Cellular ...

Slides used in TDDE48 (Mobile Networks) @ LiU, Sweden, Fall 2021
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")
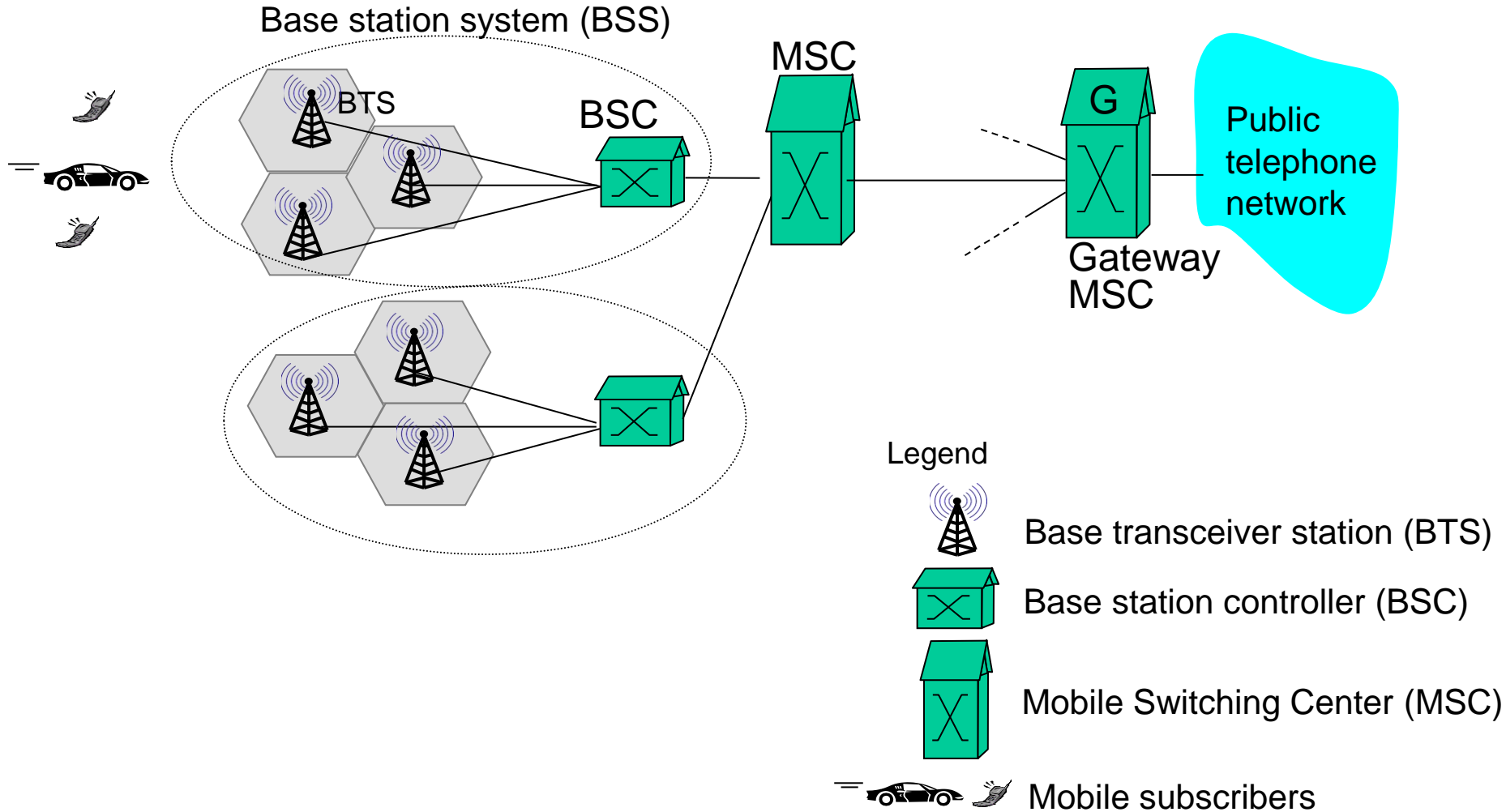
Background: Cellular network technology

□ 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 …
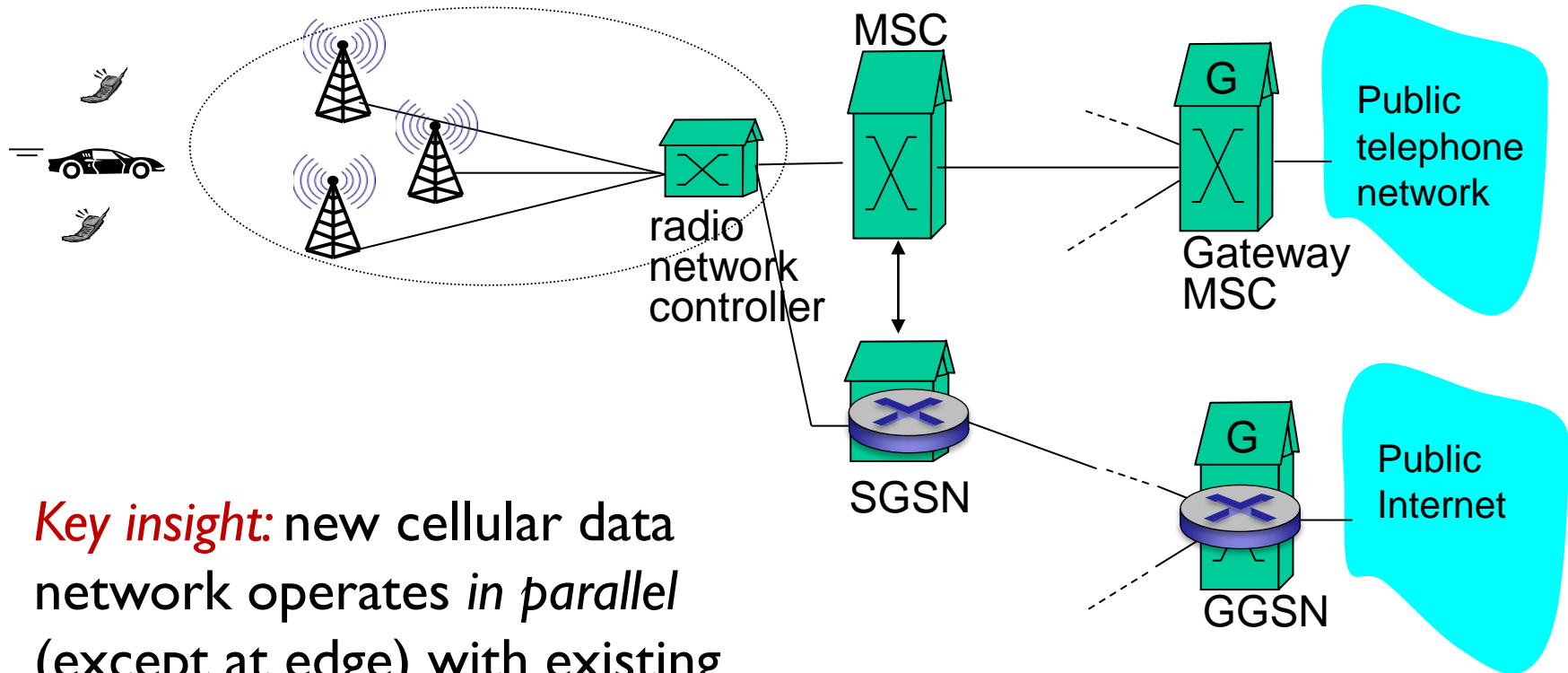 - OFDM (OFDMA for downlink and SC-OFDM for uplink)
- ○ 5G …

□ 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.
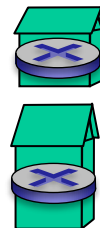
2G (voice) network architecture

Base station system (BSS)

MSC

BSC

G

Public telephone network

Gateway MSC

Legend

Base transceiver station (BTS)

Base station controller (BSC)

Mobile Switching Center (MSC)

Mobile subscribers

3G (voice+data) network architecture

MSC

G

Public telephone network

radio network controller

Gateway MSC

SGSN

G

Public Internet

GGSN

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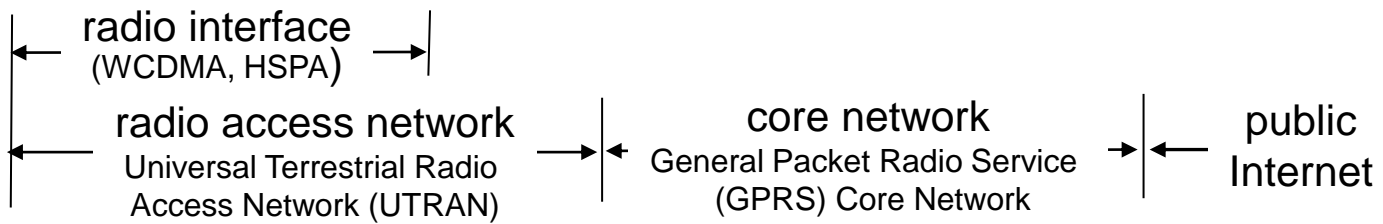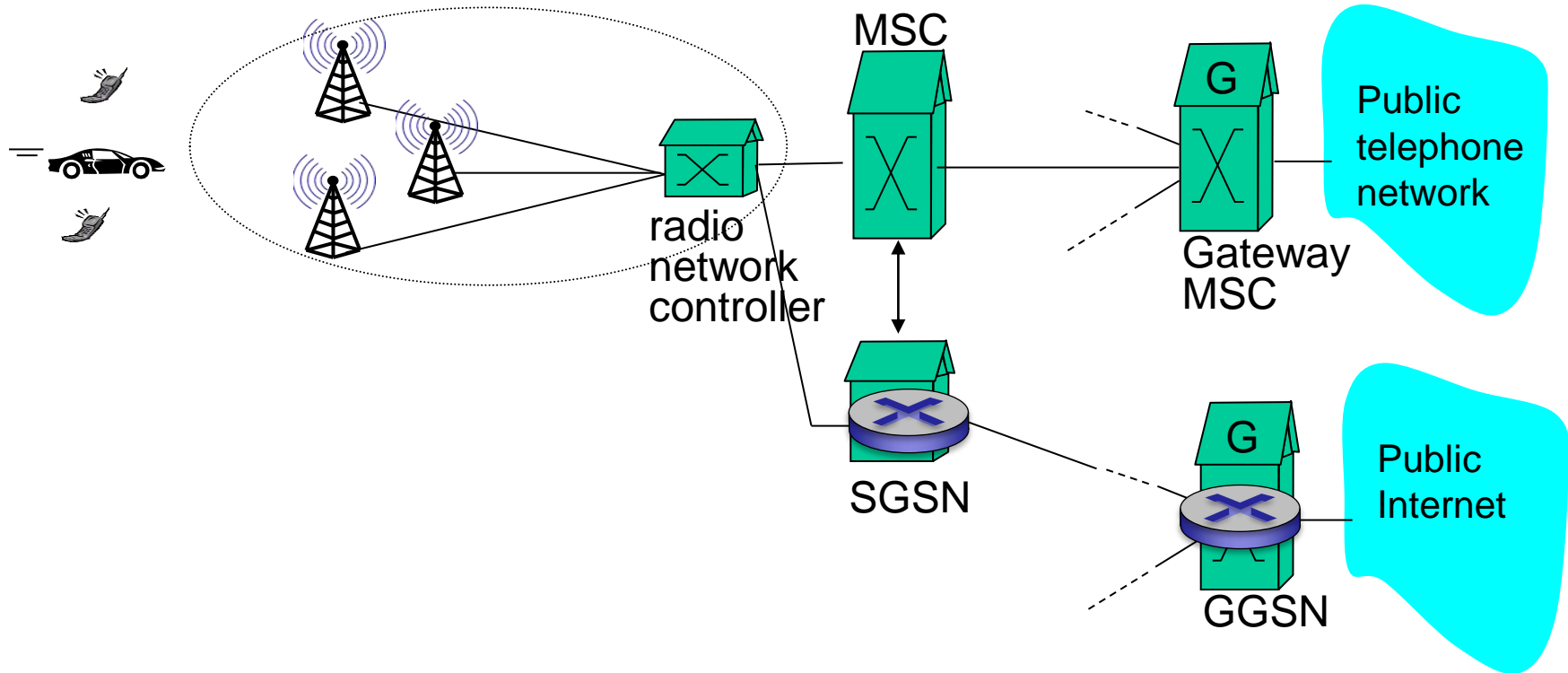
- voice network *unchanged* in core
- data network operates in parallel

Serving GPRS Support Node (SGSN)
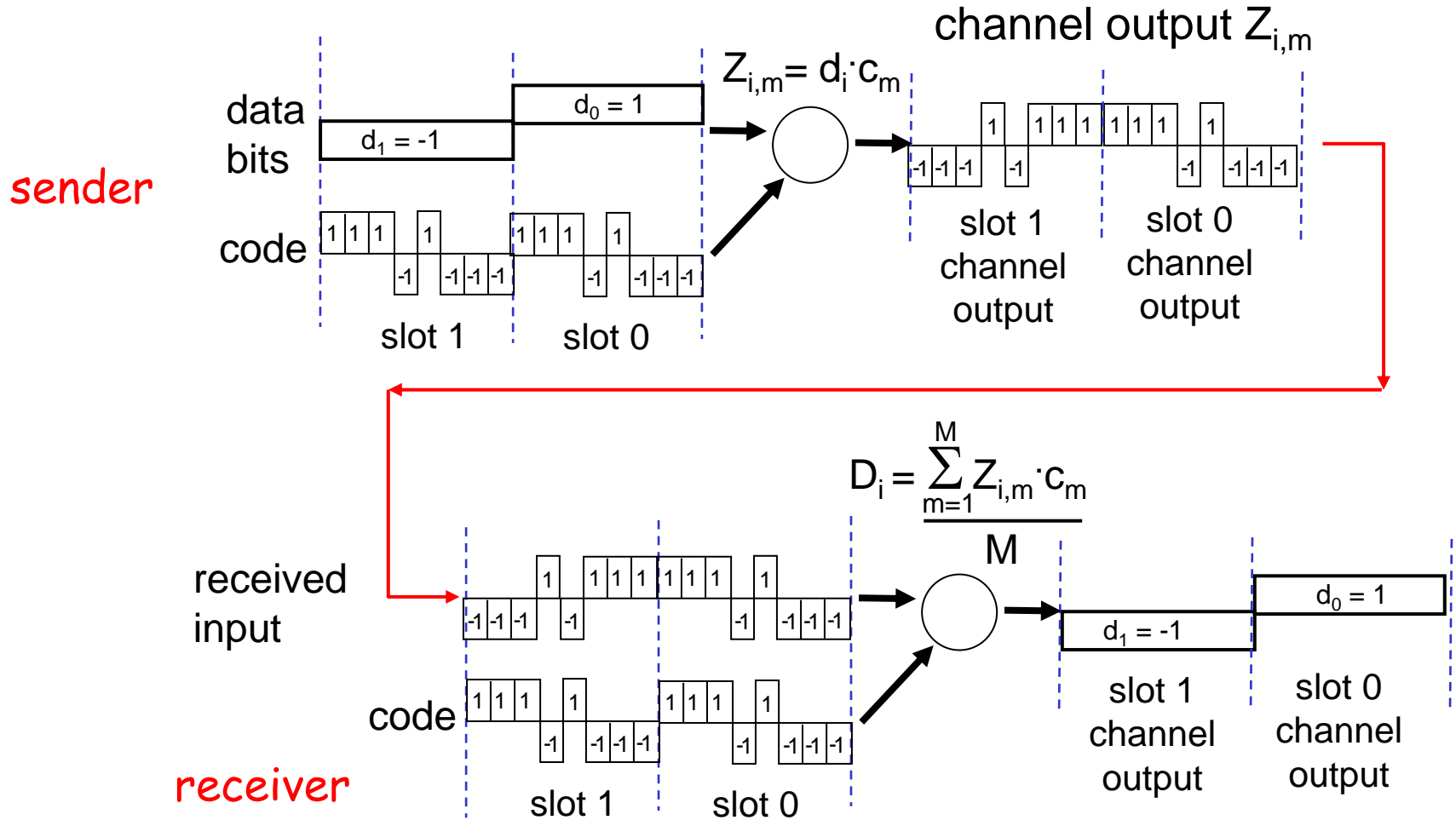
Gateway GPRS Support Node (GGSN)

3G (voice+data) network architecture

MSC

G

Public telephone network

radio network controller

Gateway MSC

SGSN

G

Public Internet

GGSN

radio interface
(WCDMA, HSPA)

radio access network
Universal Terrestrial Radio
Access Network (UTRAN)

core network
General Packet Radio Service
(GPRS) Core Network
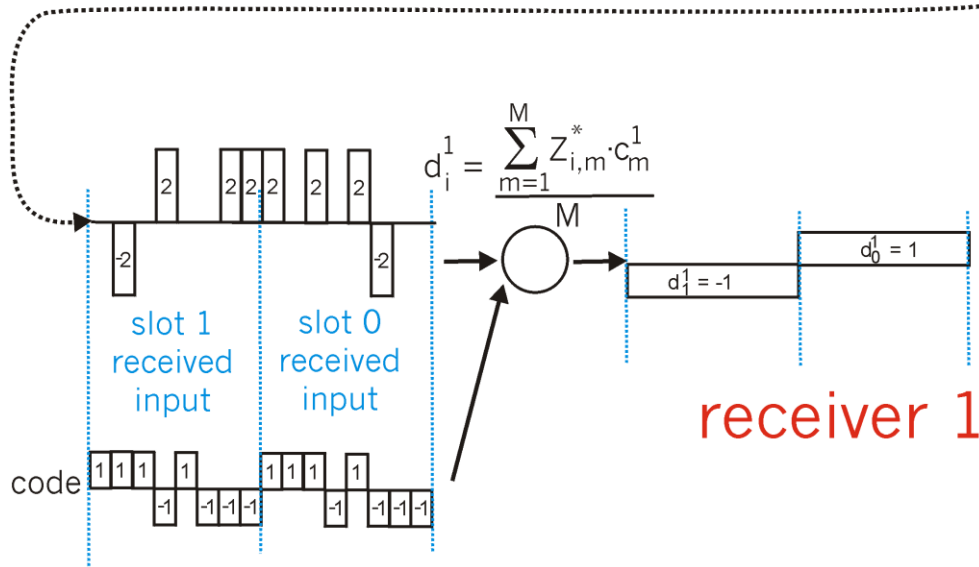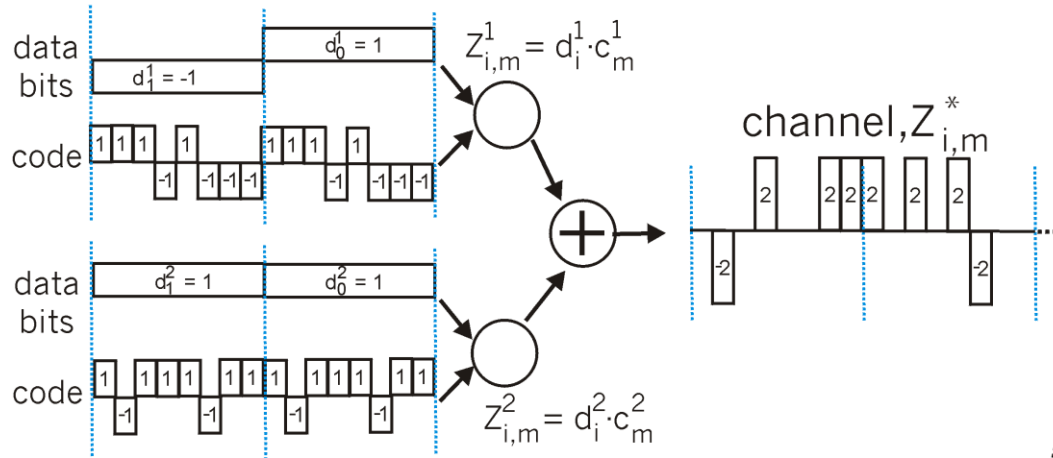
public Internet

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

channel output $Z_{i,m}$

$Z_{i,m} = d_i \cdot c_m$

sender

data bits

$d_1 = -1$

$d_0 = 1$

code

slot 1   slot 0

slot 1 channel output   slot 0 channel output

$D_i = \dfrac{\sum\limits_{m=1}^{M} Z_{i,m} \cdot c_m}{M}$

receiver

received input

code

slot 1   slot 0

$d_1 = -1$

$d_0 = 1$

slot 1 channel output   slot 0 channel output
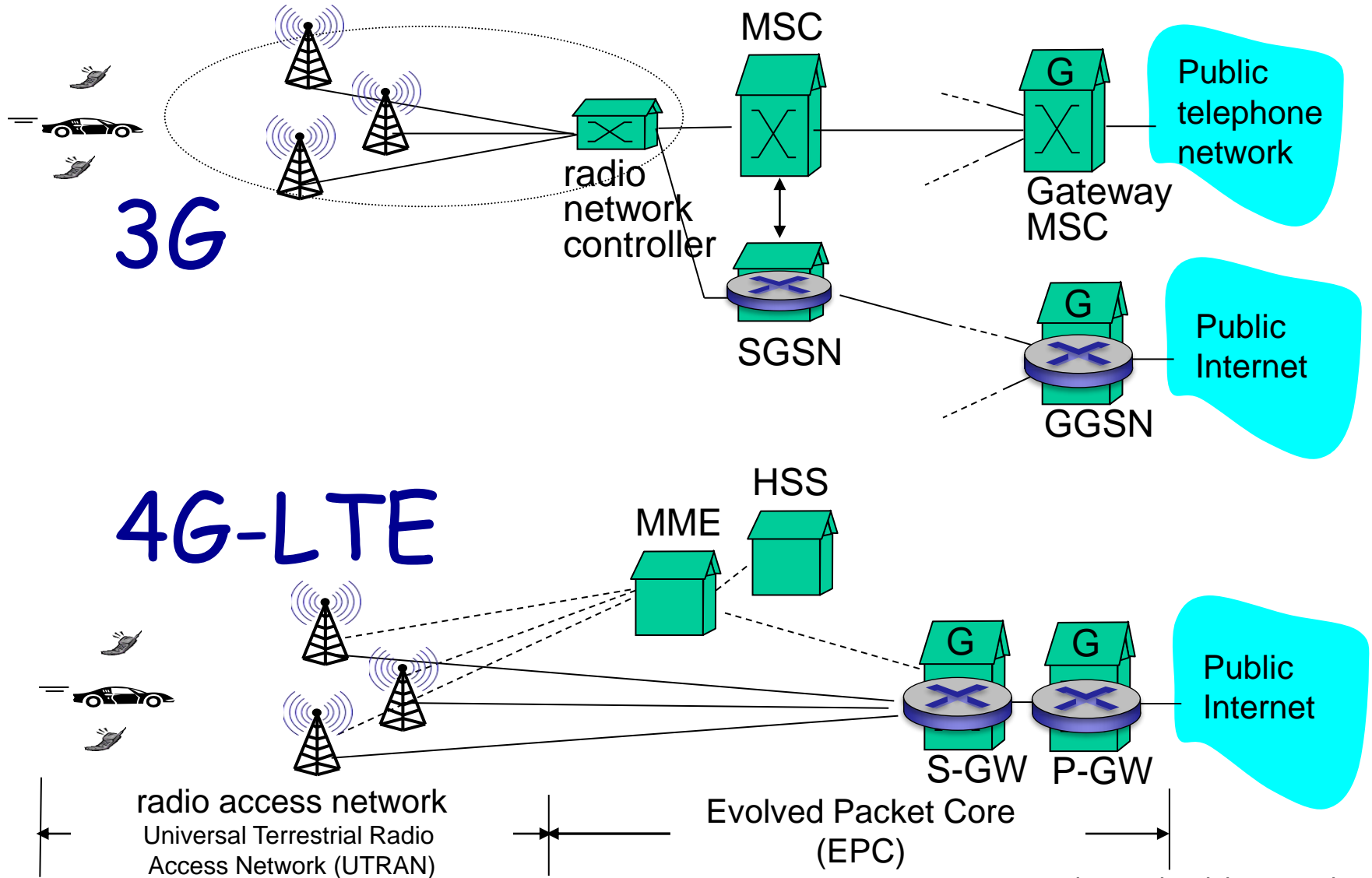
8

CDMA: two-sender interference
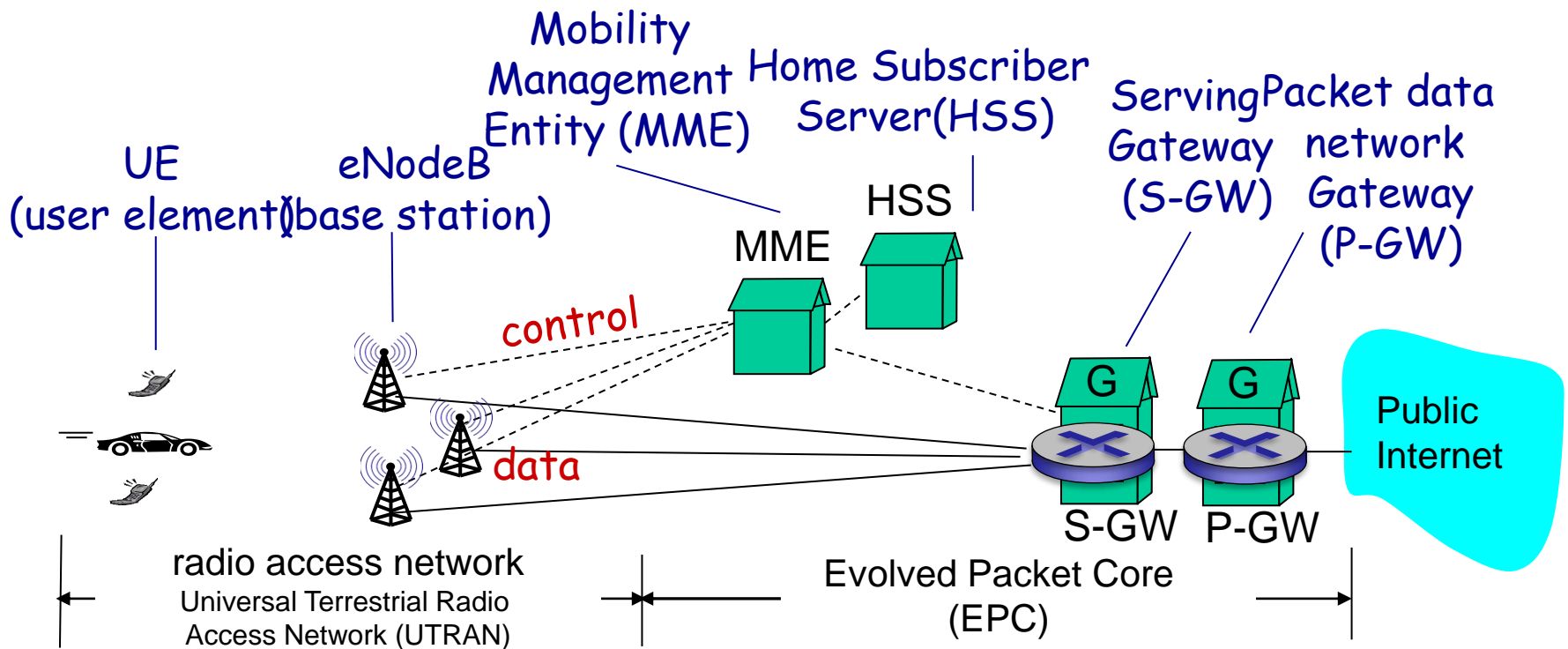
senders

receiver 1

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

3G

MSC

radio network controller

Gateway MSC

Public telephone network

SGSN

GGSN

Public Internet

4G-LTE

HSS

MME

G G

S-GW P-GW

Public Internet

radio access network
Universal Terrestrial Radio
Access Network (UTRAN)

Evolved Packet Core
(EPC)

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

Mobility
Management
Entity (MME)
Home Subscriber
Server(HSS)
Serving Packet data
Gateway network
(S-GW) Gateway
(P-GW)

UF
(user element)
eNodeB
(base station)
HSS
MME

control

data

G   G

Public
Internet

S-GW P-GW

radio access network
Universal Terrestrial Radio
Access Network (UTRAN)

Evolved Packet Core
(EPC)

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
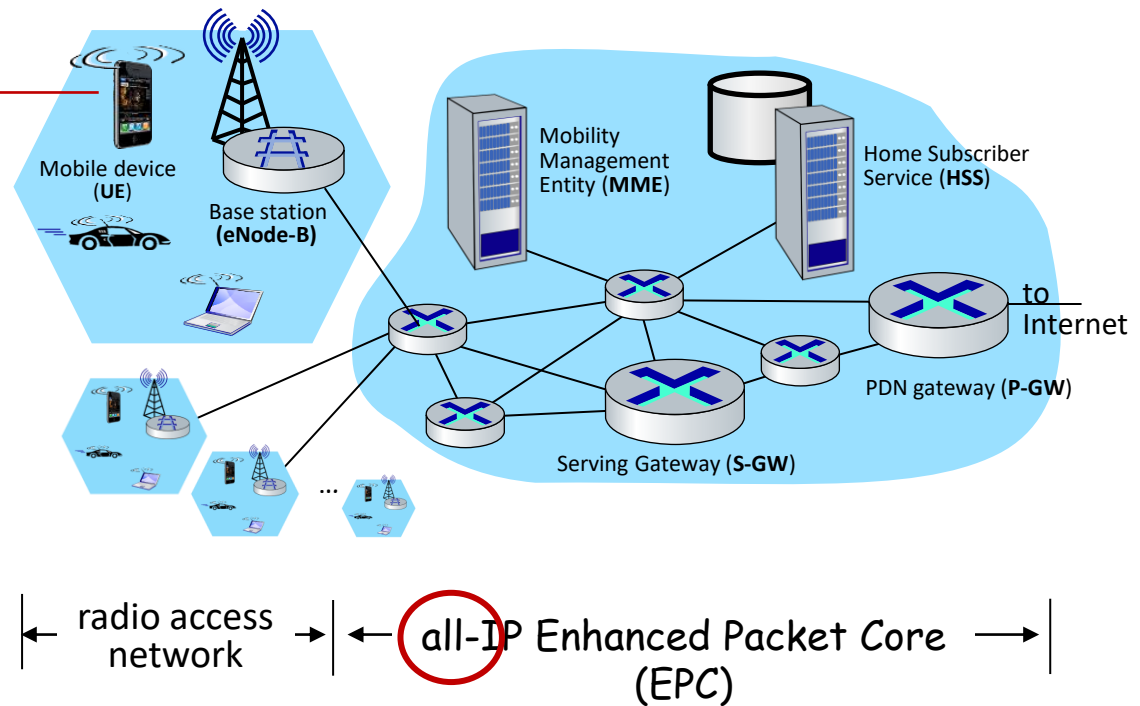- interconnected to wired Internet

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
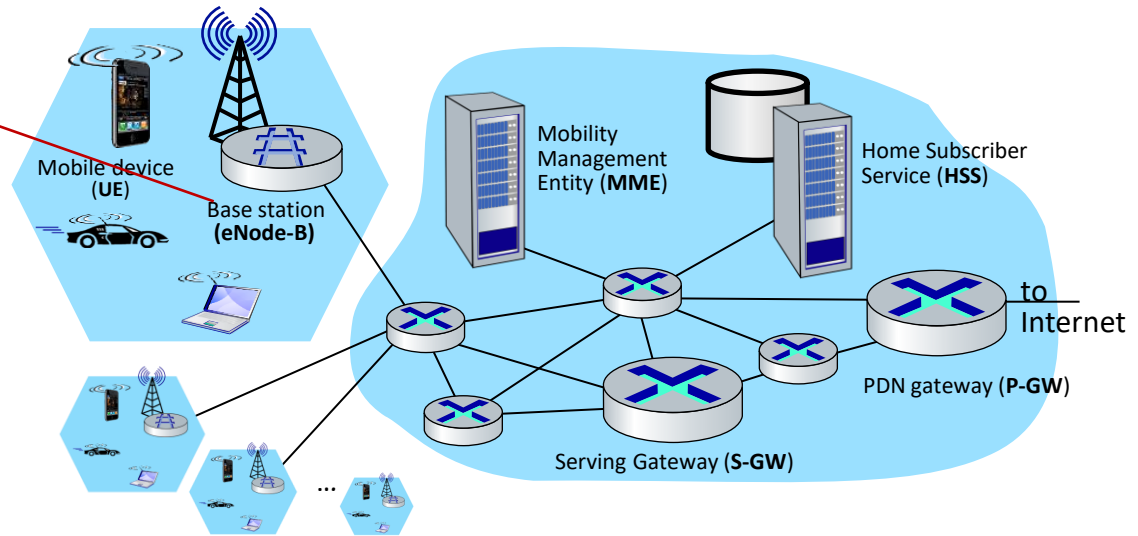
Mobile device:

- 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)

Mobile device
(**UE**)

Base station
(**eNode-B**)

Mobility Management Entity (**MME**)

Home Subscriber Service (**HSS**)

to Internet

PDN gateway (**P-GW**)

Serving Gateway (**S-GW**)

...

radio access network

all-IP Enhanced Packet Core (EPC)

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
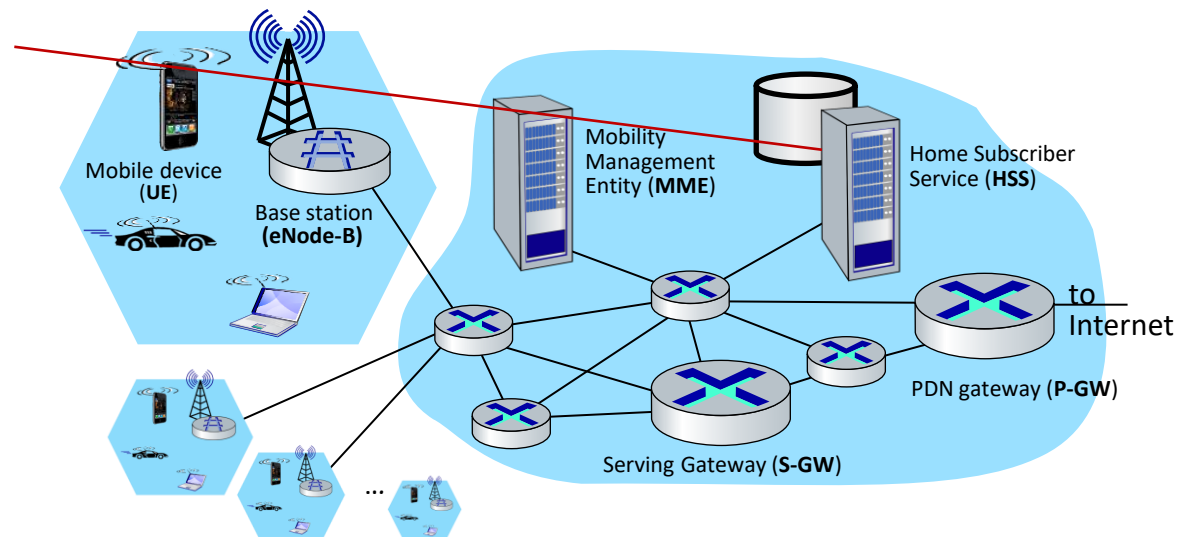
- LTE jargon: eNode-B

Mobile device (**UE**)

Base station (**eNode-B**)

Mobility Management Entity (**MME**)

Home Subscriber Service (**HSS**)

PDN gateway (**P-GW**)

to Internet

Serving Gateway (**S-GW**)

- 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

Mobile device (**UE**)

Base station (**eNode-B**)

Mobility Management Entity (**MME**)

Home Subscriber Service (**HSS**)

to Internet

PDN gateway (**P-GW**)

Serving Gateway (**S-GW**)

...

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

Mobile device (**UE**)

Base station (**eNode-B**)

Mobility Management Entity (**MME**)

Home Subscriber Service (**HSS**)

to Internet

PDN gateway (**P-GW**)

Serving Gateway (**S-GW**)

...
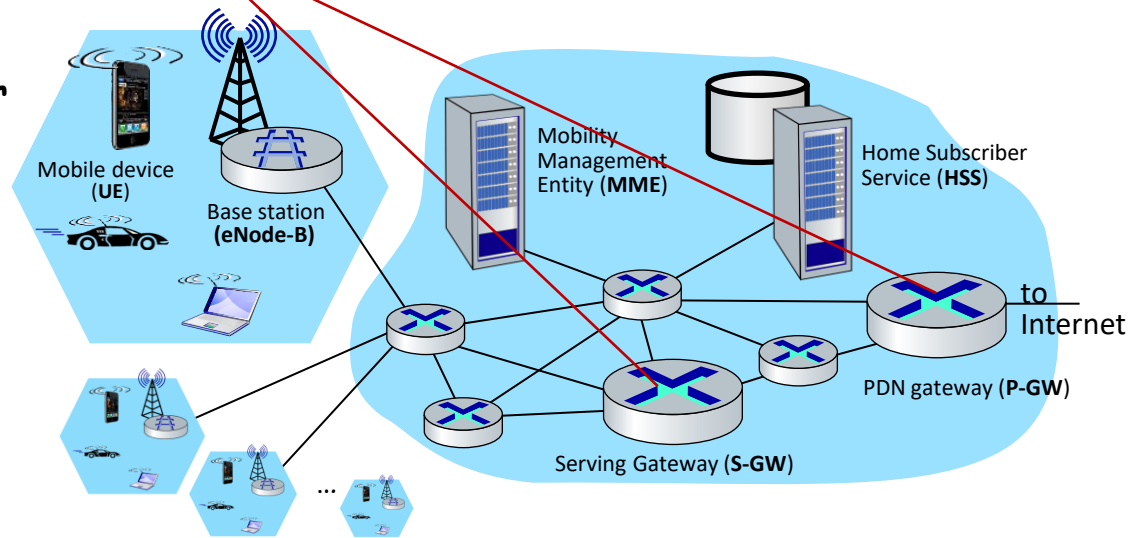
Elements of 4G LTE architecture

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

Mobile device (**UE**)

Base station (**eNode-B**)

Mobility Management Entity (**MME**)

Home Subscriber Service (**HSS**)

to Internet

PDN gateway (**P-GW**)

Serving Gateway (**S-GW**)
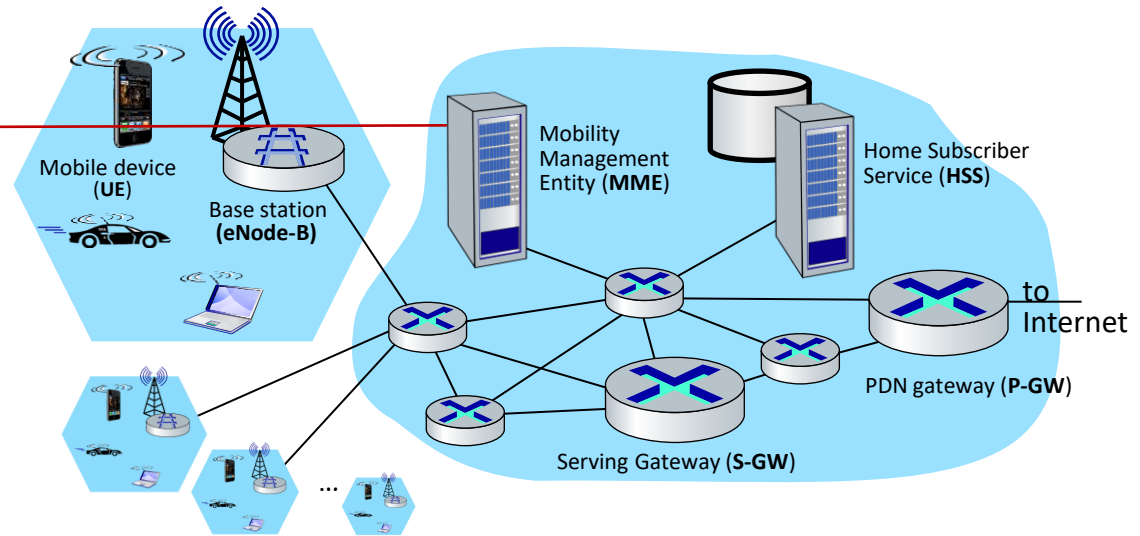
LTE: data plane control plane separation
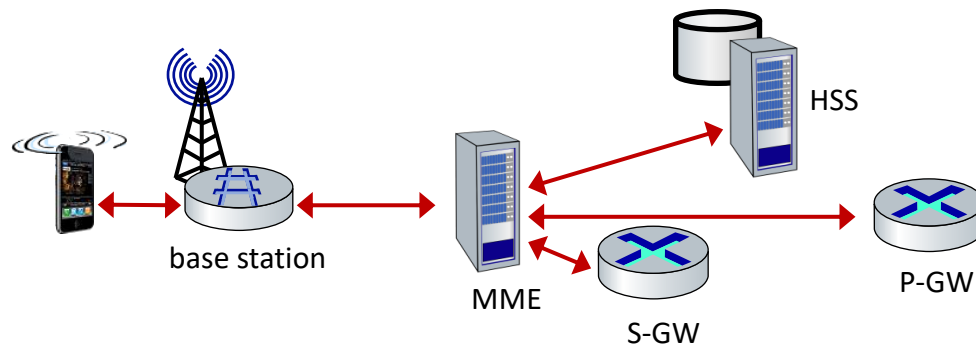
control plane

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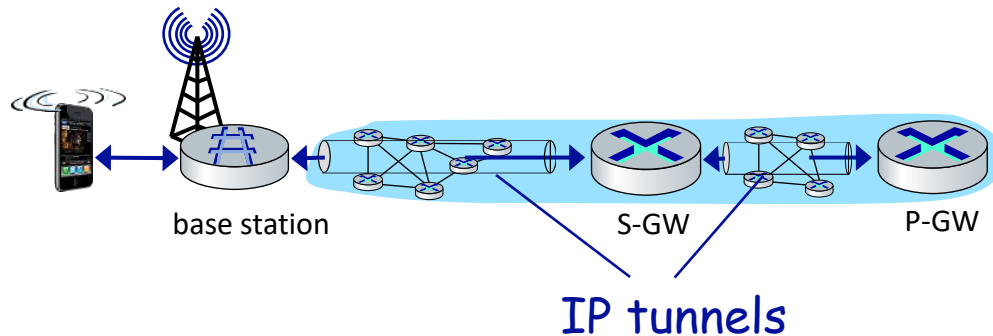
data plane

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

IP tunnels

LTE data plane protocol stack: first hop

Application
Transport
IP
Packet Data Convergence
Radio Link
Medium Access
Physical

Link

IP
Packet Data Convergence
Radio Link
Medium Access
Physical

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

base station

S-GW

P-GW

data plane

LTE data plane protocol stack: first hop

base station
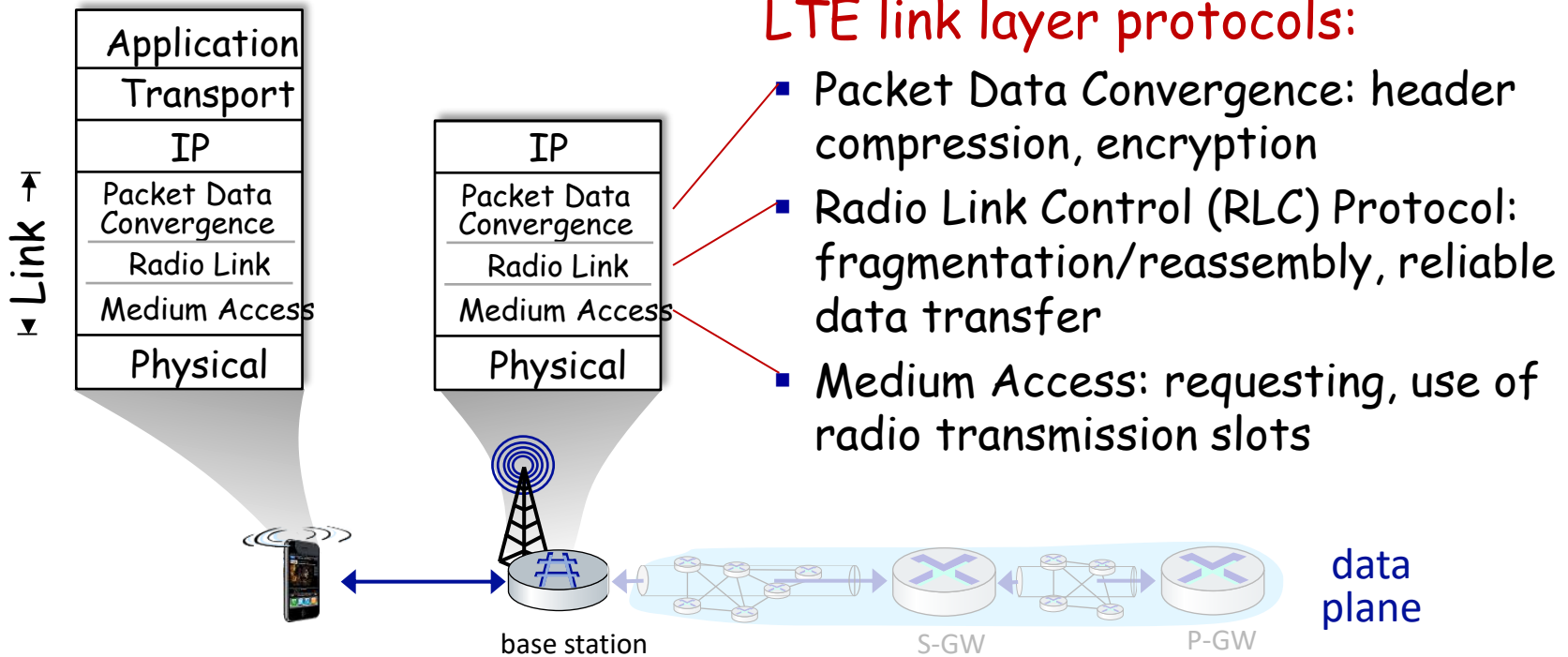
LTE radio access network:

- 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
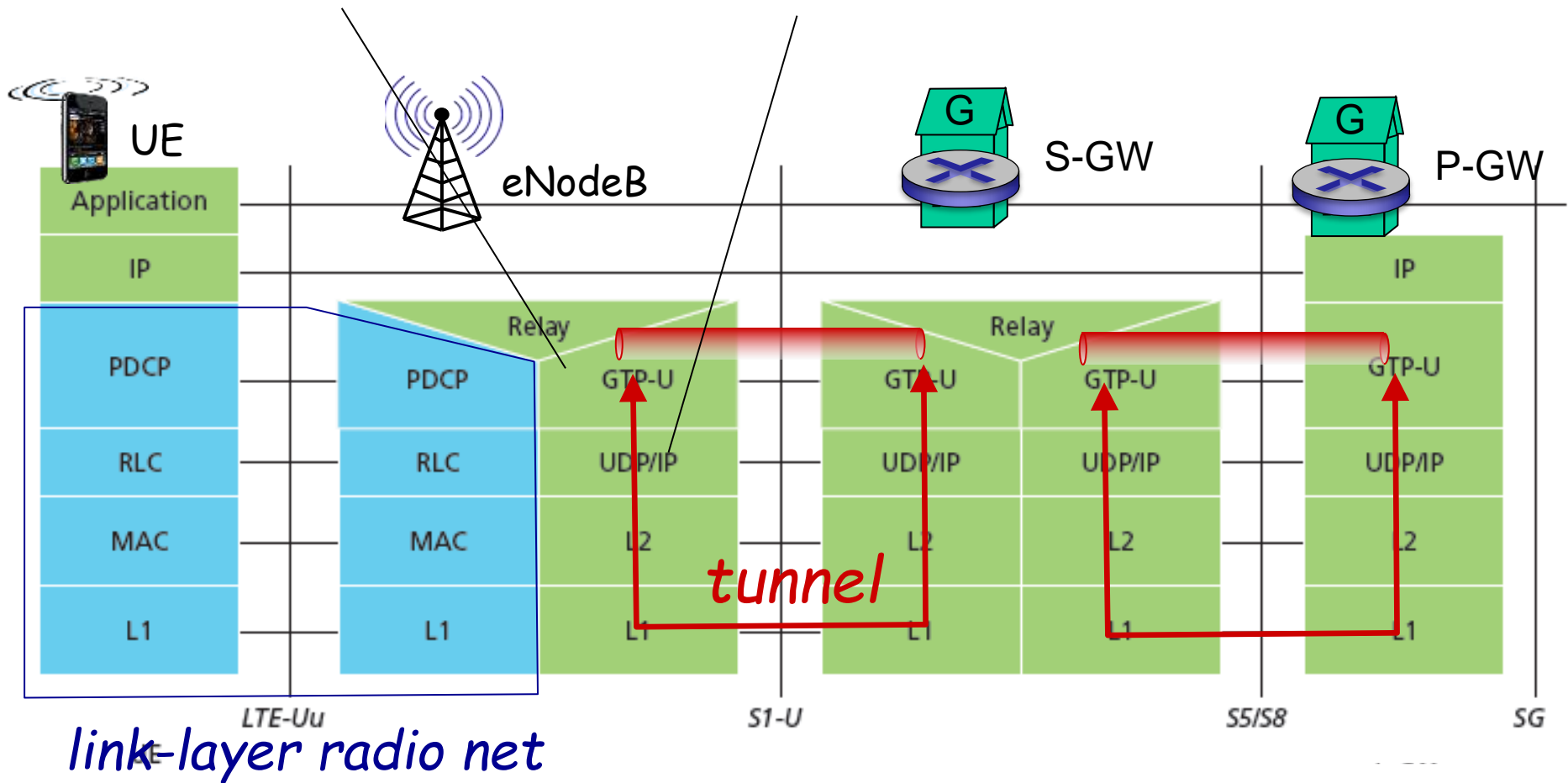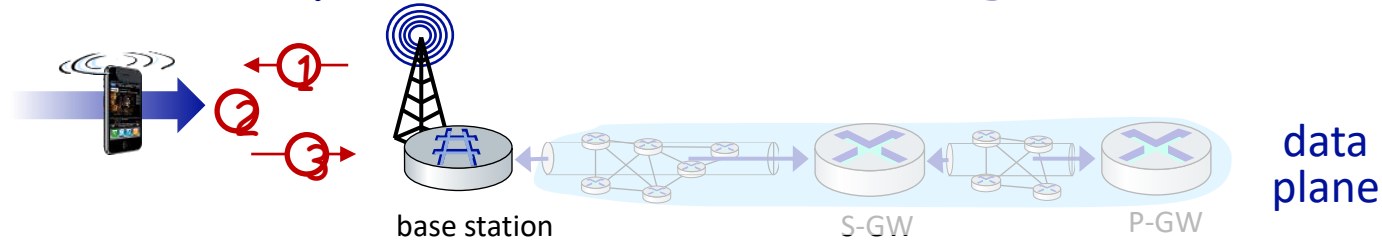 - 100's Mbps per device possible
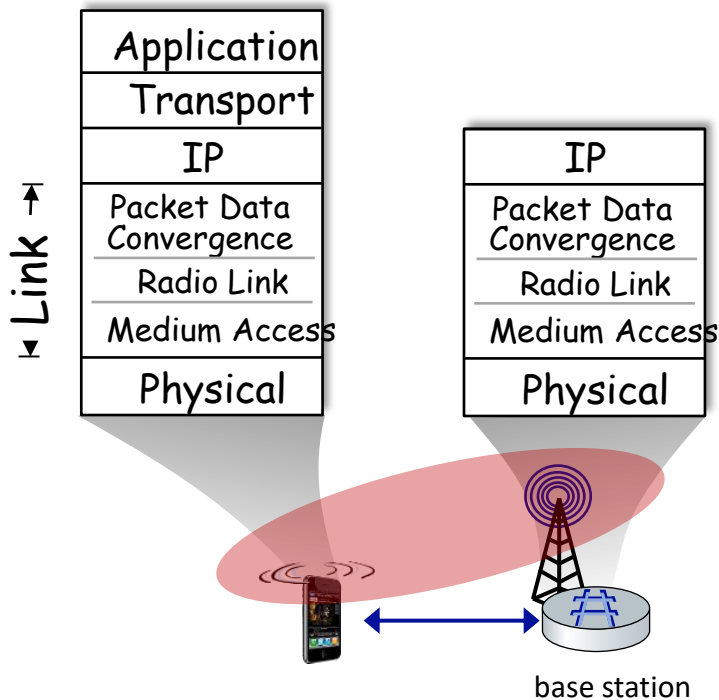
LTE data plane protocol stack: packet core
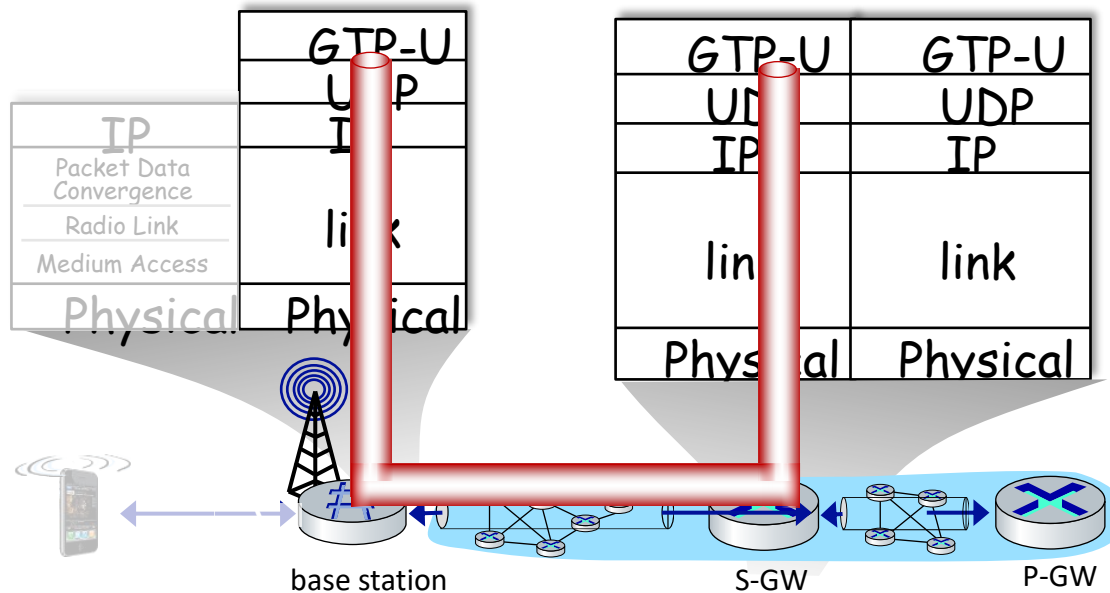
tunneling:

- 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
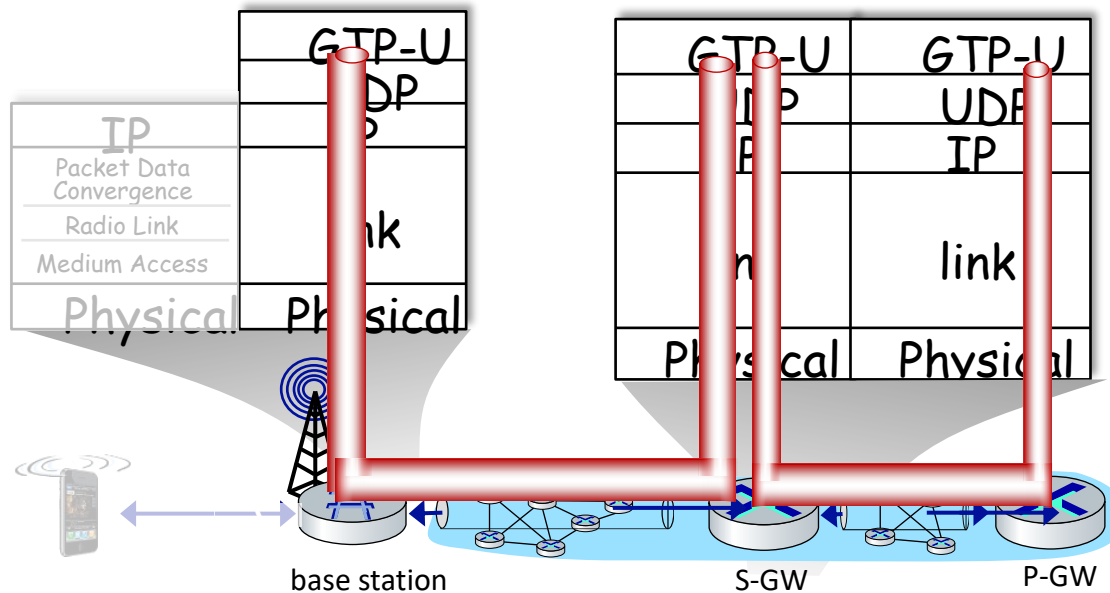
tunneling:

- 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

UE

eNodeB

S-GW

P-GW

| Application |
| IP |
| PDCP |
| RLC |
| MAC |
| L1 |

| PDCP |
| RLC |
| MAC |
| L1 |

| Relay |
| GTP-U |
| UDP/IP |
| L2 |
| L1 |

| GTP-U |
| UDP/IP |
| L2 |
| L1 |

| Relay |
| GTP-U |
| UDP/IP |
| L2 |
| L1 |

| IP |
| GTP-U |
| UDP/IP |
| L2 |
| L1 |

tunnel

LTE-Uu

S1-U

S5/S8

SG

link-layer radio net

LTE data plane: associating with a BS

base station   S-GW   P-GW   data plane

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

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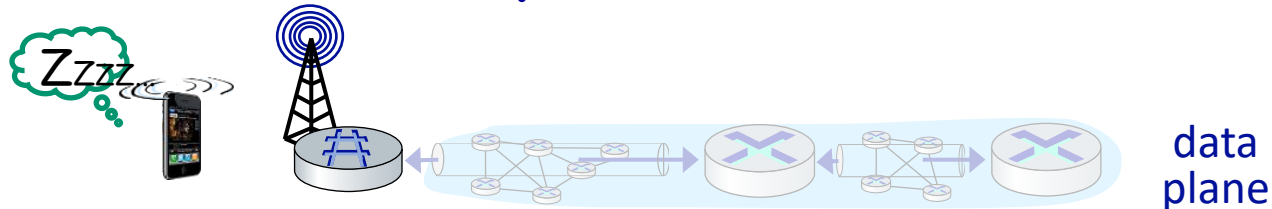
as in WiFi, Bluetooth: LTE mobile may put radio to "sleep" to conserve battery:

- 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

UE

Packet Switched EPC

S1 Interface

eNB

X2

X2

eNB

X2 Interface

eNB

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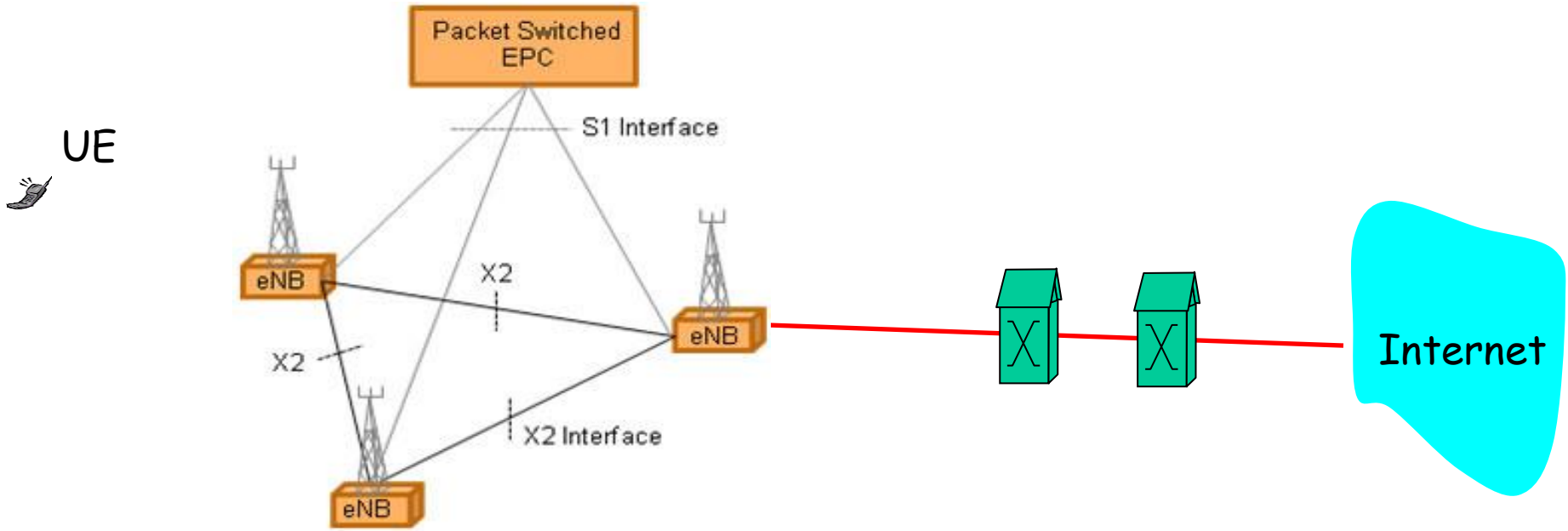
☐ ITU, IMT-advanced, 3GPP, and LTE-Advanced ...

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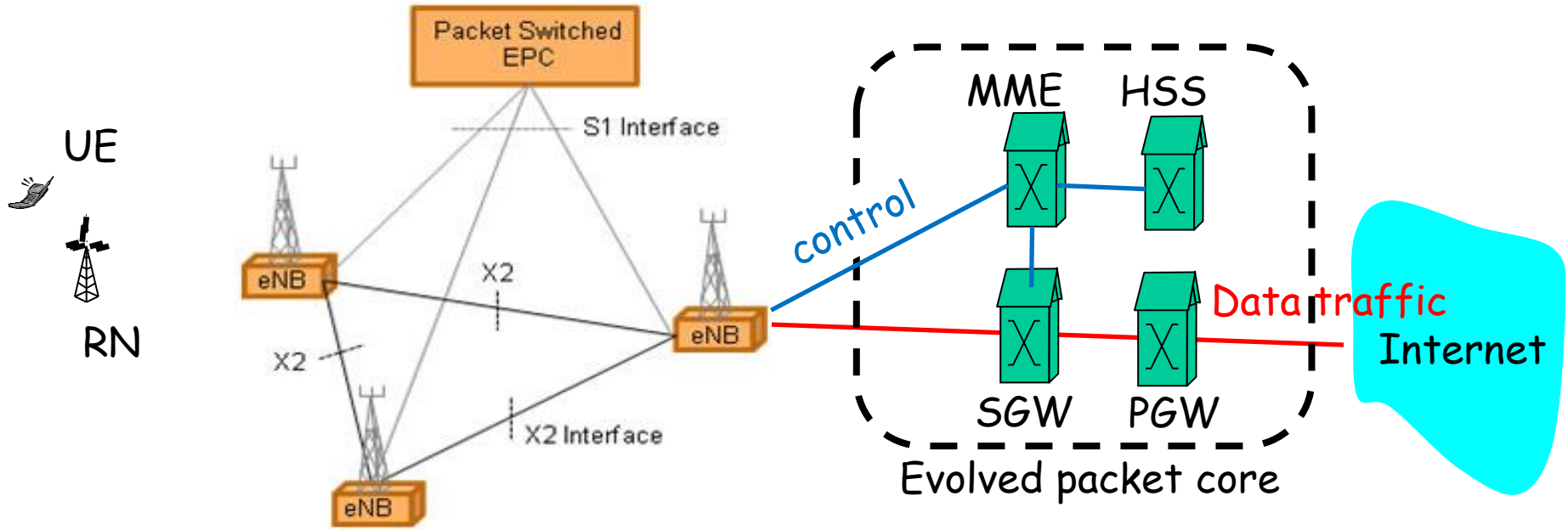
- ☐ ITU, IMT-advanced, 3GPP, and LTE-Advanced ...
- ☐ Relays

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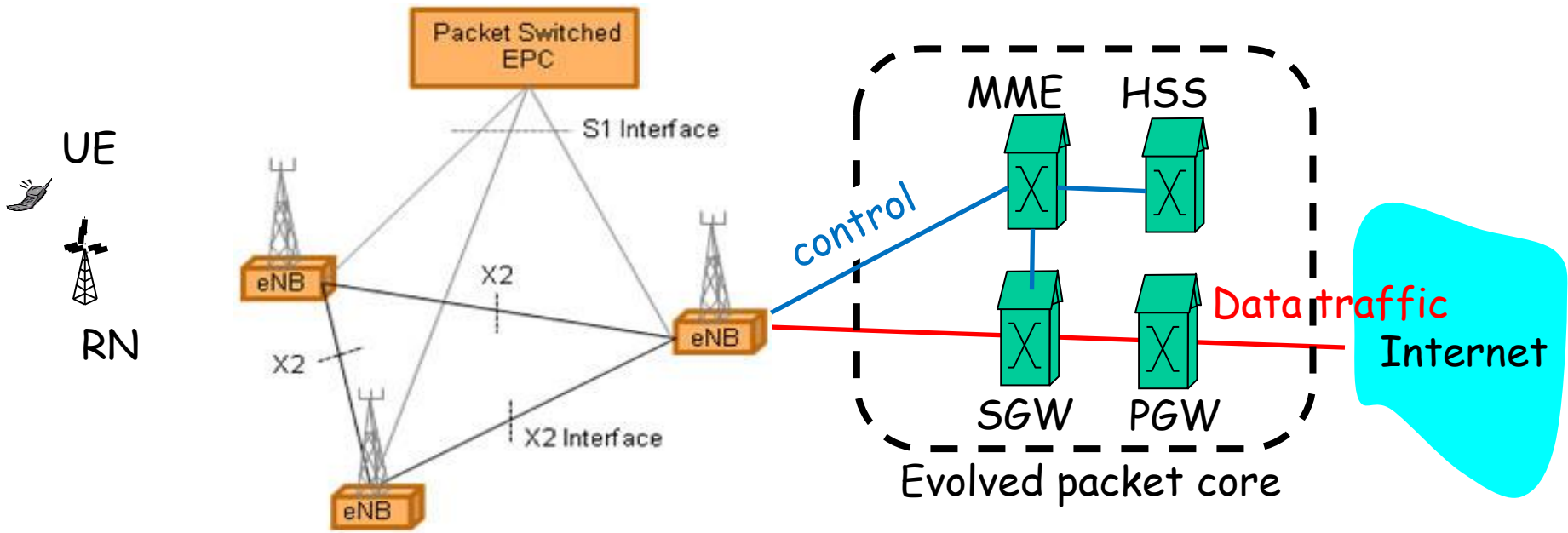
- ITU, IMT-advanced, 3GPP, and LTE-Advanced ...
- Relays
- HetNets etc.
- Carrier aggregation
- Downlink (OFDMA) vs uplink (SC-OFDM)

Overview

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)
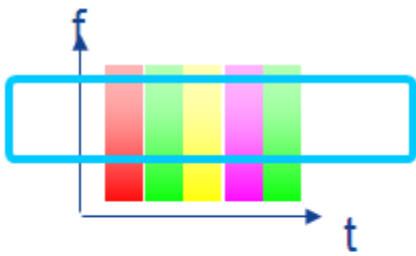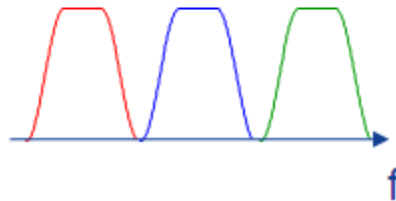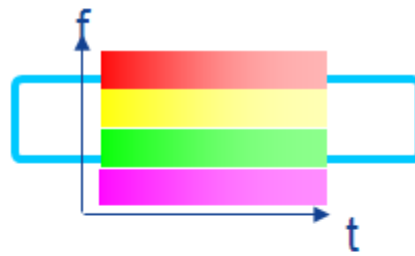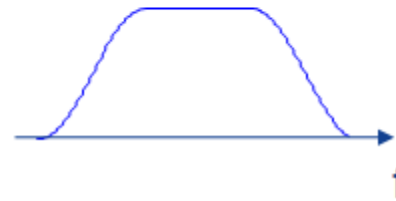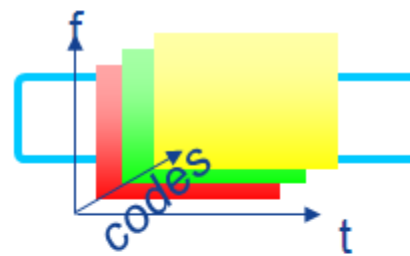
❑ Data symbols are independently modulated and transmitted over a high number of closely spaced orthogonal subcarriers.

❑ Available modulation schemes for E-UTRA downlink: QPSK, 16QAM, and 64QAM (with 2, 4 , and 6 bits/symbol, respectively)

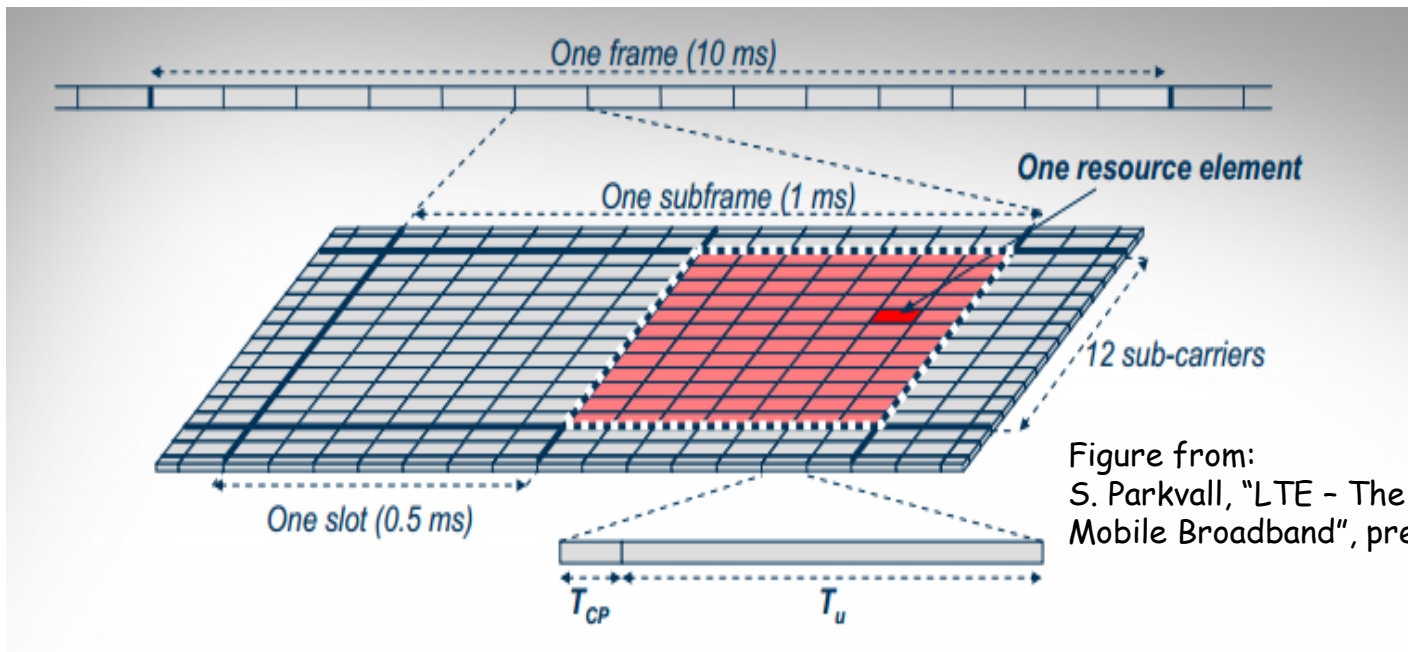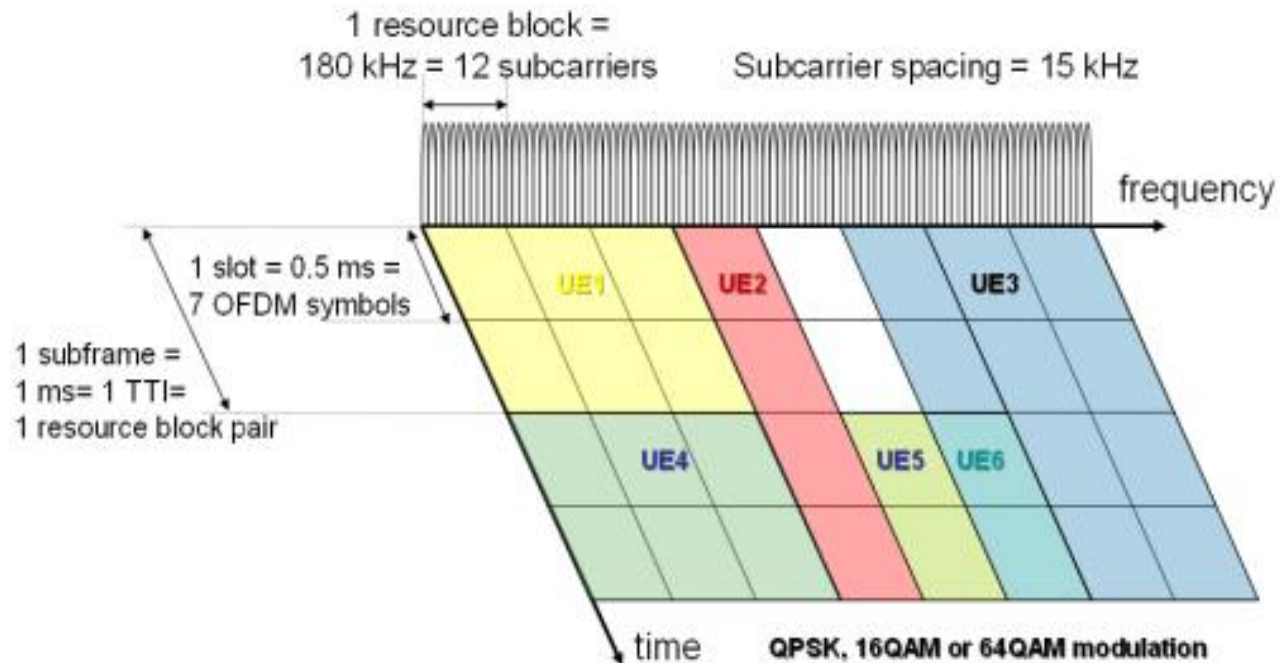❑ OFDM signal is generated using Inverse Fast Fourier Transform (IFFT) digital signal processing*f*

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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)
☐ ƒ **Resource element (RE)**
   ○ One subcarrier during one OFDM symbol
☐ ƒ **Resource block (RB)**
   ○ 12 subcarriers during one slot (180 kHz × 0.5 ms)

1 resource block =
180 kHz = 12 subcarriers   Subcarrier spacing = 15 kHz

frequency

1 slot = 0.5 ms =
7 OFDM symbols

UE1   UE2   UE3

1 subframe =
1 ms= 1 TTI=
1 resource block pair
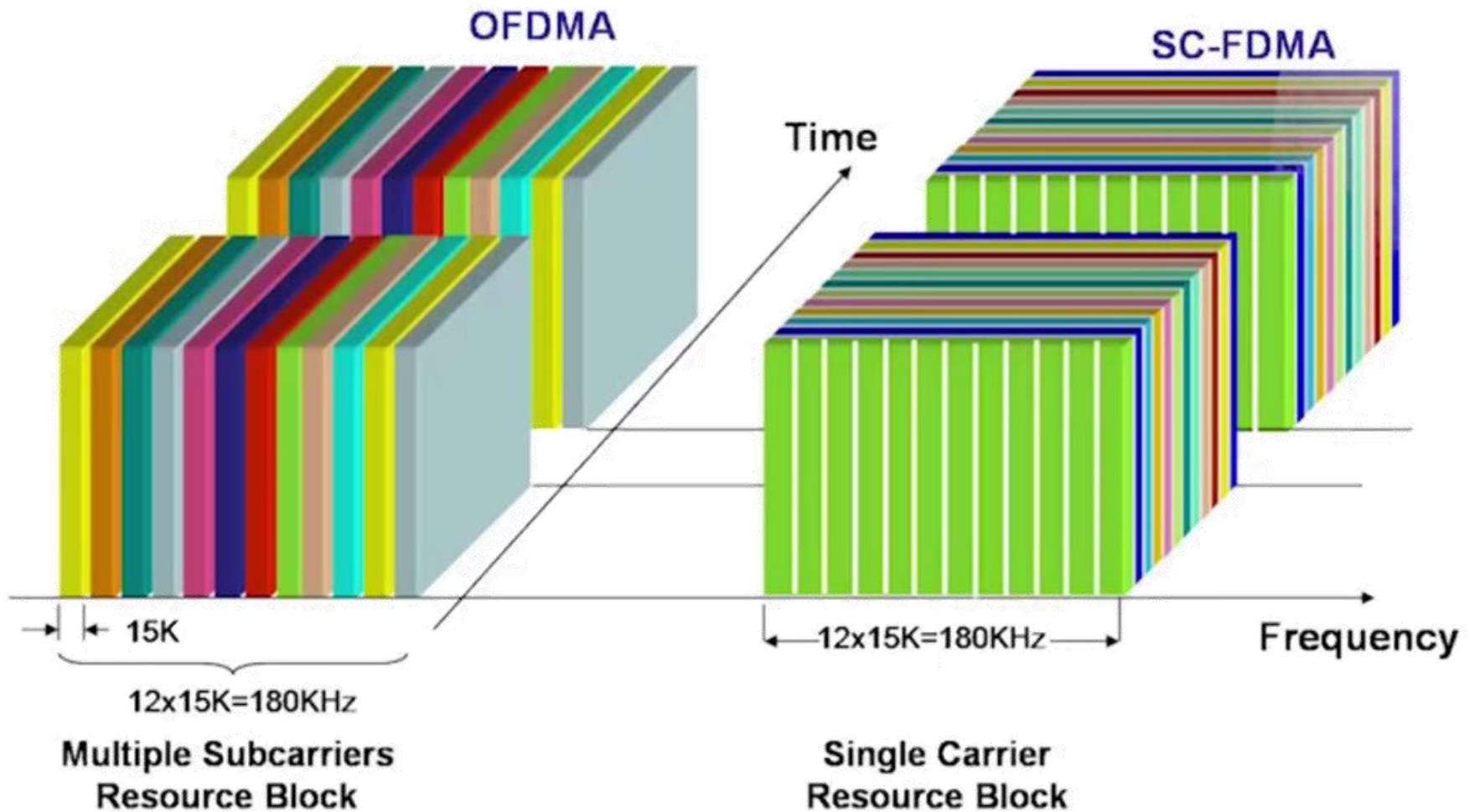
UE4   UE5 UE6

time   QPSK, 16QAM or 64QAM modulation

- 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
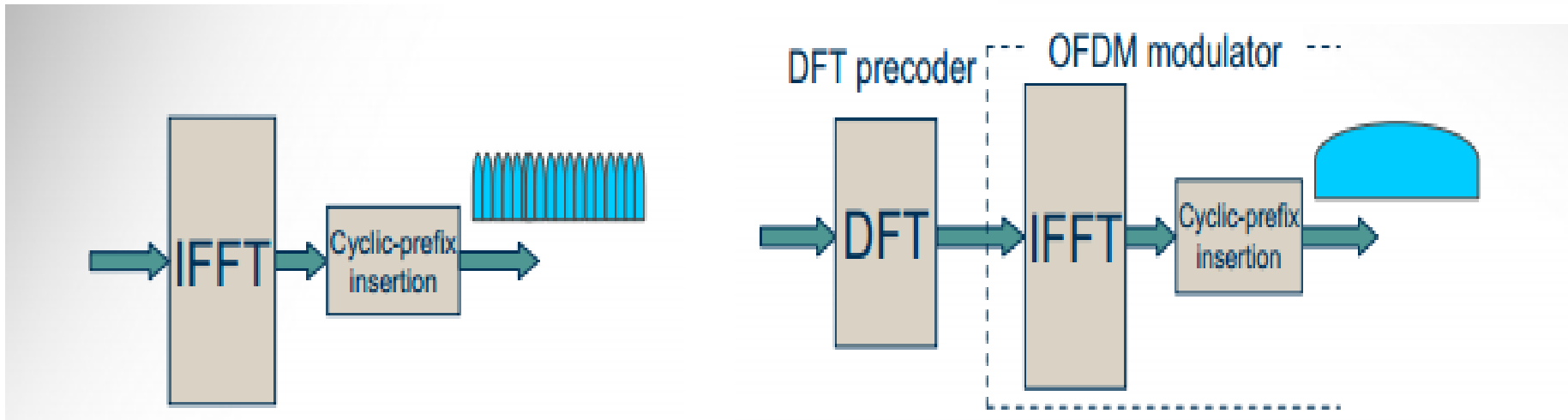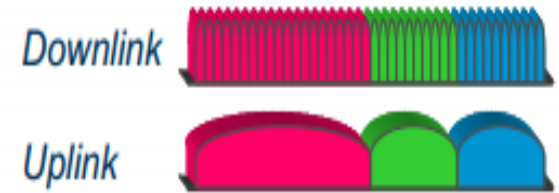 - Quality of Service requirements
  - Service priorities, etc.

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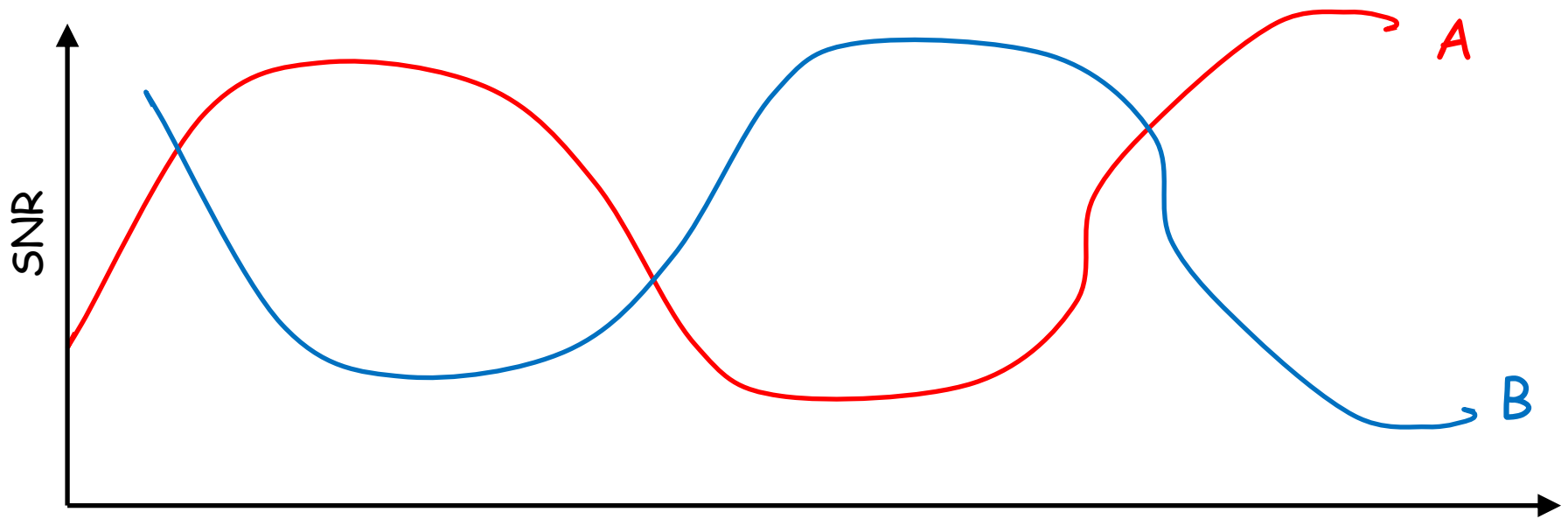
□ Scheduling decisions done in the base station
□ Scheduling algorithm is a vendor-specific, but typically takes into account
  ○ Radio link quality situation of different users
  ○ Overall interference situation
  ○ Quality of Service requirements
  ○ Service priorities, etc.

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

Downlink vs Uplink

OFDMA

SC-FDMA

Time

Frequency

15K

12x15K=180KHz

12x15K=180KHz

Multiple Subcarriers Resource Block

Single Carrier Resource Block

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Downlink vs uplink

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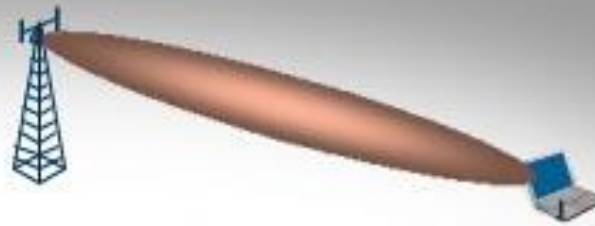- Robust to time dispersion
- ƒ Bad power-amplifier efficiency

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

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Multi-antenna (*slide from Ericsson)
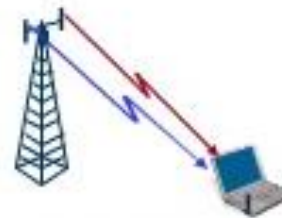

Multi-Antenna Transmission Techniques

Diversity for improved system peformance

Beam-forming for improved coverage (less cells to cover a given area)

SDMA for improved capacity (more users per cell)

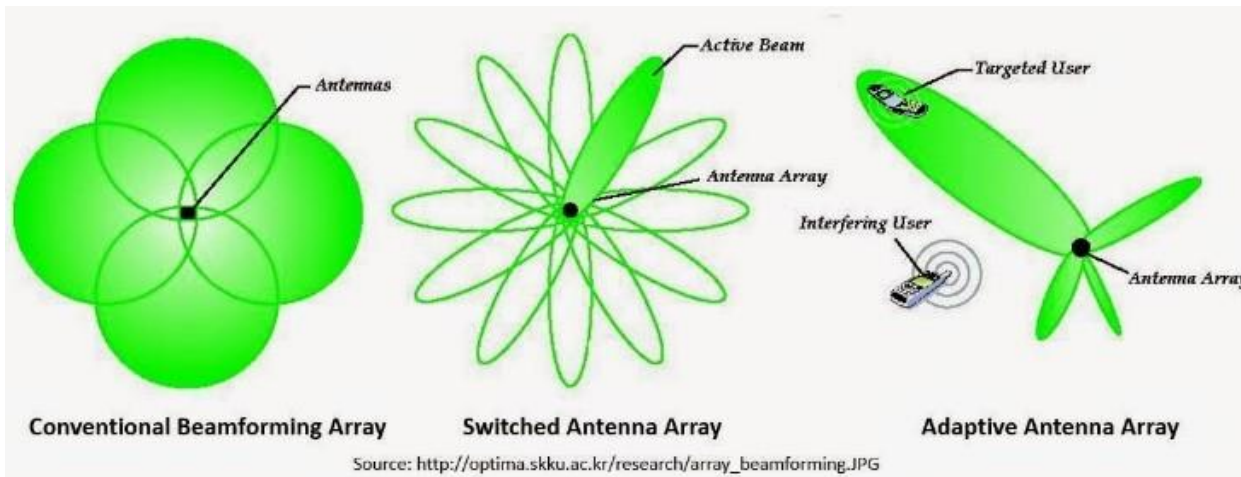**Multi-layer transmisson** ("MIMO") for higher data rates in a given bandwidth

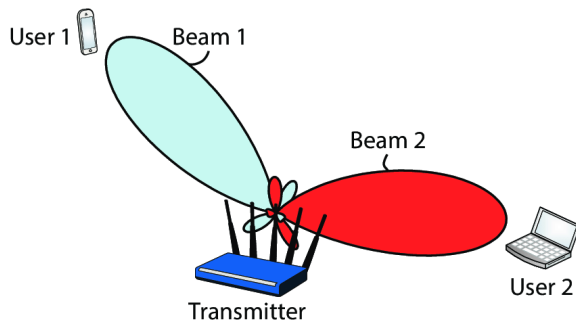The multi-antenna technique to use depends on what to achieve

Ericsson Confidential   22

2009-04-20   ERICSSON

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Beamforming

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

Conventional Beamforming Array   Switched Antenna Array   Adaptive Antenna Array

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

Multi-antenna examples

Spatial multiplexing

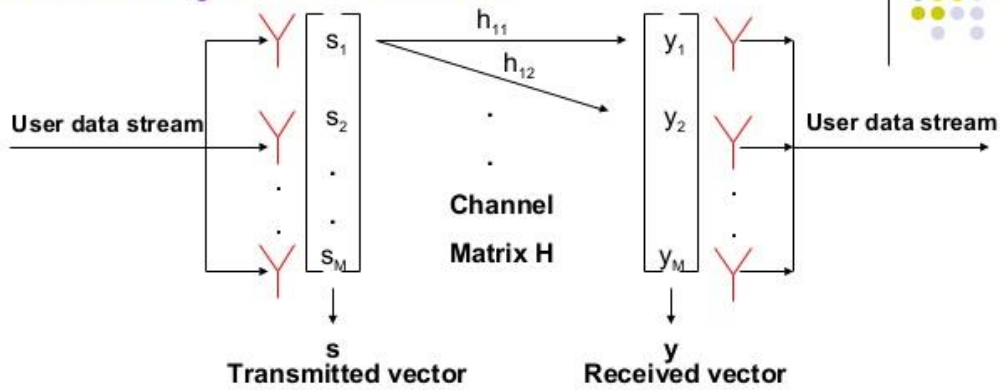Determine the time delay to locations of users and adjust phase accordingly …

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 $1-p^M$.

Diversity for improved system performance

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MIMO System Model

Where $\mathbf{H} = M_R$

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{21} & \cdots & h_{M1} \\ h_{12} & h_{22} & \cdots & h_{M2} \\ \cdot & \cdot & \cdots & \cdot \\ h_{1M} & h_{2M} & \cdots & h_{MM} \end{bmatrix}$$

h_{ij} is a Complex Gaussian random variable that models fading gain between the ith transmit and jth receive antenna

$$y = Hs + n$$

Precoding

Filtering

$$H = \begin{bmatrix} h_{1,1} & \cdots & h_{1,K} \\ \vdots & \ddots & \vdots \\ h_{M,1} & \cdots & h_{M,K} \end{bmatrix}$$

$y = H\,s + n$

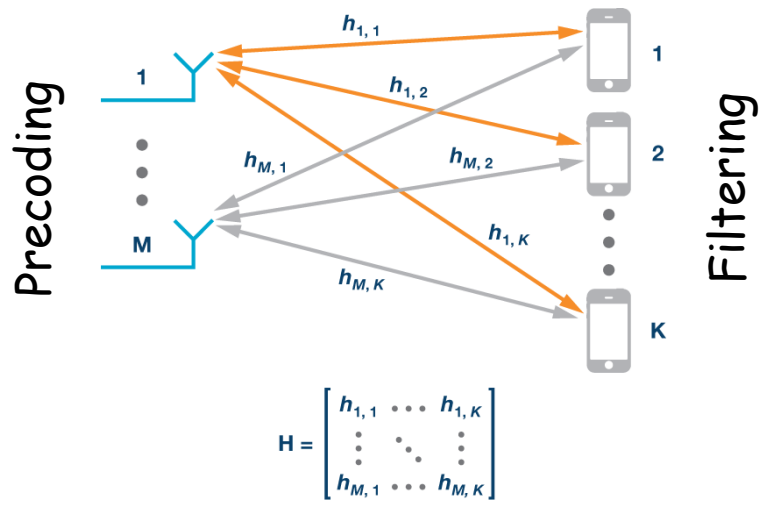*One example receiver side estimate …*

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

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

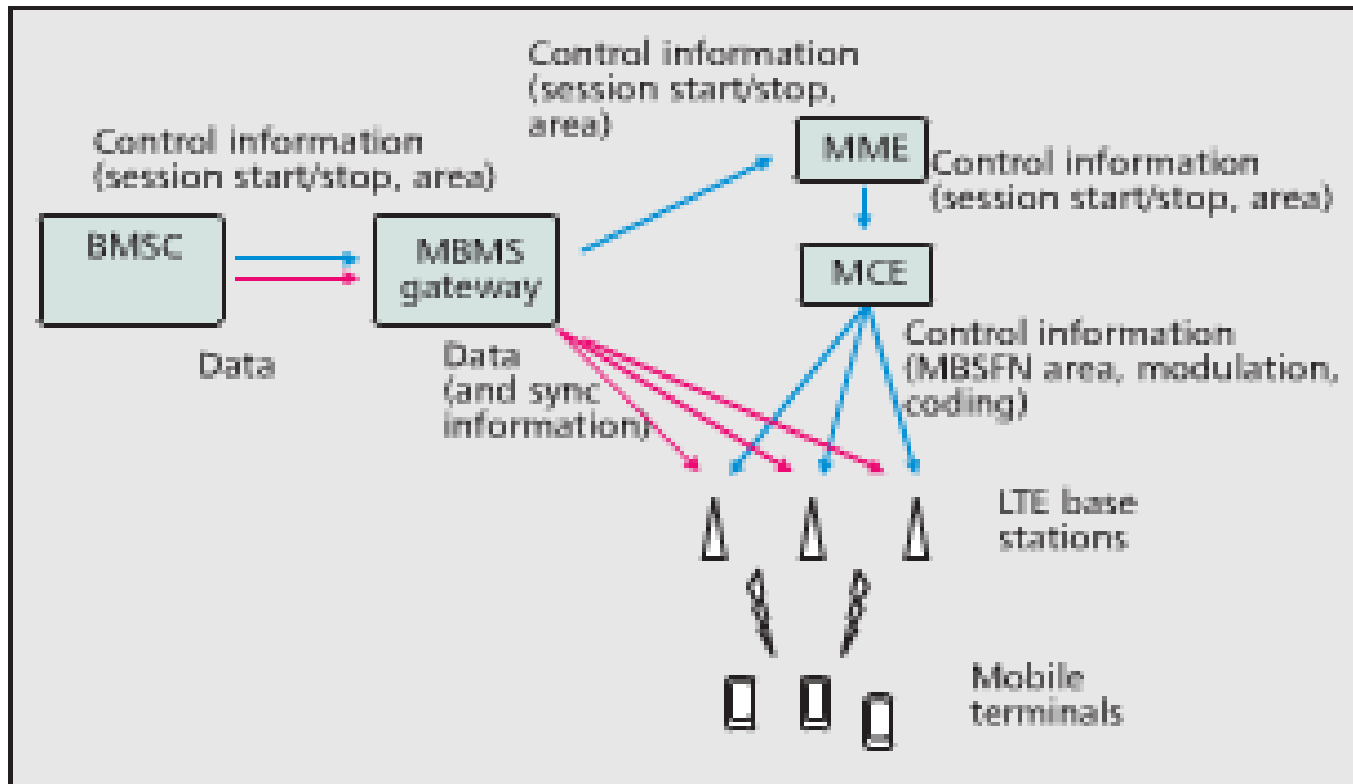# Evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-advanced

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.

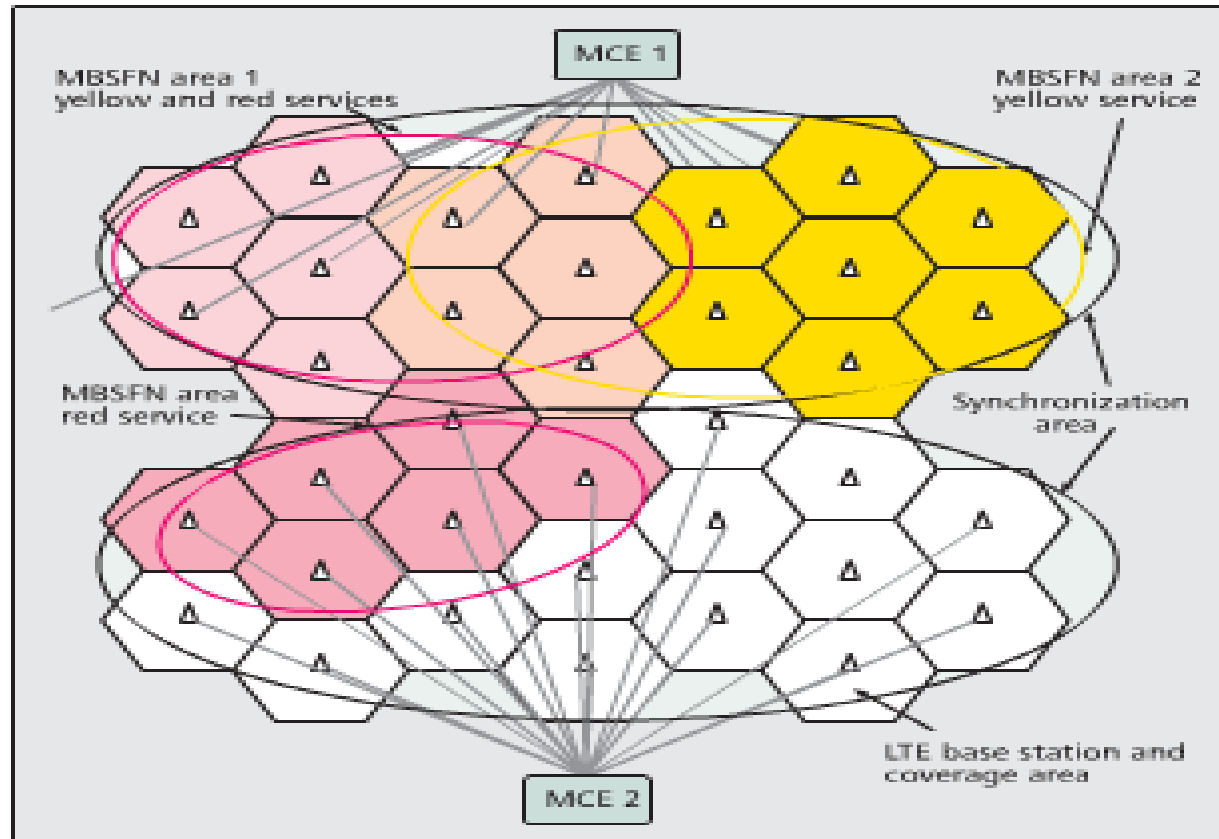# Evolved Multimedia Broadcast/Multicast Service (eMBMS) in LTE-advanced

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.

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Global cellular network: a network of IP networks
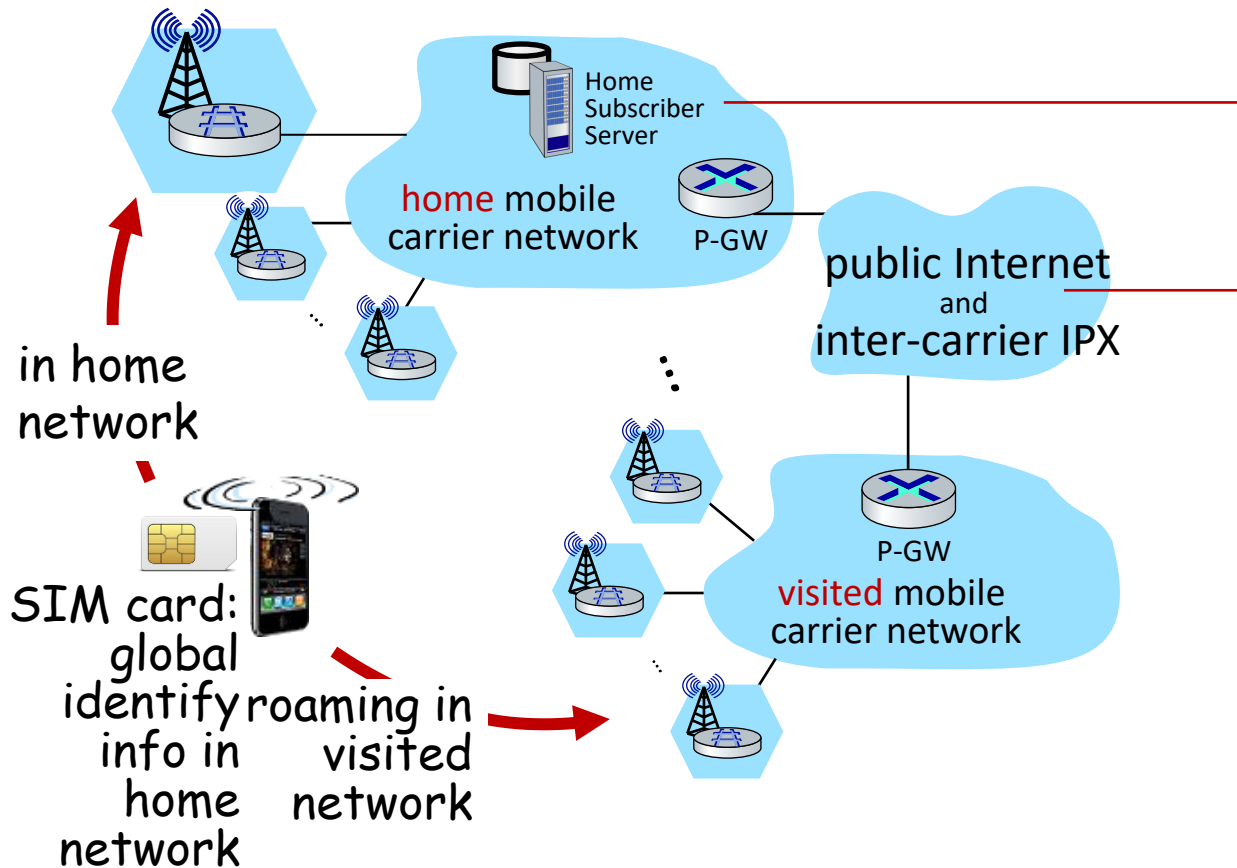
home network HSS:
- identify & services info, while in home network and roaming

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. ...
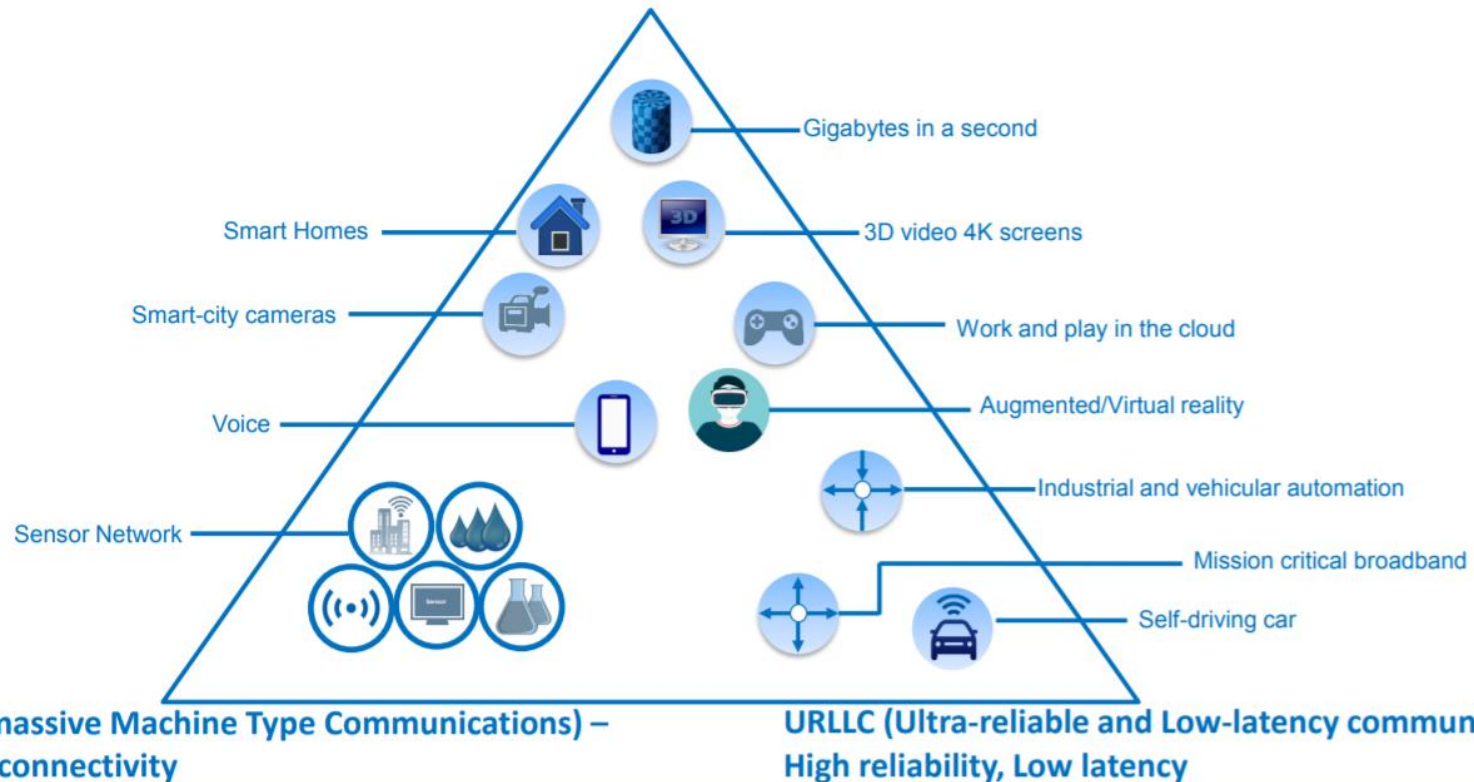
5G NR (New radio) aspects

- 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)
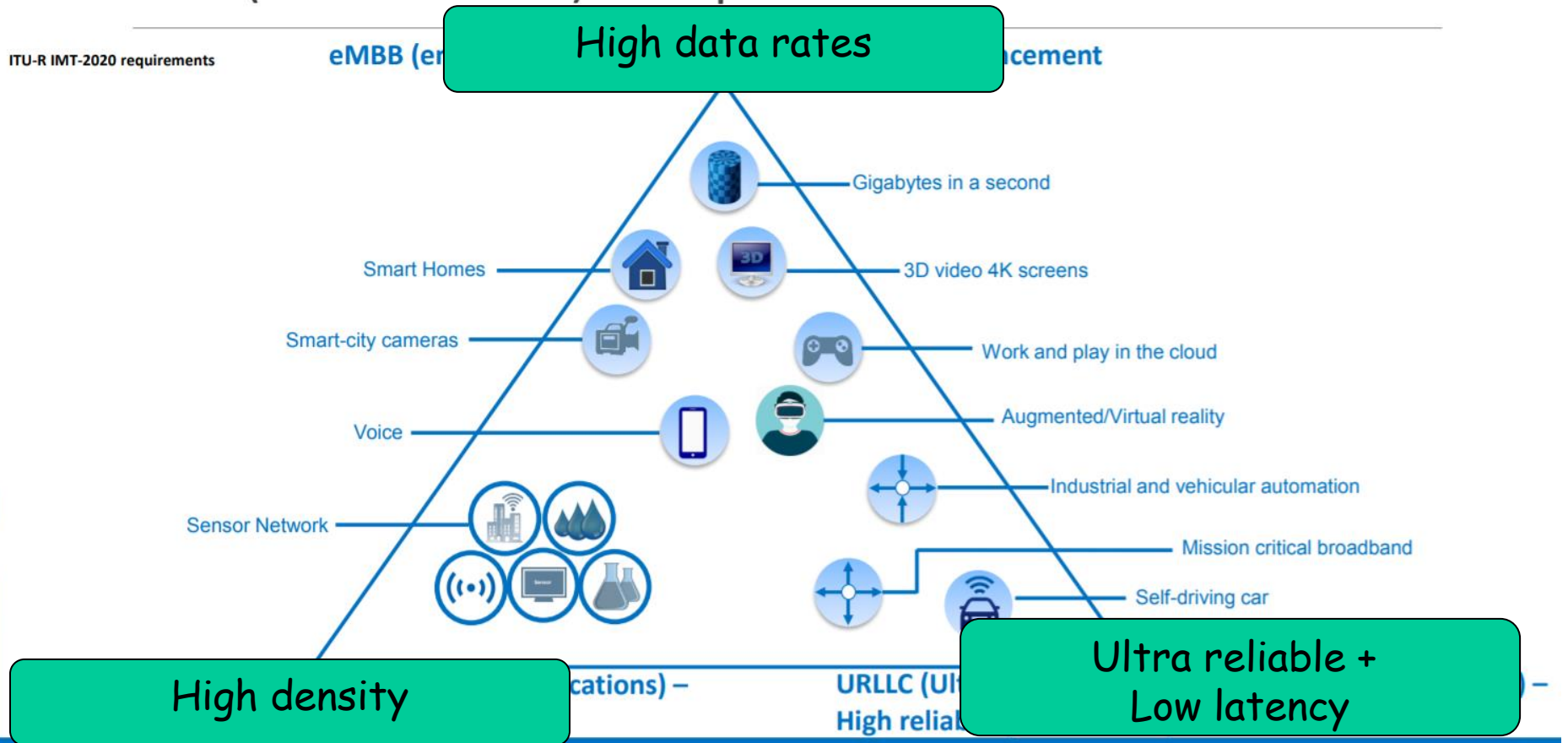
... wish list ...

5G High Level Requirements and Wish List
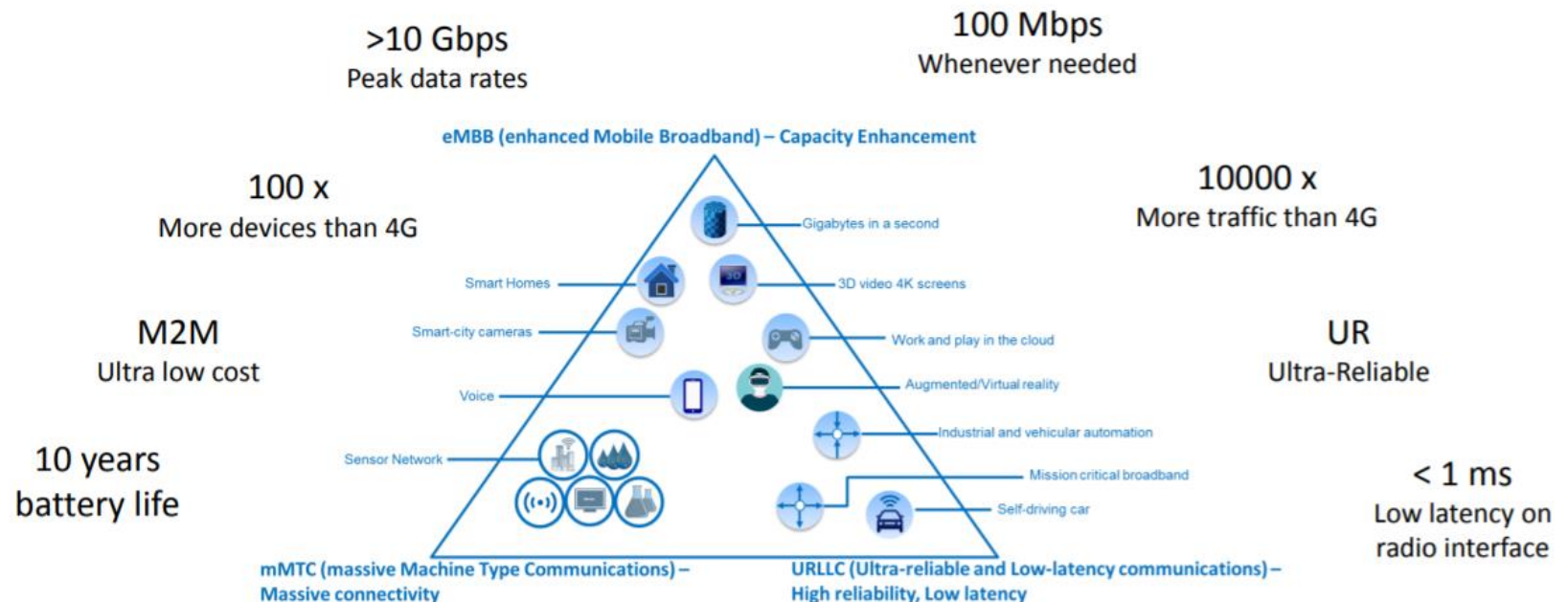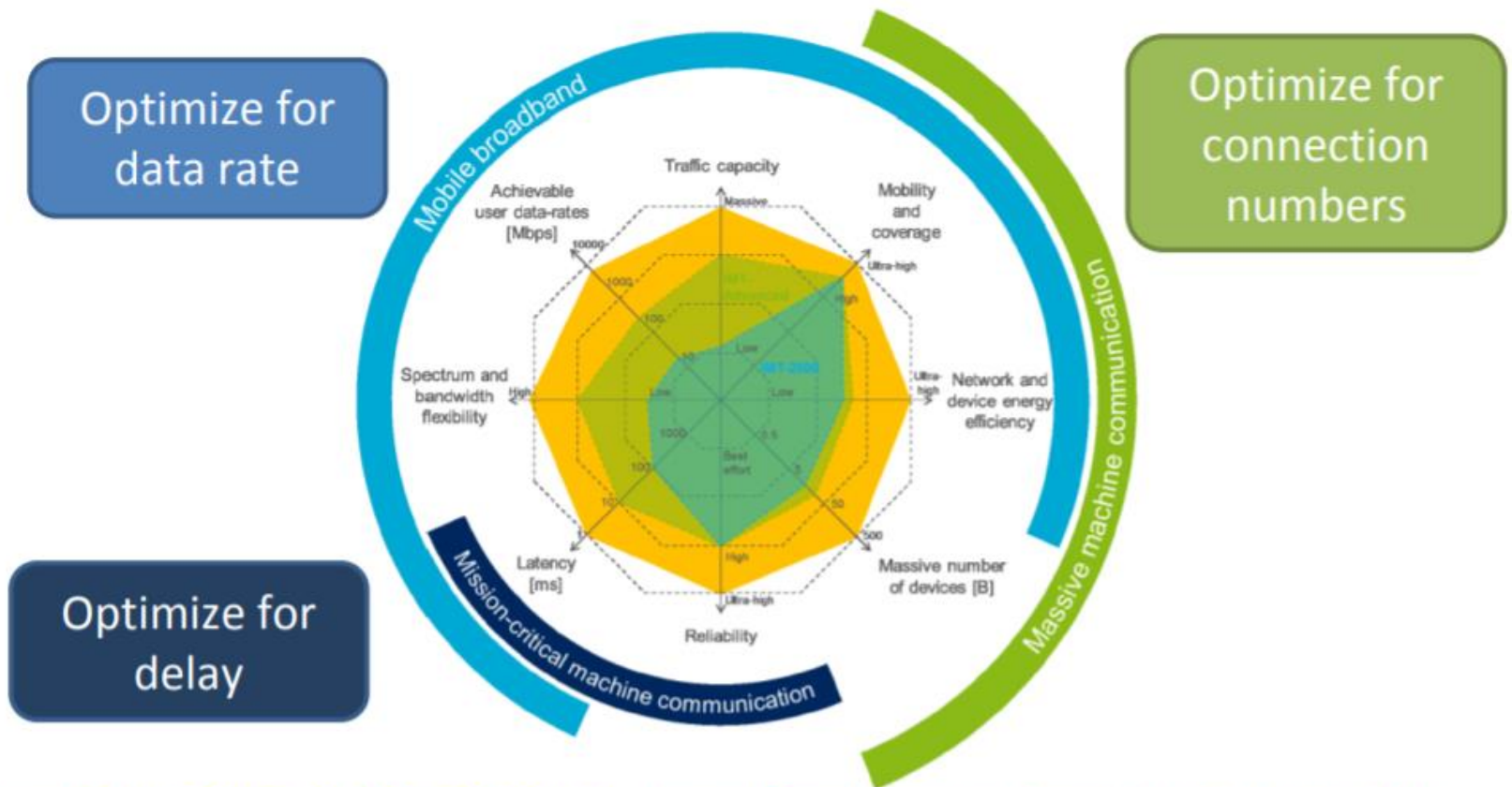
5G goals/targets/requirements ...

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

eNodeB

- Inter-cell RRM
- RB control
- Connection Mobility Control
- Radio Admission Control
- eNB measurement configuration and provision
- Dynamic resource allocation (scheduler)
- RRC
- PDCP
- RLC
- MAC
- PHY

E-UTRAN

S1

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

MME

- NAS security
- Idle state mobility handling
- EPS Bearer Control

holds idle UE info
QoS enforcement

S-GW

- Mobile anchoring

P-GW

- UE IP address allocation
- Packet filtering

EPC

Internet