

# Cellular systems – 5G and beyond

## Part I

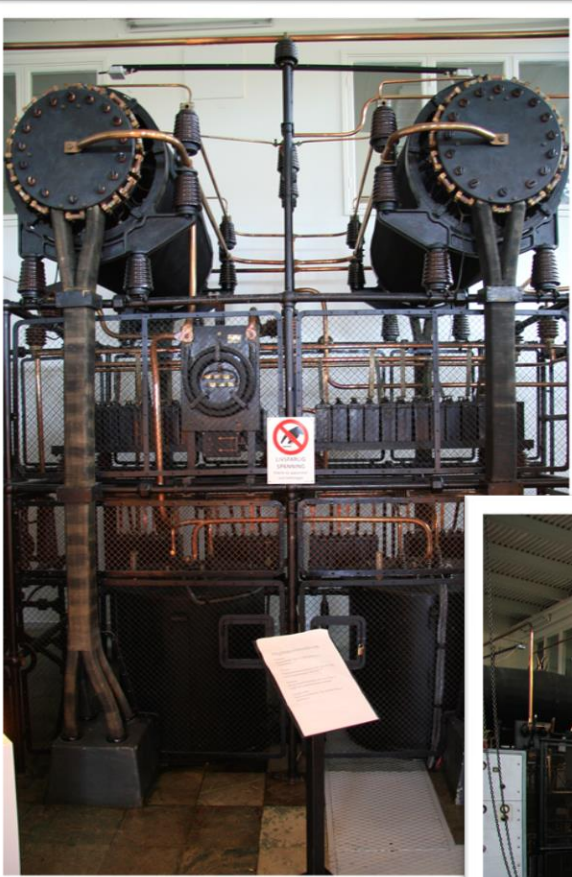
Dr Stefan Parkvall  
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Senior Expert, Ericsson Research  
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# Grimeton, early 1920s



Ernst F. W. Alexandersson  
Civ. Ing., KTH



# Outline



- Introduction
- Cellular systems and basics for LTE (4G) and NR (5G)
- LTE evolution
- NR
- Standardization in practice
- 6G



# Introduction



# Inauguration of a new Pope

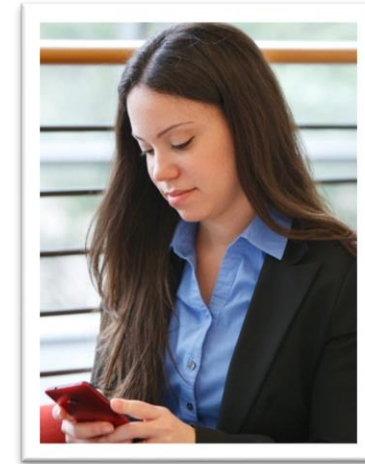




# Inauguration of a new Pope



# 4G – mobile broadband



## LTE – the global standard for mobile broadband

### High peak data rates

- 2008: 300 Mbit/s DL, 75 Mbit/s UL
- Now: 25 Gbit/s DL, 9.6 Gbit/s UL

### Low latency

- 5 ms user plane, 50 ms control plane

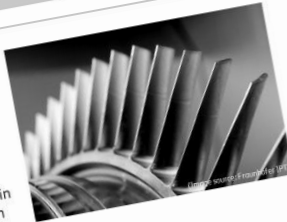


# 5G – going *beyond* the smartphone



## Complex metalworks not possible to monitor today

- Ericsson has together with the Fraunhofer IPT research center optimized the production of BLaded dISKS, BLISKS.
- A BLISK is used in turbines such as jet engines. It consists through 5G technology
- BLISKS are one of the most difficult machining parts to produce, and the rework rates are very high (~25%)
- A key aspect of BLISK production (and metal processing in general) is that the process is not monitored – if data can be collected during manufacturing and used to finetune the process, rework rates can be significantly reduced



## 5GEM

### 5G Enabled World Class Manufacturing

- Evaluate 5G technology in a manufacturing industry
- Understand ICT opportunities and solutions



Partners: SKF, CHALMERS, ERICSSON



## CMA

### Test Site for Future Automated and Shared Mobility Systems

- Exploring the use of 5G networks for intelligent transport systems
- Investigating "as-a-service" offerings for network operators and automotive OEMs

- Reduced vehicle fleet operations cost
- Enter service awareness and reduced travel time for passengers
- Usage of cellular networks in new markets

Partners: SCANIA, ERICSSON, IRII - INTEGRATED TRANSPORT RESEARCH LAB, SWEDISH INSTITUTE OF TECHNOLOGY



## REMOTE OPERATION

### Robot remote control with haptic feedback over LTE

- Evaluate mobile communication in industrial reliability



## 5G NETMOBIL

- Develop overall communication infrastructure for tactile connected driving beyond the self-contained sensor based autonomous driving
- improved road traffic safety, less environmental impact, and higher efficiency of road transportation
- Provide 5G communication technologies and network architecture for tactile connected driving
- Low latency required by real-time vehicle control and cooperative maneuvers
- High reliability and availability for highly mobile environments
- Use cases:
  - Parallel cooperative driving of a fleet of farm machinery in off-road areas
  - Tactile connected driving of vehicles at intersections of urban roads
  - High-density platooning of trucks in automotive test field



## PIMM

### Pilot for Industrial Mobile Communication in Mining

- Explore future 5G Use Cases in underground mining
- Evaluate mobile communication infrastructure in an industrial context

- Increased Productivity and Improved Safety
- Industrial 5G requirements
- Understand eco system, business models, etc.

Partners: TeliaSonera, VOLVO, ABB, BOLIDEN, ERICSSON, etc.



## WITool

### Wireless Internet of Tools

- Enable IoT for construction equipment OEM (Husqvarna) and rental companies (Cramo)
- Capillary network connectivity, cloud, service enablement and machine analytics capabilities
- Demonstrated through automation of return process of machines at Cramo depot

- Efficient fleet management enabled by predictive maintenance and resource planning
- Automated processes, for example return process
- New business models
- Making use of generated data to improve products

Partners: Cramo, Husqvarna, ERICSSON





# 6G – *a trusted platform delivering ever-present intelligent communication including connectivity, data, and compute*

"6G" is broader than radio access alone

"6G" is the overall solution around 2030

"6G" is still in the research phase

The image shows a stack of four presentation slides, each with a hamburger menu icon in the top right corner.

- Slide 1: Some drivers for future technology evolution**  
Outside in perspective
- Slide 2: Use-case scenarios**  
Use-case scenarios enabled by the network platform  
The Internet of Senses  
Next-gen devices  
Multi-sensory computing  
Algorithms for the Internet of Senses  
Trustworthy Intelligence  
Network platform
- Slide 3: 6G – Capabilities**  
Extreme devices  
Security and privacy  
"Classical" communication  
New capability dimension
- Slide 4: Technology**
  - Limitless connectivity**
    - Network adaptability
    - End-to-end functions
    - Extreme performance
    - Embedded devices everywhere
  - Trustworthy Systems**
    - Security assurance
    - Service availability
    - Solutions built on conf. computing
    - Secure identities & protocols
  - Cognitive network**
    - Data-driven operations
    - Distributed intelligence
    - Continuous learning
    - Intent-based management
    - Explainable & trustworthy AI
    - Cognitive system
  - Network compute fabric**
    - Unified telco-IT ecosystem
    - Unified execution environment
    - Unified data infrastructure
    - Unified application management



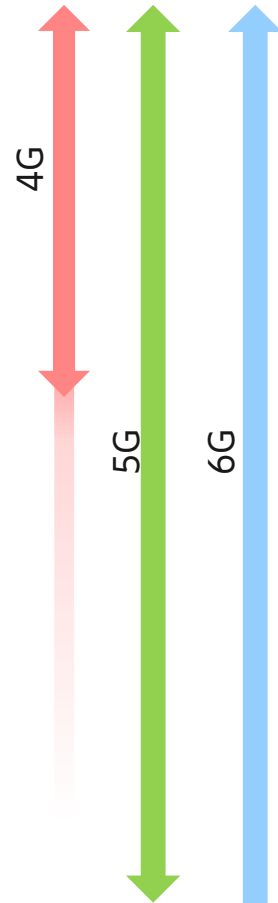
# Basics of cellular systems



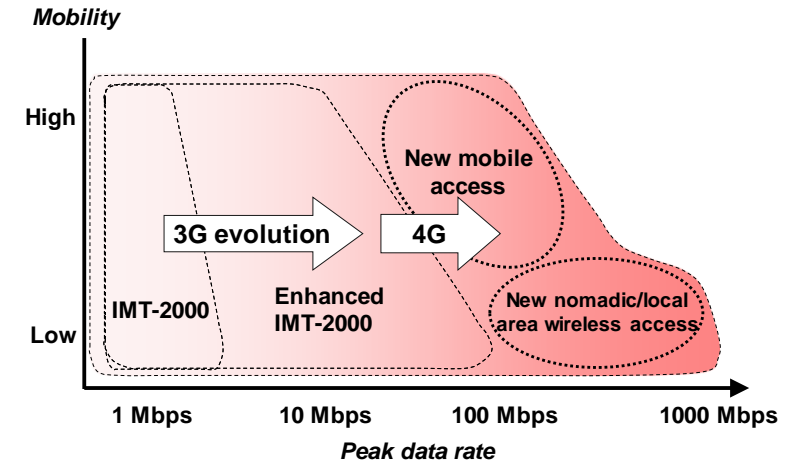
# What do we require from a wireless system?



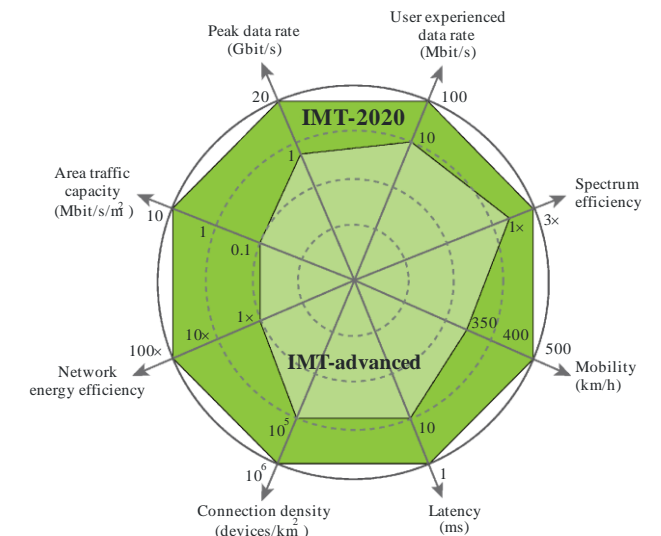
- Coverage
- Mobility
- High data rates
- High capacity
- Low latency
- High connection density
- High reliability
- ...



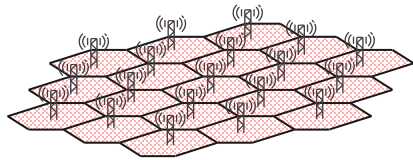
4G  
"The van diagram"



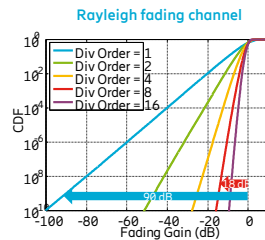
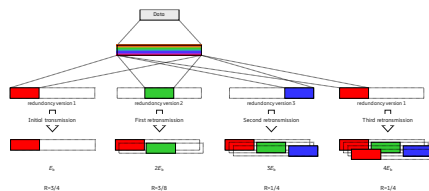
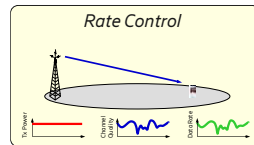
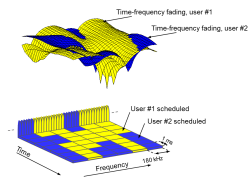
5G  
"The spider diagram"



# How do we get it?



- Spectrum
- Multiple cells
- Overall architecture
- Rate control, channel-dependent scheduling
- Hybrid-ARQ
- Diversity
- Fast processing
- Low overhead
- ...

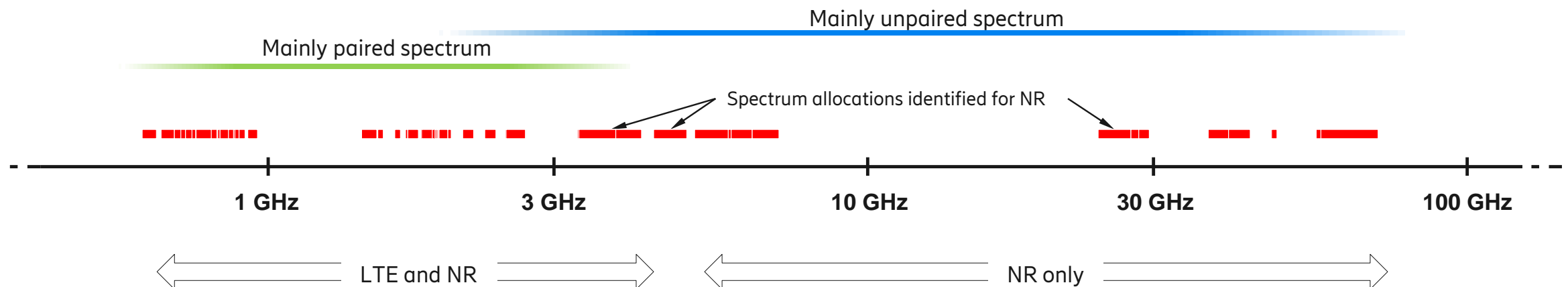




# What about spectrum?



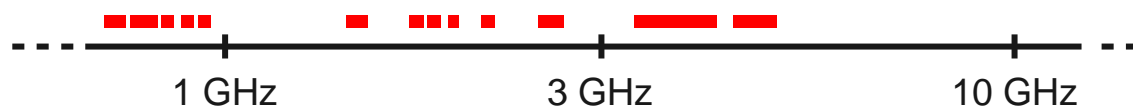
- “Lower” frequency bands
  - Reasonable bandwidths
  - Good for coverage
  - Typically FDD (frequency-division duplex)
- “Higher” frequency bands
  - Wide bandwidths ➡ high data rates
  - Challenging link budgets; beamforming crucial
  - Typically TDD (time-division duplex)



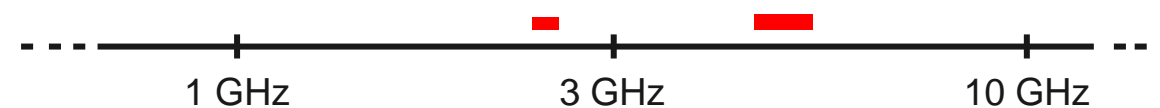
# What about spectrum?



- Licensed spectrum
  - Exclusive right to a certain frequency range
  - Control of the interference situation
  - 'High' output power ➡ long range
  - Typically associated with a license cost
- Examples:  
LTE, NR (and other cellular systems)



- Unlicensed spectrum
  - Anyone can use the radio frequencies
  - Unpredictable interference situation
  - Relatively low output power ➡ short range
  - No license cost
- Examples:  
WiFi, Bluetooth, LTE (later releases), NR

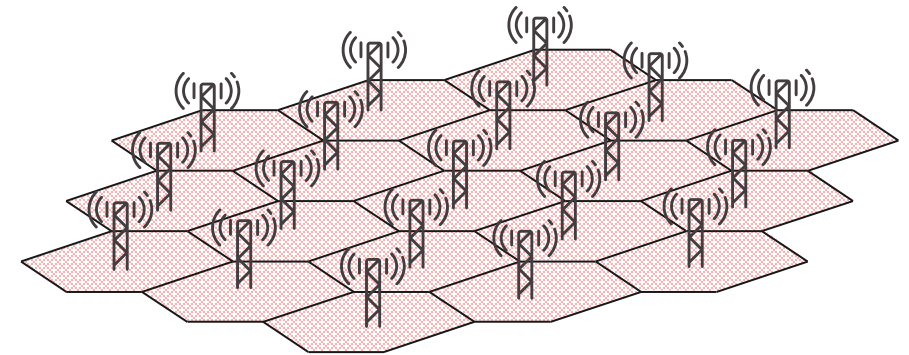




# Why is it called 'cellular'?



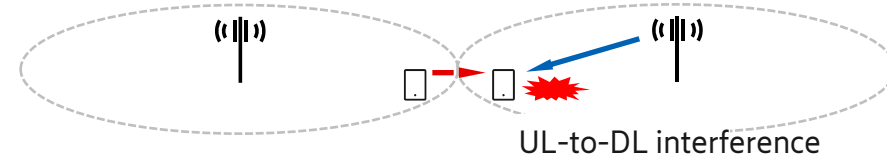
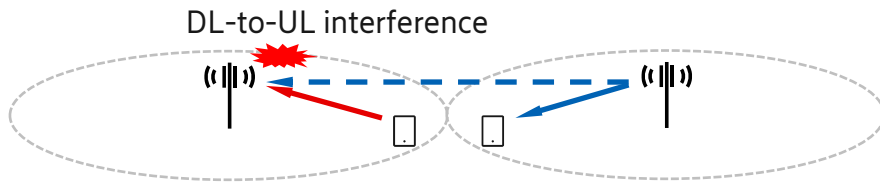
- Multiple cells used to cover a large area
  - Inter-site distance depends on scenario
    - ~100-300 m in dense urban (city centers),
    - ~several kilometers in rural
- Output power
  - Downlink; ~ 20 – 100 W (macro), <1 W (indoor)
  - Uplink; 200 mW
- Same frequency used in all cells ("reuse 1")
  - Inter-cell interference suppressed through processing gain (channel coding), interference level depends on instantaneous activity in neighboring cells



# Inter-cell interference in TDD networks



- Large power difference between DL and UL in wide-area networks
  - BS: above-rooftop antennas, Tx:  $\sim +46$  dBm, Rx:  $\sim -100$  dBm ➔ huge difference!
  - UE: non-elevated antennas, Tx:  $+23$  dBm

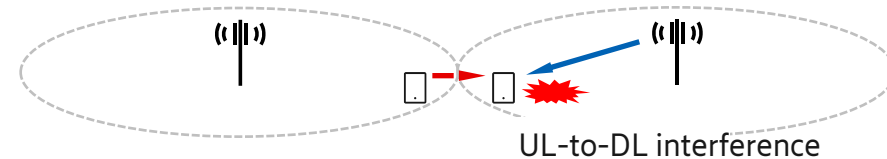
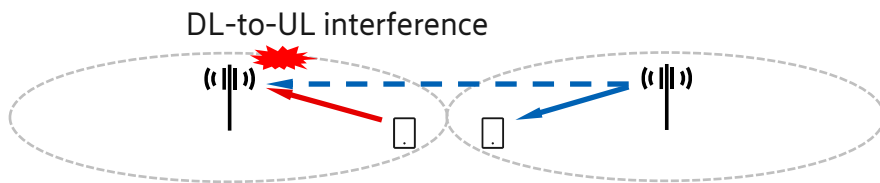




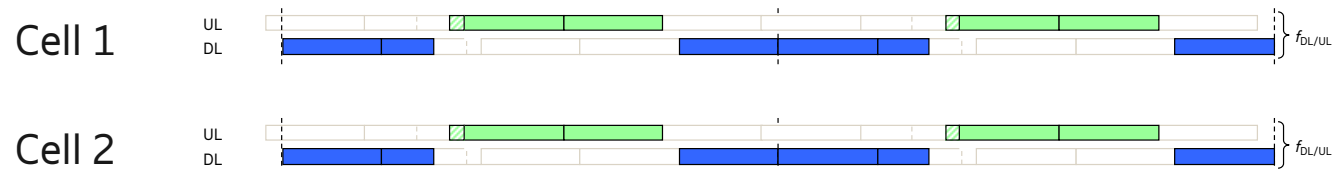
# Inter-cell interference in TDD networks



- Large power difference between DL and UL in wide-area networks
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  - UE: non-elevated antennas, Tx:  $+23$  dBm

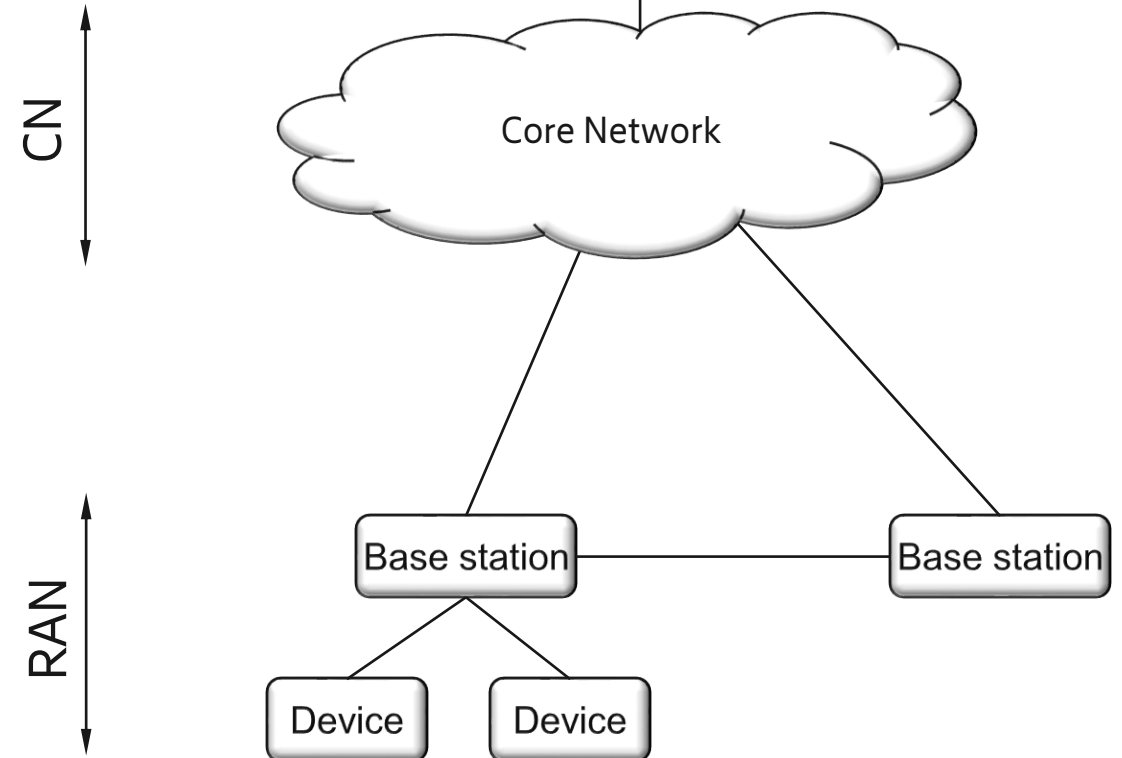


- Classical solution: same UL/DL allocation in all cells
  - “DL collides with DL”; avoids DL-to-UL interference
  - Guard period set taking inter-site distance into account



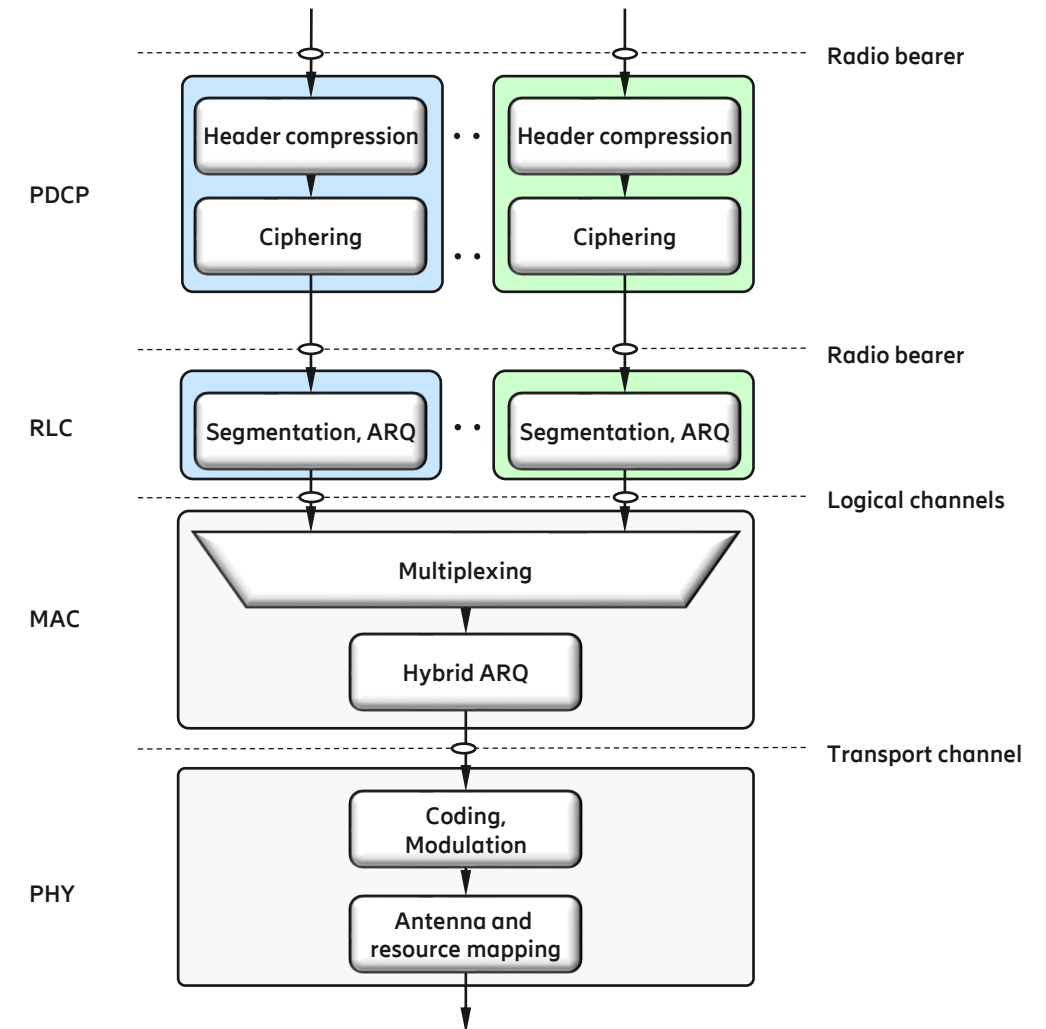
# Network architecture

- Core Network
  - Authentication, charging, setting up end-to-end connections, ...
- Radio-Access Network
  - Radio-related functionality, e.g. scheduling, radio-resource handling, retransmission protocols, coding/modulation, multi-antenna schemes, ...



# Protocol architecture

- Packet Data Convergene Protocol
  - Header compression to reduce overhead
  - Ciphering for security
- Radio Link Control
  - Segmentation/concatenation
  - RLC retransmissions
  - In-sequence delivery
- Medium Access Control
  - Multiplexing of radio bearers
  - Hybrid-ARQ retransmissions
- Physical Layer
  - Coding, Modulation
  - Multi-antenna processing
  - Resource mapping

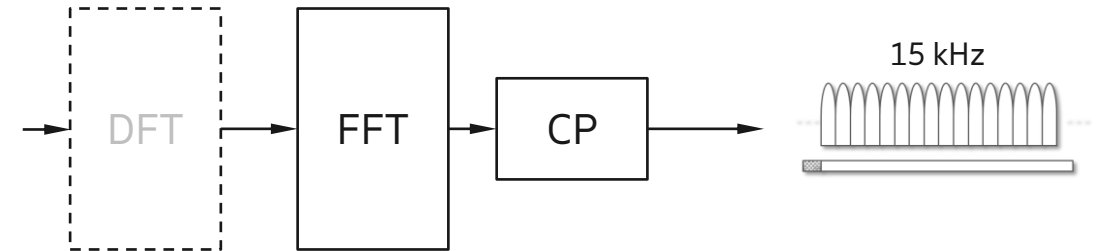




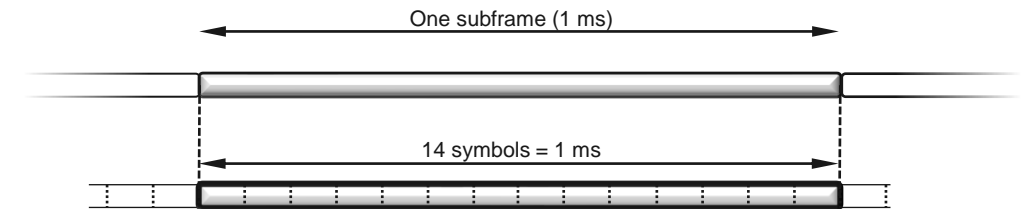
# LTE waveform and frame structure



- Conventional OFDM, 15 kHz subcarrier spacing
  - Downlink: plain OFDM
  - Uplink: DFT-precoded OFDM (device PA efficiency)



- Transmissions organized into 1 ms subframes



# Channel-dependent scheduling

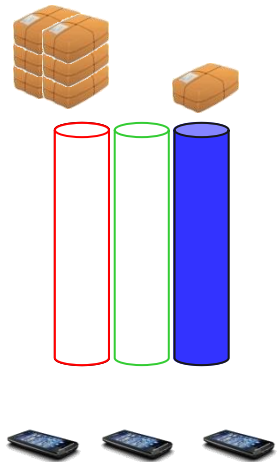


— To whom do we give the radio resources?

# Channel-dependent scheduling



- To whom do we give the radio resources?
- Dedicated channel
  - Resources assigned at “call setup”
  - Independent of instantaneous traffic
  - “Circuit-switched”





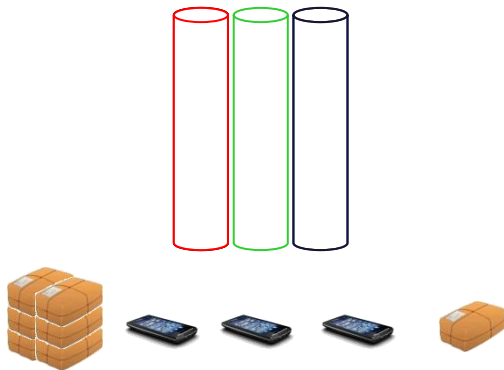
# Channel-dependent scheduling



— To whom do we give the radio resources?

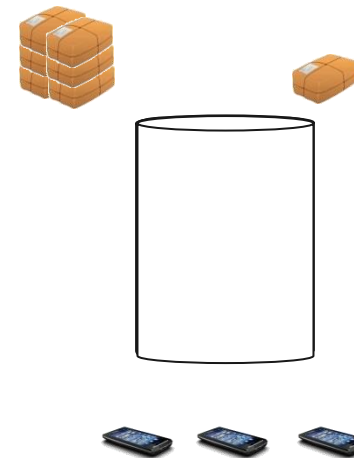
— Dedicated channel

- Resources assigned at “call setup”
- Independent of instantaneous traffic
- “Circuit-switched”



— Shared channel

- Dynamic sharing of common resource
- Adapts to instantaneous traffic situation
- “Packet-switched”



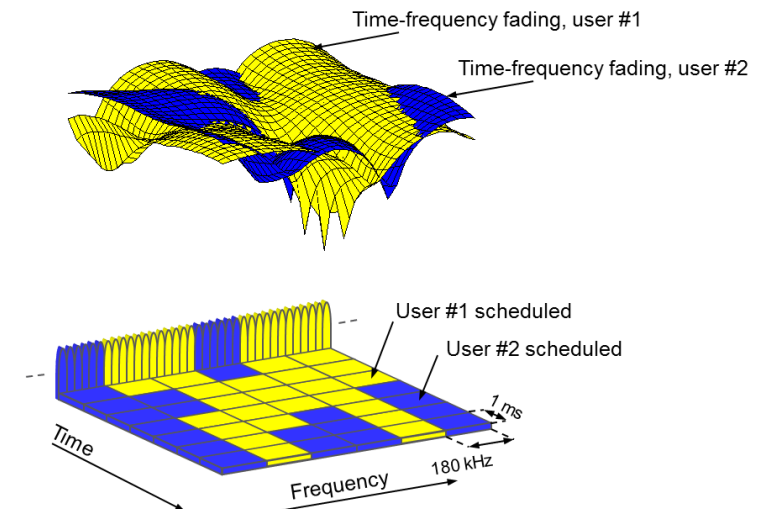
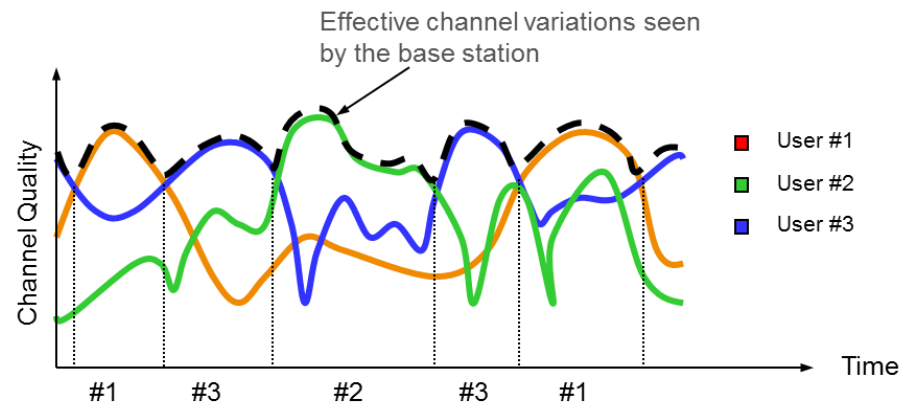
# Channel-dependent scheduling



- Scheduling determines at each time instant...
  - ...to whom to assign the shared channel
  - ...which data rate to use (rate adaptation)

- Basic idea: transmit at fading peaks (and with a high data rate)
  - In time domain only...

...or in time and frequency domains



# How to do scheduling and link adaptation?



- Scheduling
  - which UE to receive/transmit data
  - at what data rate
  - from which radio bearers (in downlink)
- The scheduler impacts the processing at multiple protocol layers

Payload size



Which bearers



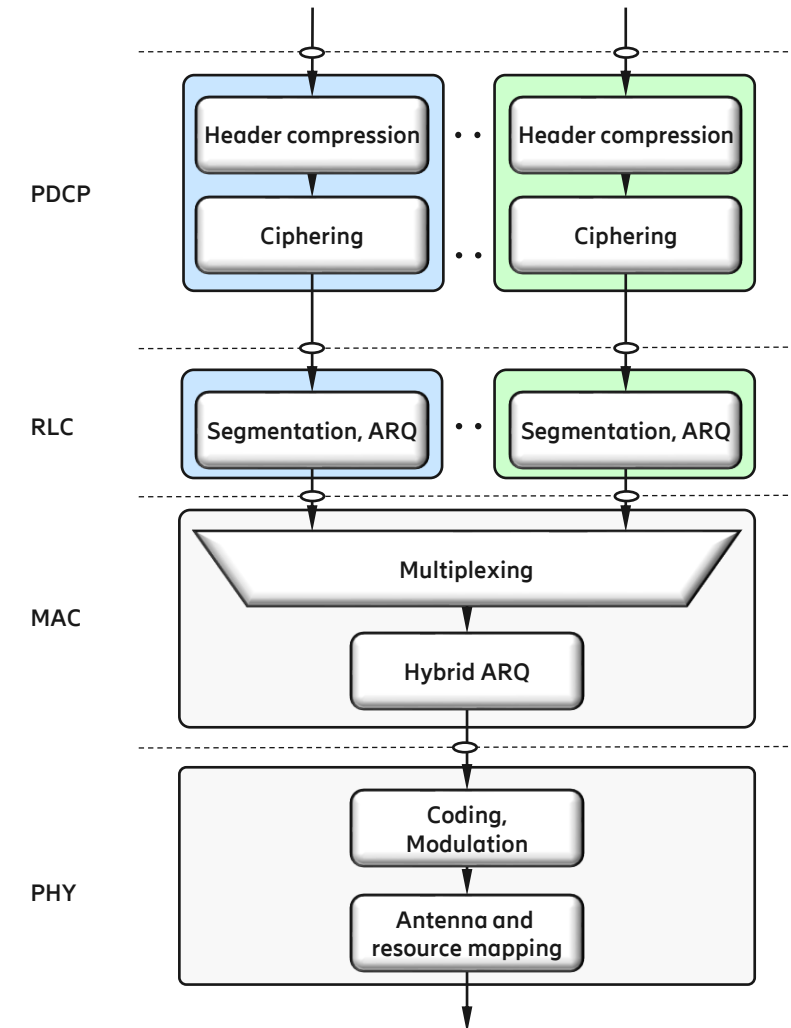
New data or retransmission



Modulation and coding scheme



#MIMO layers



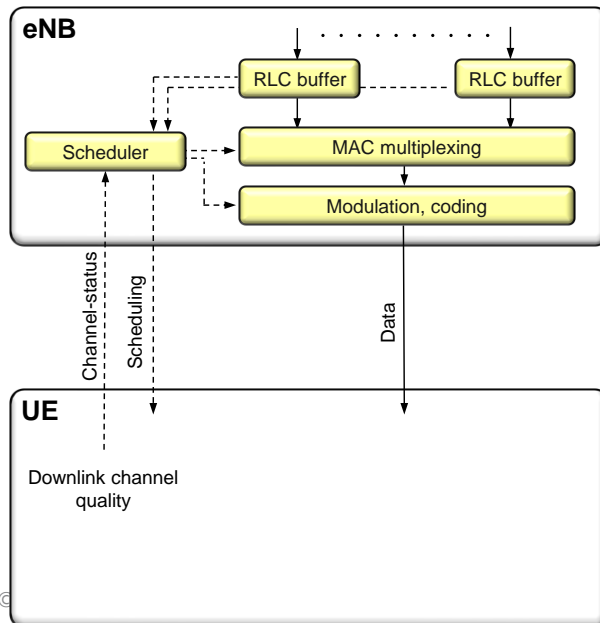


# How to do scheduling and link adaptation?



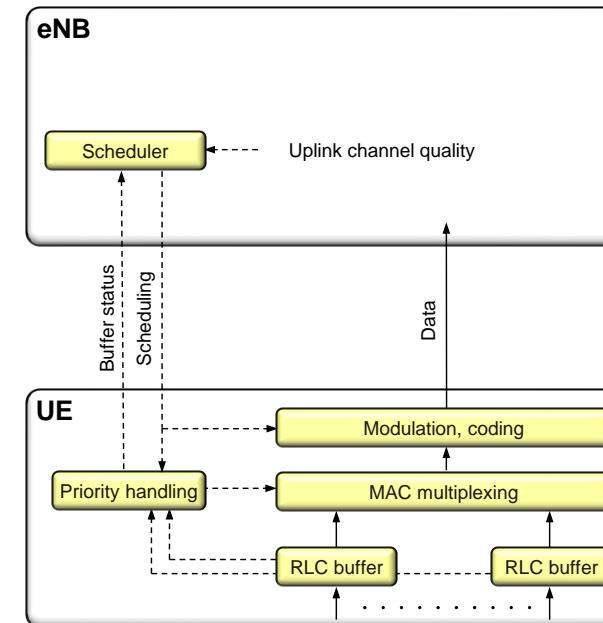
## — Downlink

- The device periodically reports channel quality
- The base station schedules based on channel quality and amount of data



## — Uplink

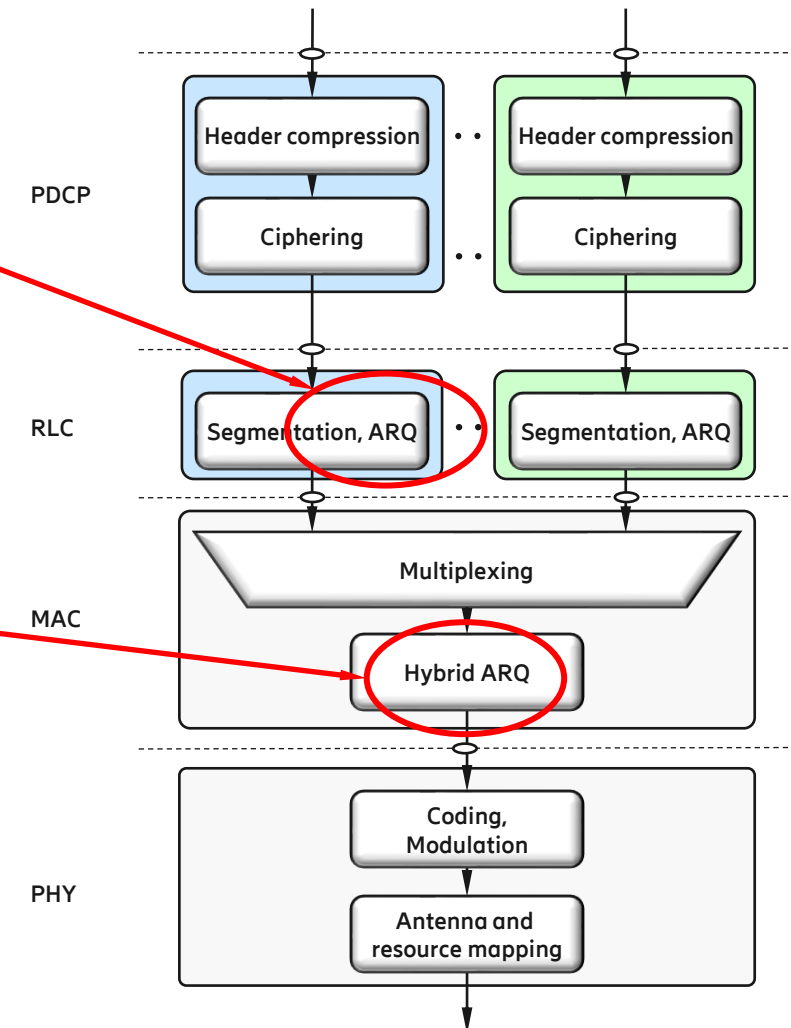
- Scheduling request; indicating presence of data
- Upon detecting a scheduling request, the base station requests e.g. buffer status and schedules the data transmission



# How to handle occasional reception errors?



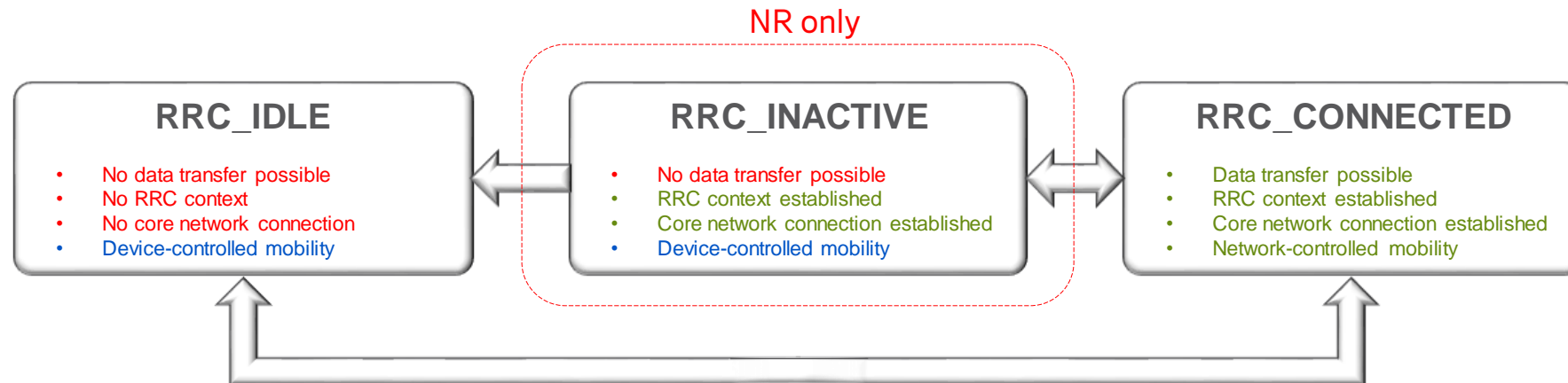
- RLC retransmissions – reliable
  - Handles errors missed by the hybrid-ARQ
  - Selective repeat protocol, status reports sent inband
  - Roundtrip time depends on configuration, ~ 10 ms to 100 ms
- Hybrid-ARQ retransmissions – fast
  - Handles most errors
  - Success/failure indicated outband after reception of each scheduled data unit
  - Retransmissions scheduled a few ms later



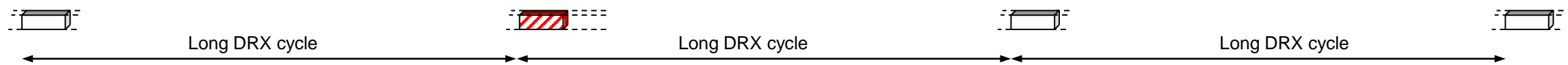
# What about the battery lifetime?



- States; most of the time the handset is in IDLE (low power consumption)



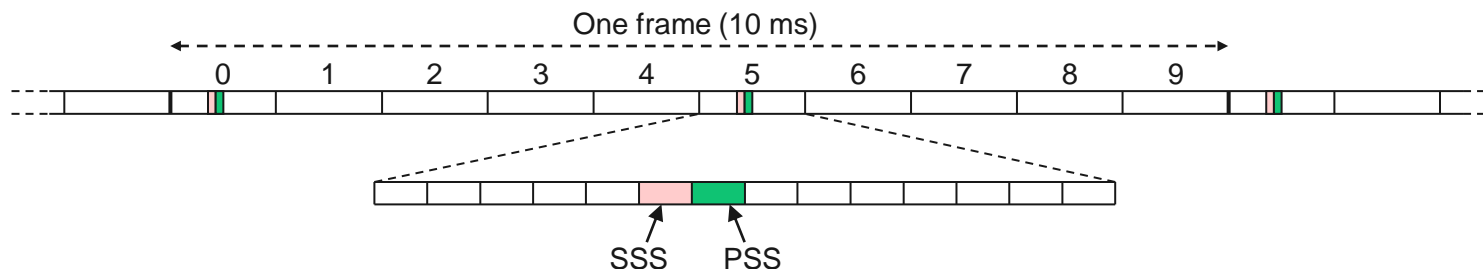
- Discontinuous reception (DRX) is used in all modes (differing in details and parameters)



# How to connect to the network?



- At power-up, the UE enters IDLE mode
- Need to obtain system information (the configuration of the network)
- Cell search – downlink time synchronization
  - Scan for synchronization signals (PSS and SSS), transmitted every 5 ms
  - Provides frame and subframe sync, as well as cell ID
- Once a cell is found, read system information (periodically transmitted) and perform random access

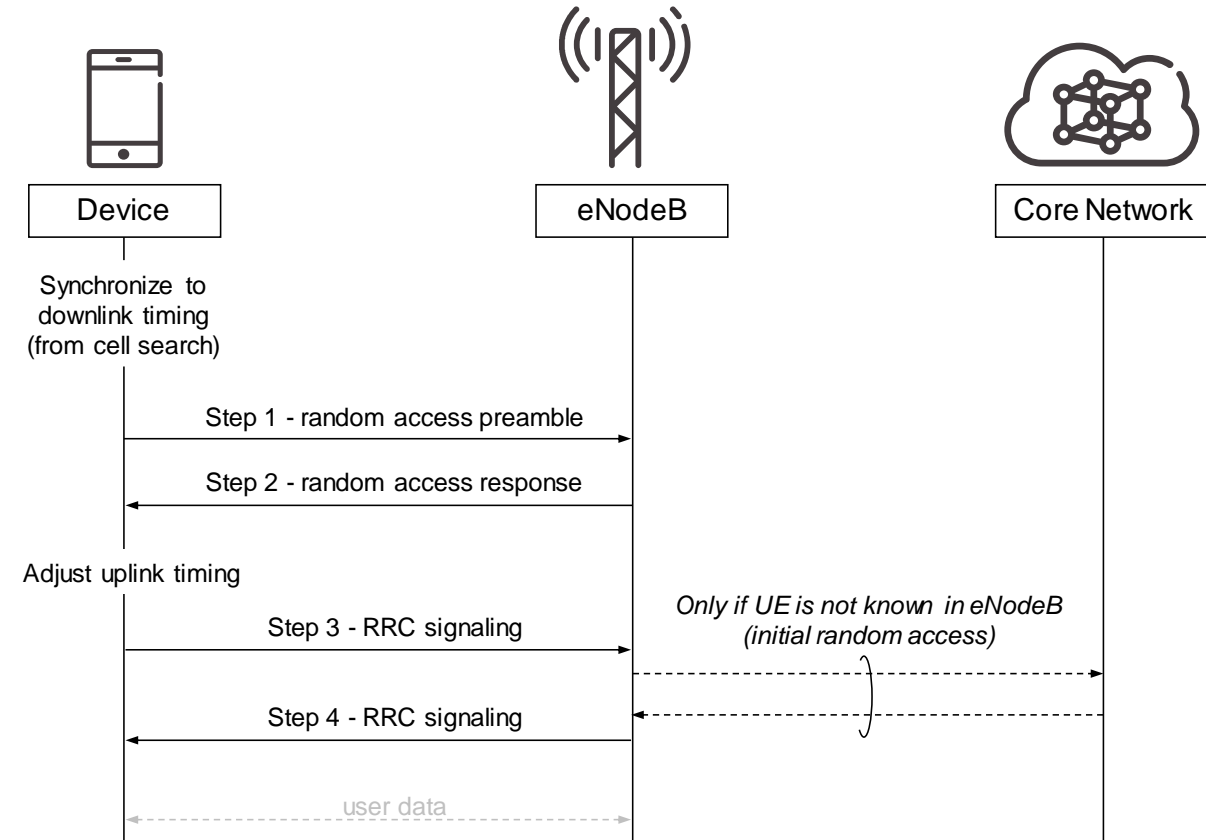




# How to connect to the network?



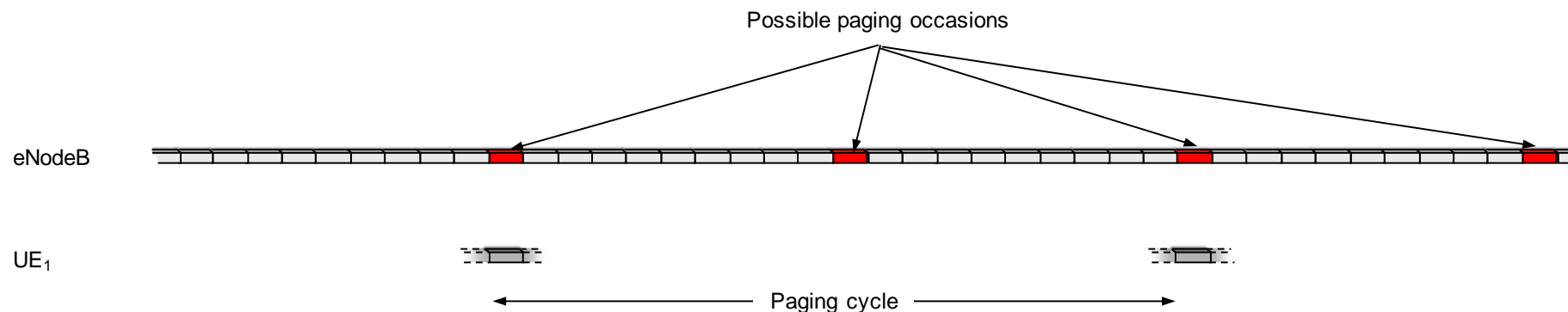
- Random access —  
UE-initiated connection establishment
- Step 1 — preamble transmission
  - select one of 64 preambles and transmit
- Step 2 — random-access response
  - obtain network response, adjust uplink timing
- Step 3, 4 — contention resolution
  - transmit (on regular data channel) UE identity and request a connection



# How to connect to the network?



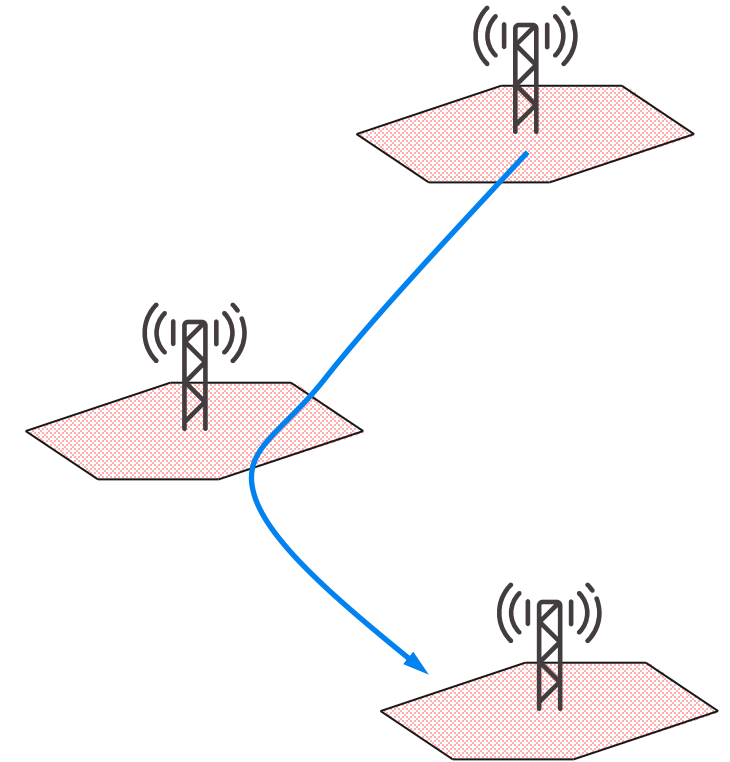
- Paging – network-initiated connection establishment for UEs in idle state
- The UE regularly (~once per second) wakes up to check for paging
  - Paging message containing the identity of the paged UE scheduled on the data channel
- If paged, perform random access and connect to the network



# What happens when you move around?



- Mobility is a cornerstone of cellular systems
- The UE regularly performs cell search to find 'better' cells
- Connected state mobility
  - The network determines when to connect to a different cell
  - The network knows the UE location on a cell level
- Idle state mobility
  - The UE determines when to select a different cell
  - The network does not know the UE location on a cell level



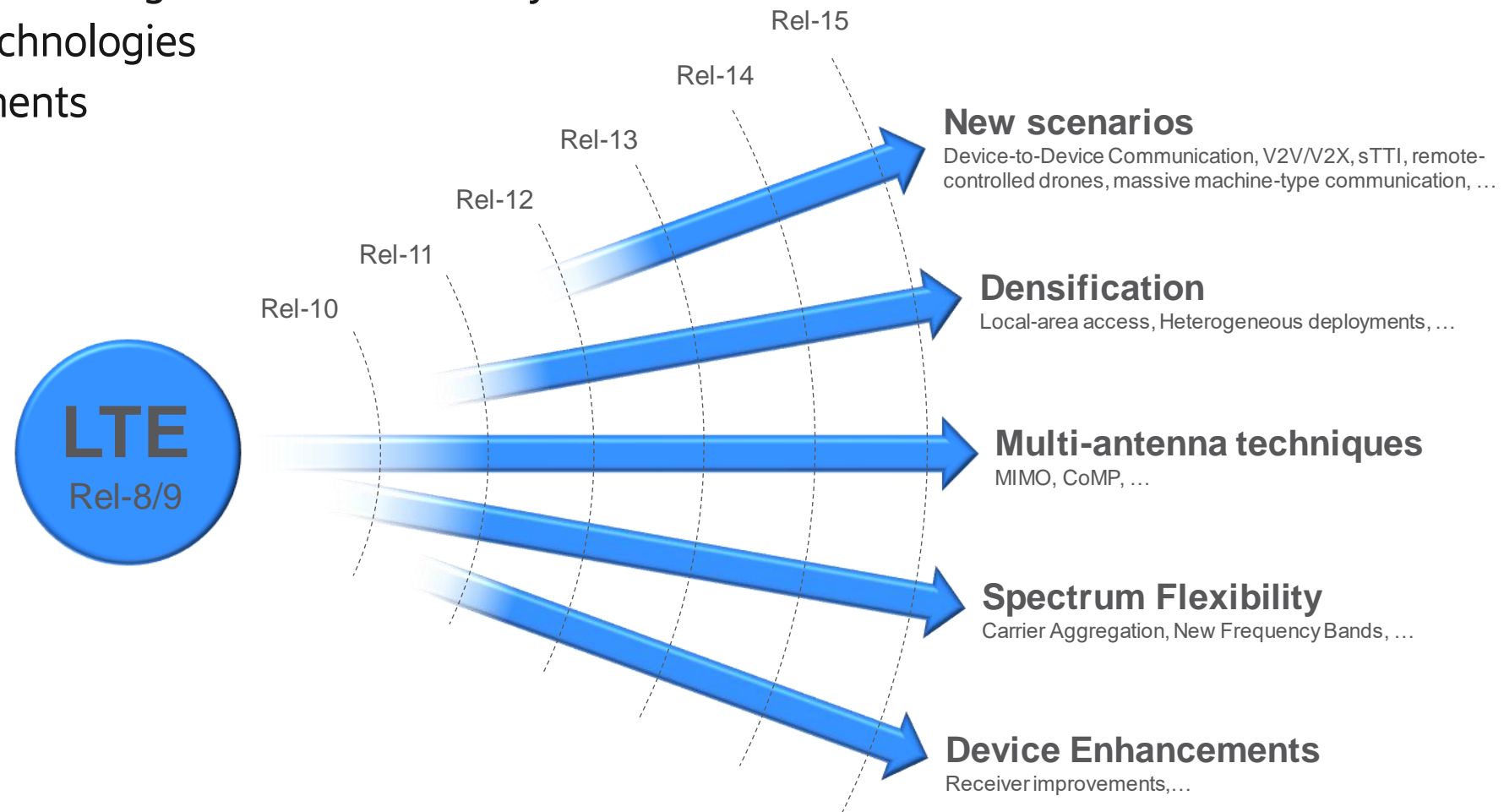


# LTE evolution

# Extensions please!

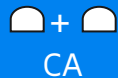
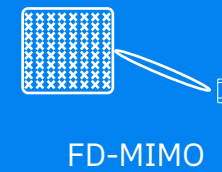
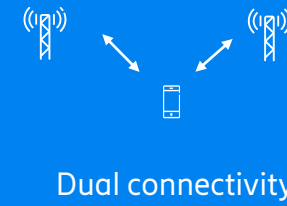
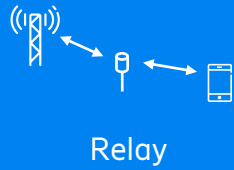


- LTE has been continuously evolving over more than 15 years
  - To incorporate new technologies
  - To meet new requirements





# Extensions – some examples!



# Carrier aggregation



- What?
  - Multiple component carriers in parallel
- Why?
  - Exploitation of fragmented spectrum
  - Higher bandwidth ➡ higher data rates



Inter-band aggregation

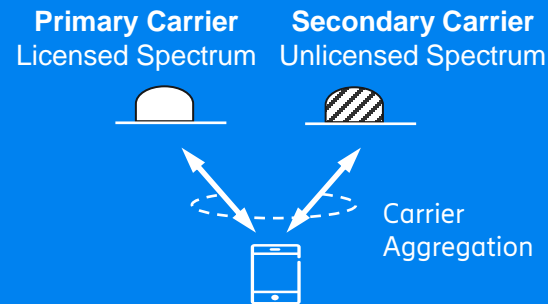


Intra-band aggregation, contiguous component carriers



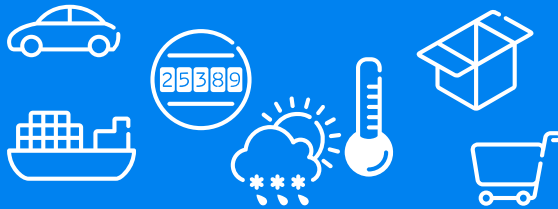
Intra-band aggregation, non-contiguous component carriers

# License-assisted access



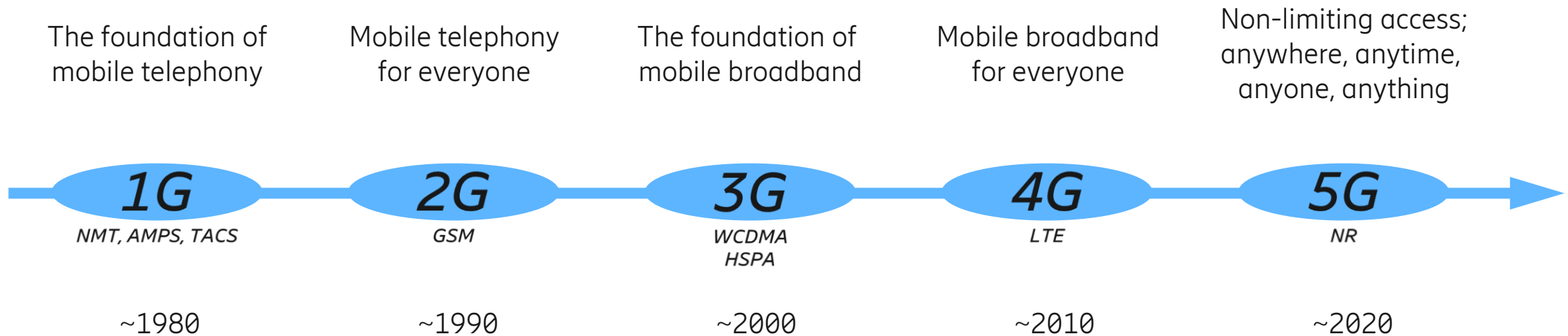
- Operator-deployed small cells in 5 GHz band
- License-assisted access
  - Using carrier aggregation to combine licensed and unlicensed spectrum
  - Licensed carrier for initial access, mobility, critical data, ...
  - Unlicensed carrier(s) to boost data rates and capacity
- Listen-before-talk on the unlicensed carrier
- Initially downlink-only (Rel-13) but supports uplink as well in later releases

# Massive machine-type communication



- Internet of Things (IoT)
  - Sensors, actuators, ...
- Large number of devices
- Low data rates (10 – 100 kbit/s)
- Wide-area coverage
- Low cost
- Low power consumption (~10 years on an AA battery)
- Two technologies; cat-M and NB-IoT
  - Integral parts of 5G – can be deployed on the same carrier as NR

# So...what happens now?



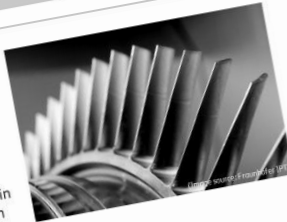


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- Evaluate 5G technology in a manufacturing industry
- Understand ICT opportunities and solutions



Partners: SKF, CHALMERS, ERICSSON



Photo: SKF

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Photo: Scania

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Photo: ABB

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- Develop overall communication infrastructure for tactile connected driving beyond the self-contained sensor based autonomous driving
- improved road traffic safety, less environmental impact, and higher efficiency of road transportation
- Provide 5G communication technologies and network architecture for tactile connected driving
- Low latency required by real-time vehicle control and cooperative maneuvers
- High reliability and availability for highly mobile environments
- Use cases:
  - Parallel cooperative driving of a fleet of farm machinery in off-road areas
  - Parallel connected driving of vehicles at intersections of urban roads
  - Tactile connected platooning of trucks in automotive test field
  - High-density platooning of trucks in automotive test field



## PIMM

### Pilot for Industrial Mobile Communication in Mining

- Explore future 5G Use Cases in underground mining
- Evaluate mobile communication infrastructure in an industrial context

- Increased Productivity and Improved Safety
- Industrial 5G requirements
- Understand eco system, business models, etc.

Partners: TeliaSonera, VOLVO, ABB, BOLIDEN, ERICSSON, SICK, etc.



Photo: Boliden

## WITool

### Wireless Internet of Tools

- Enable IoT for construction equipment OEM (Husqvarna) and rental companies (Cramo)
- Capillary network connectivity, cloud, service enablement and machine analytics capabilities
- Demonstrated through automation of return process of machines at Cramo depot

- Efficient fleet management enabled by predictive maintenance and resource planning
- Automated processes, for example return process
- New business models
- Making use of generated data to improve products

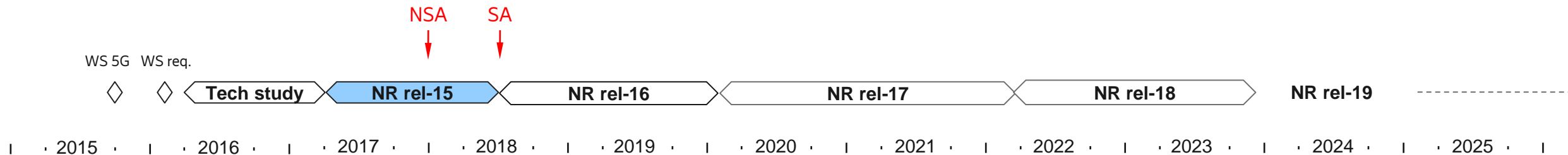
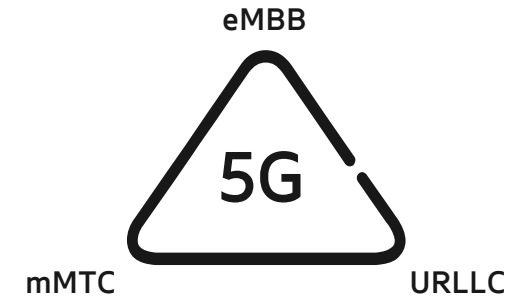
Partners: Cramo, Husqvarna, ERICSSON



# NR Release 15 – The first 5G release



- Release 15 – the first release of NR radio access standardized by 3GPP
  - Completed in June 2018
  - Focuses on eMBB and (partially) on URLLC



## ITU IMT-2020

Vision

requirements

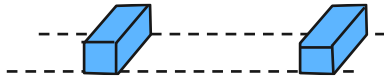
proposals

specifications

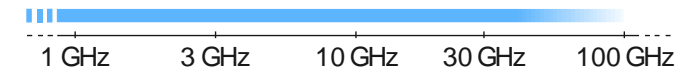
# NR characteristics – some examples



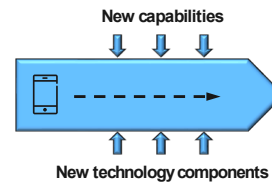
Ultra-lean design



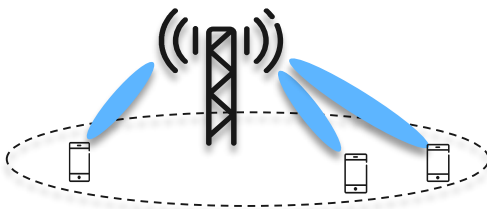
Wide spectrum range



Forward compatibility



Multi-antenna support



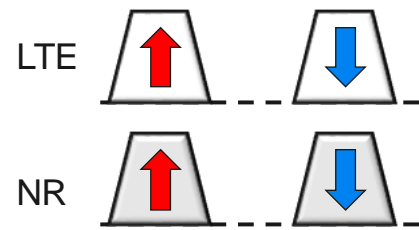
Low latency



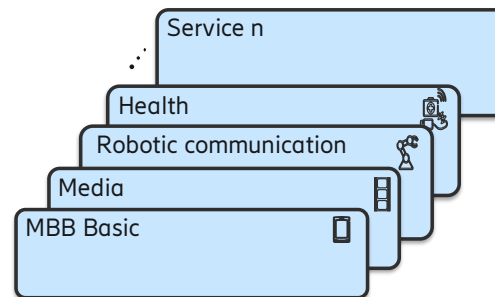
# NR characteristics – some examples



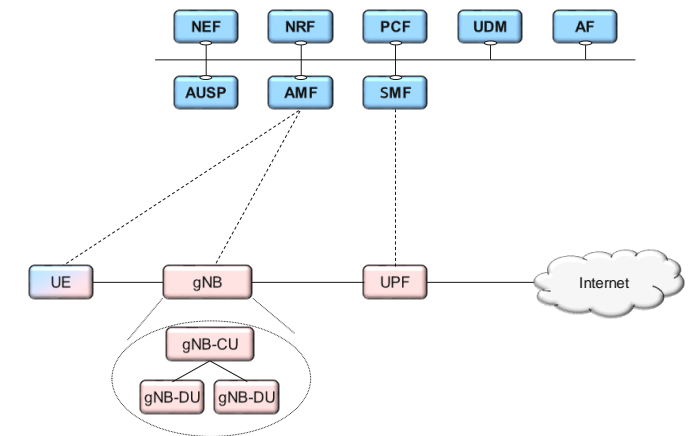
## LTE – NR coexistence



## Network slicing



## Modular architecture DU/CU split, CP/UP split

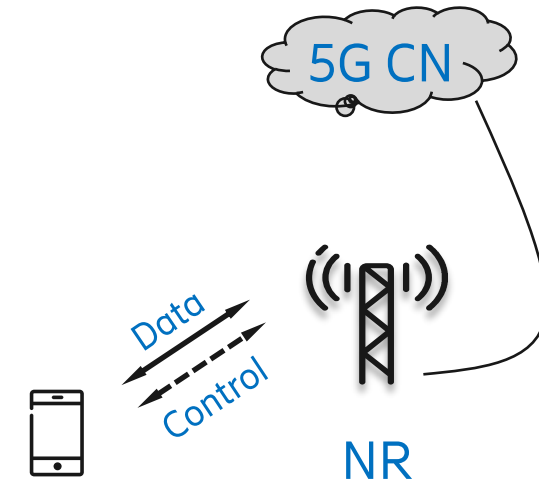
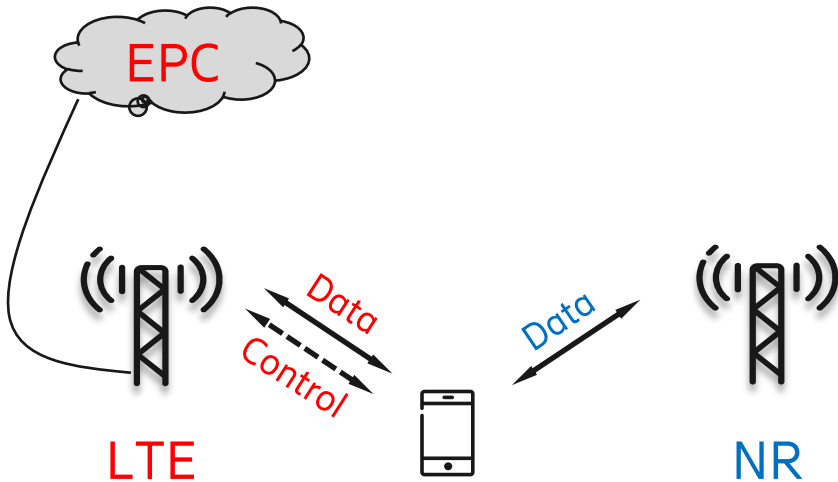


# Architectural options



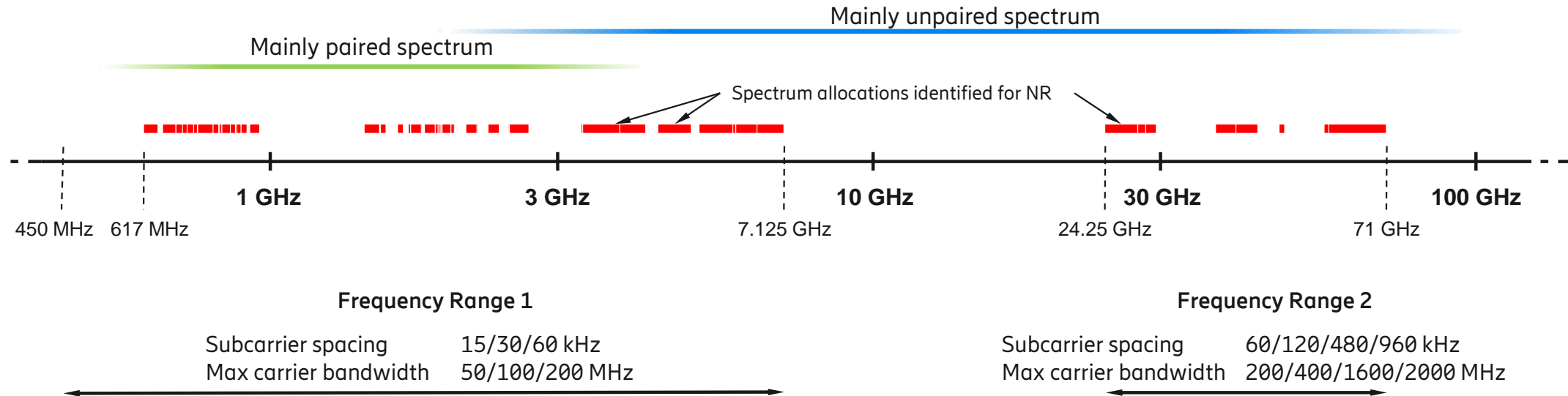
- Non-standalone NR (December 2017)
  - LTE handling initial access and mobility
  - NR is a “data rate booster”
  - Connects to EPC

- Stand-alone NR (June 2018)
  - NR handles initial access and mobility
  - Connects to 5G CN





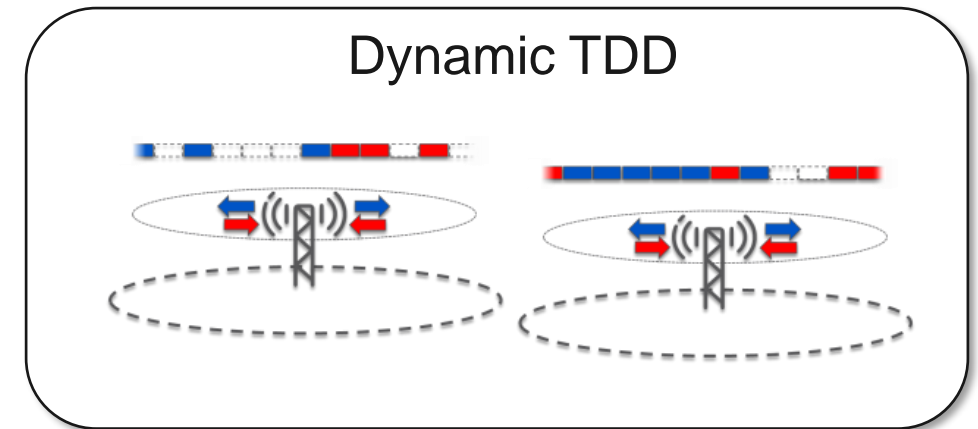
# 5G spectrum



# Dynamic TDD



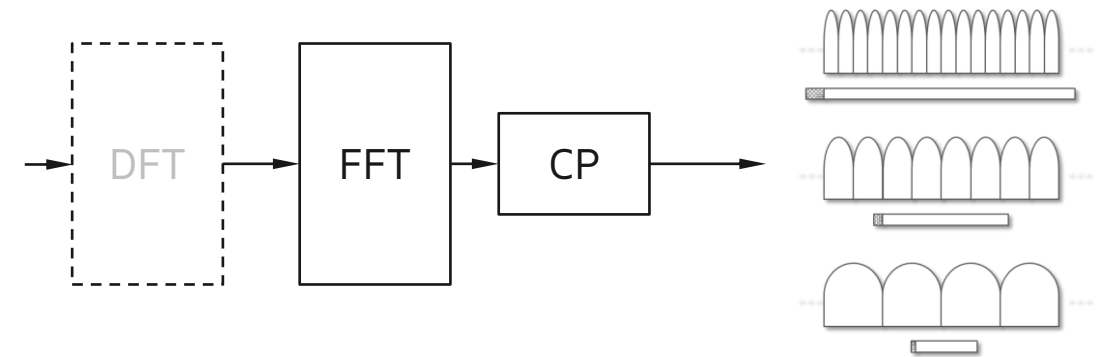
- Dynamic assignment of resources to downlink and uplink
  - Possible to inform the UE about a semi-static uplink/downlink allocation
- “Macro” deployment — semi-static operation
  - Less dynamic traffic variations
  - Important to avoid TDD-specific interference
- “Small-cell” deployments — dynamic operation
  - More dynamic traffic variations
  - TDD-specific interference less critical



# NR waveform and frame structure

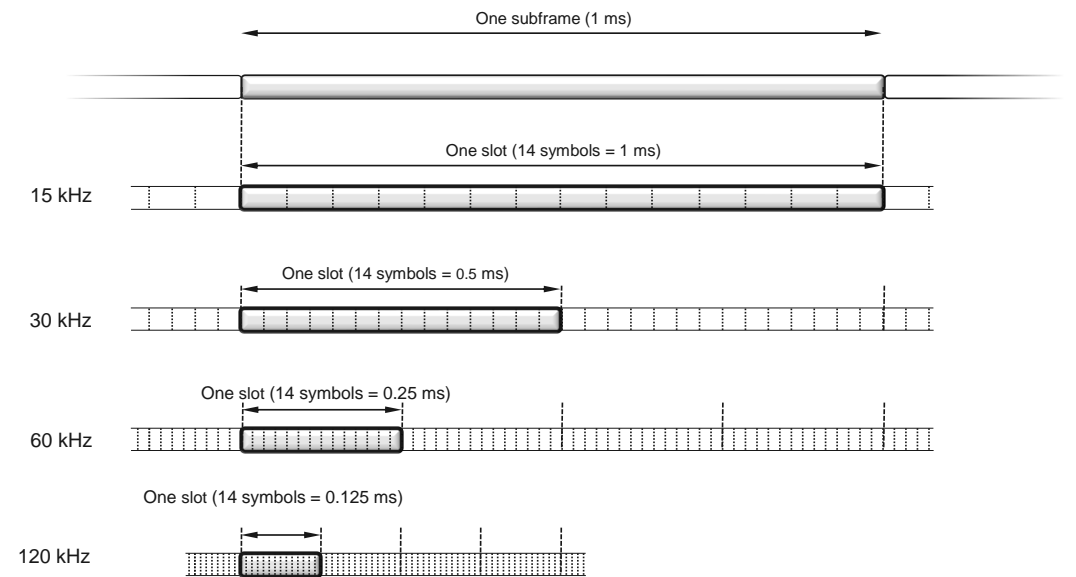


- Conventional OFDM (DL and UL)
  - Scalable numerology to handle a wide range of carrier frequencies
  - DFT-precoding optional in UL



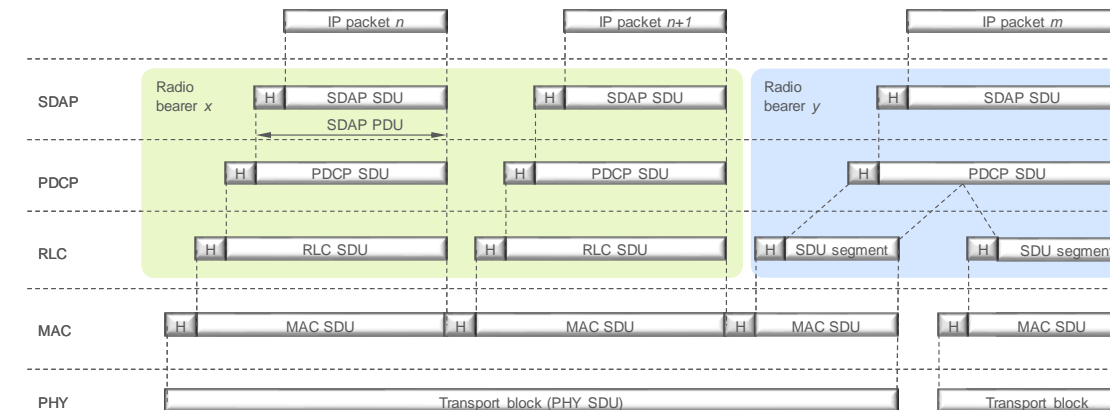
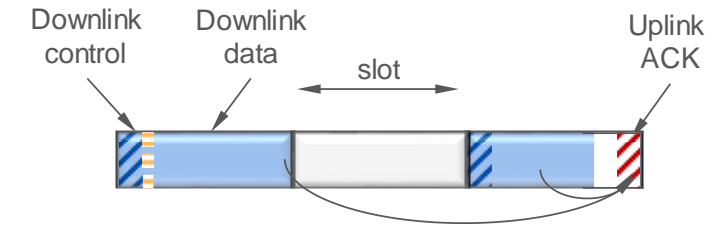
- Slot duration depends on subcarrier spacing

New in NR



# Optimized for low latency

- Latency-friendly frame structure
  - Front-loaded DM-RS
  - Transmissions can use parts of a slot
- Fast processing time
  - ACK a few symbols after data ends ("same slot")
- Higher-layer protocols (MAC, RLC)
  - Optimized header structure to enable preprocessing
  - No reordering in RLC



# Multi-antenna transmission



Common toolbox – but different tools suitable for different frequency ranges

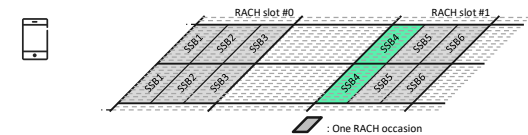
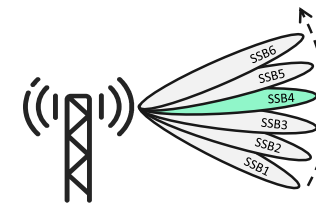
- Lower frequencies (“sub-6”)
  - Similar to LTE but enhanced
  - Ten to hundreds of antenna elements
  - Capacity, end-user data throughput
- Higher frequencies (“mm-wave”)
  - Many hundreds of antenna elements (“Massive MIMO”)
  - Focus on beam-forming for coverage



# Beamforming



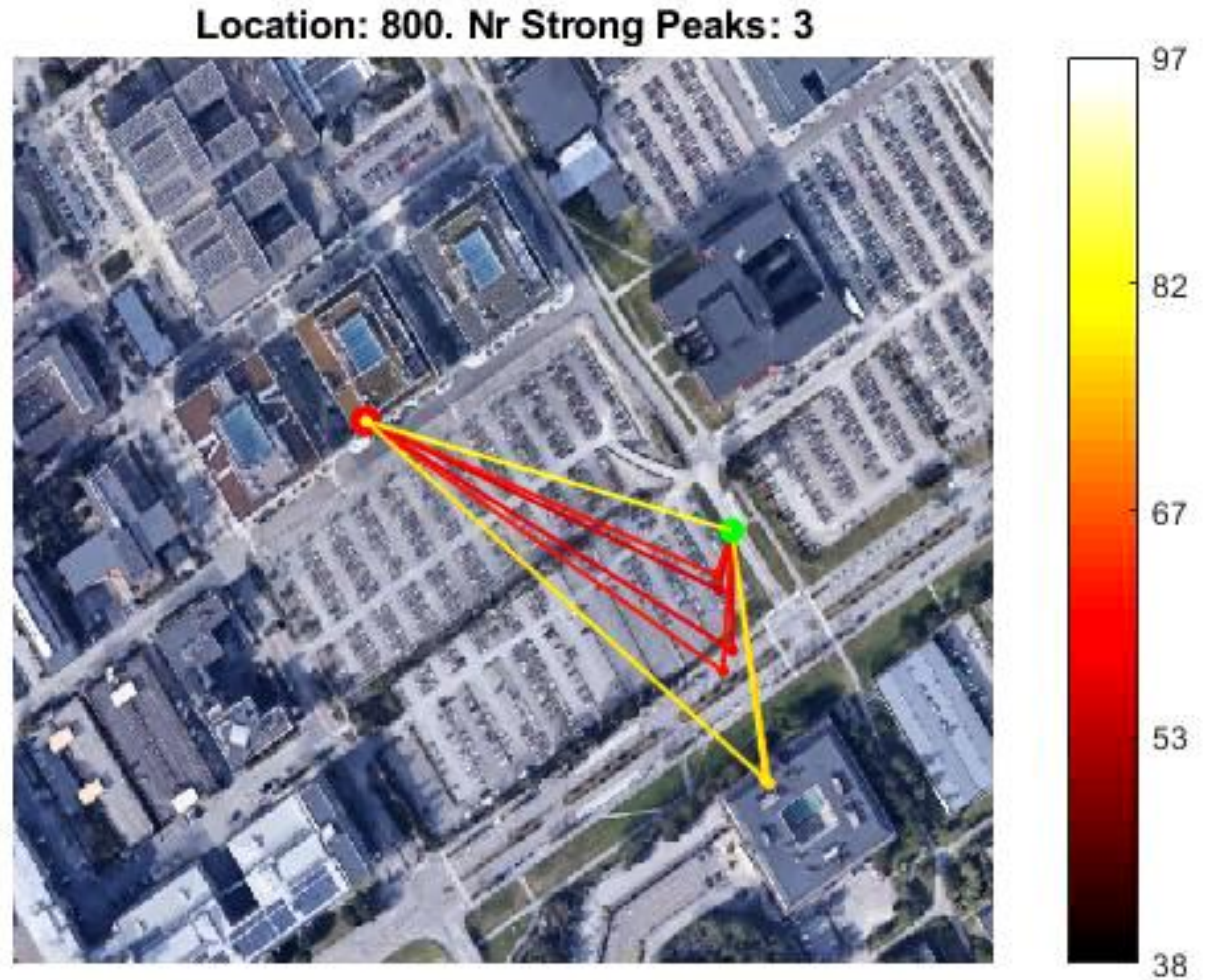
- Beamforming crucial at higher frequency bands
  - Challenging to “point in the right direction”
- Initial access
  - Sweep downlink beams, the handset will find (at least) one of the beams
- During data transmission
  - Measure on candidate beams and report to the network





# Beamforming

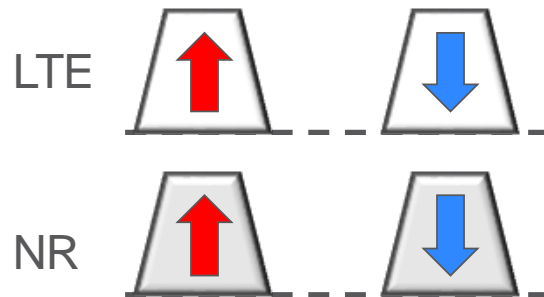
- Example of beam reflections (measurements done in Kista)



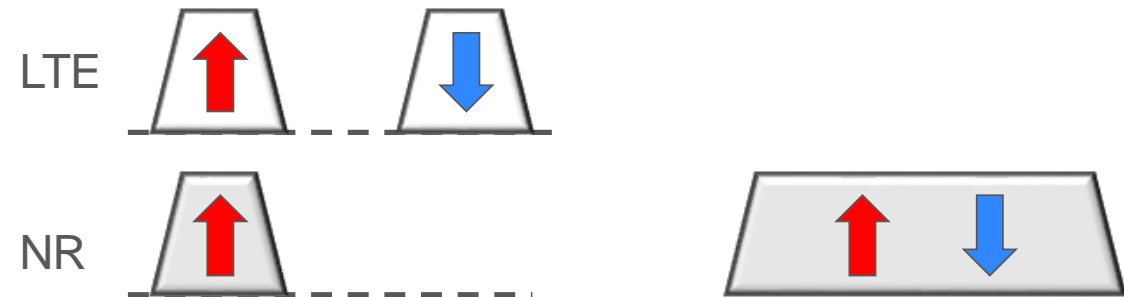
# NR-LTE coexistence



- NR can coexist with LTE on the same carrier
  - Example: NB-IoT or cat-M for MTC on same carrier as NR



**Downlink and uplink co-existence**

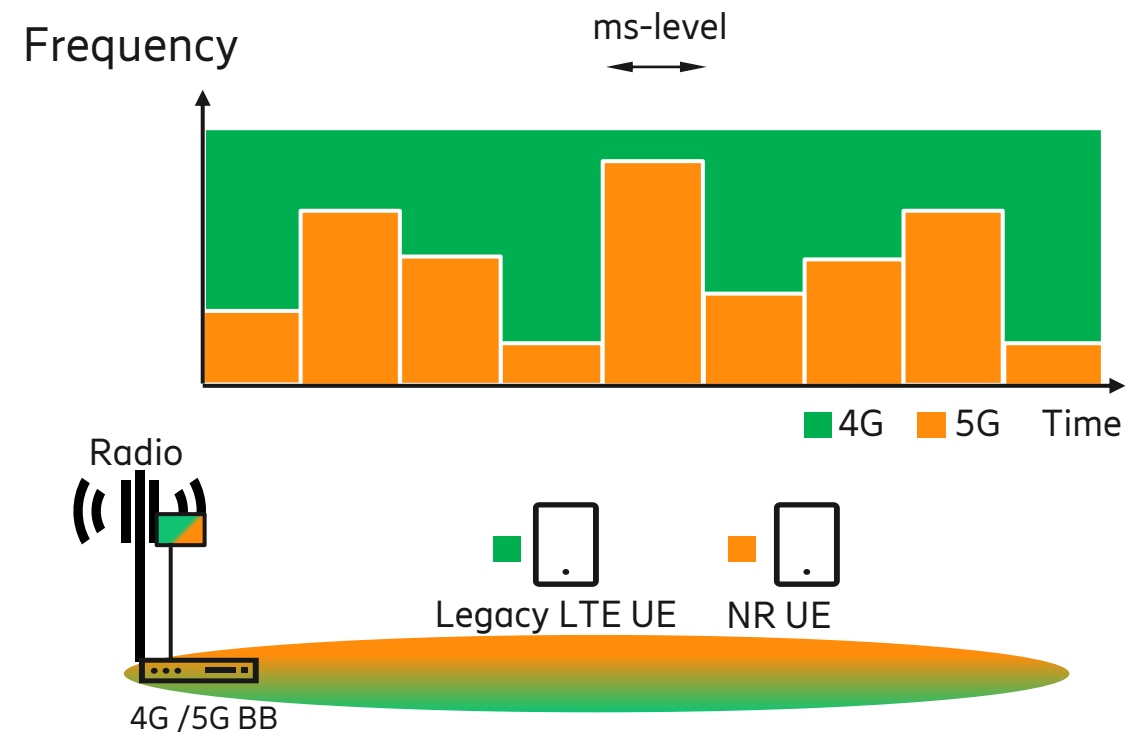


**Uplink-only co-existence**

# Ericsson spectrum sharing



- Gradually introduce 5G in 4G band based on NR device penetration
- Lowest cost 5G introduction:  
Shared radio + share baseband + shared spectrum
- Smooth and fast network migration



# For further information...



## Open the 3GPP specifications...



## ...or read The Books!

Available in English, Chinese, Korean, Japanese, and Greek.

