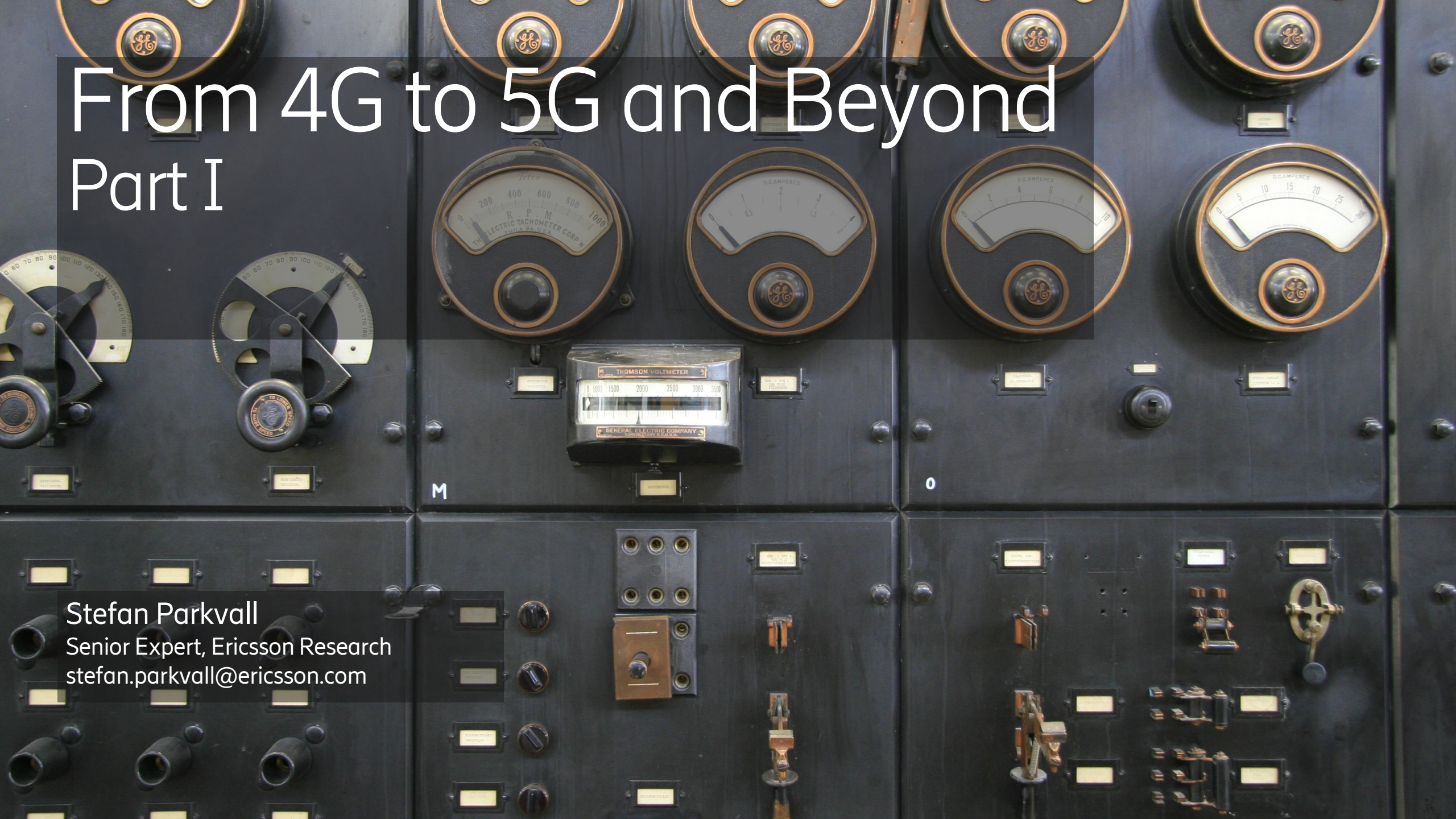
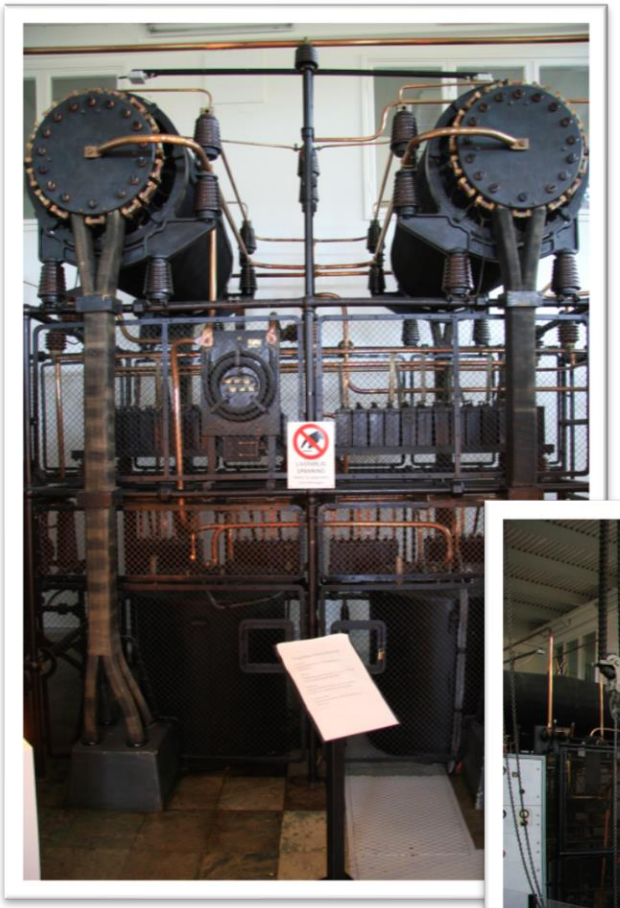
From 4G to 5G and Beyond
Part I

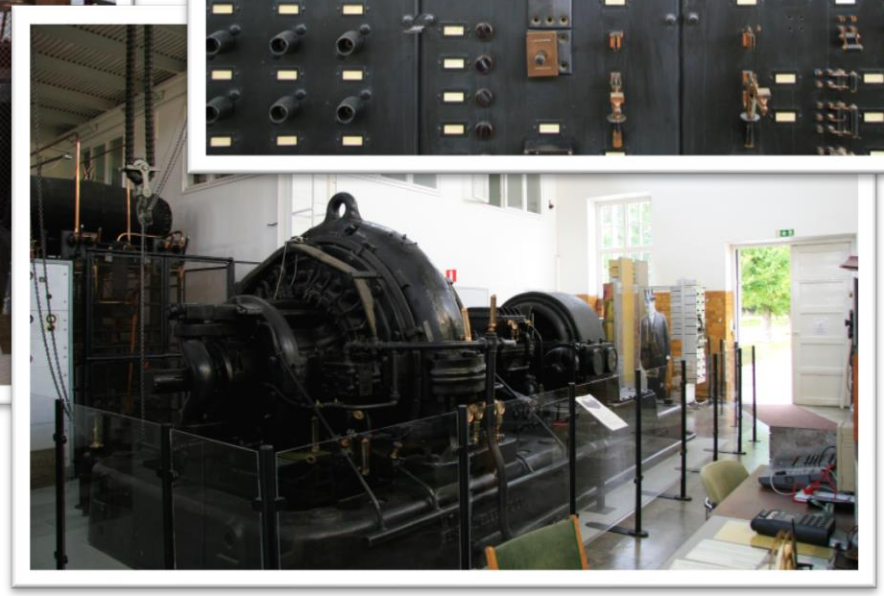


Stefan Parkvall
Senior Expert, Ericsson Research
stefan.parkvall@ericsson.com

Grimeton, early 1920s

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



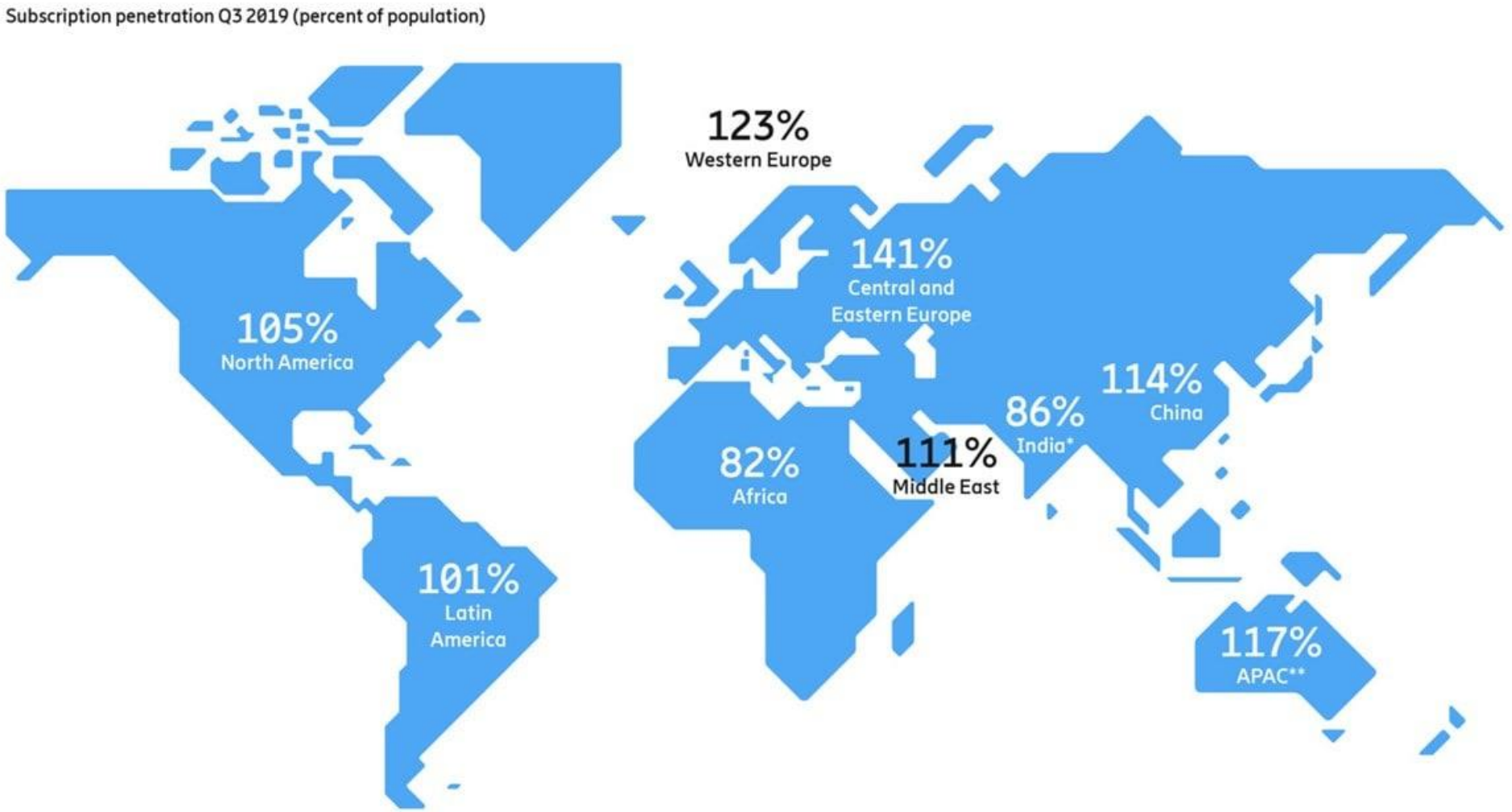


Outline

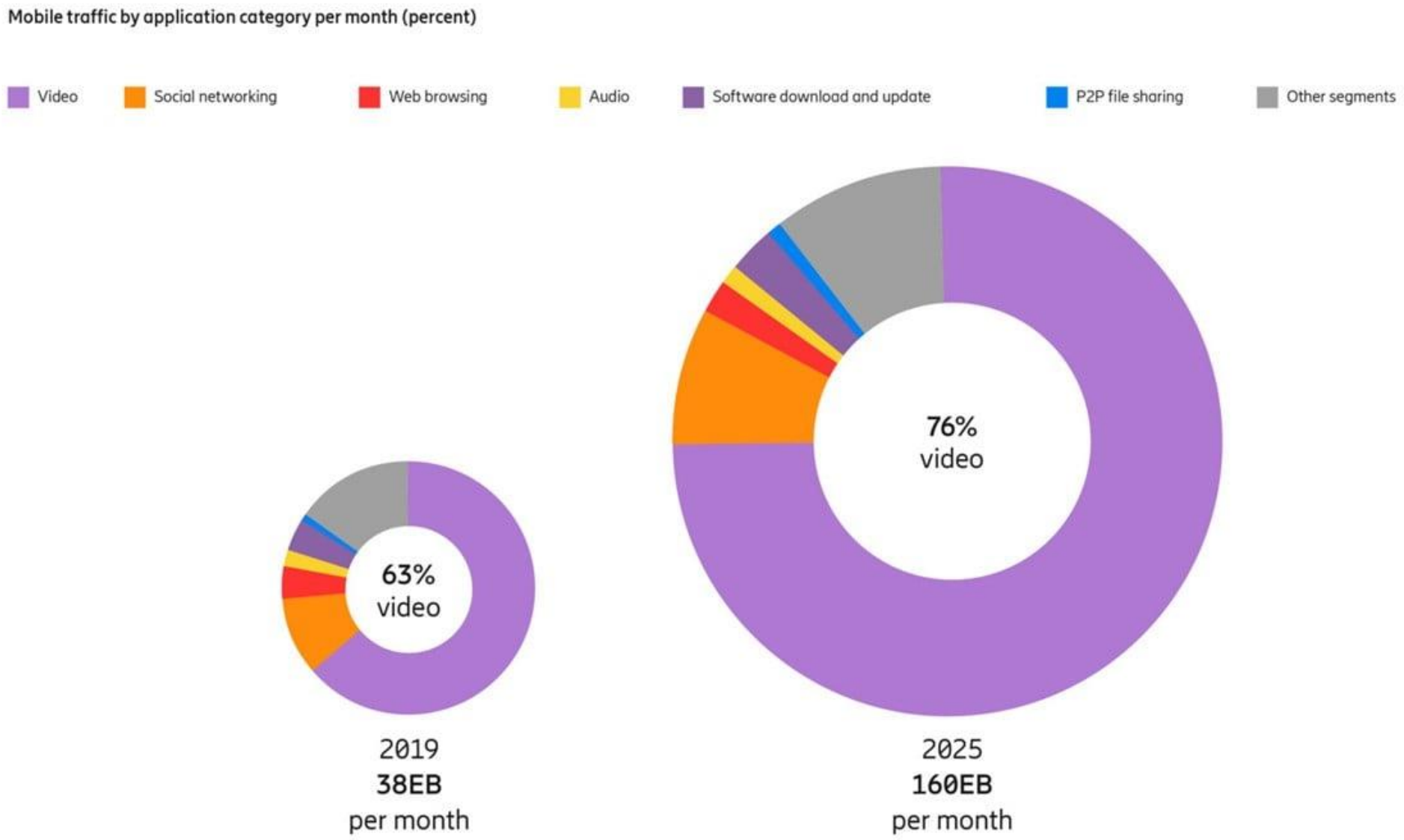
- Introduction
- LTE (4G)
- LTE evolution
- NR (5G)
- NR evolution and beyond
- Standardization in practice

Introduction

Mobile subscriptions 6.2B

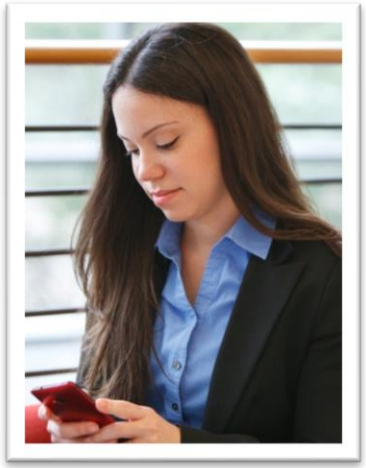


Total traffic 38 EB/month, +68% year-to-year



Inauguration of a new Pope

4G – mobile broadband



LTE – worldwide standard for mobile broadband

High peak data rates

300 Mbit/s DL, 75 Mbit/s UL initially

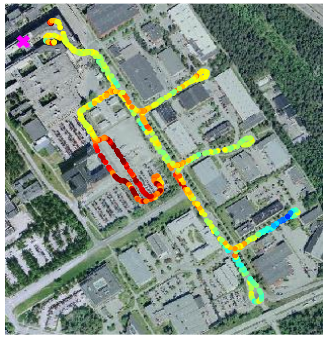
25 Gbit/s DL, 9.6 Gbit/s UL currently

Low latency

5 ms user plane, 50 ms control plane

LTE – 4G mobile broadband in 3GPP

From early studies…



~2007

…via trials…

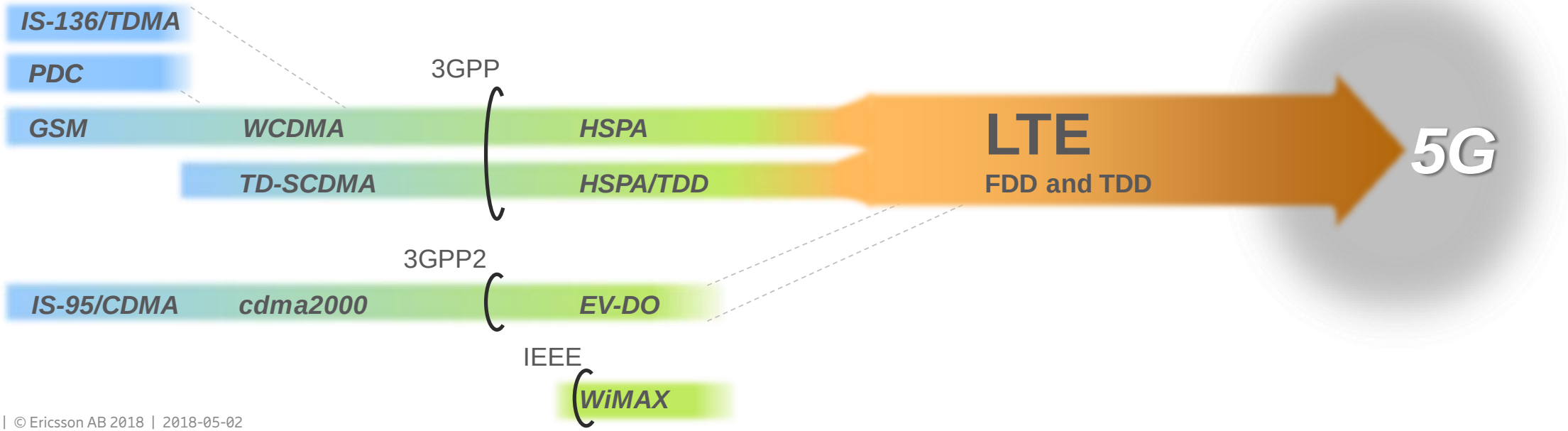
~2005

…to commercial operation!

2009

Truly global standard

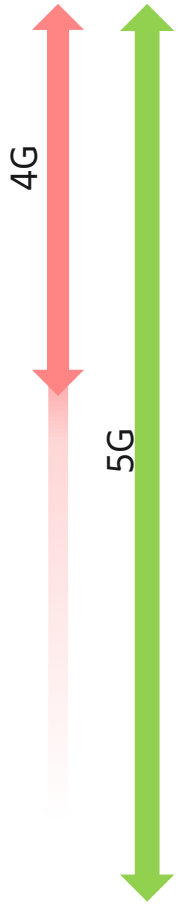
— LTE is a *global* technology for mobile broadband
  — Convergence of 3GPP and 3GPP2 technology tracks
  — Convergence of FDD and TDD into a single technology track



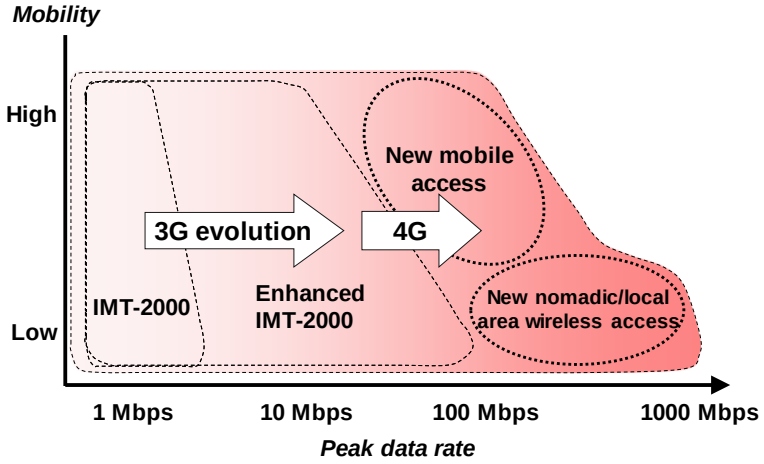
LTE – 4G

What do we require from a wireless system?

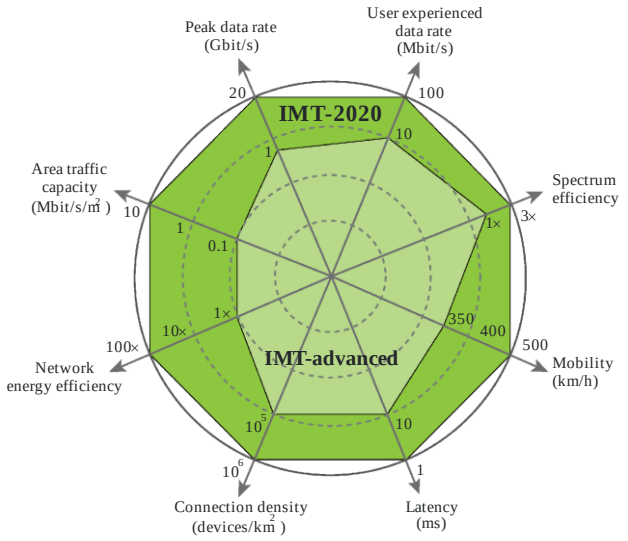
- Coverage
- Mobility
- High data rates
- High capacity
- Low latency
- High connection density
- High reliability
- …



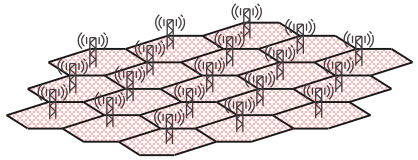
4G
"The van diagram"

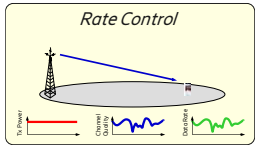


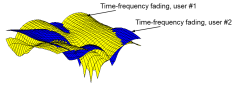
5G
"The spider diagram"

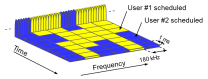


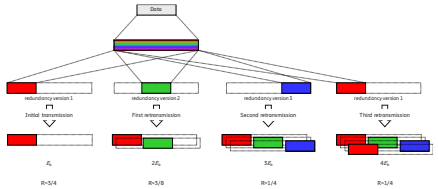
How do we get it?

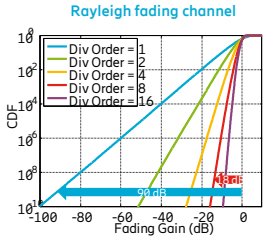












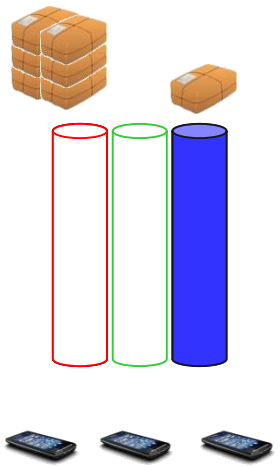
- Multiple cells
- Rate control
- Channel-dependent scheduling
- Hybrid-ARQ
- Diversity
- Fast processing
- Low overhead
- …

Channel-dependent scheduling

— To whom do we give the radio resources?

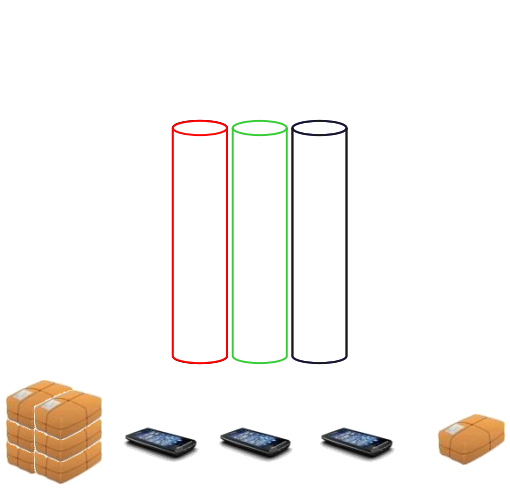
Channel-dependent scheduling

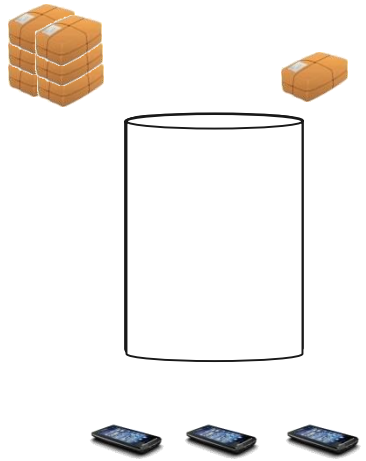
- To whom do we give the radio resources?
- Dedicated channel
  - Resources assigned at "call setup"
  - Independent of instantaneous traffic
  - "Circuit-switched"



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"

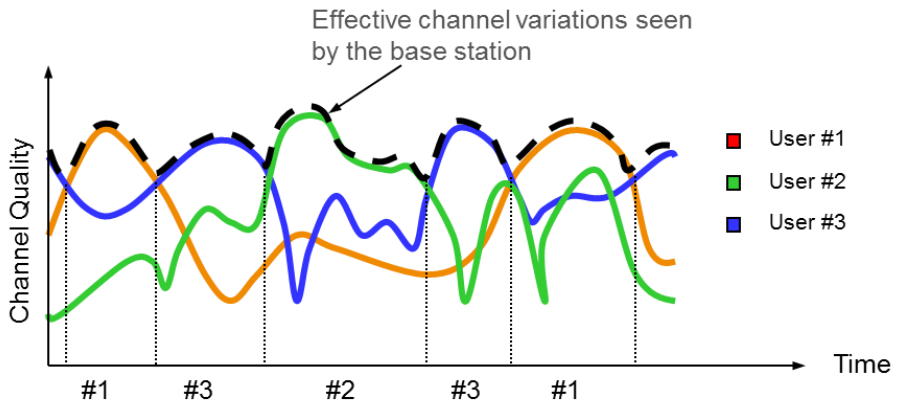




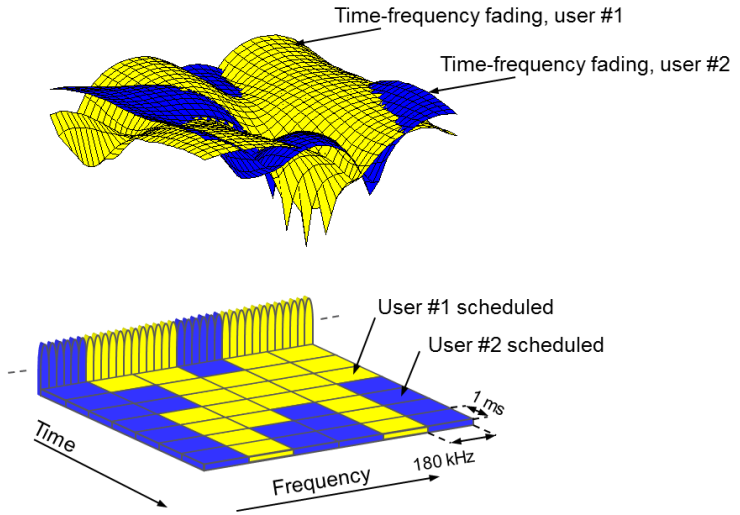
Channel-dependent scheduling

- 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...

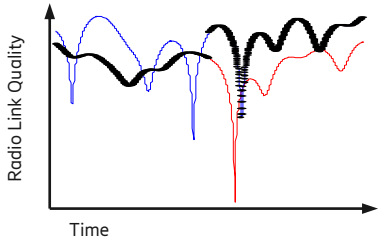


...or in time and frequency domains

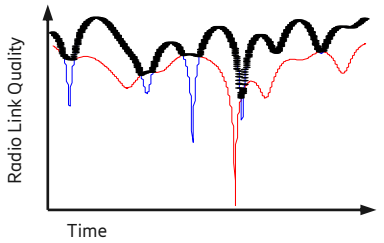


Channel-dependent scheduling

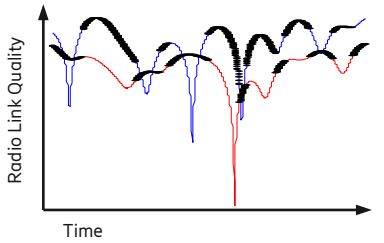
- Round Robin (RR)
  - Cyclically assign the channel to users, not taking quality conditions into account
  - Simple but poor performance



- Max C/I
  - Assign the channel to the user with the best **absolute** quality
  - High system throughput but not fair

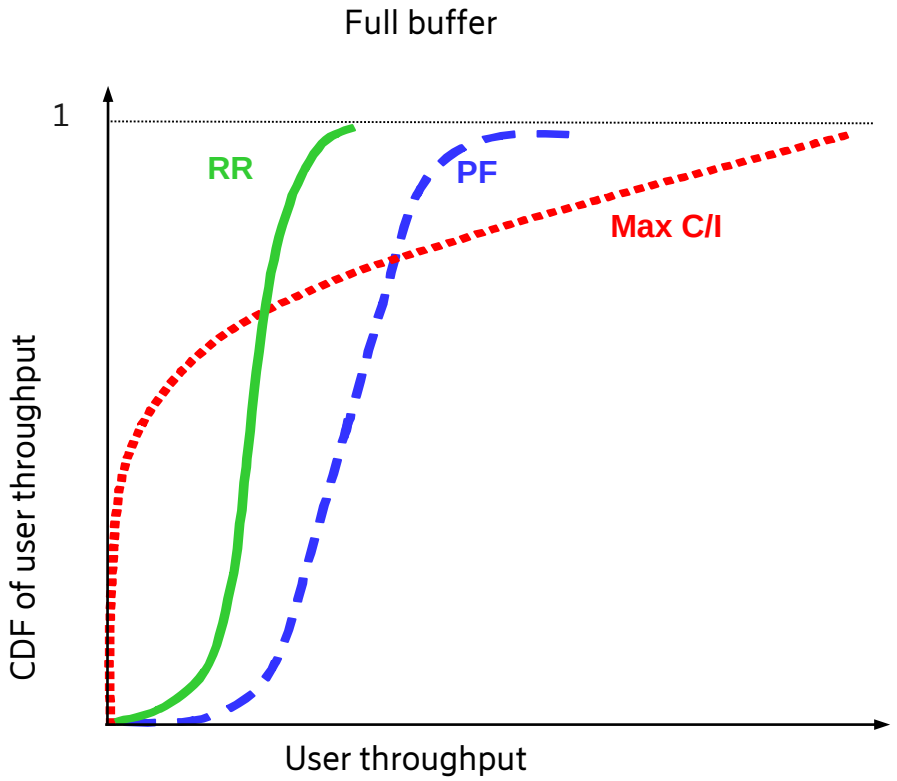


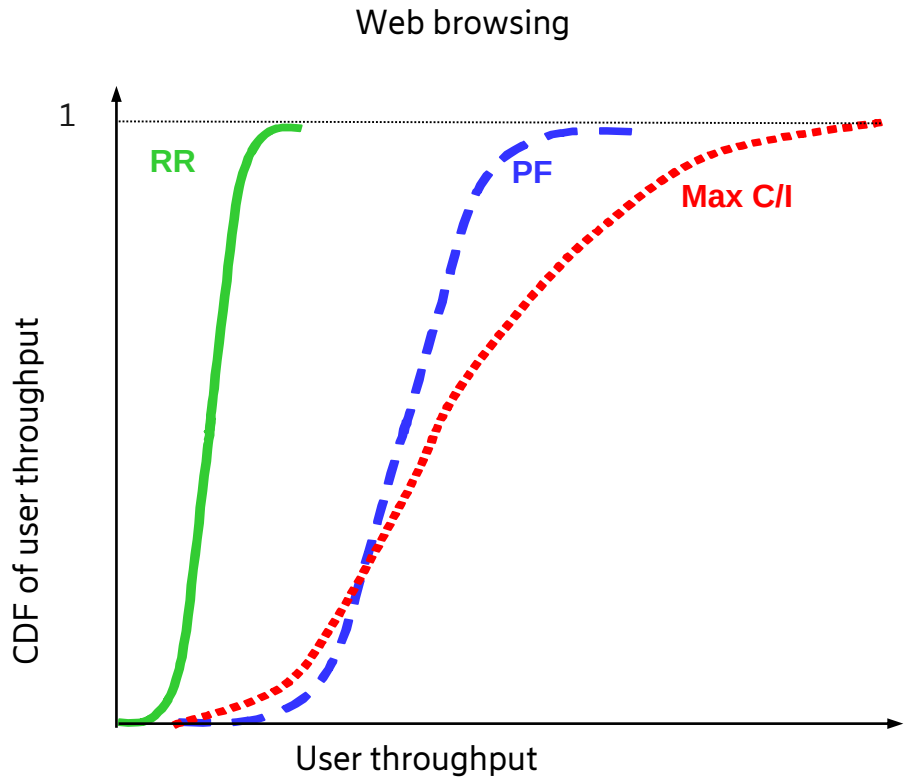
- Proportional Fair (PF)
  - Assign the channel to the user with the best **relative** quality
  - High throughput, fair



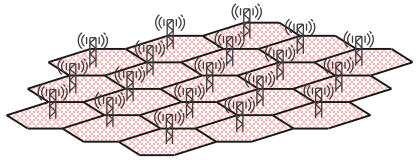
Channel-dependent scheduling

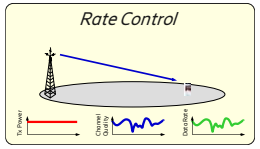
— The larger the unfairness, the higher the system throughput...
...true for full buffers but realistic traffic complicates the picture

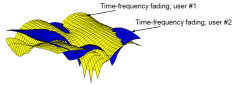


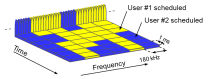


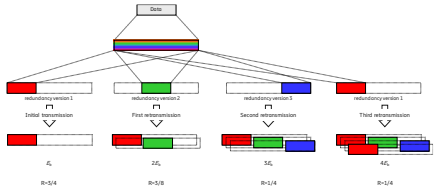
How do we get it?

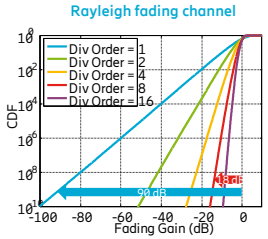










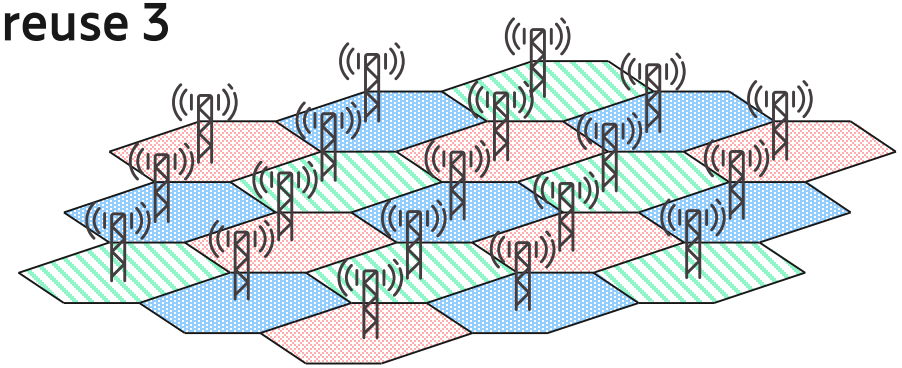


- Multiple cells
- Rate control
- Channel-dependent scheduling
- Hybrid-ARQ
- Diversity
- Fast processing
- Low overhead
- …

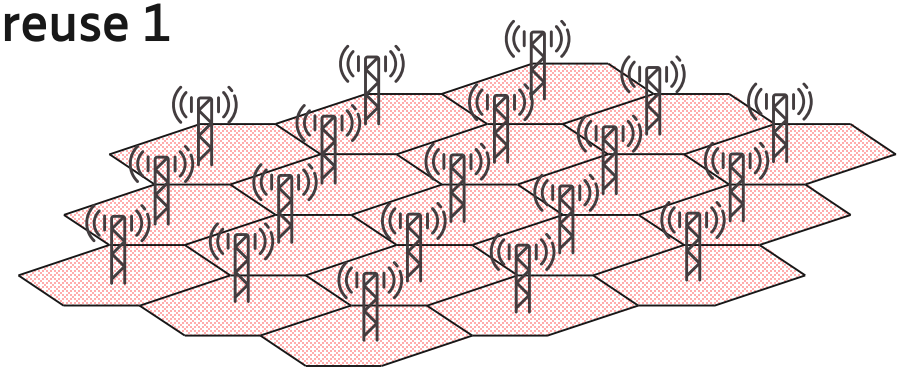
Why is it called 'cellular'?

- Multiple cells used to cover a large area
  - capacity and coverage
- LTE uses frequency reuse one
  - The same frequency is used in all cells
- Inter-cell interference
  - suppressed through processing gain (channel coding)
  - interference experienced in one cell depends on the instantaneous activity in neighboring cells

reuse 3

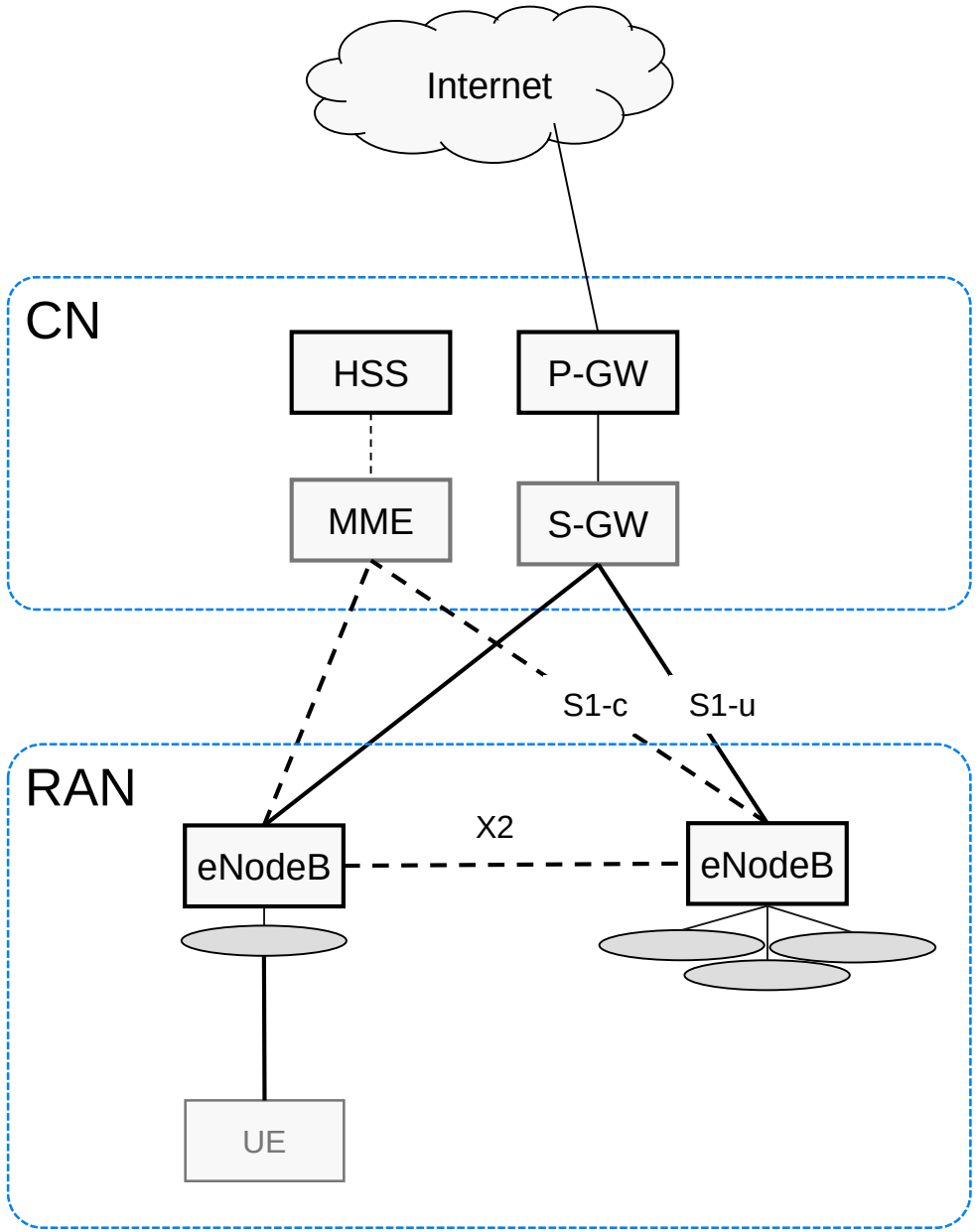


reuse 1

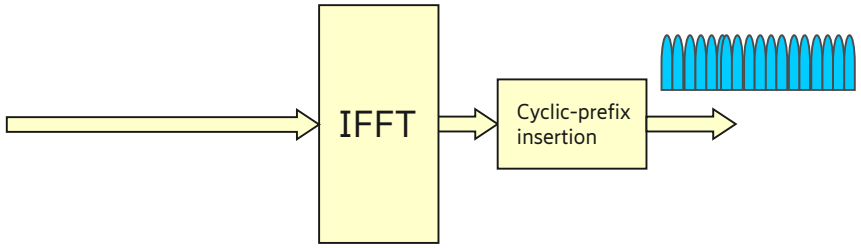


LTE network architecture

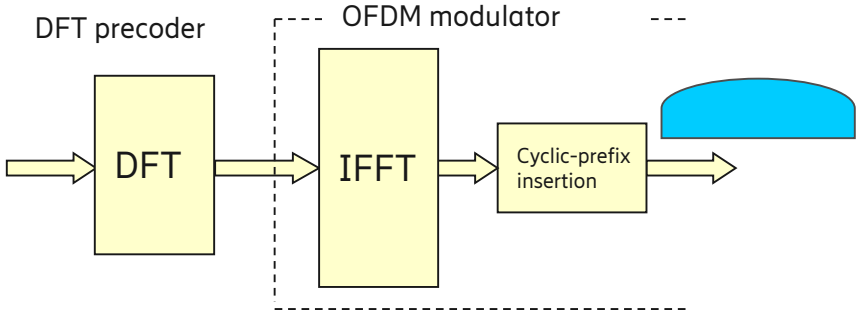
- Core Network
  - Authentication, charging, setting up end-to-end connections, ...
- Radio-Access Network
  - Radio-related functionality, e.g. scheduling, radio-resource handling, retransmission protocols, coding/modulation, multi-antenna schemes



LTE waveform



- Downlink – OFDM
  - Cyclic prefix ➡ robust to time dispersion
  - Many subcarriers ➡ power-amplifier inefficiency
- Subcarrier spacing Δf = 15 kHz in LTE
  - Small Δf ➡ long cyclic prefix, sensitive to phase noise
  - Large Δf ➡ short cyclic prefix, robust to phase noise

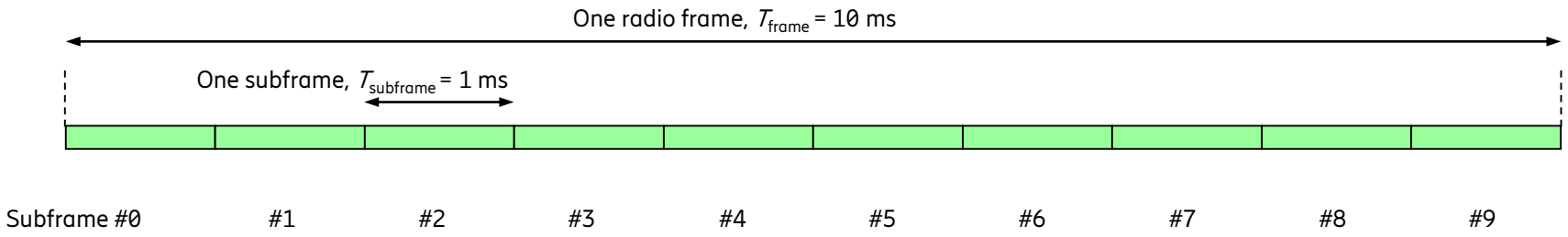


- Uplink – DFT-spread OFDM
  - Improves transmitter power-amplifier efficiency at the cost of a more complex receiver

Time-domain structure

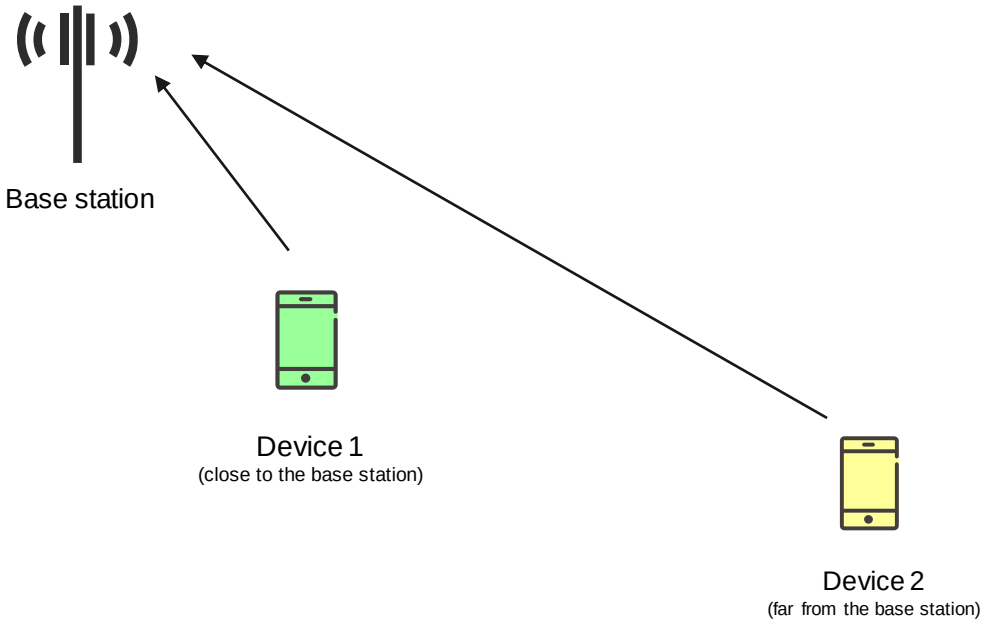
— In LTE, transmissions are organized into 1 ms long subframes
— Each subframe consists fo 14 OFDM symbols

— Scheduling, link adaptation, hybird-ARQ retransmissions, etc operate on subframe level

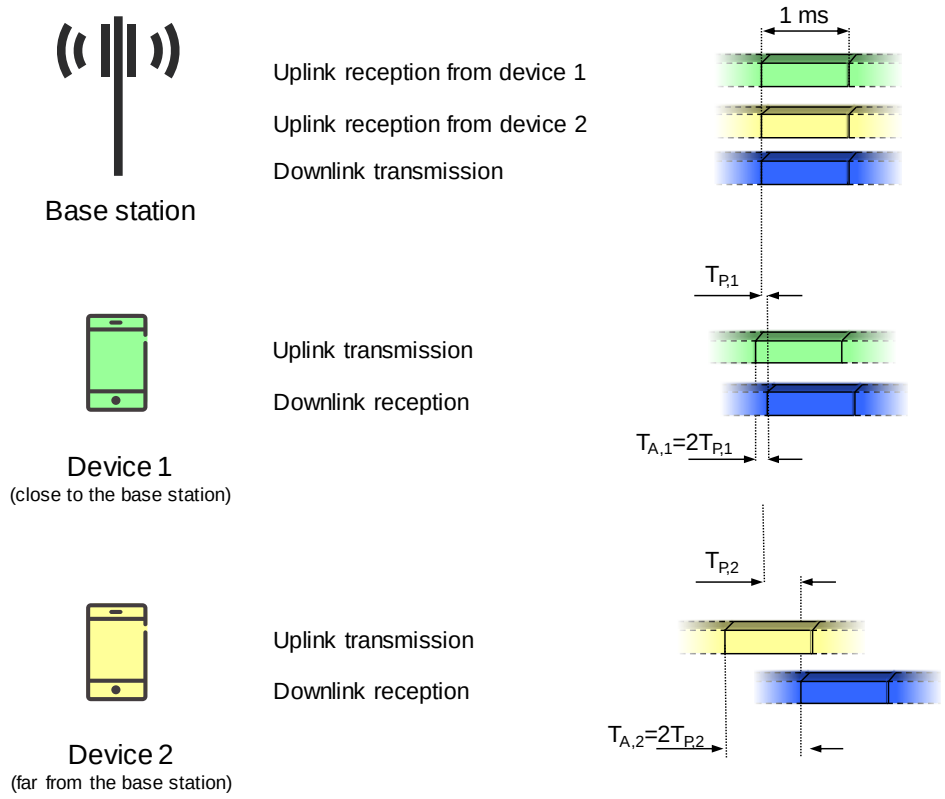


Uplink – power control and timing advance

— Power control – adjust uplink transmission power (assuming a reference data rate) to control interference

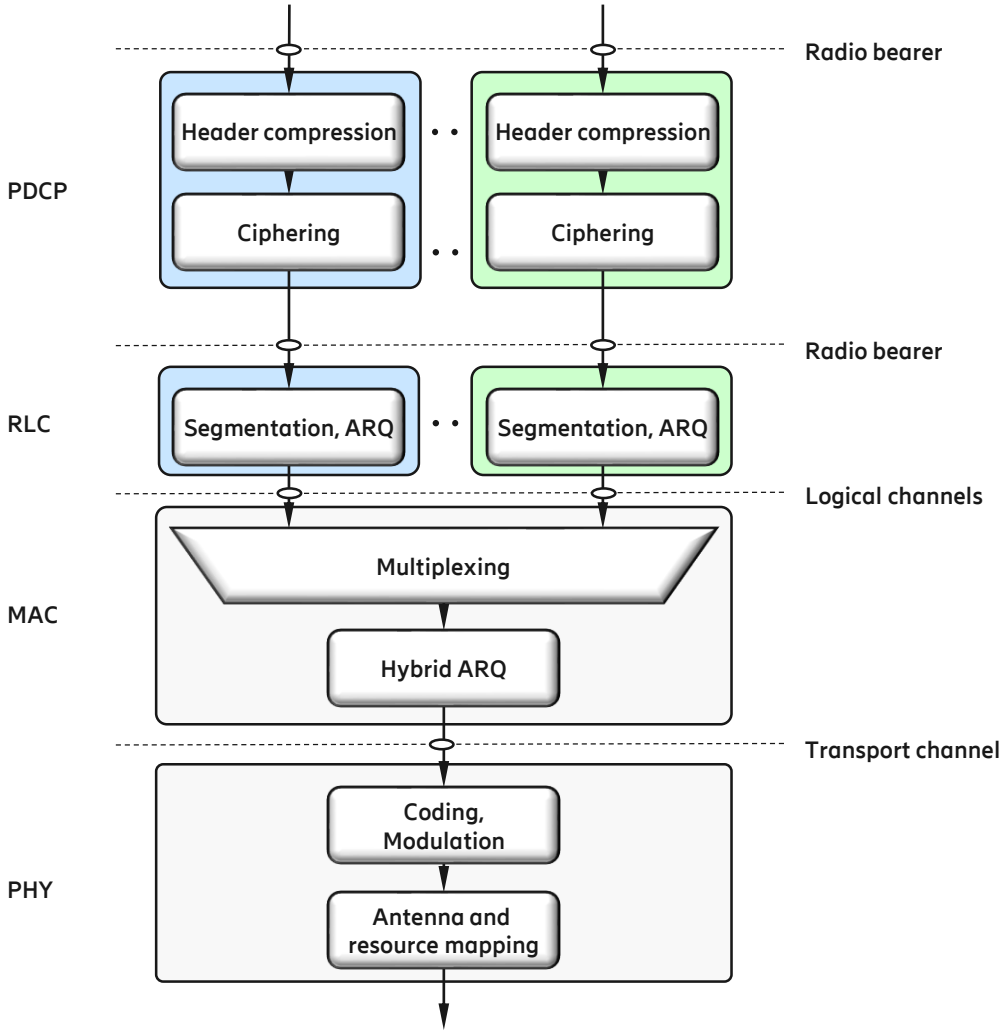


— Timing advance – adjust uplink timing to ensure subframe alignment at the base station

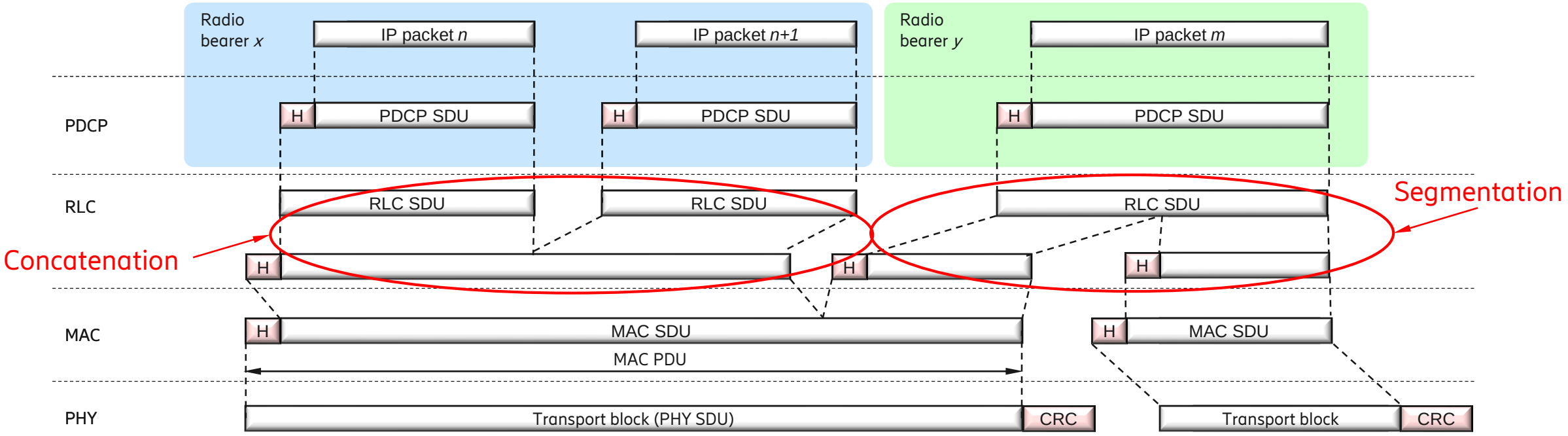


LTE protocol stack

- 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

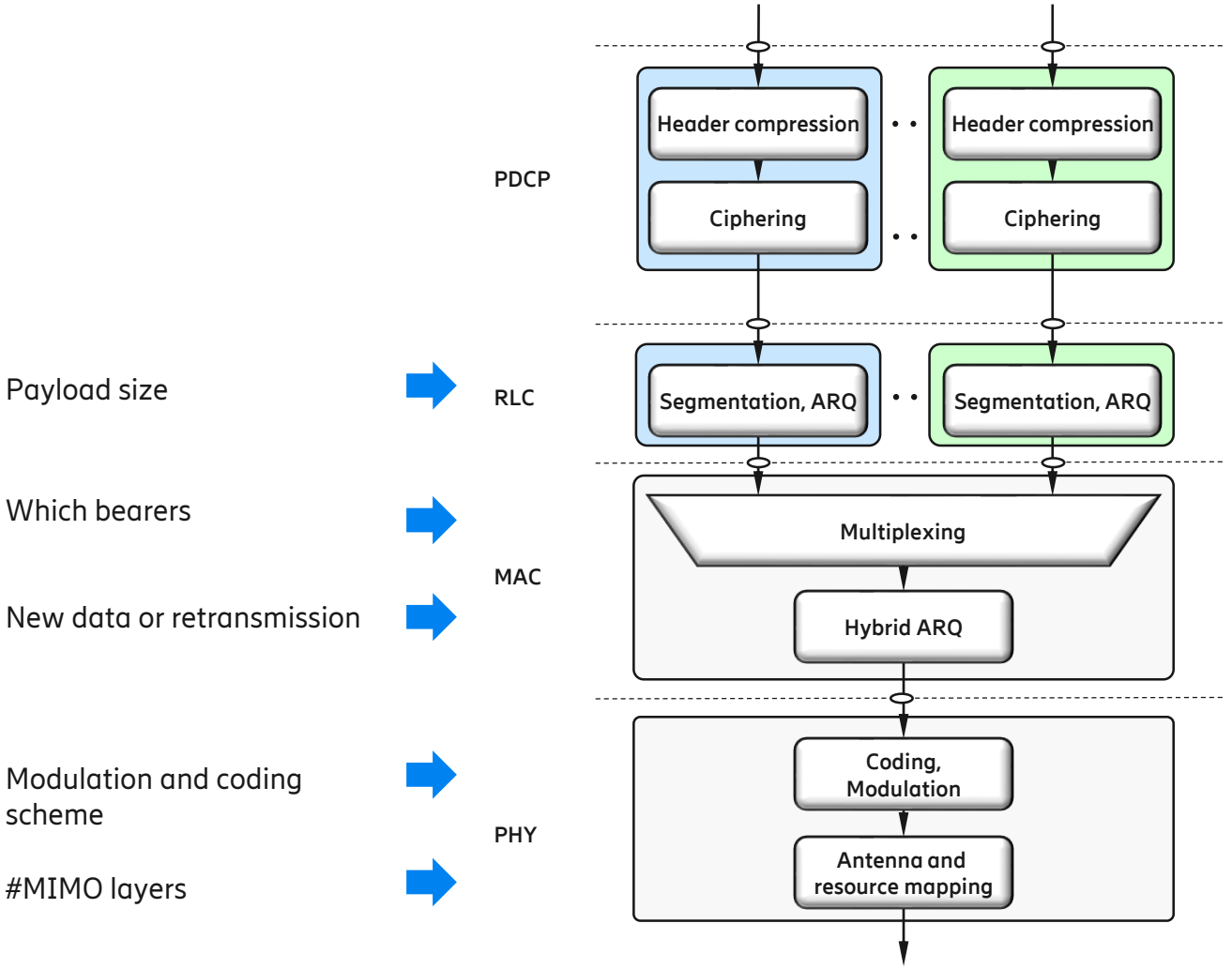


LTE protocol stack



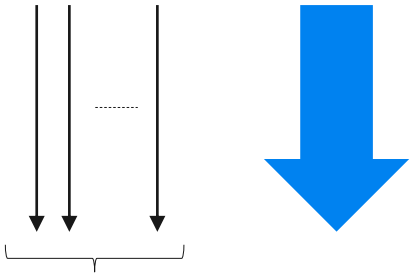
How to do scheduling and link adaptation?

- 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?

- The UE must know if it is scheduled or not
- Downlink control information (DCI) informs the UE about (among other things)
  - time/frequency resources
  - MIMO layers
  - modulation scheme and code rate
- Each UE monitors a set of control channels for *potential* scheduling information

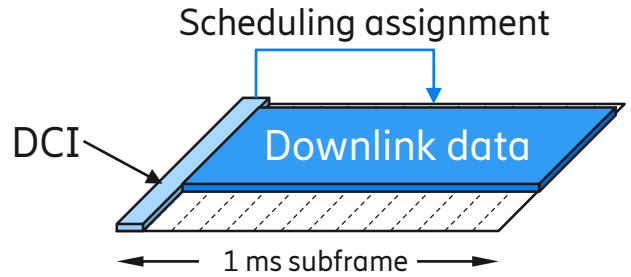


Monitor a set of control channels for DCI intended for this UE

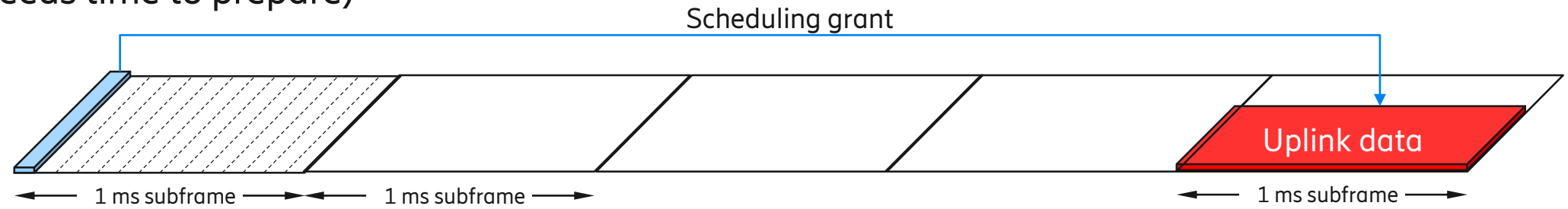
If scheduled ➡ receive data

How to do scheduling and link adaptation?

- Downlink scheduling
  - Control and data in the same 1 ms subframe

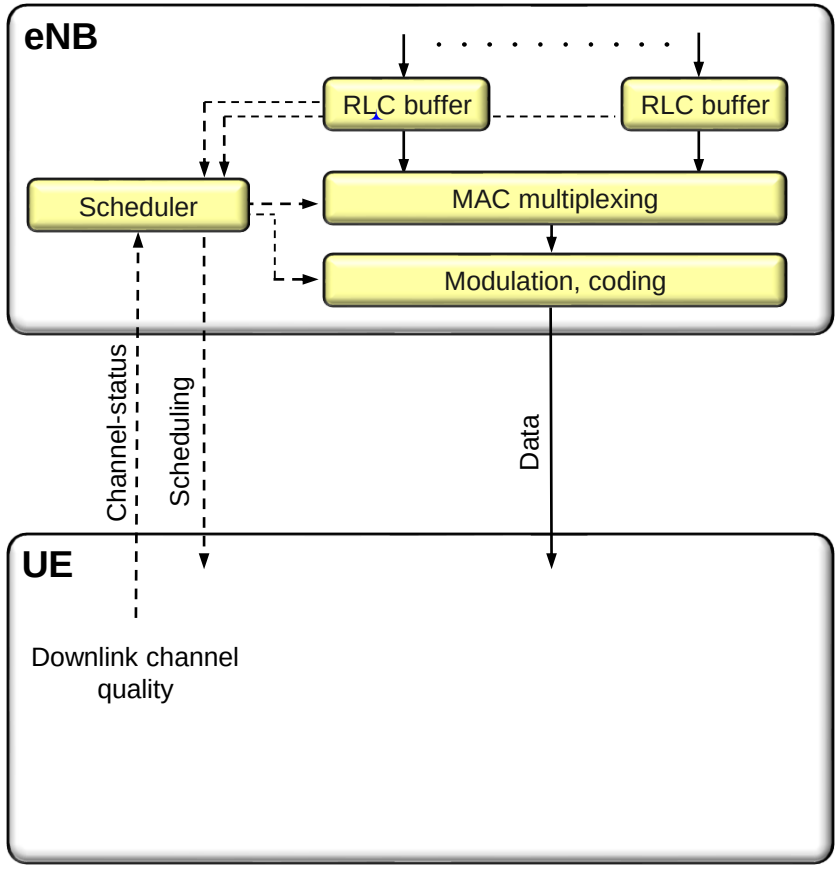


- Uplink scheduling
  - Uplink data in a later subframe (the UE needs time to prepare)



What does the scheduler need to know?

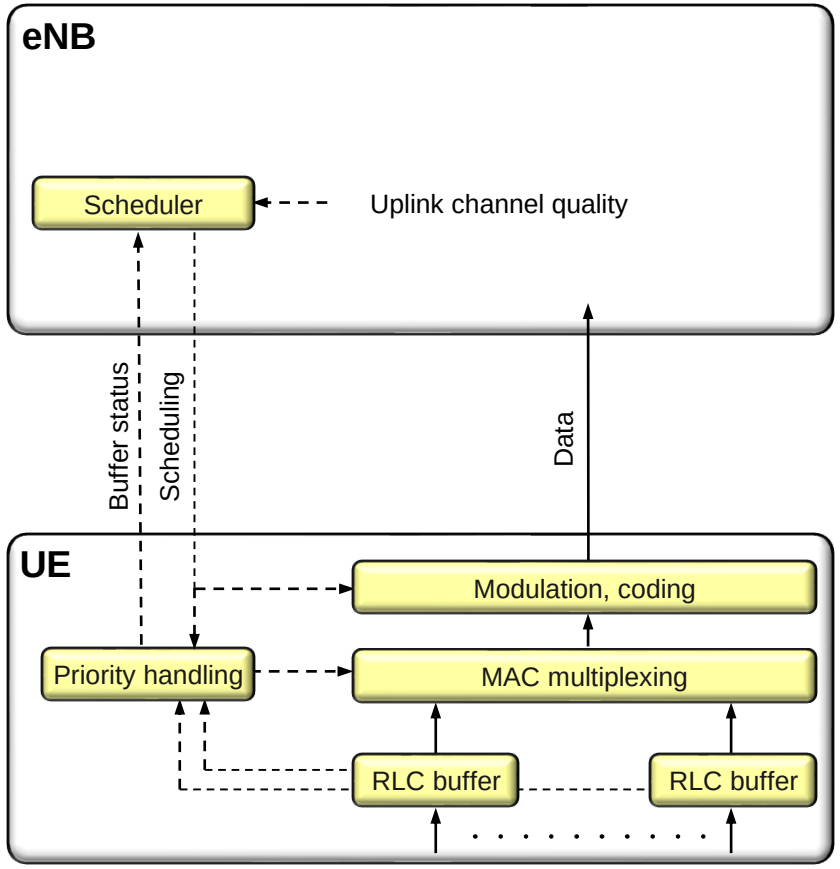
- Downlink scheduling
  - The UE periodically (a few ms apart) measures and reports Channel-State Information (CSI) to the base station
  - Schedulign based on CSI and amount of data awaiting transmission



Downlink

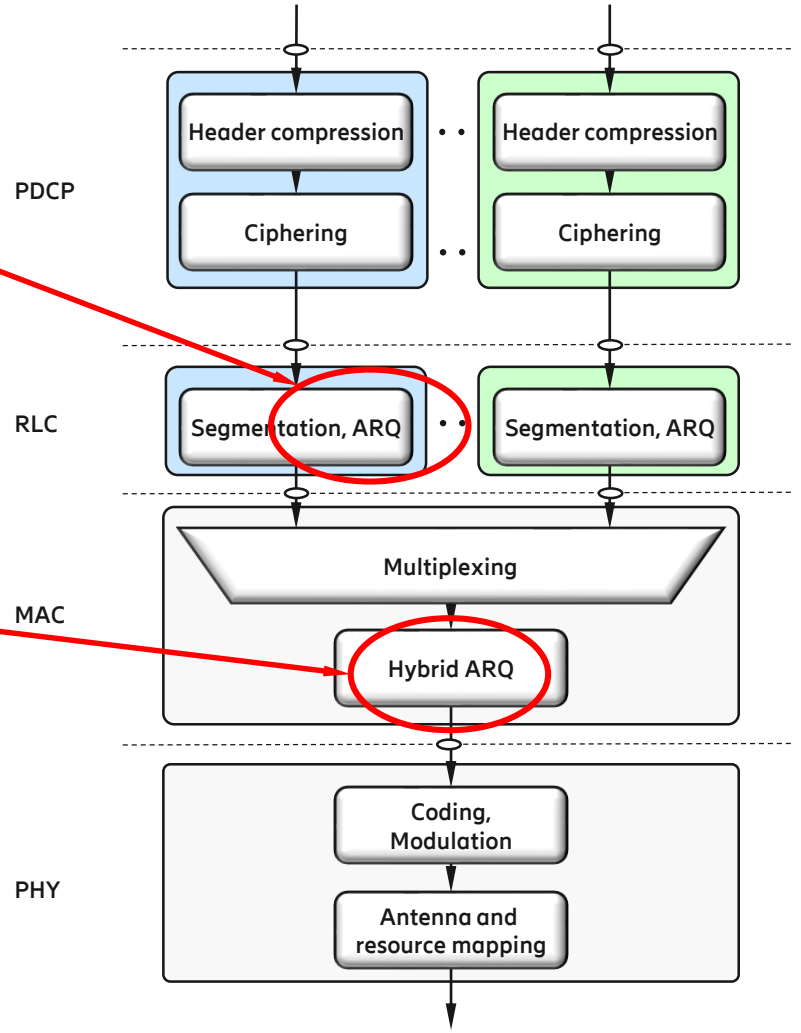
What does the scheduler need to know?

- Uplink scheduling
  - Schedulign request – one-bit flag indicating presence of data
  - Upon detecing a schedulign request, the base station requests
    - Buffer status report (BSR) – amount of data in the transmission buffers
    - Power headroom report (PHR) – amount of available output power
  - Scheduling based on BSR, PHR, and (optionally) any channel knowledge



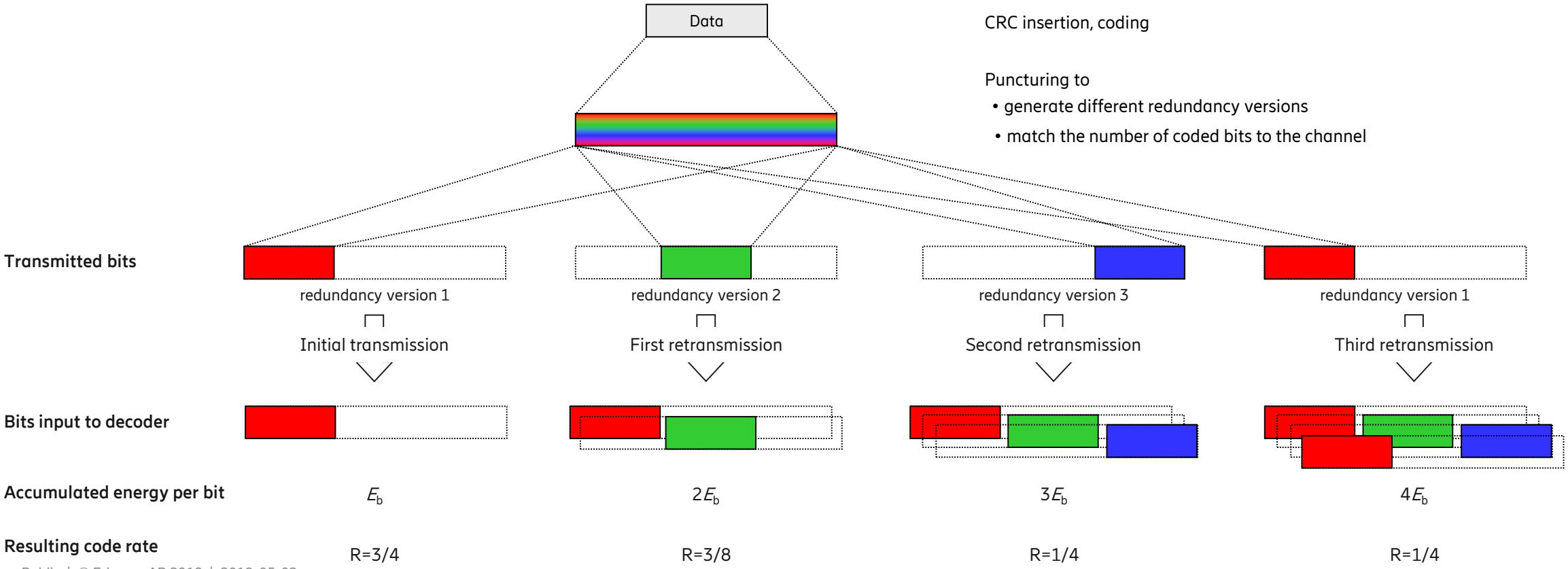
How to handle occasional reception errors?

- RLC retransmissions – reliable
  - Handles errors missed by the hybrid-ARQ
  - Selective repeat protocol, status reports sent inband
  - Roundtrip time depends on configuration, ~several 10 ms to 100 ms
- Hybrid-ARQ retransmsisions – fast
  - Handles most errors
  - Success/failure indicated outband after reception of each 1 ms subframe of data
  - Retransmsisions scheduled 8 ms later



How to handle occasional reception errors?

— Hybrid-ARQ supports soft combining and incremental redundancy



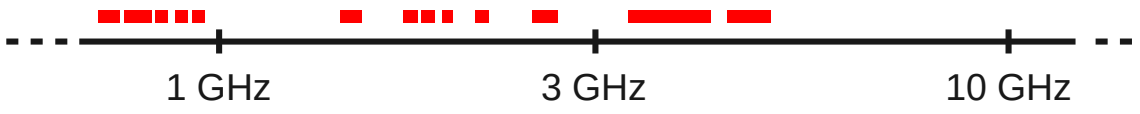
What about spectrum?

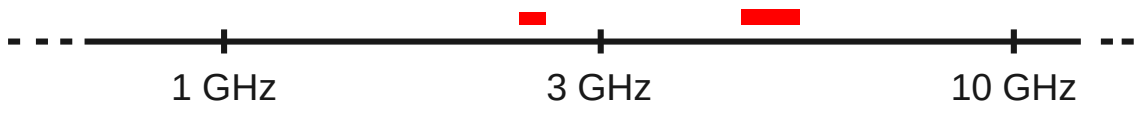
- Licensed spectrum
  - Exclusive right to a certain frequency range
  - Control of the interference situation
  - ‘High’ output power ➡ long range
  - Typically associated with a license cost

  - 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

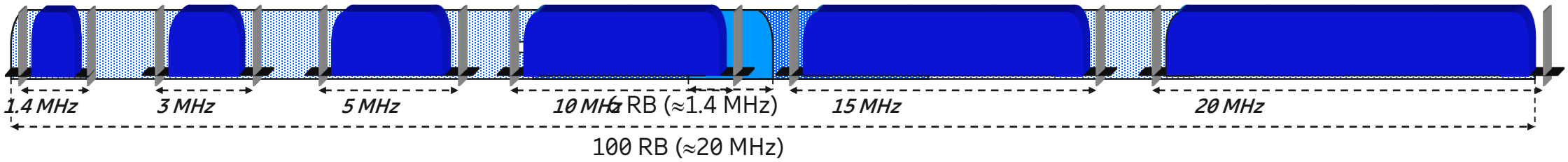
  - Examples:
    WiFi, Bluetooth, LTE (later releases), NR





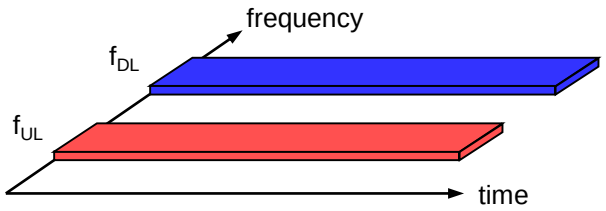
What about spectrum?

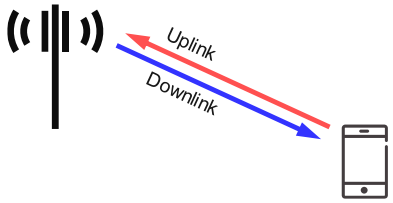
- Operators have different spectrum allocations
  - LTE supports both FDD and TDD *with a single radio-access technology*
  - Core specifications support any bandwidth from 1.4 to 20 MHz
  - Radio requirements defined for a limited set of spectrum allocations

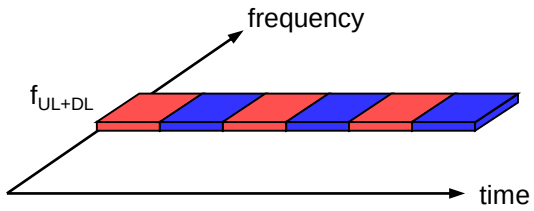


What about spectrum?

- Paired spectrum (FDD)
  - UL and DL separated in frequency
  - Typically licensed bands
  - Most (wide area) cellular systems
- Unpaired spectrum (TDD)
  - UL and DL separeted in time
  - Unlicensed and some licensed bands

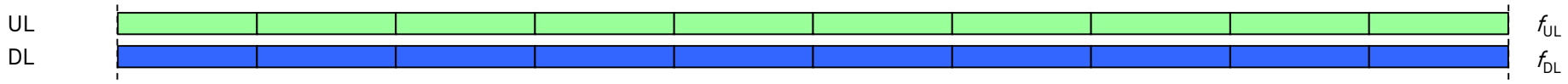




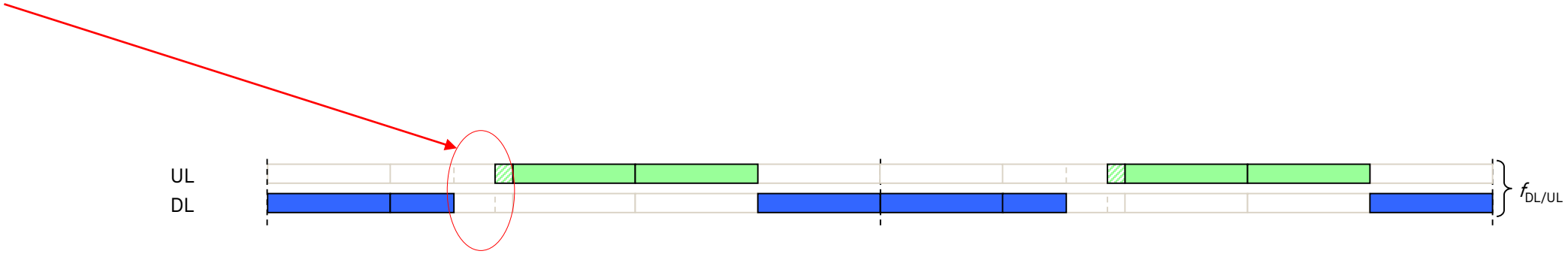


Time-domain structure – FDD vs TDD

- FDD
  - Frequency separation of UL and DL

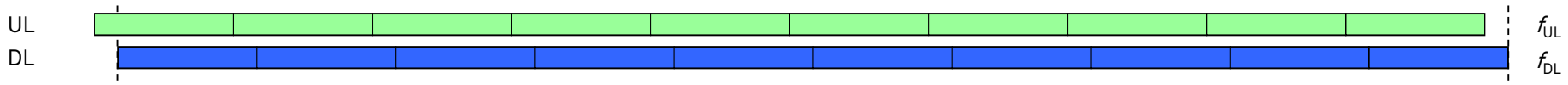


- TDD
  - Guard period to separate UL and DL in time domain

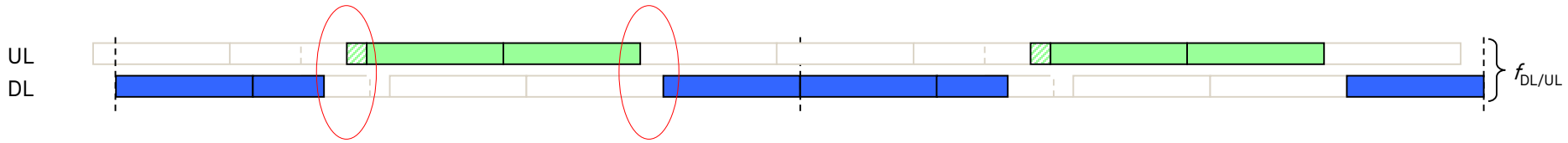


Time-domain structure – FDD vs TDD

- FDD
  - Frequency separation of UL and DL



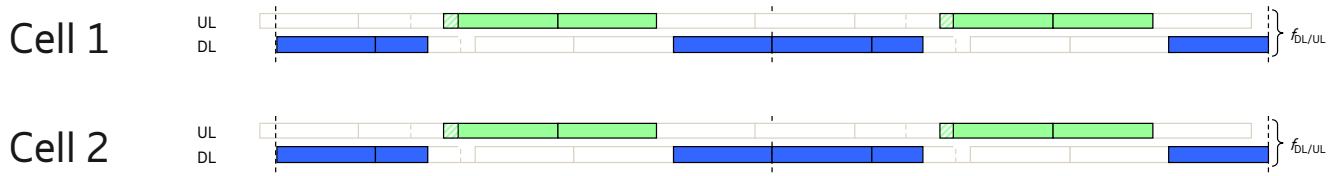
- TDD
  - Guard period to separate UL and DL in time domain
  - Timing advance distributes the guard between DL-to-UL and UL-to-DL switch



Inter-cell interference in TDD networks

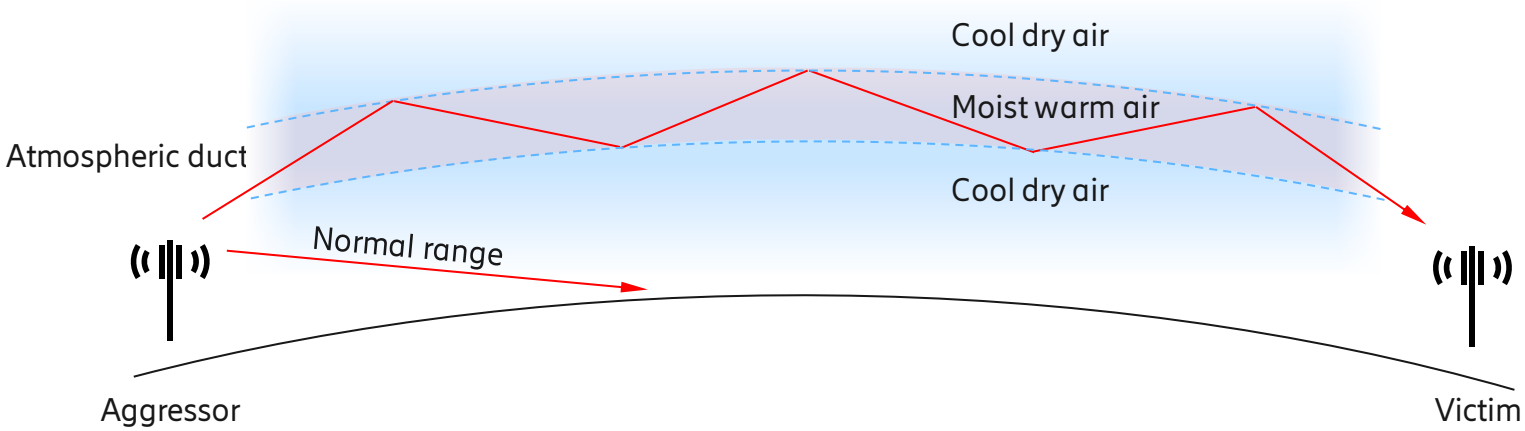
- Large power difference between DL and UL in wide-area networks
  - BS: above-rooftop antennas, Tx: ~ +46 dBm, Rx: ~ -90 dBm ➡ huge difference!
  - UE: non-elevated antennas, Tx: +23 dBm

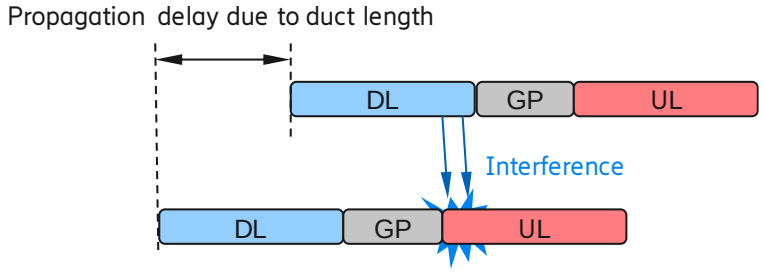
- Solution: same UL/DL allocation in all cells
  - "DL collides with DL"; avoids DL-to-UL interference
  - Guard period set taking inter-site distance into account



Inter-cell interference in TDD networks

- Remote interference
  - DL-to-UL interference requiring very large gaurd period at specific qeather conditions

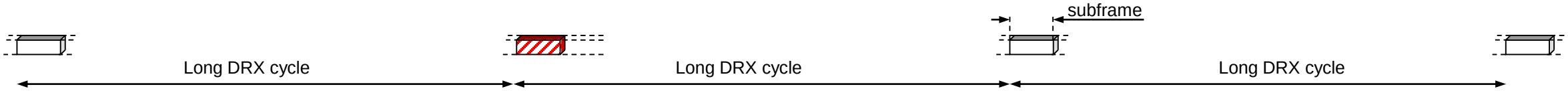




What abou the battery lifetime?

— UE states; most of the time the UE is in IDLE (low power consumption)

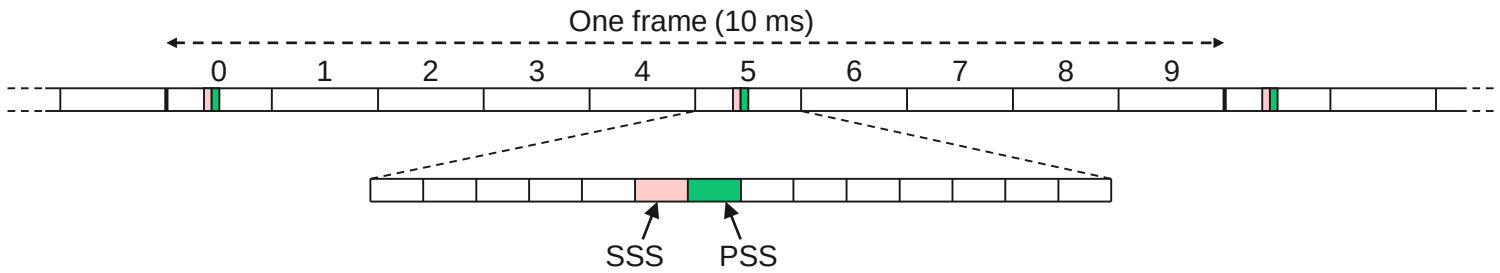
— Discontinuous reception (DRX) in connected mode and idle mode



How to connect to the network?

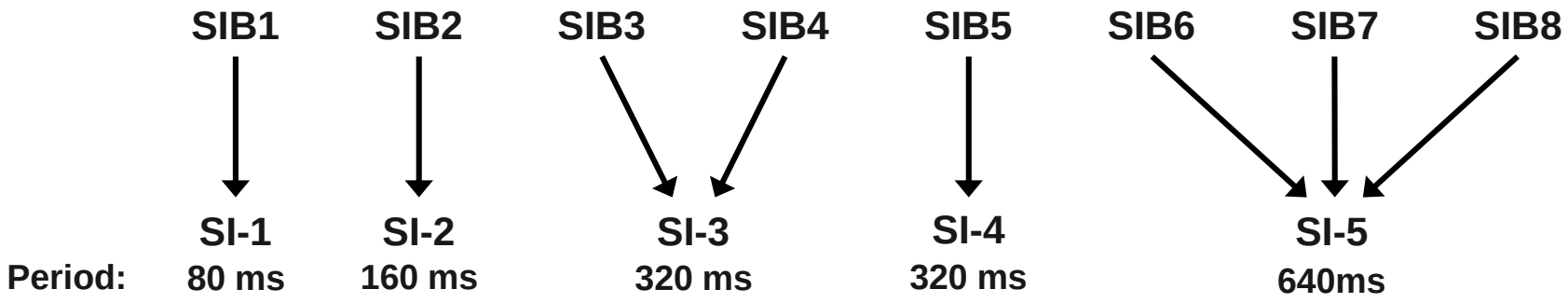
— At power-up, the UE enters IDLE mode
— Need to obtain system information (the configuration fo the network)

— 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



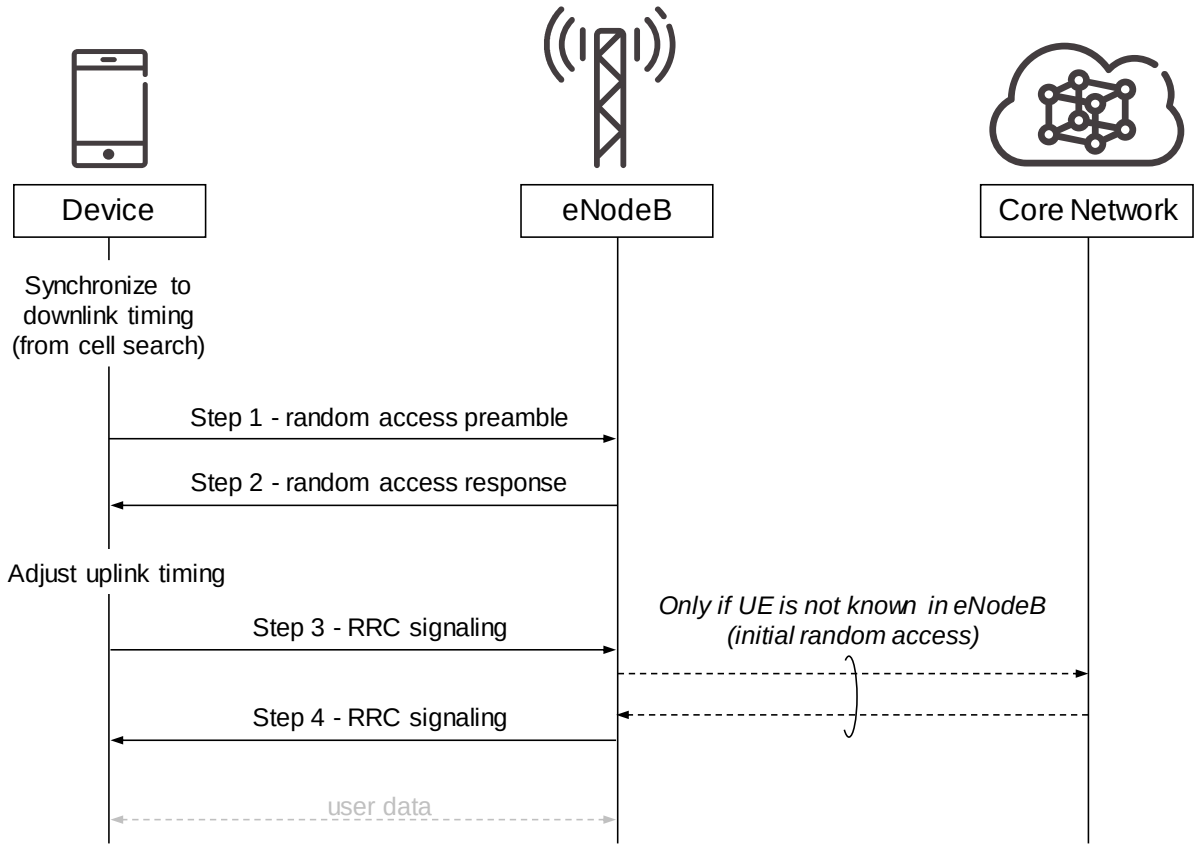
How to connect to the network?

- Once downlink sync is found, read system information
- Periodically transmitted, always present
  - Master information block (MIB), once every 40 ms
  - System information blocks (SIBs), once every 80 – 640 ms



How to connect to the network?

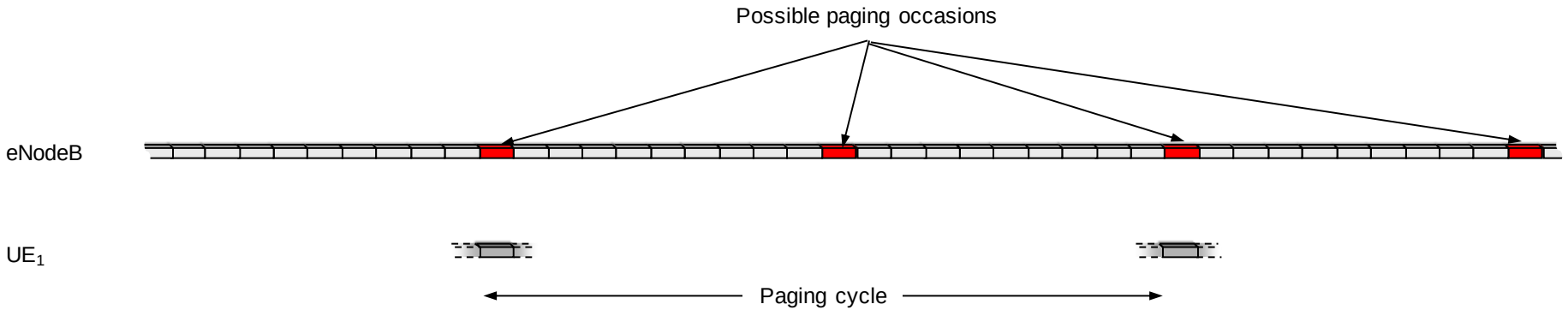
- Random access –
  UE-initiated connection esablishment
- Step 1 – preamble transmission
  - select on of 64 preambles and transmit
- Step 2 – random-access response
  - obtain network response, adjust uplink timing
- Step 3, 4 – contention resolution
  - transmit (on regular data channel) UE identity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



How to connect to the network?

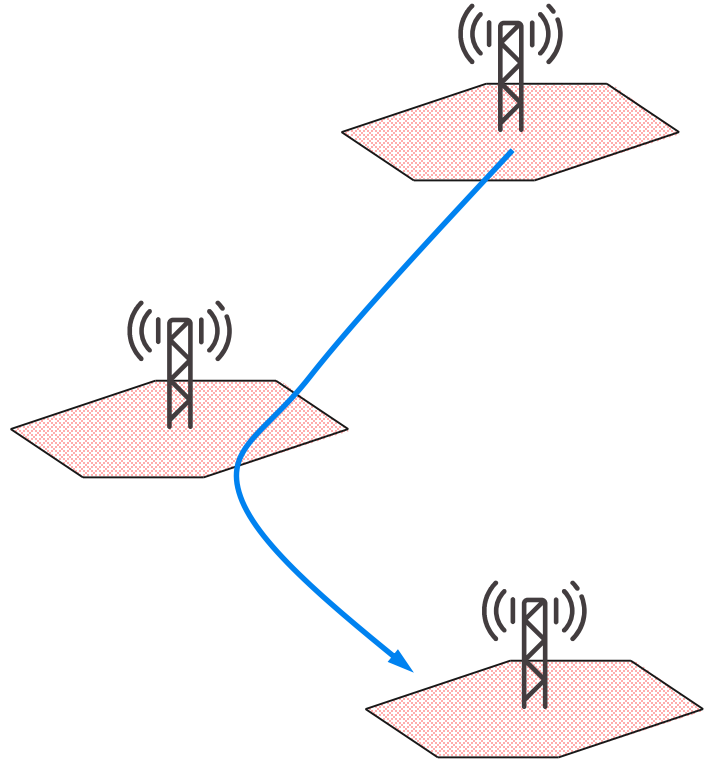
- Paging – network-initiated connection establishment for UEs in idle state

- The UE regularly (~once per second) wakes up to check for paging
  - Paging message containign the identity of the paged UE scheduled on the data channel
- If paged, perform random access and connect to the network



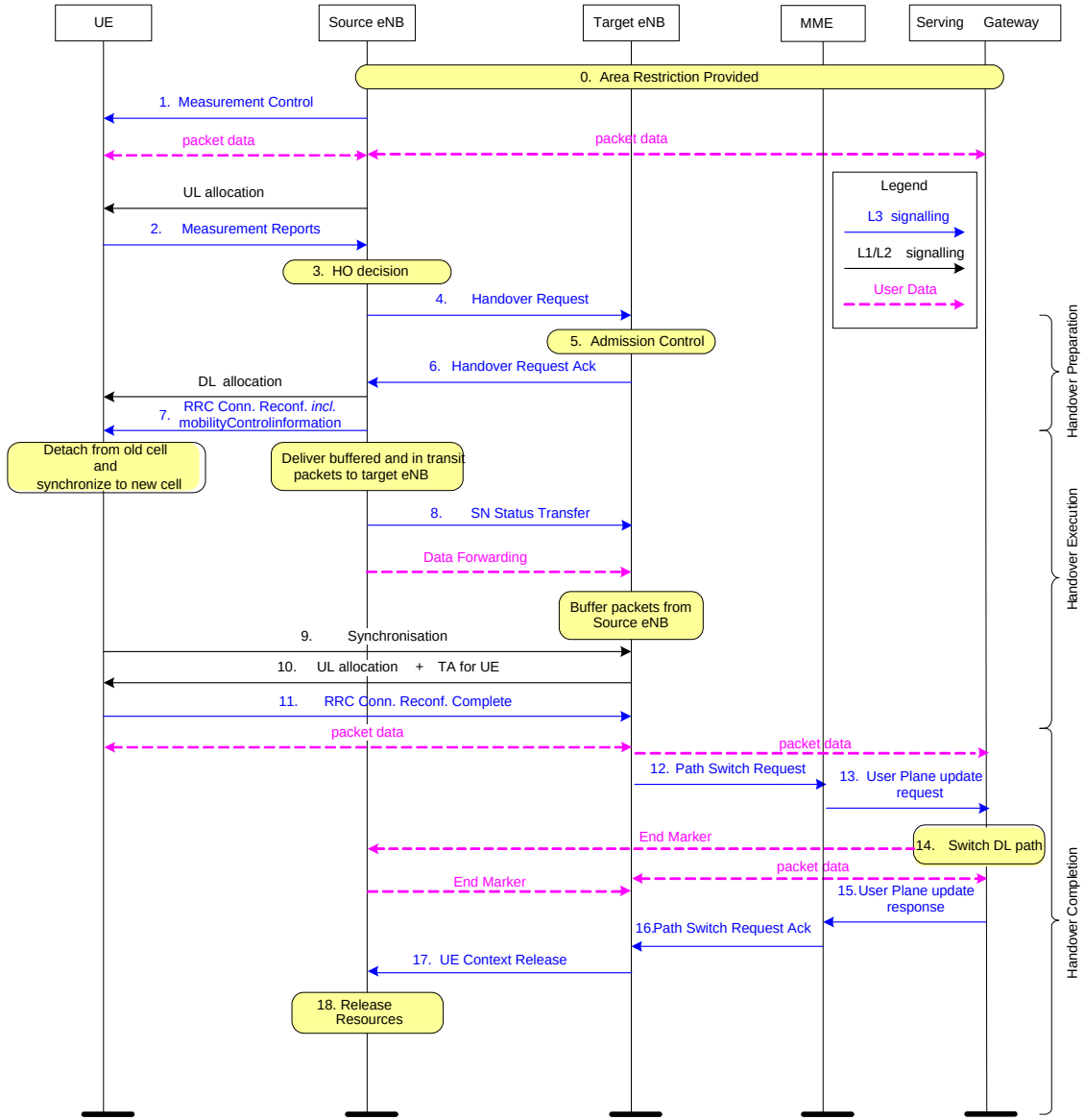
What happens when I move around?

- 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

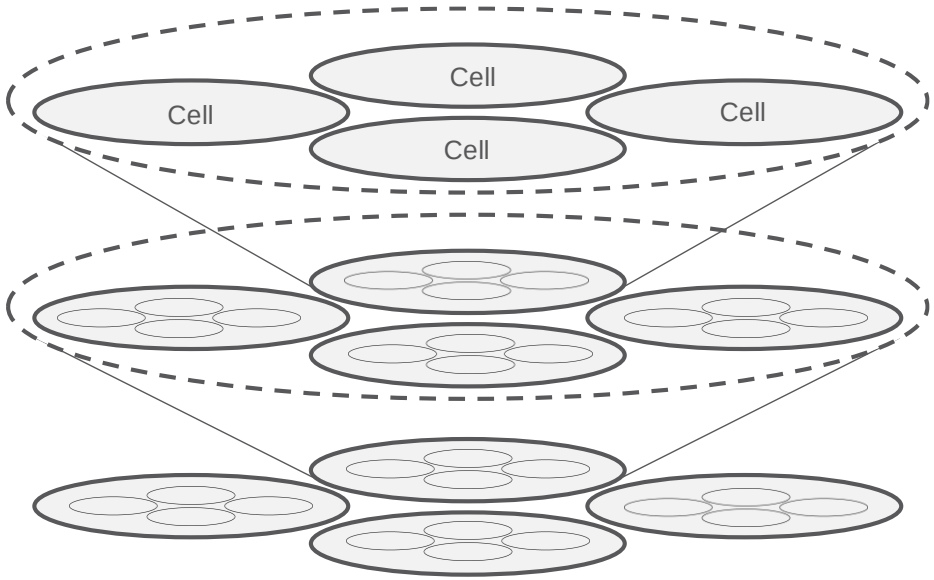


Mobility in connected state

- Search for candidate cells
- If a stronger cell is detected ➡ inform the network
- The networks decides if a handover to a neighboring cell is needed or not
- Send handover command to the UE
- The UE uses random access to connect to the new cell
- The network reroutes data to the new cell



Mobility in idle state

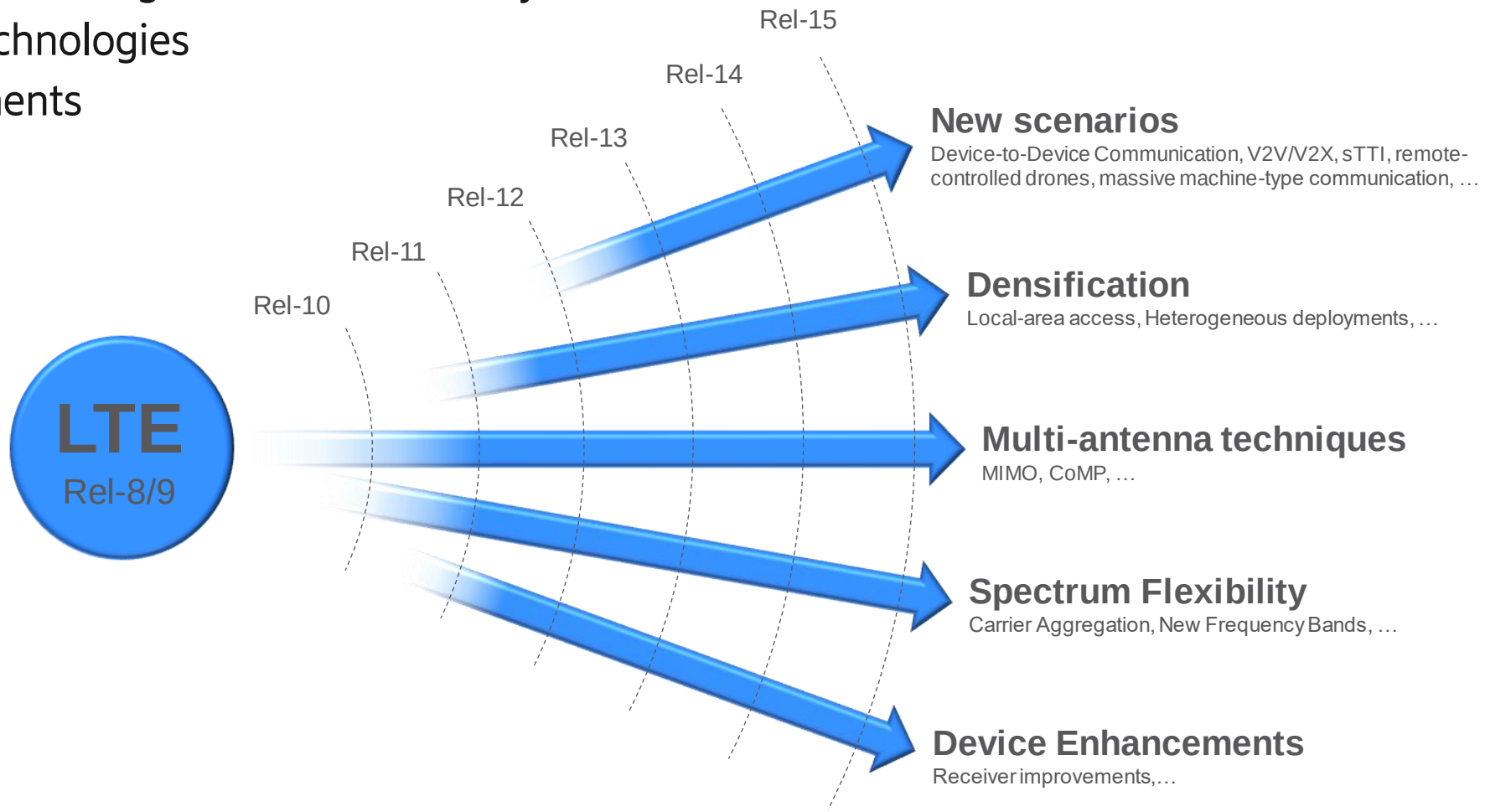


- Search for candidate cells
- If a stronger cell is detected ➡ camp on the new cell (‘cell reselection’)
- If the new cell is in a new tracking area ➡ inform the network
- UE position knwon on tracking-area level only
  - needed for paging purposes – don’t want to page across the whole network

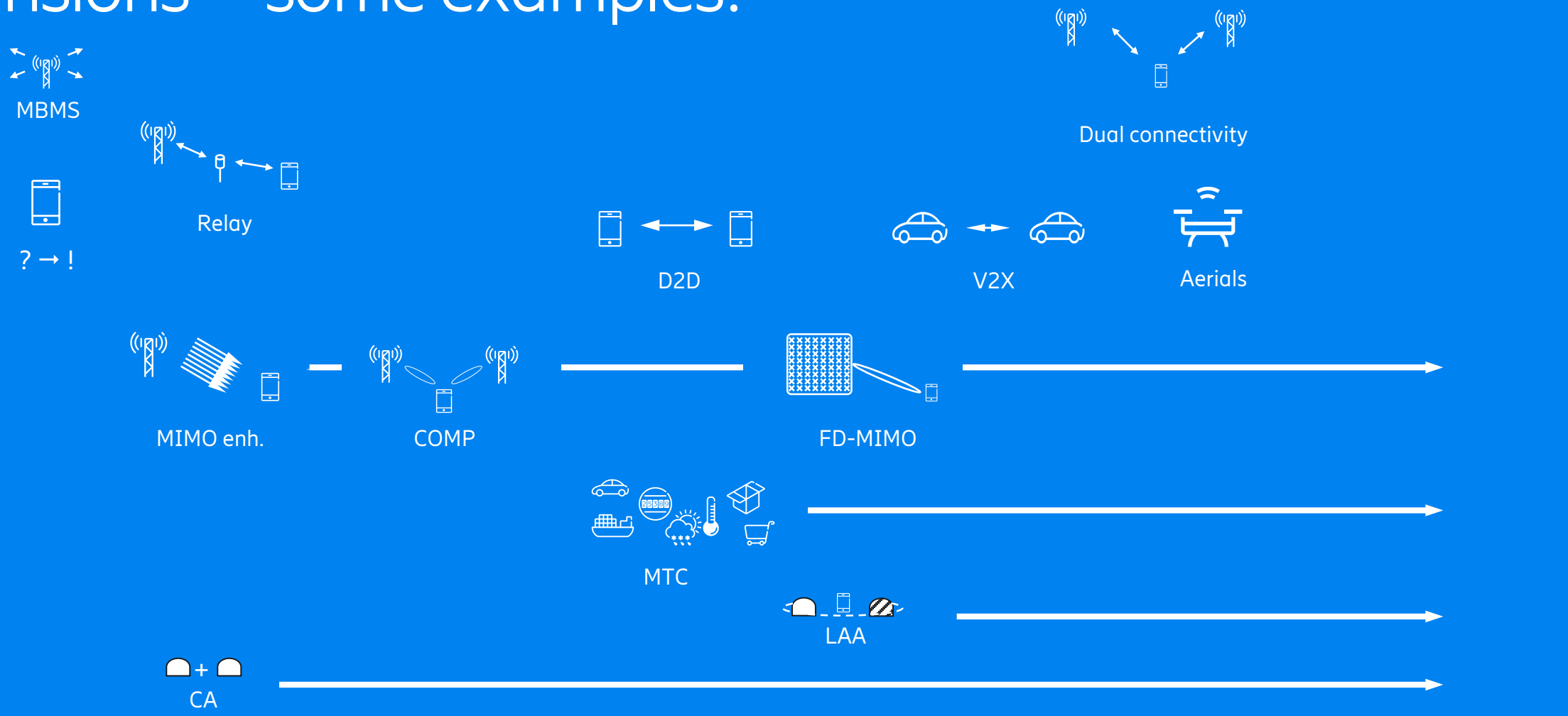
LTE evolution

Extensions please!

- LTE has been continously evolving over more than 10 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

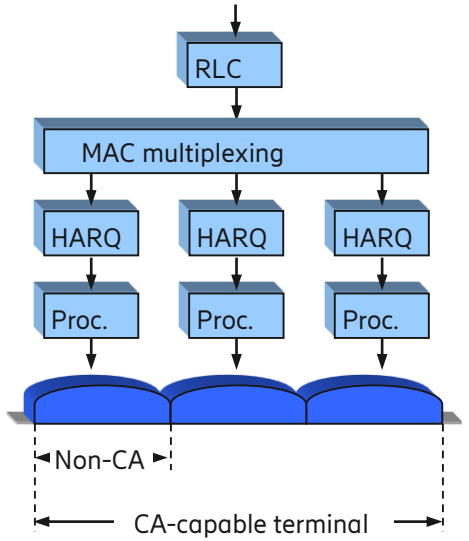
Inter-band aggregation

Intra-band aggregation, contiguous component carriers

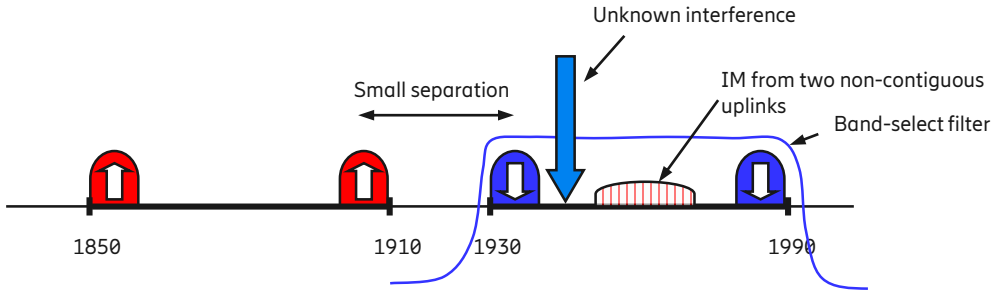
Intra-band aggregation, non-contiguous component carriers

Carrier aggregation

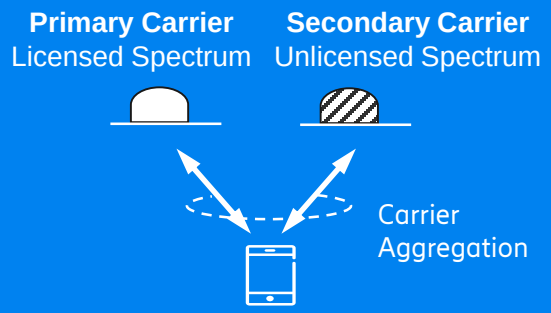
- Baseband implementation
  - Processing per component carrier
  - Relatively straightforward,
    Complexity ~ aggregated data rate



- RF implementation
  - Challenging, especially on the terminal side
    - *True for any radio-access technology!*
  - Complexity depends on band combinations
  - Insertion loss, harmonics, intermodulation, …

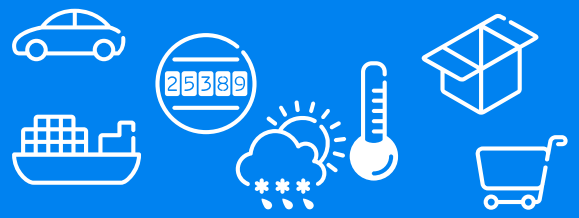


License-assisted access



- 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, mobiblity, 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

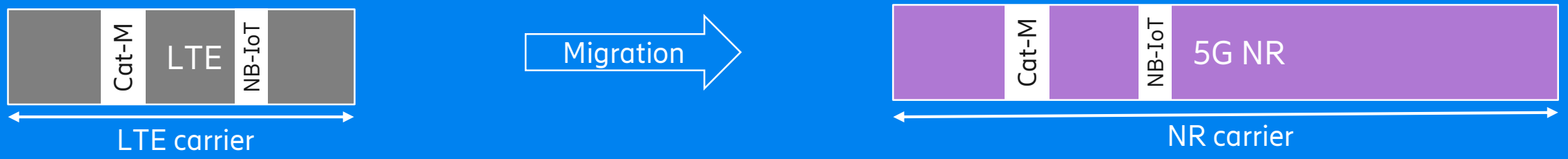


- Internet of Things (IoT)
  - Sensors, actuators, ...
- Large number of devices
- Low data rates (10 – 100 kbit/s)
- Wide-area coverage
- Low cost
- Low power consumption (~10 years on an AA battery)
- Two technologies; cat-M1 and NB-IoT
  - Both have evolved over multiple releases

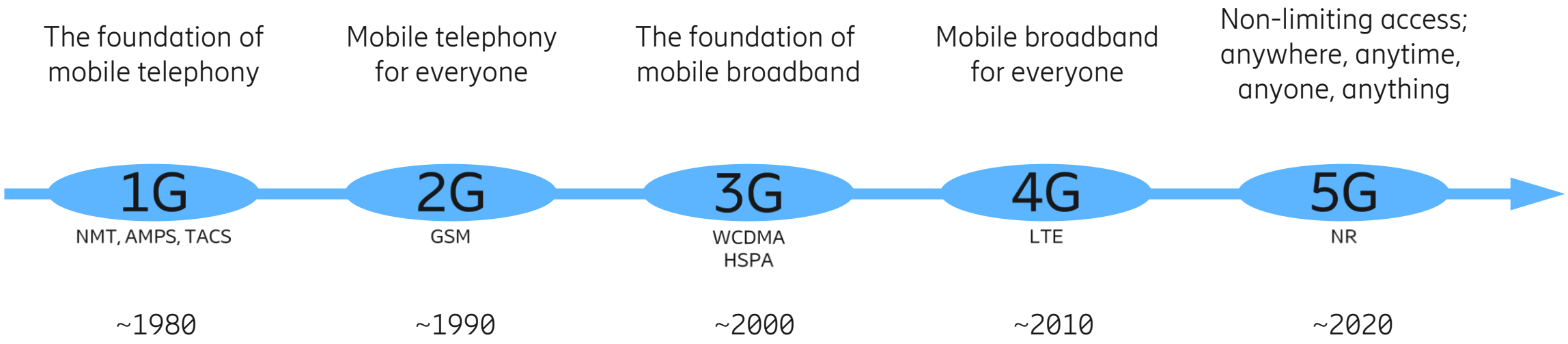
Cat-m1 and NB-IoT

- NB-IoT; 21/63 kbps in 200 kHz, 164 dB MCL, idle-mode mobility
- Cat-M1; 300/375 kbps in 1.4 MHz, 160 dB MCL, idle and active-mode mobility, voice

- Integral parts of 5G – NB-IoT/Cat-M1 can be deployed on the same carrier as NR
  - Multiple NR tools; same subcarrier spacing, reserved resources, ...



So…what's next?



For further information…

Open the 3GPP specifications…

…or read The Books!

Available in English, Chinese, Korean and Japanese.