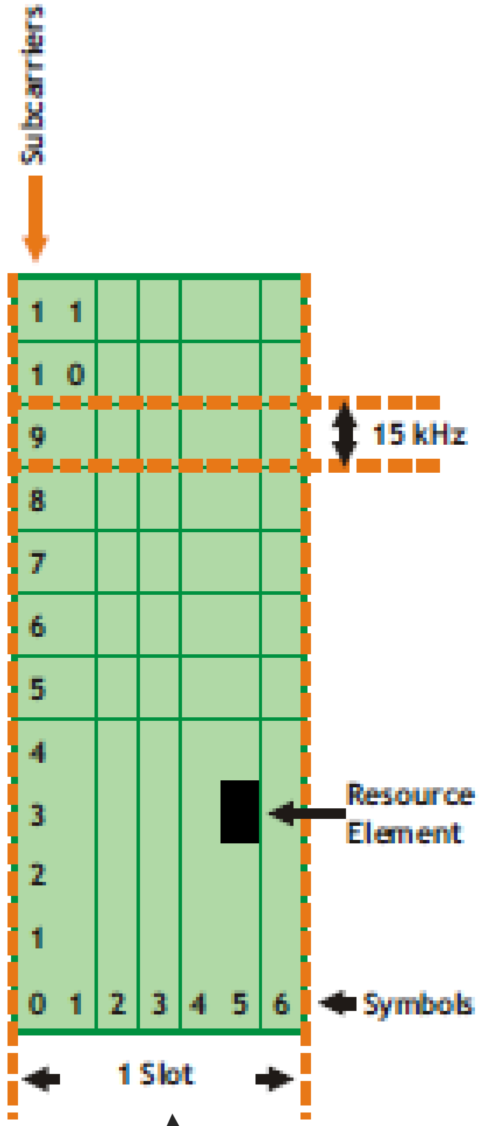
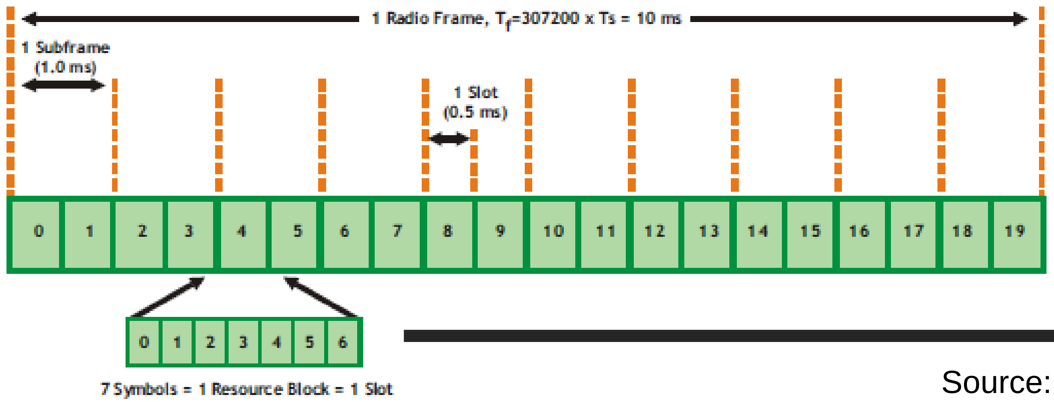
Cellular Networks – Long Term Evolution (LTE) (3/3)

- 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





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Evolution of C-V2X

D2D

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

C-V2X

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

5G for V2X

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

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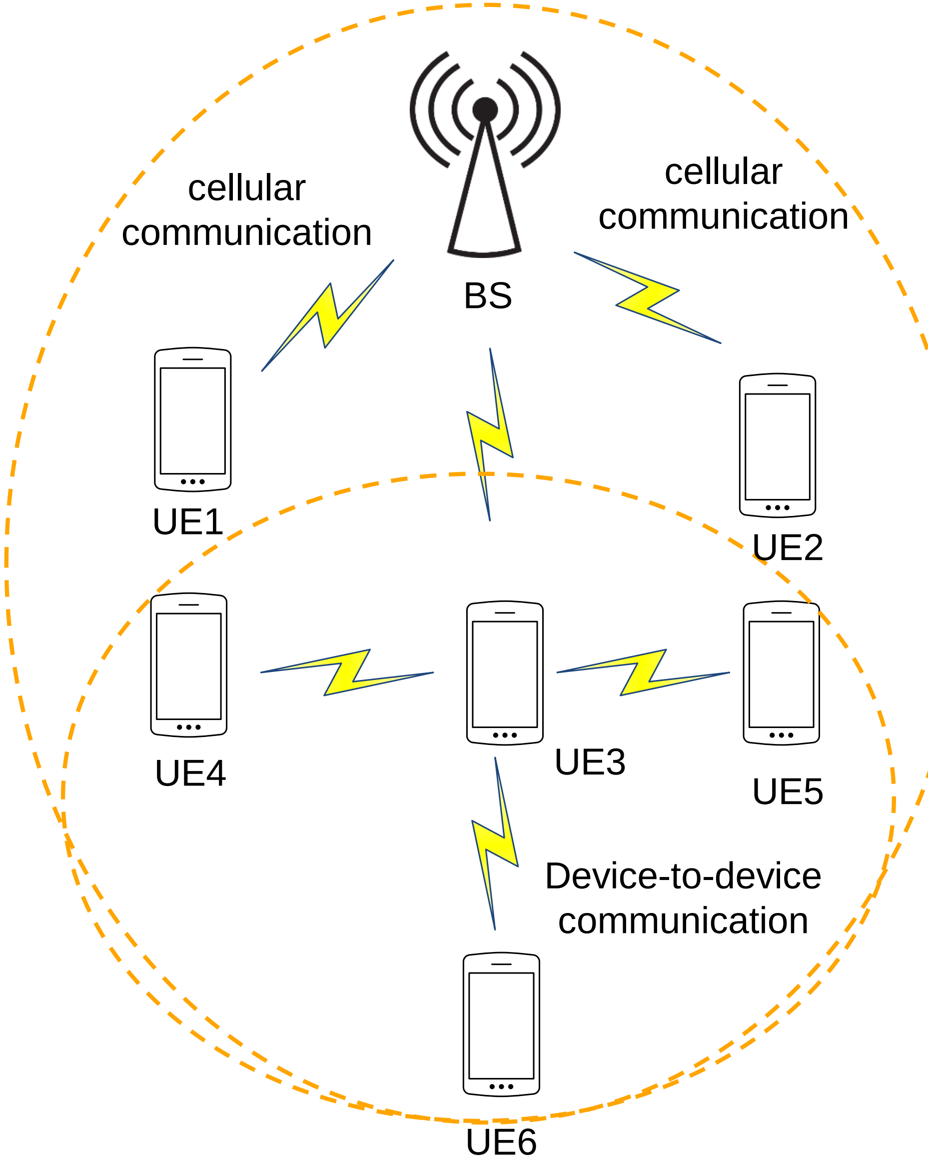
Device-to-Device Communication

- 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



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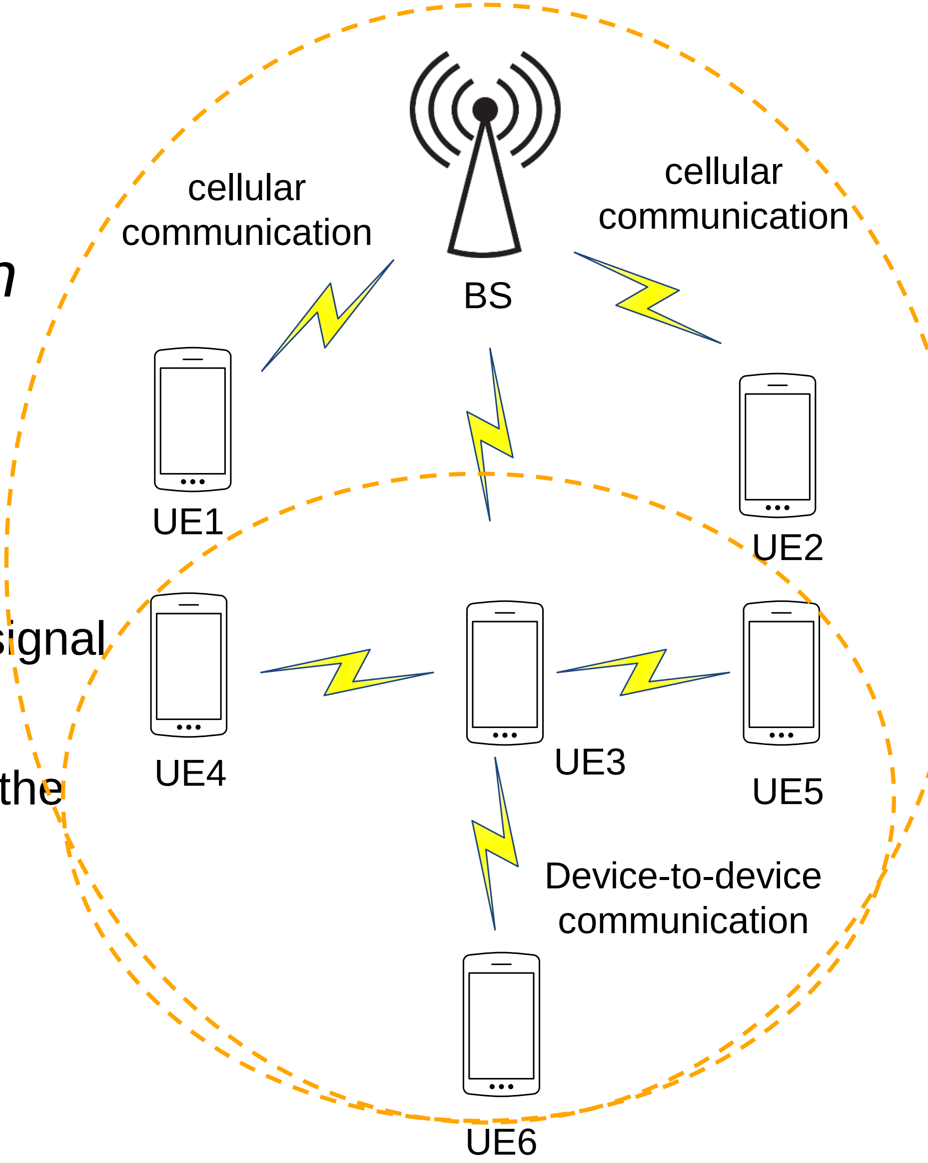
D2D Communication - Coverage Extension



- **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

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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

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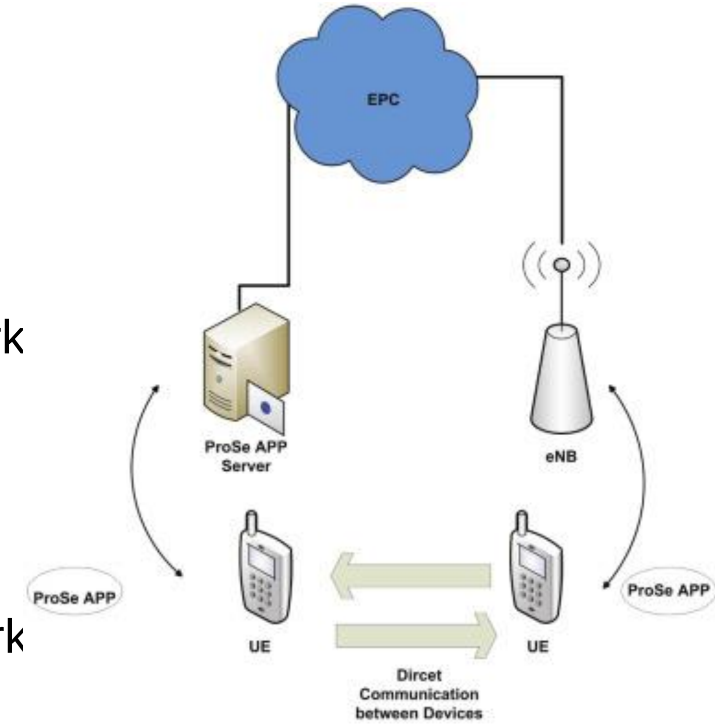
D2D Proximity-based Services (ProSe)

- ► 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**



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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
- Some physical layer and MAC layer schemes for synchronization available

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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

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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

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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 βB of them
  - ► Choosing optimal value of f and β is challenging

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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**

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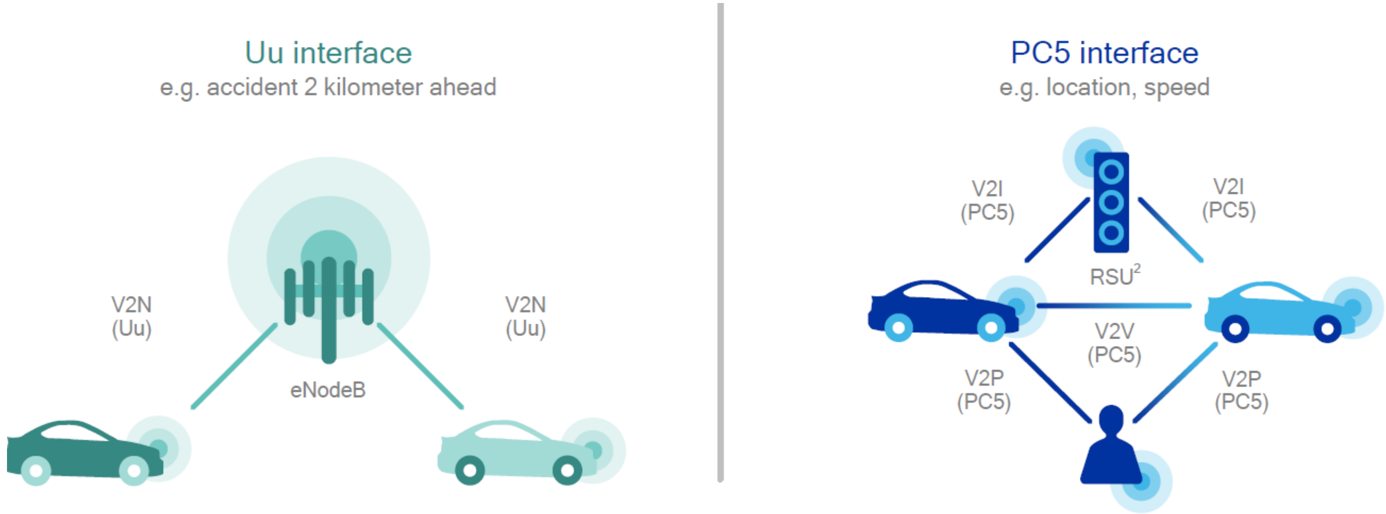
Cellular V2X (C-V2X)

- ► 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 Device-to-Device (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:
  - ► Short-range, network-less, direct communications → **LTE-V2X PC5**
  - ► Long-range cellular network communications → **LTE-V2X Uu**



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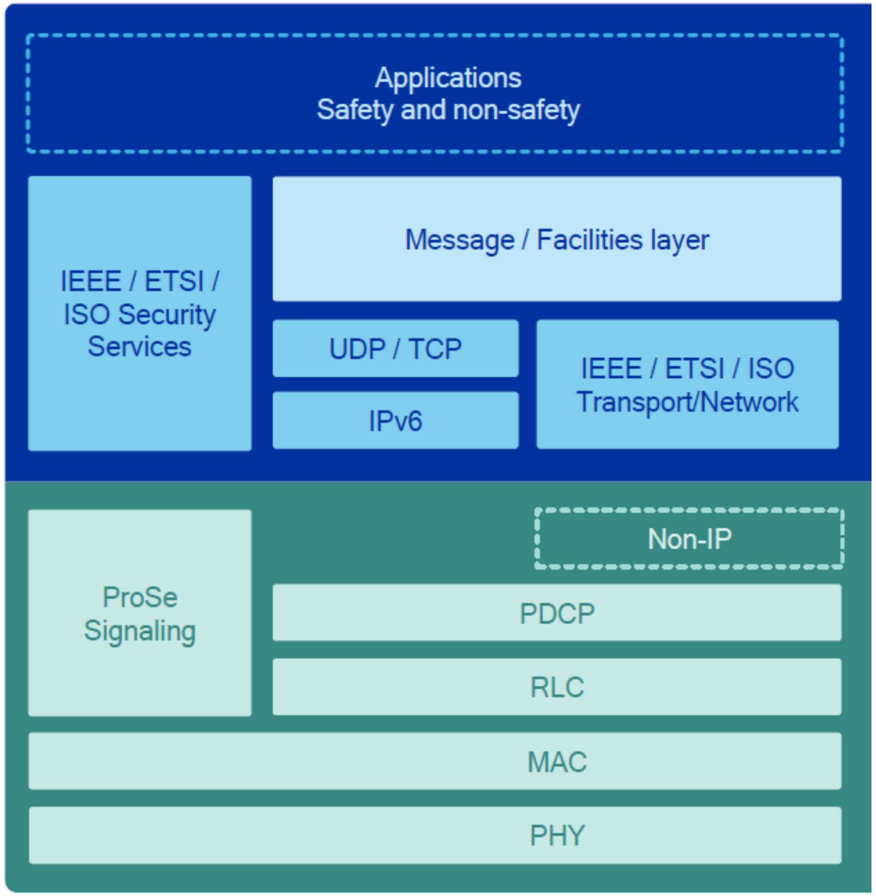
Cellular V2X (C-V2X) Protocol Stack

- 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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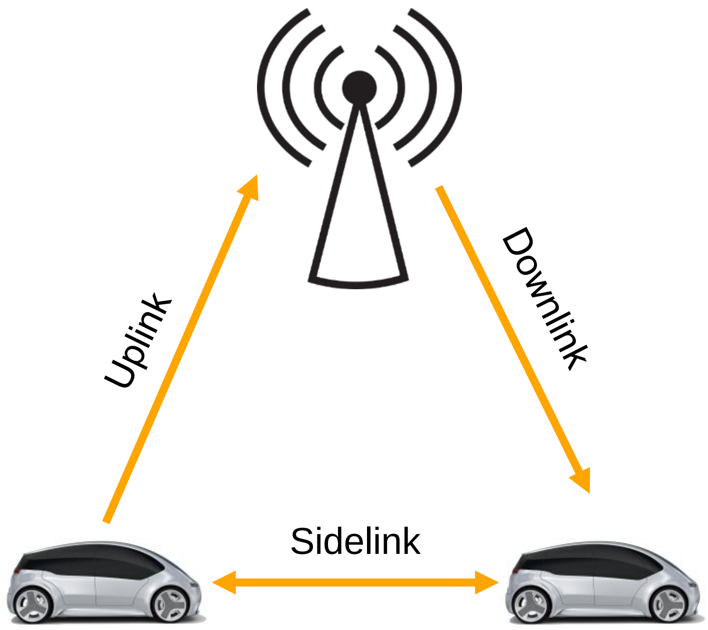
C-V2X Radio Interfaces

- ► 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



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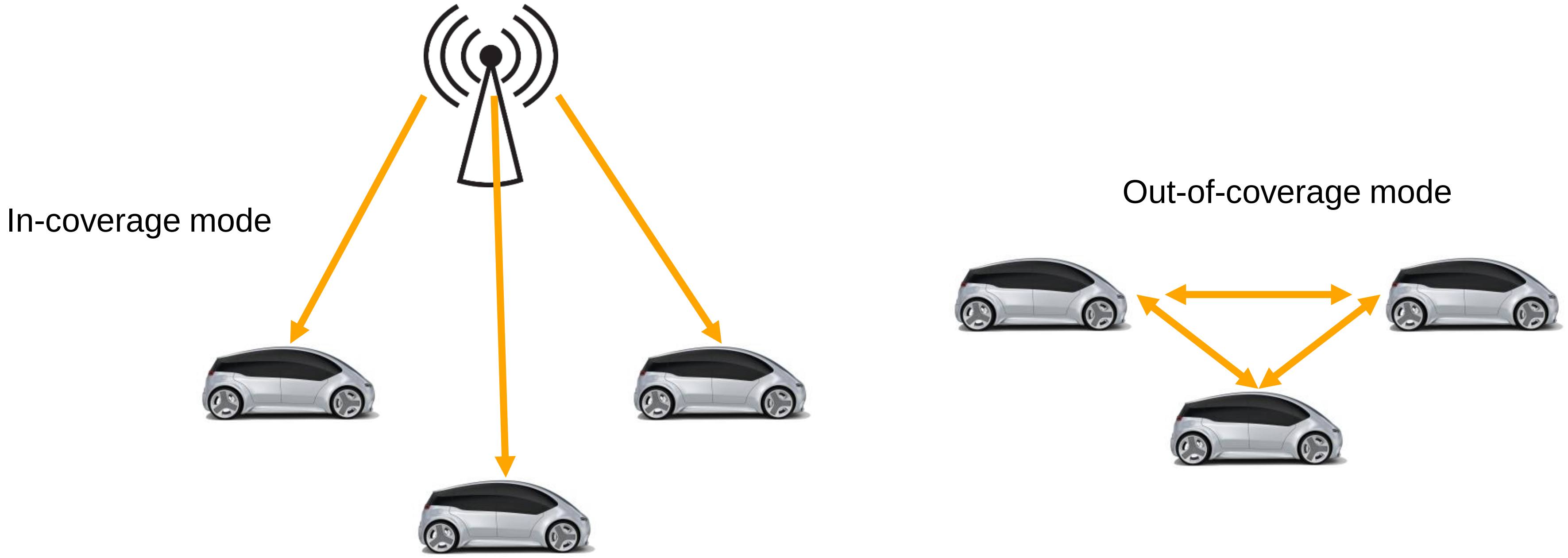
C-V2X Communication Mode

- **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**



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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

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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

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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**

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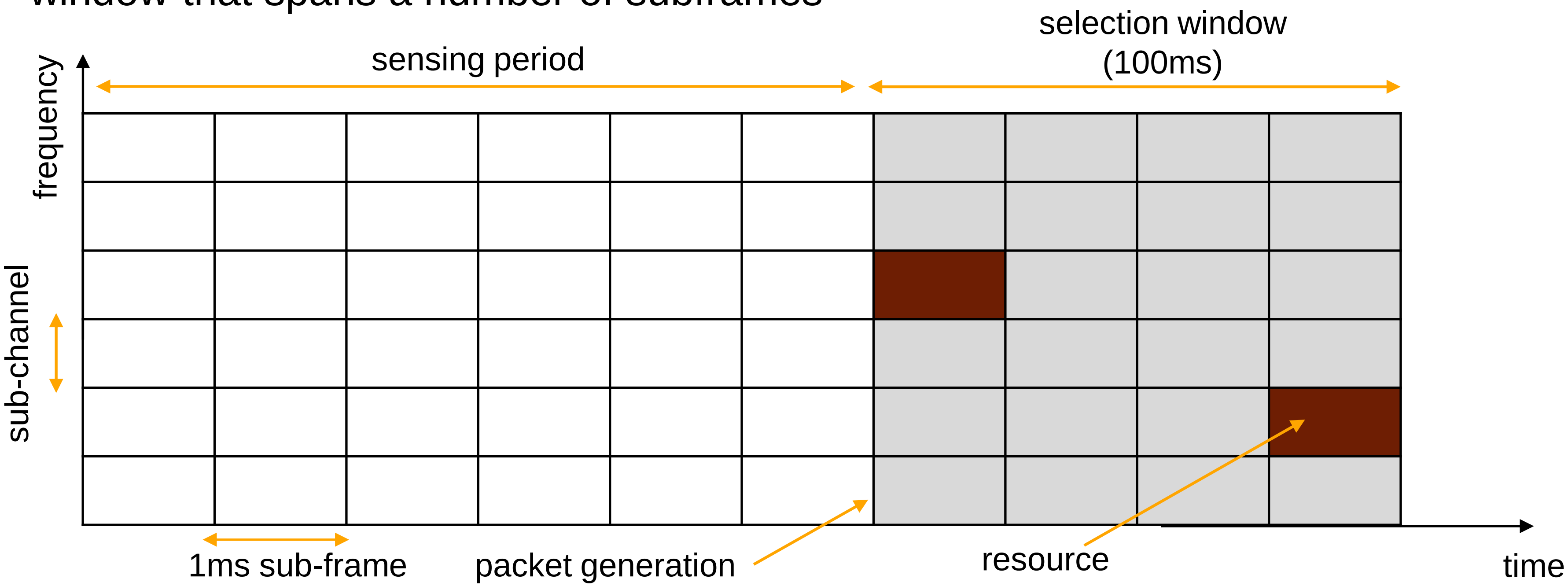
Sensing-based Semi-Persistent Scheduling (SPS)

- 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



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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. 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**

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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**

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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

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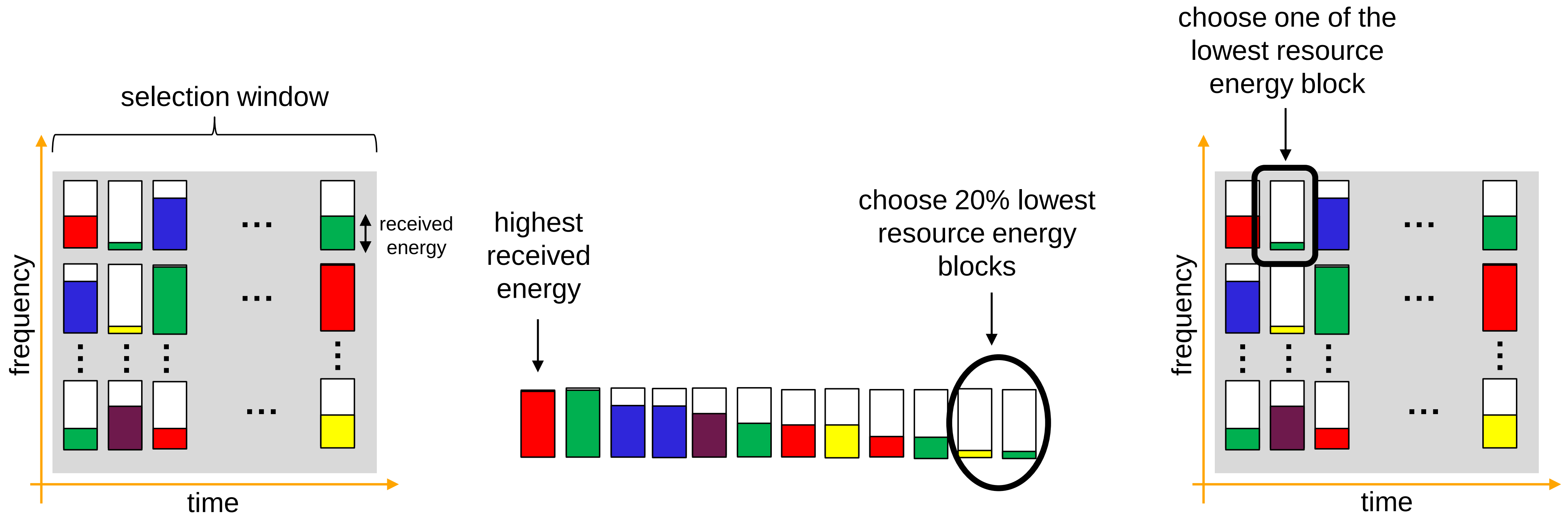
Resource Reservation in SPS (4/4)

Measure resource energy on available resources

Rank resources based on received energy

Choose one of the lowest energy resources for transmission



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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

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C-V2X Communication Mode 3 (2/2)

- 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**

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C-V2X Communication Mode 3 (1/2)

- ► 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

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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

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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

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Literature

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- ► Amr Nabil et al.: “Performance Analysis of Sensing-Based Semi-Persistent Scheduling in C-V2X Networks”, 2018
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