Cellular …

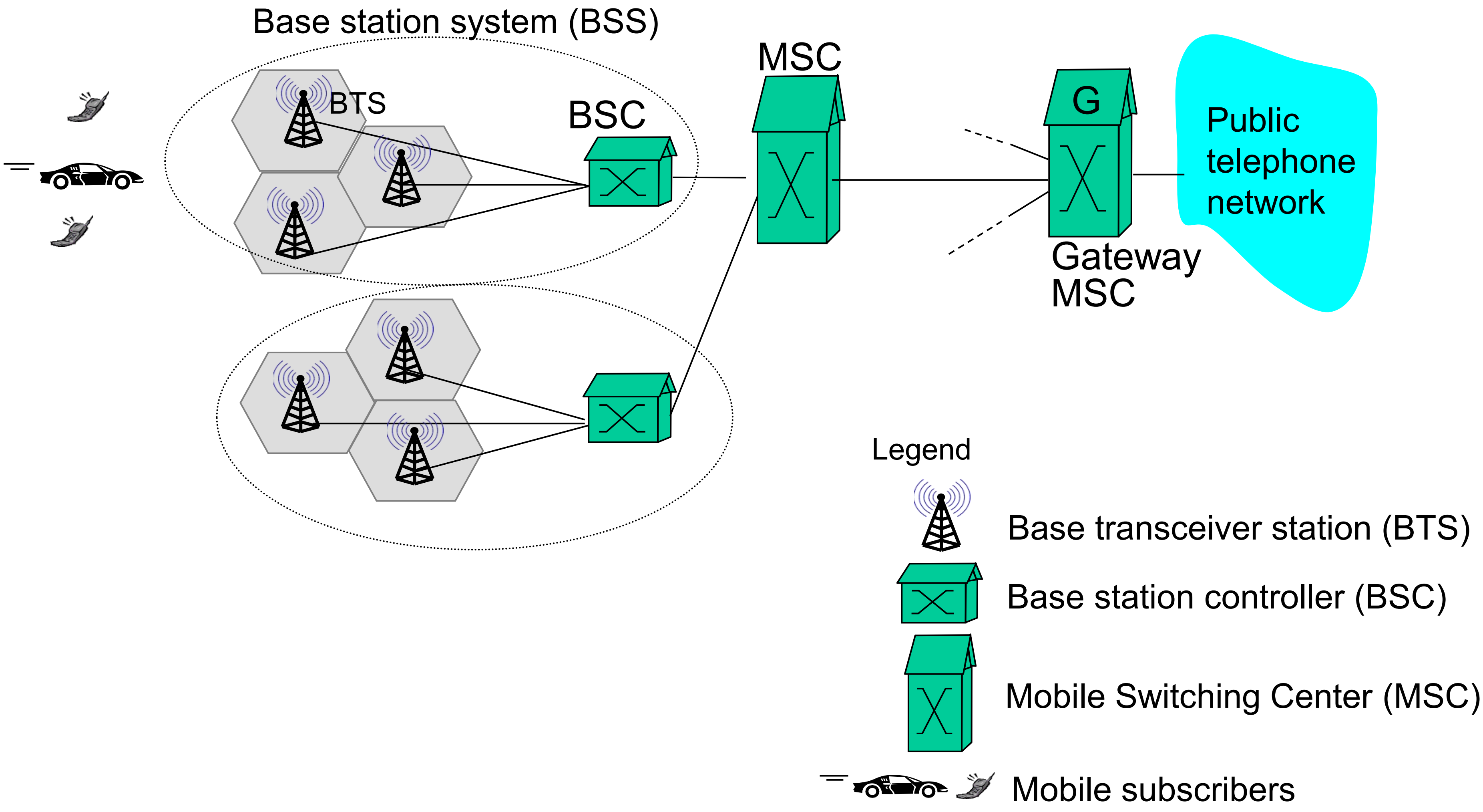
Slides used in TDDE48 (Mobile Networks) @ LiU, Sweden, Fall 2023
Niklas Carlsson (https://www.ida.liu.se/~nikca89/)

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")

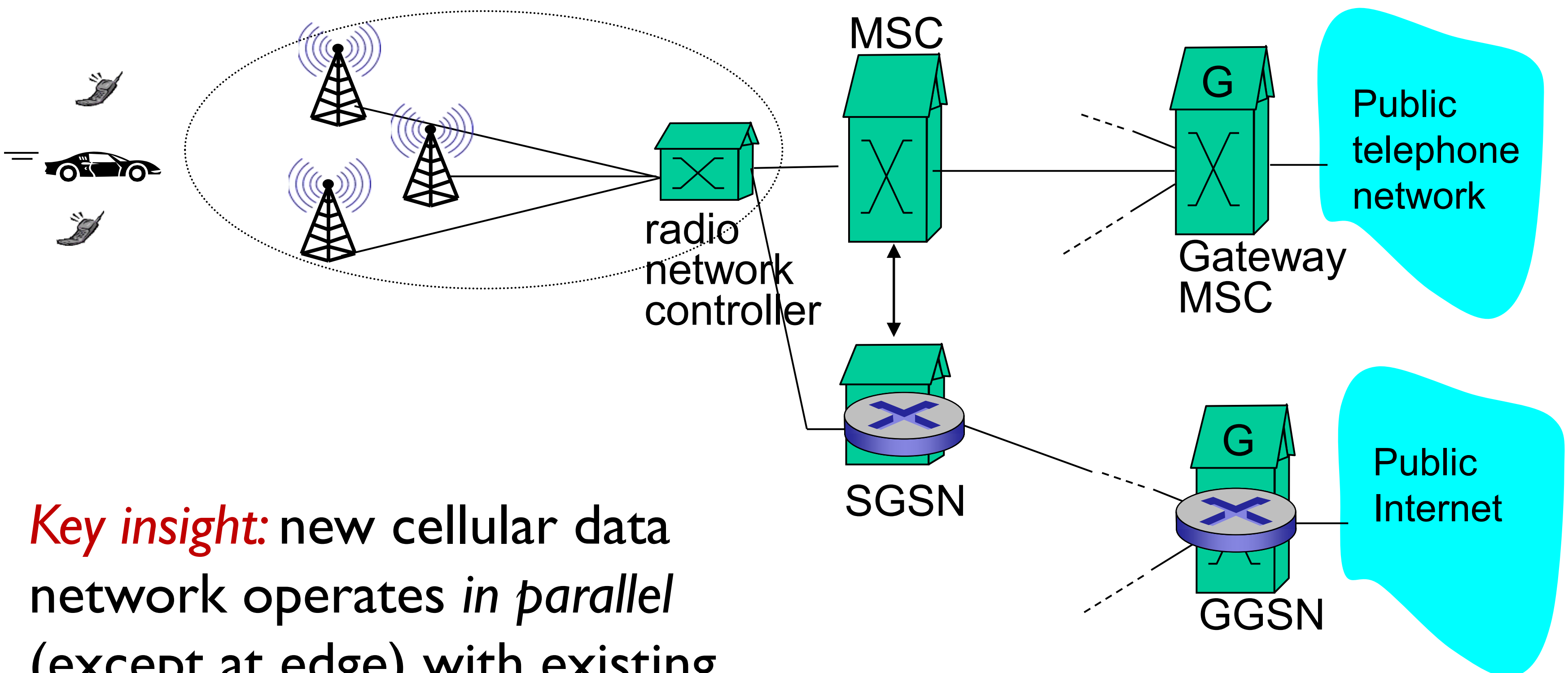
Background: Cellular network technology

- 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)
- 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

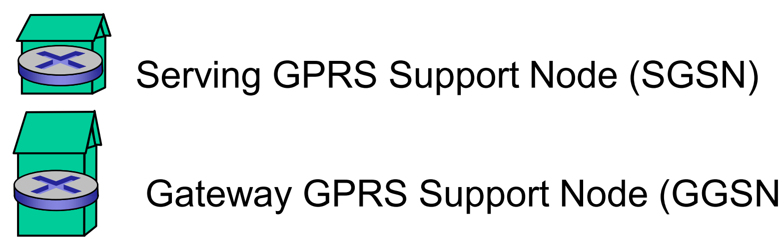


3G (voice+data) network architecture

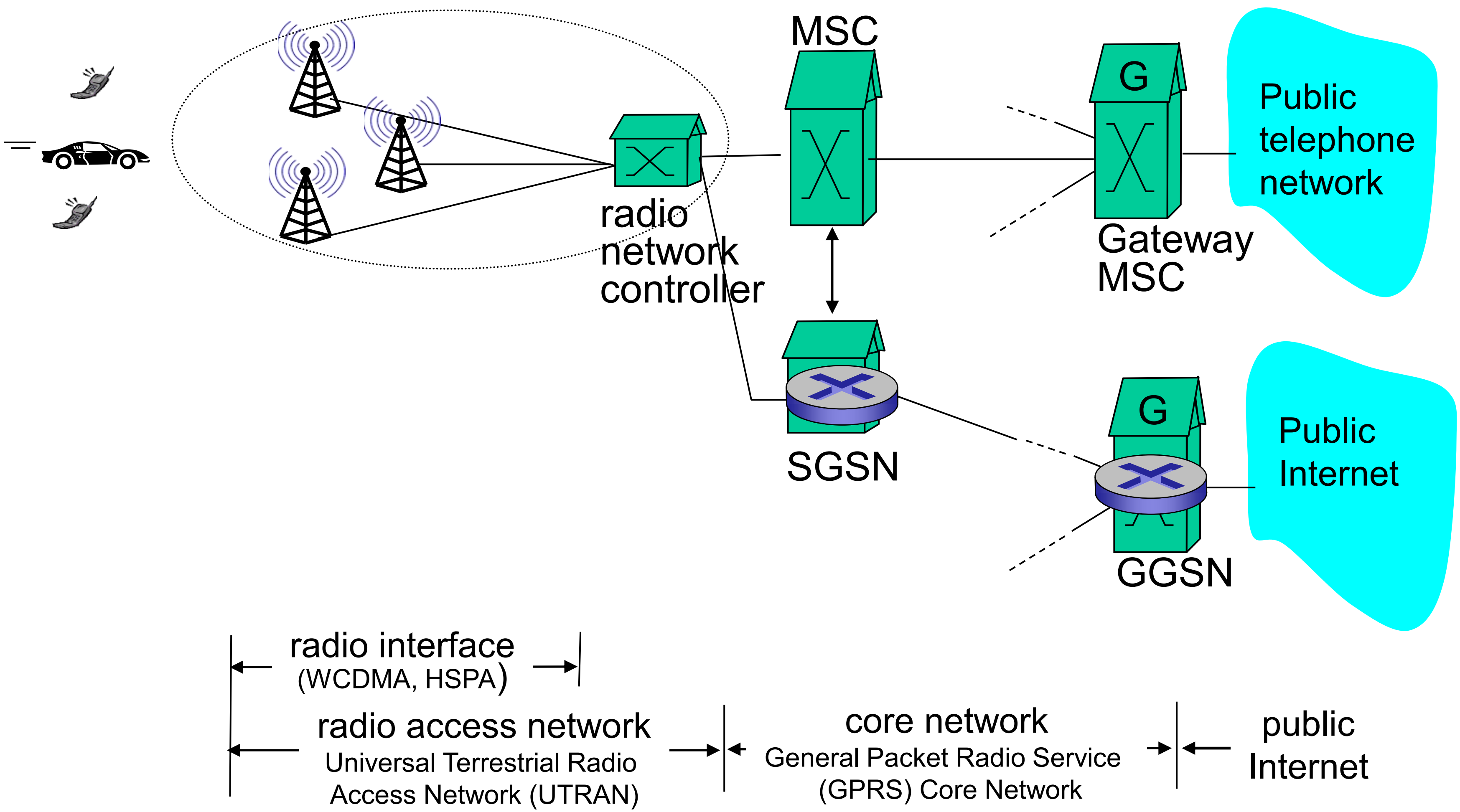


Key insight: new cellular data network operates *in parallel* (except at edge) with existing cellular voice network

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



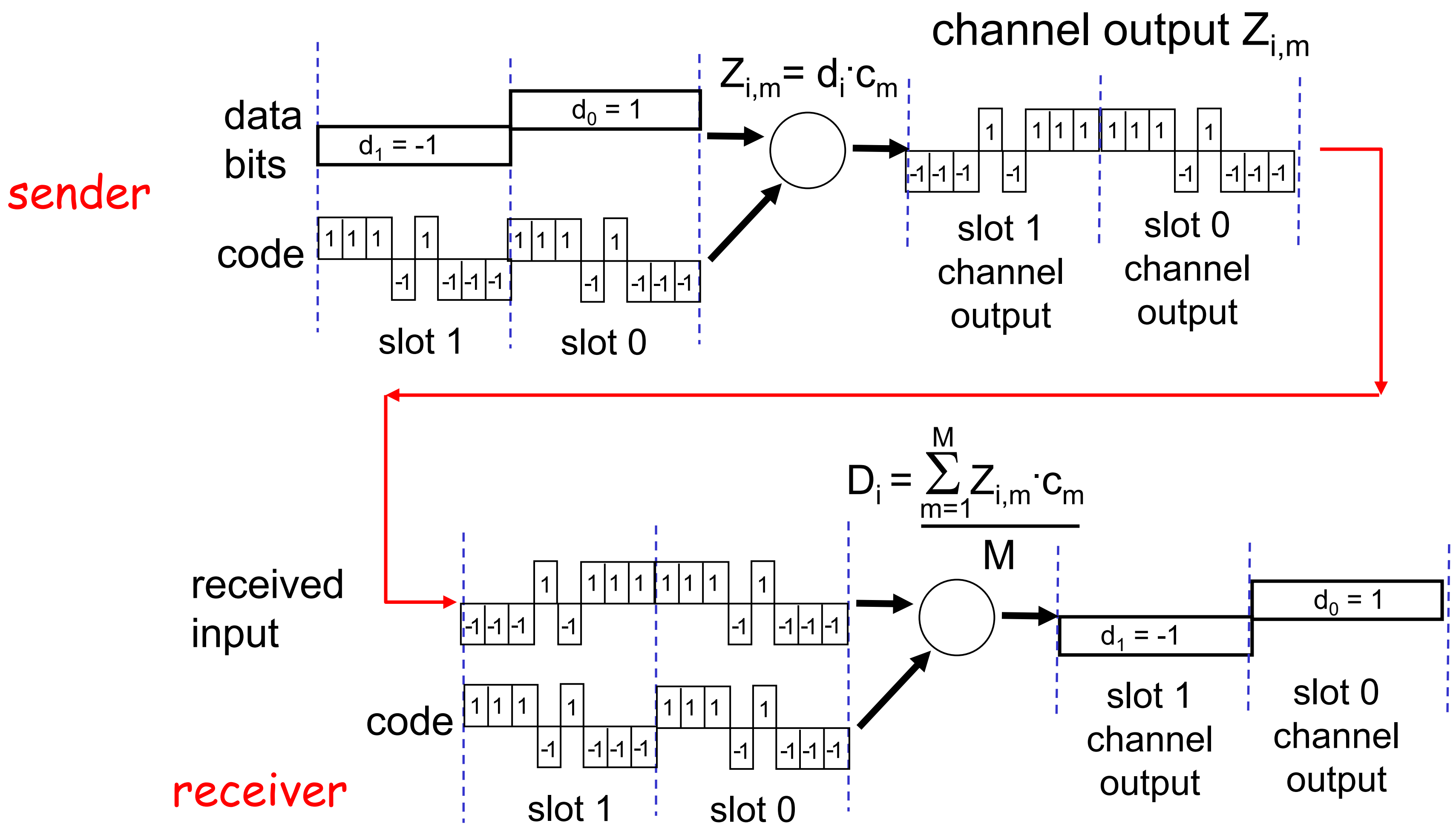
3G (voice+data) network architecture



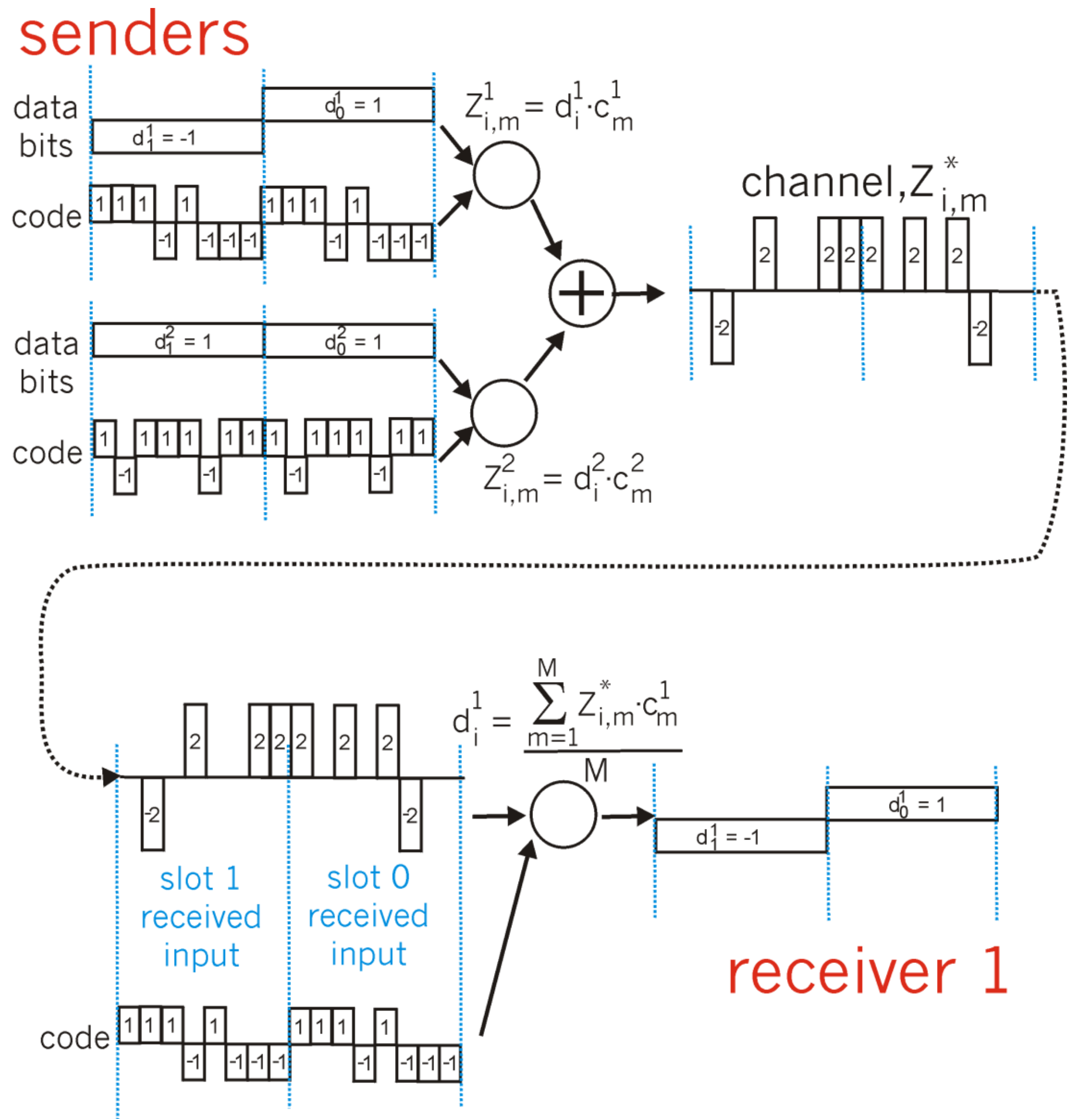
Code Division Multiple Access (CDMA)

- 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



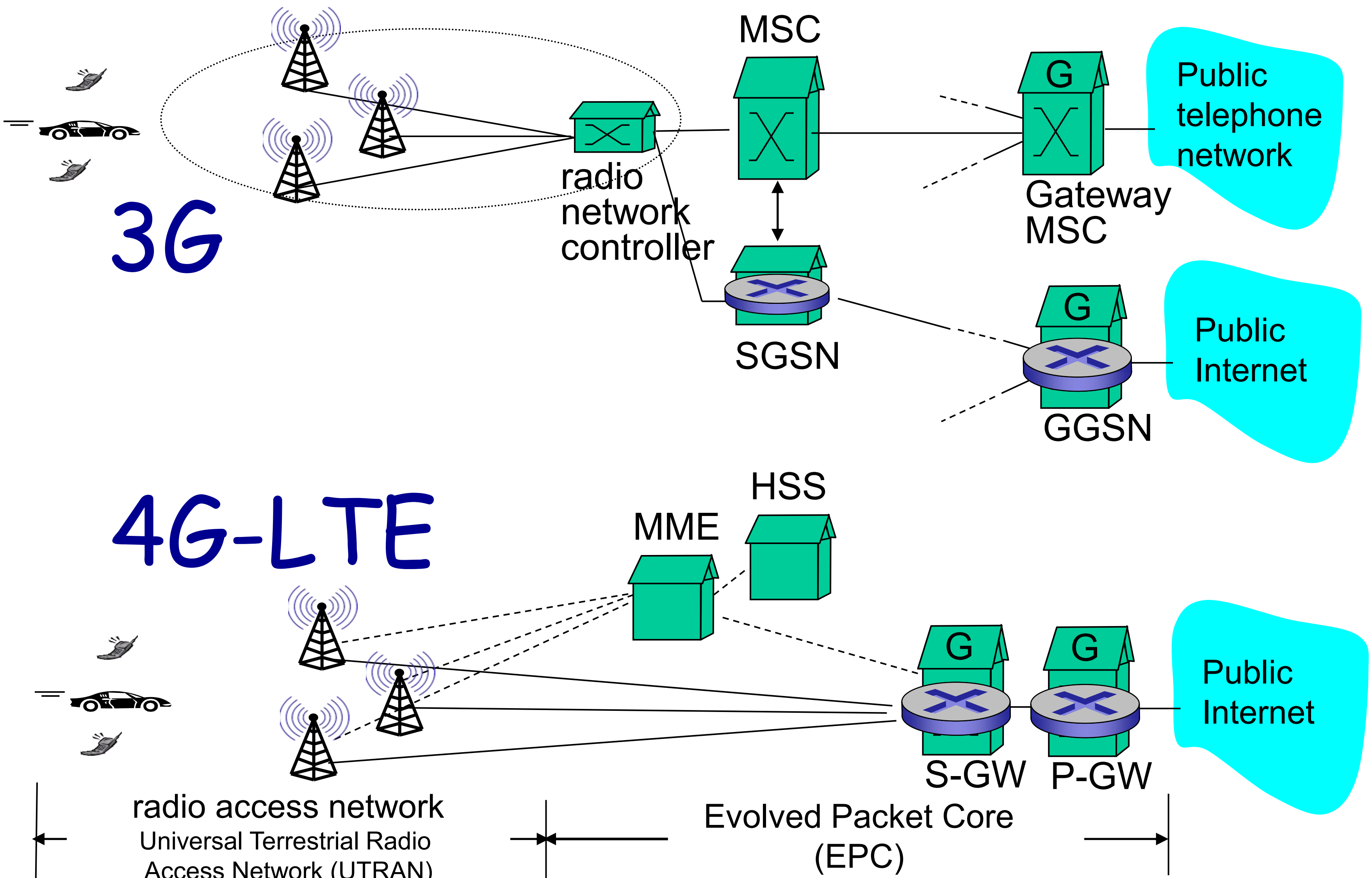
CDMA: two-sender interference



Practical chipping codes …

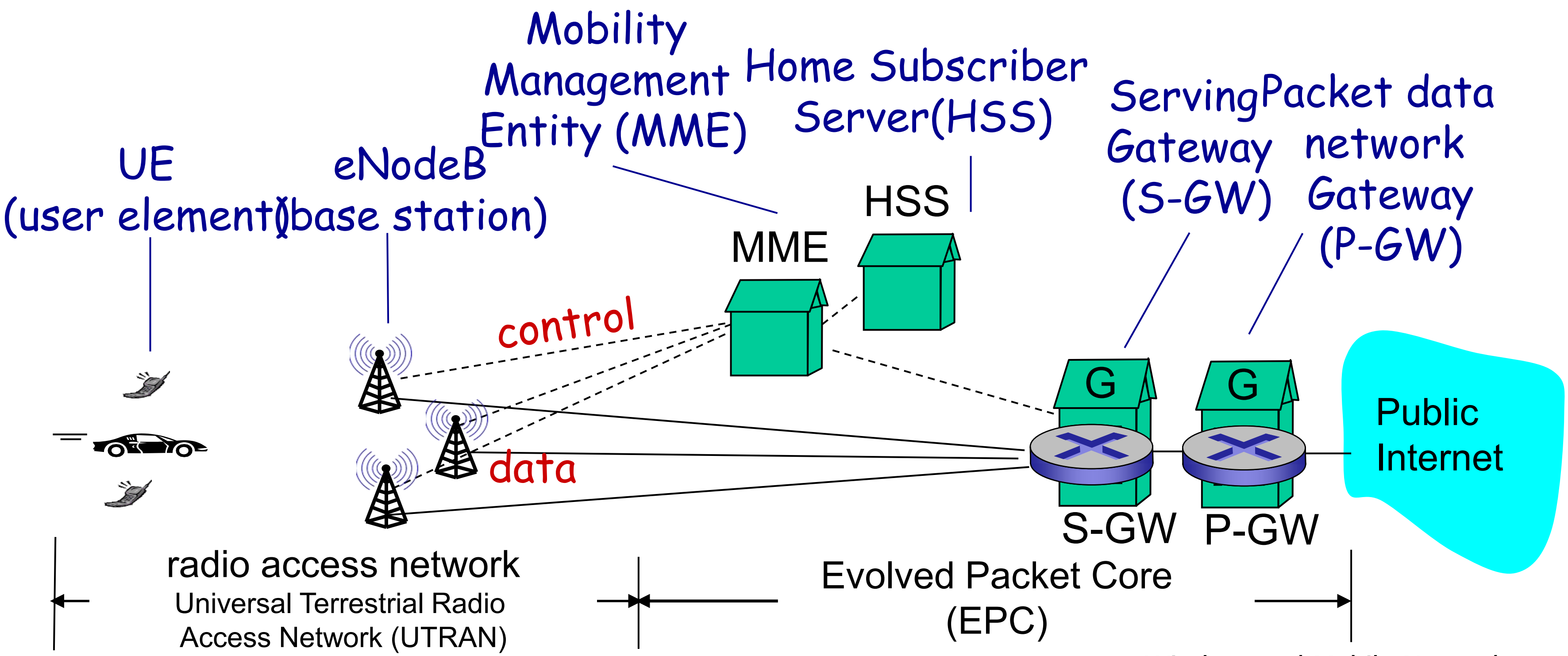
- Orthogonal even under offset?
  - No synchronization …
  - Random sequence; high probability low cross-correlation
- Different chip lengths?
  - different rates, take advantage of silence, more calls

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



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

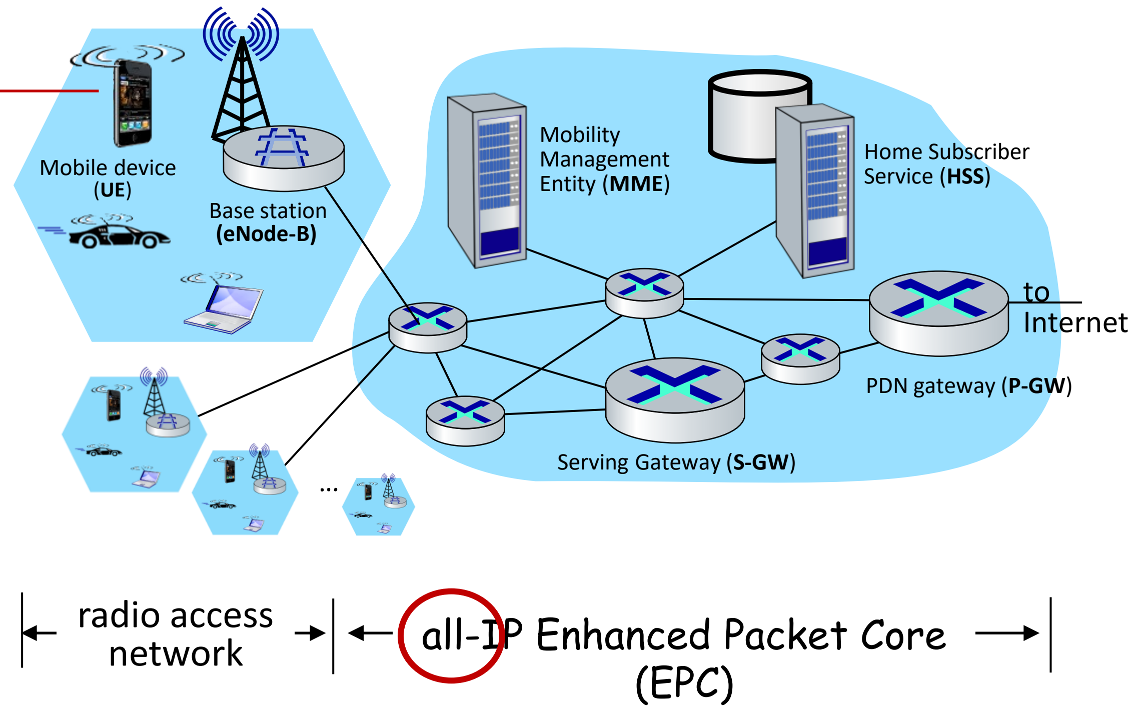
differences from wired Internet

- different wireless link layer
- mobility as a 1st 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

Elements of 4G LTE architecture

Mobile device:

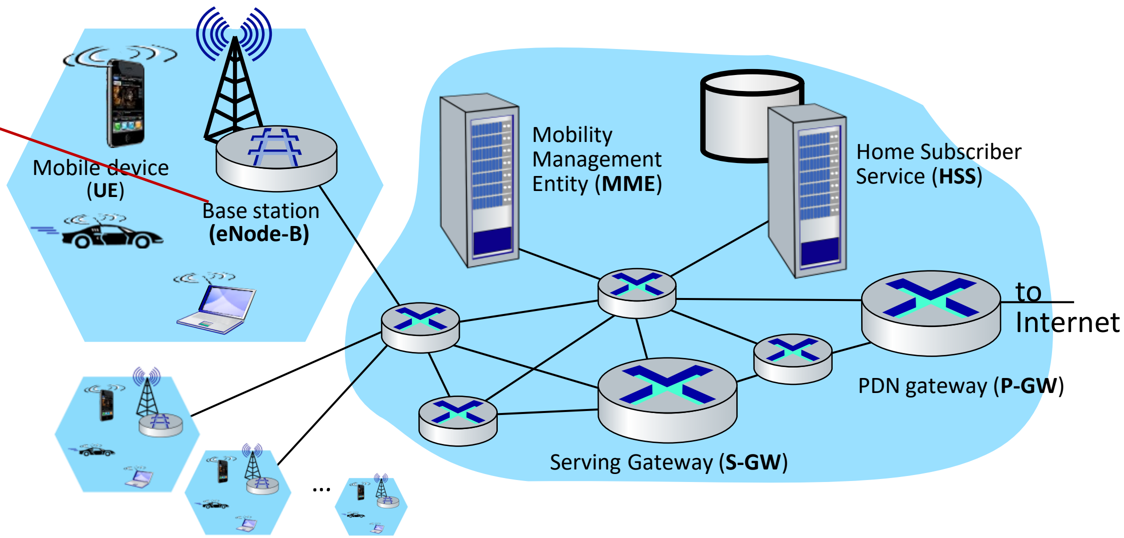
- smartphone, tablet, laptop, IoT, ... with 4G LTE radio
- 64-bit International Mobile Subscriber Identity (IMSI), stored on SIM (Subscriber Identity Module) card
- LTE jargon: User Equipment (UE)



Elements of 4G LTE architecture

Base station:

- at "edge" of carrier's network
- manages wireless radio resources, mobile devices in its coverage area ("cell")
- coordinates device authentication with other elements
- similar to WiFi AP but:
  - active role in user mobility
  - coordinates with nearly base stations to optimize radio use
- LTE jargon: eNode-B

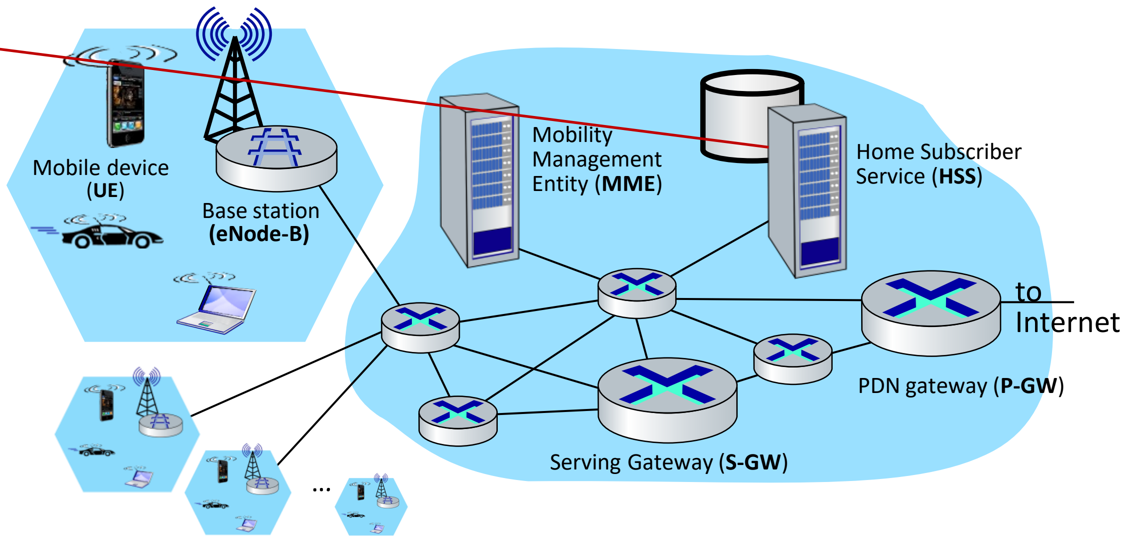


- Admission control and congestion control
- Scheduling and allocation of resources to UEs
- State transition: IDLE to CONNECTED
- Control mobility in connected mode
- Buffering of data during handover

Elements of 4G LTE architecture

Home Subscriber Service (HSS)

- stores info about mobile devices for which the HSS's network is their "home network"
- works with MME in device authentication

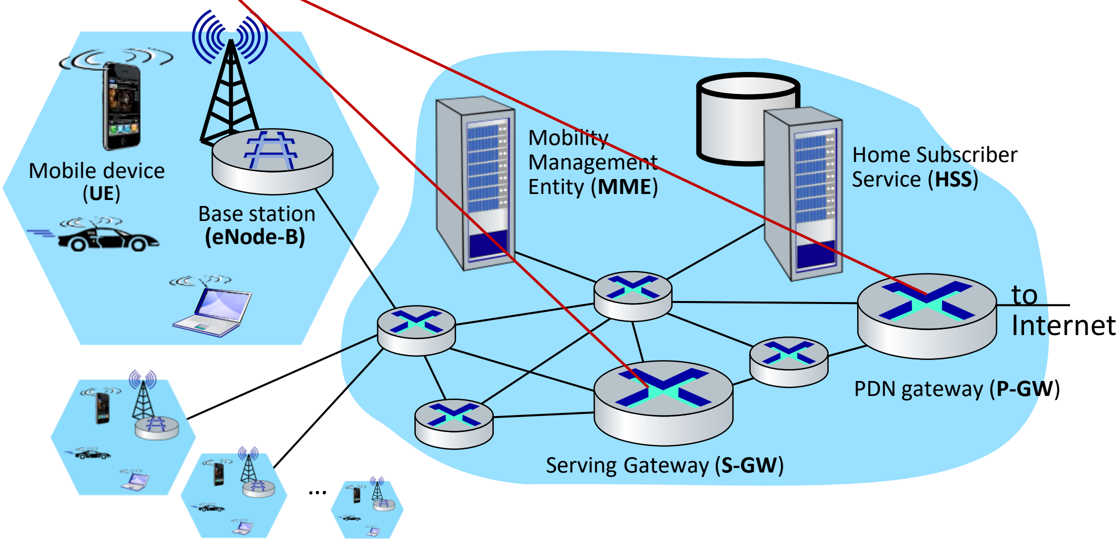


Elements of 4G LTE architecture

Serving Gateway (S-GW), PDN Gateway (P-GW)

- lie on data path from mobile to/from Internet
- P-GW
  - gateway to mobile cellular network
  - Looks like any other internet gateway router
  - Allocate IP for UE
  - Maps packets into different QoS-based bearers

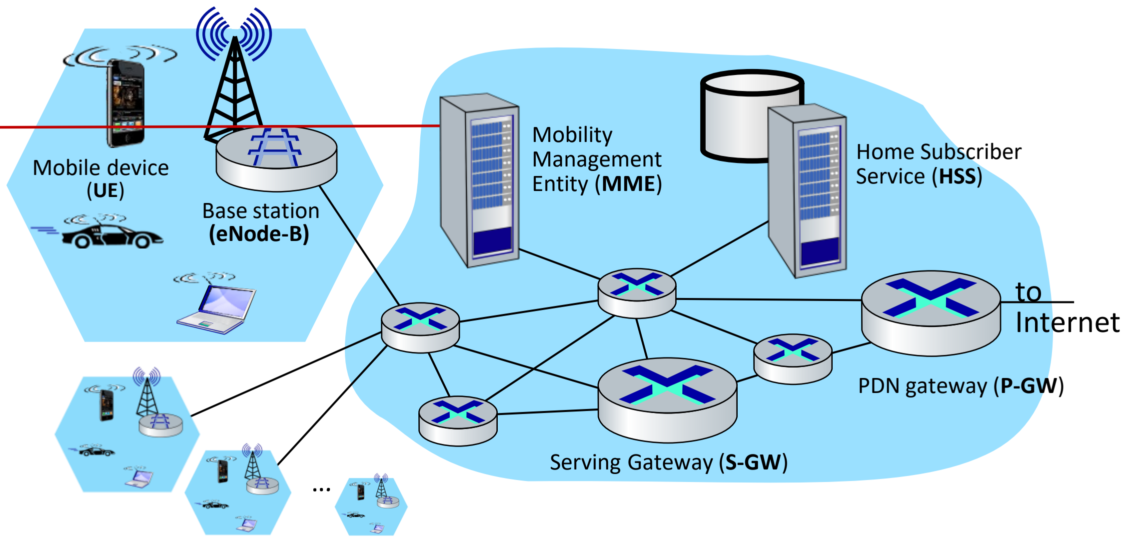
  Provides NAT services
- S-GW
  - Mobility anchor for data bearers
  - Buffer downlink data when UE in IDLE mode
- other routers:
  - extensive use of tunneling



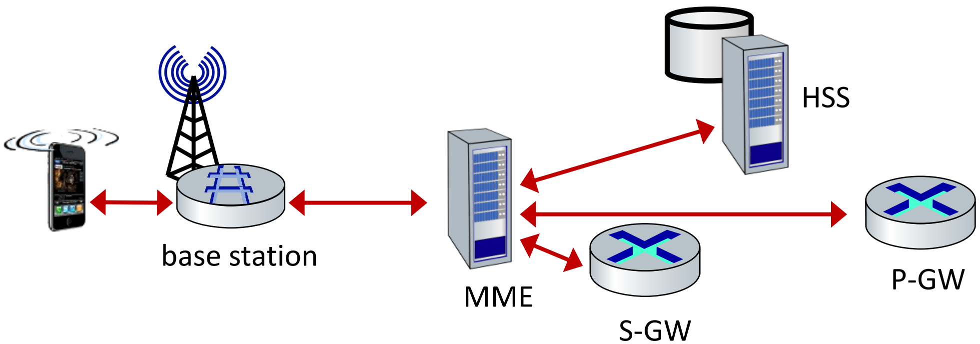
Elements of 4G LTE architecture

Mobility Management Entity (MME)

- device authentication (device-to-network, network-to-device) coordinated with mobile home network HSS
- mobile device management:
  - device handover between cells
  - tracking/paging device location
- path (tunneling) setup from mobile device to P-GW

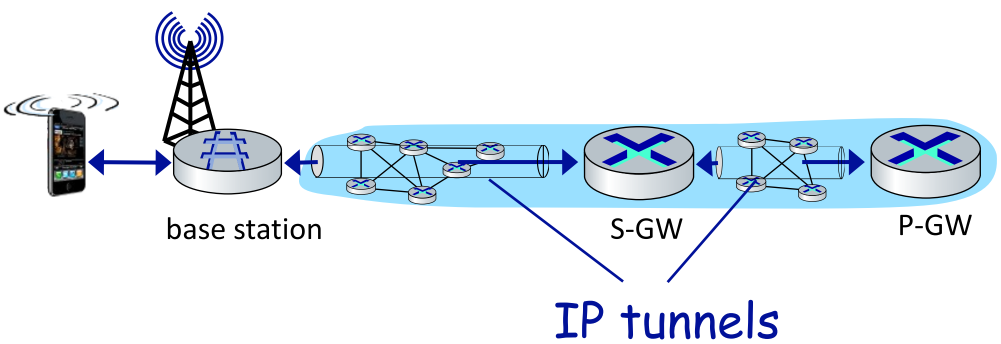


LTE: data plane control plane separation



control plane

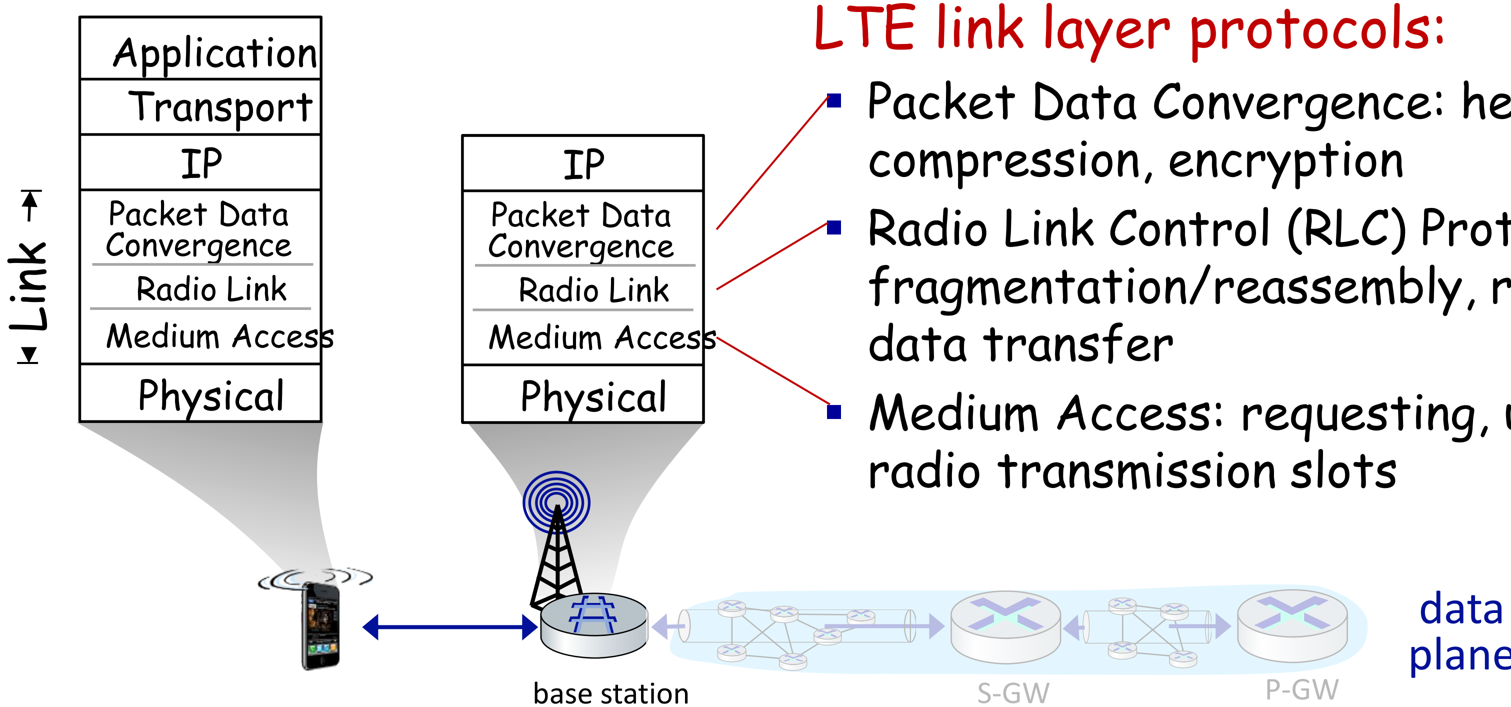
- new protocols for mobility management , security, authentication (later)



data plane

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

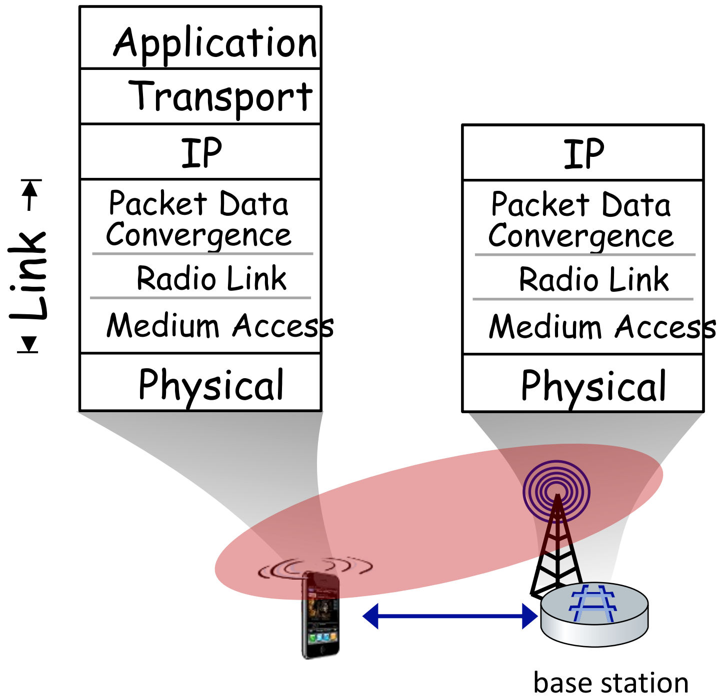
LTE data plane protocol stack: first hop



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

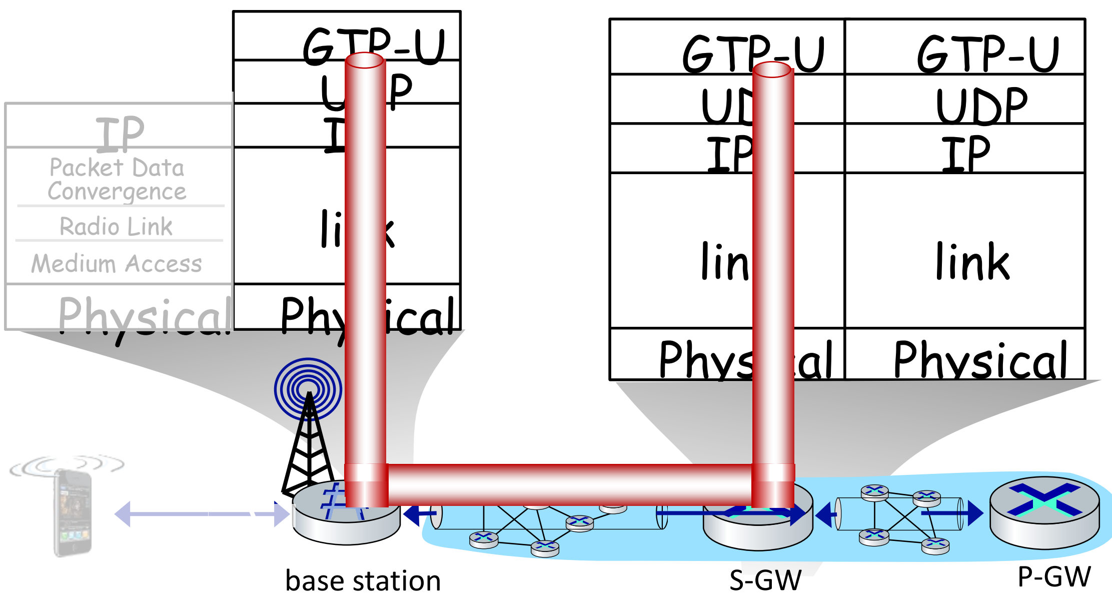
LTE data plane protocol stack: first hop



LTE radio access network:

- downstream channel: OFDMA (orthogonal frequency division multiplexing)
  - "orthogonal": minimal interference between channels
  - upstream: SC-OFDM (Single carrier OFDM)
- each active mobile device allocated two or more 0.5 ms time slots over 12 frequencies
  - Split into RB (resource blocks): Sort of like "time x frequency" chunk
  - scheduling algorithm not standardized – up to operator
  - 100's Mbps per device possible

LTE data plane protocol stack: packet core



tunneling:

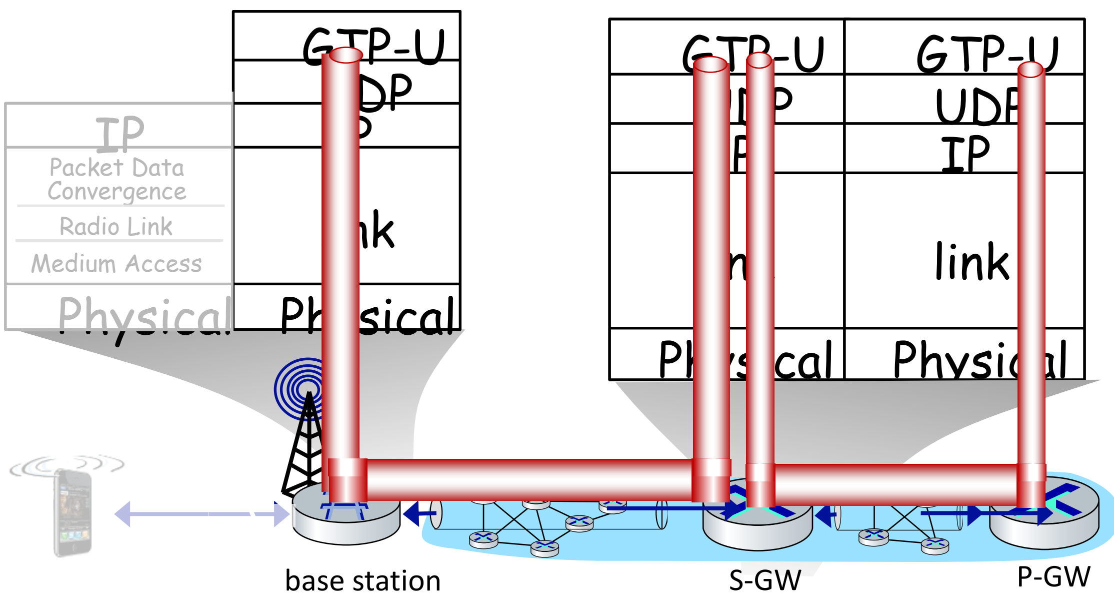
- mobile datagram encapsulated using GPRS Tunneling Protocol (GTP), sent inside UDP datagram to S-GW

Quality of Service in LTE

- QoS from eNodeB to SGW: min and max guaranteed bit rate
- QoS in radio access network: one of 12 QCI values

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}	

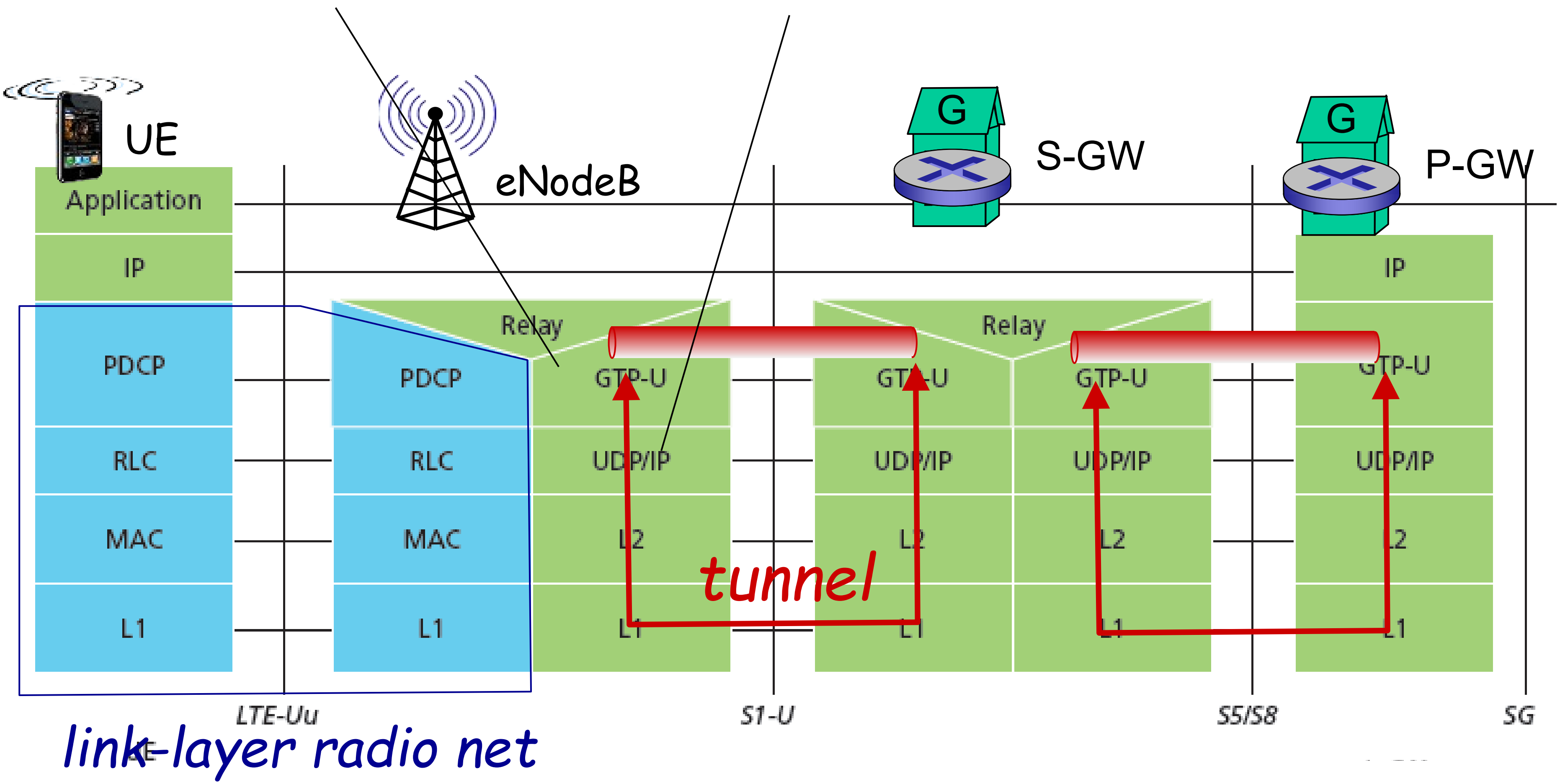
LTE data plane protocol stack: packet core



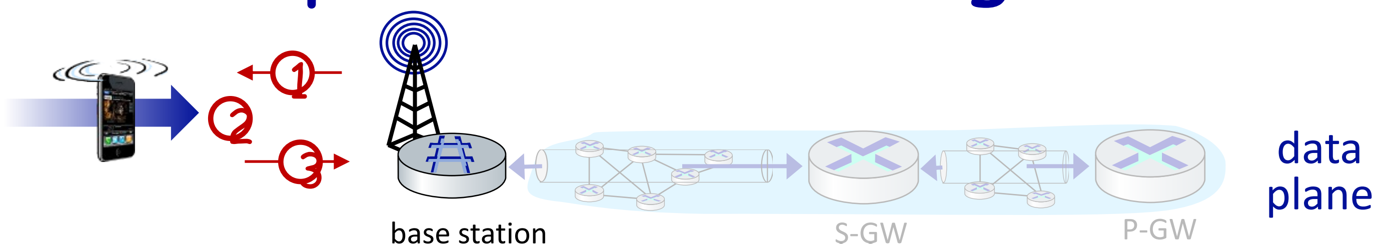
tunneling:

- 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



LTE data plane: associating with a BS



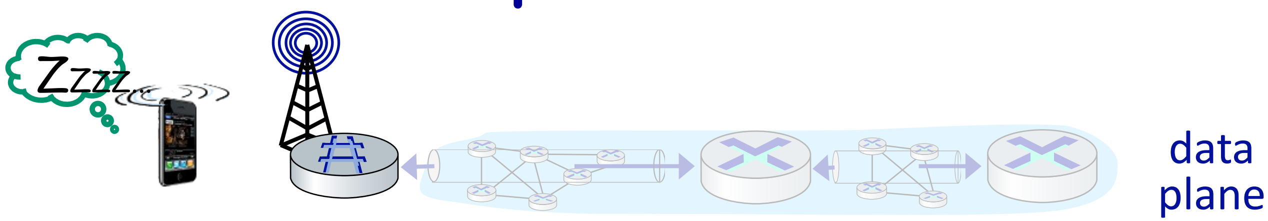
① BS broadcasts primary synch signal every 5 ms on all frequencies
- BSs from multiple carriers may be broadcasting synch signals

② mobile finds a primary synch signal, then locates 2nd synch signal on this freq.
- mobile then finds info broadcast by BS: channel bandwidth, configurations; BS's cellular carrier info
- mobile may get info from multiple base stations, multiple cellular networks

③ mobile selects which BS to associate with (*e.g.*, preference for home carrier)

④ more steps still needed to authenticate, establish state, set up data plane

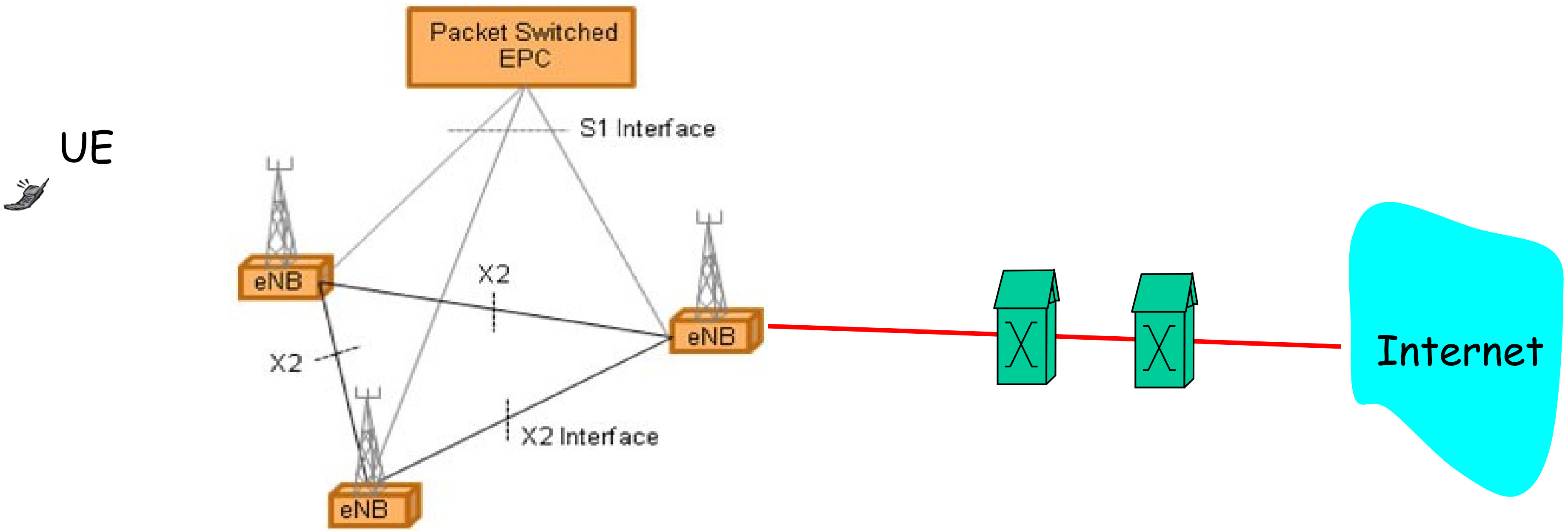
LTE mobiles: sleep modes



as in WiFi, Bluetooth: LTE mobile may put radio to "sleep" to conserve battery:

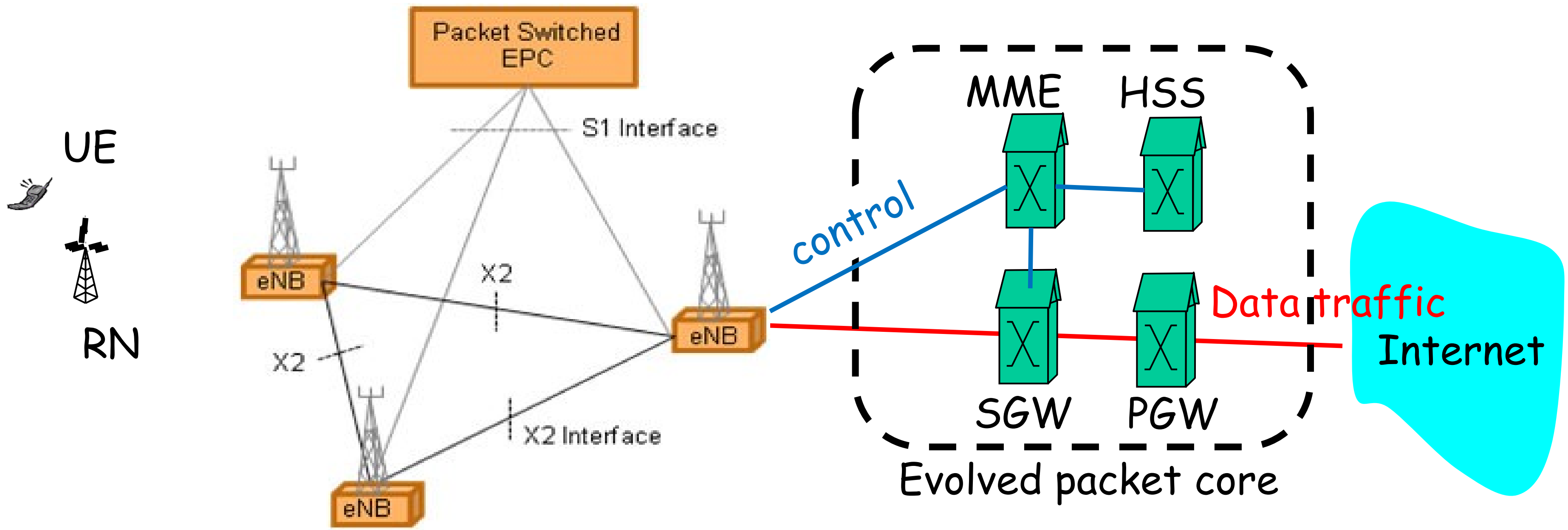
- light sleep: after 100's msec of inactivity
  - wake up periodically (100's msec) to check for downstream transmissions
- deep sleep: after 5-10 secs of inactivity
  - mobile may change cells while deep sleeping – need to re-establish association

LTE and LTE-Advanced



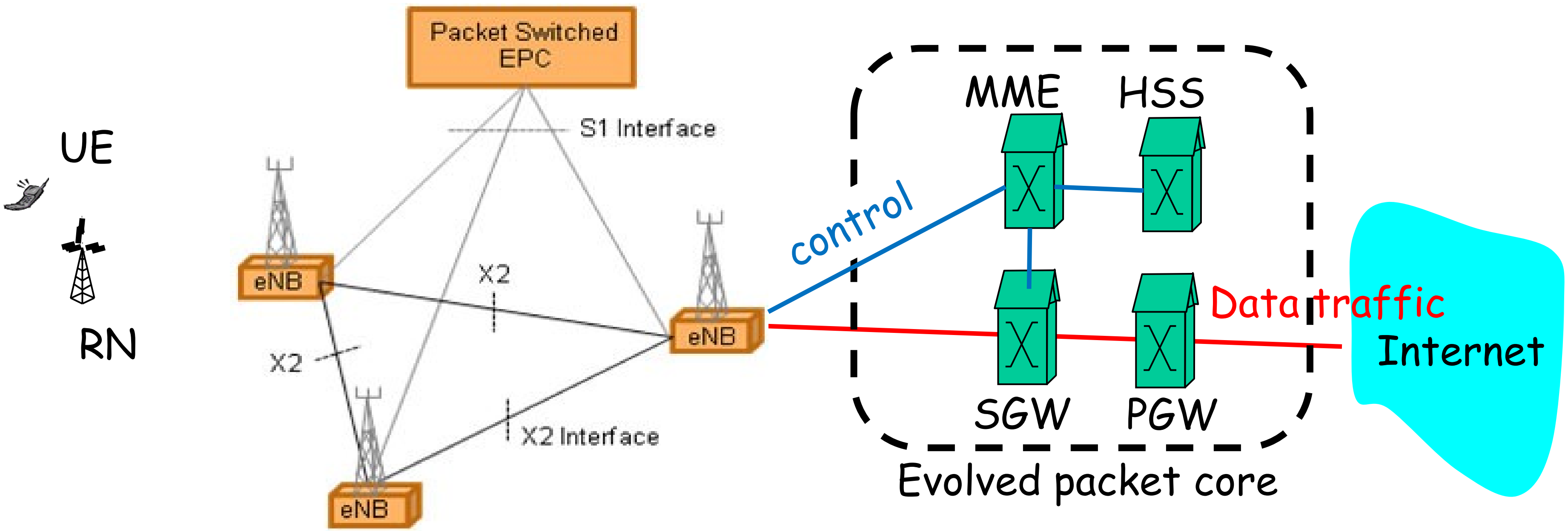
- ITU, IMT-advanced, 3GPP, and LTE-Advanced ...

LTE and LTE-Advanced



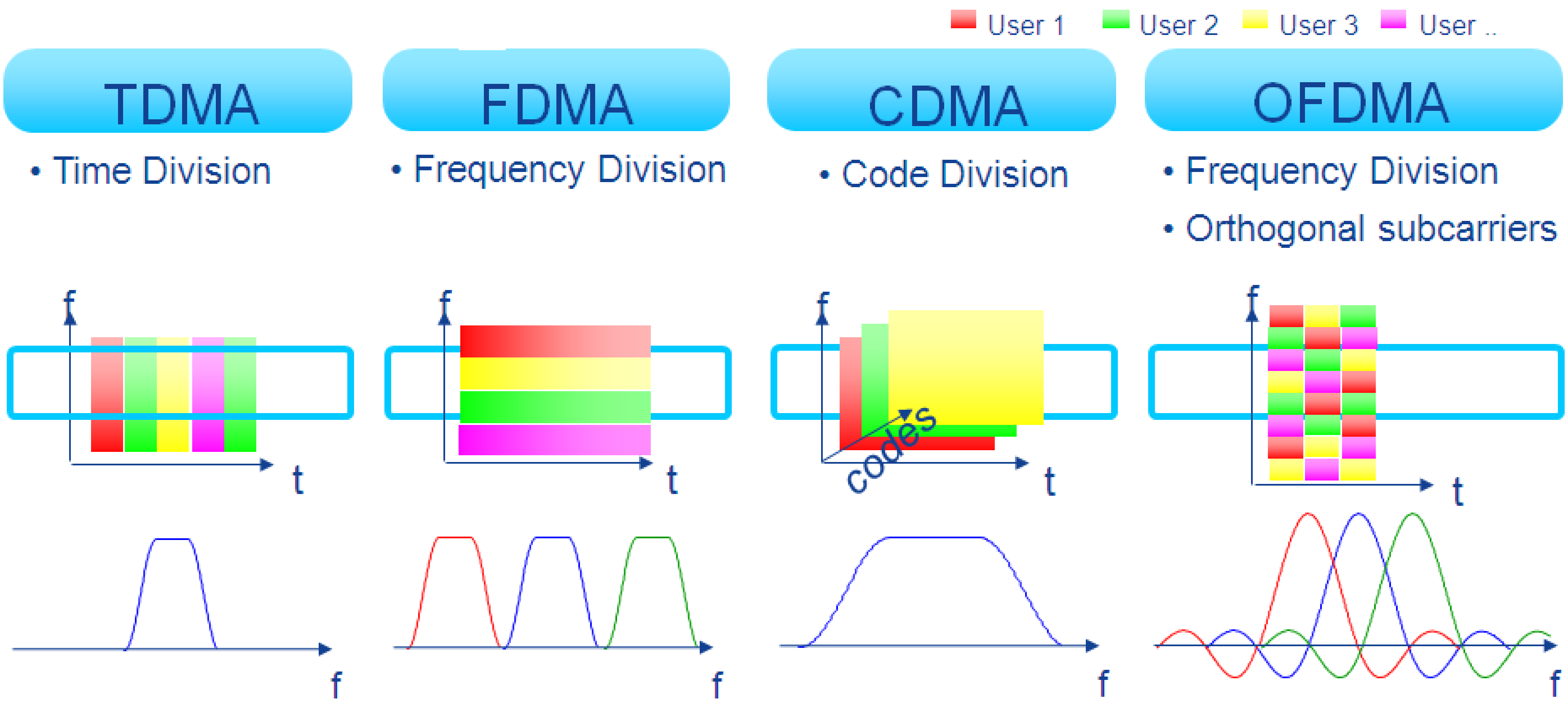
- ITU, IMT-advanced, 3GPP, and LTE-Advanced ...
- Relays

LTE and LTE-Advanced



- ITU, IMT-advanced, 3GPP, and LTE-Advanced ...
- Relays
- HetNets etc.
- Carrier aggregation
- Downlink (OFDMA) vs uplink (SC-OFDM)

Overview



User 1
User 2
User 3
User ..
TDMA
• Time Division
FDMA
• Frequency Division
CDMA
• Code Division
OFDMA
• Frequency Division
• Orthogonal subcarriers
f
t
codes
f

LTE downlink (OFDMA-based)

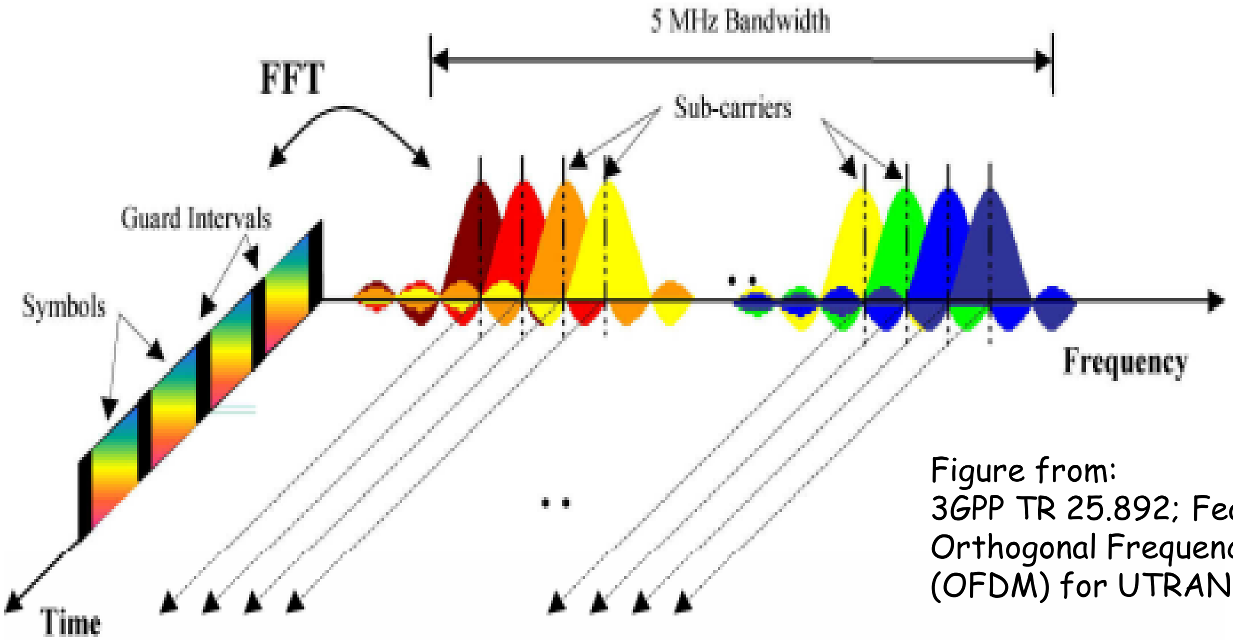


Figure from:
3GPP TR 25.892; Feasibility Study for Orthogonal Frequency Division Multiplexing (OFDM) for UTRAN enhancement (Release 6)

- 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

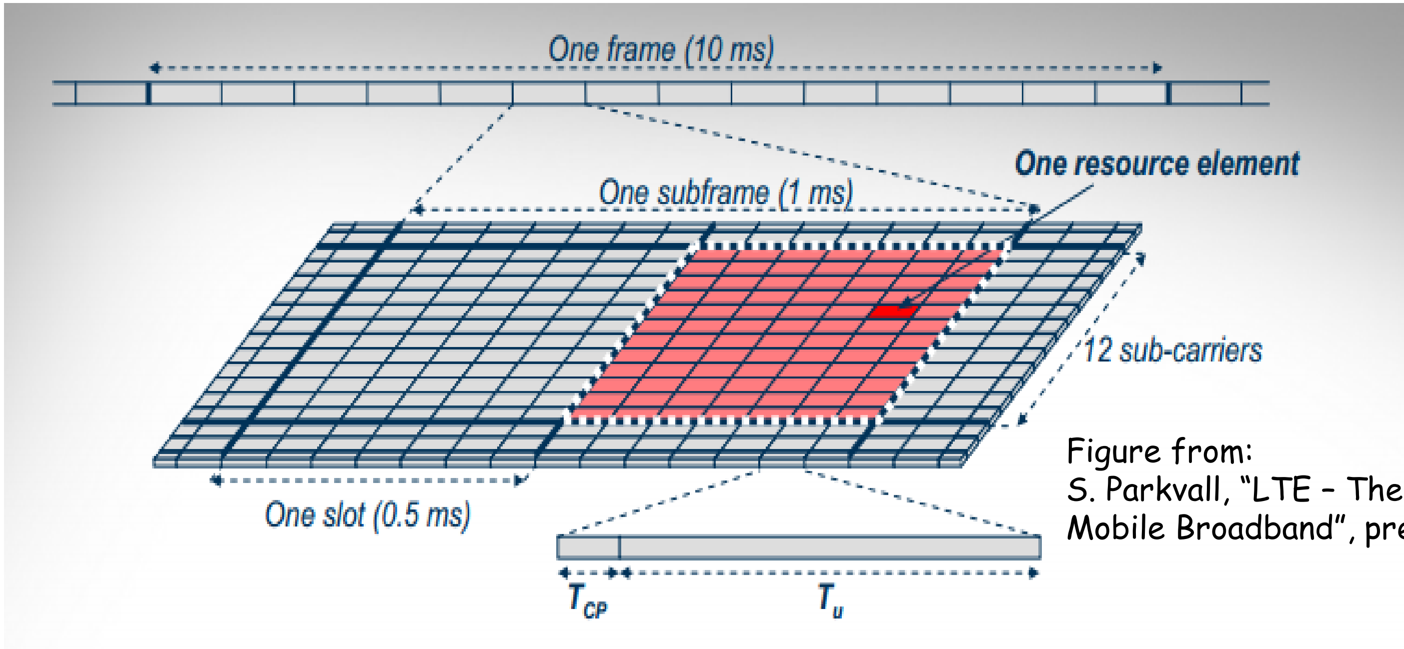
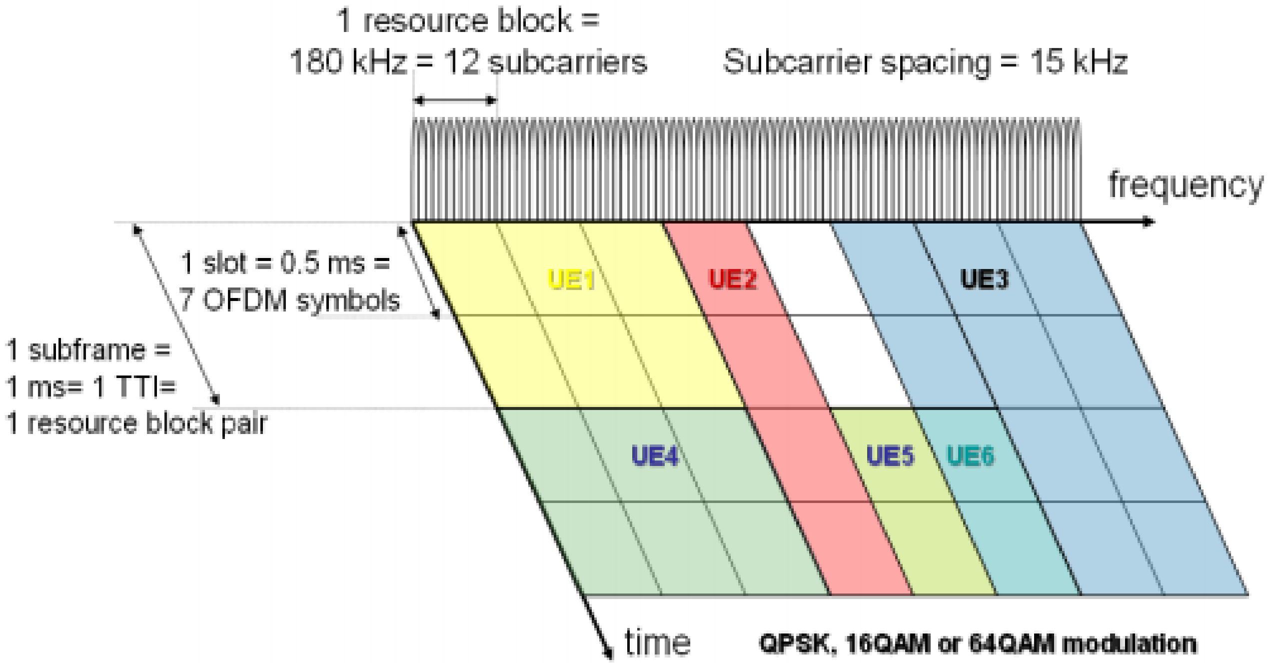
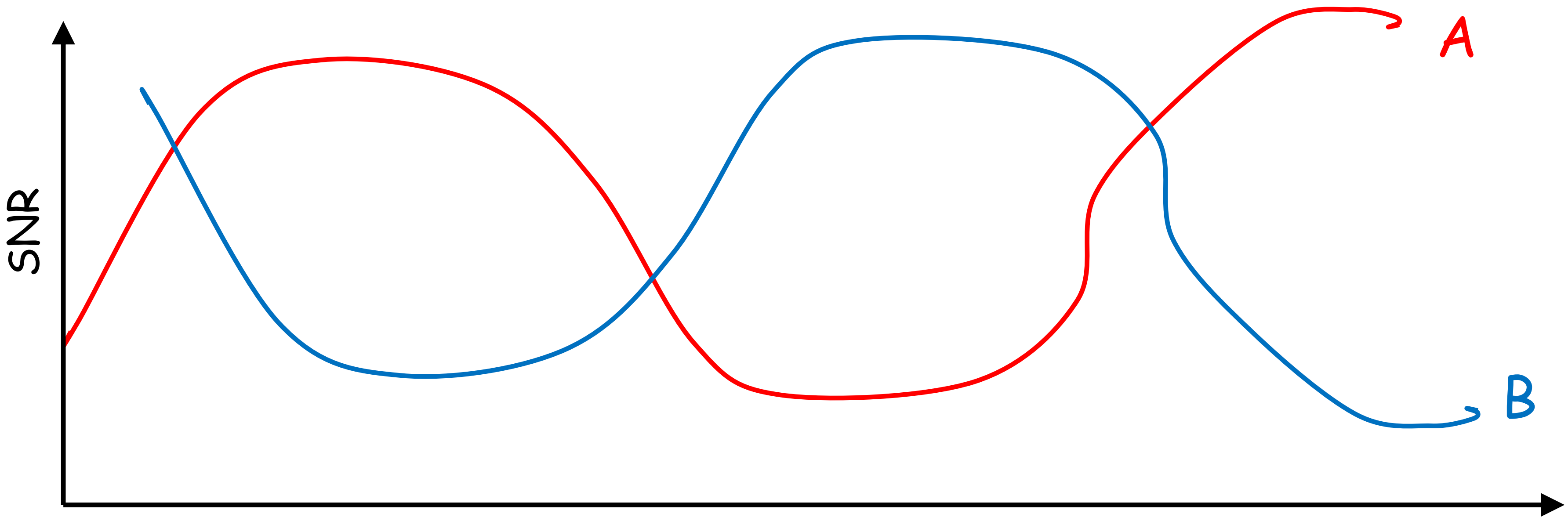


Figure from:
S. Parkvall, "LTE – The Global Standard for Mobile Broadband", presentation, Ericsson Research

- 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.



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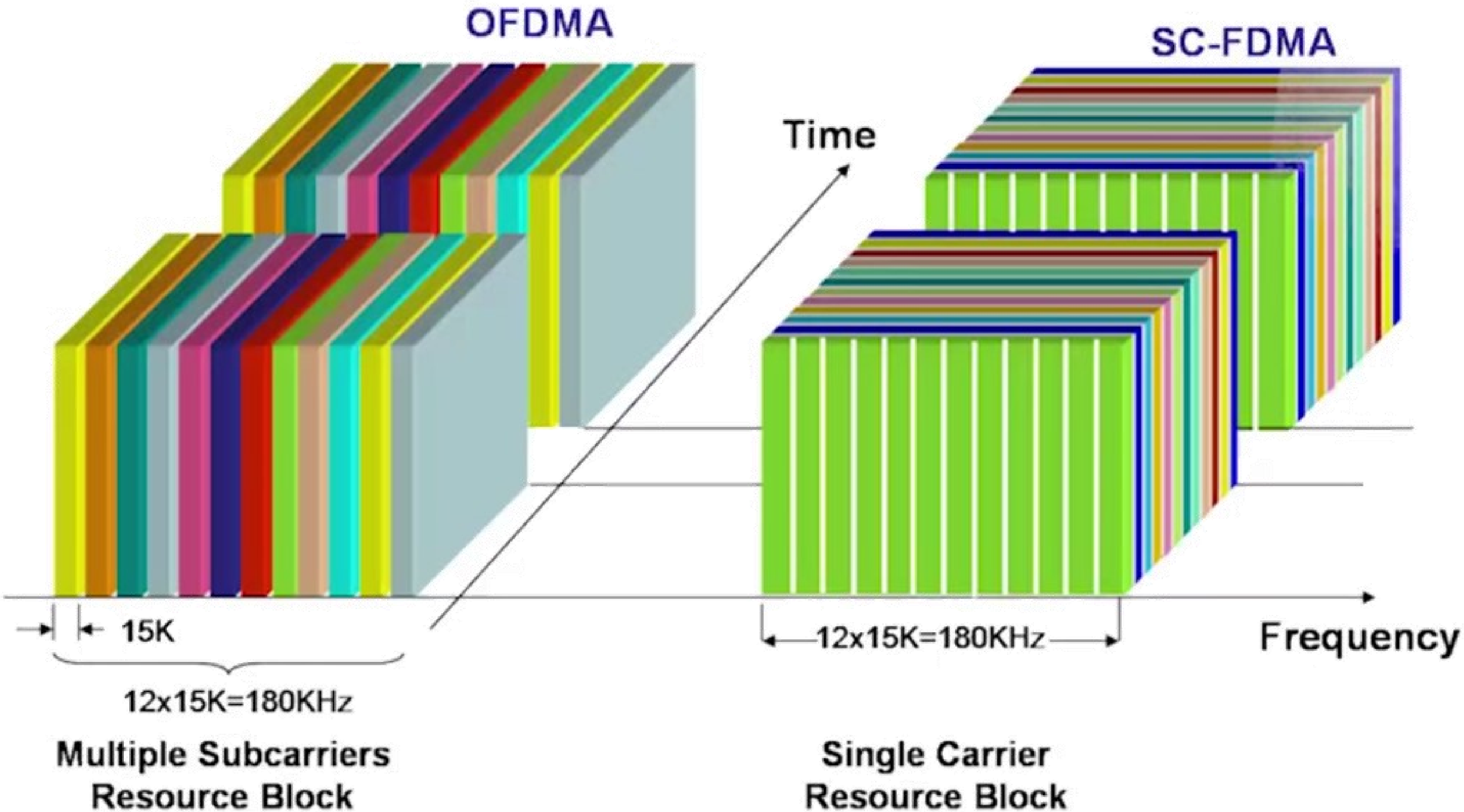
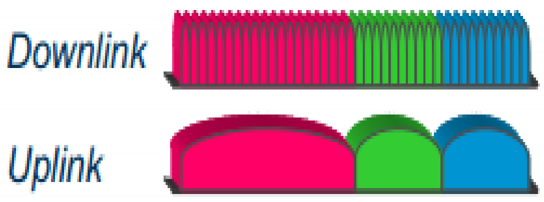
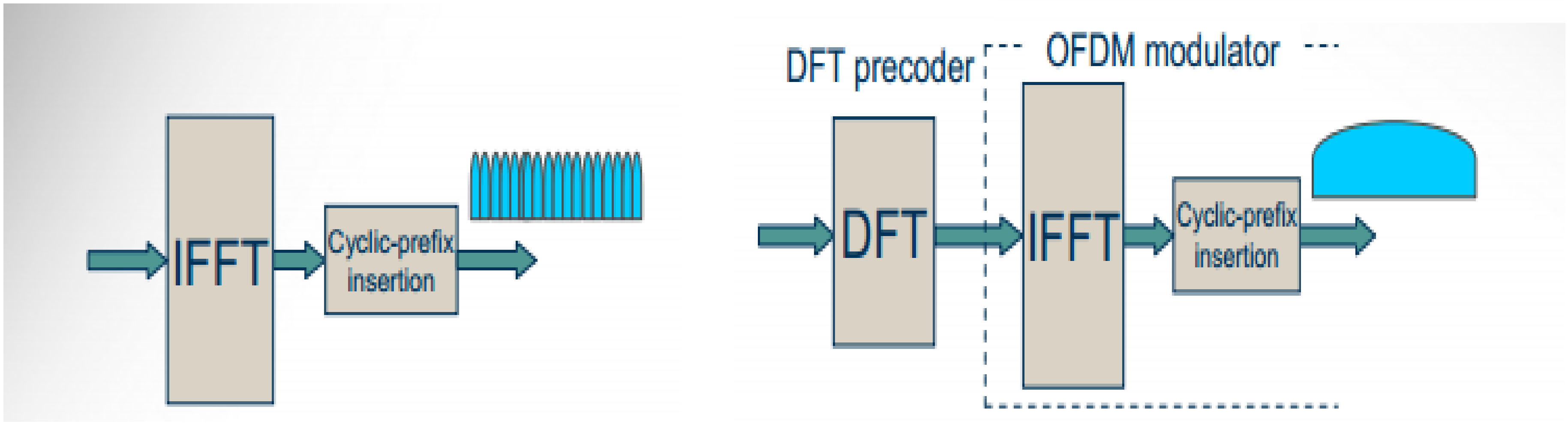
Hint: QPSK (2bits/symbol), 16QAM (4bit/symbol), and 64QAM (6 bits/symbol)

Downlink vs Uplink



Downlink vs uplink

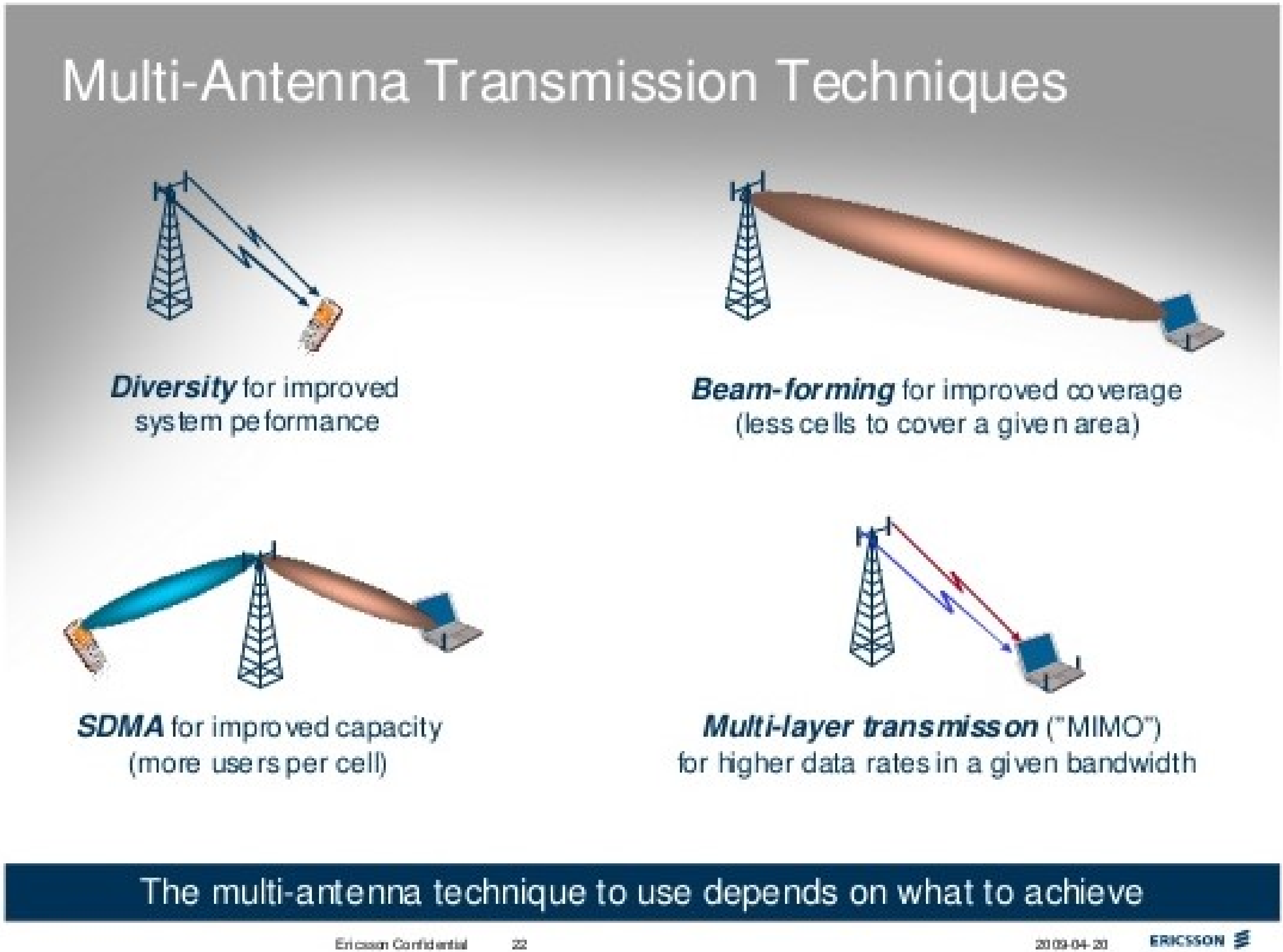




- Parallel transmission on large number of narrowband subcarriers
- Avoids own-cell interference
- Robust to time dispersion
- Bad power-amplifier efficiency

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

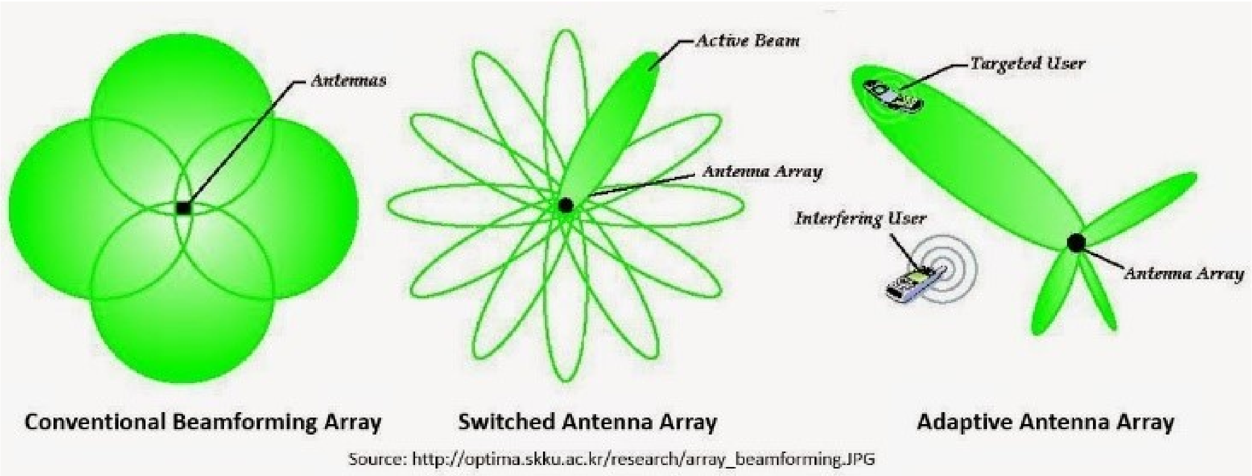
Multi-antenna (*slide from Ericsson)



Beamforming

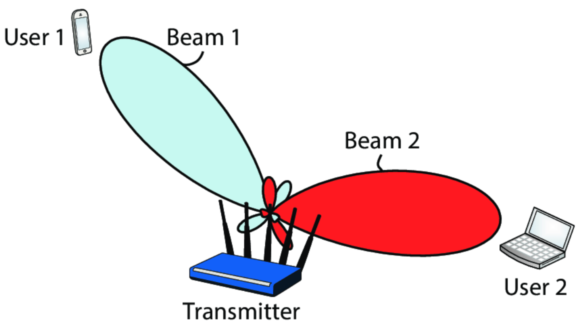
Advantages:

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



Multi-antenna examples

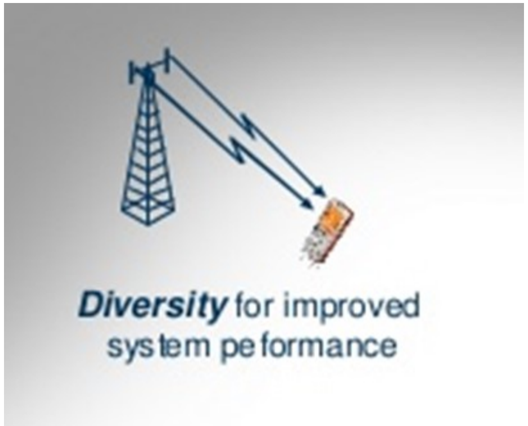
Spatial multiplexing



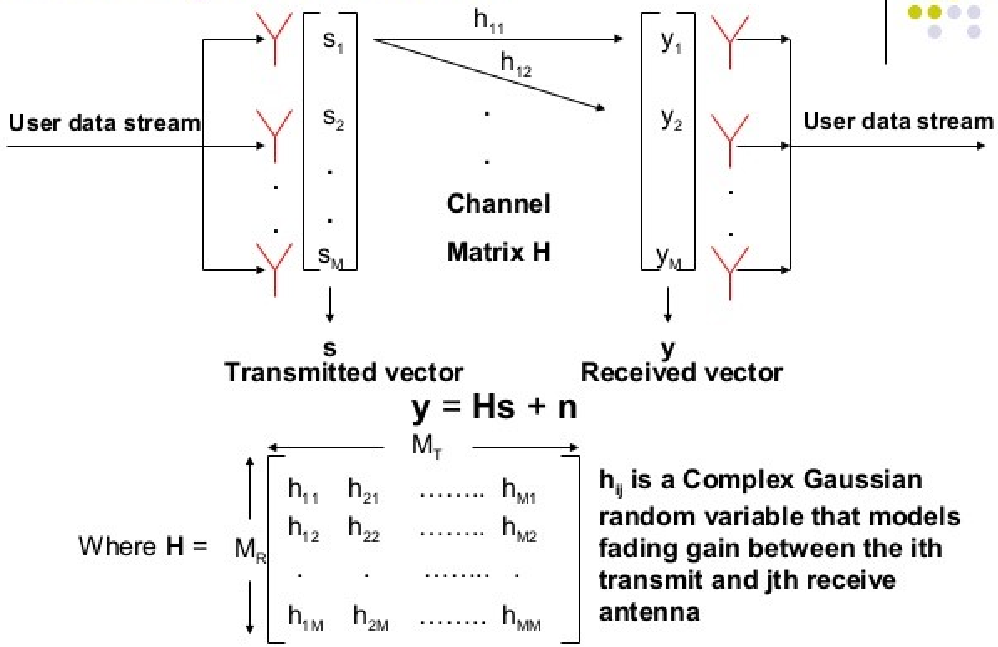
Determine the time delay to locations of users and adjust phase accordingly …

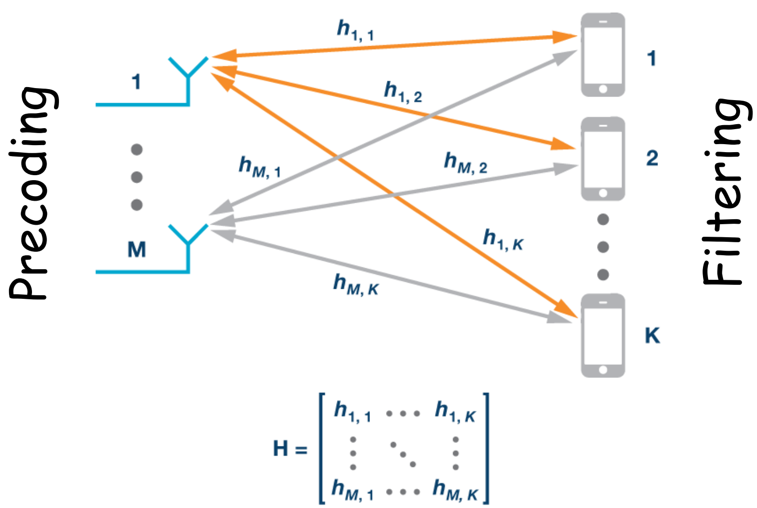
Spatial diversity

- Different antennas see "outages" at different times
  - Multiple paths to receiver
  - Path lengths d_1 and d_2
  - Multi-path fading: Small movements make big difference …
- "Outage" with probability p
- M independent antennas send same signal: at least on success $1-p^M$.



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*

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

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

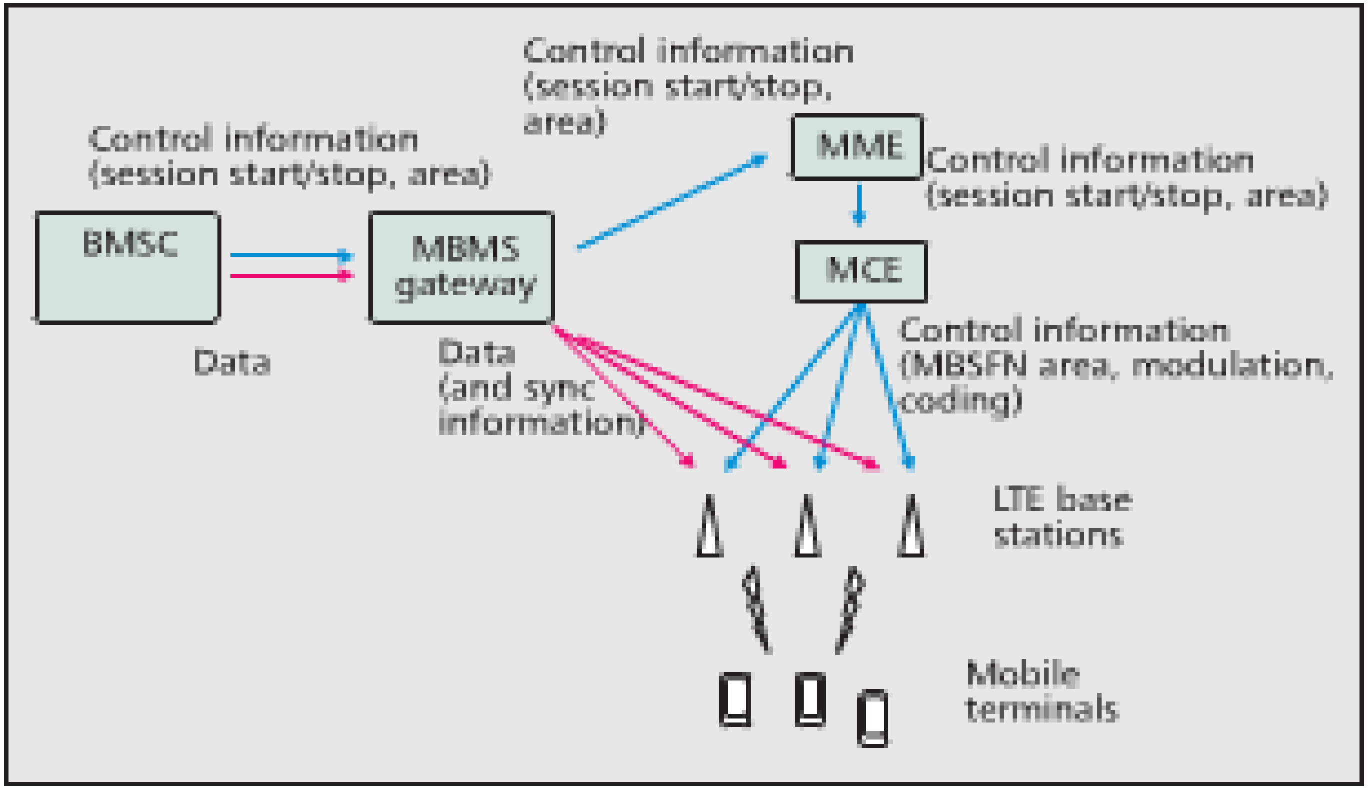


Figure 4. *RAN architecture for SFN across LTE base stations.*

- 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

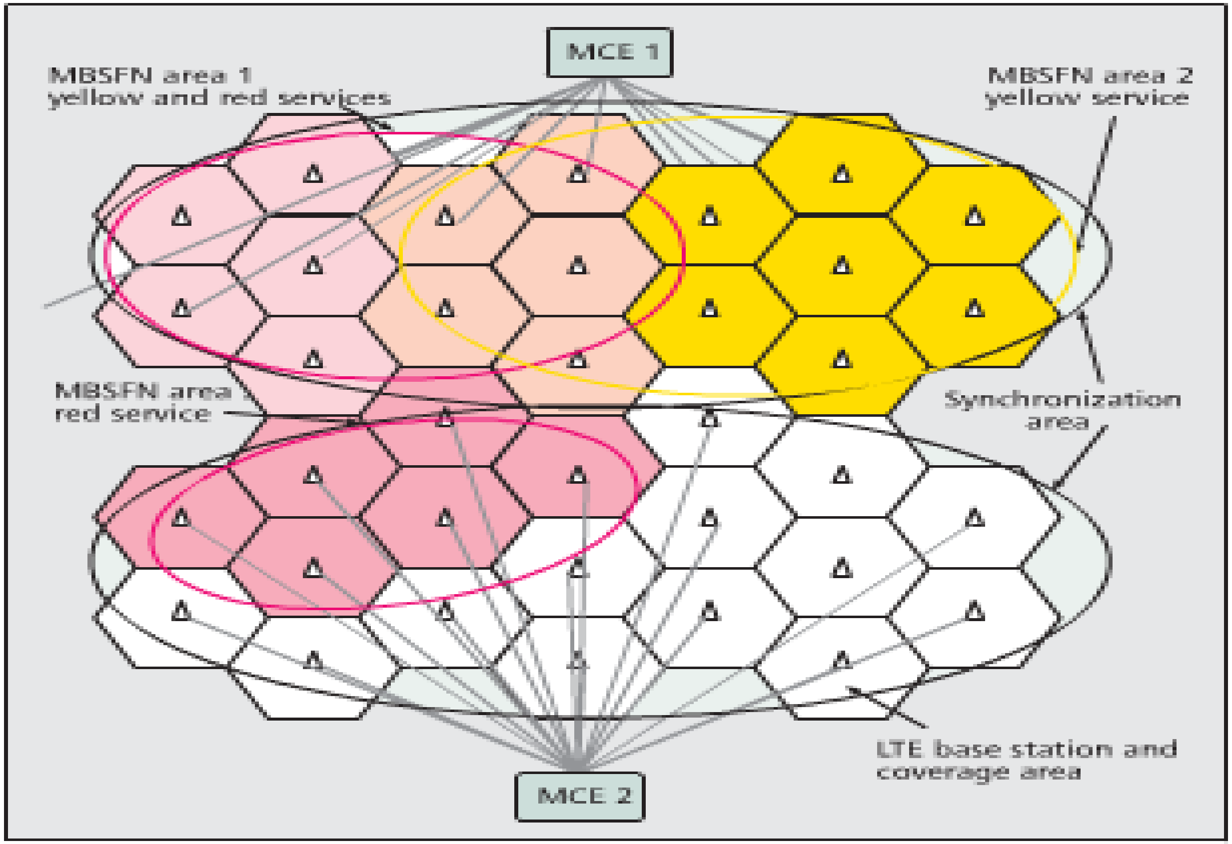
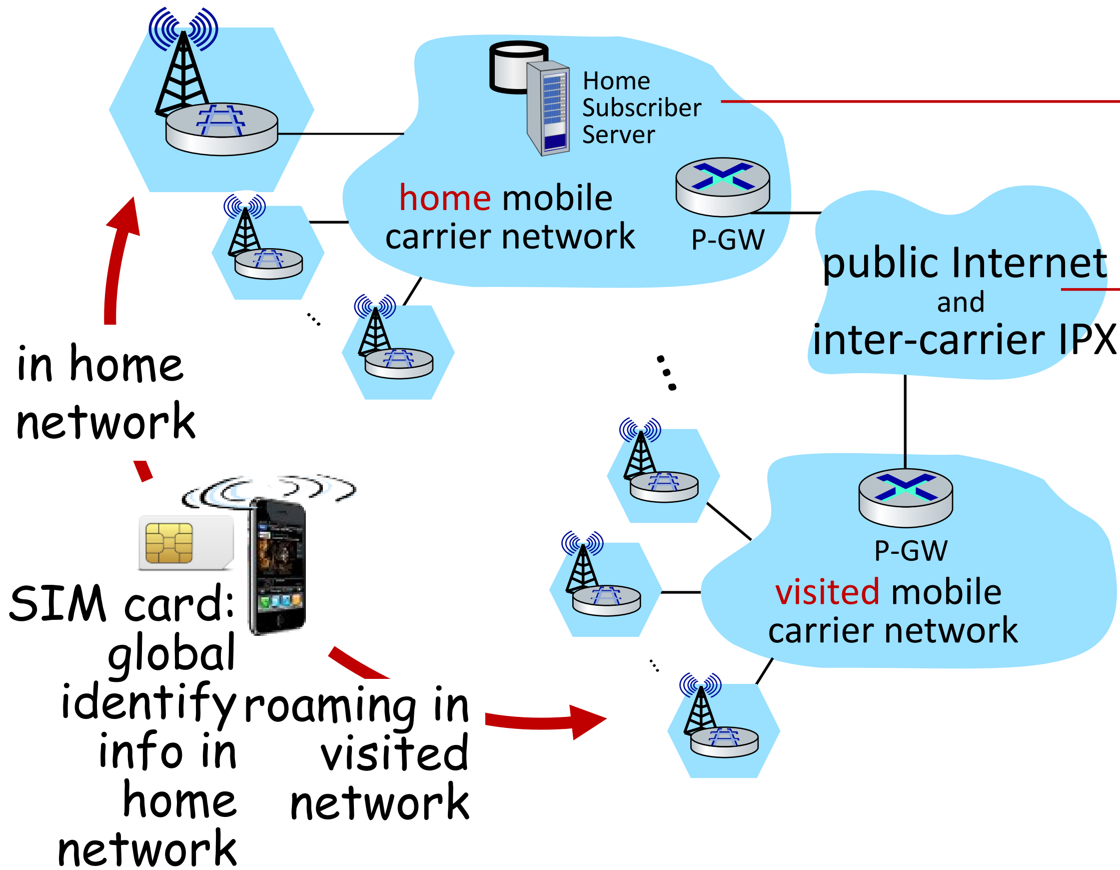


Figure 5. *Example with two MBMS services with different services areas.*

- 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 ...

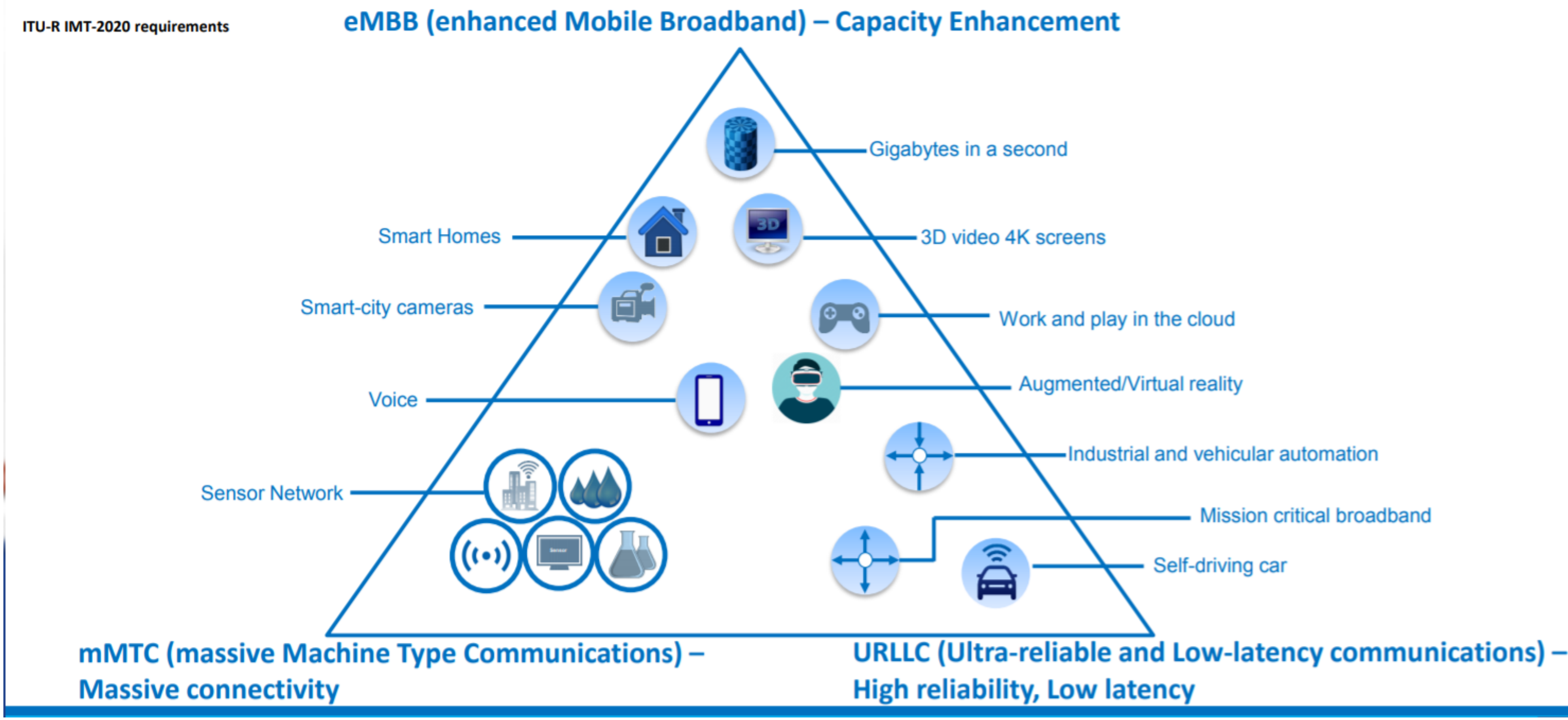
- Advanced network (e.g., SDN, NVF, context-aware, content-aware)
- Multi-RAT (Radio Access Technology)
- Advanced D2D
- Edge computing, etc. ...

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)

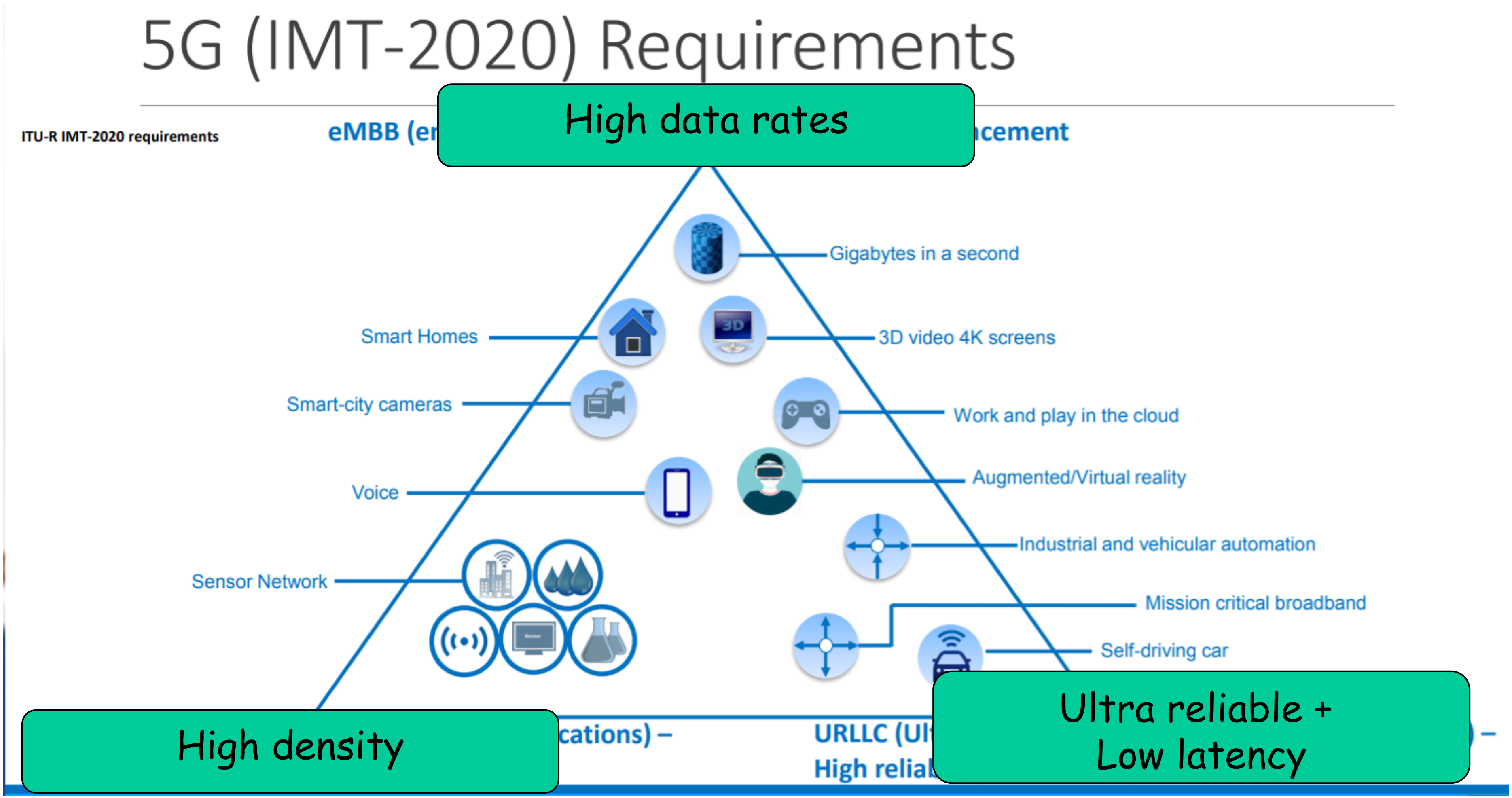
Use-case-driven requirements …

5G (IMT-2020) Requirements



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

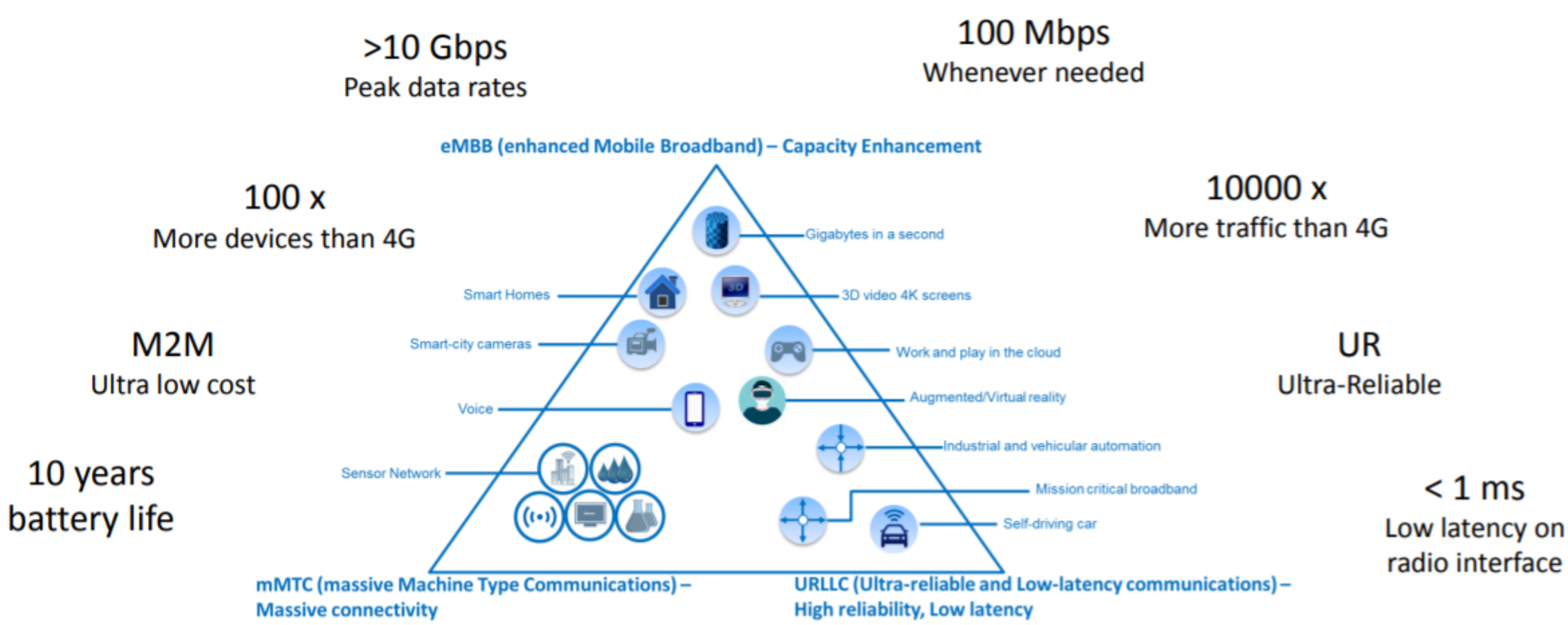
Use-case-driven requirements …



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 ...

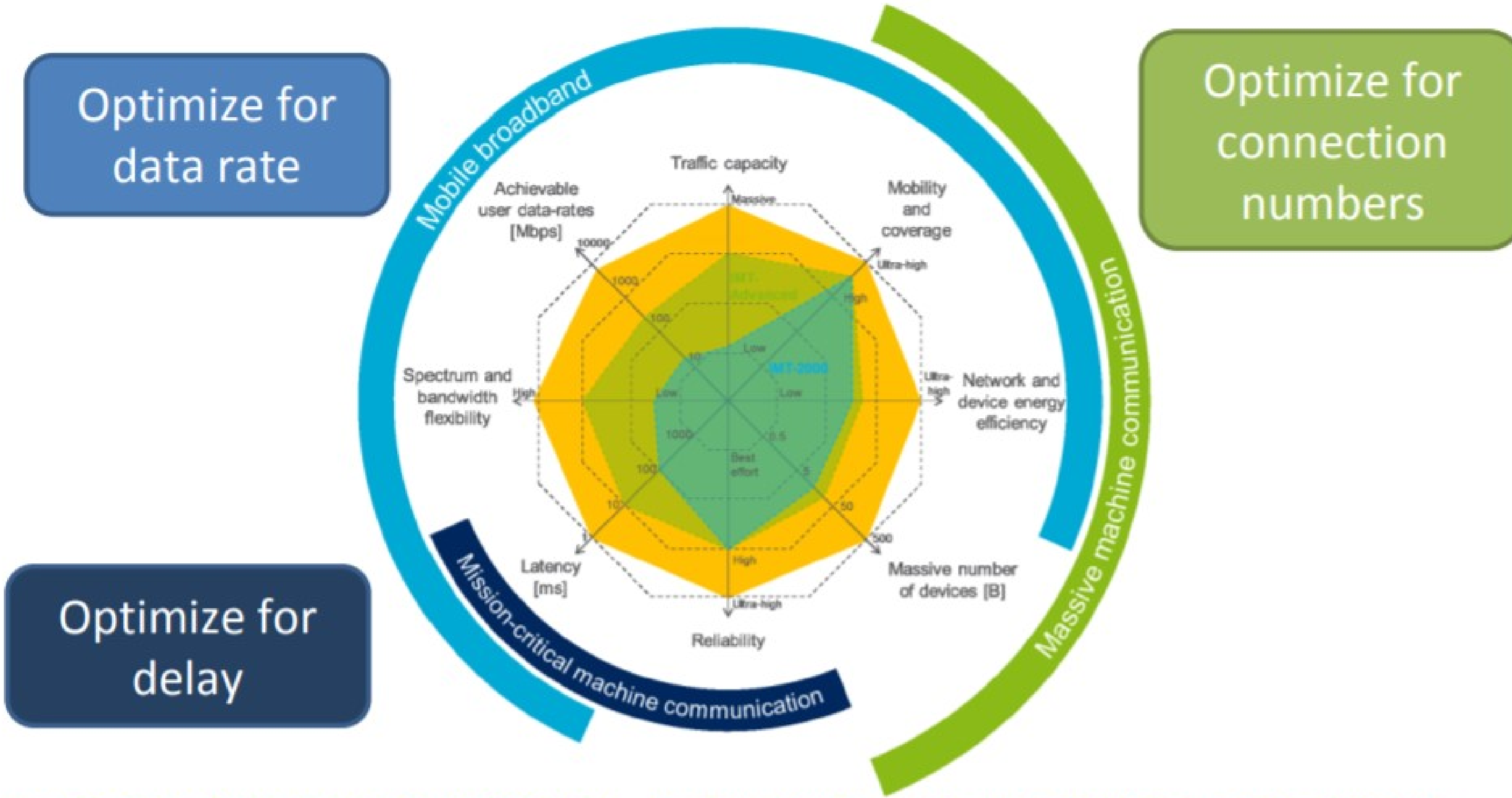


Image Source: 5G-From Research to Standardisation - Bernard Barani European Commission, Globecom2014

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

More slides …

Functional split of major LTE components

handles idle/active UE transitions
pages UE
sets up eNodeB-PGW tunnel (aka bearer)

holds idle UE info
QoS enforcement