Cellular …

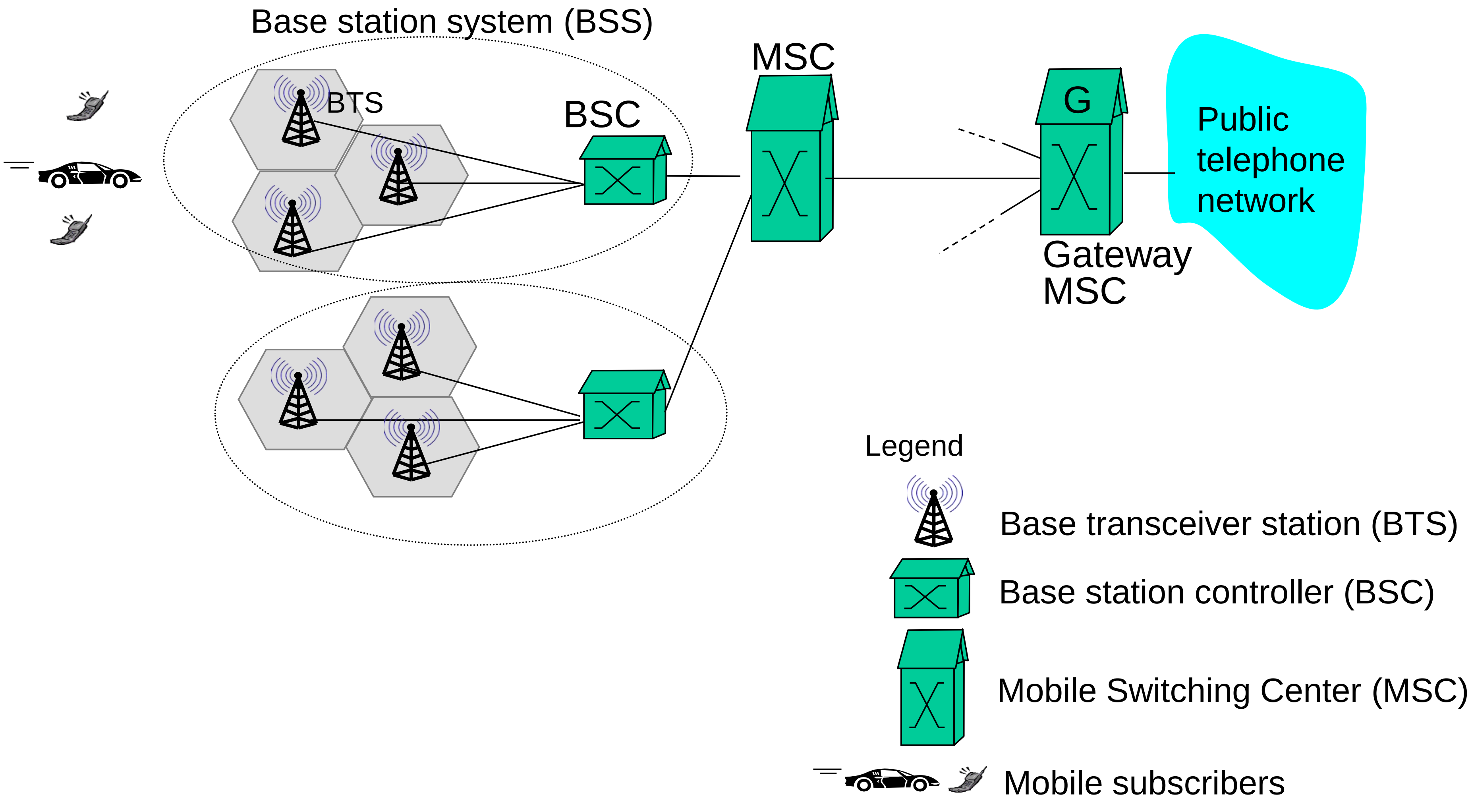
Slides used in TDDE48 (Mobile Networks) @ LiU, Sweden, Fall 2025
Niklas Carlsson (https://www.ida.liu.se/~nikca89/)

Slides for this lecture are adapted or based on various on-line resources, including lectures notes by Jim Kurose and Keith Ross for the recommended book "Computer Networking: A Top-Down Approach")

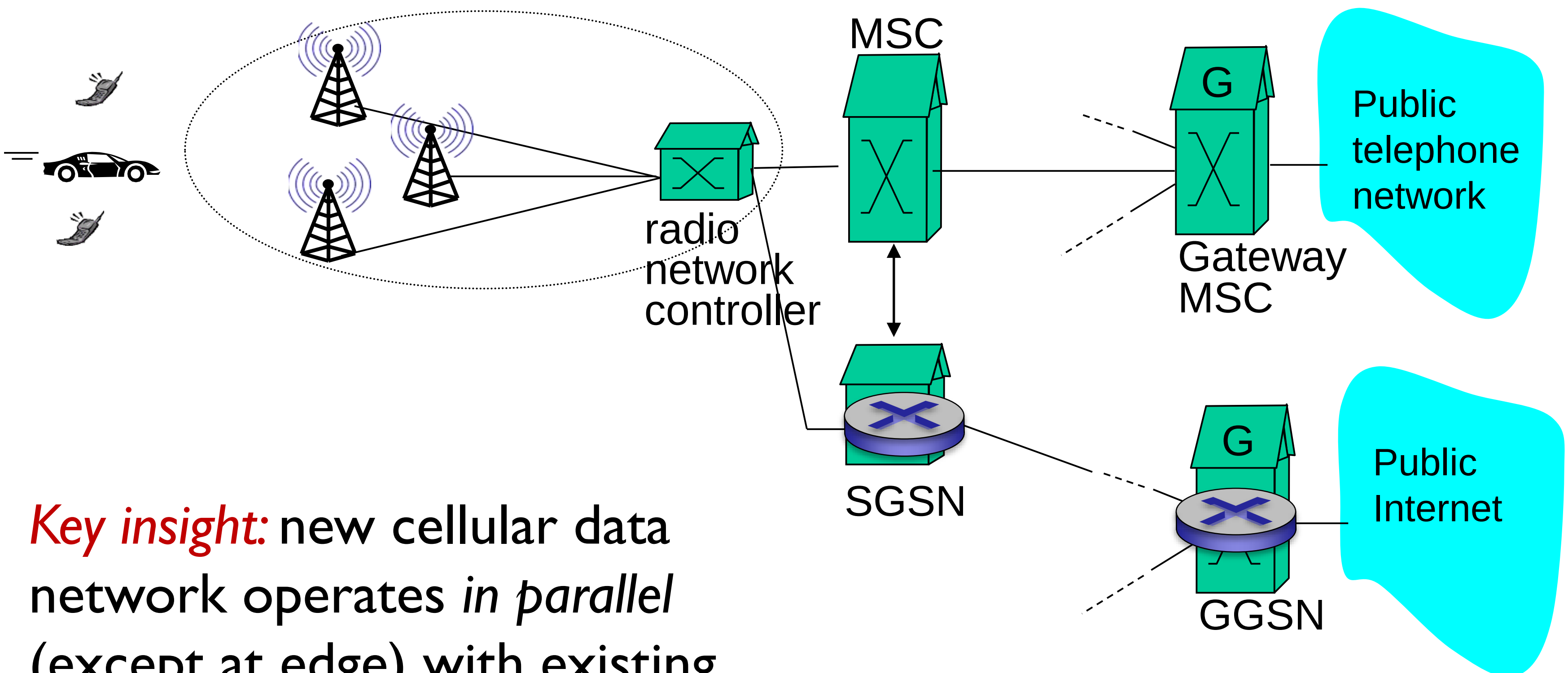
Background: Cellular network technology

- Overview
  - 1G: Analog voice (no global standard …)
  - 2G: Digital voice (again … GSM vs. CDMA)
  - 3G: Digital voice and data
    - Again … UMTS (WCDMA) vs. CDMA2000 (both CDMA-based)
    - and … 2.5G: EDGE (GSM-based)
  - 4G: LTE, LTE-Advanced …
    - OFDM (OFDMA for downlink and SC-OFDM for uplink)
  - 5G: 5G New Radio (NR)
    - 5G NR based/build on LTE and OFDM (+ mmWave, etc. shorter range)
    - Yet lower delays, smaller cells, higher bw, computing at edge, virtualization
- Trends
  - Advanced networks (SDN, NVF), everything on cloud, immersive experience, tele presence, massive connectivity, D2D, …
  - More data, packet-based switching, shared channel, directional (spatial reuse), multi-antenna, etc.
  - Other goals: Seamless with other technologies, QoS for multimedia, etc.

2G (voice) network architecture

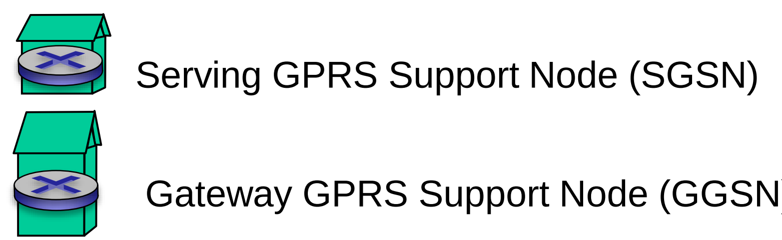


3G (voice+data) network architecture

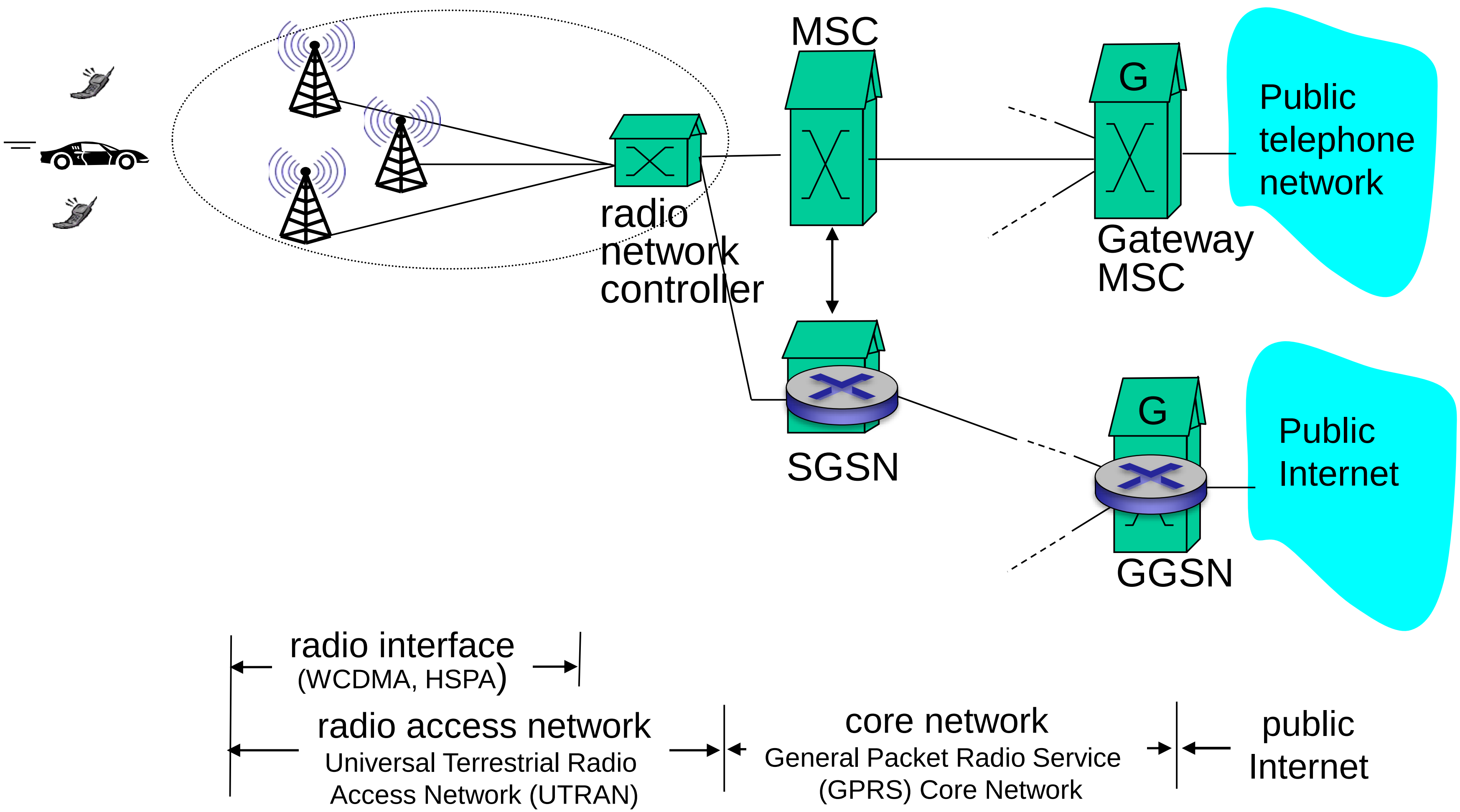


Key insight: new cellular data network operates *in parallel* (except at edge) with existing cellular voice network

- voice network *unchanged* in core
- data network operates in parallel



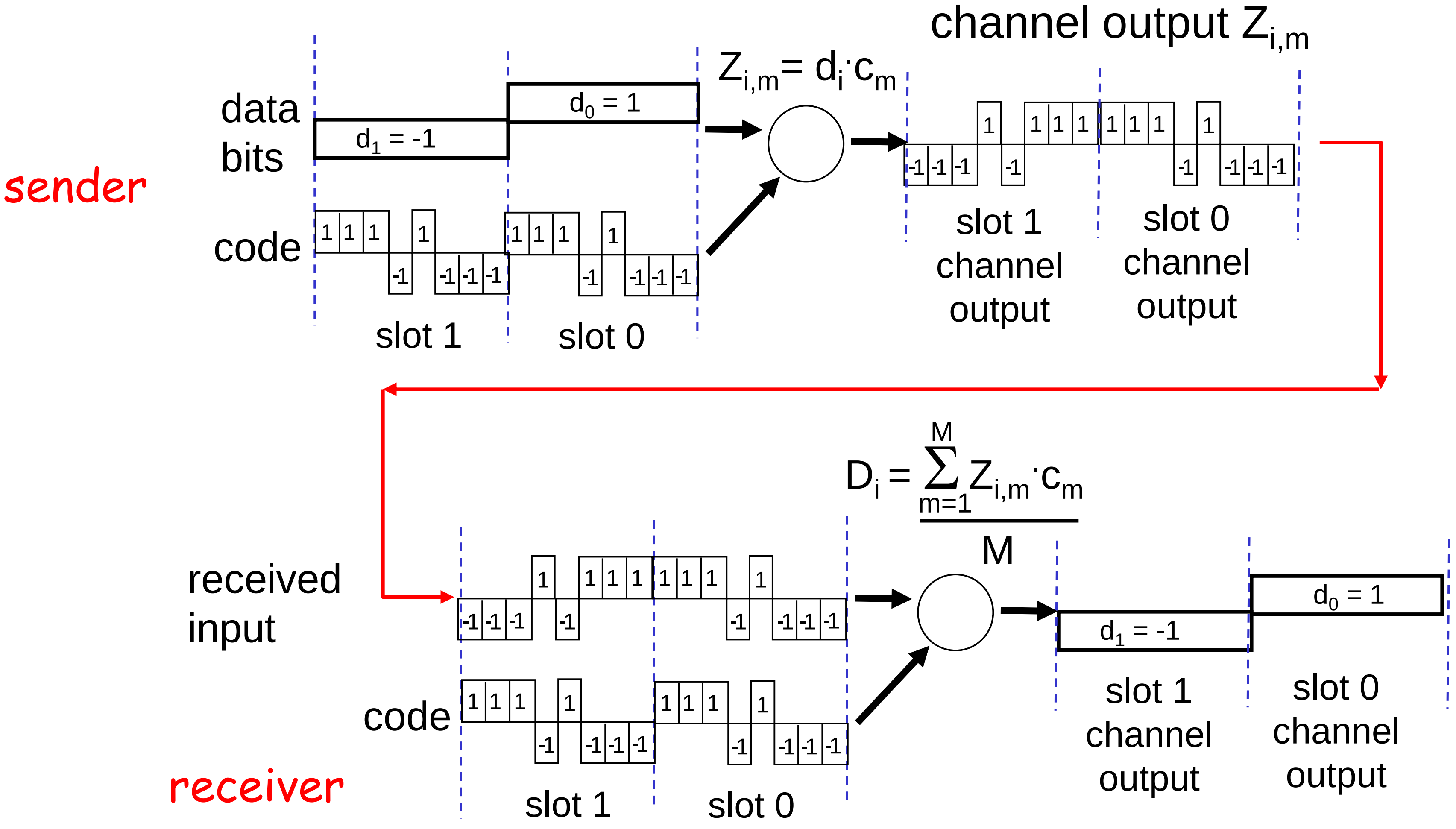
3G (voice+data) network architecture



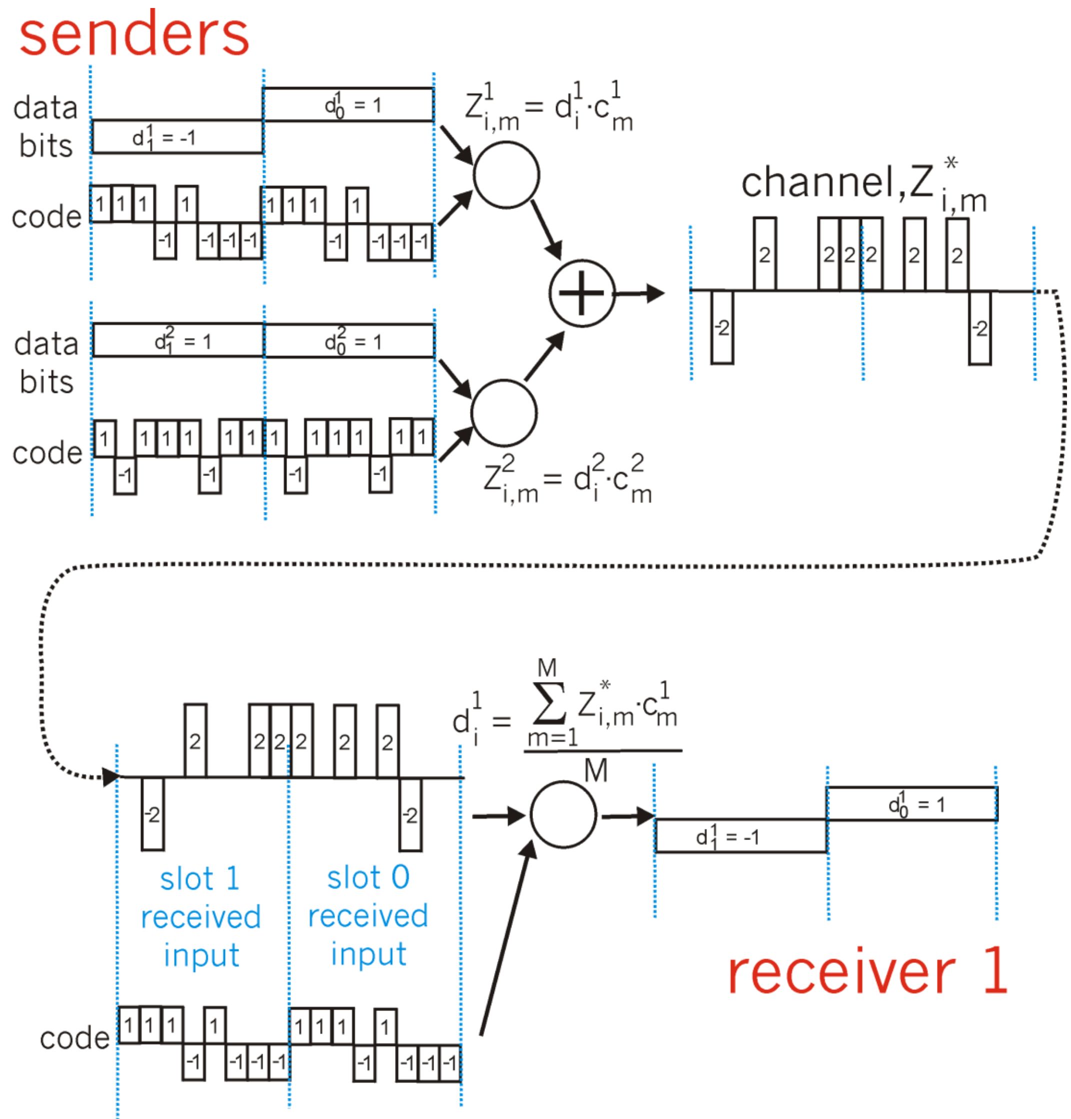
Code Division Multiple Access (CDMA)

- used in several wireless broadcast channels (cellular, satellite, etc) standards
- unique "code" assigned to each user; i.e., code set partitioning
- all users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data
  - *encoded signal* = (original data) X (chipping sequence)
  - *decoding:* inner-product of encoded signal and chipping sequence
- allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")

CDMA Encode/Decode



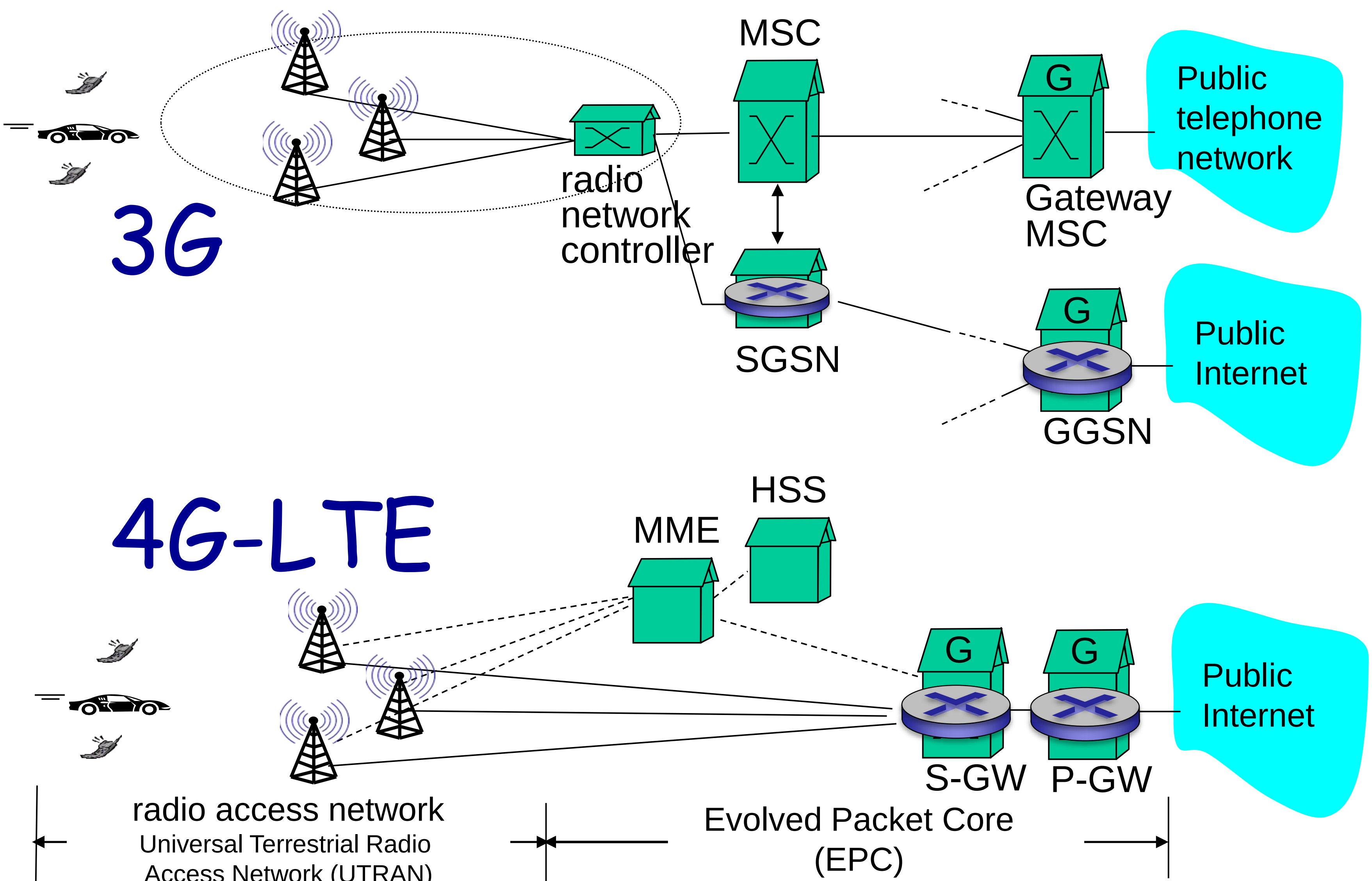
CDMA: two-sender interference



Practical chipping codes …

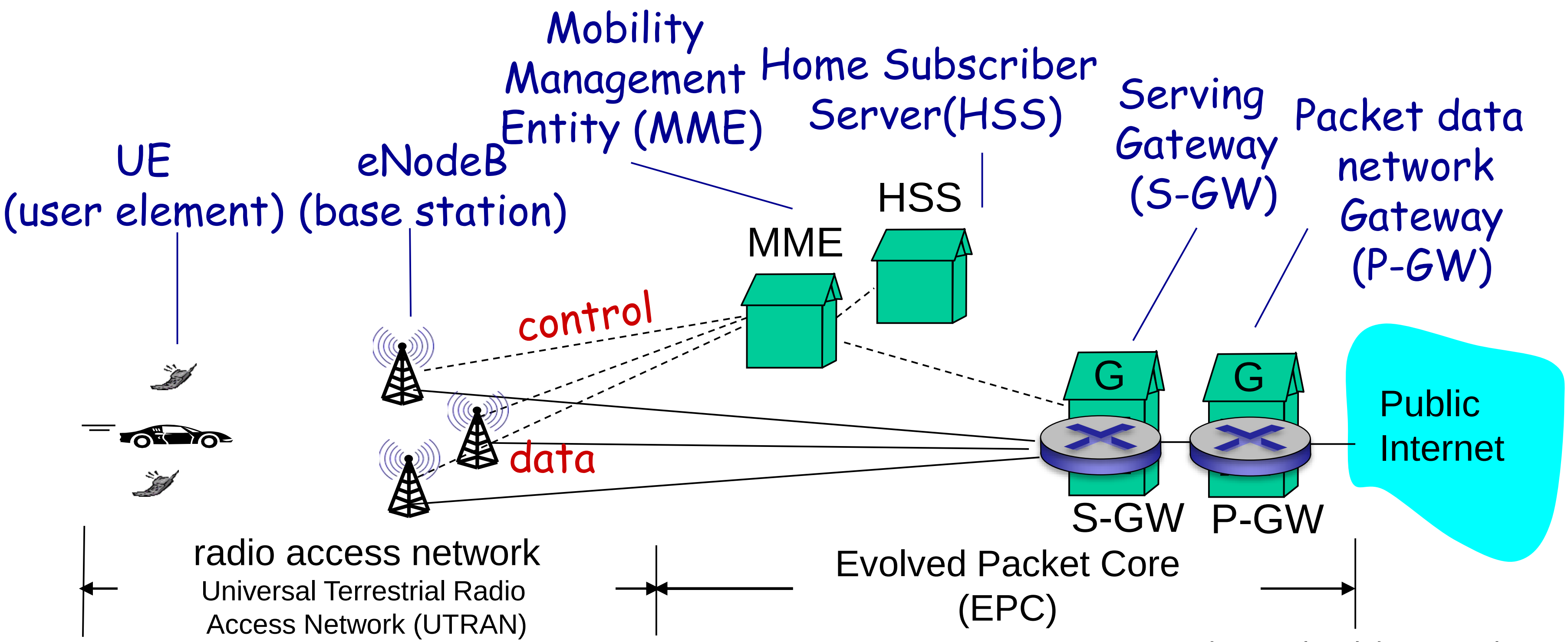
- Orthogonal even under offset?
  - No synchronization …
  - Random sequence; high probability low cross-correlation
- Different chip lengths?
  - different rates, take advantage of silence, more calls

3G versus 4G LTE network architecture

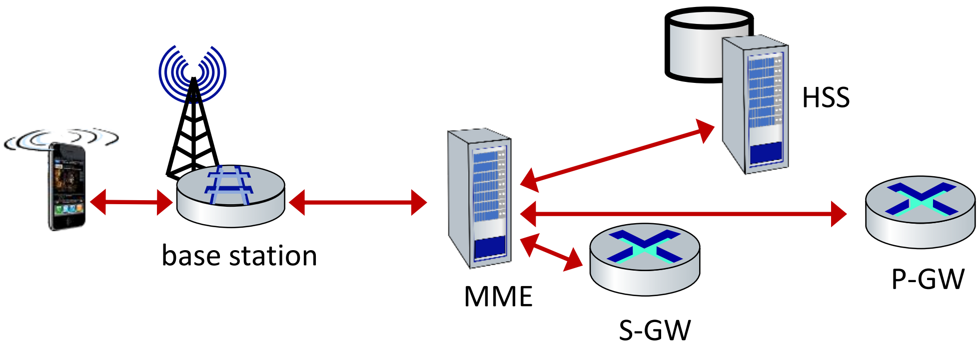


4G: differences from 3G

- all IP core: IP packets tunneled (through core IP network) from base station to gateway
- no separation between voice and data – all traffic carried over IP core to gateway

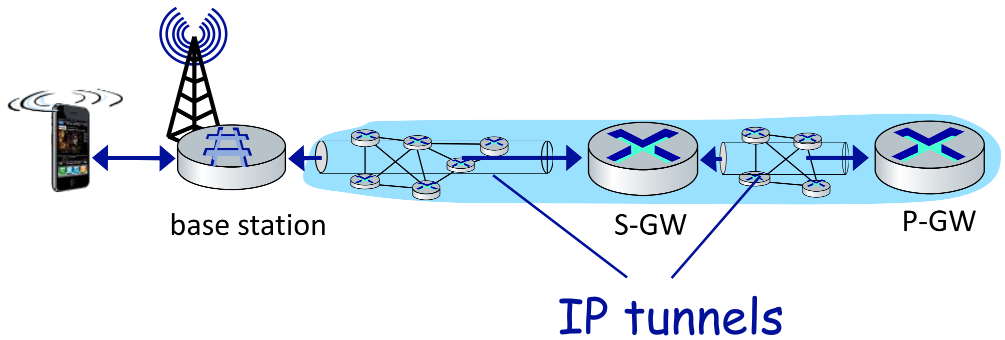


LTE: data plane control plane separation



control plane

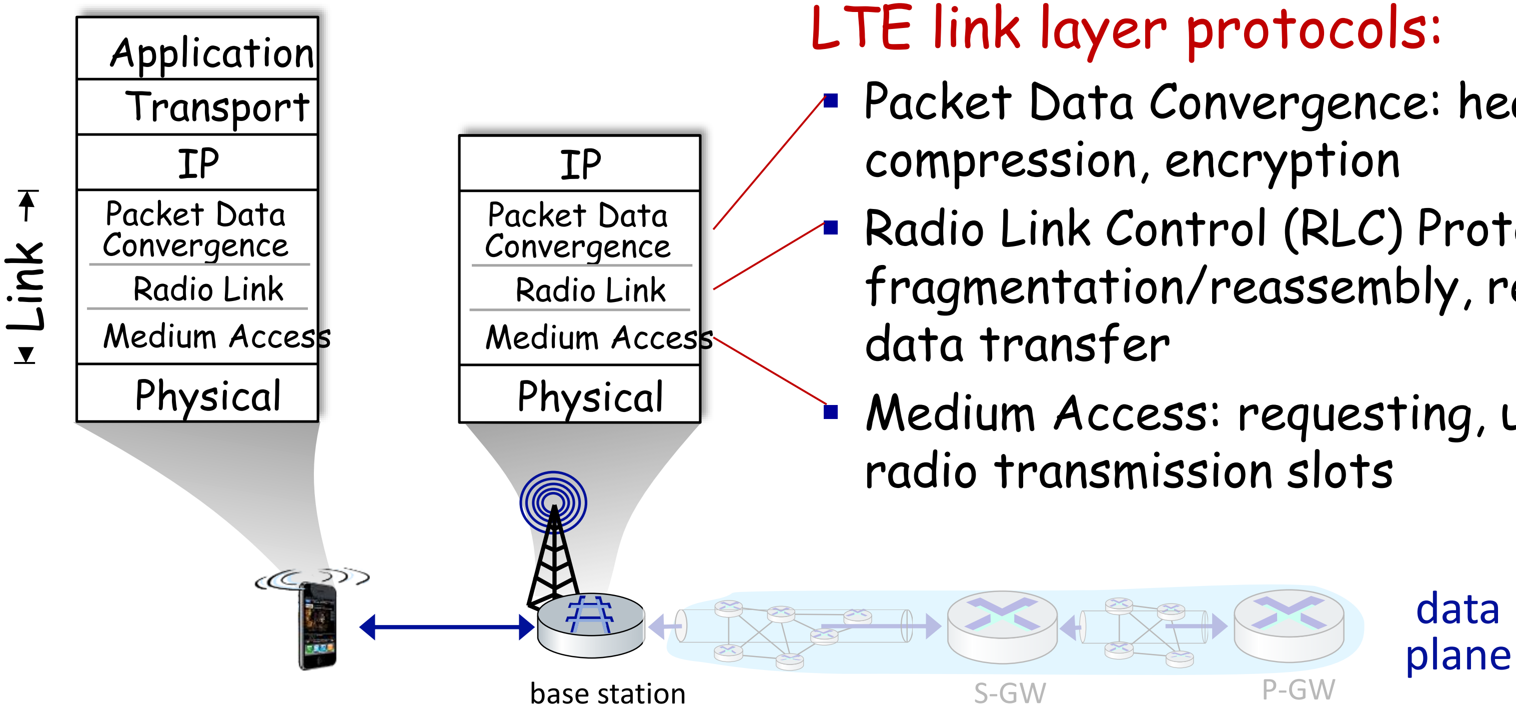
- new protocols for mobility management , security, authentication (later)



data plane

- new protocols at link, physical layers
- extensive use of tunneling to facilitate mobility

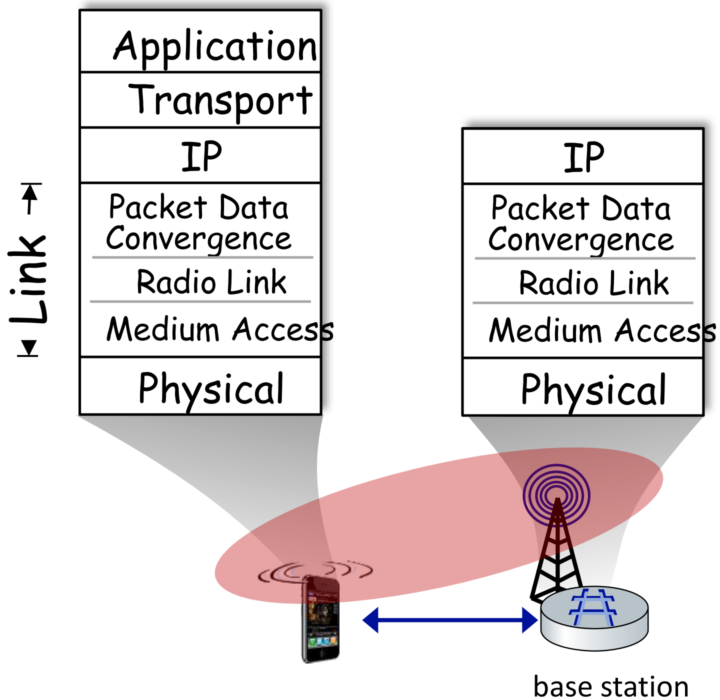
LTE data plane protocol stack: first hop



LTE link layer protocols:

- Packet Data Convergence: header compression, encryption
- Radio Link Control (RLC) Protocol: fragmentation/reassembly, reliable data transfer
- Medium Access: requesting, use of radio transmission slots

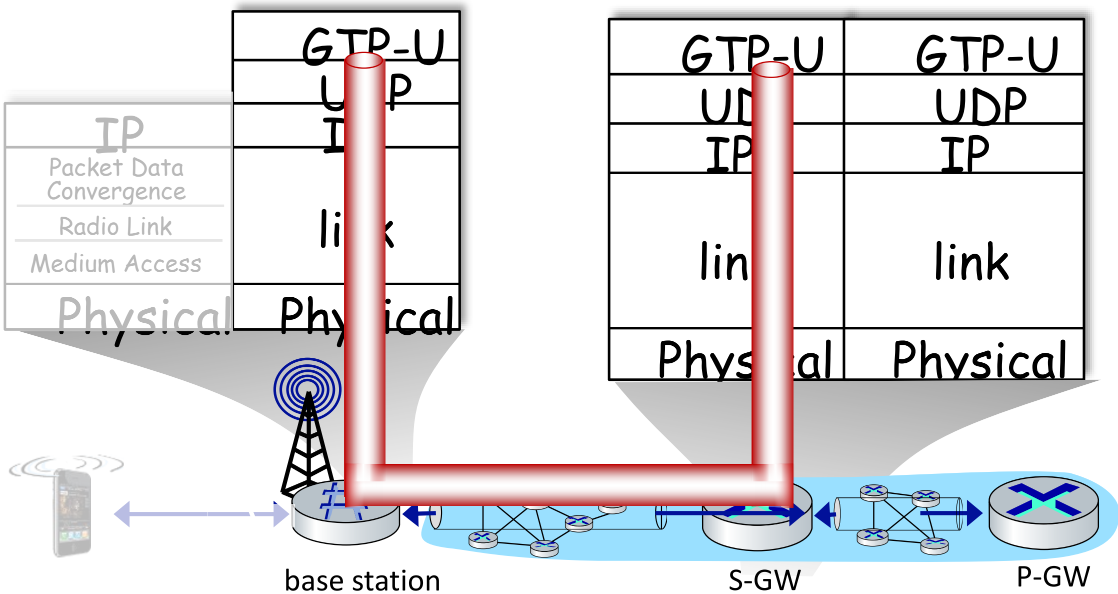
LTE data plane protocol stack: first hop



LTE radio access network:

- downstream channel: OFDMA (orthogonal frequency division multiplexing)
- upstream: SC-OFDM (Single carrier OFDM)

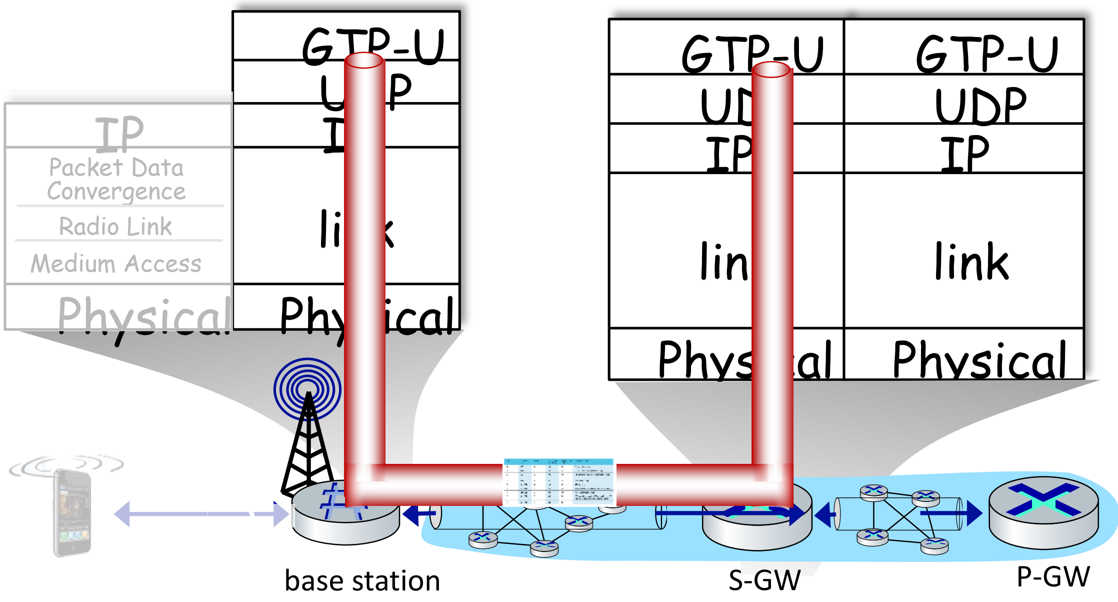
LTE data plane protocol stack: packet core



tunneling:

- mobile datagram encapsulated using GPRS Tunneling Protocol (GTP), sent inside UDP datagram to S-GW

LTE data plane protocol stack: packet core



tunneling:

- mobile datagram encapsulated using GPRS Tunneling Protocol (GTP), sent inside UDP datagram to S-GW

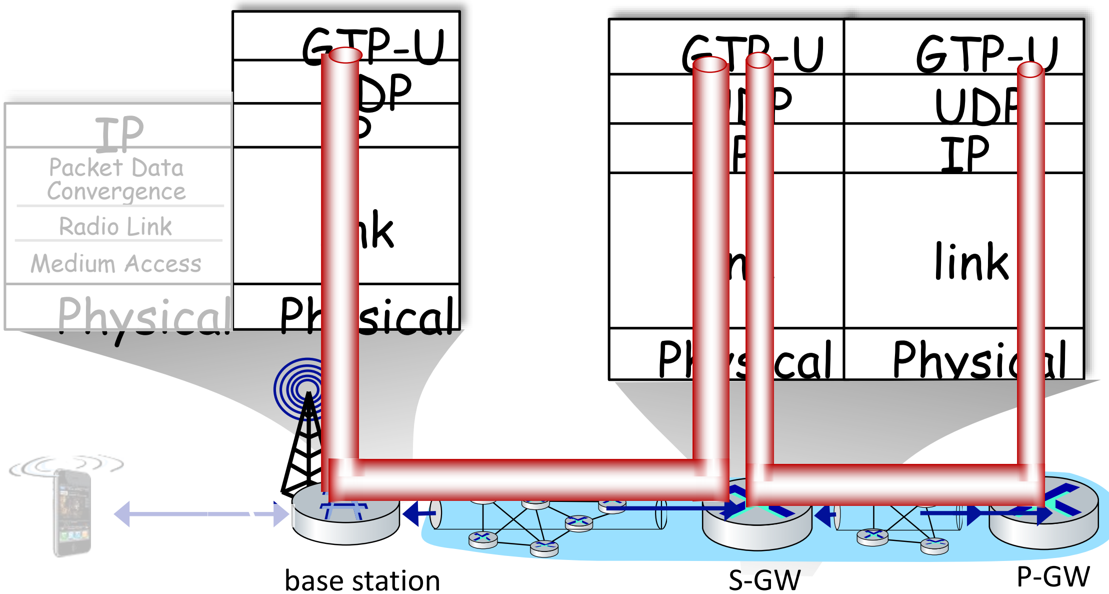
LTE data plane protocol stack: packet core

tunneling:

- mobile datagram encapsulated using

QCI	RESOURCE TYPE	PRIORITY	PACKET DELAY BUDGET (MS)	PACKET ERROR LOSS RATE	EXAMPLE SERVICES
1	GBR	2	100	10^{-2}	Conversational voice
2	GBR	4	150	10^{-3}	Conversational video (live streaming)
3	GBR	5	300	10^{-6}	Non-conversational video (buffered streaming)
4	GBR	3	50	10^{-3}	Real-time gaming
5	Non-GBR	1	100	10^{-6}	IMS signaling
6	Non-GBR	7	100	10^{-3}	Voice, video (live streaming), interactive gaming
7	Non-GBR	6	300	10^{-6}	Video (buffered streaming)
8	Non-GBR	8	300	10^{-6}	TCP-based (for example, WWW, e-mail), chat, FTP, p2p file sharing, progressive video and others
9	Non-GBR	9	300	10^{-6}	

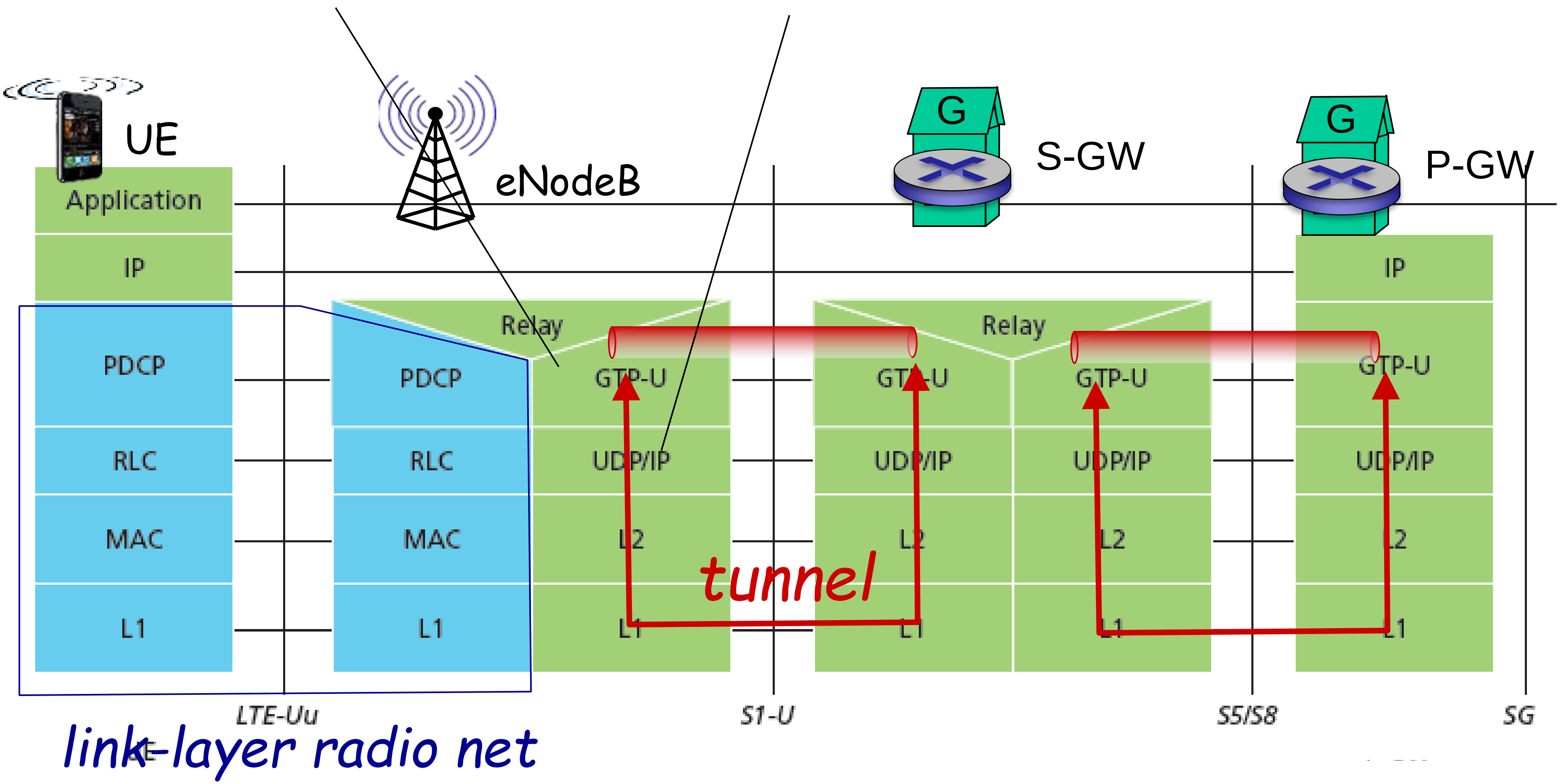
LTE data plane protocol stack: packet core



tunneling:

- mobile datagram encapsulated using GPRS Tunneling Protocol (GTP), sent inside UDP datagram to S-GW
- S-GW re-tunnels datagrams to P-GW
- supporting mobility: only tunneling endpoints change when mobile user moves

Radio+Tunneling: UE – eNodeB – PGW



Overview

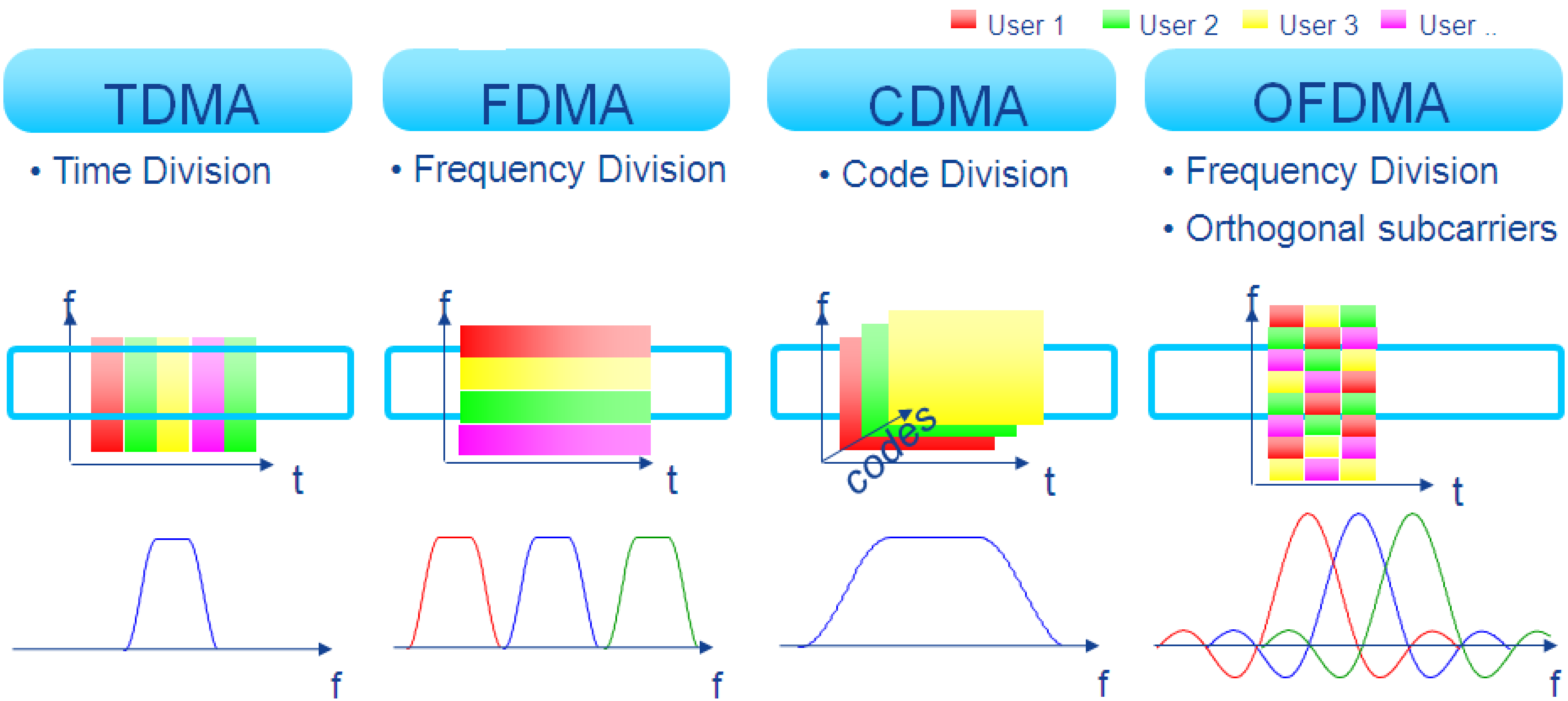


Image: http://www.ltehandbooks.com/2015/09/lte-radio-interface-ofdmofdmasc-fdma.html

LTE downlink (OFDMA-based)

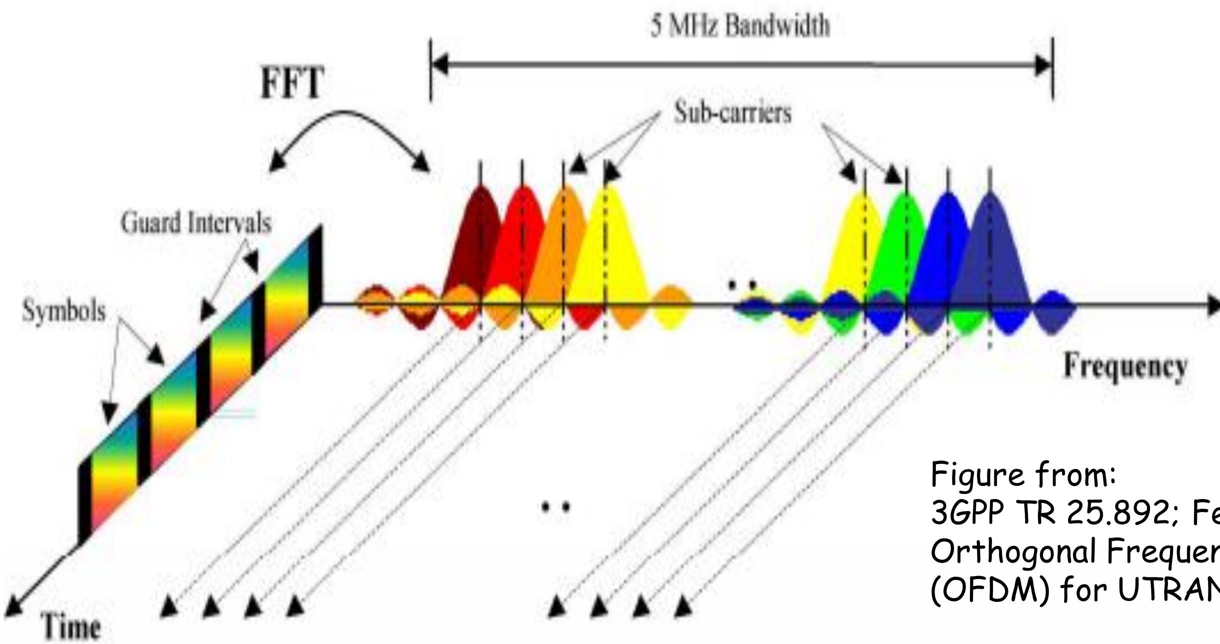


Figure from:
3GPP TR 25.892; Feasibility Study for Orthogonal Frequency Division Multiplexing (OFDM) for UTRAN enhancement (Release 6)

- Data symbols are independently modulated and transmitted over a high number of closely spaced orthogonal subcarriers.
- Available modulation schemes for E-UTRA downlink: QPSK, 16QAM, and 64QAM (with 2, 4 , and 6 bits/symbol, respectively)
- OFDM signal is generated using Inverse Fast Fourier Transform (IFFT) digital signal processing

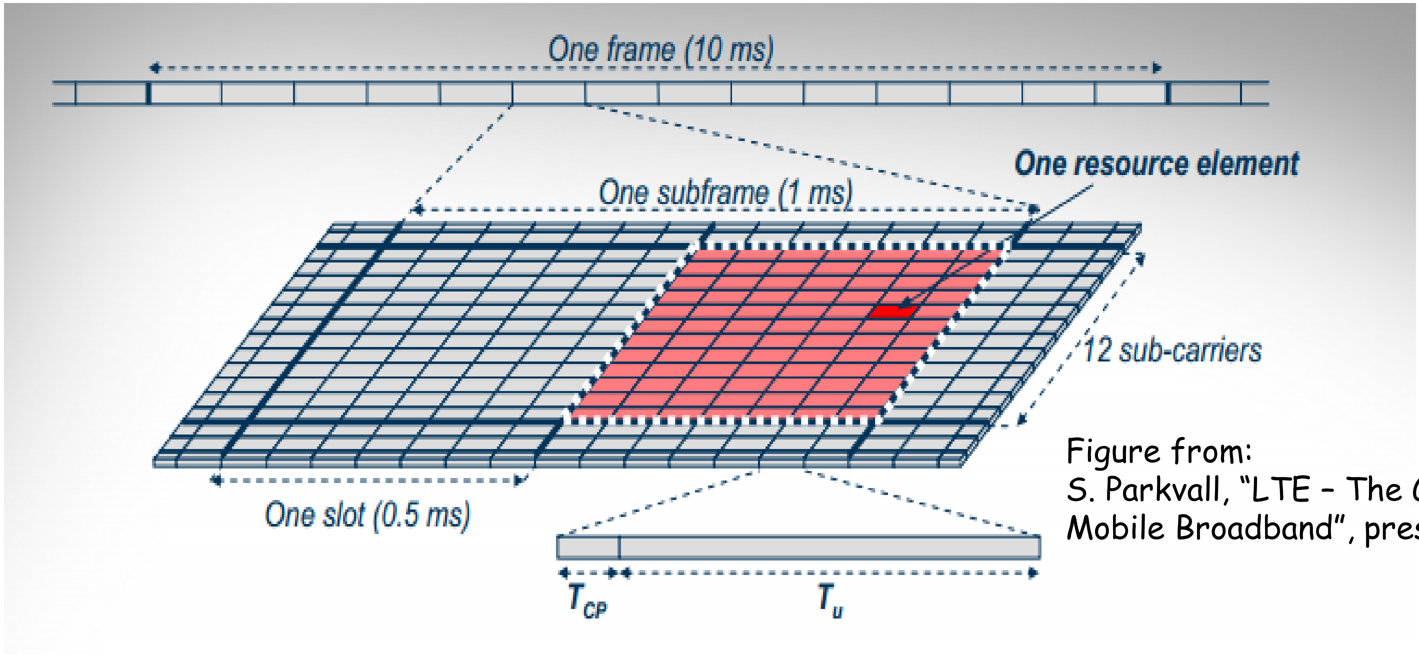
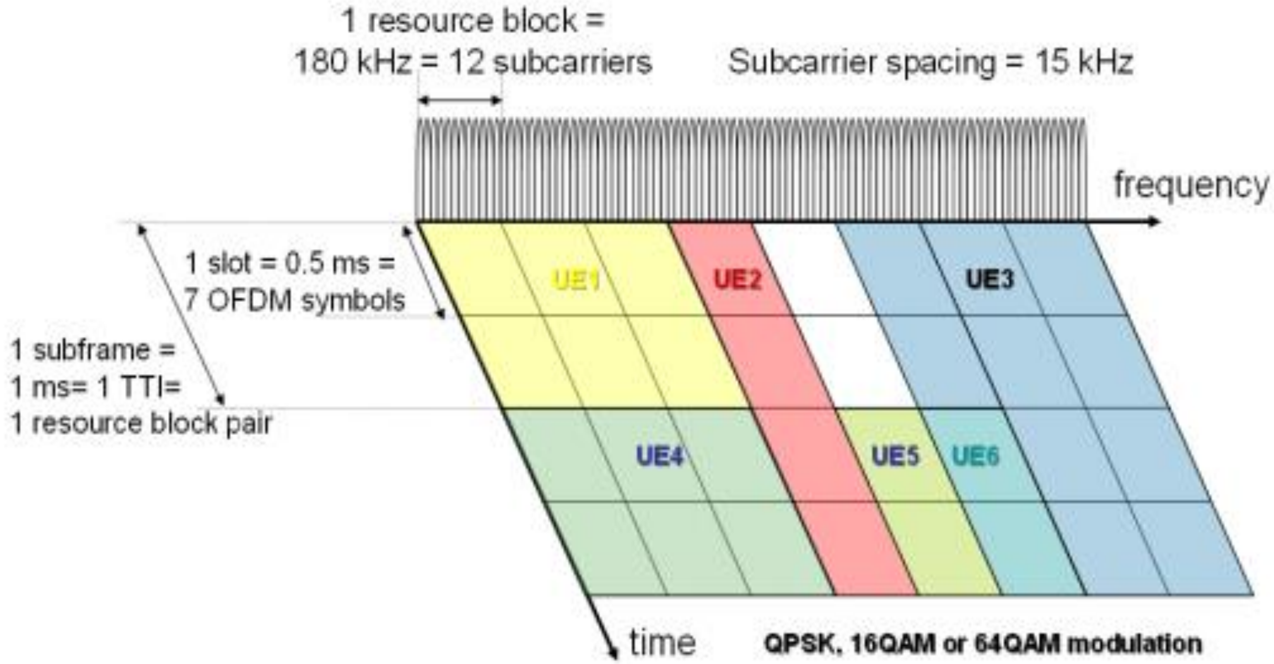
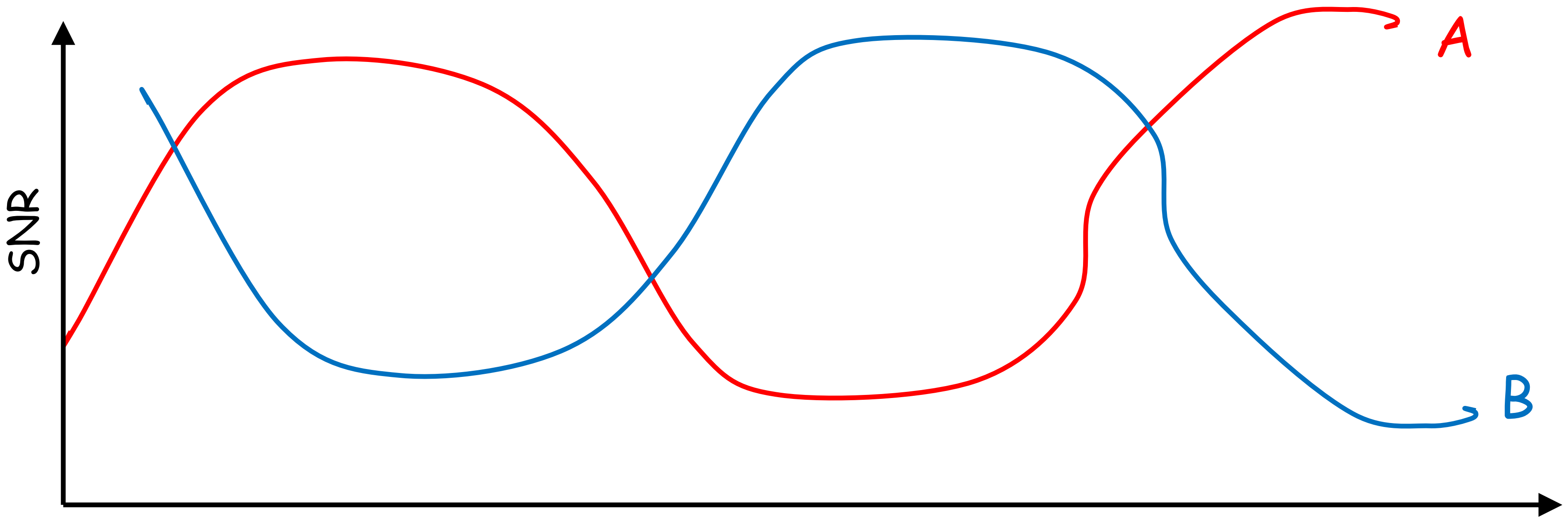


Figure from:
S. Parkvall, "LTE – The Global Standard for Mobile Broadband", presentation, Ericsson Research

- Time domain structure:
  - 10 ms frame consisting of 10 subframes of length 1 ms
  - Each subframe consists of 2 slots of length 0.5 ms
  - Each slot consists of 7 OFDM symbols (6 symbols in case of extended CP)
- Resource element (RE)
  - One subcarrier during one OFDM symbol
- Resource block (RB)
  - 12 subcarriers during one slot (180 kHz × 0.5 ms)



- Scheduling decisions done in the base station
- Scheduling algorithm is a vendor-specific, but typically takes into account
  - Radio link quality situation of different users
  - Overall interference situation
  - Quality of Service requirements
  - Service priorities, etc.



- Scheduling decisions done in the base station
- Scheduling algorithm is a vendor-specific, but typically takes into account
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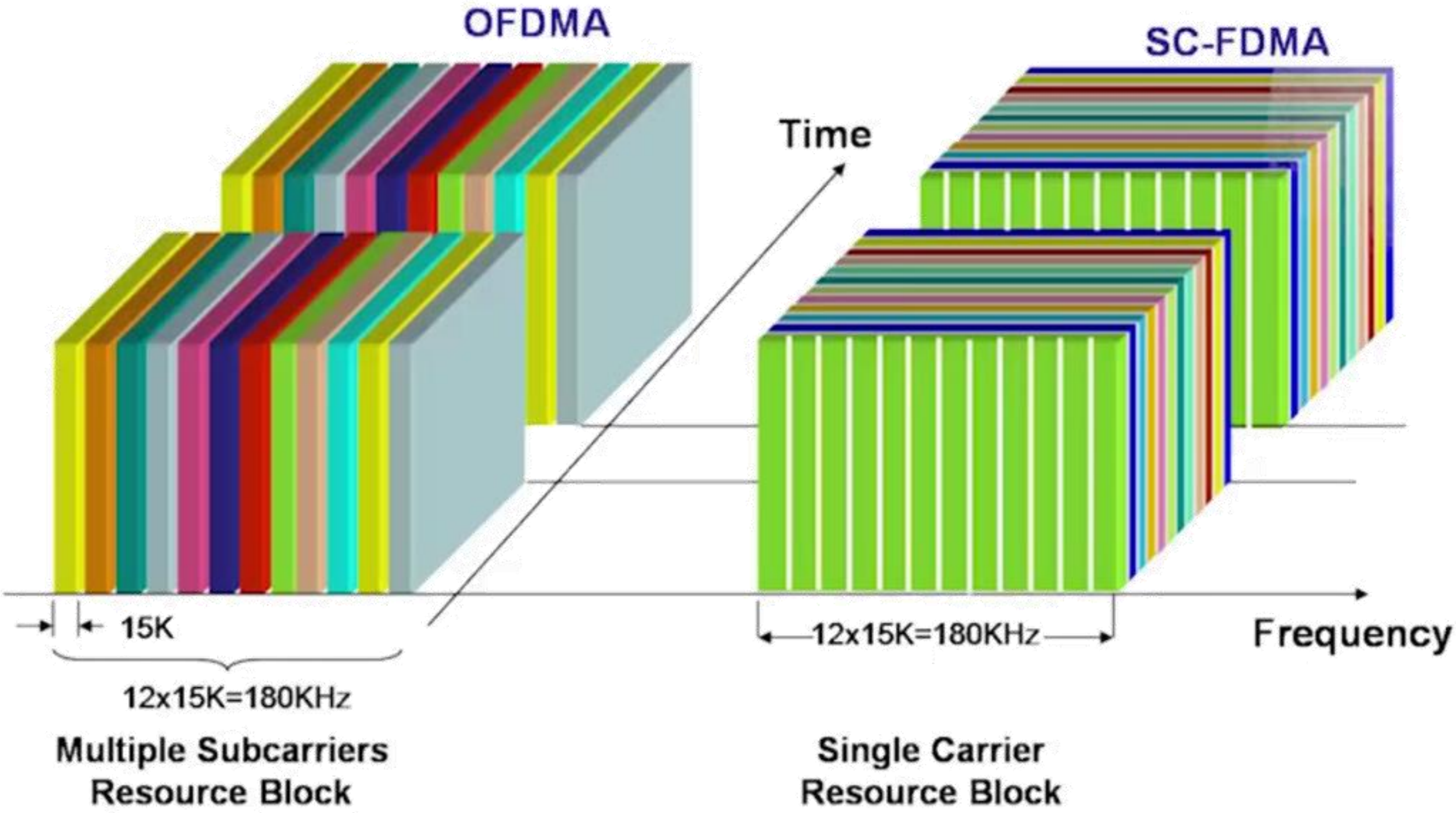
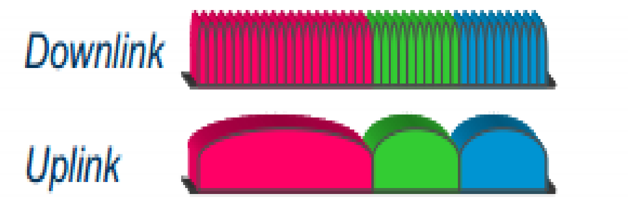
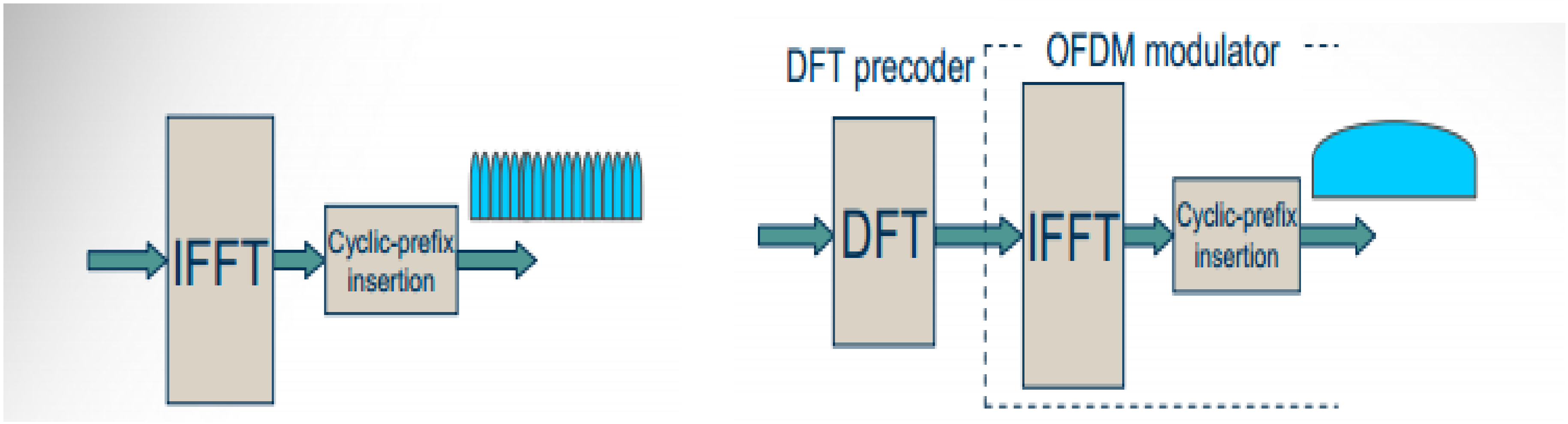
Hint: QPSK (2bits/symbol), 16QAM (4bit/symbol), and 64QAM (6 bits/symbol)

Downlink vs Uplink



Downlink vs uplink

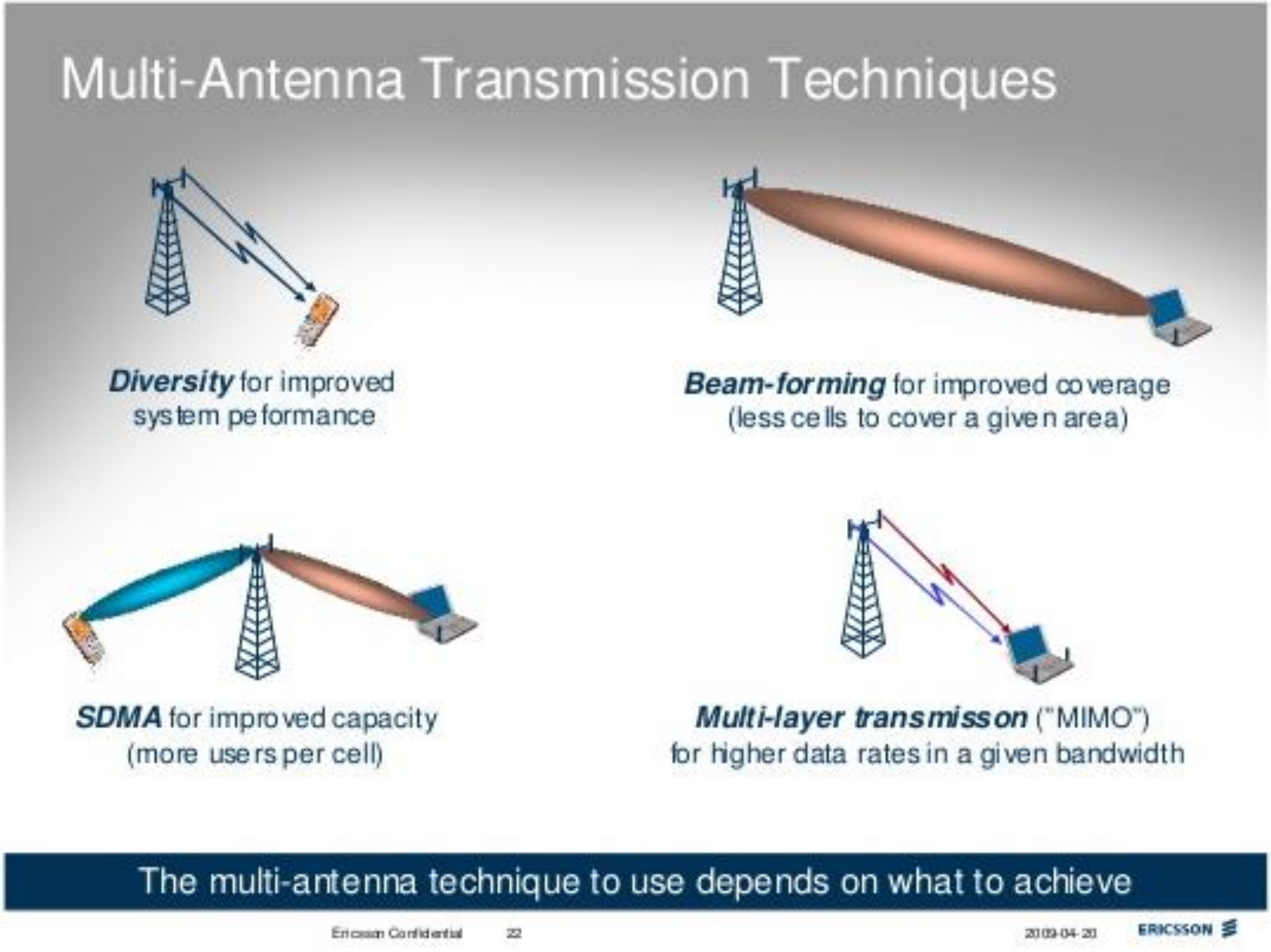




- Parallel transmission on large number of narrowband subcarriers
- Avoids own-cell interference
- Robust to time dispersion
- Bad power-amplifier efficiency

- Single carrier properties
- Better battery lifetime at phones/sender (reduced power-amplifier power)
- More complexity at receiver (equalizer needed)
- Lower throughput

Multi-antenna (*slide from Ericsson)

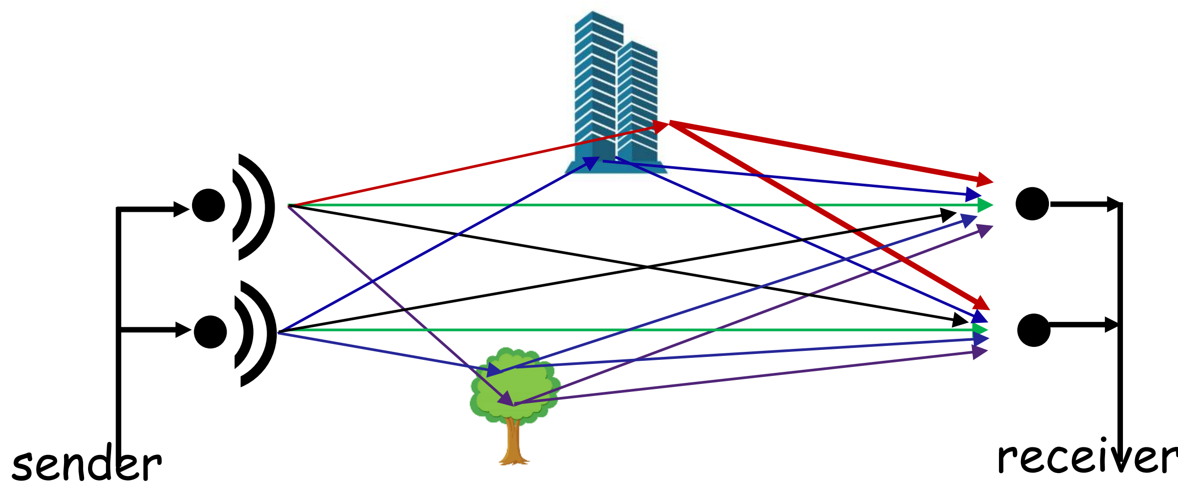


MIMO transmission: single user

Single User MIMO: spatial *diversity*

- multiple transmit/receive antenna to/at one user at same time
- *exploit multipath:* use multiple antennas to increase number of paths for transmitted signal between transmitter and receiver

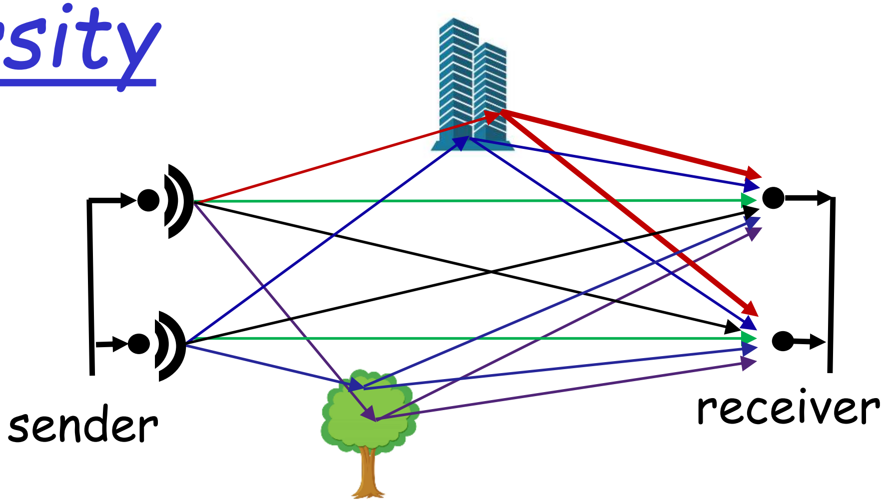
  - multipath: signals arriving at receiver not the same (e.g., some at higher quality)
  - antenna gain: increase SNR by combining multiple signals



12 signal paths from one sender (with two antennae) to one receiver (with two antennae)

MIMO: spatial diversity

- increase reliability, range by sending / receiving ***redundant** streams of information in parallel* along different spatial paths between transmit and receive antennas

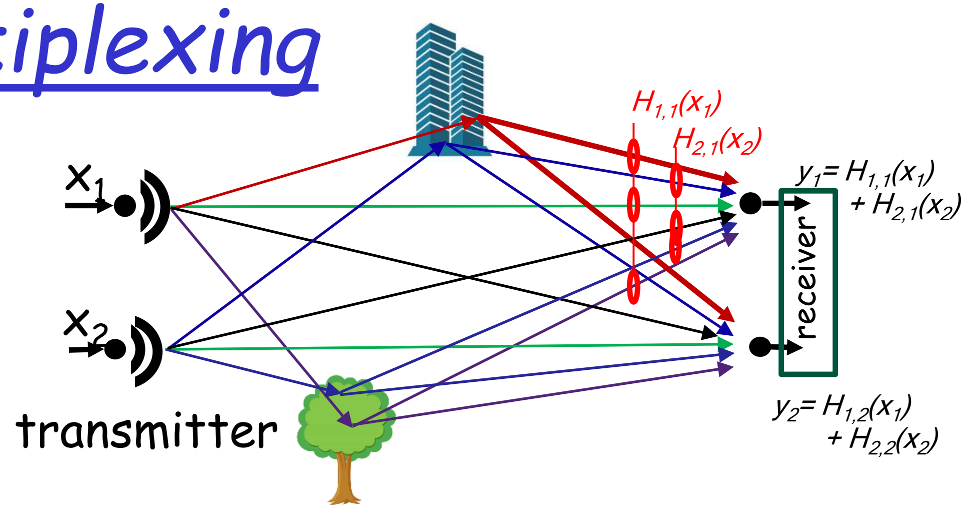


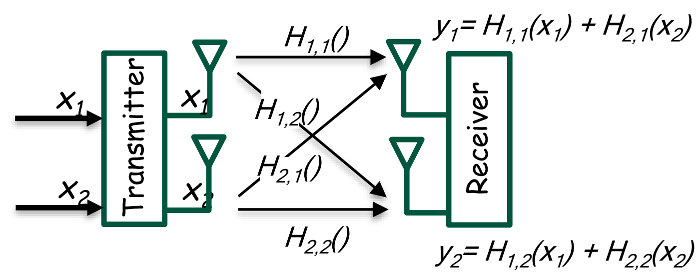
- *improved reliability:* unlikely that all paths degraded at same time
- *improved range:* multiple antennas gather more signal at receiver

Example:
- "Outage" with probability p
- M independent antennas send same signal: at least one success with probability $1-p^M$.

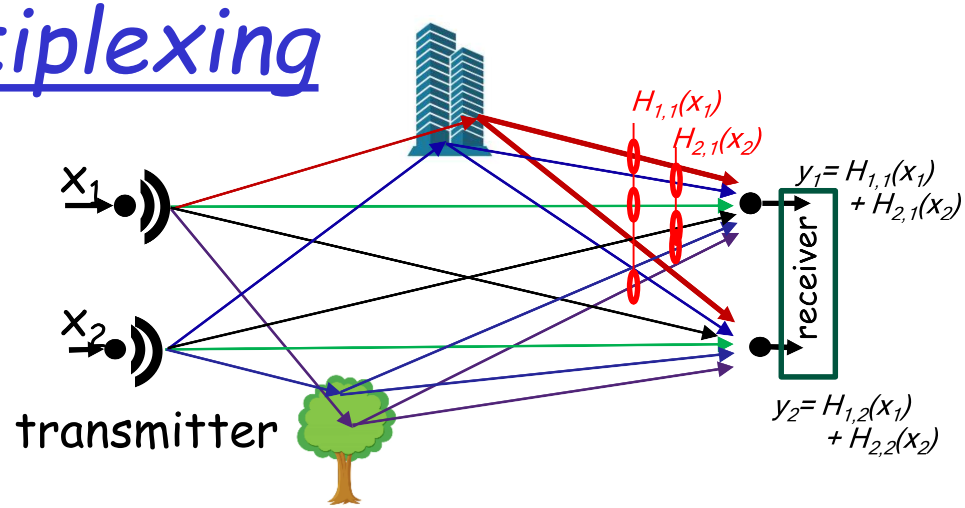
MIMO: spatial multiplexing

- send two *different streams of information,* x_1 and x_2 in parallel along different spatial paths from transmitter to receiver
- spatial *multiplexing* differs from spatial *diversity*





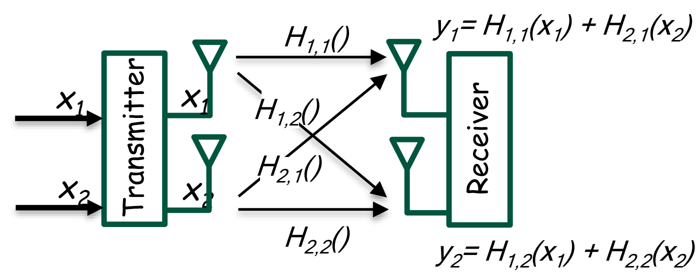
MIMO: spatial multiplexing



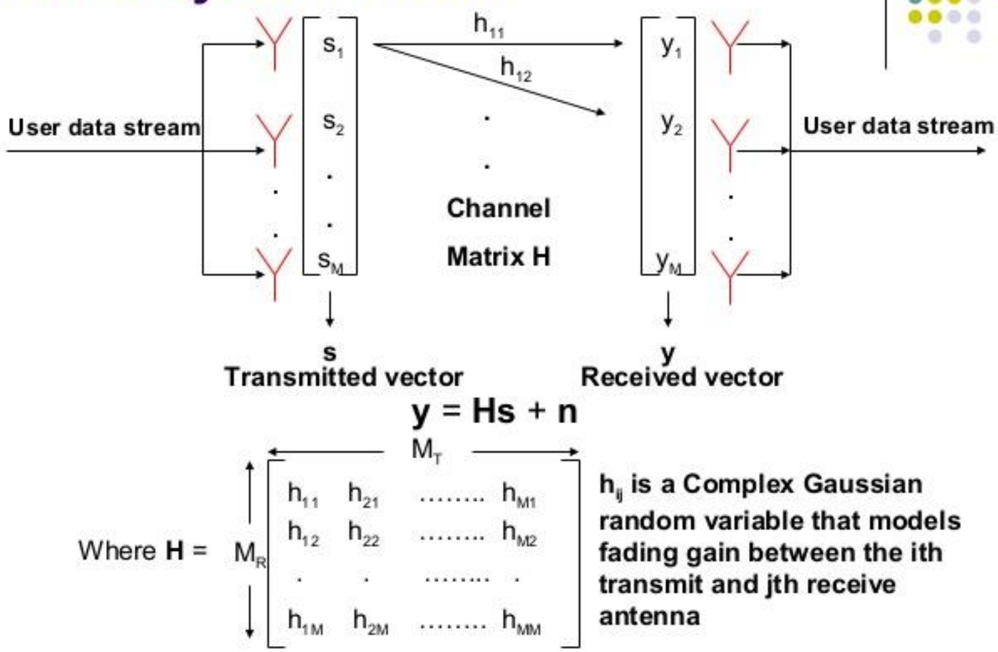
$$y_1 = H_{1,1}(x_1) + H_{2,1}(x_2)$$
$$y_2 = H_{1,2}(x_1) + H_{2,2}(x_2)$$

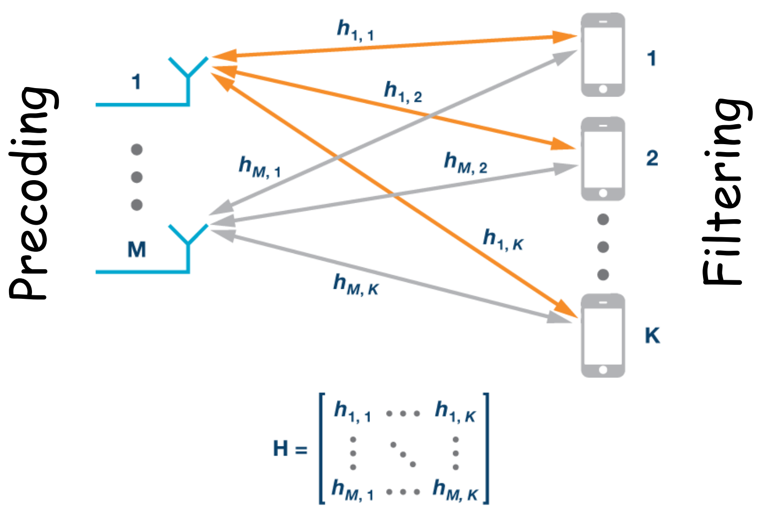
Two equations with two unknowns

- but $H_{i,j}(x_i)$ are time-varying stochastic quantities



MIMO System Model





$y = H\,s + n$

One example receiver side estimate …

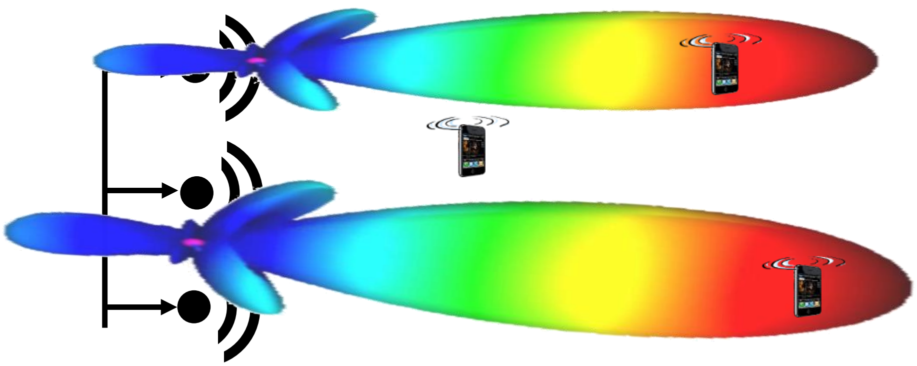
$$s' = H^{-1} y = s + error$$

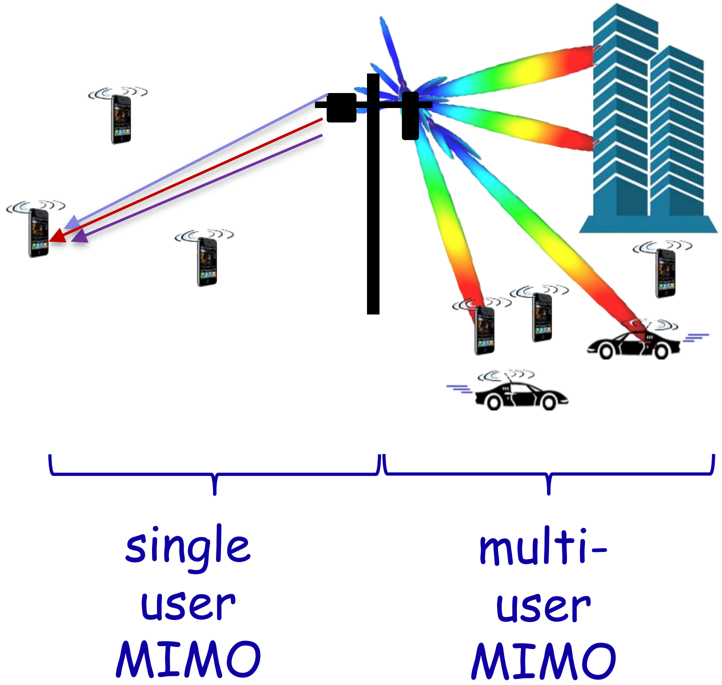
Note:

- *H based on channel estimation (fading) using known reference of pilot signal*
- *Stability depends on condition number of H*
- *Want* cond*(H) close to 1*
- *Decomposition methods, rather than pure inversion*

Multi-user MIMO

- multiple transmit antenna send to *different* users at same time
  - "spatial multiplexing"
- *exploit directional antenna:* send to geographically separated users at same time via beamforming

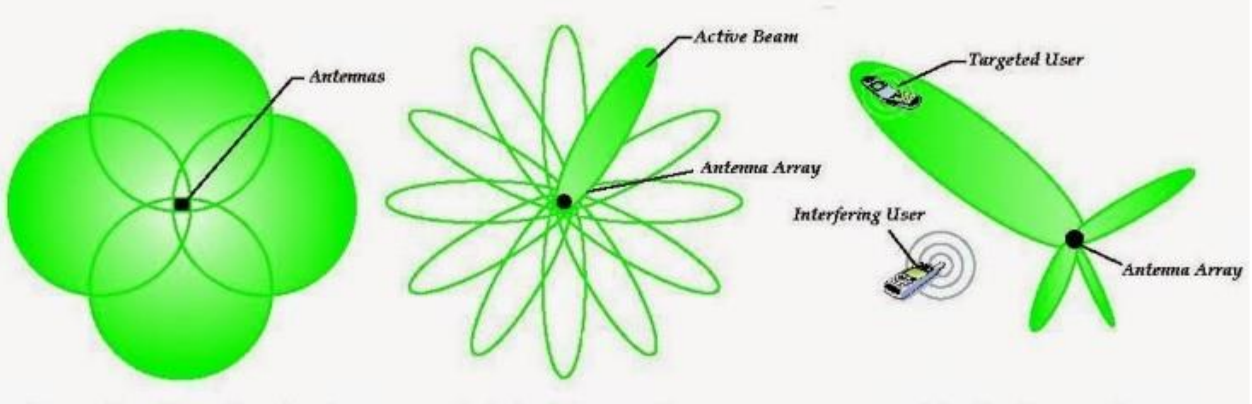




Beamforming

Advantages:

- Beam towards user
- Strong receive signal
- Save transmit power (by sending same signal at lower power)
- Less interference



Source: http://optima.skku.ac.kr/research/array_beamforming.JPG

4G/5G cellular networks

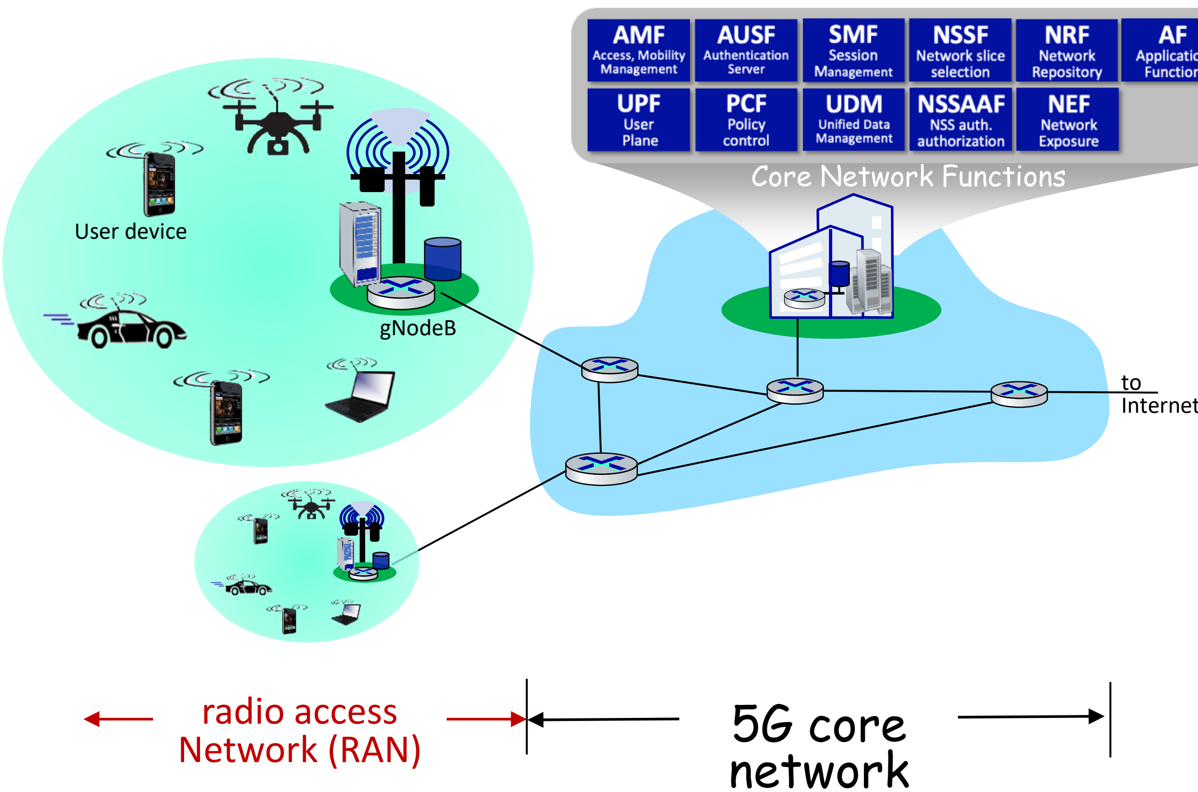
similarities to wired Internet

- edge/core distinction, but both belong to same carrier
- global cellular network: a network of networks
- widespread use of protocols we've studied: HTTP, DNS, TCP, UDP, IP, NAT, separation of data/control planes, SDN, Ethernet, tunneling
- interconnected to wired Internet

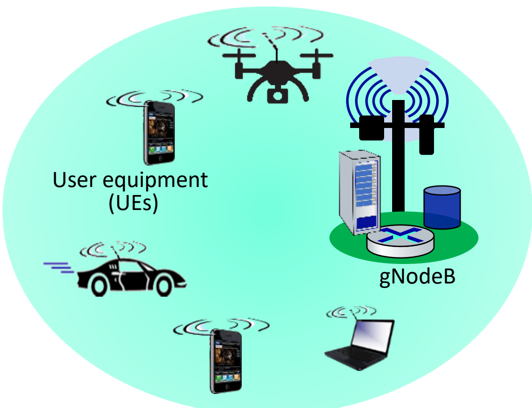
differences from wired Internet

- different wireless link layer
- mobility as a 1^{st} class service
- user "identity" (via SIM card)
- business model: users subscribe to a cellular provider
  - strong notion of "home network" versus roaming on visited nets
  - global access, with authentication infrastructure, and inter-carrier settlements

Architectural Elements of 5G



5G Radio Access Network (RAN)

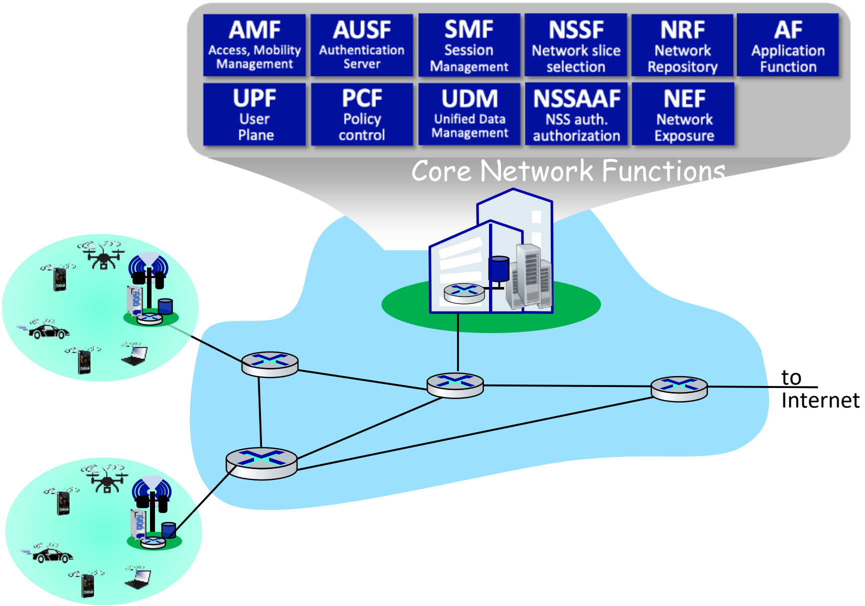


5G RAN: edge network connecting devices to base station

- provides link-layer service, as first hop between devices and larger network
- limited geographic scope
- under control of a single service provider
- somewhat analogous to WiFi LAN
- RAN components:
  - many devices (User Equipment: UE)
  - radio channel (New Radio: NR)
  - one base station (Next Generation Node B: gNodeB, gNB)

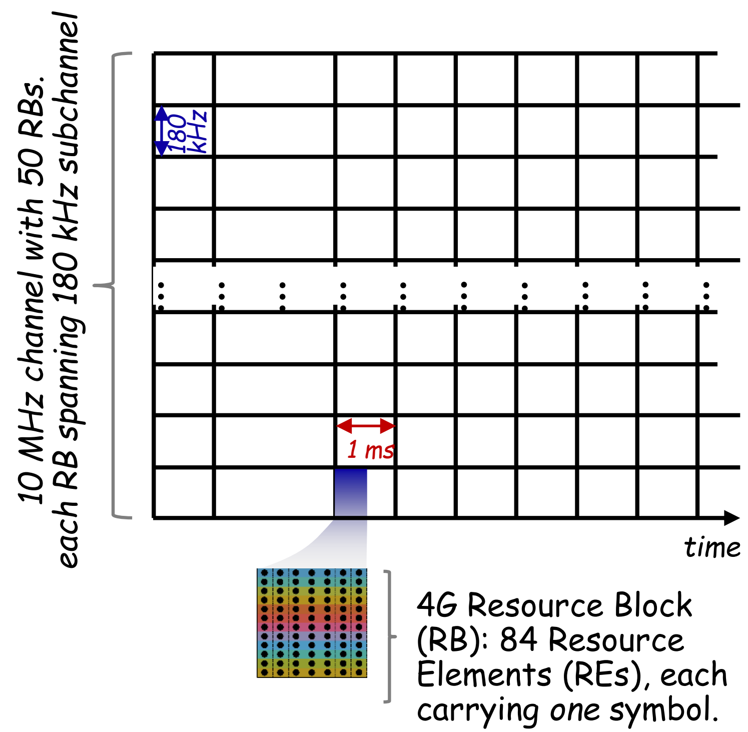
5G Core Network

- Core situated between RAN and other endpoints (Core, larger Internet)
  - single Core; multiple RANs
- consist of links, routers, servers, providing services to devices and base stations
  - "all IP" Core, but very different services than traditional Internet apps
- clear logical separation between control-plane, user plane:
  - *CUPS:* Control-Plane and User-Plane Separation

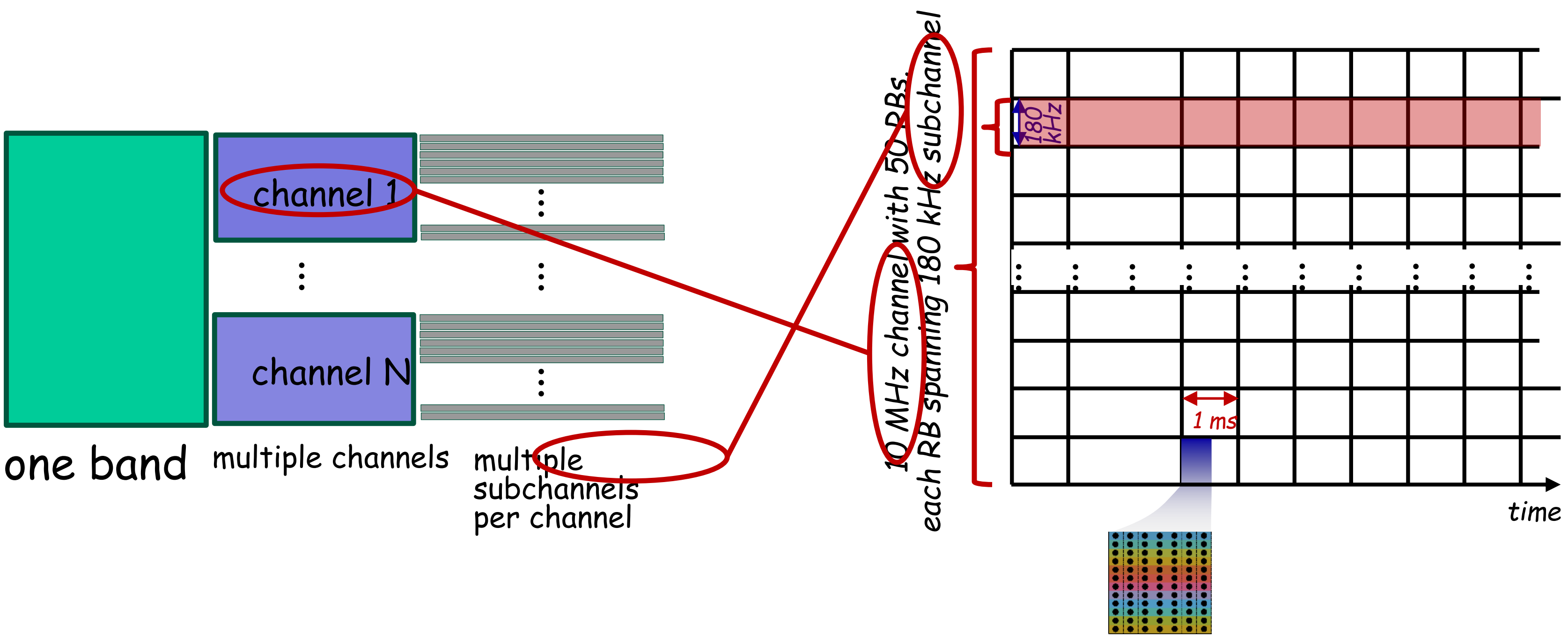


Resource Blocks (RB)

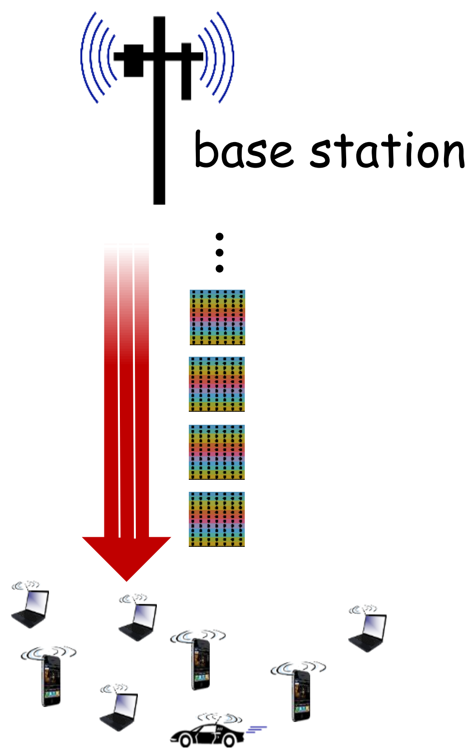
- Resource Element (RE): holds one transmitted OFDMA symbol, in one time minislot on one subcarrier frequency
- Resource Block (RB): bundle of neighboring (time, frequency) Resource Elements
  - 4G: 84 symbols (12 neighboring subcarriers, 7 consecutive minislots)
  - 5G: multiple bundlings possible
  - *RB is smallest unit of transmission scheduling: all symbols in RB have same source, destination*



5G Bands, Channels, Subchannels



Downlink physical channels

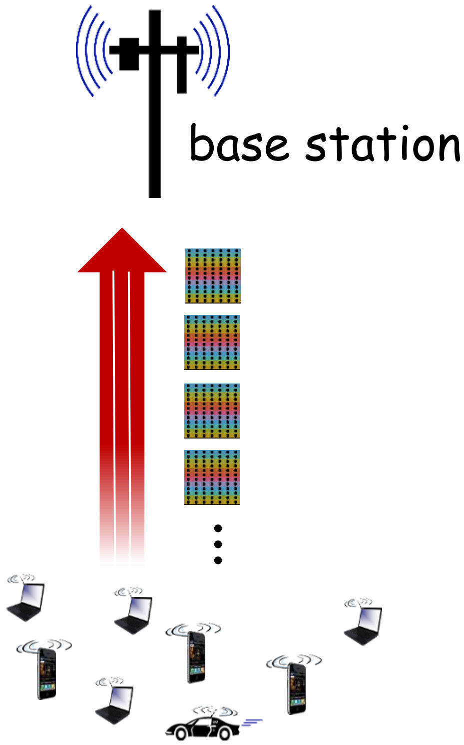


Physical channel

set of Resource Blocks (RBs) carrying similar type of data (radio channel information RBs, user and control RBs, RB allocation information)

- downlink RBs transmitted from base station to devices
- three 5G downlink physical channels:
  - Physical Downlink Shared Channel (PDSCH)
  - Physical Downlink Control Channel (PDCCH)
  - Physical Broadcast Channel (PBCH)

Uplink physical channels

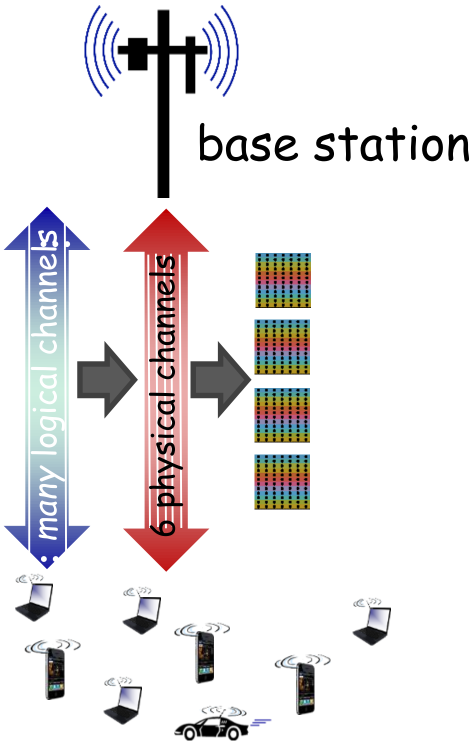


Physical channel

set of Resource Blocks (RBs) carrying similar type of data (radio channel information RBs, user and control RBs, RB allocation information)

- uplink RBs transmitted from devices to base station
- three 5G uplink physical channels:
  - Physical Uplink Shared Channel (PUSCH)
  - Physical Random-Access Channel (PRACH)
  - Physical Uplink Control Channel (PUCCH)

Uplink/downlink *logical* channels

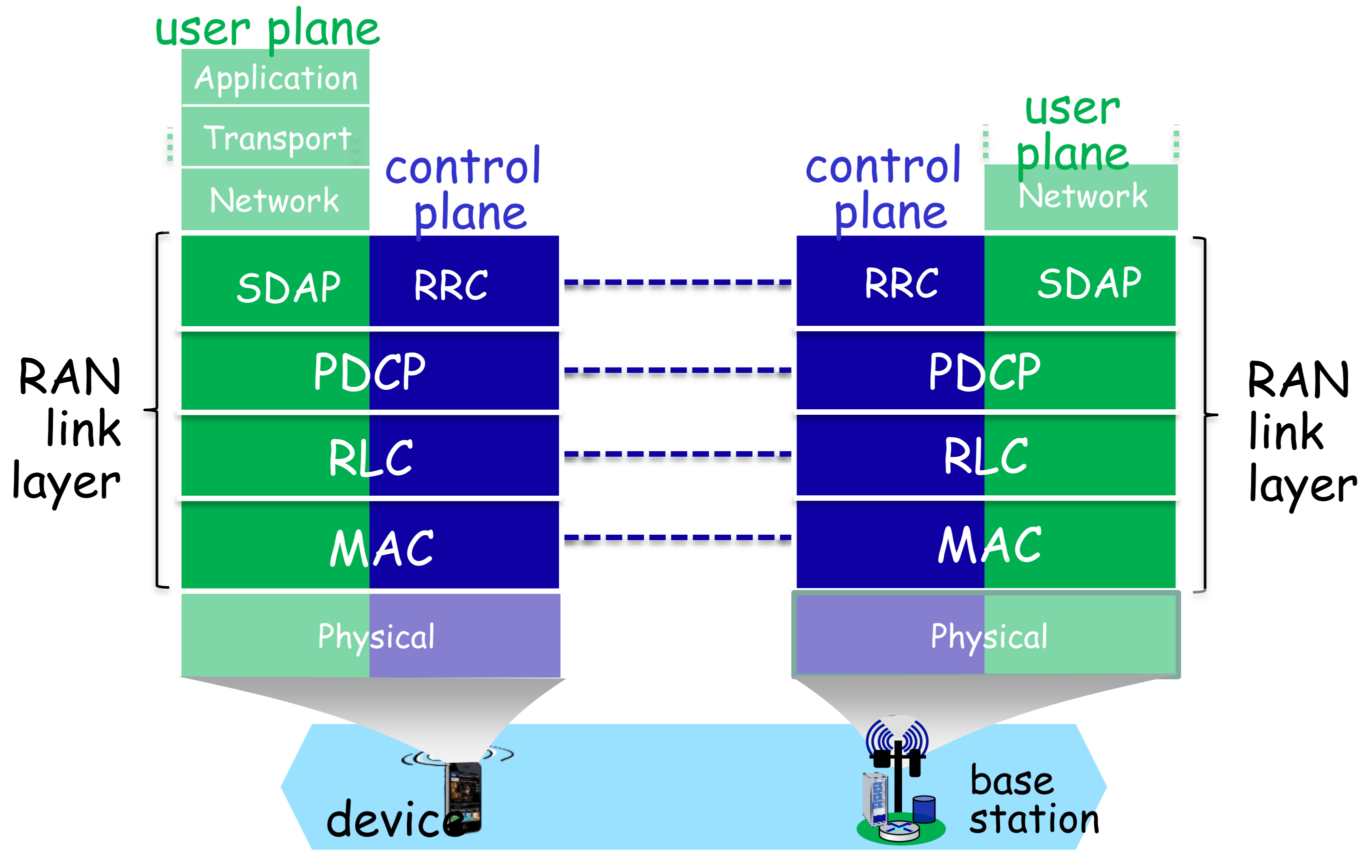


logical channel

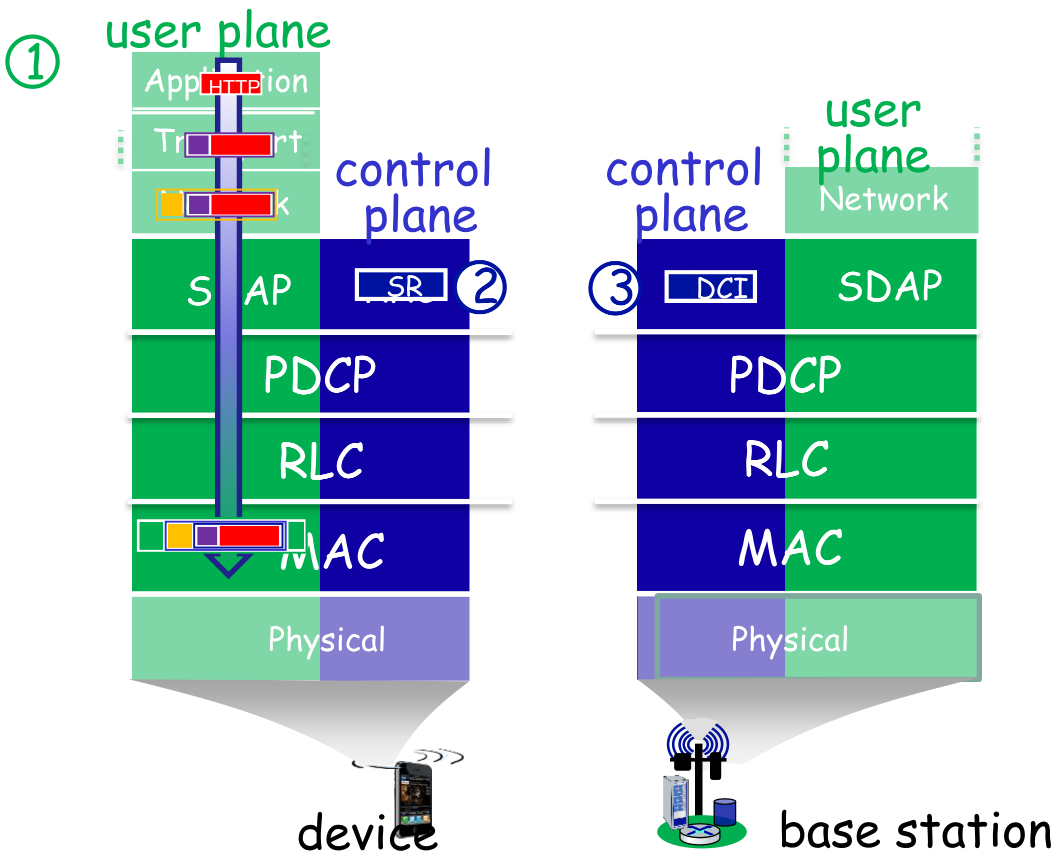
Set of Resource Blocks (RBs) carrying similar type of data. Logical channels are mapped onto physical channels, with one or more logical channel mapped to same physical channel

- individual, per-device logical channels, as well as shared logical channels among devices

RAN protocol stack (at device, base station)



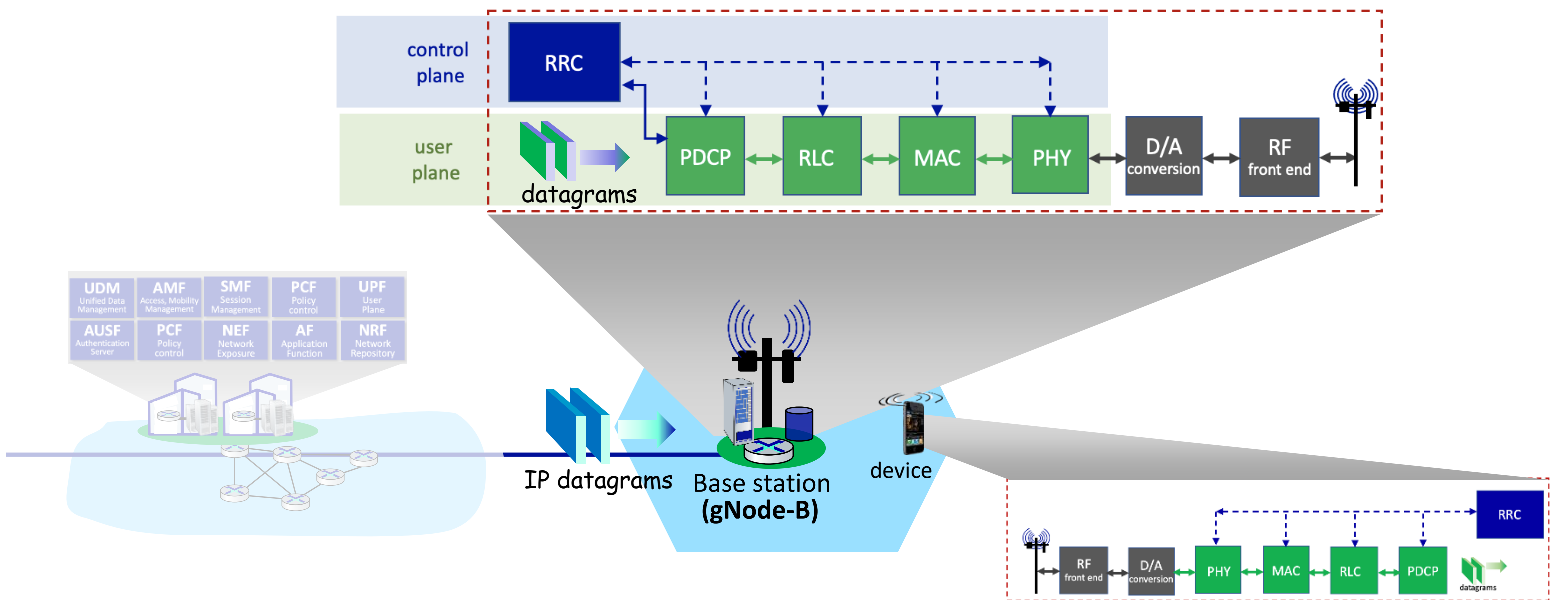
Retrospective: "A day in the life"* (5G RAN)



1. HTTP/3 request in UDP segment, in IP datagram, into 5G frame. Enter, wait, 5G MAC frame scheduling queue
2. device's control plane sends SR Scheduling Req) on Physical Uplink Control Channel (PUCCH) to base station
3. base station control plane send DCI message Physical Downlink Control Channel (PDCCH) granting upstream RBs
4. device sends frame in allocated RBs

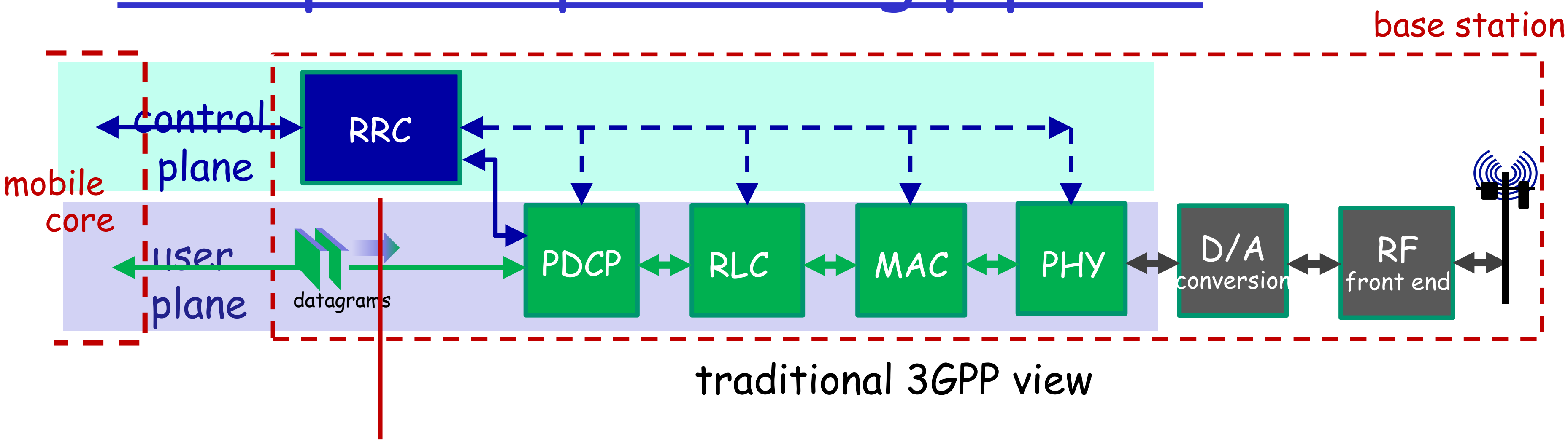
RAN packet processing pipeline: context

RAN: transfers datagrams between mobile core and devices



protocol processing pipeline in UE

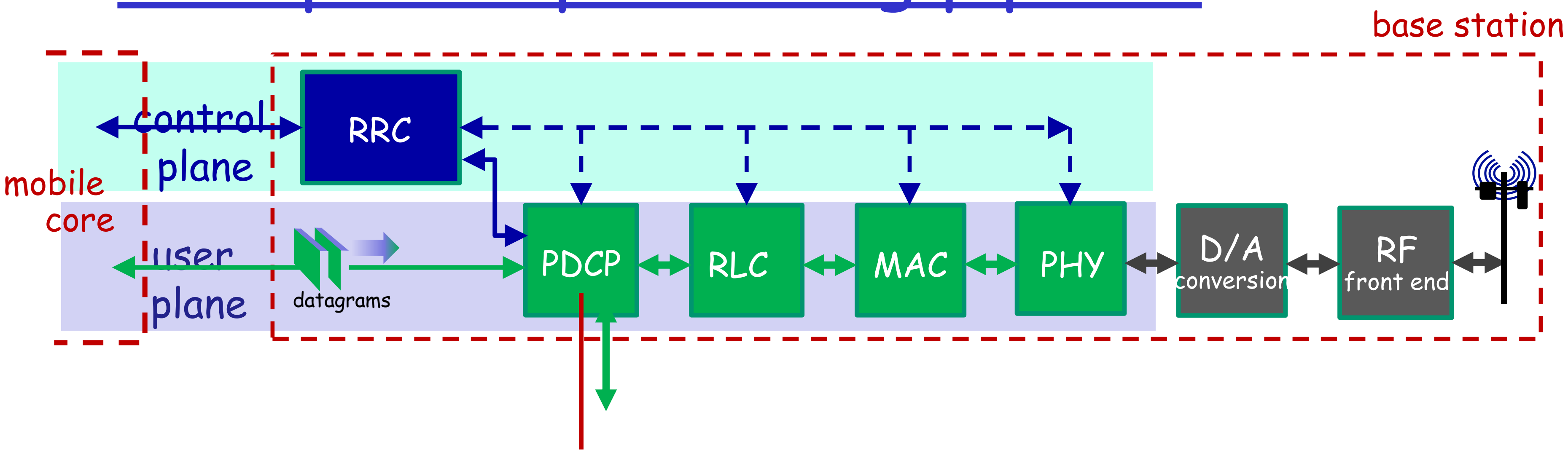
RAN packet processing pipeline



RRC (Radio Resource Control)

- configures coarse-grained, policy-related aspects of pipeline (e.g., scheduling prioritization, security)
- this implements the RAN's control plane
- does not process user plane packets

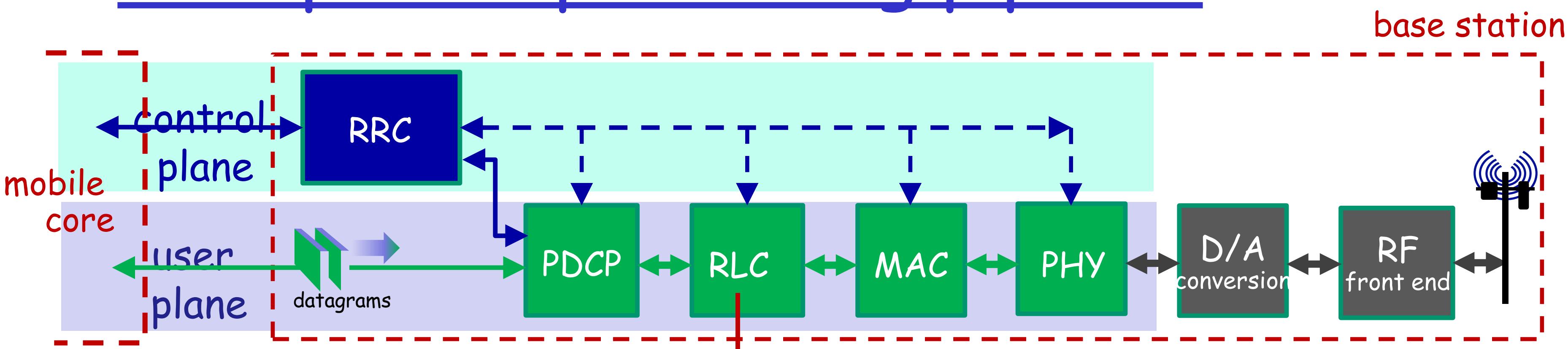
RAN packet processing pipeline



PDCP (Packet Data Convergence Protocol)

- compress/decompress IP headers
- ciphering, integrity protection

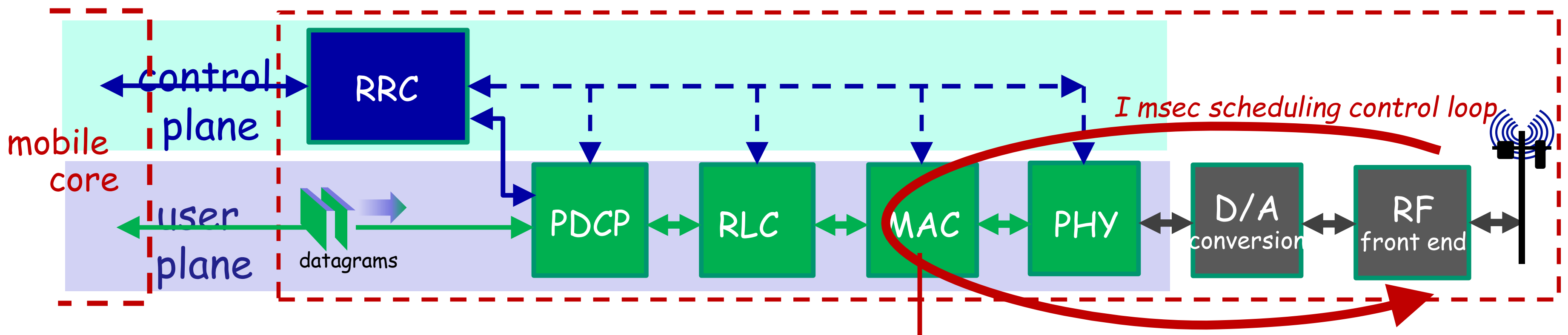
RAN packet processing pipeline

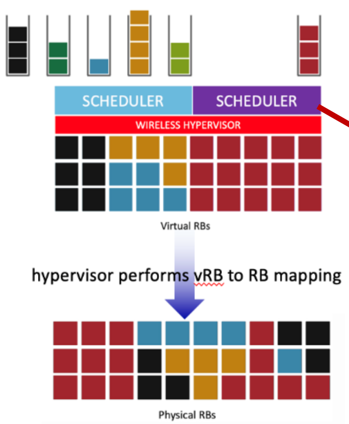


RLC (radio link control)

- link-layer frame segmentation/reassembly
- reliable data transfer (ARQ)

RAN packet processing pipeline

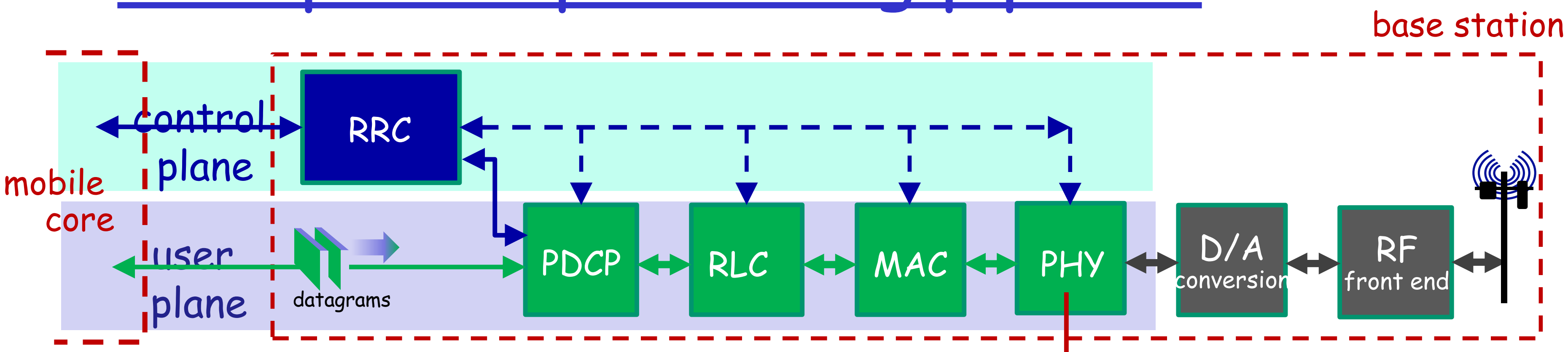




MAC (Media Access Control)

- buffering, multiplexing/demultiplexing frames
- scheduling: real-time scheduling frame decisions

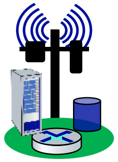
RAN packet processing pipeline



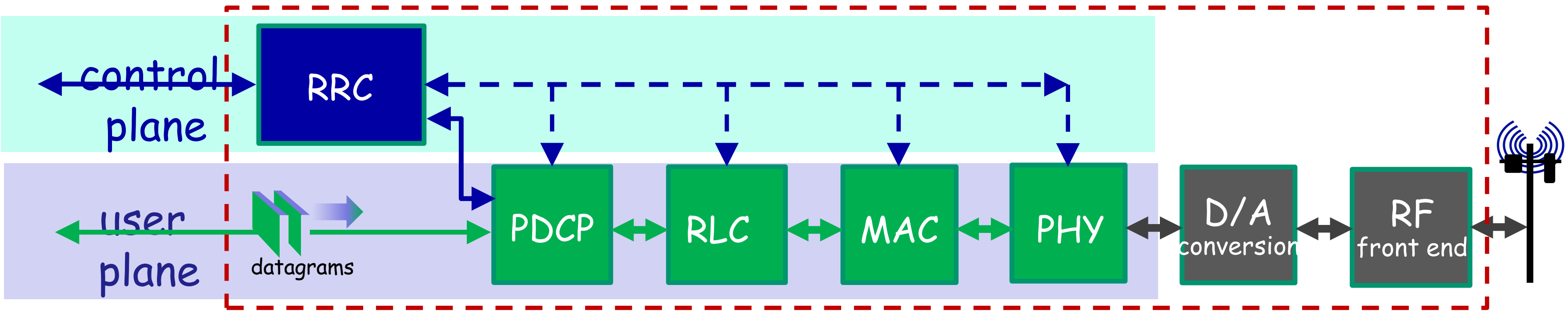
PHY (Physical Layer)
- modulation, coding

Split RAN

- *Q:* how is RAN *functionality* partitioned between physical elements (i.e.,., "split" across centralized and distributed locations)?
  - historically: no split - implemented in base station

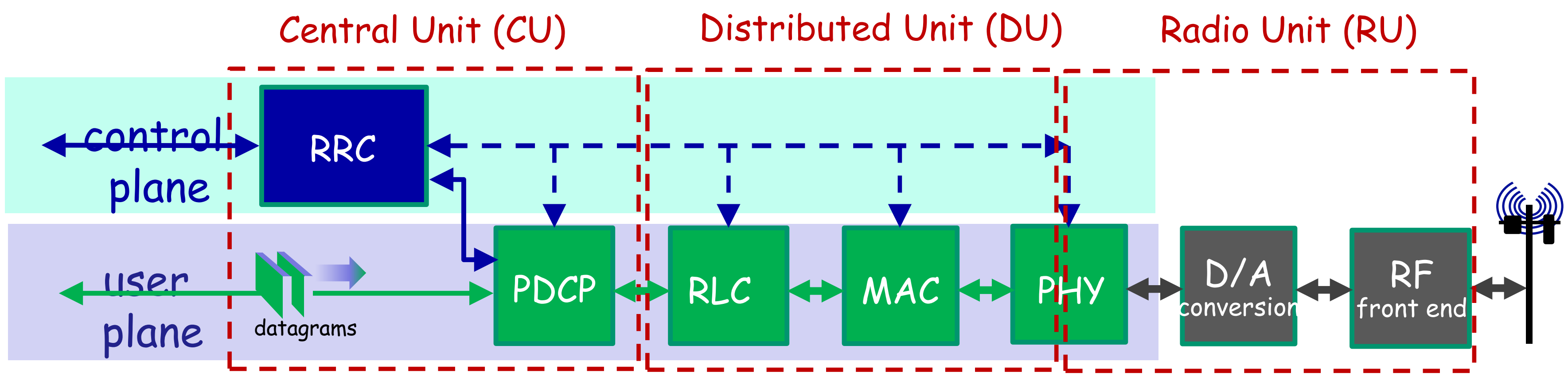


Monolithic base station



Split RAN

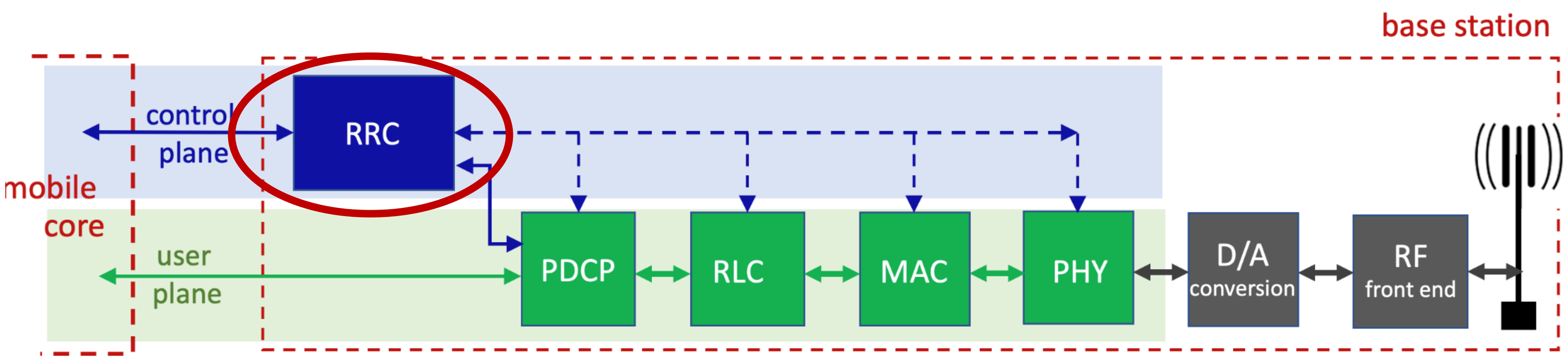
- *Q:* how is RAN *functionality* partitioned between physical elements (i.e,., "split" across centralized and distributed locations)?
  - historically: no split - implemented in base station
  - O-RAN: three "units" - *where* units are implemented is an *implementation* choice



Software-defined RAN

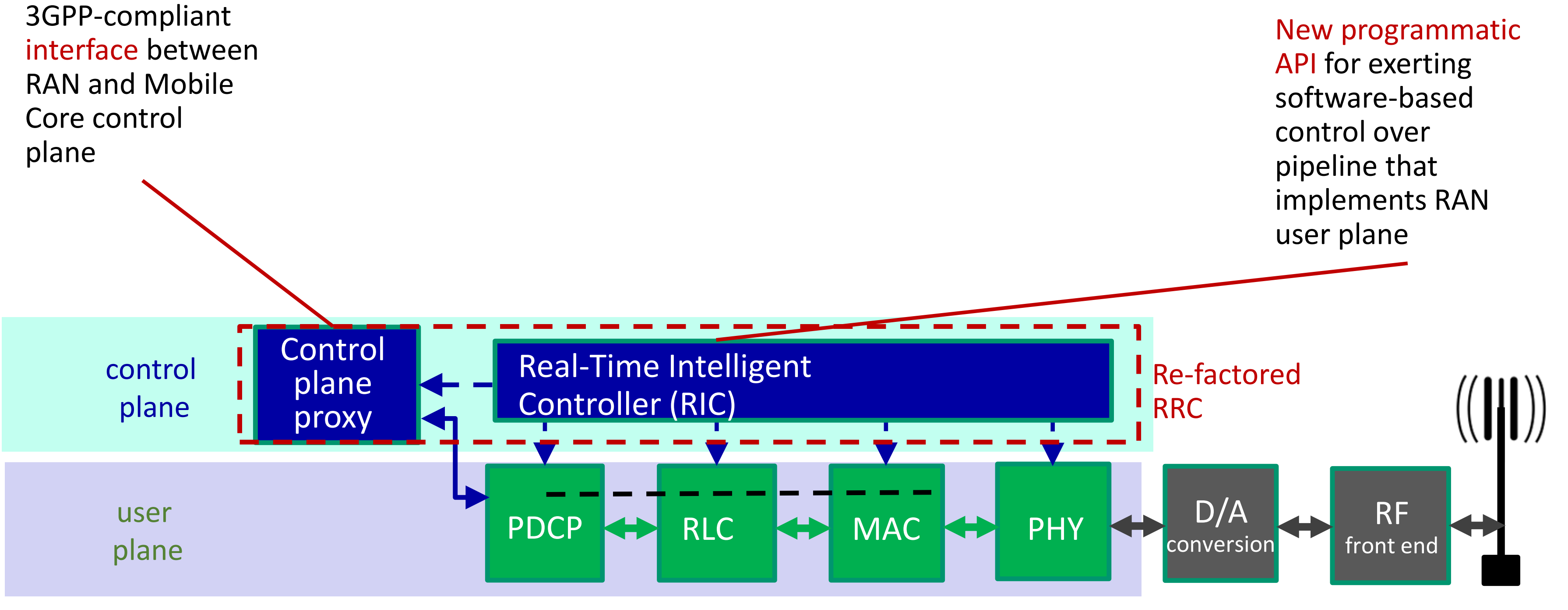
Recall our earlier description of traditional RAN base station (below)

- tightly coupled control and data planes
- let's focus on control / management: RRC *implementation*



Software-defined RAN

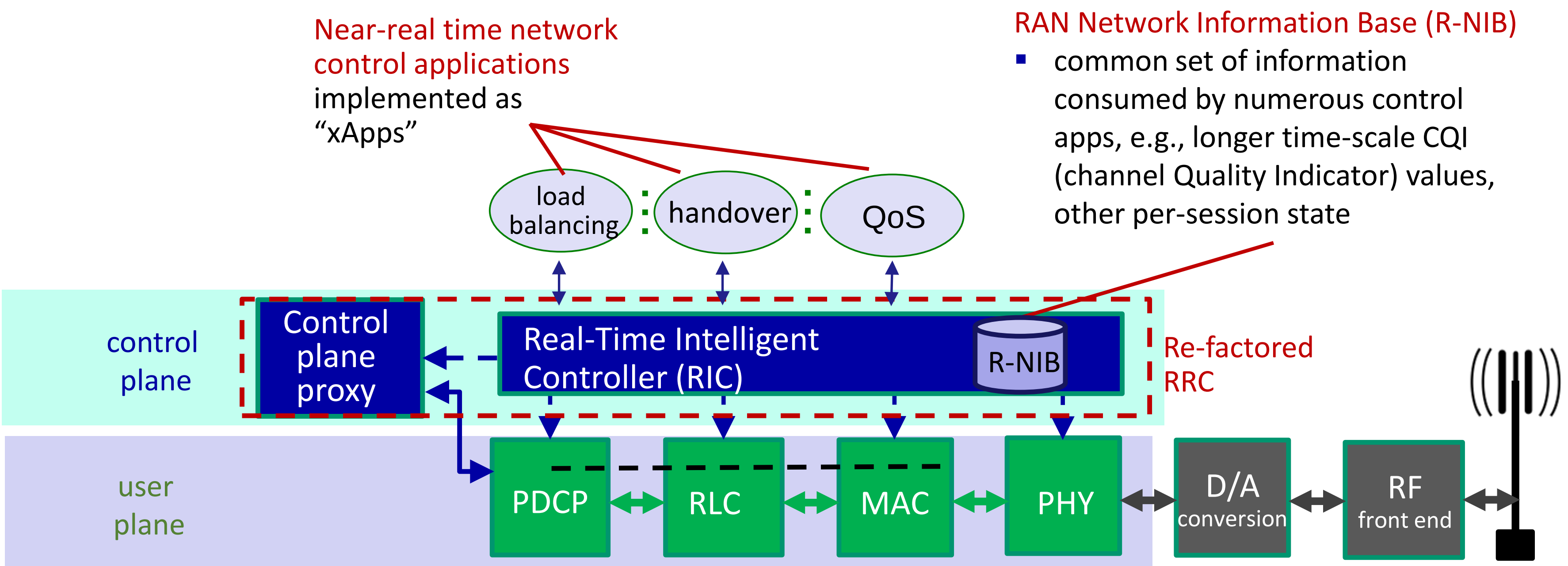
- *SD-RAN:* implementing RAN using SDN approach



SDN-controlled switches

Software-defined RAN

- *SD-RAN:* implementing RAN using SDN approach

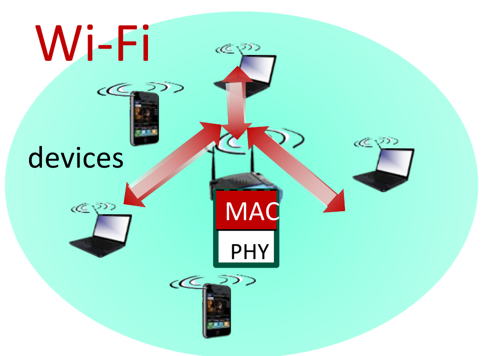


SDN-controlled switches

RAN: operator's "secret sauce"

- combination of standardized specifications + implementation strategies:
  - interfaces, high-level functions standardized
  - implementation of some functions, e.g., RB assignment to channels, frame scheduling, not standardized – up to the network operator.
  - *implementation choices are the technical "secret sauces"*

RAN/WLAN scheduling: the "big picture"



All packets to/from all devices in edge network must pass through base station

- 4G/5G and WiFi 6/7: OFDMA RB scheduling
- *downlink MAC scheduler:* which frames to send from base station to which devices in which order in which RBs (if OFDMA)?
- *uplink MAC scheduler:* which devices send which frames in which order in which RBs to base station (if OFDMA)

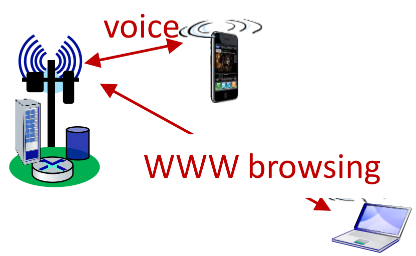
Wireless MAC scheduling: considerations

Channel aware or channel unaware?

- does scheduler consider quality of channel between base station and device?

QoS aware or QoS unaware?

- does scheduler consider QoS (quality of service) needed by (or guaranteed to) device?



Priorities, Fair scheduling?

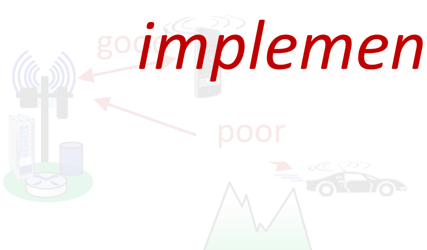
- Does scheduler provide priority among different types of traffic (user, control, real-time)?
- does scheduler consider *fairness* among UEs?
- fairness: no standard definition

"We are all equally important"

MAC scheduling considerations

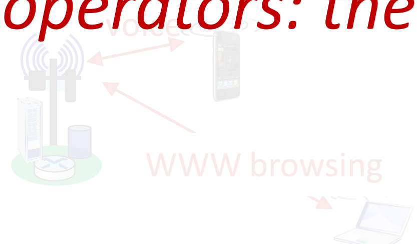
Channel aware or channel unaware?

- does scheduler consider quality of channel between base station and device?



QoS aware or QoS unaware?

- does scheduler consider QoS (quality of service) needed by device?

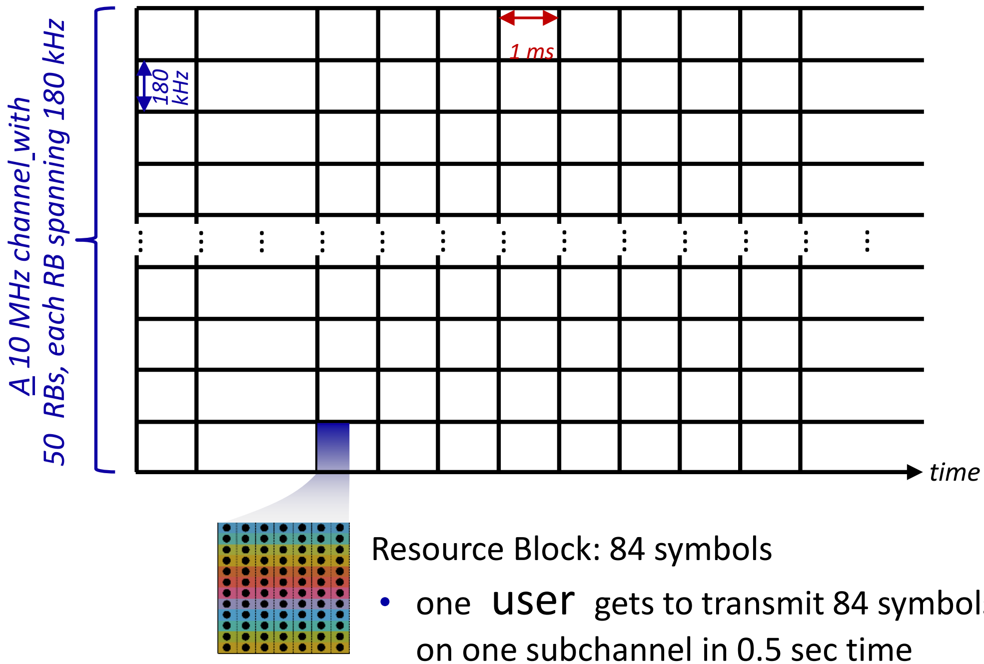


Priorities, Fair scheduling?

- Does scheduler provide priority among different types of traffic (user, control, real-time)?
- does scheduler consider fairness among UEs?
- fairness: no standard definition

- *Standards do not dictate answers to these questions!*
- *Scheduling algorithms, parameters up to network implementers, operators: their "secret sauce"*

RAN scheduling: Resource Blocks



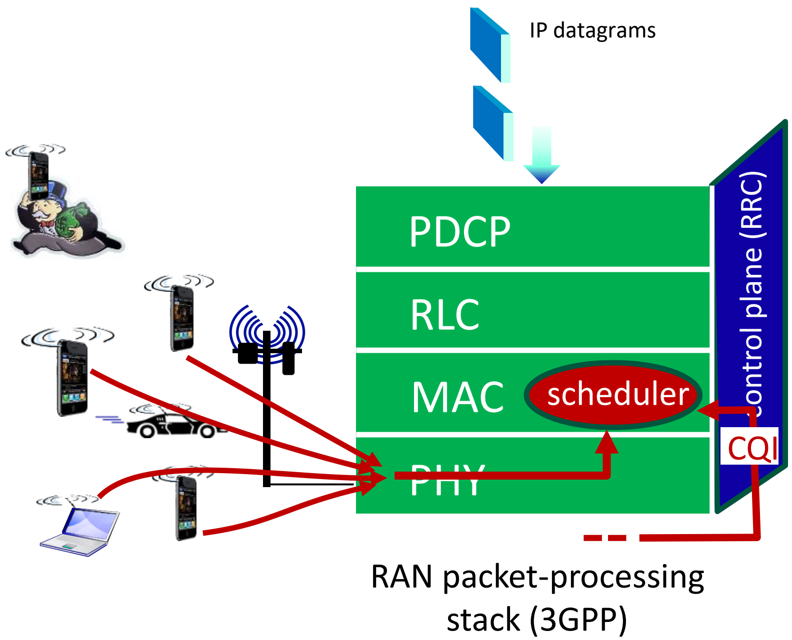
Resource Block: 84 symbols

- one user gets to transmit 84 symbols on one subchannel in 0.5 sec time interval
- 50 subchannels per 10MHz channel

Scheduling:

- Base station decides which frames/packets get assigned to which RBs for transmission to user
- scheduling interval: 1 msec
- scheduling complexity:
  - 50 subchannels per 10MHz channel
  - 100's (?) active user

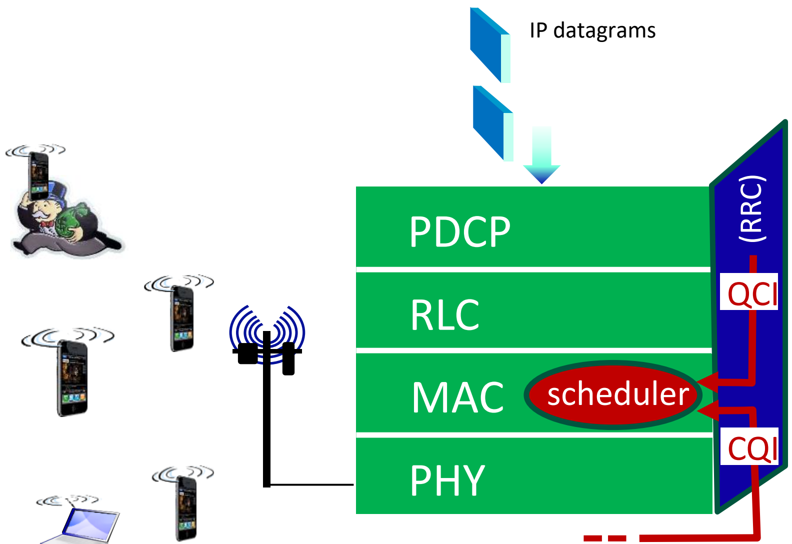
RAN scheduling: Channel Quality Indicator



Channel Quality Indicator (CQI):

- user measures quality of received reference signals (embedded in RBs), reports quality back to base station
- 4-bit CQI value maps to modulation scheme to use (e.g., which QAM?) and expected throughput

RAN scheduling: QoS Class Indicator



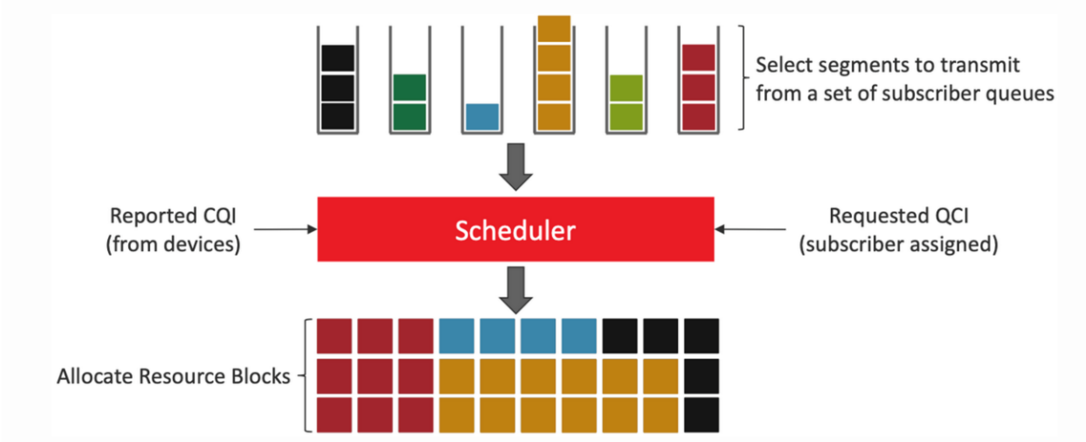
RAN packet-processing stack (3GPP)

QCI: QoS Class Indicator

- *QoS* network wants to provide to a particular device (e.g., delay, guaranteed bit rate QoS guarantees)
- scheduler determines allocation of available radio spectrum to ensure all UEs meet their QoS requirements

Priority	QCI	Max delay	Max loss	Application
2	1	100ms	.01	Voice
3	4	50 ms	.001	Real-time gaming
6	7	300 ms	.000001	Streaming video
8	8	600	.000001	Web browsing, TCP

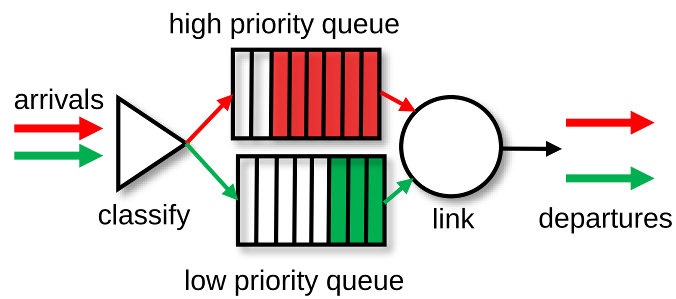
4G/5G scheduling: abstraction



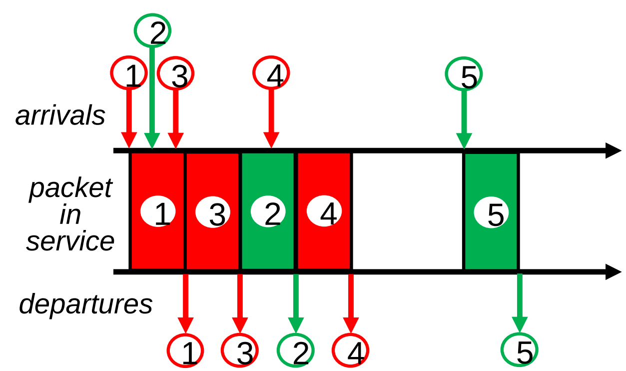
Scheduling policies: priority

Priority scheduling:

- arriving traffic *classified*, queued by class
  - any header fields can be used for classification, e.g., control versus user data



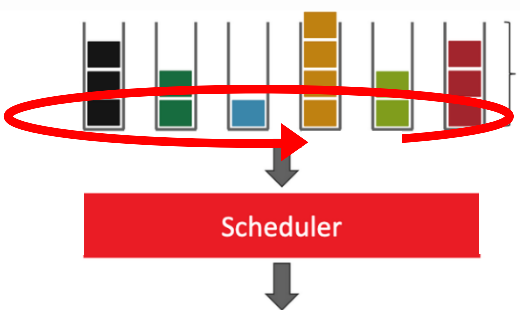
- send packet from highest priority queue that has buffered packets
  - scheduling within priority class could be another scheduling discipline



Round Robin scheduling (per UE)

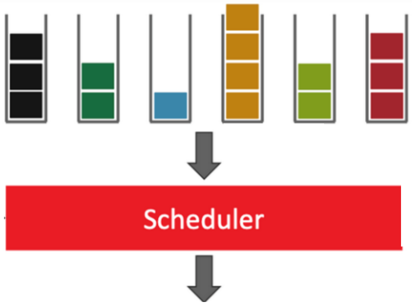
- scheduler cyclically scans device queues, mapping packets/frame from each device (if available) to an RB in turn
- channel unaware, QoS unaware
- fair (by turns) but not necessarily throughput-fair since different devices may have different channel quality

Each device has its own queue



Maximum Throughput (MT) scheduling

- find device (UE) *i*, with highest quality channel over all RBs, *k:*
  - $d^i_k(t)$: expected data rate for UE^i using *k*th RB at time *t* (e.g., based on CQI)
  - at *t*: select $\max_{i,k} \{d^i_k(t)\}$, *assign* UE^i frame to RB_k
- maximizes overall immediate throughput
- channel aware, QoS unaware, throughput unfair

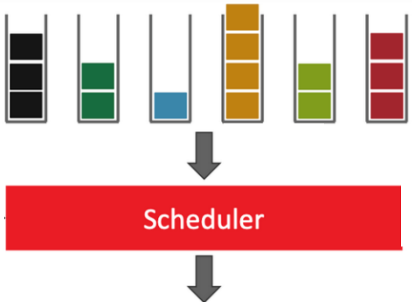


Blind Equal Throughput (BET) scheduling (per device)

- scheduler maintains exponentially-weighted-moving-average of data rate received at each UE^i at time t, $R^i(t)$:

$$R^i(t) = (1-\beta) \cdot r^i(t) + \beta \cdot R^i(t-1)$$

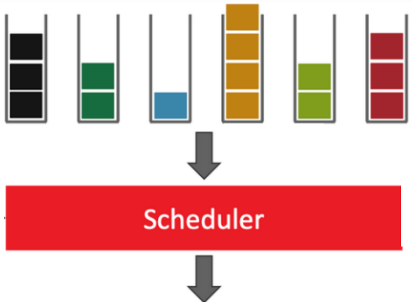
  where $r^i(t)$ is data rate achieved in scheduling interval t



- at t: select $\min_i \{R^i(t-1)\}$: assign UE^i frame blindly (not know channel conditions) to (any) RB
  - assign RB to device with smallest data rate last round
- channel somewhat-aware, QoS unaware, blind throughput fair

Proportional Fairness (PF) scheduling

- combine Blind Equal Throughput (BET) and Maximum Throughput (MT) scheduling
  - $d^i_k(t)$: expected data rate for UE^i using kth RB at time t
  - $R^i(t-1)$: data rate achieved by UE^i at t
- at t: select $\max_{i,k} \{d^i_k(t) / R^i(t-1)\}$: assign UE^i



- balances high data rate with a measure of fairness
- channel aware, QoS unaware, fairness aware

More slides …

Evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-advanced

Evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-advanced

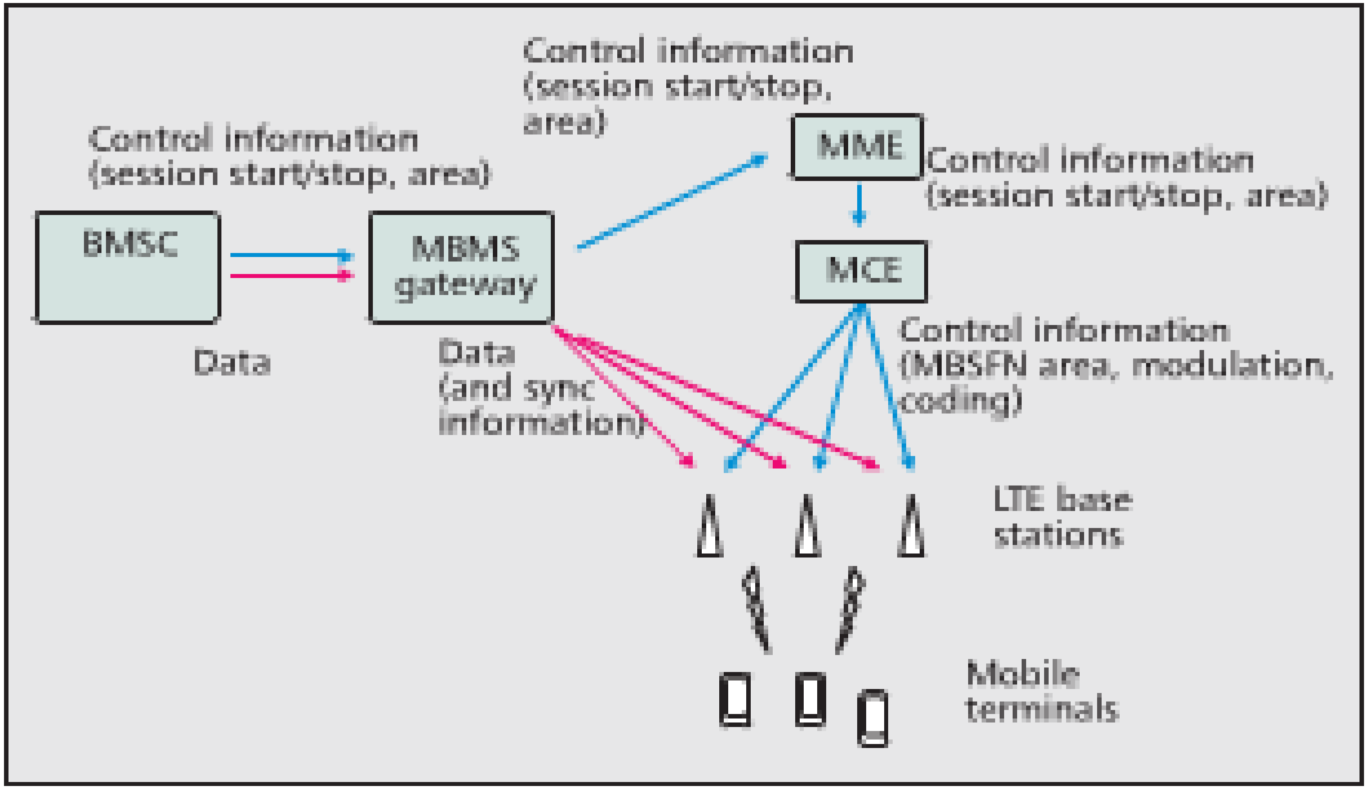


Figure 4. *RAN architecture for SFN across LTE base stations.*

- Separation of control plane and data plane

Image from: Lecompte and Gabin, Evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-Advanced: Overview and Rel-11 Enhancements, IEEE Communications Magazine, Nov. 2012.

Evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-advanced

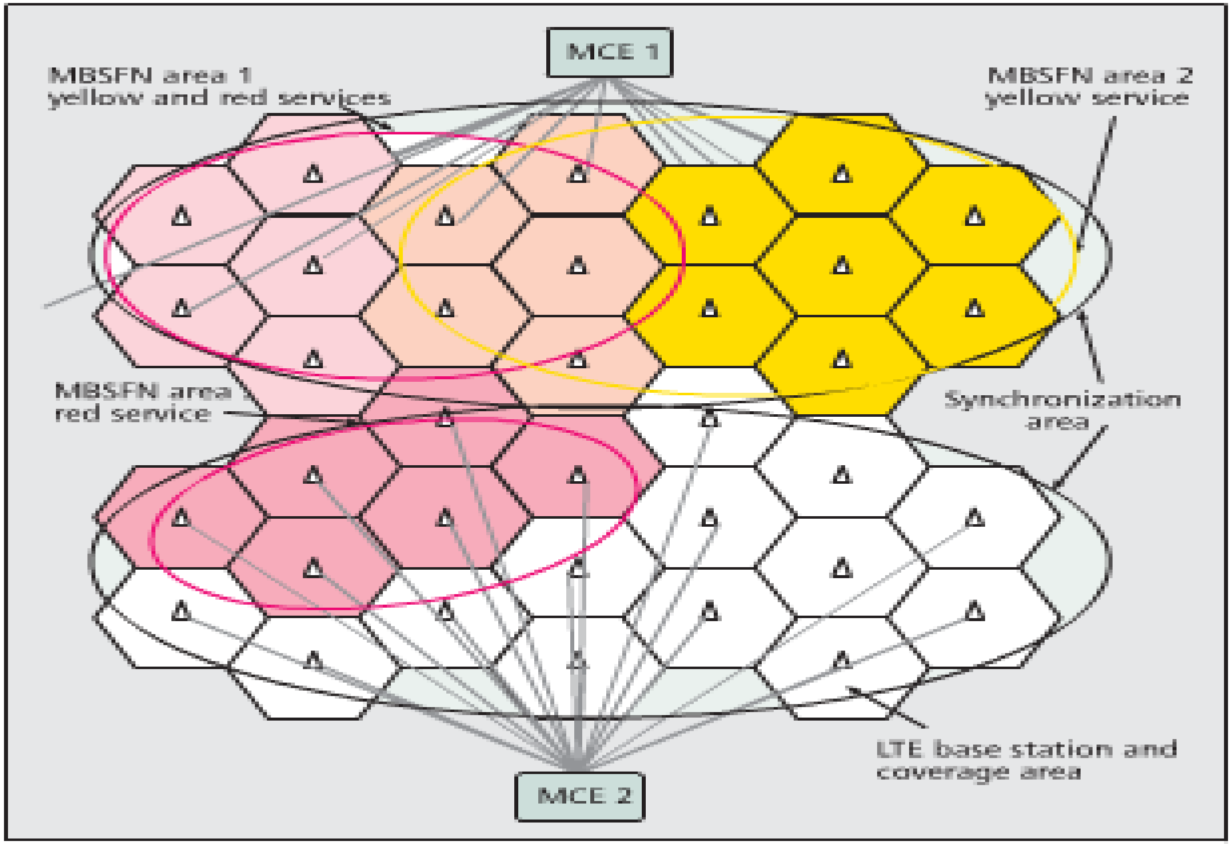
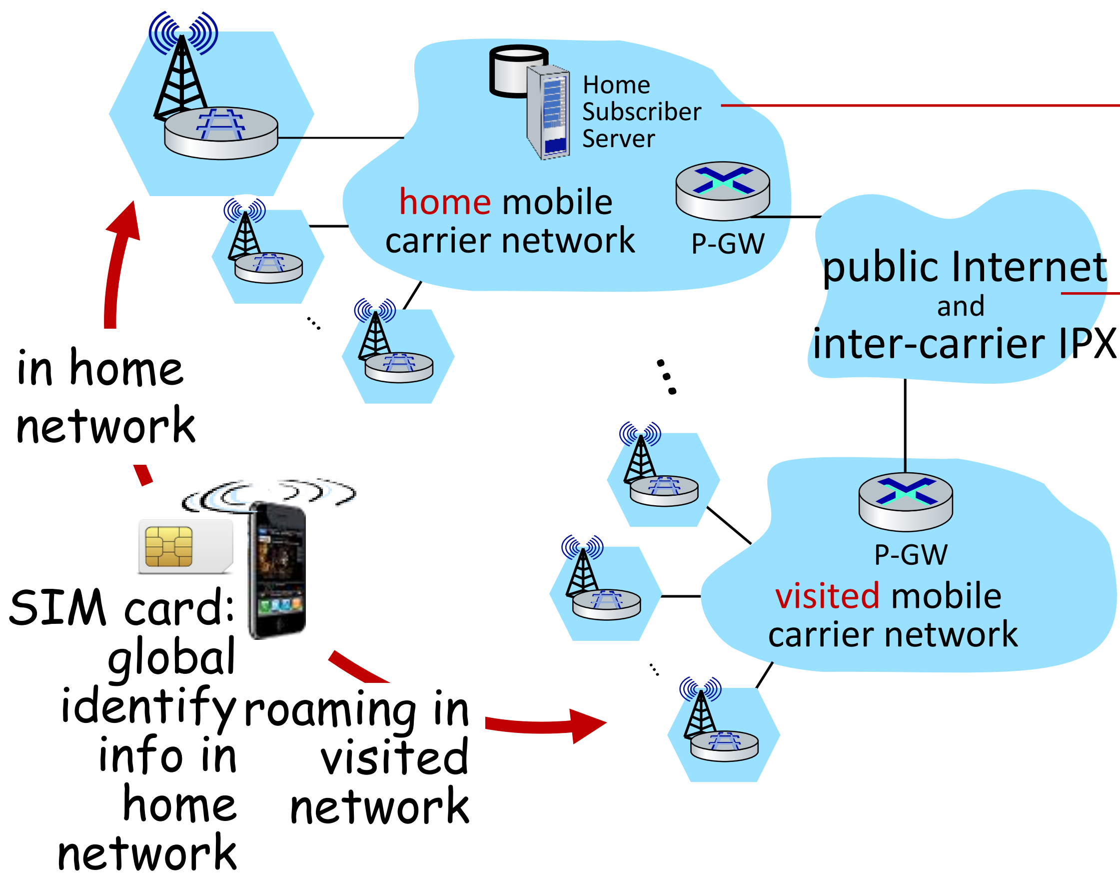


Figure 5. *Example with two MBMS services with different services areas.*

- MBMSFN and use of services areas

Image from: Lecompte and Gabin, Evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-Advanced: Overview and Rel-11 Enhancements, IEEE Communications Magazine, Nov. 2012.

Global cellular network: a network of IP networks



home network HSS:

- identify & services info, while in home network and roaming

all IP:

- carriers interconnect with each other, and public internet at exchange points
- legacy 2G, 3G: not all IP, handled otherwise

Some words about 5G

- goal: 10x increase in peak bitrate, 10x decrease in latency, 100x increase in traffic capacity over 4G

  Capacity = cell density x available spectrum x spectral efficiency

- How to achieve (radio part) ...
  - Shorter range: denser deployment
  - Open up new high-frequency spectrum (e.g., 52-24 GHz > 2 GHz)
  - MIMO for spectral efficiency

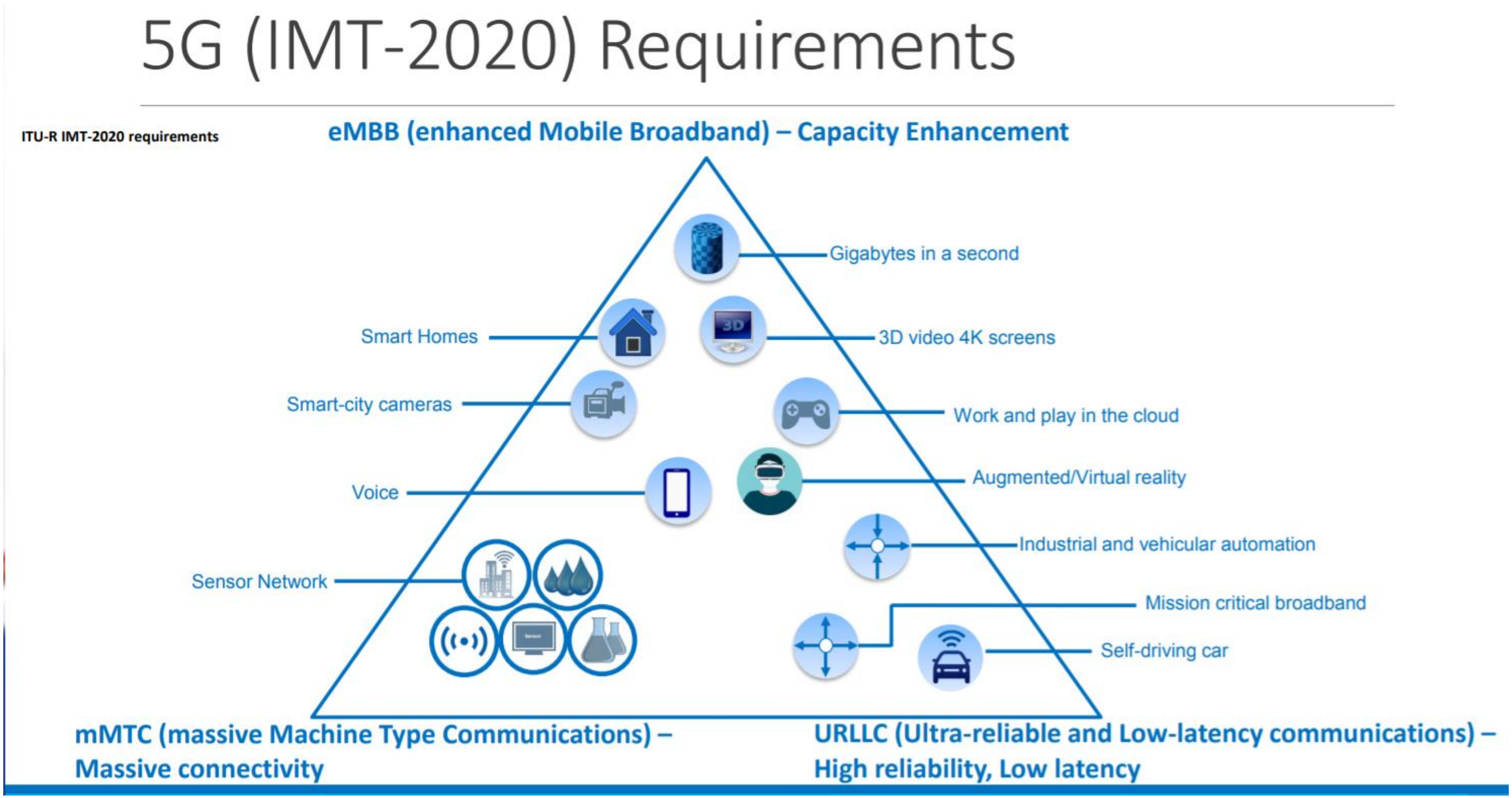
Also, and increasingly important ...

- Advanced network (e.g., SDN, NVF, context-aware, content-aware)
- Multi-RAT (Radio Access Technology)
- Advanced D2D
- Edge computing, etc. ...

5G NR (New radio) aspects

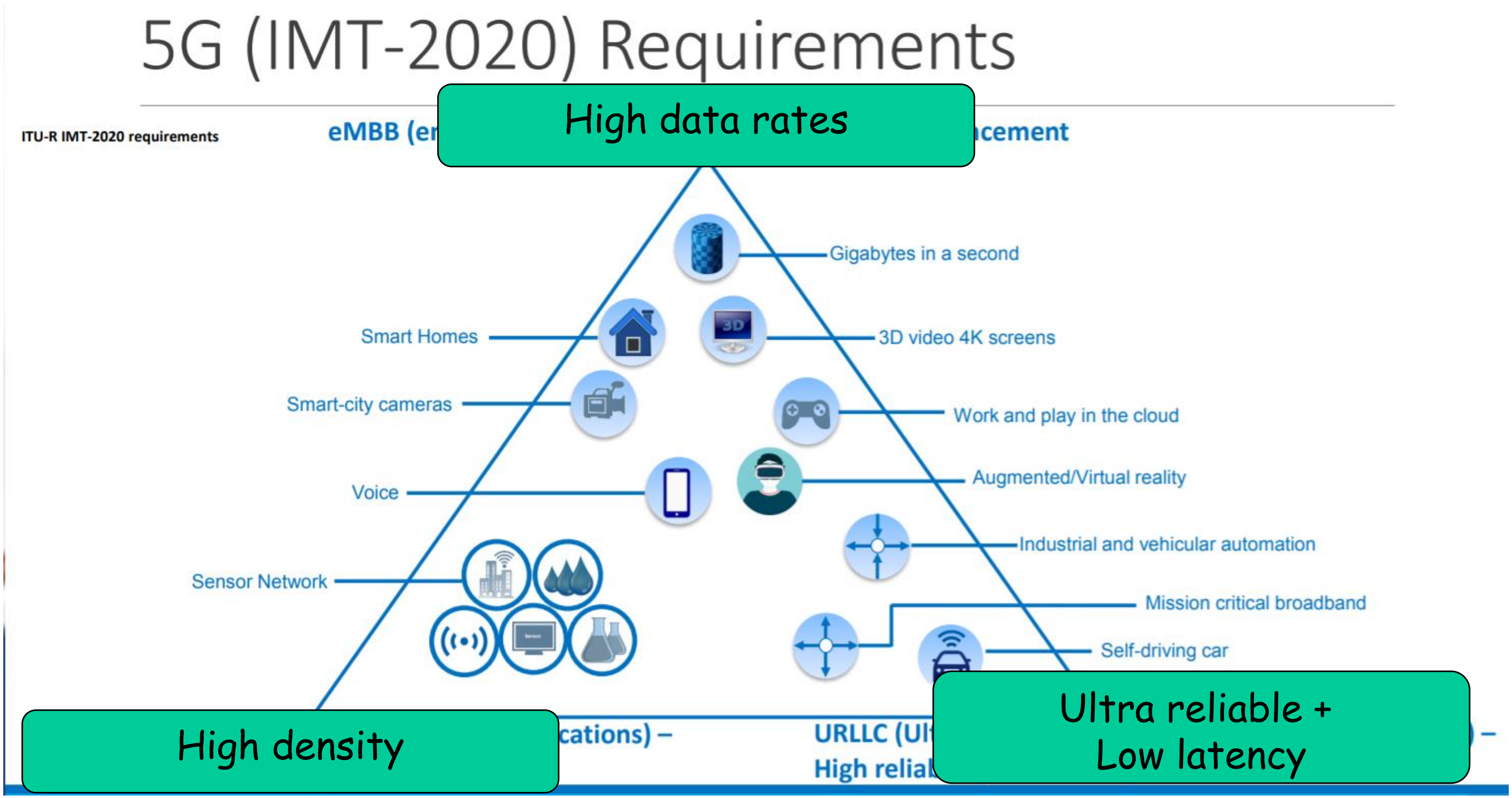
- Two frequency bands : FR1 (450 MHz–6 GHz) and FR2 (24 GHz–52 GHz): millimeter wave frequencies
  - much higher data rates, but over shorter distances
  - pico-cells: cells diameters: 10-100 m
  - massive, dense deployment of new base stations required
- not backwards-compatible with 4G
- MIMO: multiple directional antennae
  - Massive MIMO (100s of ports)
  - Beamforming (efficient per-device delivery routes)

Use-case-driven requirements …



Source: Zahid Ghadialy, "5G: An Advanced Introduction" (slides)

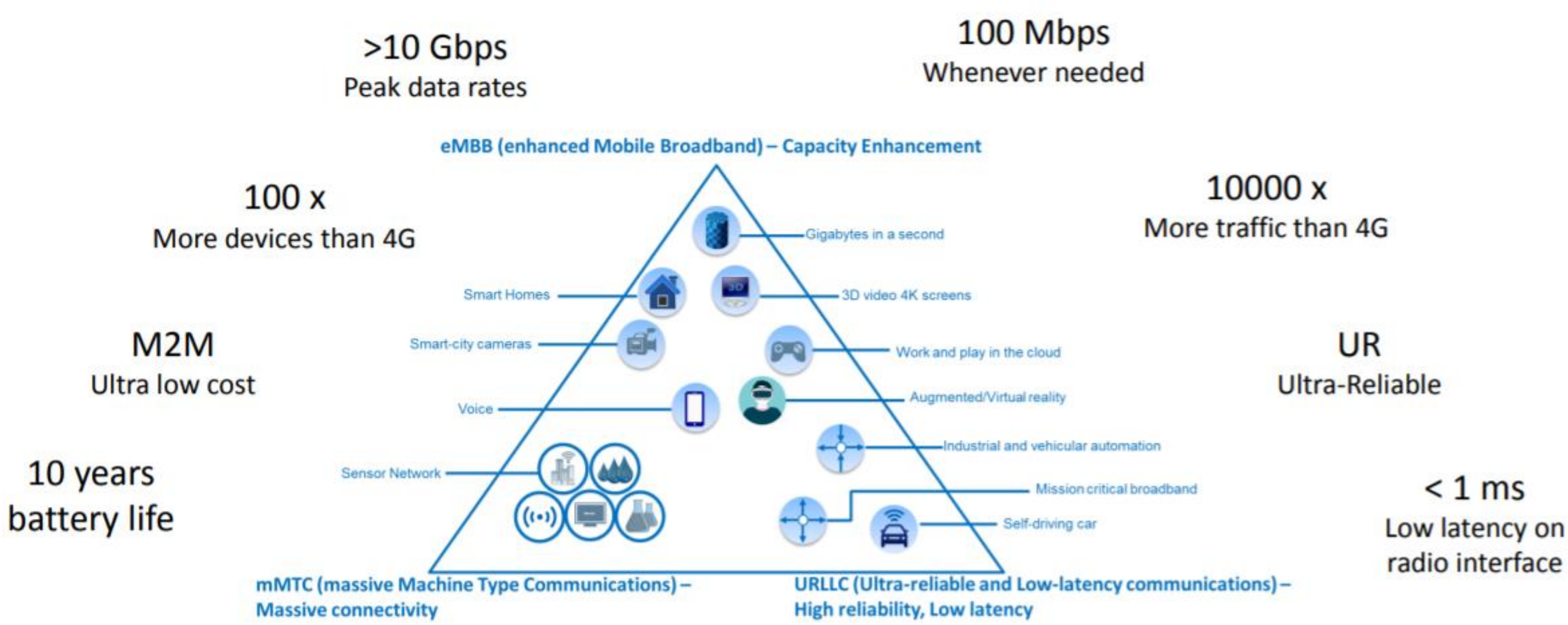
Use-case-driven requirements …



Source: Zahid Ghadialy, "5G: An Advanced Introduction" (slides)

… wish list …

5G High Level Requirements and Wish List



Source: Zahid Ghadialy, "5G: An Advanced Introduction" (slides)

5G goals/targets/requirements ...

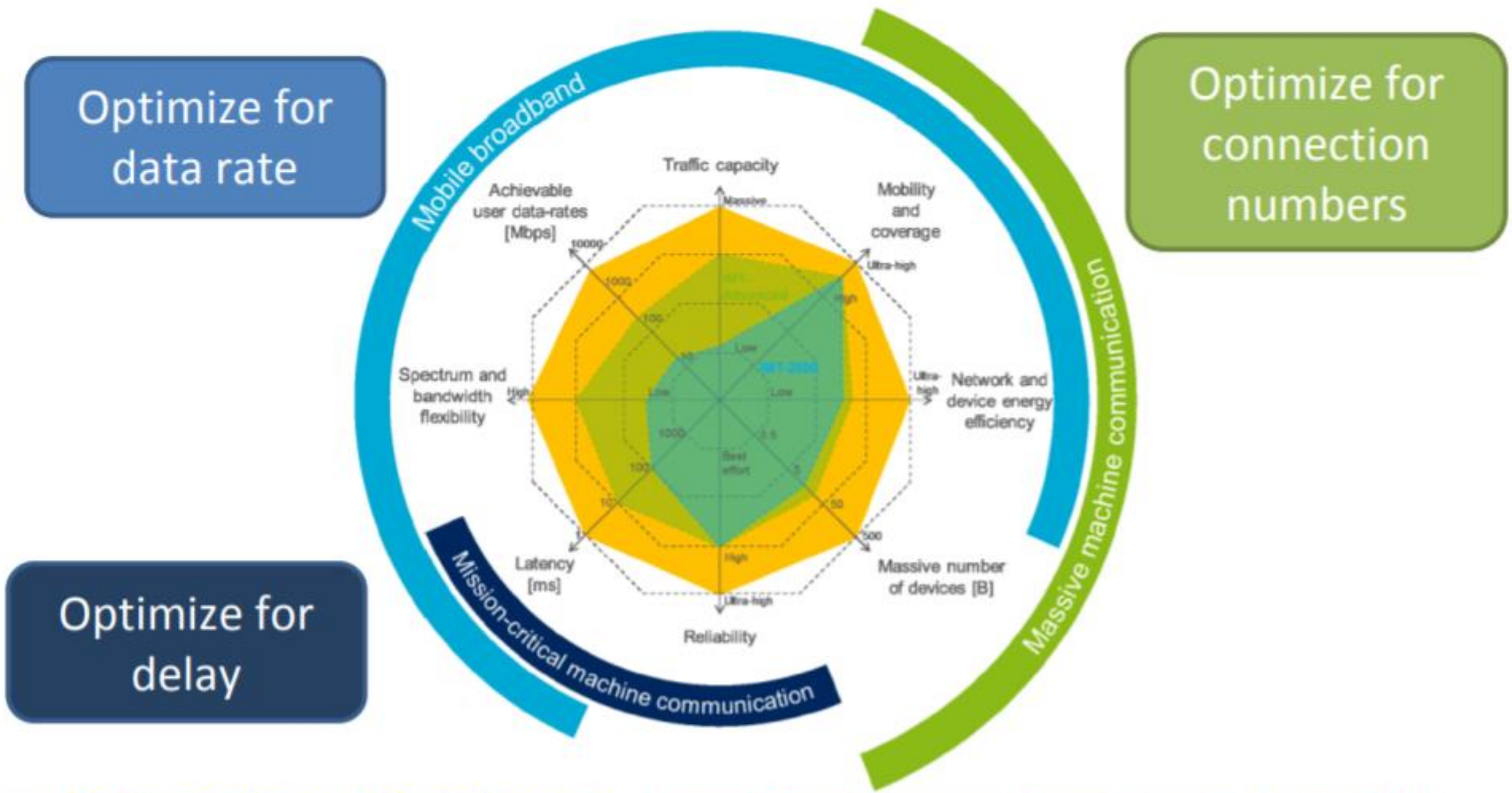


Image Source: 5G-From Research to Standardisation - Bernard Barani European Commission, Globecom2014

Source: Zahid Ghadialy, "5G: An Advanced Introduction" (slides)

More slides …

Functional split of major LTE components