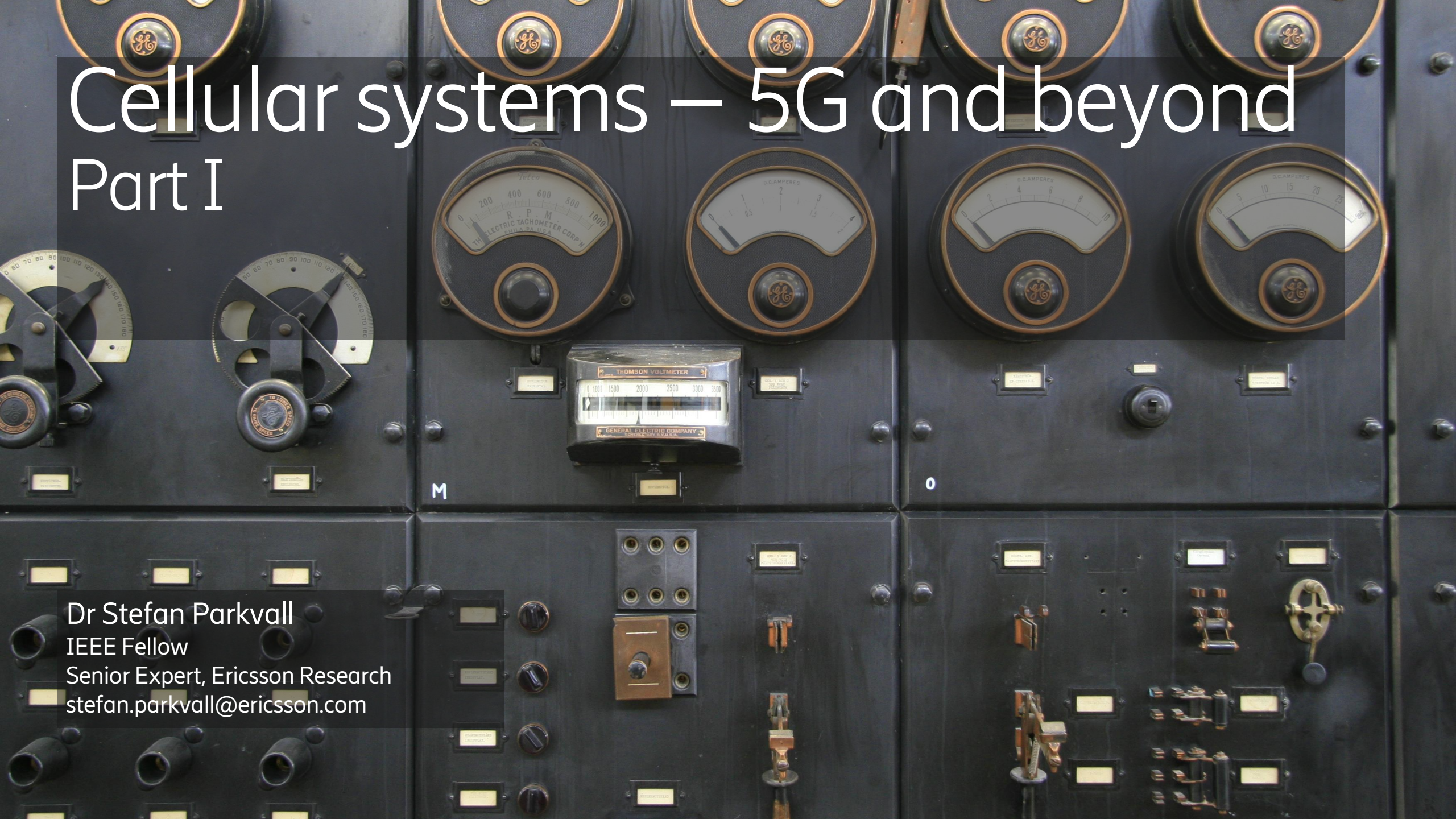
Cellular systems – 5G and beyond
Part I



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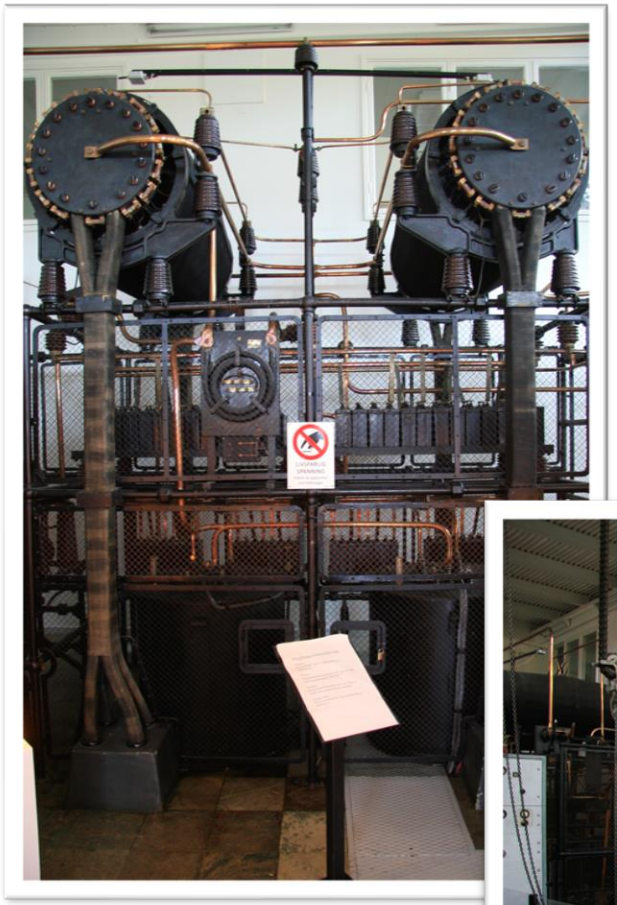
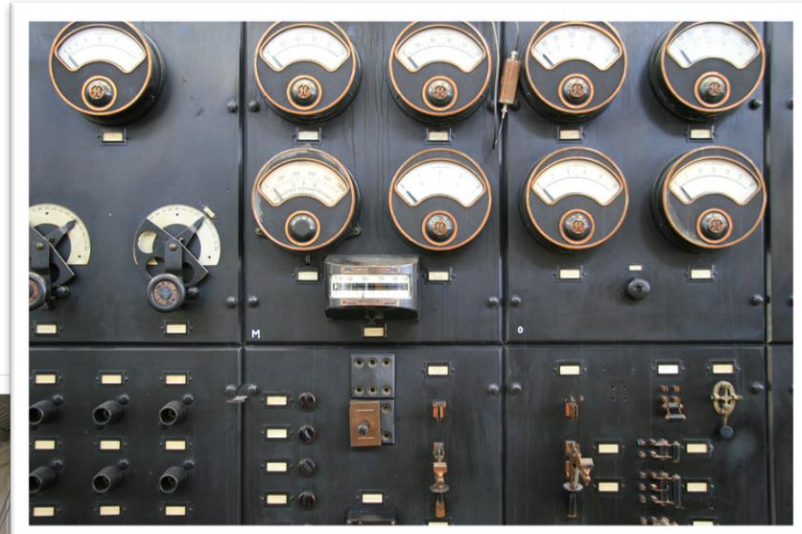
Grimeton, early 1920s

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





Outline

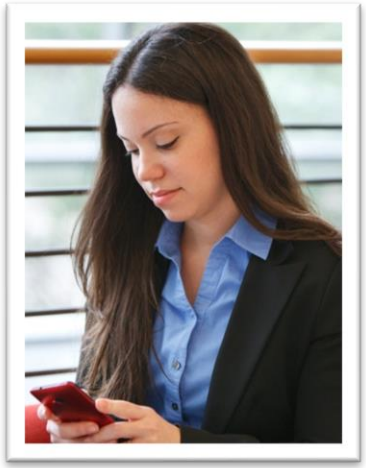
- Introduction
- Cellular systems and basics for LTE (4G) and NR (5G)
- LTE evolution
- NR
- Standardization in practice
- 6G

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

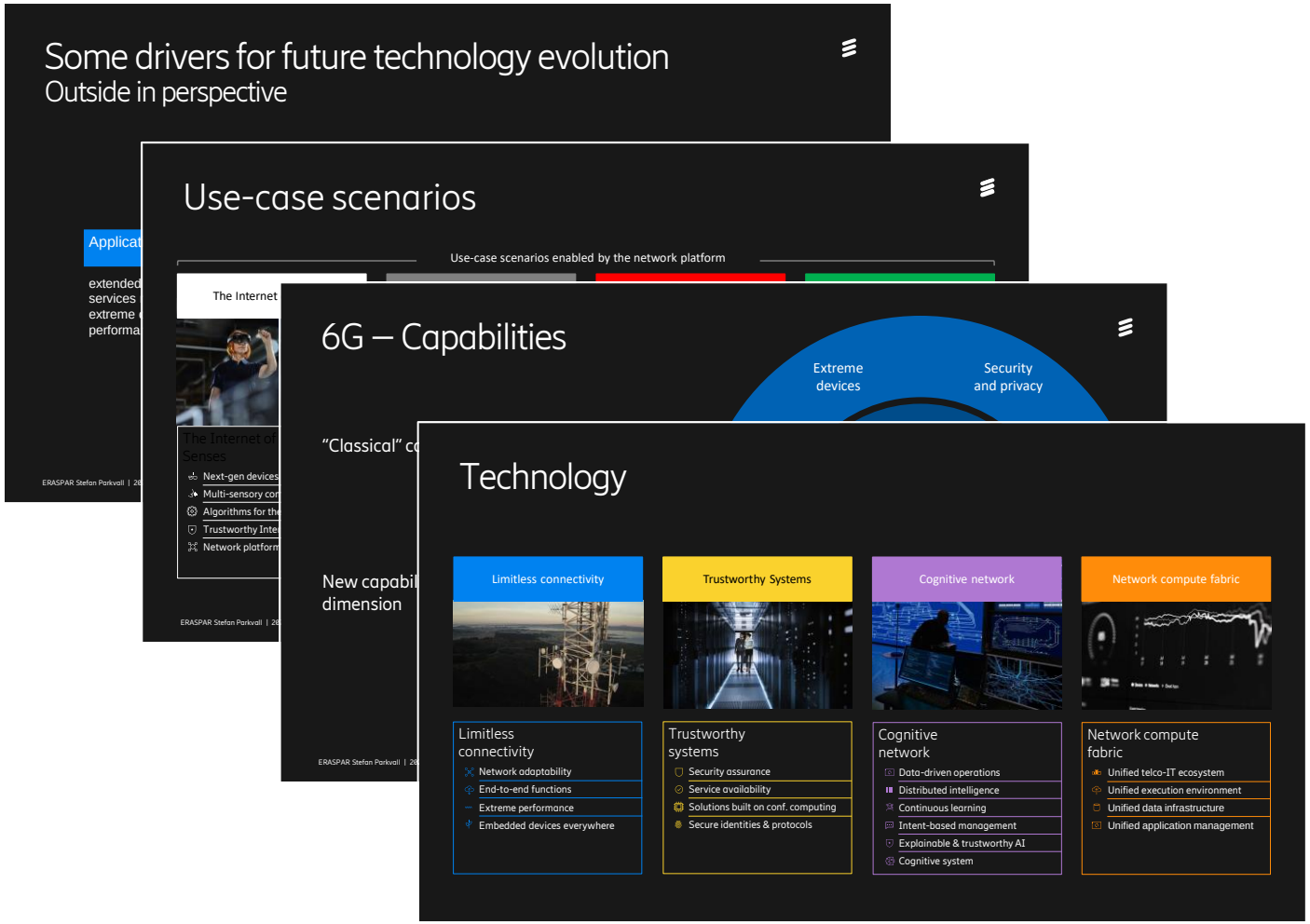
5G – going *beyond* the smartphone

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

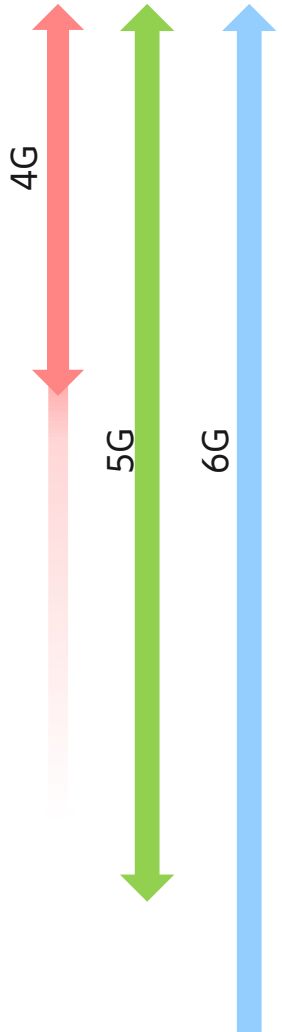
“6G” is still in the research phase



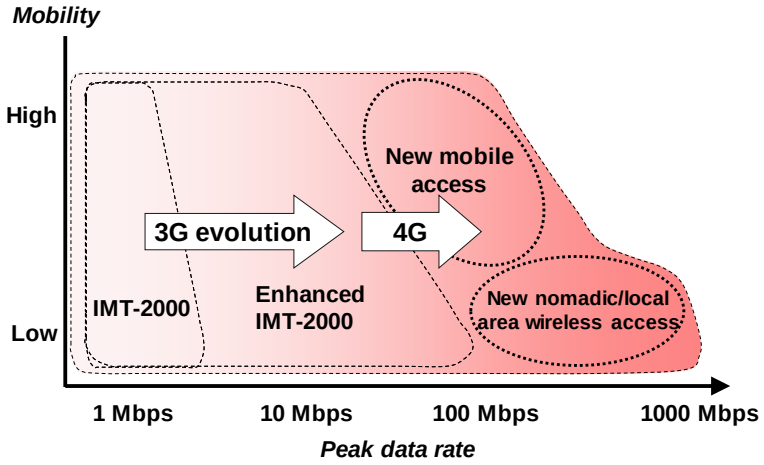
Basics of cellular systems

What do we require from a wireless system?

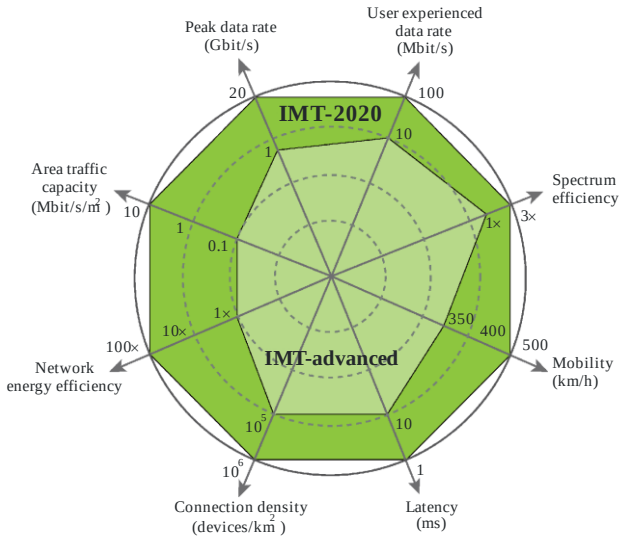
- Coverage
- Mobility
- High data rates
- High capacity
- Low latency
- High connection density
- High reliability
- …



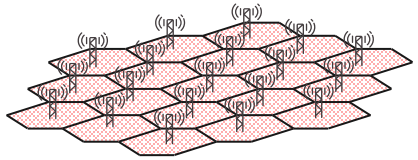
4G
"The van diagram"

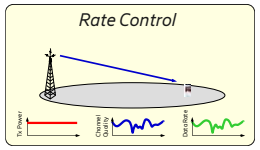


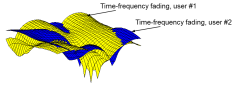
5G
"The spider diagram"

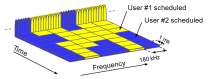


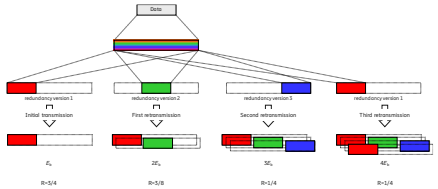
How do we get it?

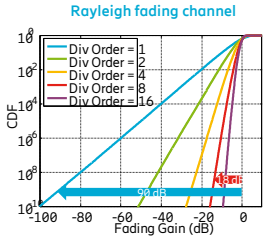








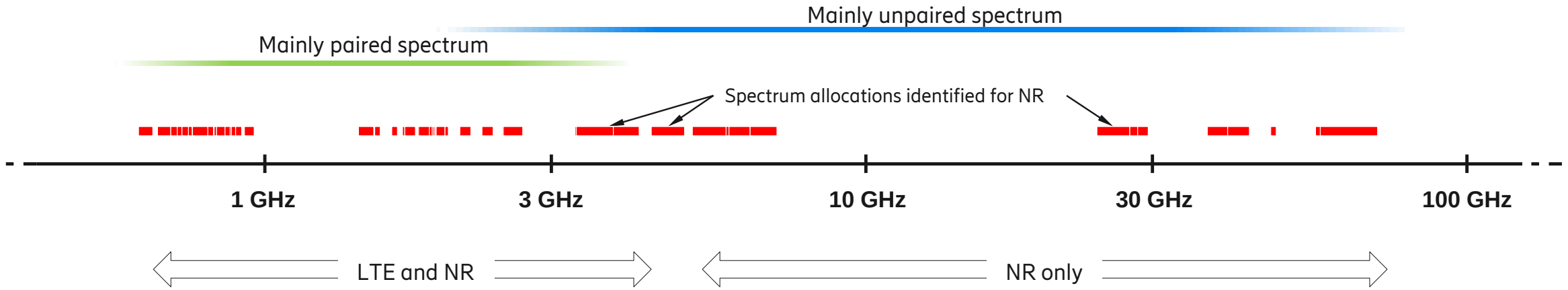




- Spectrum
- Multiple cells
- Overall architecture
- Rate control, channel-dependent scheduling
- Hybrid-ARQ
- Diversity
- Fast processing
- Low overhead
- …

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)



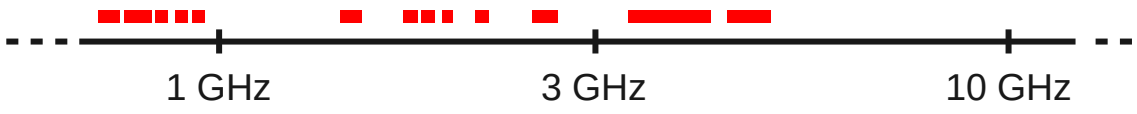
What about spectrum?

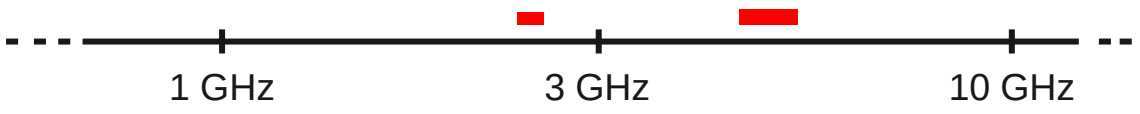
- Licensed spectrum
  - Exclusive right to a certain frequency range
  - Control of the interference situation
  - ‘High’ output power ➡ long range
  - Typically associated with a license cost

  - Examples:
    LTE, NR (and other cellular systems)

- Unlicensed spectrum
  - Anyone can use the radio frequencies
  - Unpredictable interference sitaution
  - Relatively low output power ➡ short range
  - No license cost

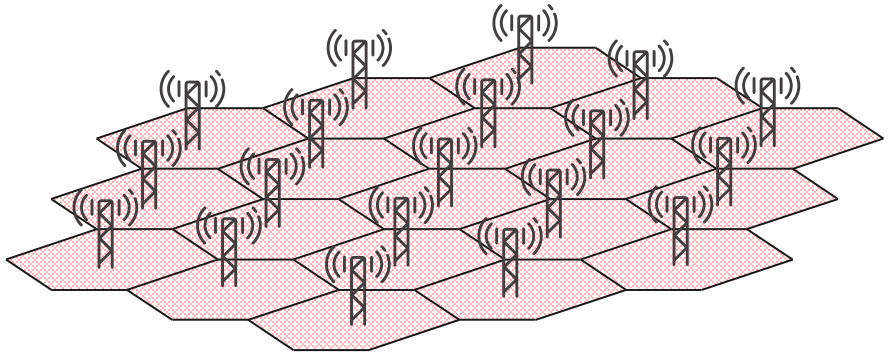
  - Examples:
    WiFi, Bluetooth, LTE (later releases), NR





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



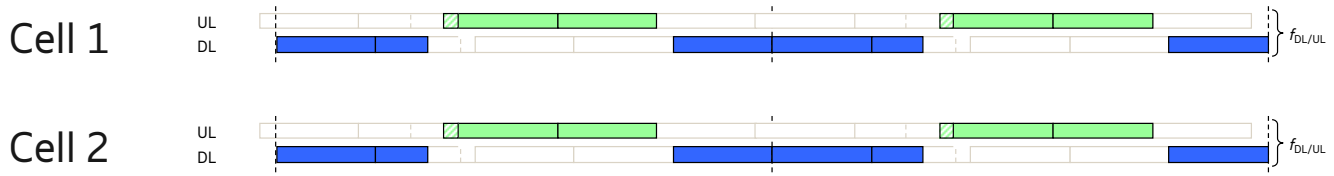
Inter-cell interference in TDD networks

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

Inter-cell interference in TDD networks

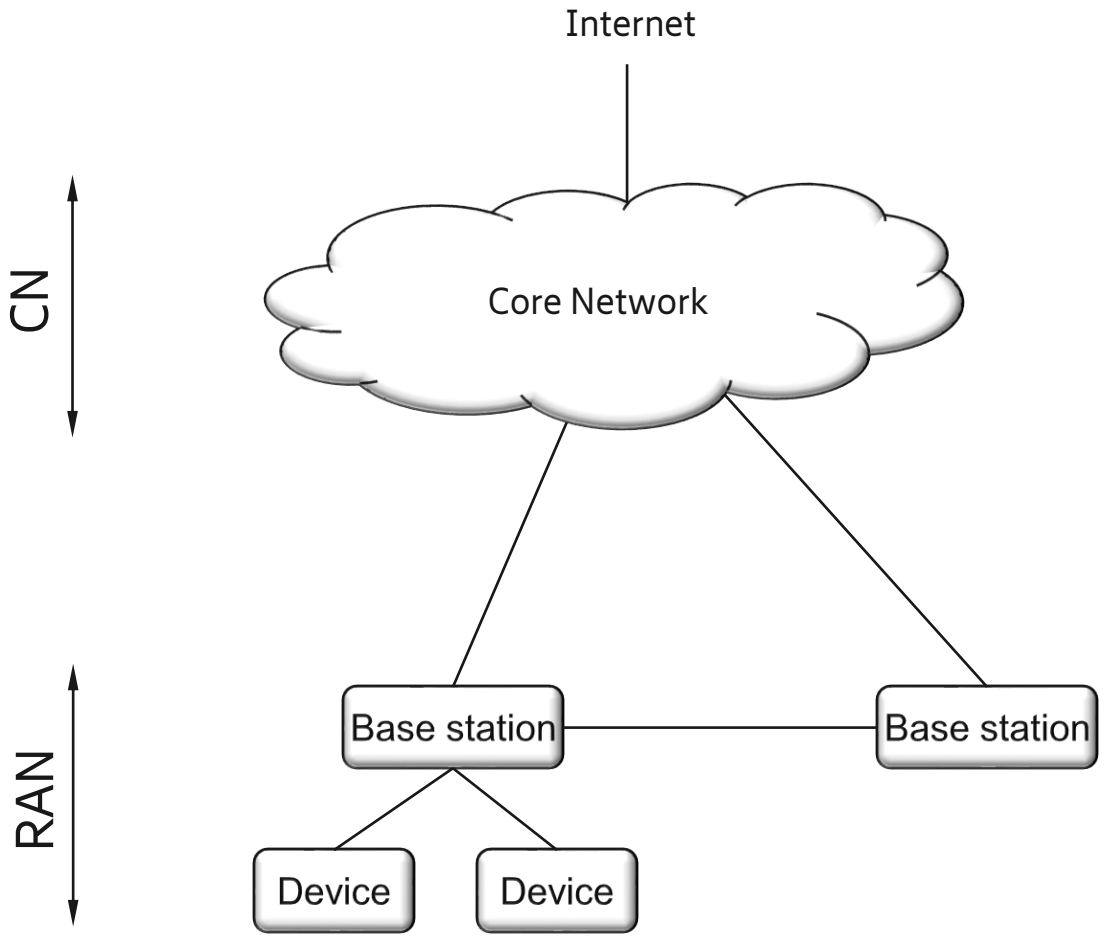
- Large power difference between DL and UL in wide-area networks
  - BS: above-rooftop antennas, Tx: ~ +46 dBm, Rx: ~ -90 dBm ➡ huge difference!
  - UE: non-elevated antennas, Tx: +23 dBm

- 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



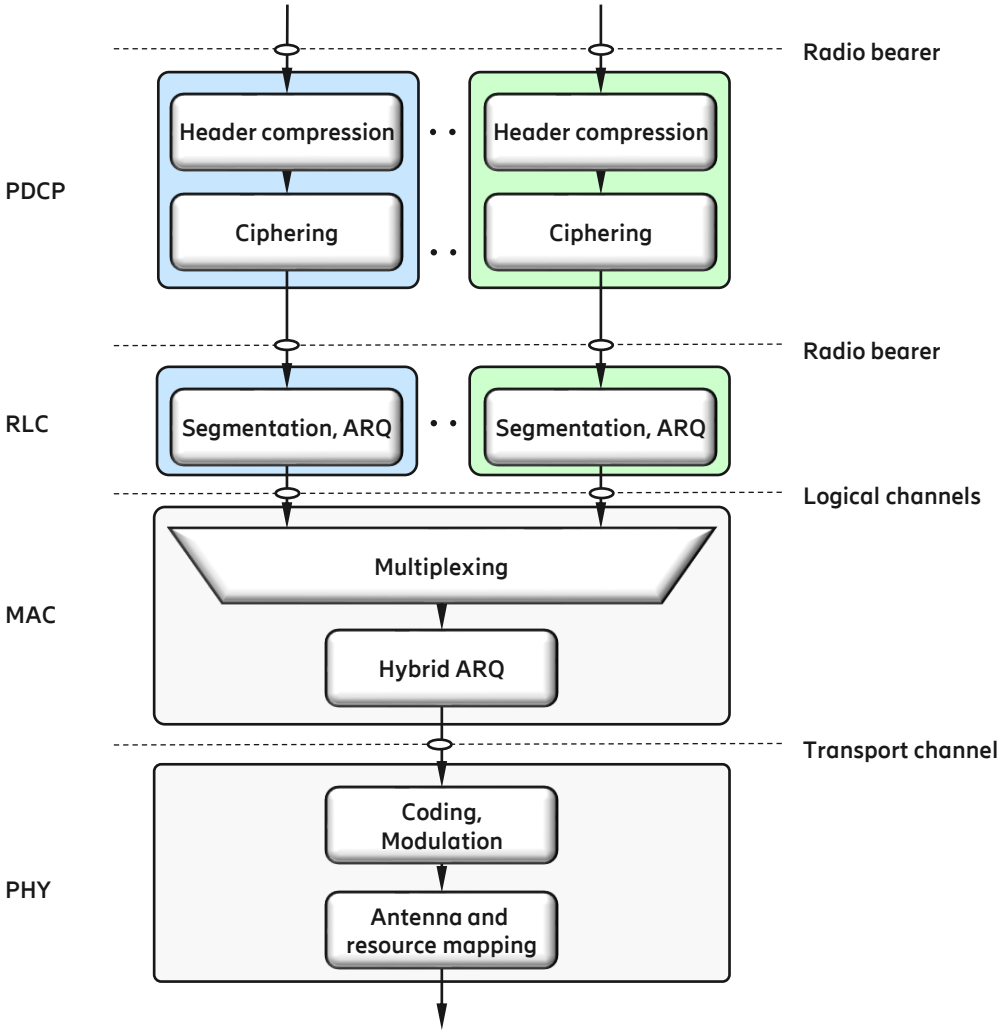
Network architecture

- 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, ...



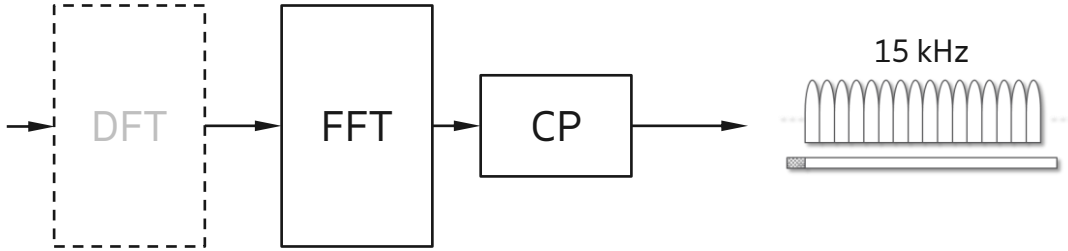
Protocol architecture

- 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

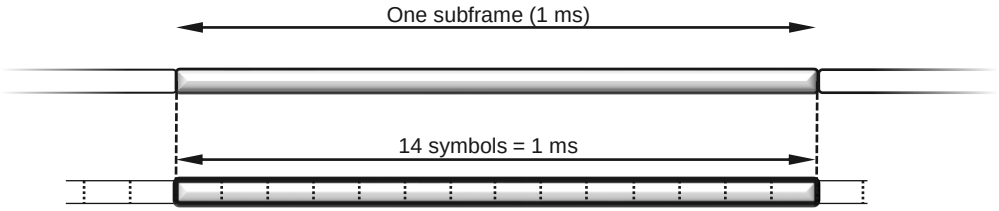


LTE waveform and frame structure

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



- Transmissions organized into 1 ms subframes

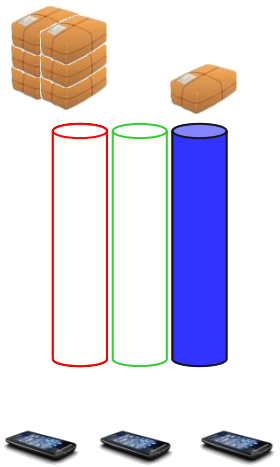


Channel-dependent scheduling

— To whom do we give the radio resources?

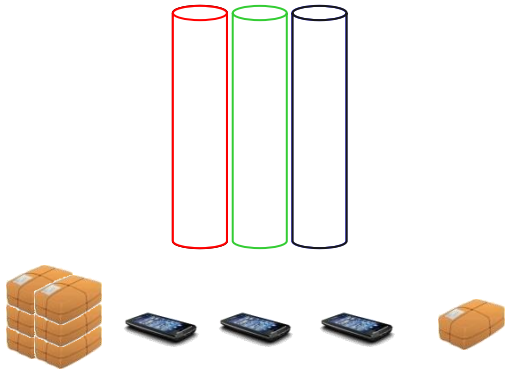
Channel-dependent scheduling

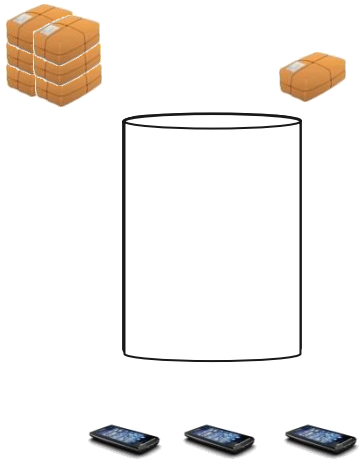
- To whom do we give the radio resources?
- Dedicated channel
  - Resources assigned at "call setup"
  - Independent of instantaneous traffic
  - "Circuit-switched"



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"

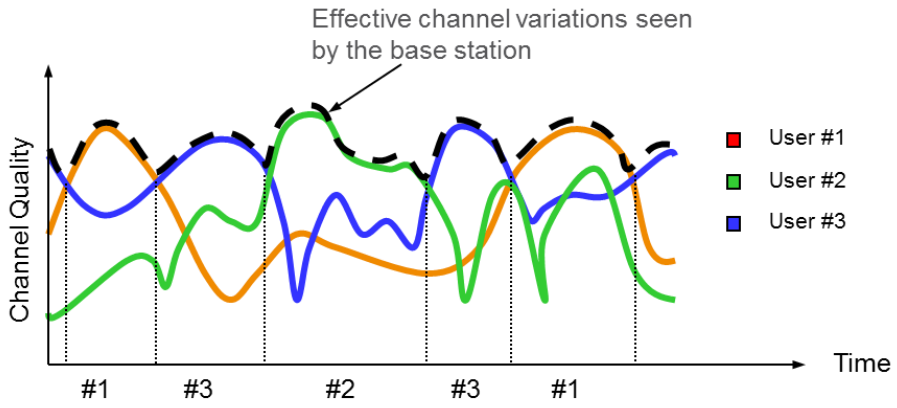




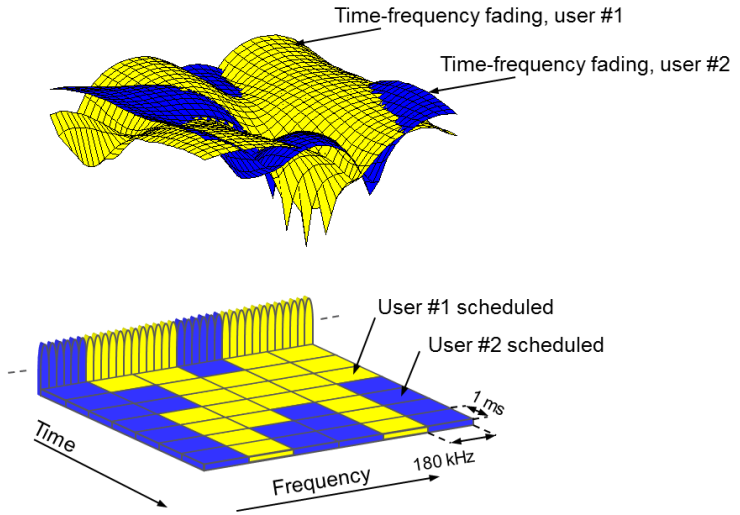
Channel-dependent scheduling

- 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...

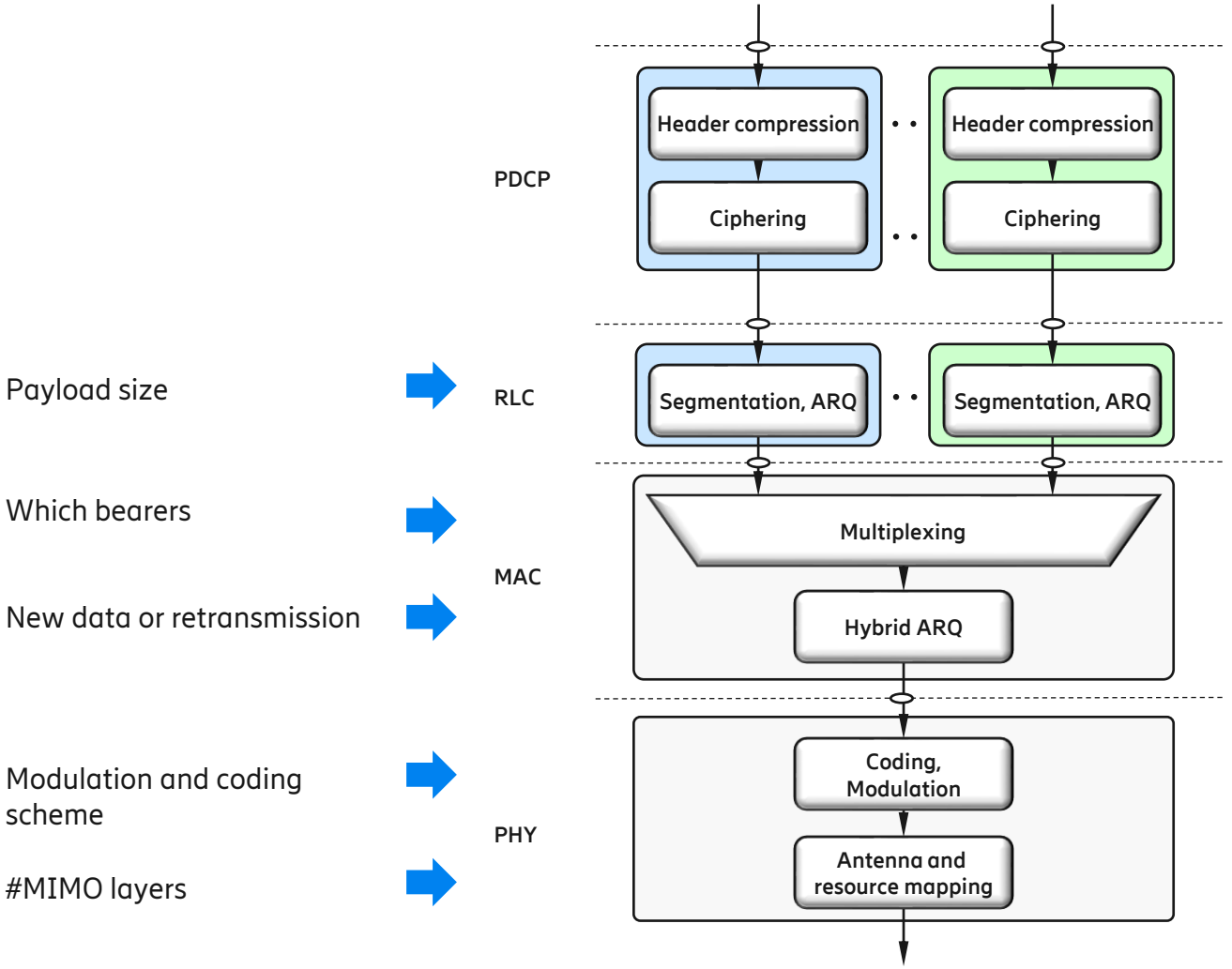


...or in time and frequency domains



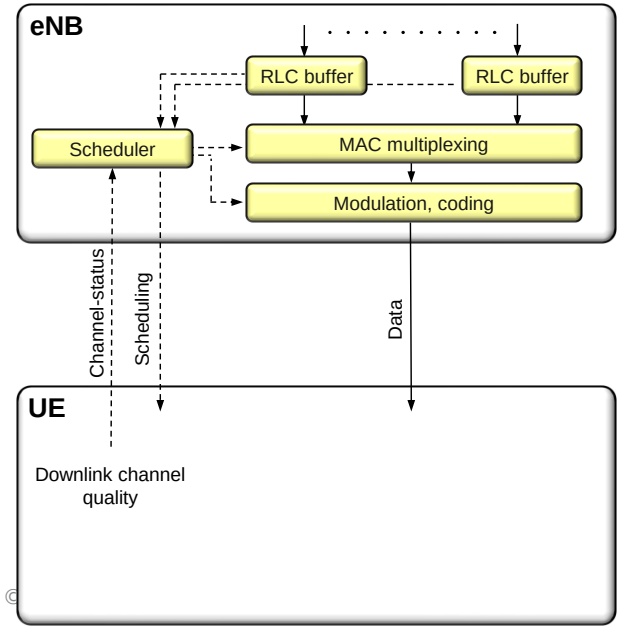
How to do scheduling and link adaptation?

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

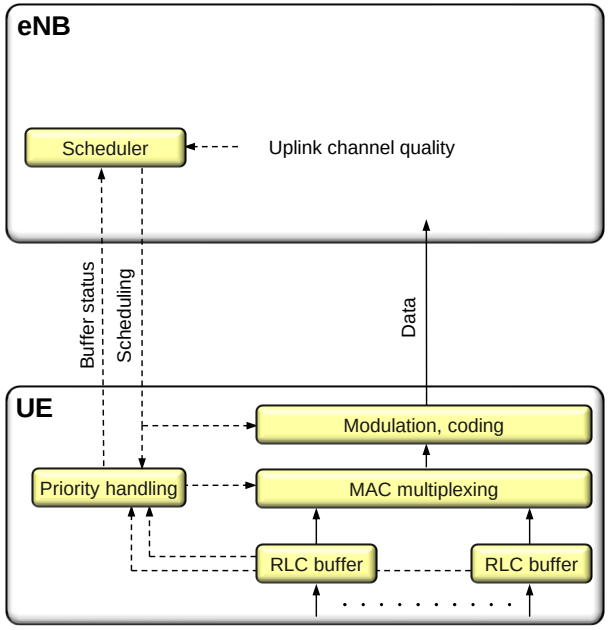


How to do scheduling and link adaptation?

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

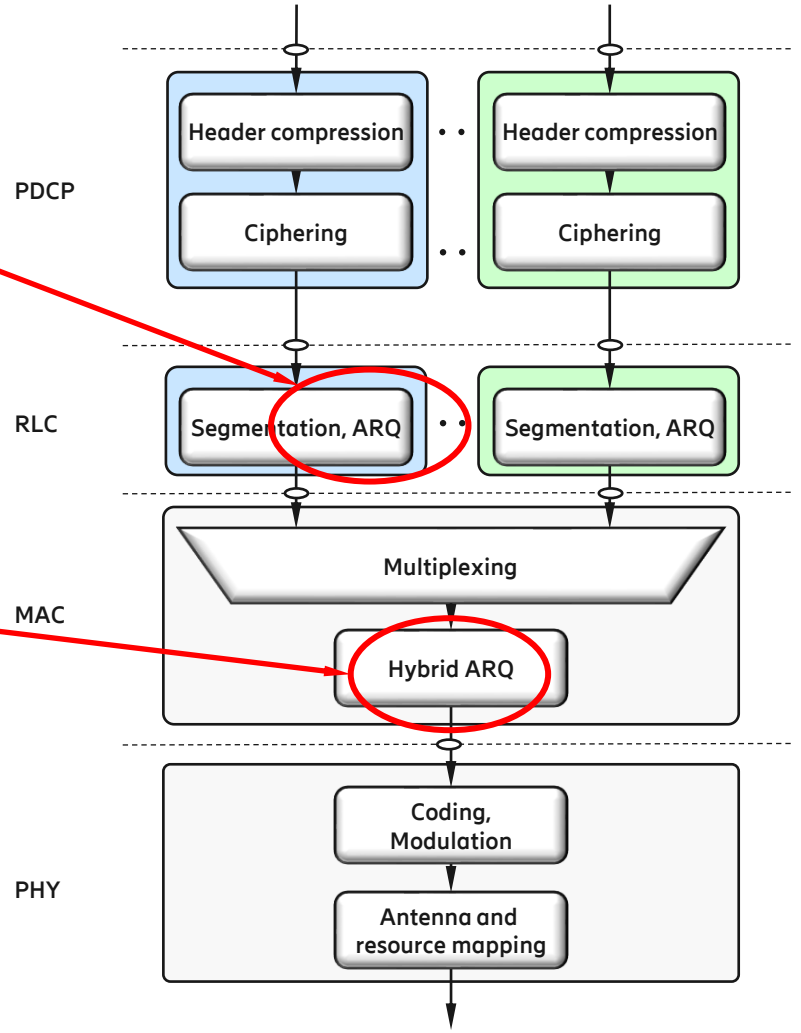


- Uplink
  - Scheduling request; indicating presence of data
  - Upon detecing a schedulign request, the base station requests e.g. buffer status and schedules the data transmission



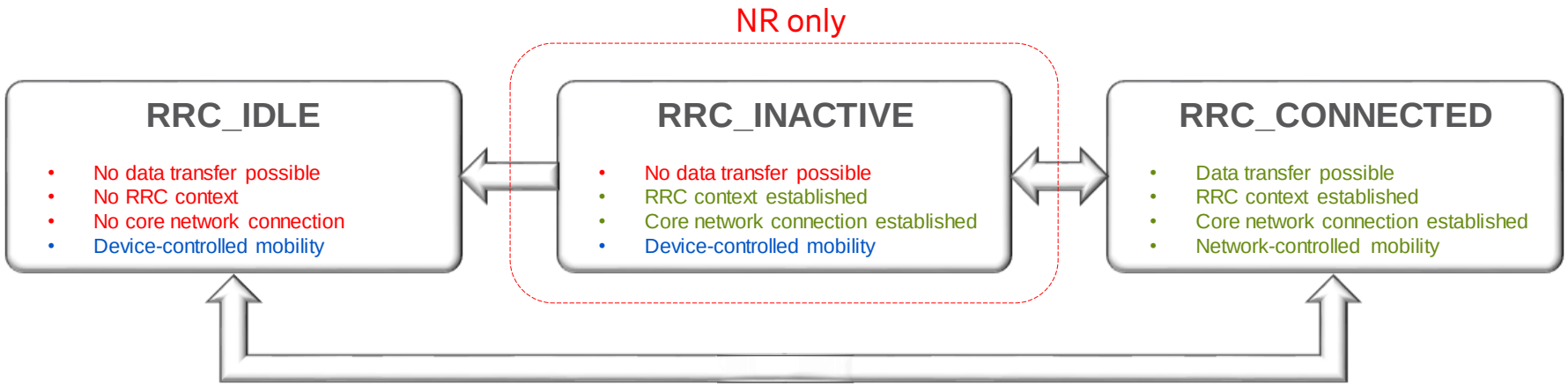
How to handle occasional reception errors?

- 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 retransmsisions – fast
  - Handles most errors
  - Success/failure indicated outband after reception of each scheduled data unit
  - Retransmsisions scheduled a few ms later

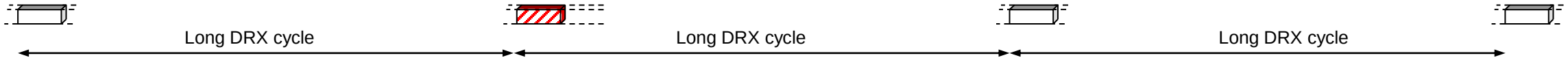


What about the battery lifetime?

— 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)

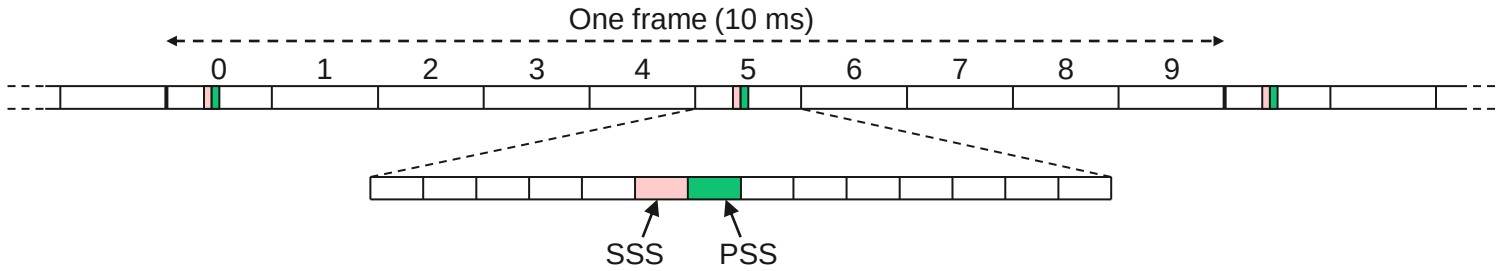


How to connect to the network?

- At power-up, the UE enters IDLE mode
- Need to obtain system information (the configuration of the network)

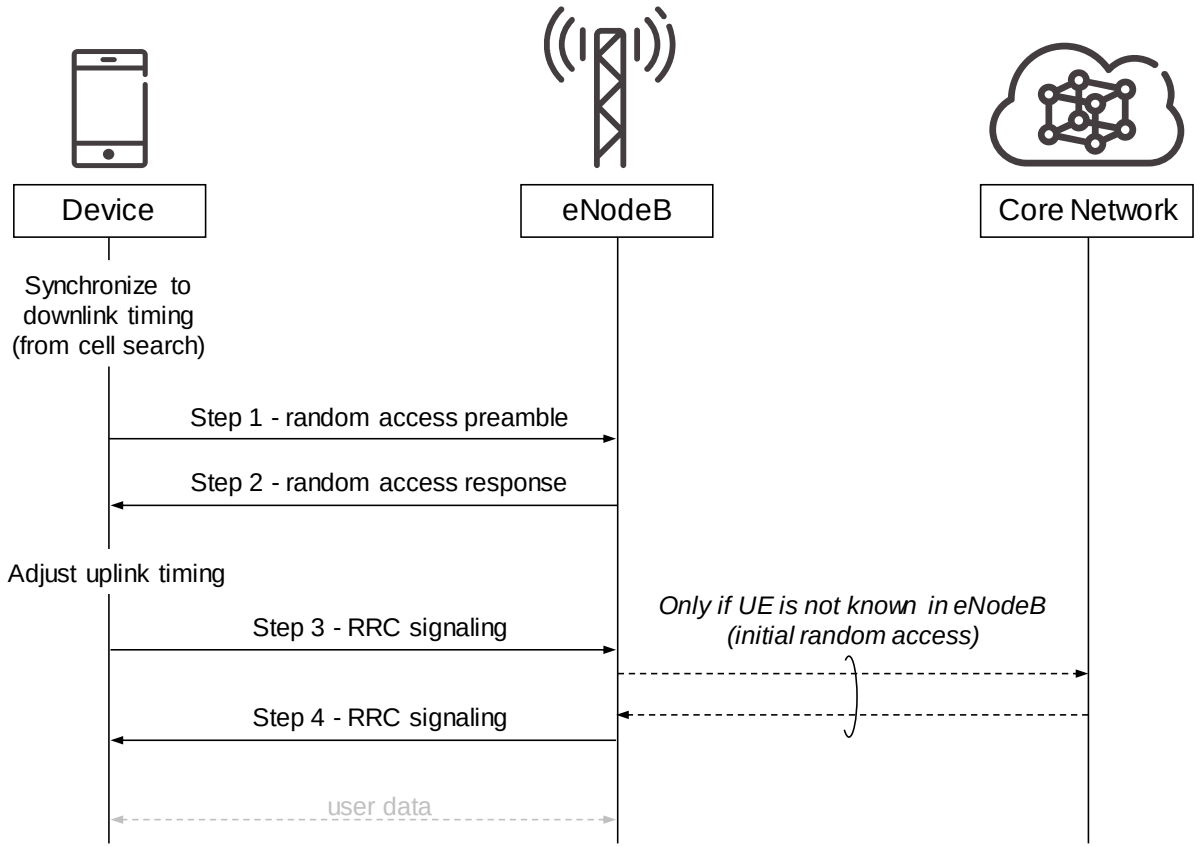
- Cell search – downlink time synchronization
  - Scan for synchronization signals (PSS and SSS), transmitted every 5 ms
  - Provides frame and subframe sync, as well as cell ID

- Once a cell is found, read system information (periodically transmitted) and perform random access



How to connect to the network?

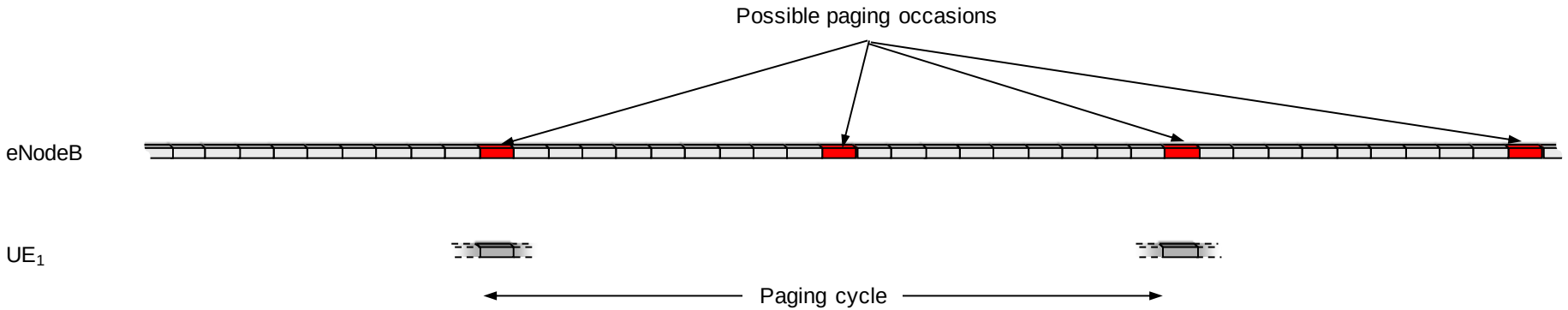
- Random access –
  UE-initiated connection esablishment
- Step 1 – preamble transmission
  - select on of 64 preambles and transmit
- Step 2 – random-access response
  - obtain network response, adjust uplink timing
- Step 3, 4 – contention resolution
  - transmit (on regular data channel) UE identity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



How to connect to the network?

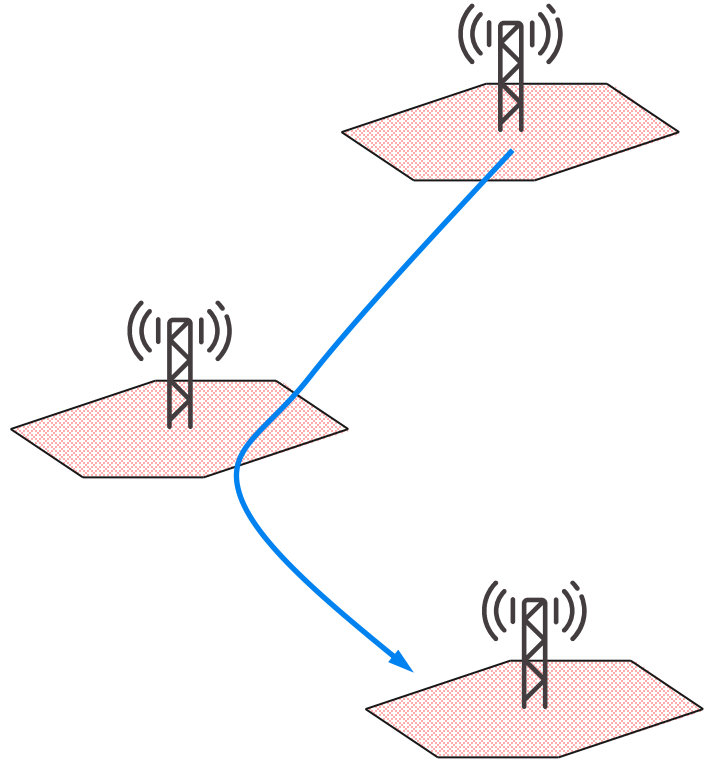
- Paging – network-initiated connection establishment for UEs in idle state

- 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?

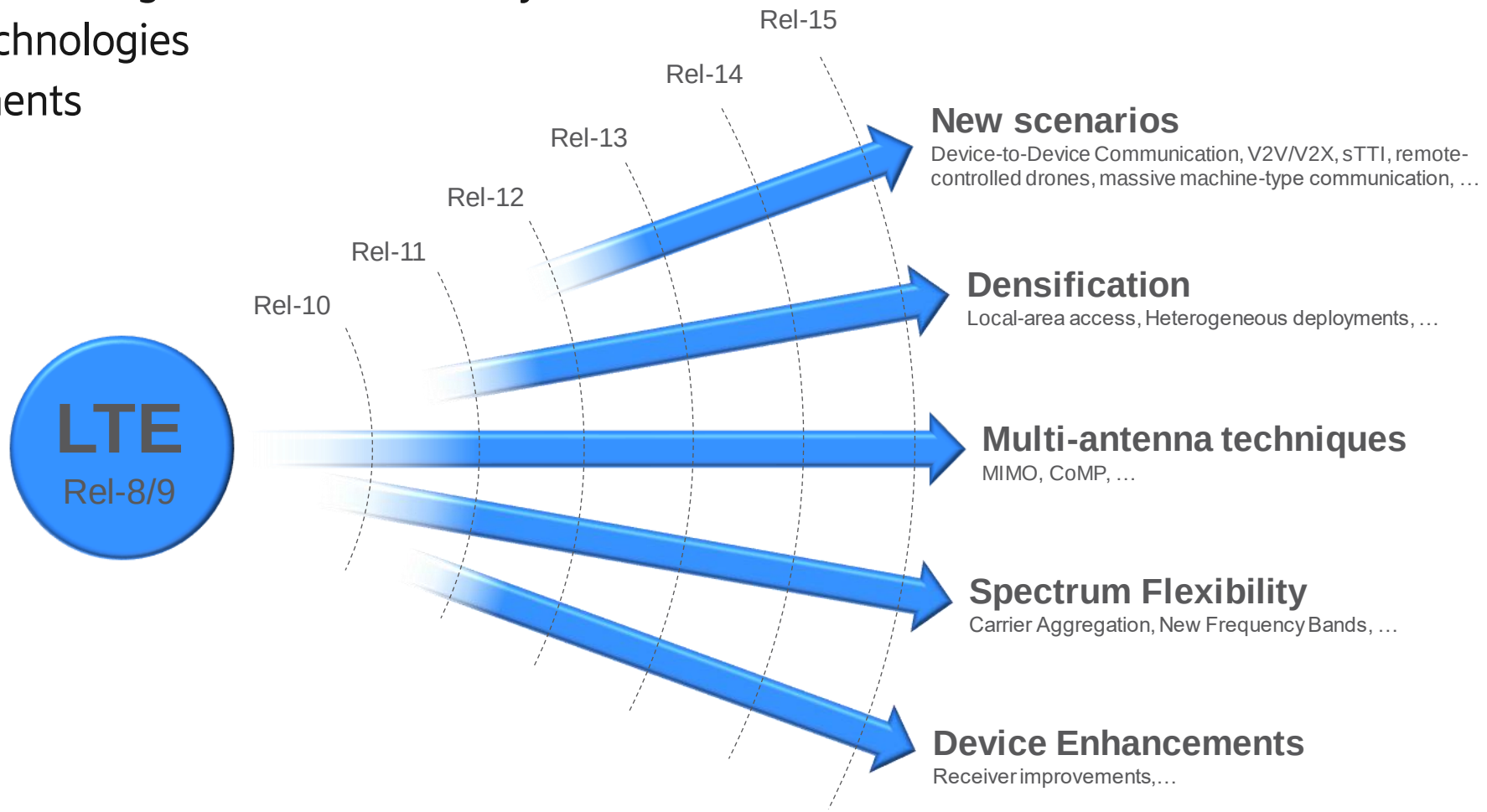
- Mobility is a cornerstone of cellular systems
- The UE regularly performs cell search to find 'better' cells
- Connected state mobility
  - The network determines when to connect to a different cell
  - The network knows the UE location on a cell level
- Idle state mobility
  - The UE determines when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



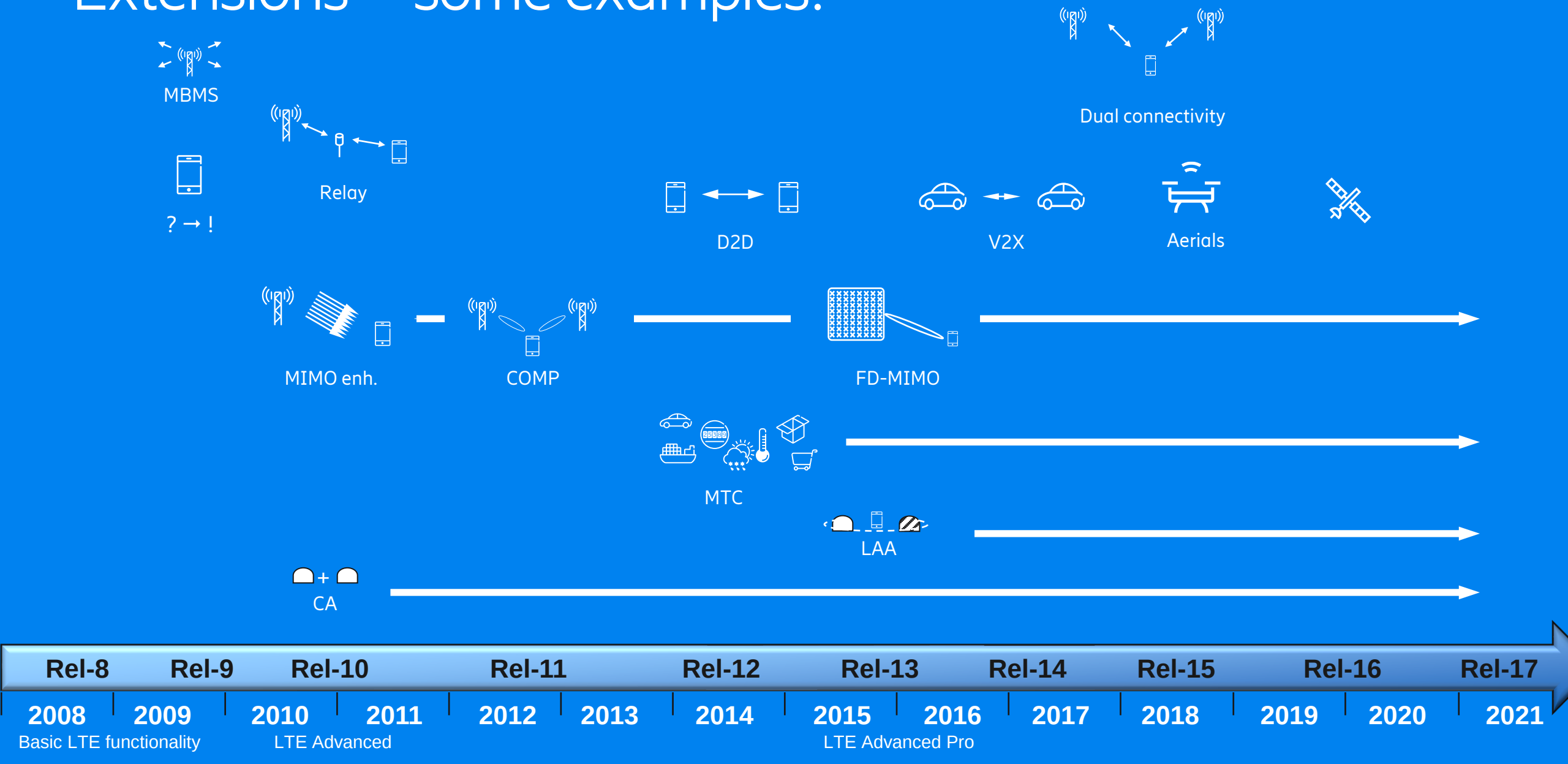
LTE evolution

Extensions please!

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



Extensions – some examples!



Carrier aggregation

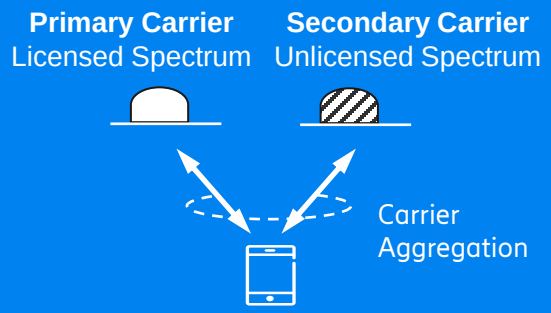
- What?
  - Multiple component carriers in parallel
- Why?
  - Exploitation of fragmented spectrum
  - Higher bandwidth ➡ higher data rates

Inter-band aggregation

Intra-band aggregation, contiguous component carriers

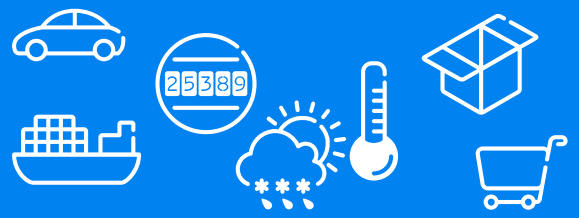
Intra-band aggregation, non-contiguous component carriers

License-assisted access



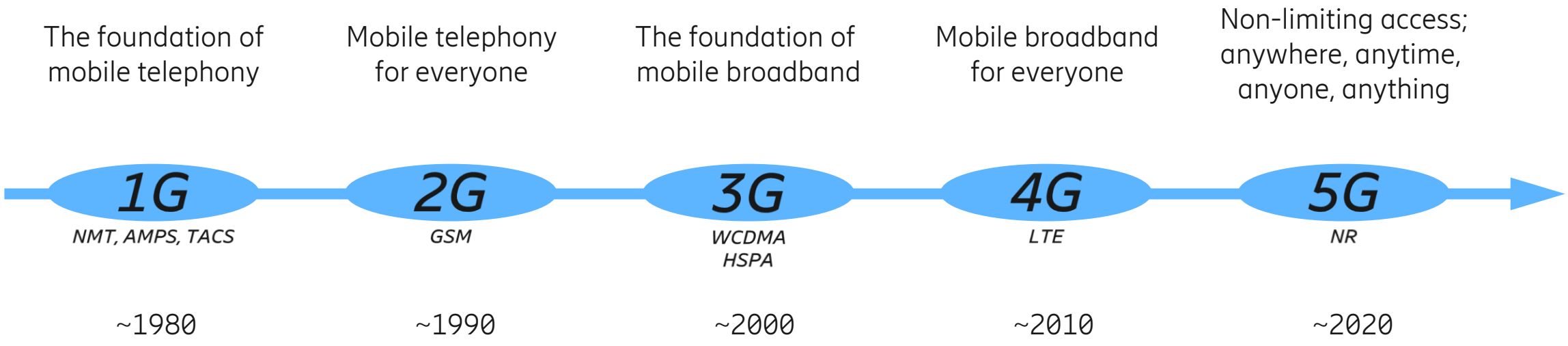
- Operator-deployed small cells in 5 GHz band
- License-assisted access
  - Using carrier aggregation to combine licensed and unlicensed spectrum
  - Licensed carrier for initial access, mobility, critical data, …
  - Unlicensed carrier(s) to boost data rates and capacity
- Listen-before-talk on the 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

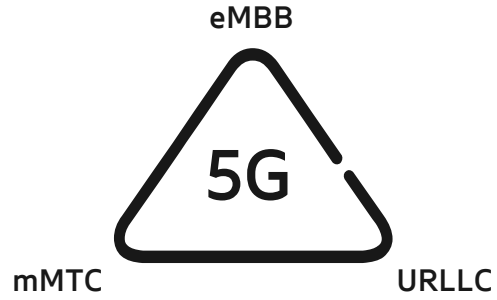
So…what happens now?

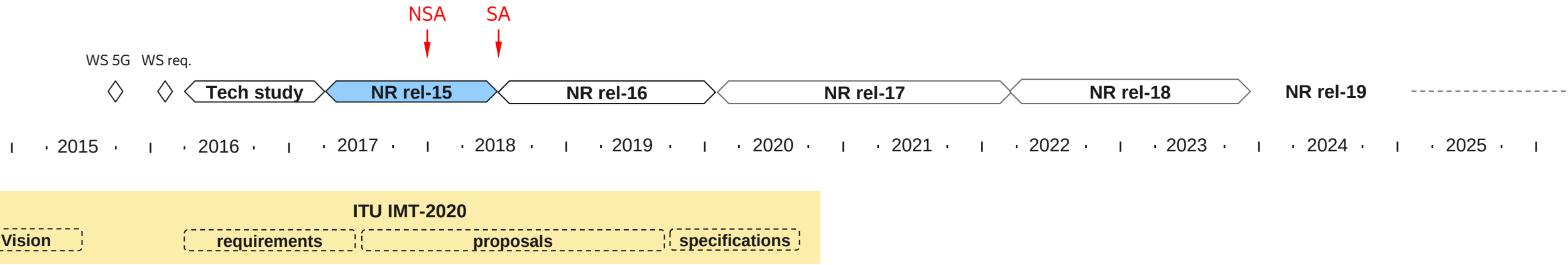


5G – going *beyond* the smartphone

NR Release 15 – The first 5G release

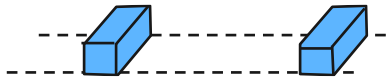
- Release 15 – the first release of NR radio access standardized by 3GPP
  - Completed in June 2018
  - Focuses on eMBB and (partially) on URLLC



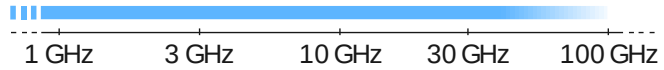


NR characteristics – some examples

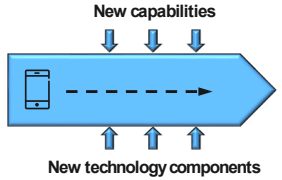
Ultra-lean design



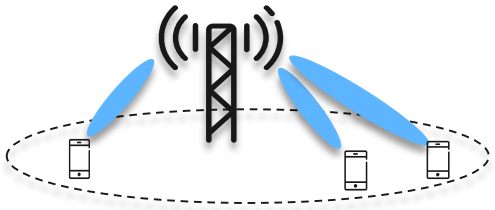
Wide spectrum range



Forward compatibility



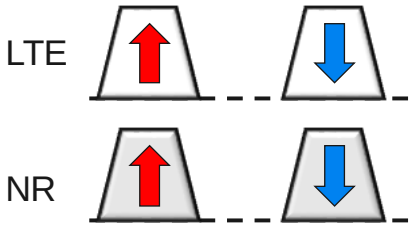
Multi-antenna support



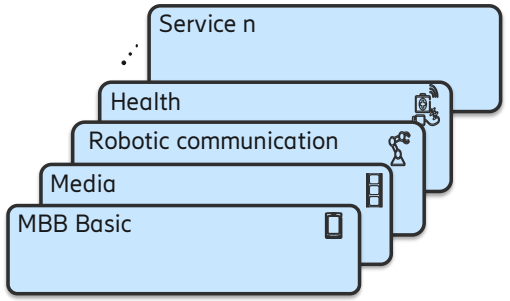
Low latency

NR characteristics – some examples

LTE – NR coexistence

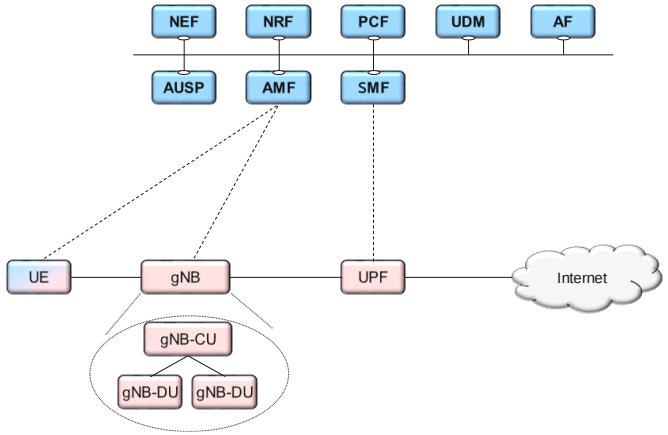


Network slicing



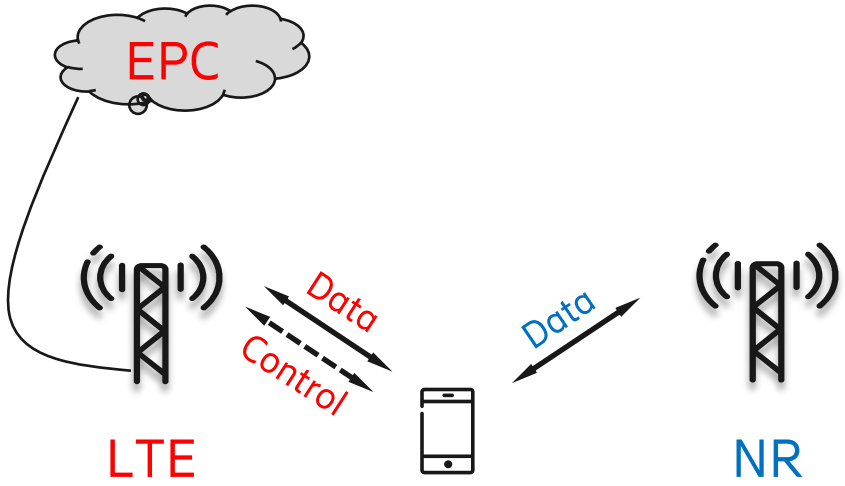
Modular architecture

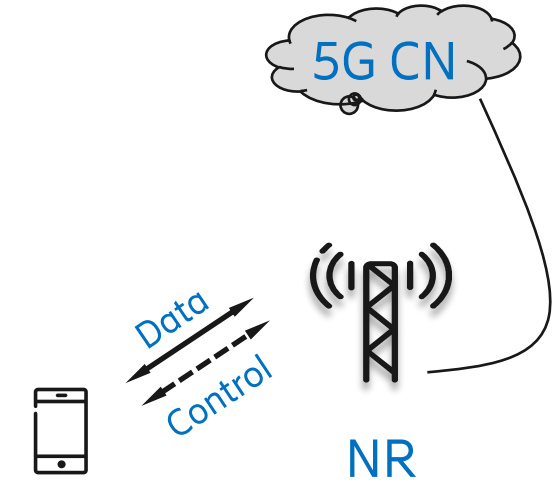
DU/CU split, CP/UP split



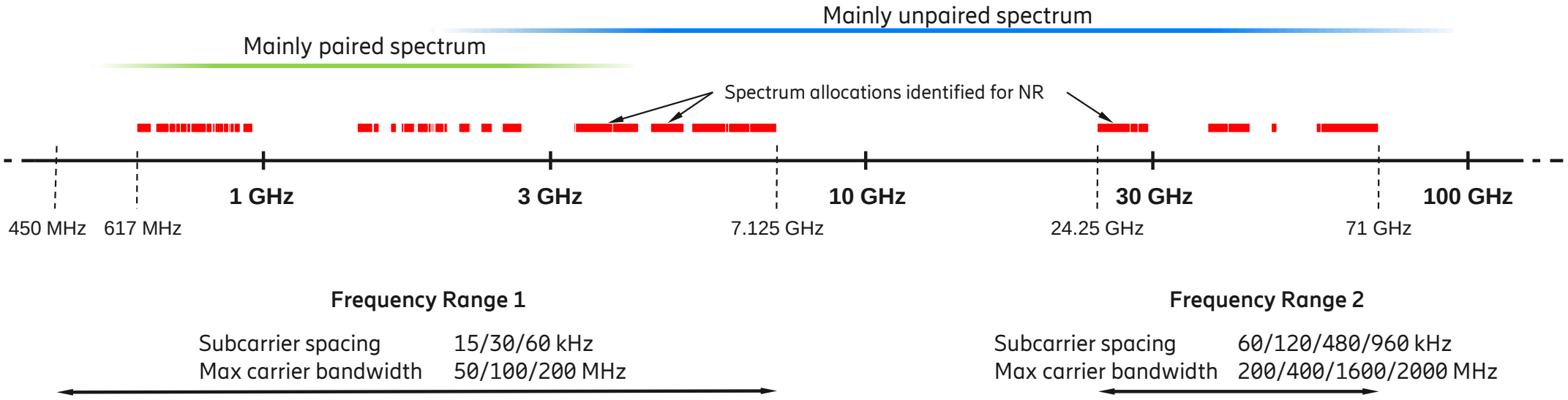
Architectural options

- 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

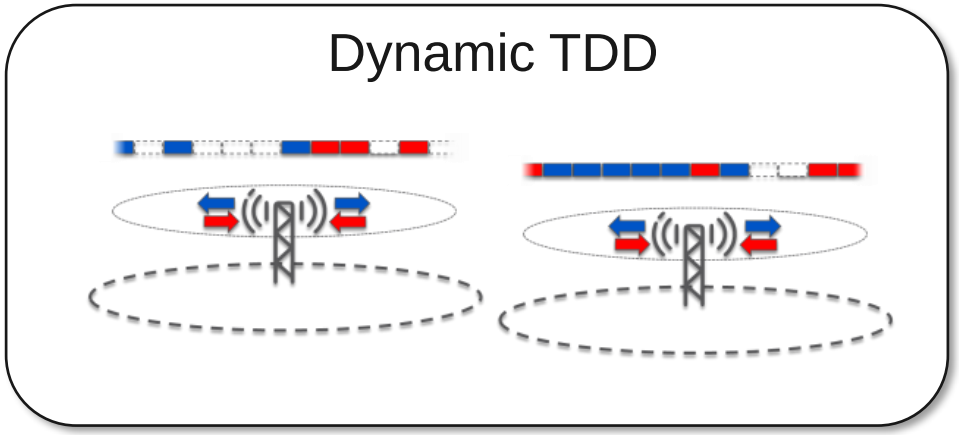

Mainly unpaired spectrum
Mainly paired spectrum
Spectrum allocations identified for NR
1 GHz
3 GHz
10 GHz
30 GHz
100 GHz
450 MHz
617 MHz
7.125 GHz
24.25 GHz
71 GHz
Frequency Range 1
Subcarrier spacing 15/30/60 kHz
Max carrier bandwidth 50/100/200 MHz
Frequency Range 2
Subcarrier spacing 60/120/480/960 kHz
Max carrier bandwidth 200/400/1600/2000 MHz

Dynamic TDD

- Dynamic assignment of resources to downlink and uplink
  - Possible to inform the UE about a semi-static uplink/downlink allocation

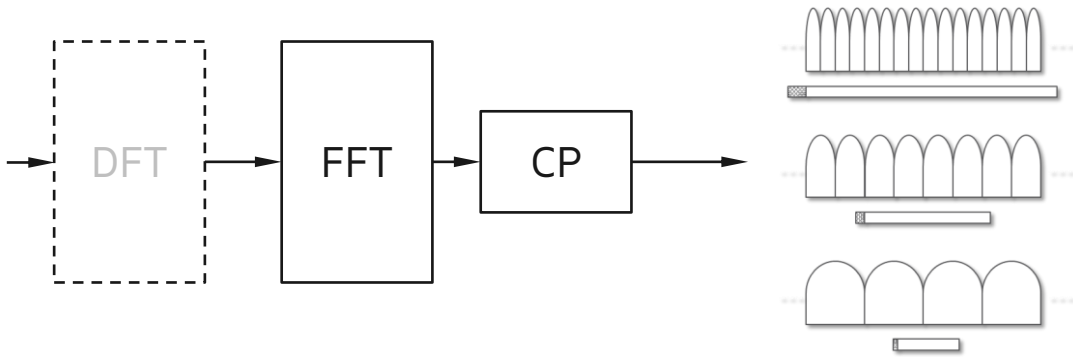
- "Macro" deployment – semi-static operation
  - Less dynamic traffic variations
  - Important to avoid TDD-specific interference

- "Small-cell" deployments – dynamic operation
  - More dynamic traffic variations
  - TDD-specific interference less critical

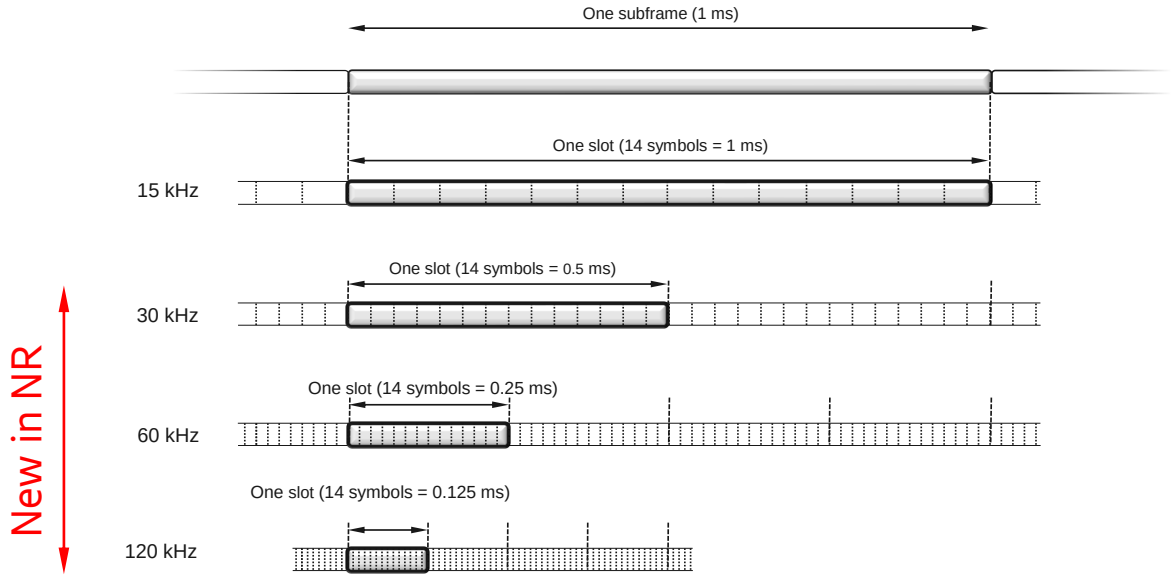


NR waveform and frame structure

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

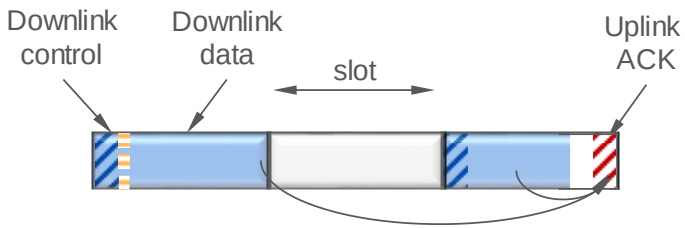


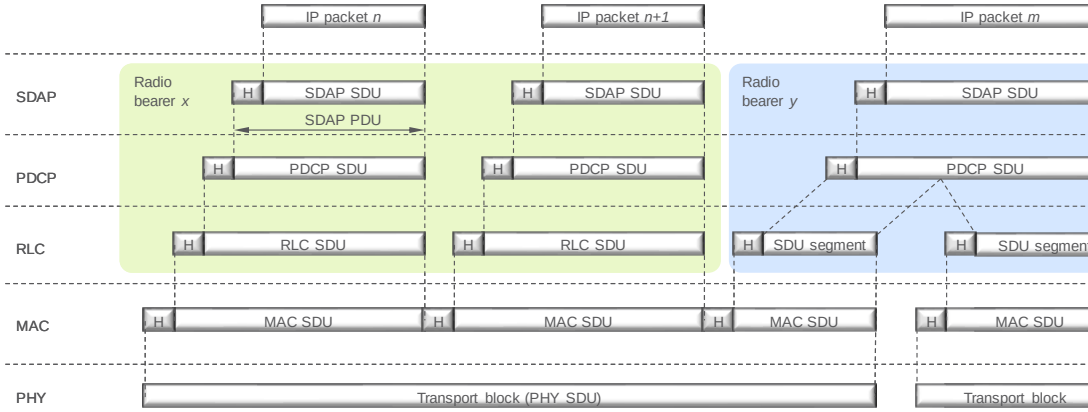
- Slot duration depends on subcarrier spacing



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





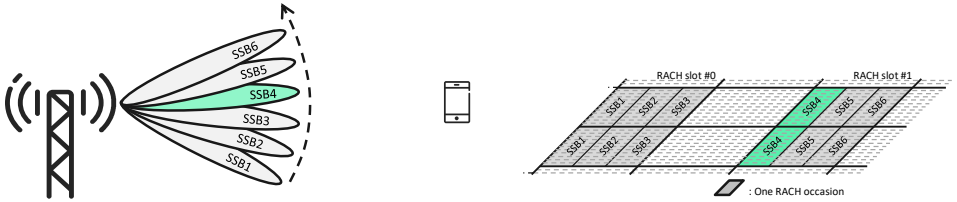
Multi-antenna transmission

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

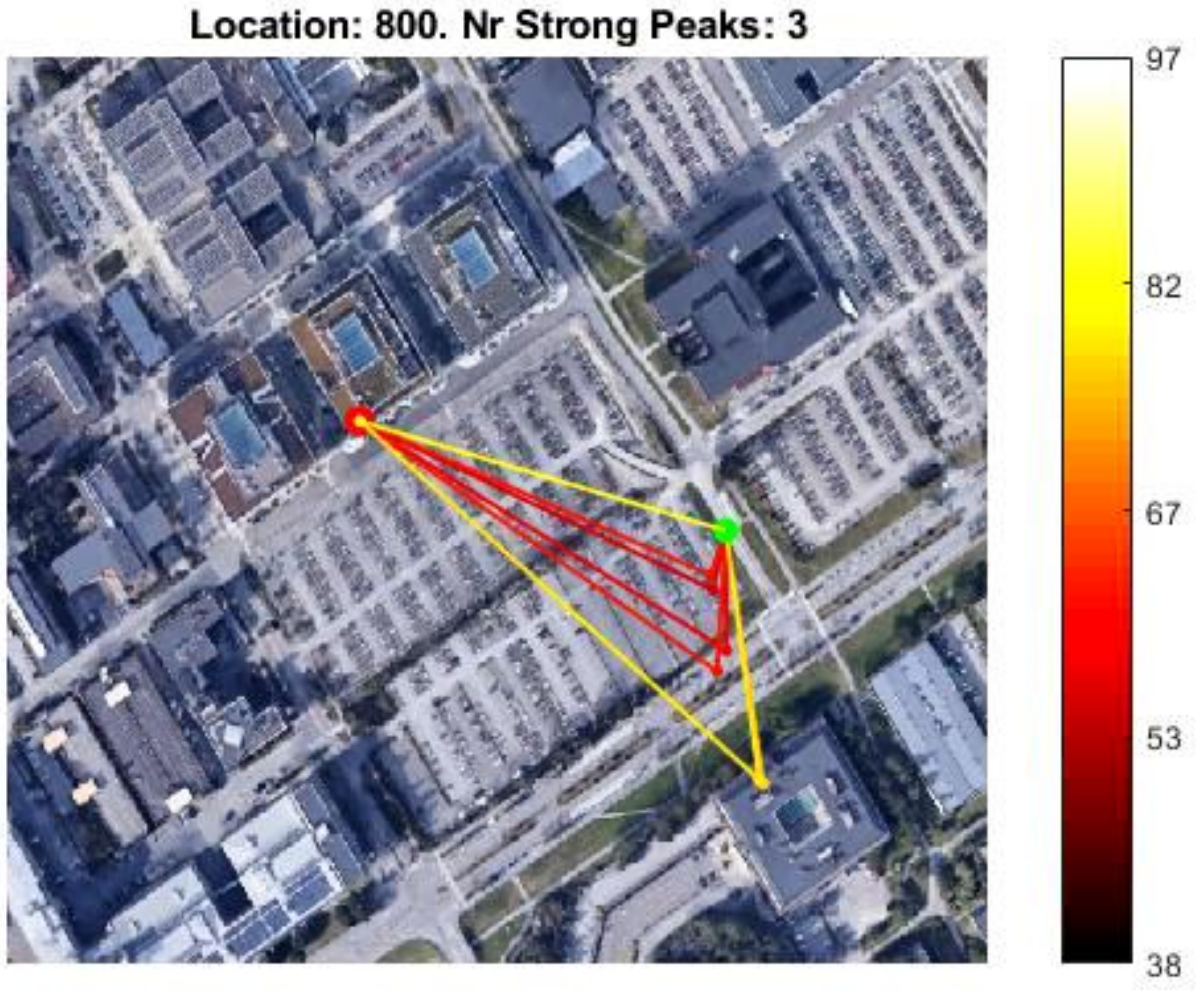
Beamforming

- 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



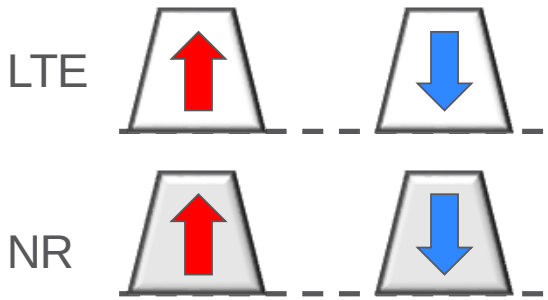
Beamforming

— Example of beam reflections (measurements done in Kista)

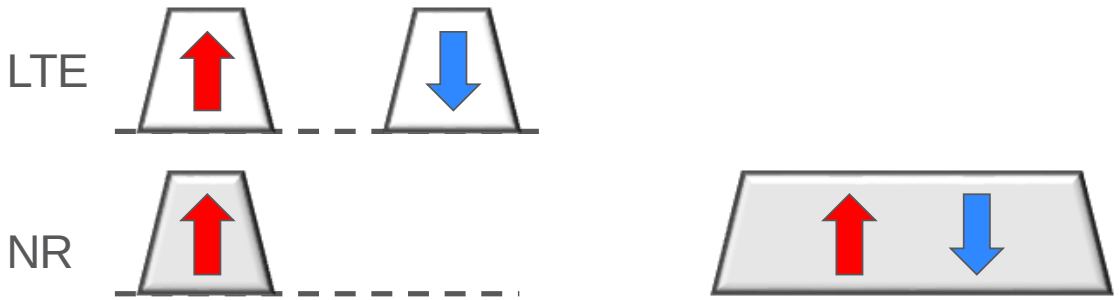


NR-LTE coexistence

- 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



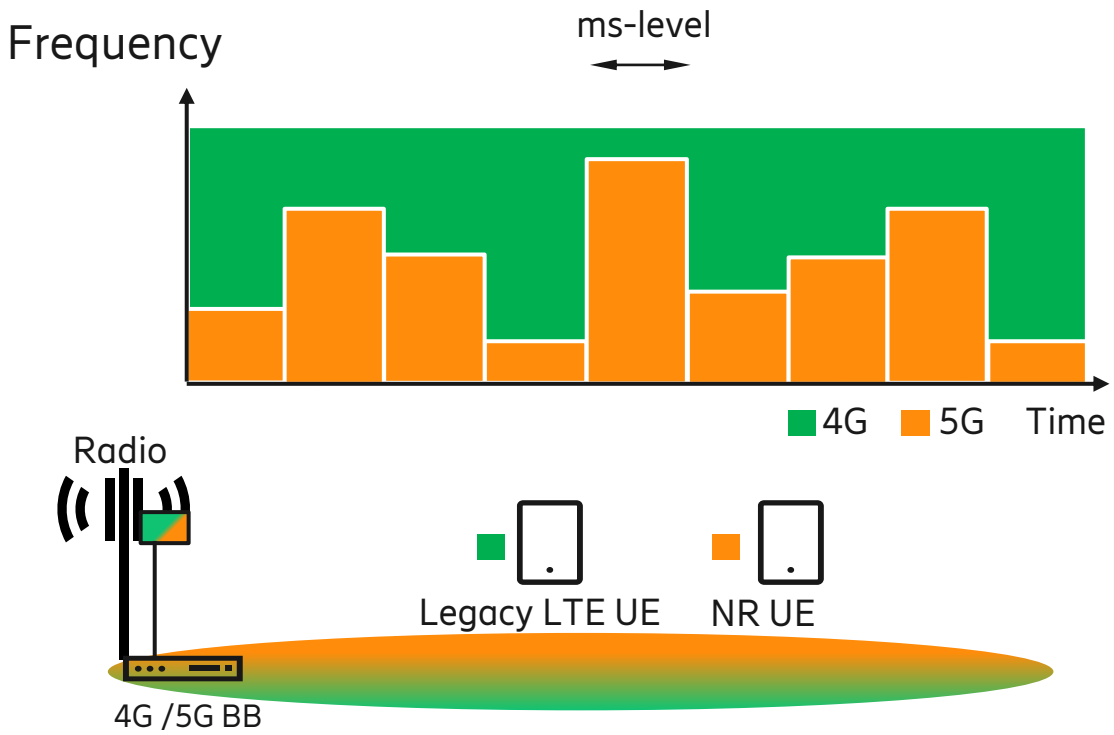
Uplink-only co-existence

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.