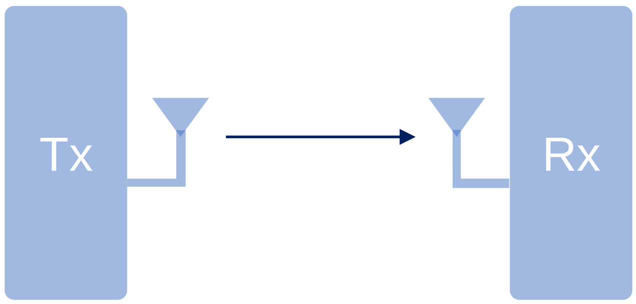
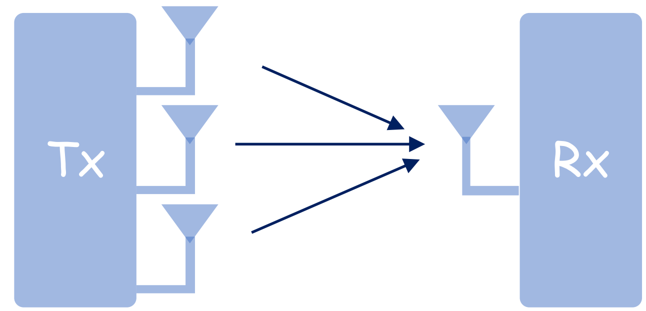
The IEEE 802.11 family of standards

continued

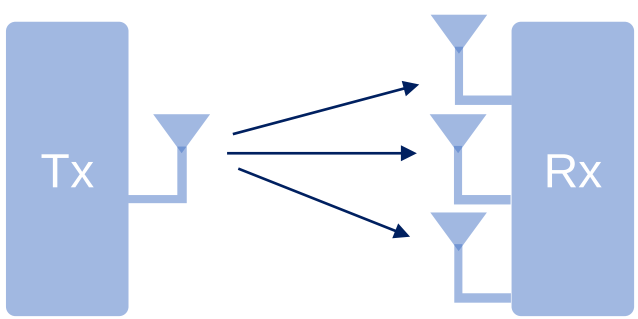
MIMO



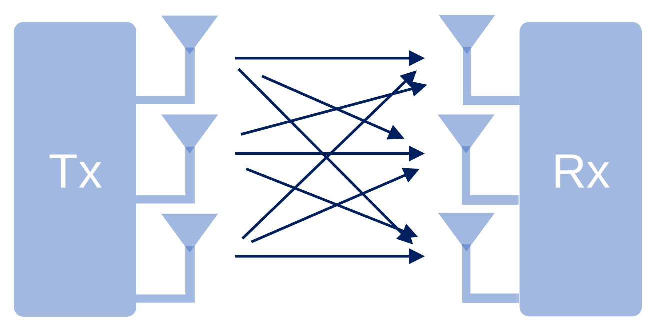
SISO (Single Input Single Output)



MISO (Multiple Input Single Output)



SIMO (Single Input Multiple Output)

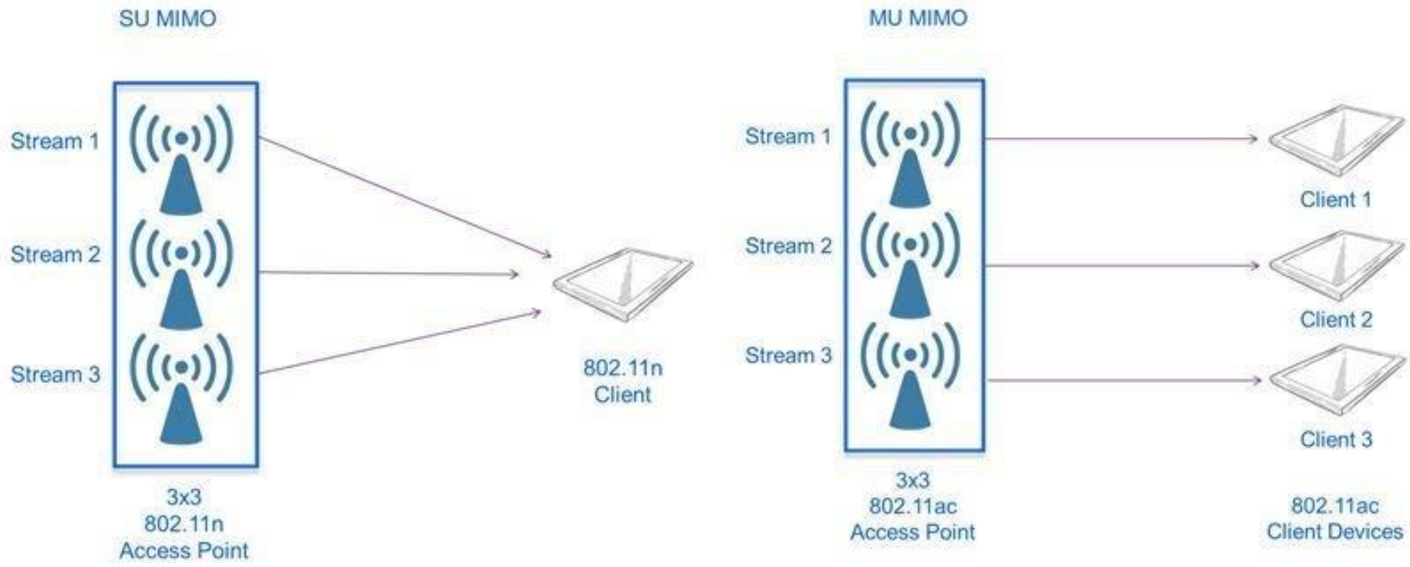


MIMO (Multiple Input Multiple Output)

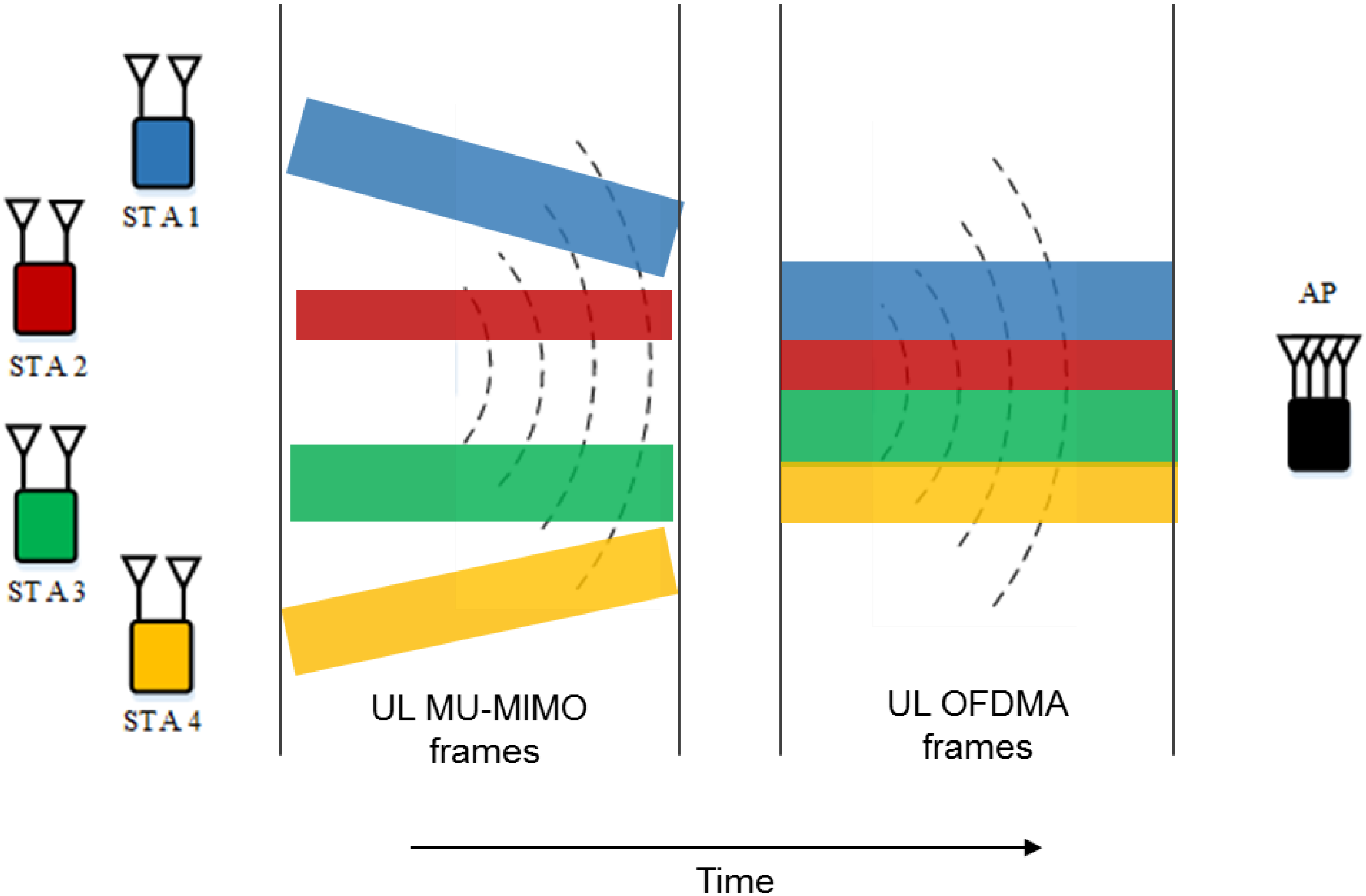
802.11 PHY enhancements

	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6	Wi-Fi 6E	Wi-Fi 7
Launch date	2007	2013	2019	2021	2024 (expected)
IEEE standard	802.11n	802.11ac	802.11ax		802.11be
Max data rate	1.2 Gbps	3.5 Gbps	9.6 Gbps		46 Gbps
Bands	2.4 GHz, 5 GHz	5 GHz	2.4 GHz, 5 GHz	6 GHz	2.4 GHz, 5 GHz, 6 Hz
Channel size	20, 40 MHz	20, 40, 80 80+80, 160 MHz	20, 40, 80 80+80, 160 MHz		Up to 320 MHz
Modulation	64-QAM	256-QAM	1024-QAM		4096-QAM
MIMO	4×4 MIMO	4×4 MIMO, DL MU-MIMO	8×8 UL/DL MU-MIMO		16×16 UL/DL MU-MIMO

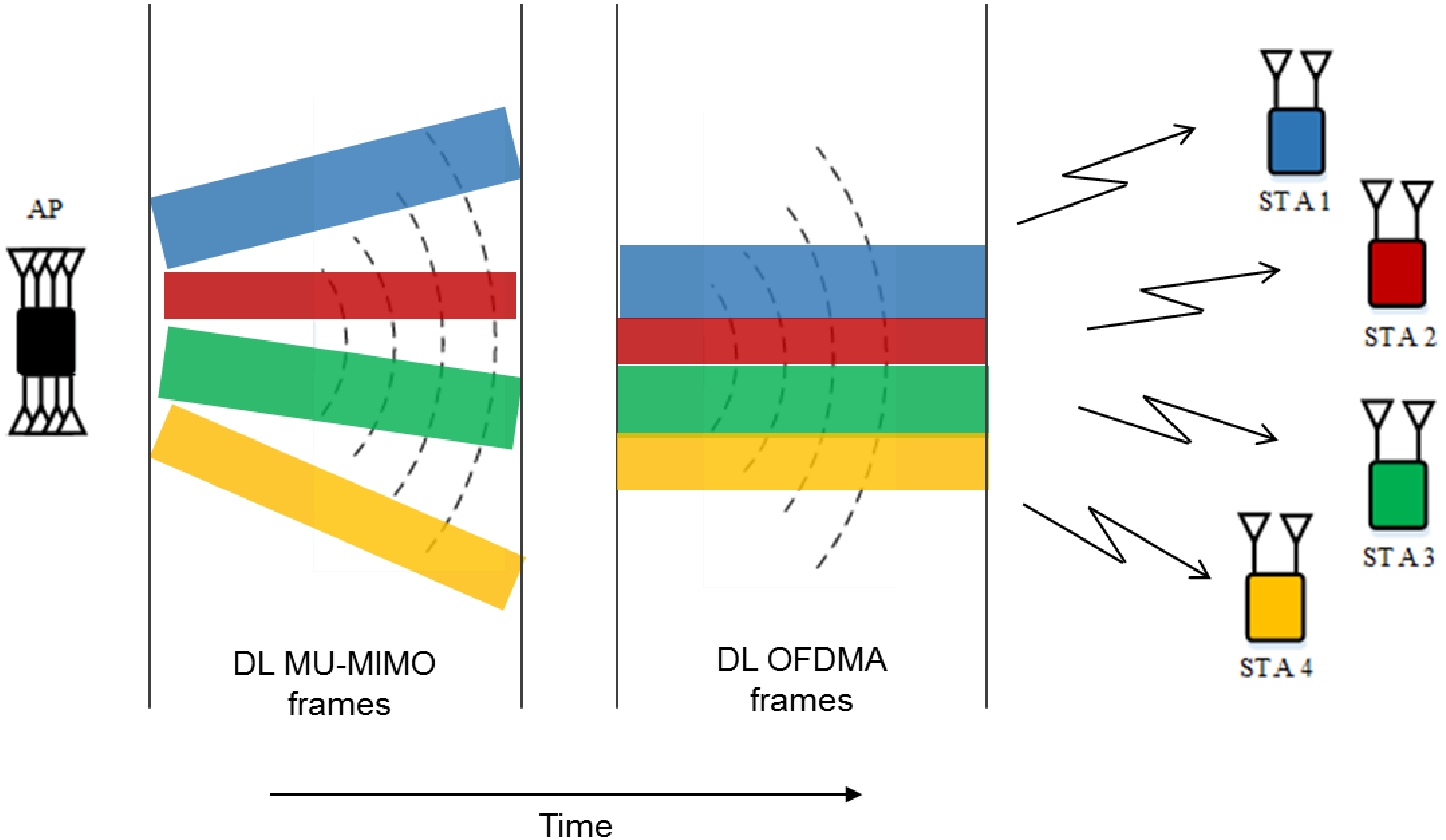
SU/MU-MIMO


SU MIMO
Stream 1
Stream 2
Stream 3
3x3
802.11n
Access Point
802.11n
Client
MU MIMO
Stream 1
Stream 2
Stream 3
3x3
802.11ac
Access Point
Client 1
Client 2
Client 3
802.11ac
Client Devices

UL MU-MIMO



DL MU-MIMO



MIMO in 802.11n

MCS index	Modulation	Coding rate	Antennas	20 MHz Mbps	40 MHz Mbps
0	BPSK	1/2	1	6.5	13.5
1	QPSK	1/2	1	13	27
2	QPSK	3/4	1	19.5	40.5
3	16-QAM	1/2	1	26	54
4	16-QAM	3/4	1	39	81
5	64-QAM	2/3	1	52	108
6	64-QAM	3/4	1	58.5	121.5
7	64-QAM	5/6	1	65	135

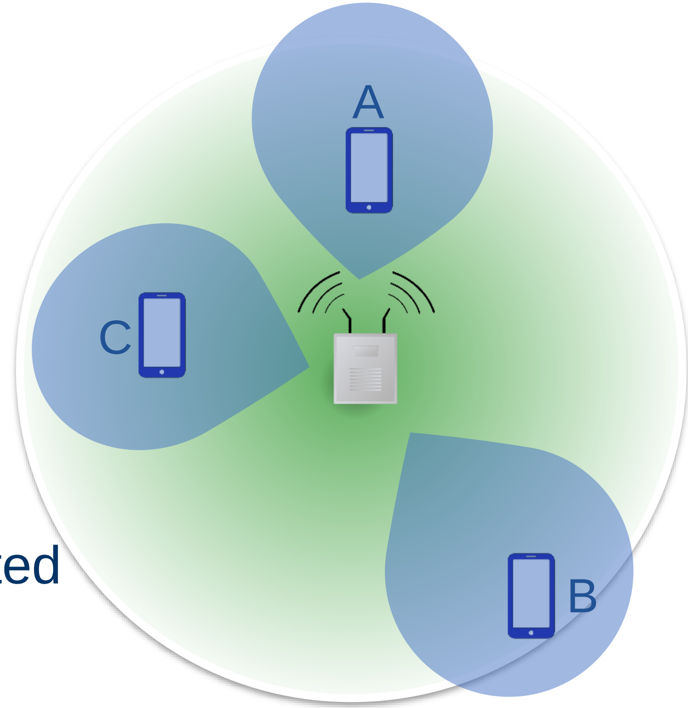
MCS index	Modulation	Coding rate	Antennas	20 MHz Mbps	40 MHz Mbps
8	BPSK	1/2	2	13	27
9	QPSK	1/2	2	26	54
10	QPSK	3/4	2	39	81
11	16-QAM	1/2	2	52	108
12	16-QAM	3/4	2	78	162
13	64-QAM	2/3	2	104	216
14	64-QAM	3/4	2	117	243
15	64-QAM	5/6	2	130	270

MIMO in 802.11ac

MCS index	Modulation	Coding rate	160 MHz Data rate (Mbps)			
			1x1	2x2	4x4	8x8
0	BPSK	1/2	65	130	260	520
1	QPSK	1/2	130	260	520	1040
2	QPSK	3/4	195	390	780	1560
3	16-QAM	1/2	260	520	1040	2080
4	16-QAM	3/4	390	780	1560	3120
5	64-QAM	2/3	520	1040	2080	4160
6	64-QAM	3/4	585	1170	2340	4680
7	64-QAM	5/6	650	1300	2600	5200
8	256-QAM	3/4	780	1566	3120	6240
9	256-QAM	5/6	866.7	1733.3	3466.7	6933.3

Omni-directional antenna

- Omni directional antenna
  - Commonly used in 802.11 WiFi networks
- Advantages
  - Coverage in all directions
  - Simpler hardware design
- Disadvantages
  - A large amount of radiated power is wasted

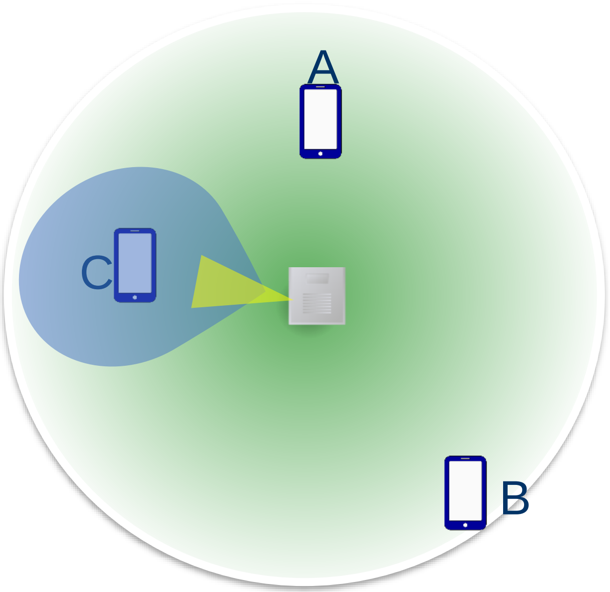


  - Can we concentrate the radiated transmission energy towards the intended receivers?
    - Can increase SNR for intended receivers
    - Reduce interference to other devices

~~Omni-~~directional antenna

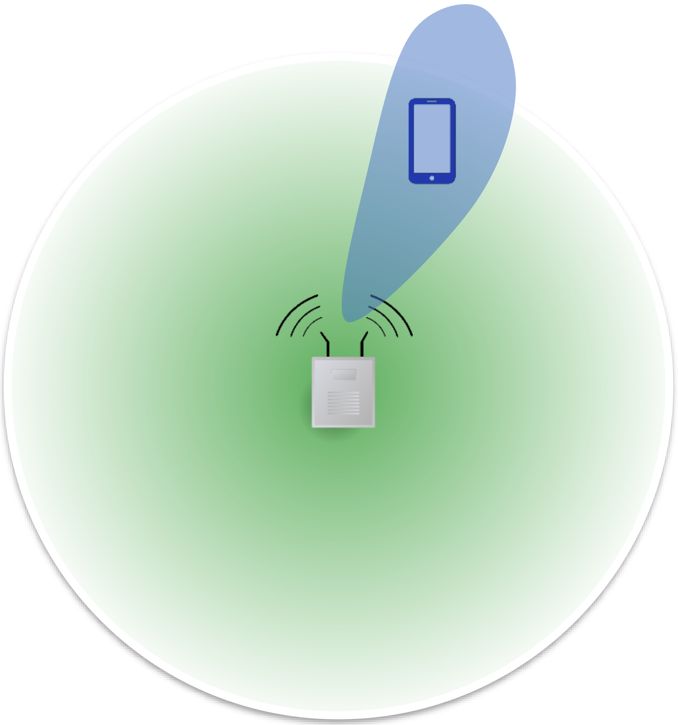
- Directional antenna
  - Widely used in special purpose applications
- Advantages
  - Higher signal strength in desired direction
  - Reduced interference to other devices
- Disadvantages
  - Coverage restricted to some direction
  - Costly - multiple antennas needed for omni coverage, capacity (similar to sectors used in cellular network base stations)

  - Solution – electronic beamforming



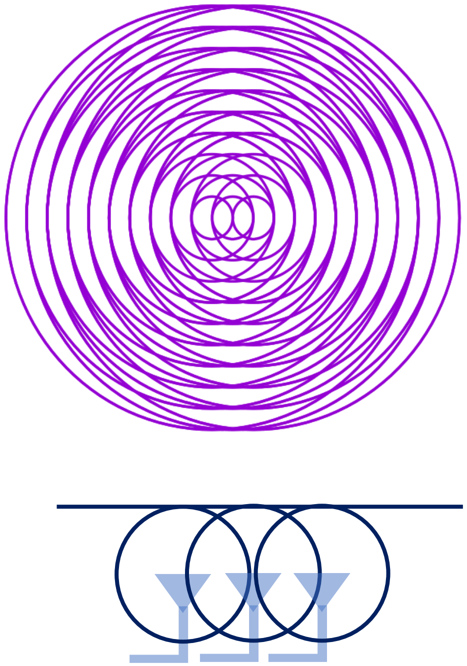
Beamforming

- Beamforming
  - Use omni-directional antennas to focus signal in specific direction
  - Exploit multiple antennas used for MIMO



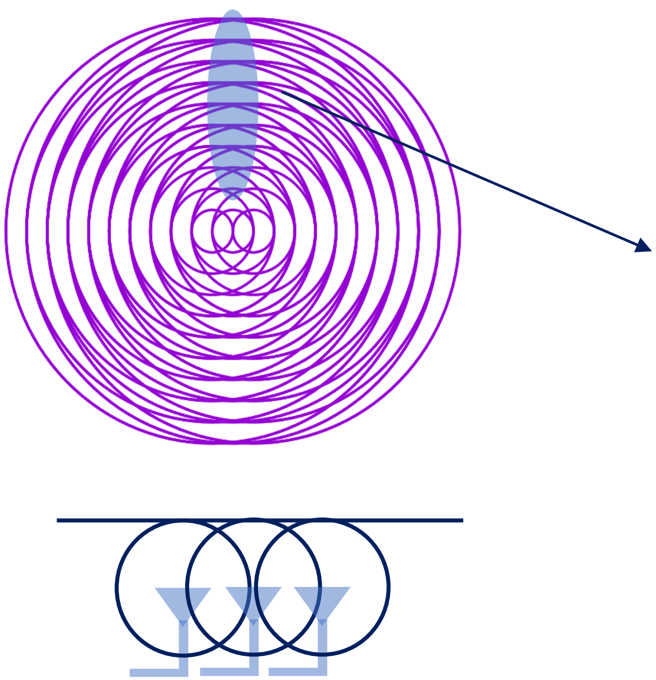
Beamforming

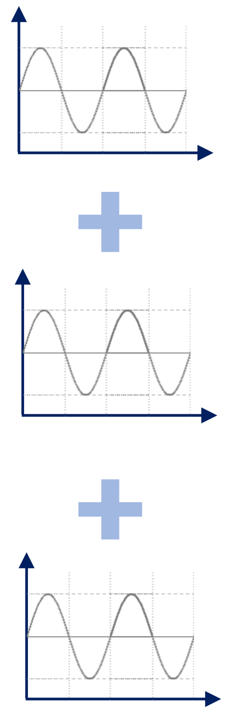
- Beamforming using multiple antenna

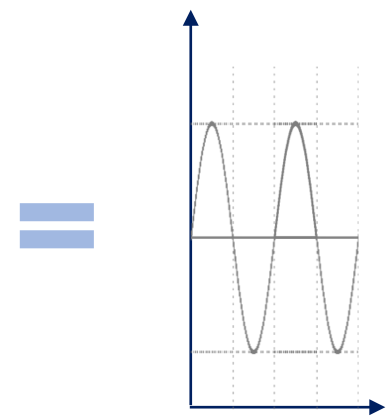


Beamforming

- Beamforming
  - Constructive interference
  - When signal meet in phase, resultant signal strength increases





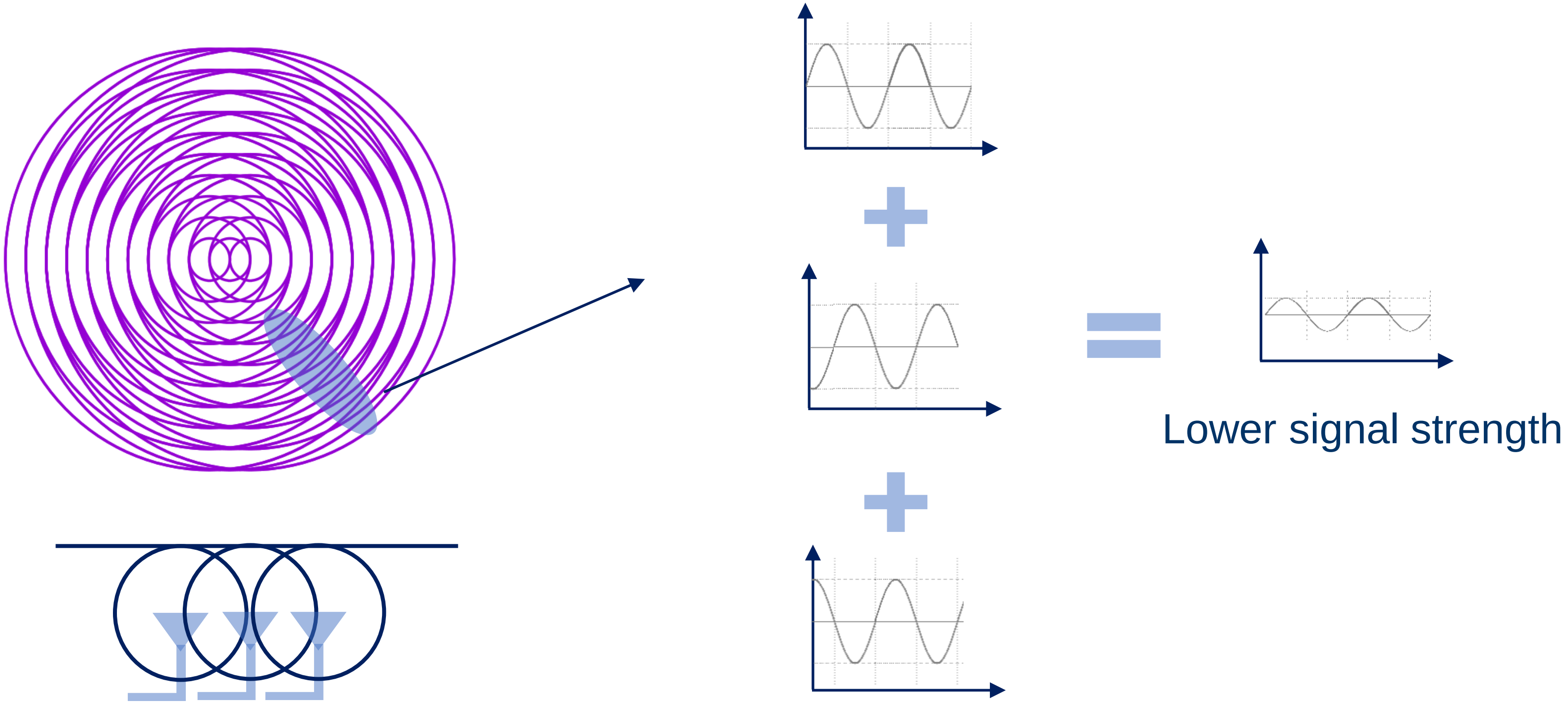


Higher signal strength; 3x in an ideal case

Beamforming

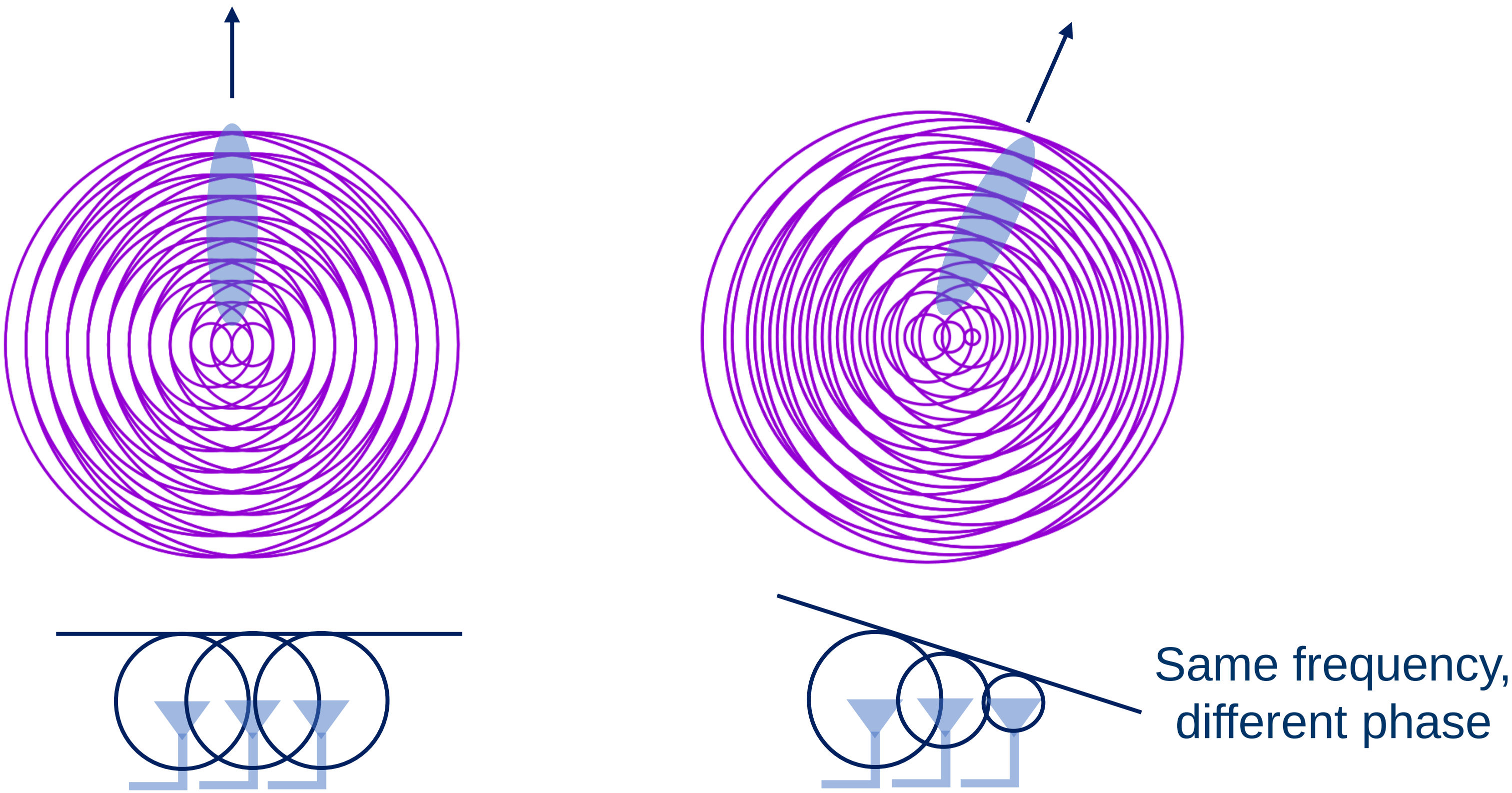
- Beamforming
  - Destructive interference
  - When signal meet out of phase, resultant signal strength weakens

Easier to achieve in higher frequencies, why?
In 5GHz 1wavelength = 6mm

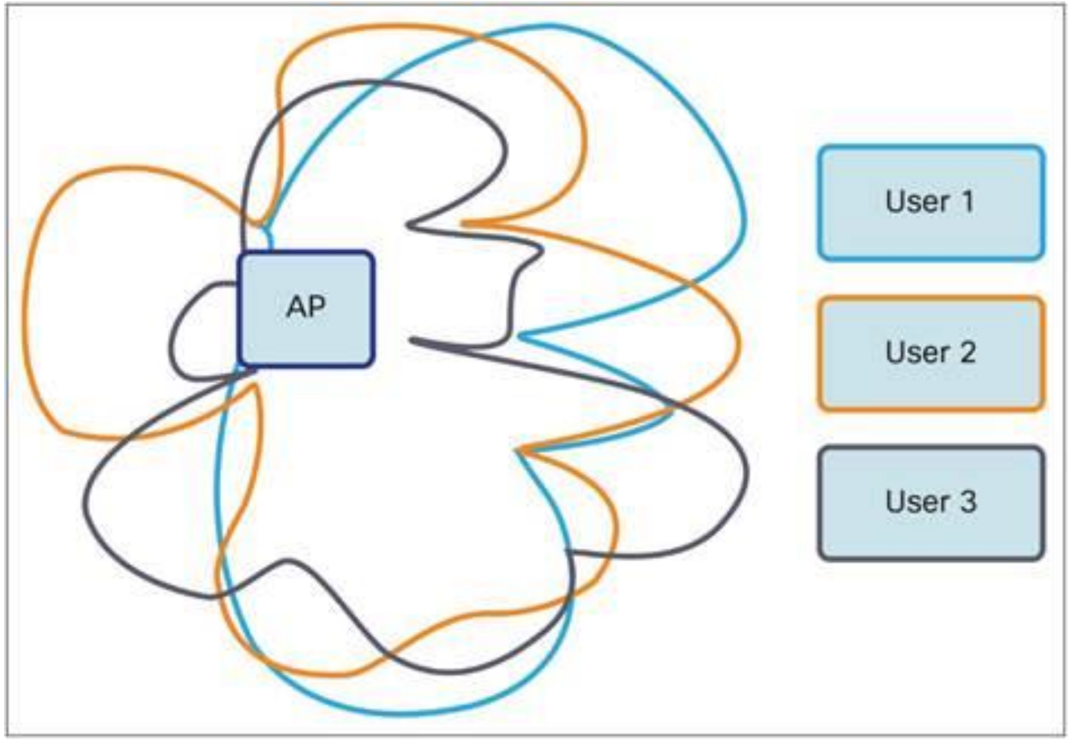


Beamforming

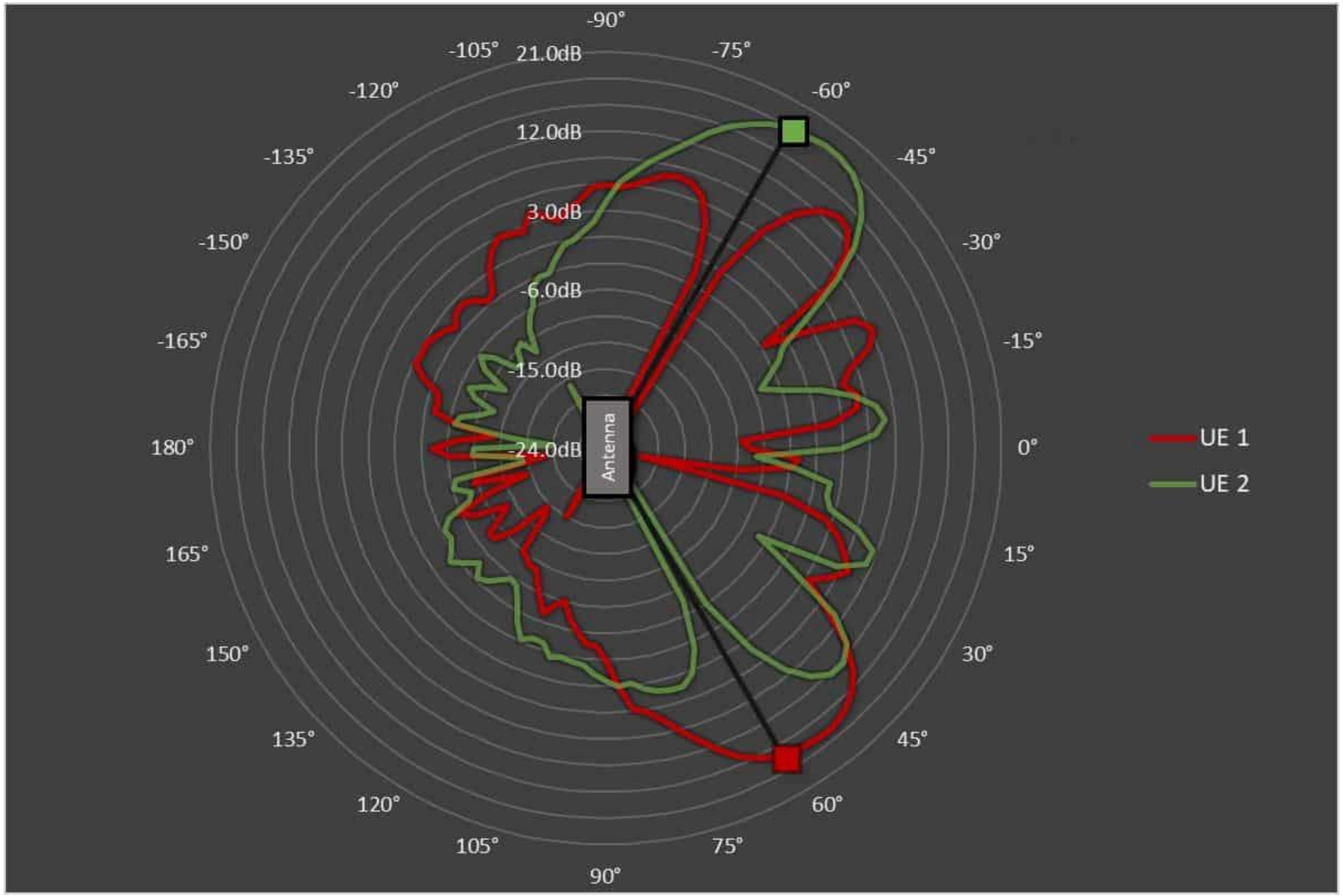
- Beamforming
  - Use omni-directional antennas to focus signal in a specific direction
  - Change the phase of signal emitting from different antenna
  - Intelligent phase modification can result in beams in desired direction



Beamforming

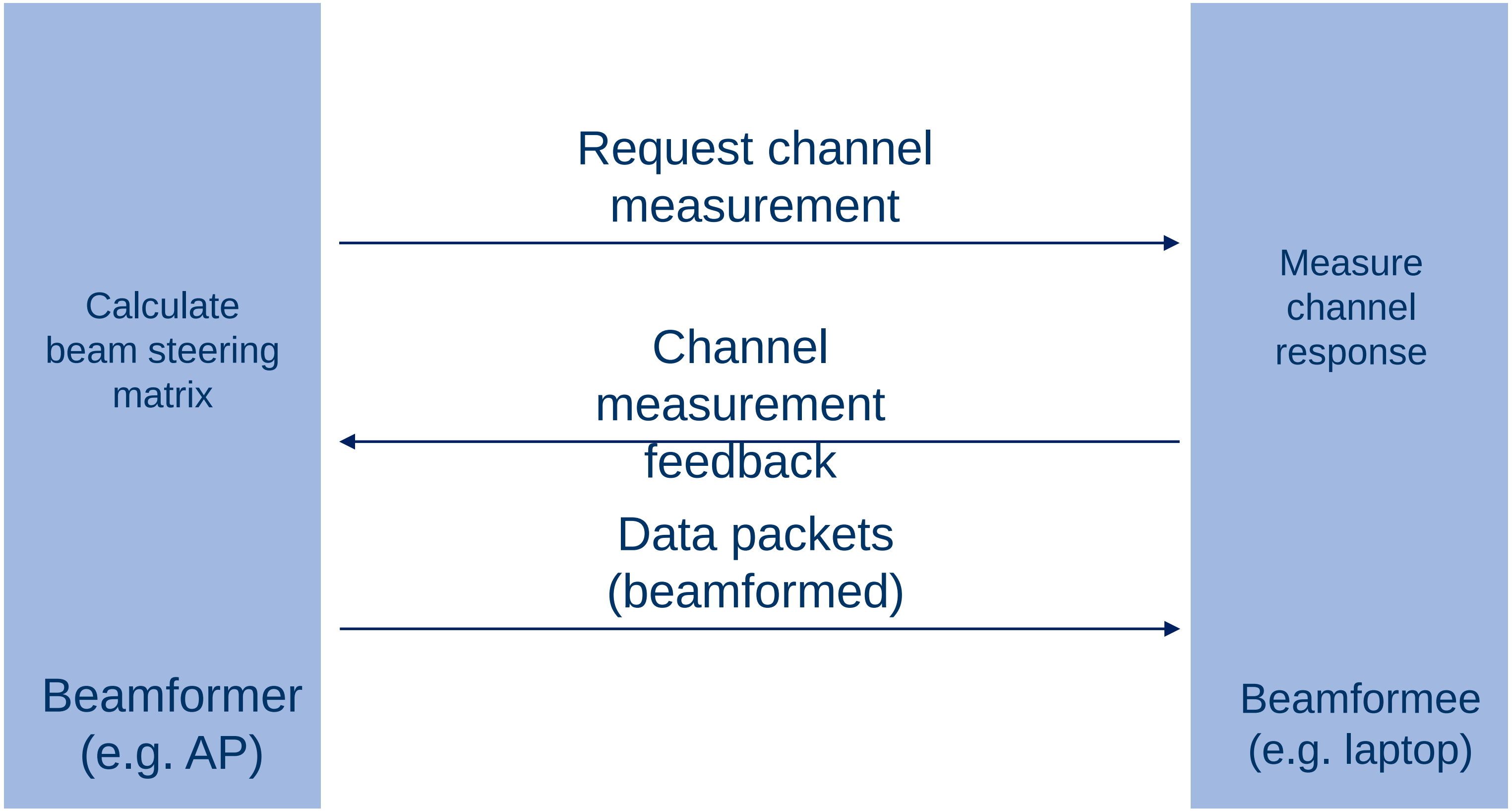


Beamforming



Beamforming

- Channel sounding procedure
  - Explicit feedback
  - Beamformer asks the beamformee to provide a feedback of channel measurement



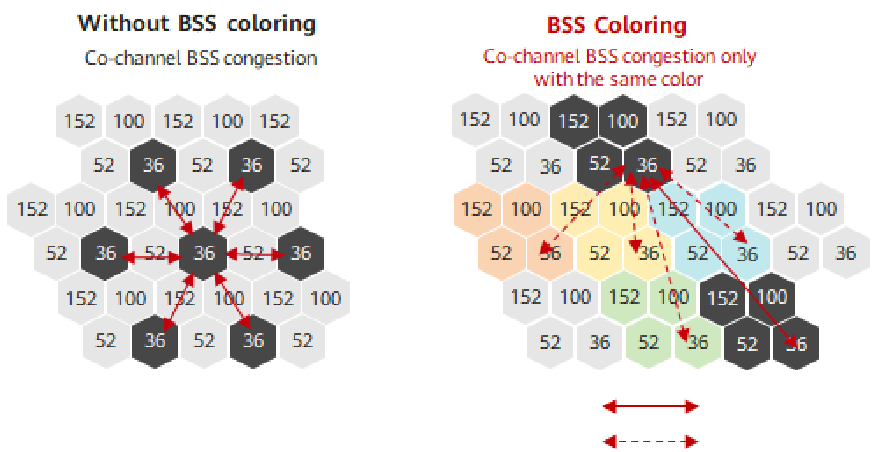
Channel matrix

Feedback matrix

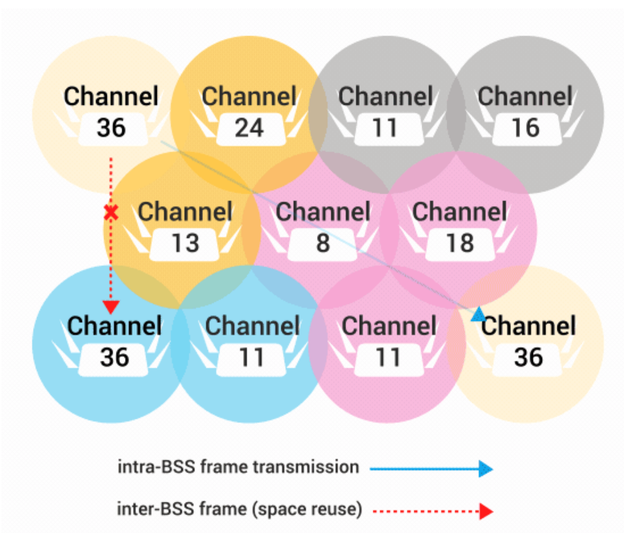
Number of subcarriers × Number of Tx antenna × Number of Rx antenna

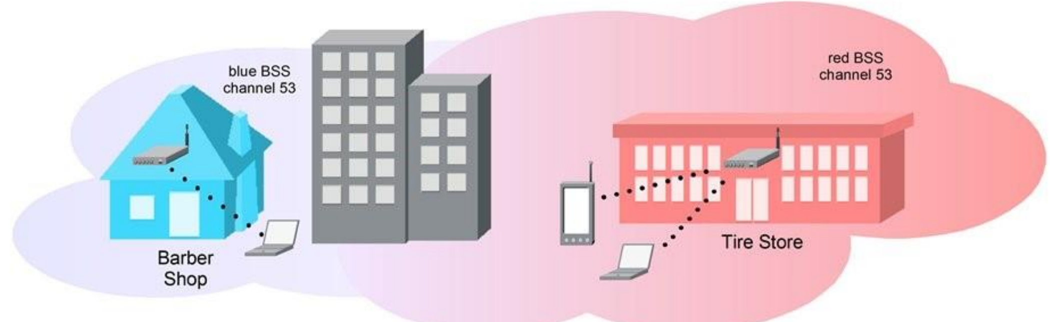
- Channel State Information (CSI)
  - Also used as feedback for MIMO spatial multiplexing
  - Challenge – the CSI matrix can be very large in size, especially for wider channel widths (e.g. 160 MHz)
  - Frequent feedback necessary for accurate beamforming – high overhead

802.11ax BSS coloring



BSS coloring supported by Wi-Fi 6





The quest for high speed wireless

- Applications driving the growth

Sync and go

High definition (4K and beyond) video streaming

Tether less interfaces
Wireless USB, PCI buses, HDMI

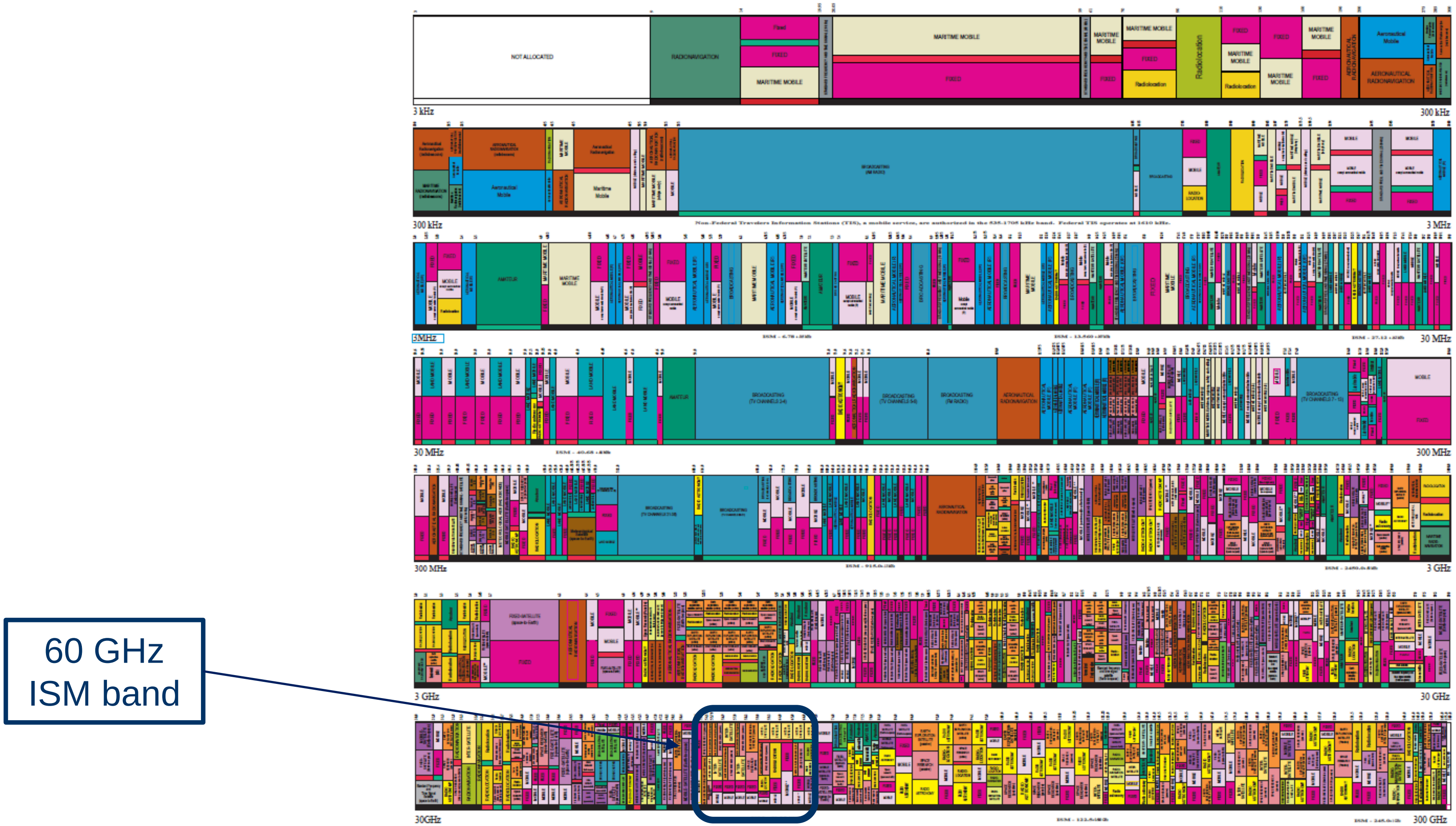
Wireless docking, screen mirroring

The quest for high speed wireless

- Virtual reality

https://www.youtube.com/watch?v=Oxfj-qoV5KE

Search for more bandwidth



Search for more bandwidth

- How can we create wireless networks that can provide multi-gigabit per second data rate?
  - Per link speed should be > 3 Gbps

Millimeter wave wireless networks

Current WiFi operates in 2.4 and 5 GHz

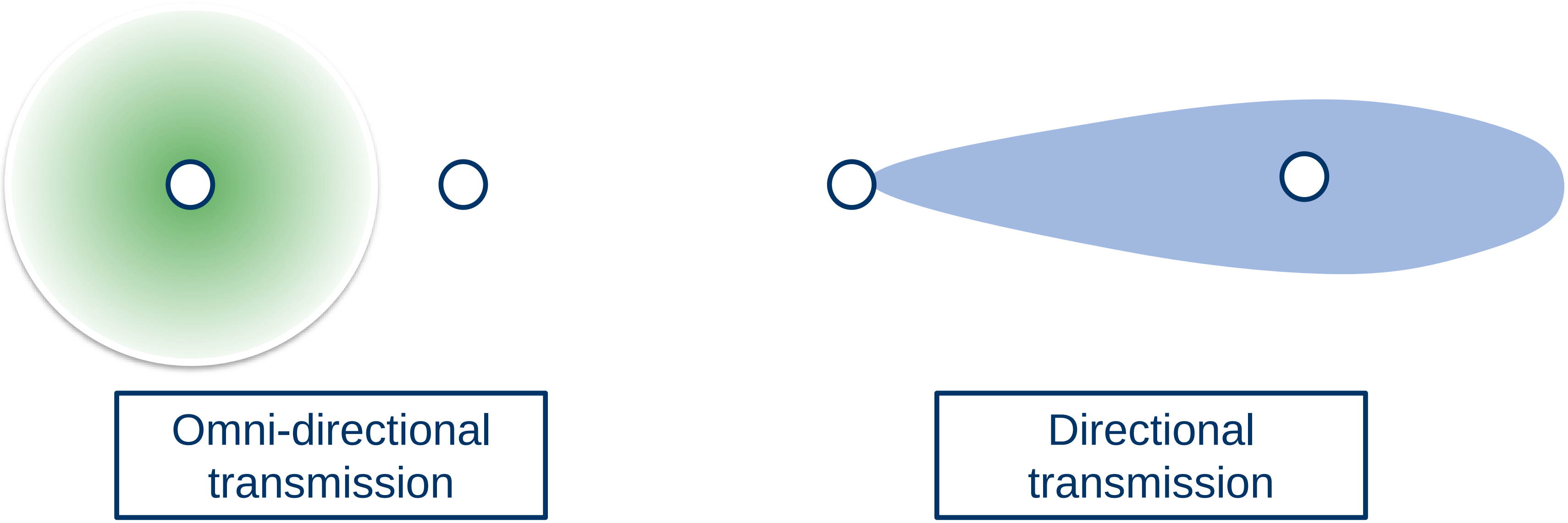
Major millimeter wave spectrum bands

Spectrum bands	Bandwidth
28 GHz	1.3 GHz
39 GHz	1.4 GHz
60 GHz	14 GHz
74 GHz	5 GHz
84 GHz	5 GHz

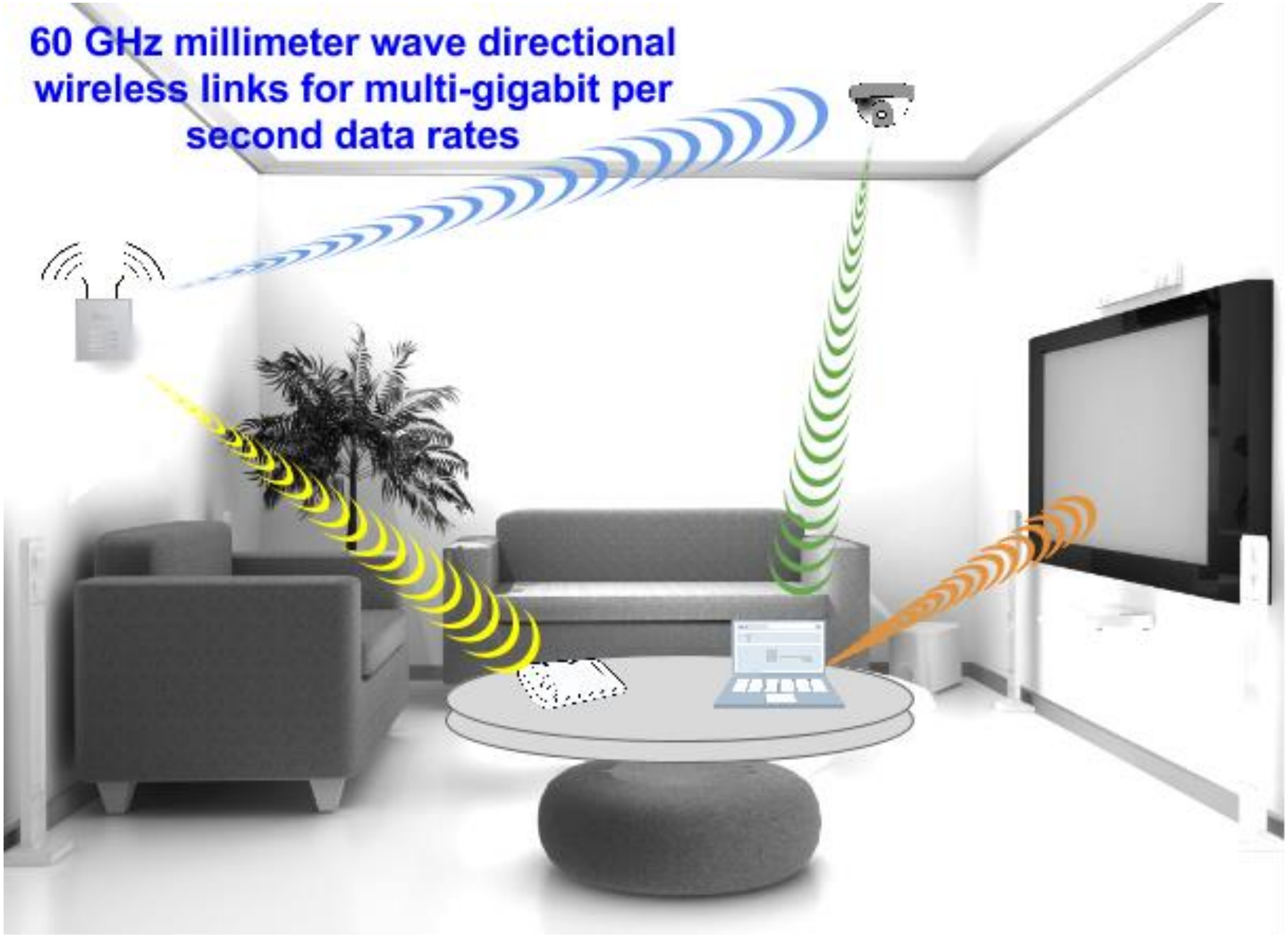
ISM

60 GHz path loss

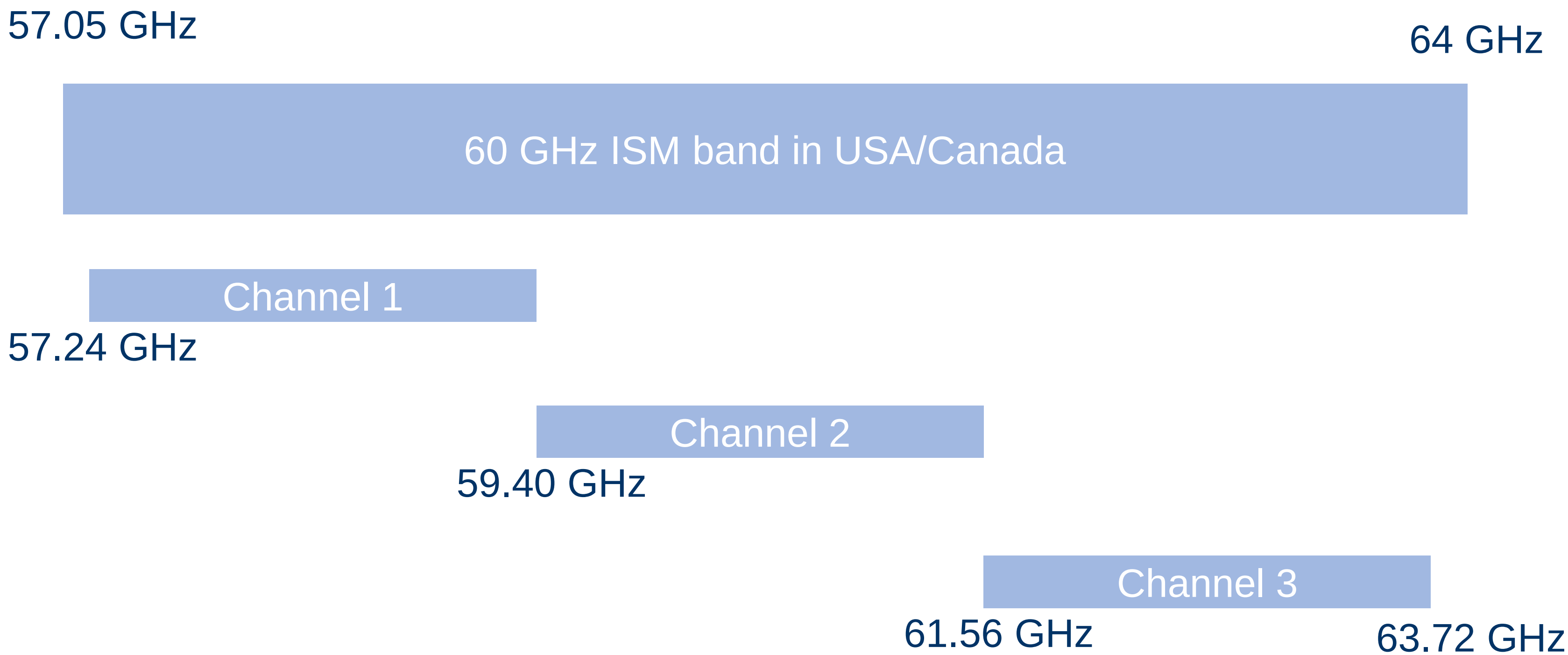
- How to deal with such high path loss?
  - Directionality – concentrate the radiated energy in one direction



60 GHz Network

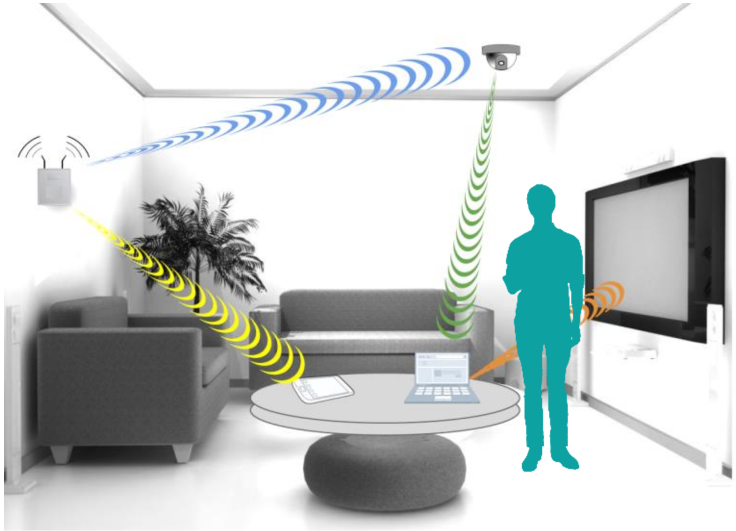


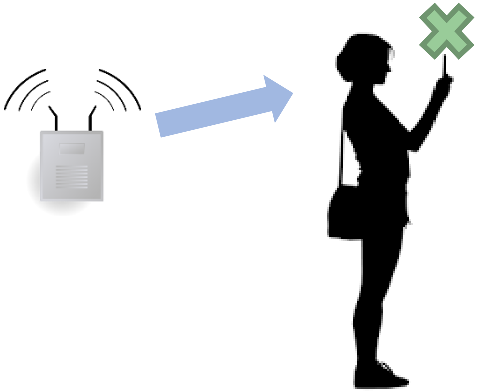
802.11ad frequency bands



Human blockage

- 60 GHz networks
  - Human mobility – results in unpredictable blockage of links





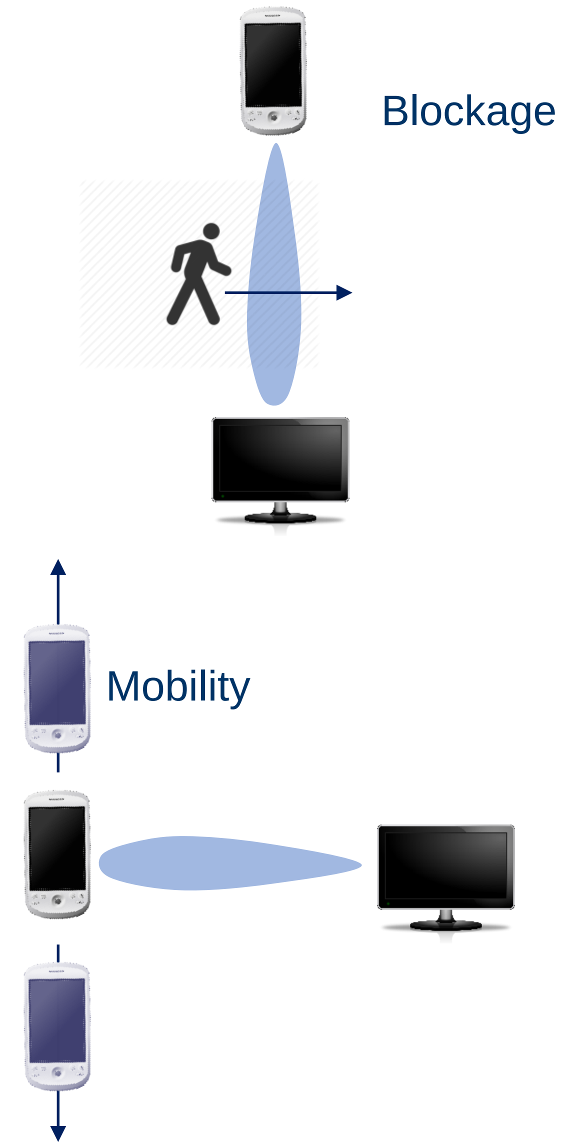
Self blockage - human body blocks link to mobile device
- specifically a challenge for mobile devices

Blockage and mobility

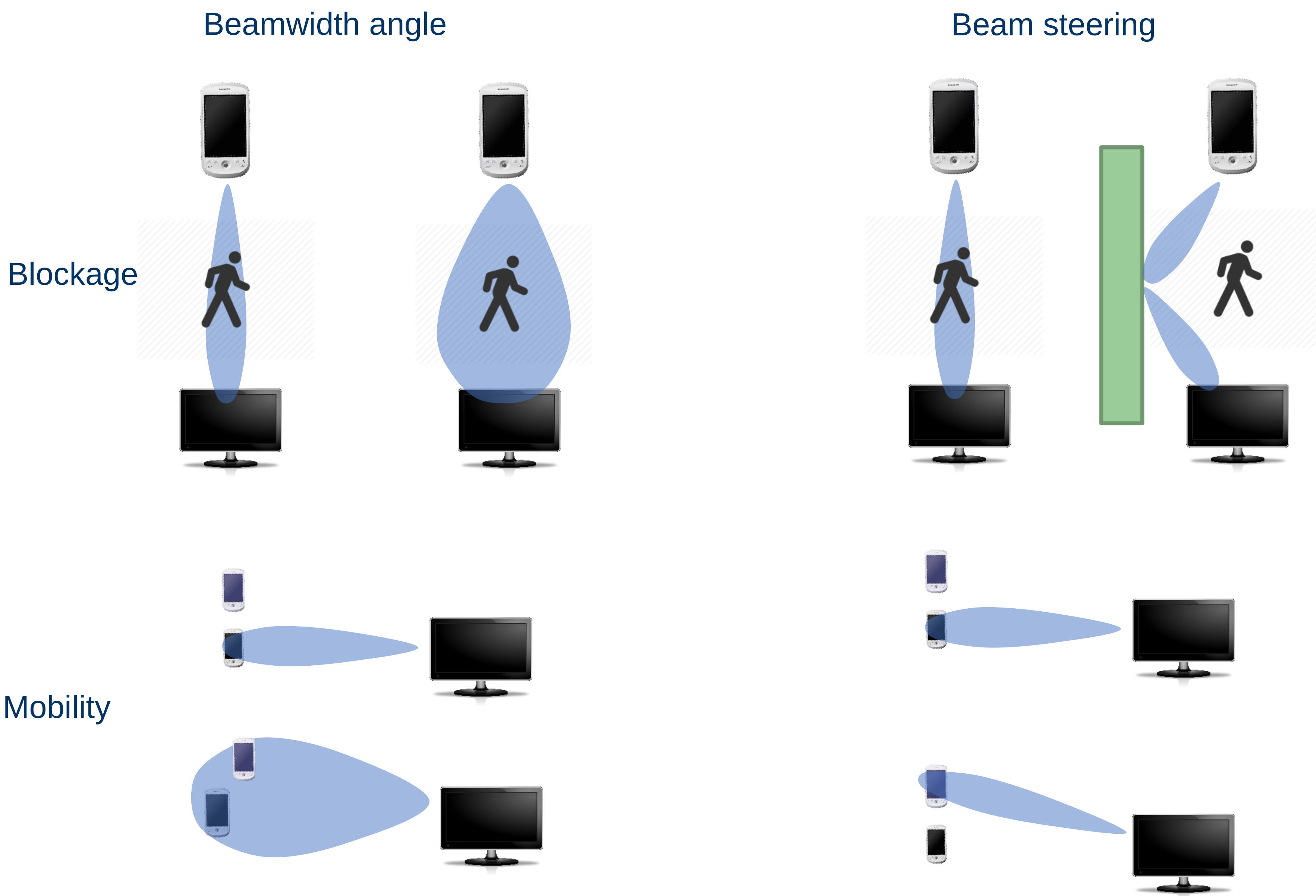
- Two important open challenges
  - Blockage and mobility

- Blockage
  - Commonly caused by human mobility over Tx, Rx path
  - Human body blockage can result in complete link outage, especially when narrow beamwidth is in use

- Mobility
  - One or both endpoints of a 60 GHz link are mobile
  - Requires constant tracking of mobile endpoints
  - Beam steering – change beam direction based on observed direction



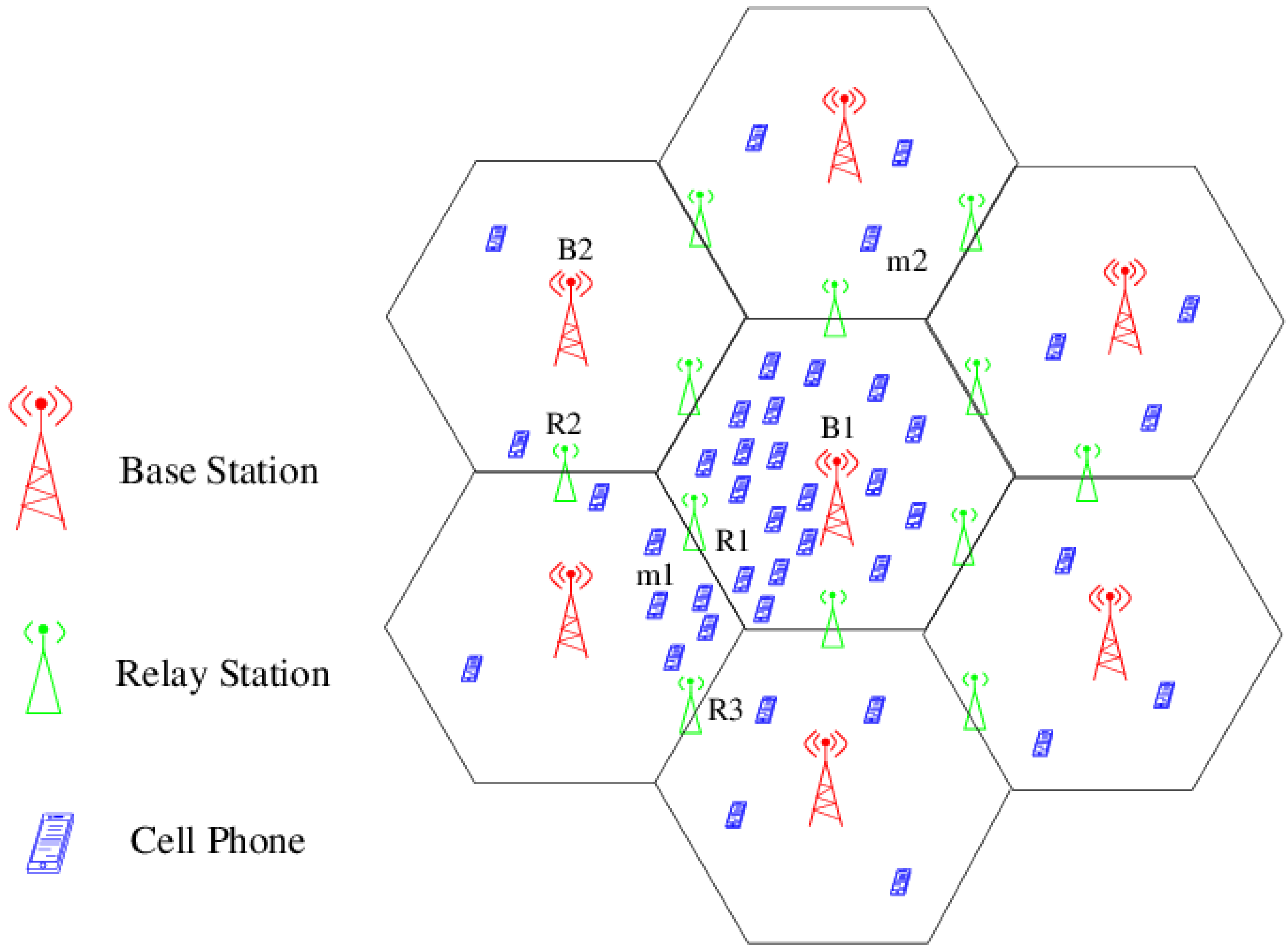
Two possible solutions



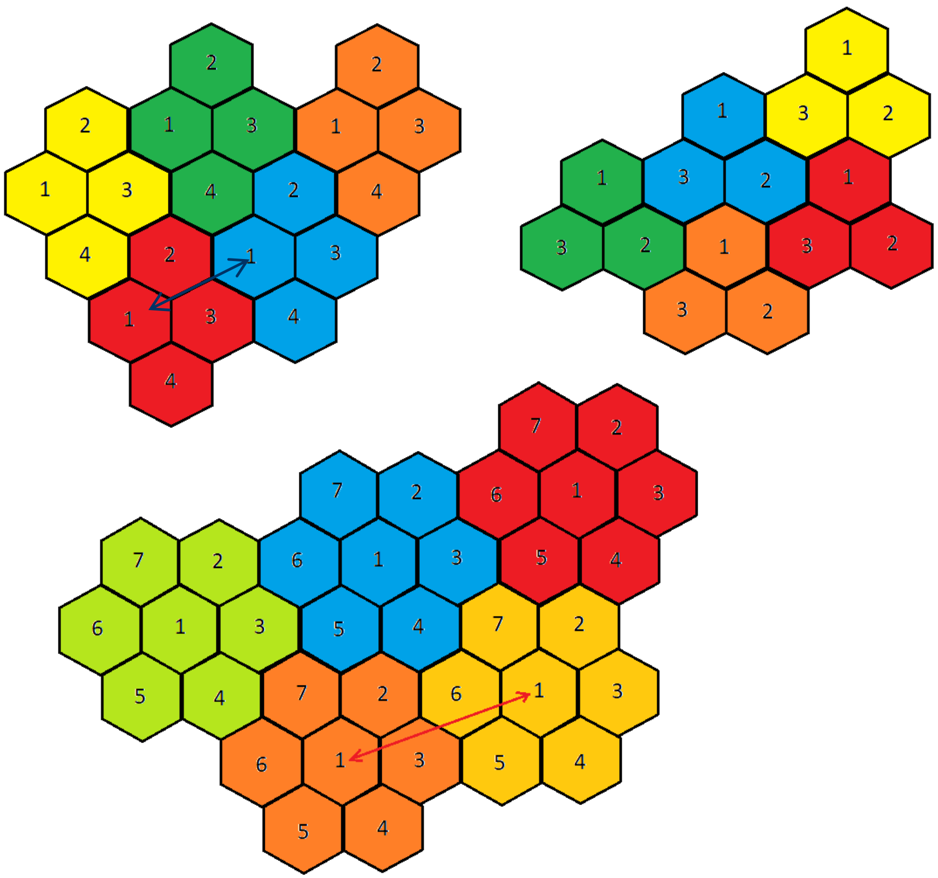
Mobile and Wireless Networks

Cellular Structure

Cellular Network Organization



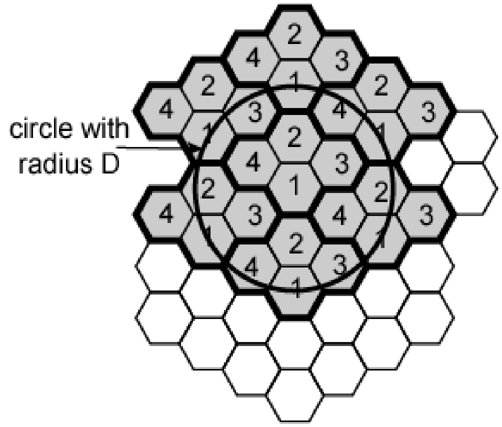
Frequency Reuse



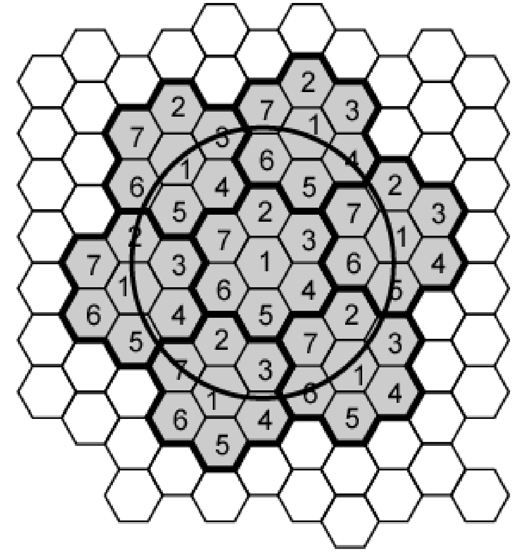
Frequency Reuse

- Power of base transceiver controlled
  - Allow communications within cell on given frequency
  - Limit escaping power to adjacent cells
  - Allow re-use of frequencies in nearby cells
  - Use same frequency for multiple conversations
- *E.g.*
  - N cells all using same number of frequencies
  - K total number of frequencies used in systems
  - Each cell has K/N frequencies
  - K=395, N=7 giving 57 frequencies per cell on average

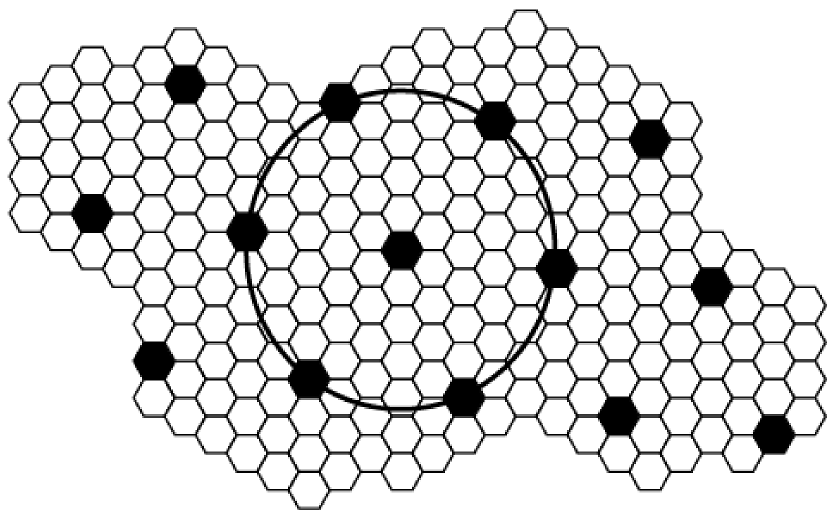
Frequency Reuse Patterns



(a) Frequency reuse pattern for N = 4

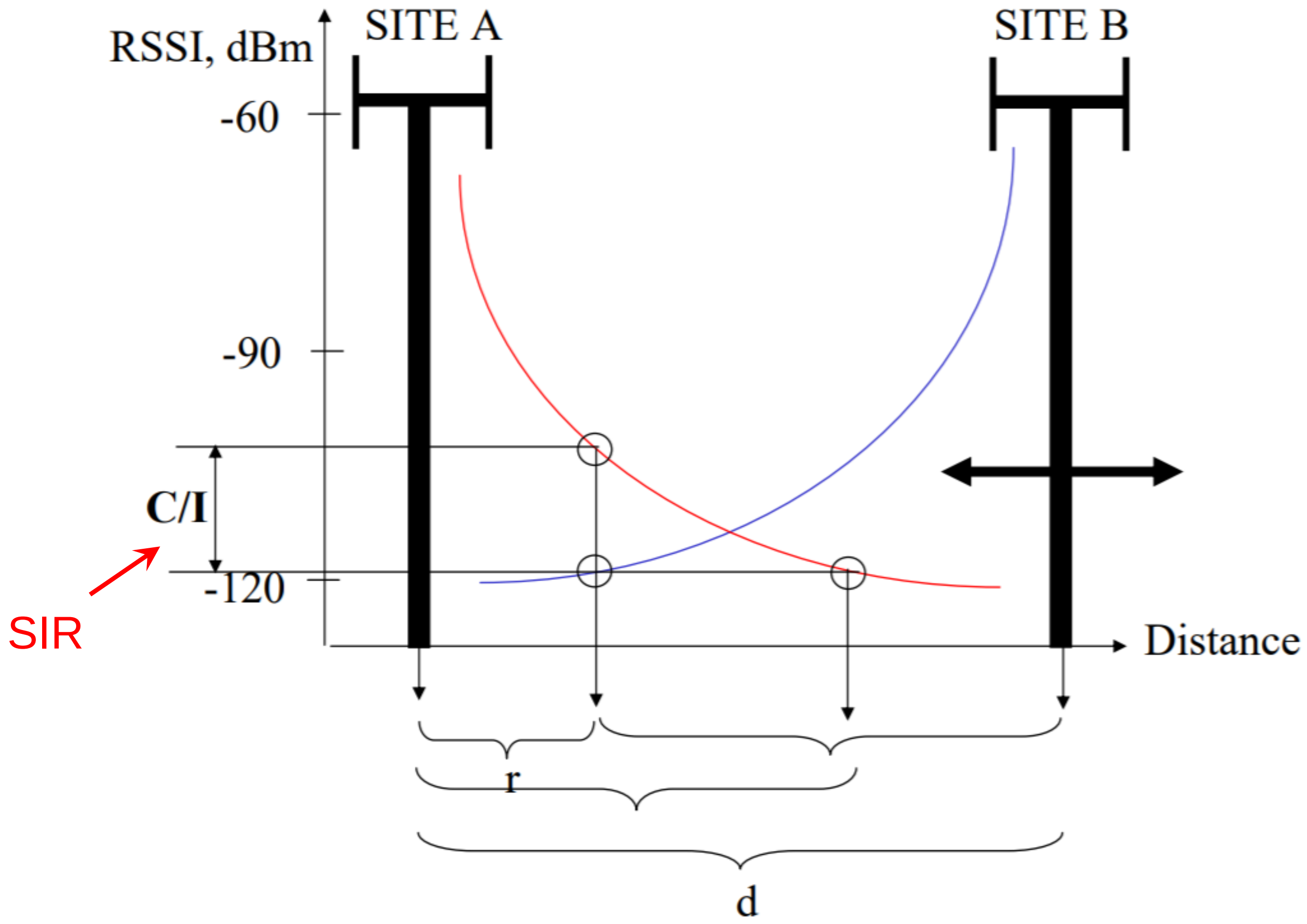


(b) Frequency reuse pattern for N = 7

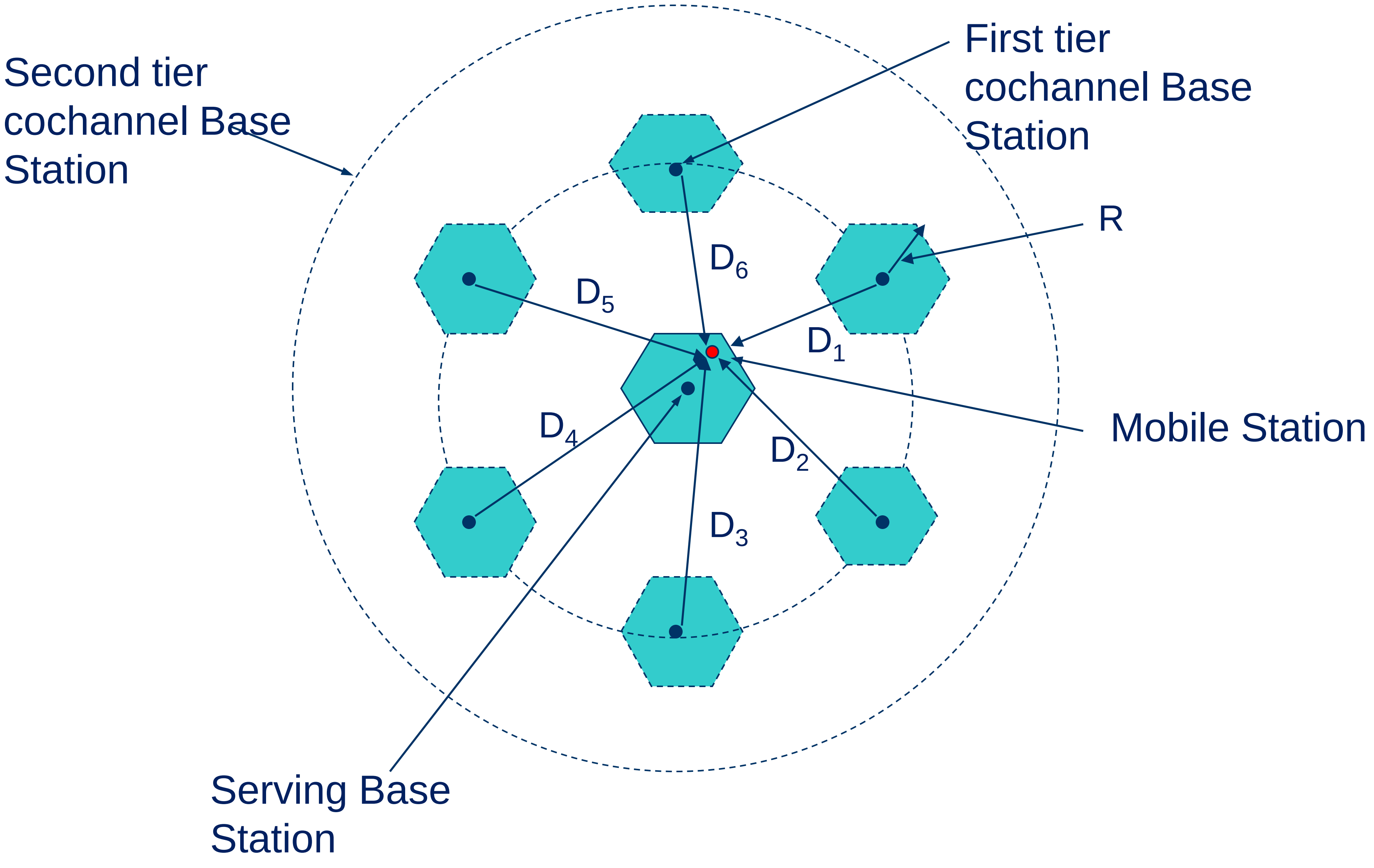


(c) Black cells indicate a frequency reuse for N = 19

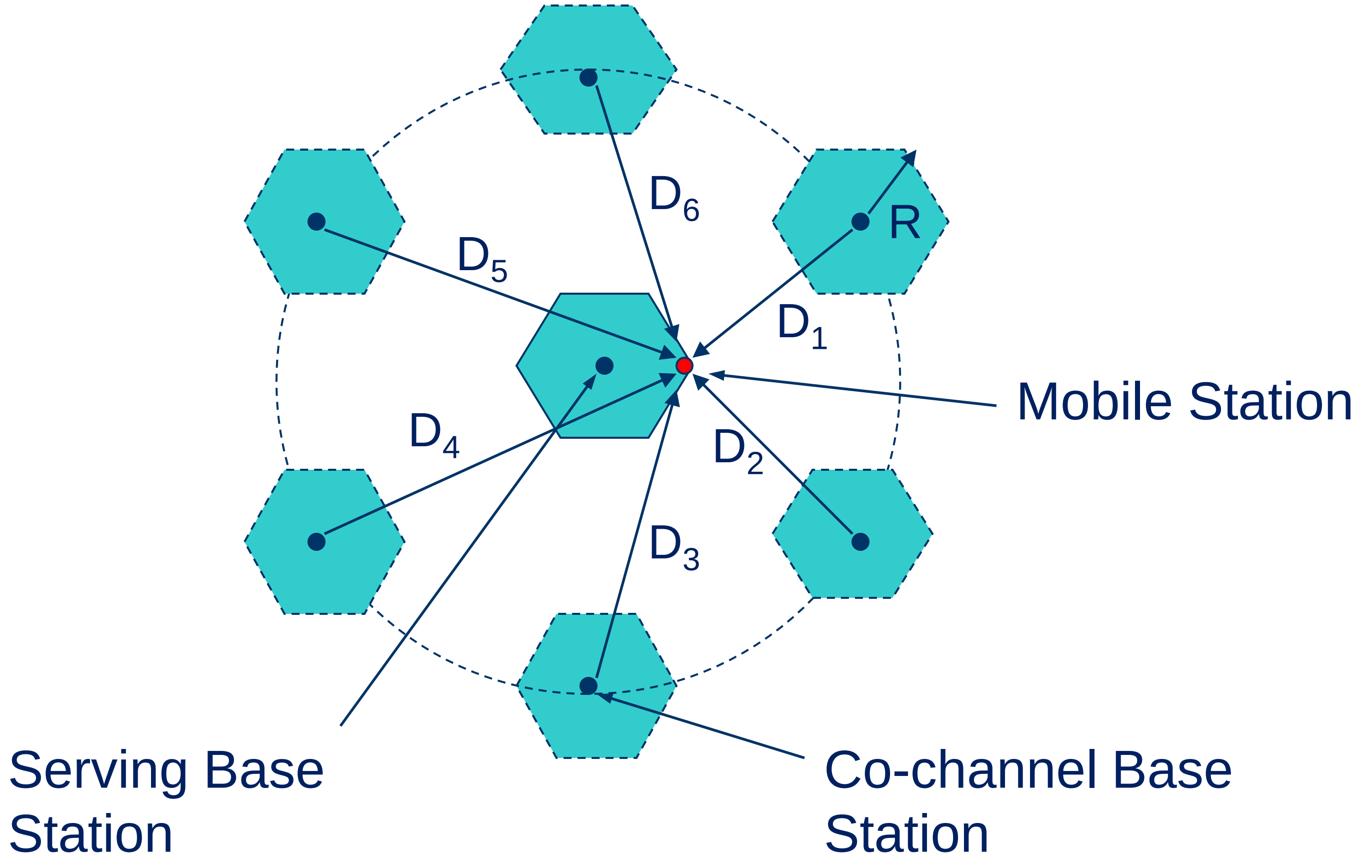
Frequency Reuse Distance



Cochannel Interference

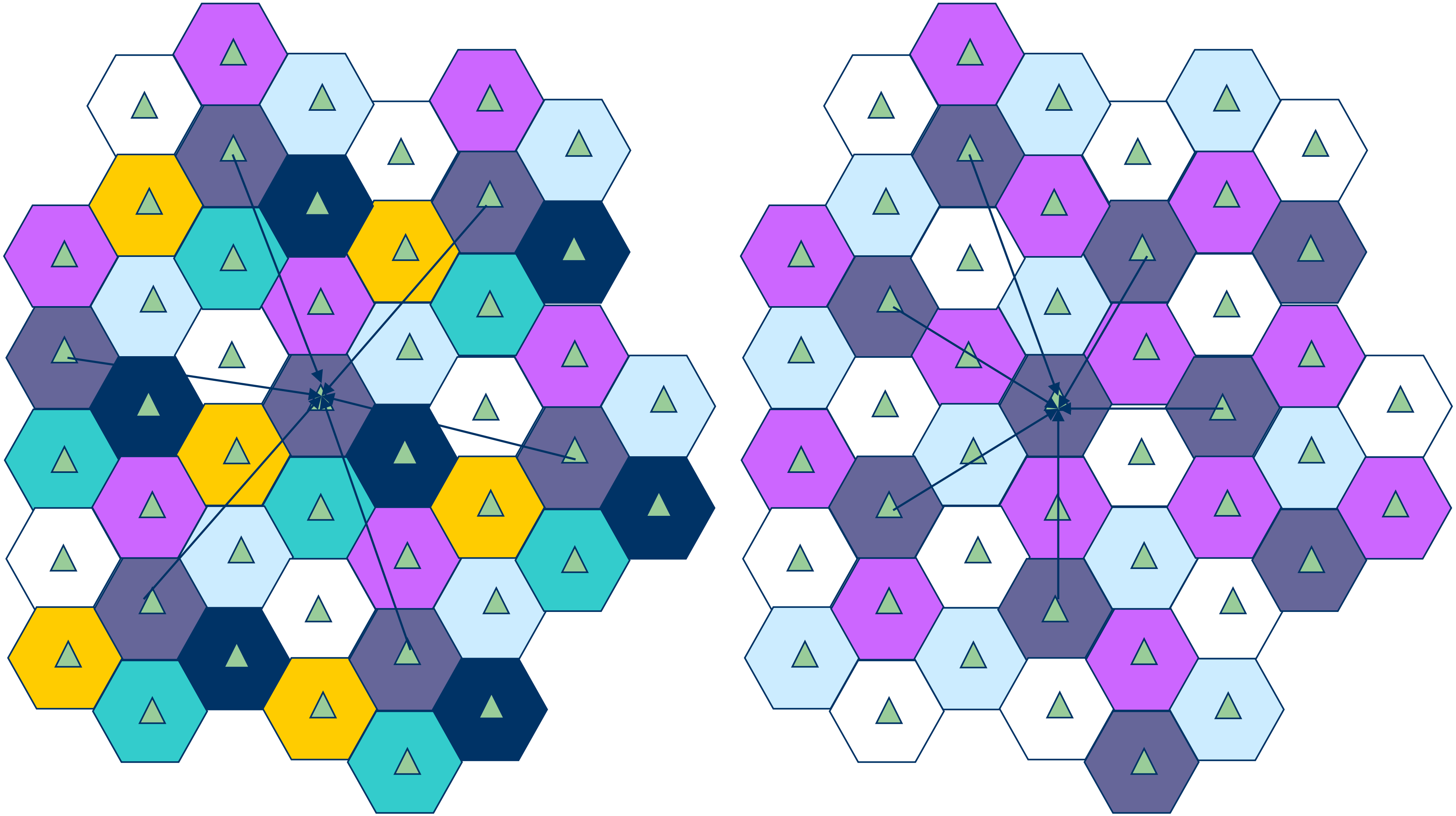


Worst Case of Cochannel Interference



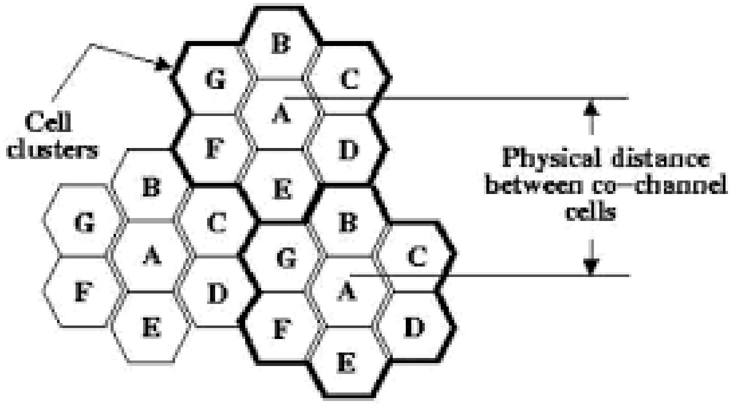
Increasing Capacity (1)

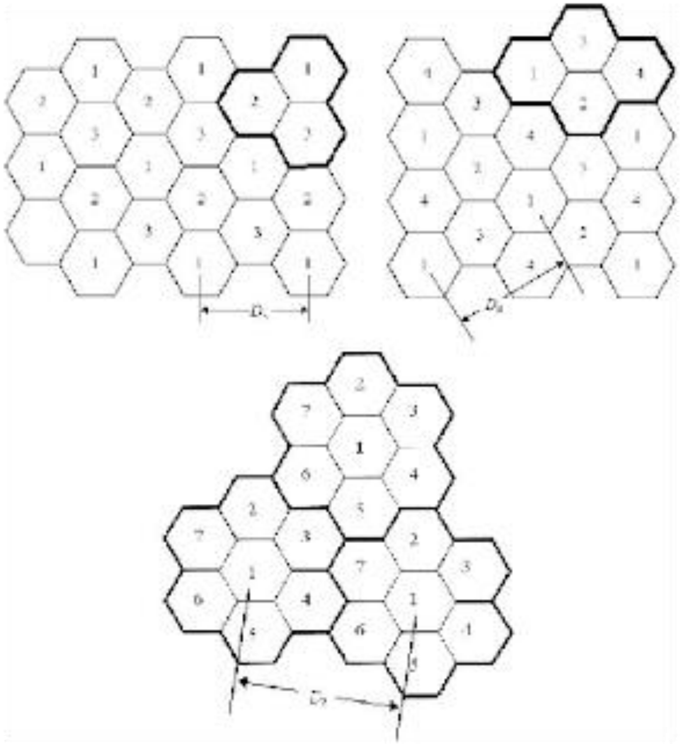
- Smaller clusters - here from 7cells to 3 cells



Interfering cells are closer when cluster size is smaller.

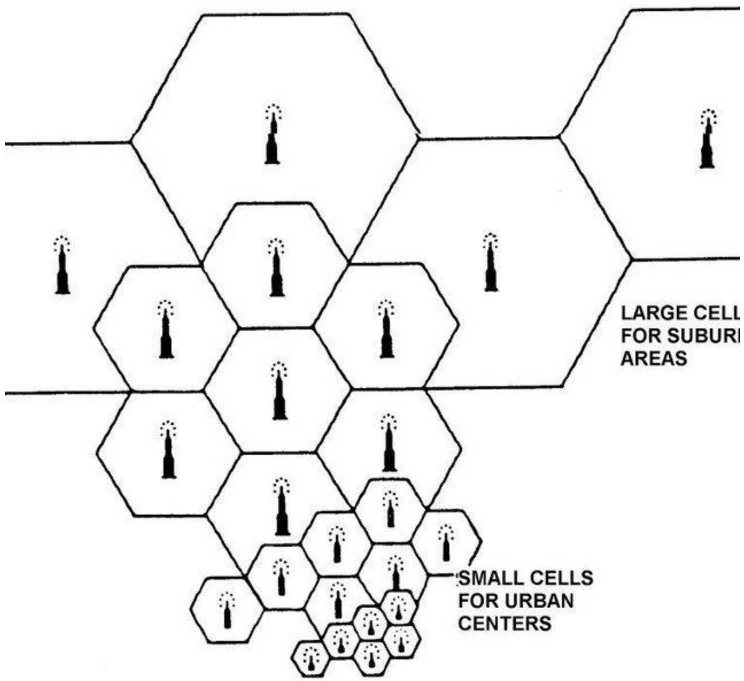
Increasing Capacity (1)





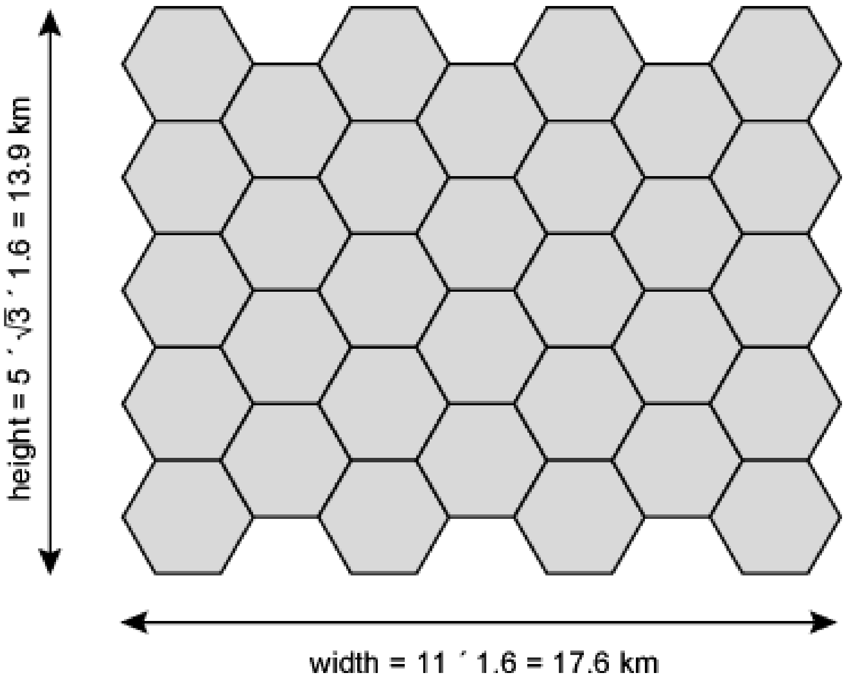
Increasing Capacity (2)

- Cell Splitting
  - Cells of high usage can be split into smaller cells
  - Leads to increased capacity but more frequent handovers

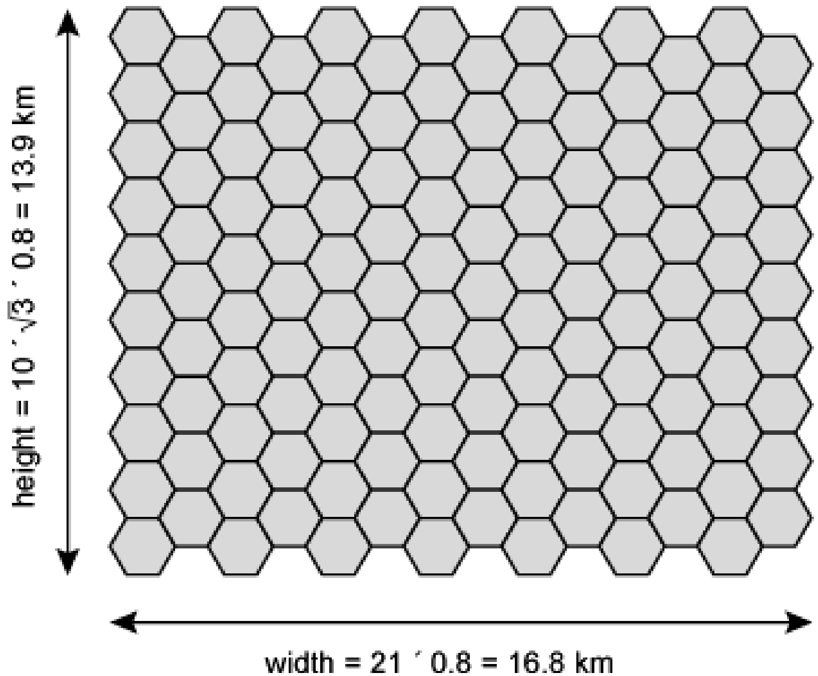


Increasing Capacity (3)

- Smaller cells



(a) Cell radius = 1.6 km



(b) Cell radius = 0.8 km

Increasing Capacity (4)

- Cell Sectoring
  - Cell divided into wedge shaped sectors
  - 3 – 6 sectors per cell
  - Each with own channel set
    - Subsets of cell's channels
  - Directional antennas

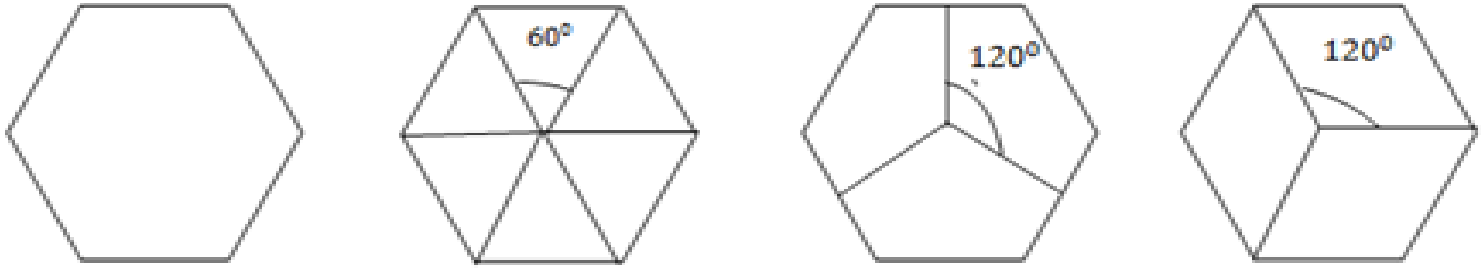
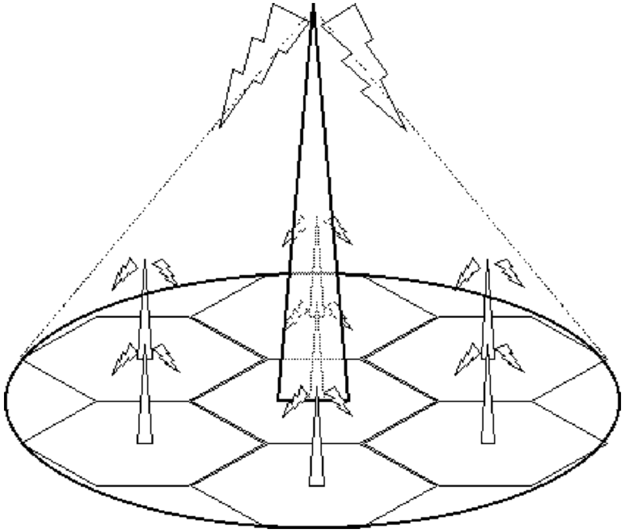


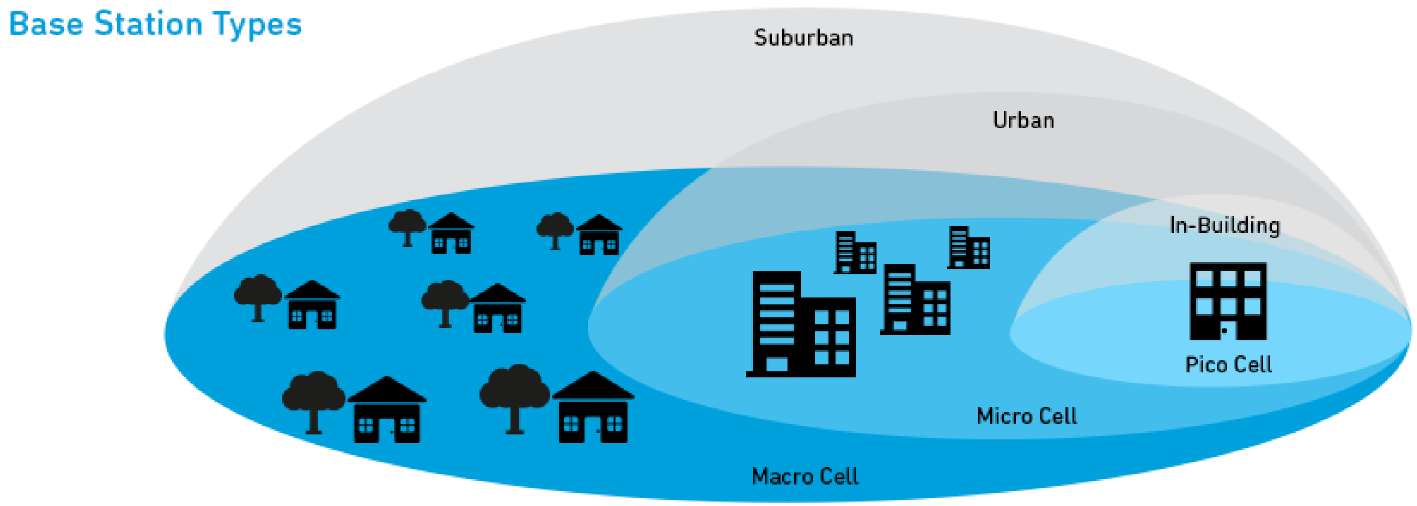
Fig: omni-directional 60^0 sectoring 120^0 sectoring

Increasing Capacity (5)

- Microcells
  - Move antennas from tops of hills and large buildings to tops of small buildings and sides of large buildings
    - Even lamp posts
  - Form microcells with reduced power
  - Good for city streets, along roads and inside large buildings



Multi-tier architectures



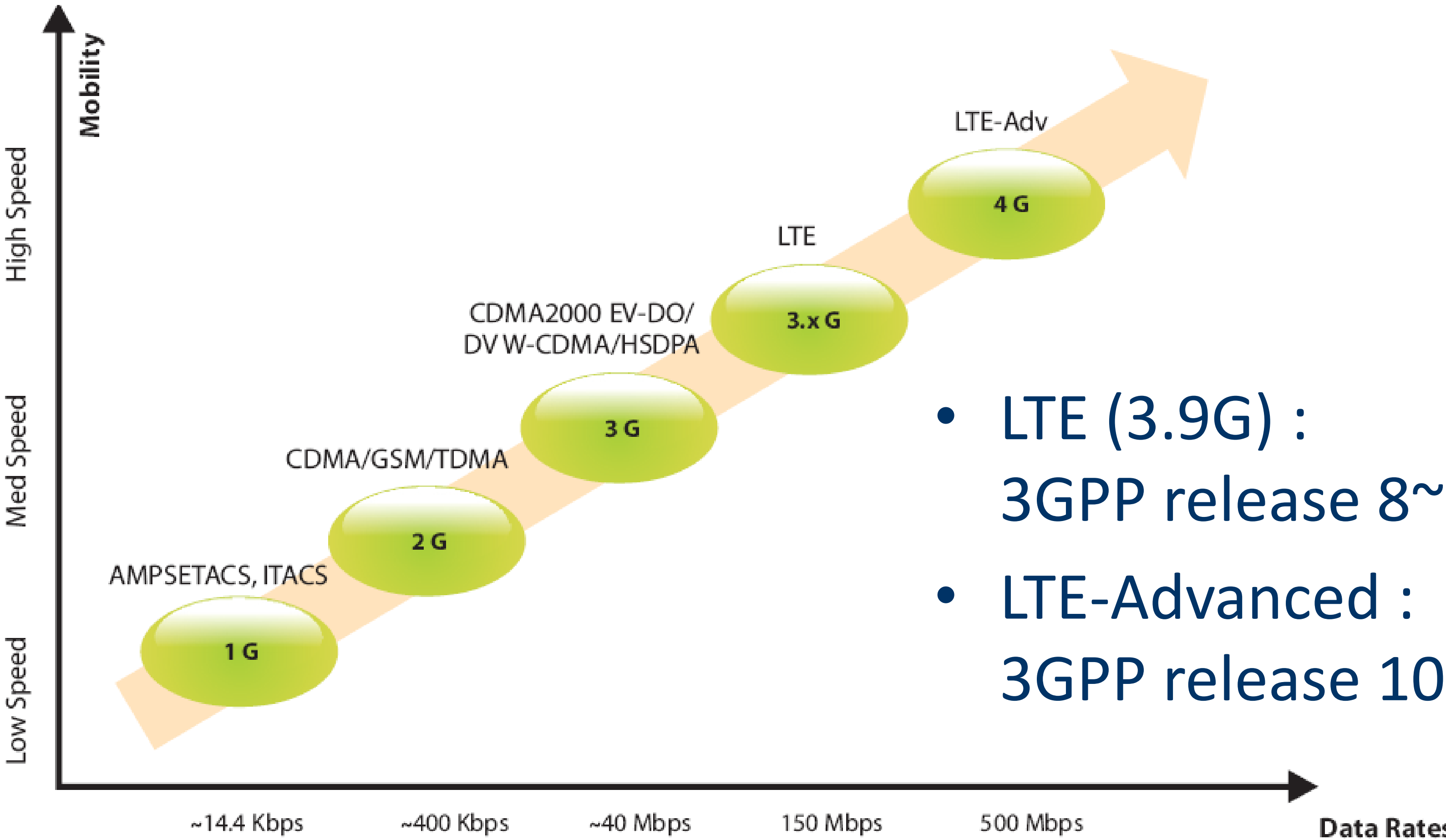
Cell Type	Output Power (W)	Cell Radius (km)	Users	Locations
Femtocell	0.001 to 0.25	0.010 to 0.1	1 to 30	Indoor
Pico Cell	0.25 to 1	0.1 to 0.2	30 to 100	Indoor/Outdoor
Micro Cell	1 to 10	0.2 to 2.0	100 to 2000	Indoor/Outdoor
Macro Cell	10 to >50	8 to 30	>2000	Outdoor

qorvo

Cellular Network Generations

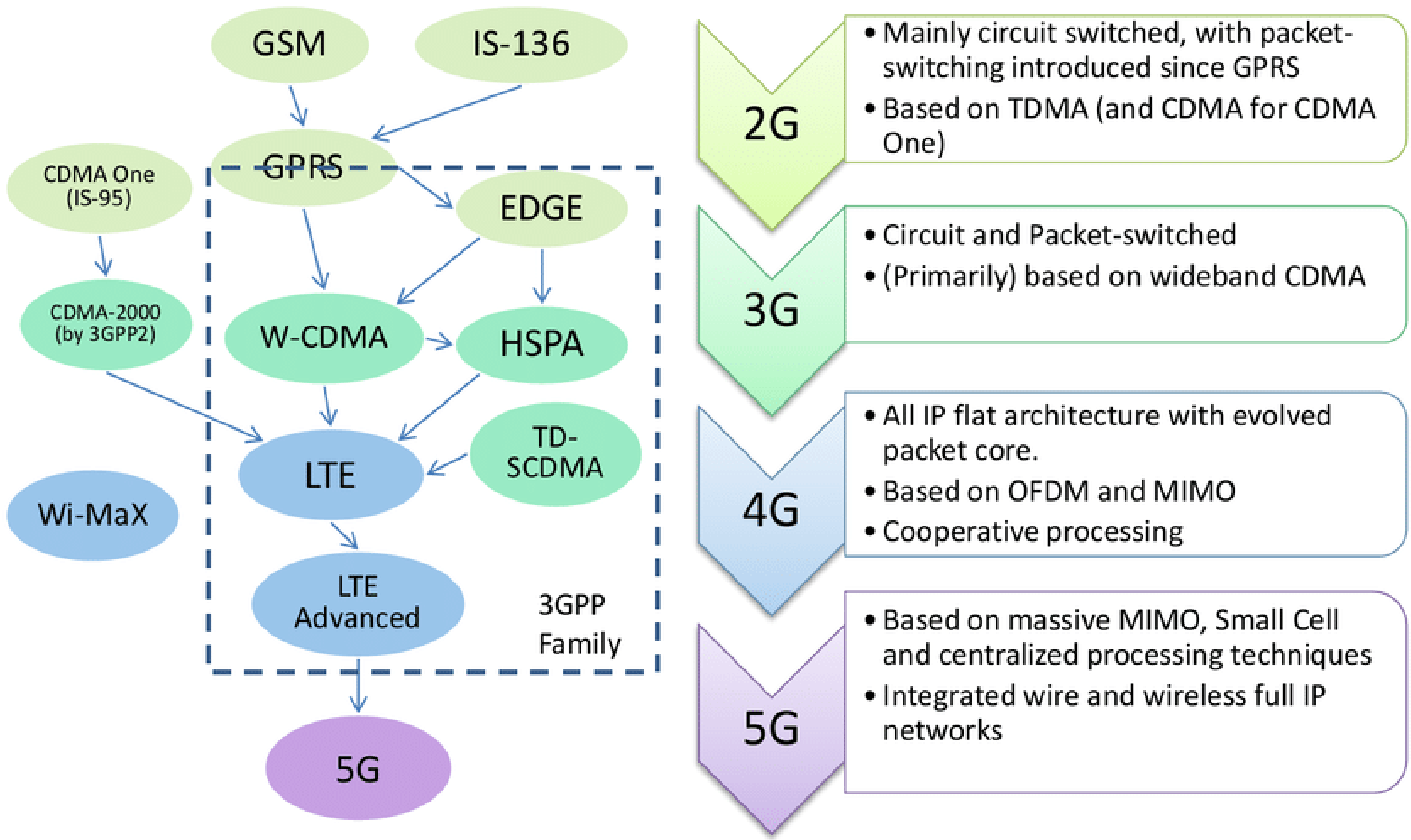
- It is useful to think of cellular Network/telephony in terms of *generations*:
  - 0G: Briefcase-size mobile radio telephones
  - 1G: *Analog* cellular telephony (end ‘70s)
  - 2G: *Digital* cellular telephony (beg ’90’s)
  - 3G: *High-speed* digital cellular telephony (including *video telephony*) (beg ’00)
  - 4G: IP-based “anytime, anywhere” voice, data, and multimedia telephony at *faster* data rates than 3G (beg ’10)
  - 5G: 10-times faster data rates, much more flexible in mobility, Internet of Things (IoT) support (cheap, low energy, massive number of devices) (beg ’20)

Evolution of Radio Access Technologies

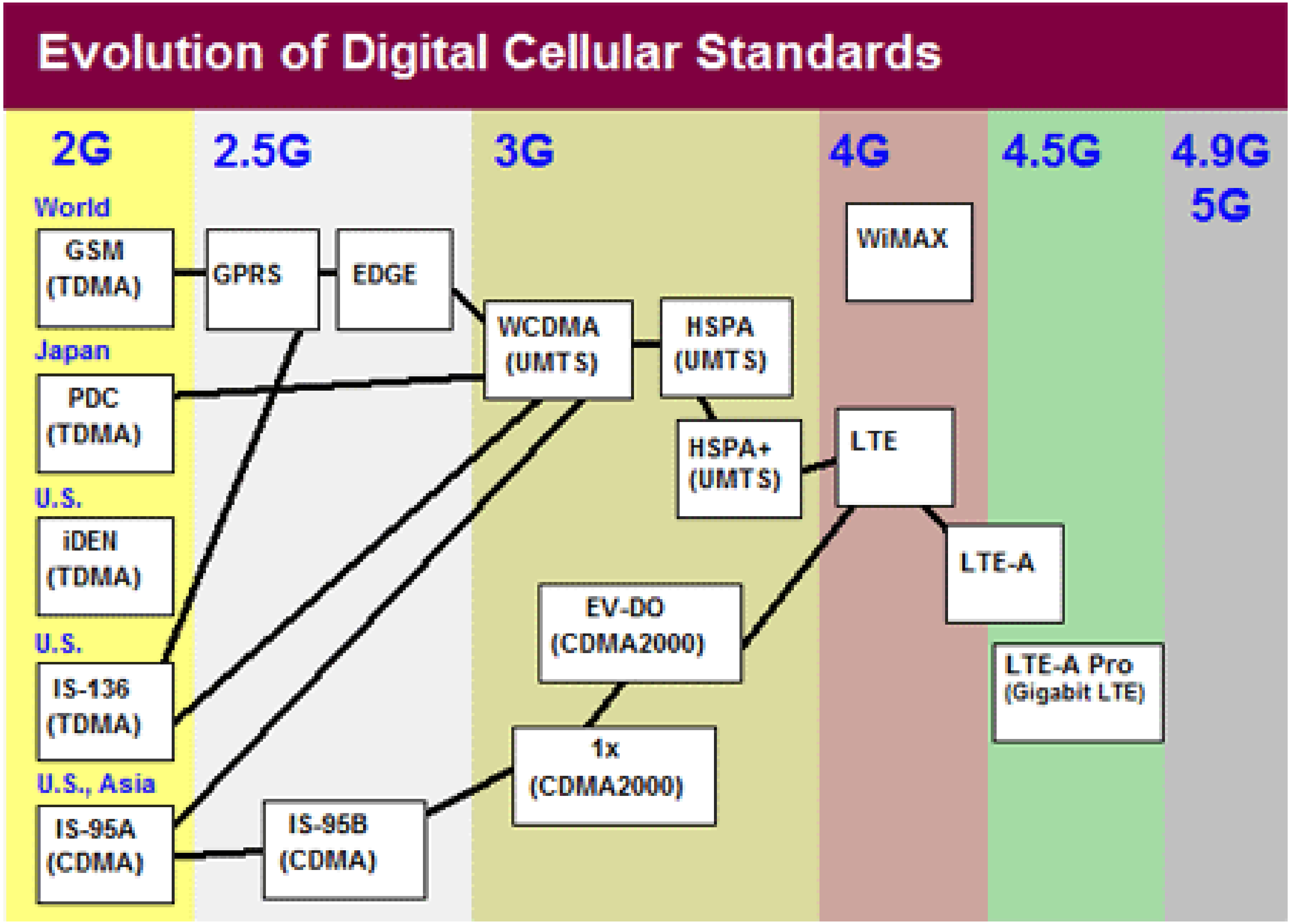


- LTE (3.9G) : 3GPP release 8~9
- LTE-Advanced : 3GPP release 10+

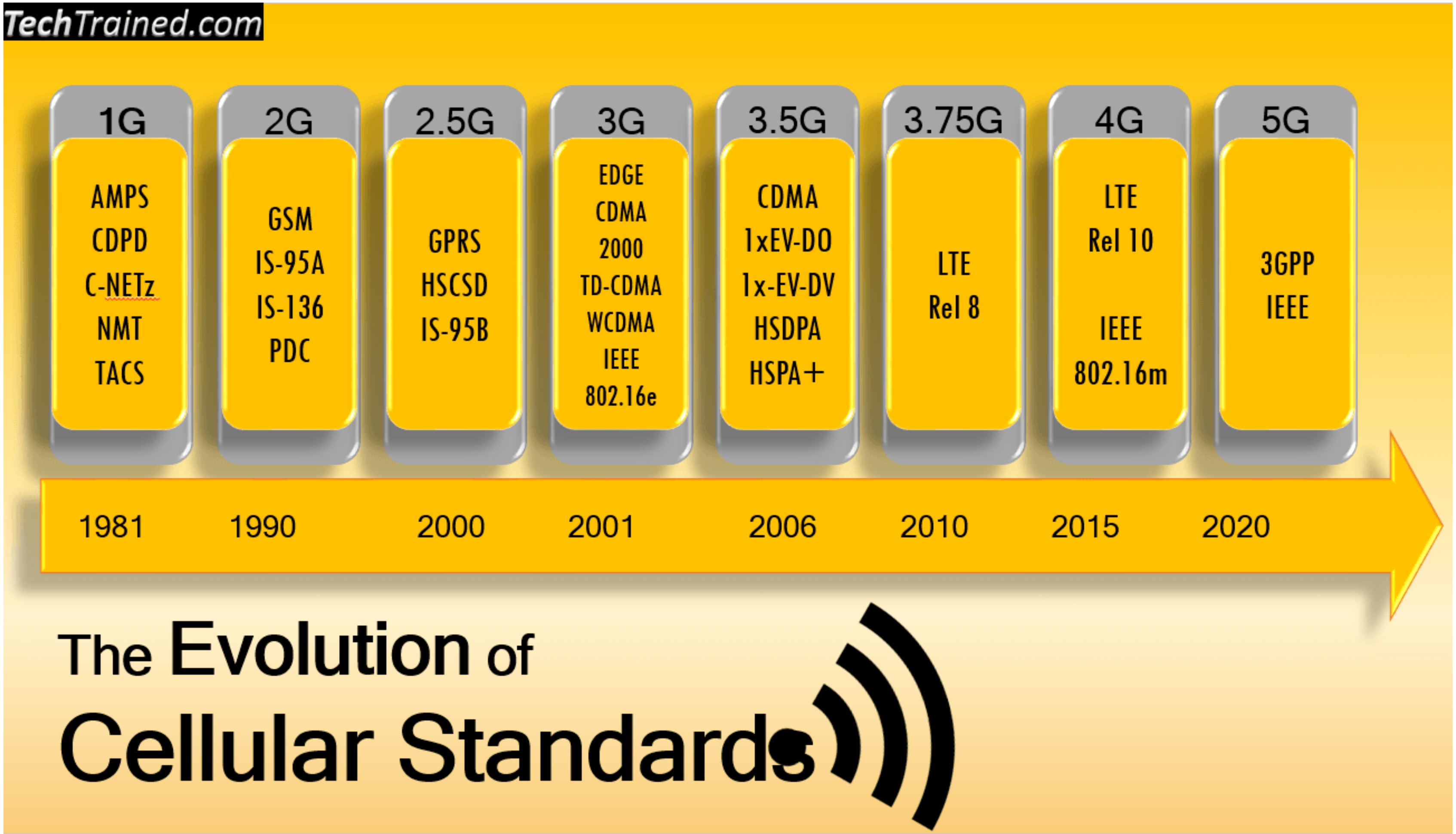
Evolution of Cellular Standards



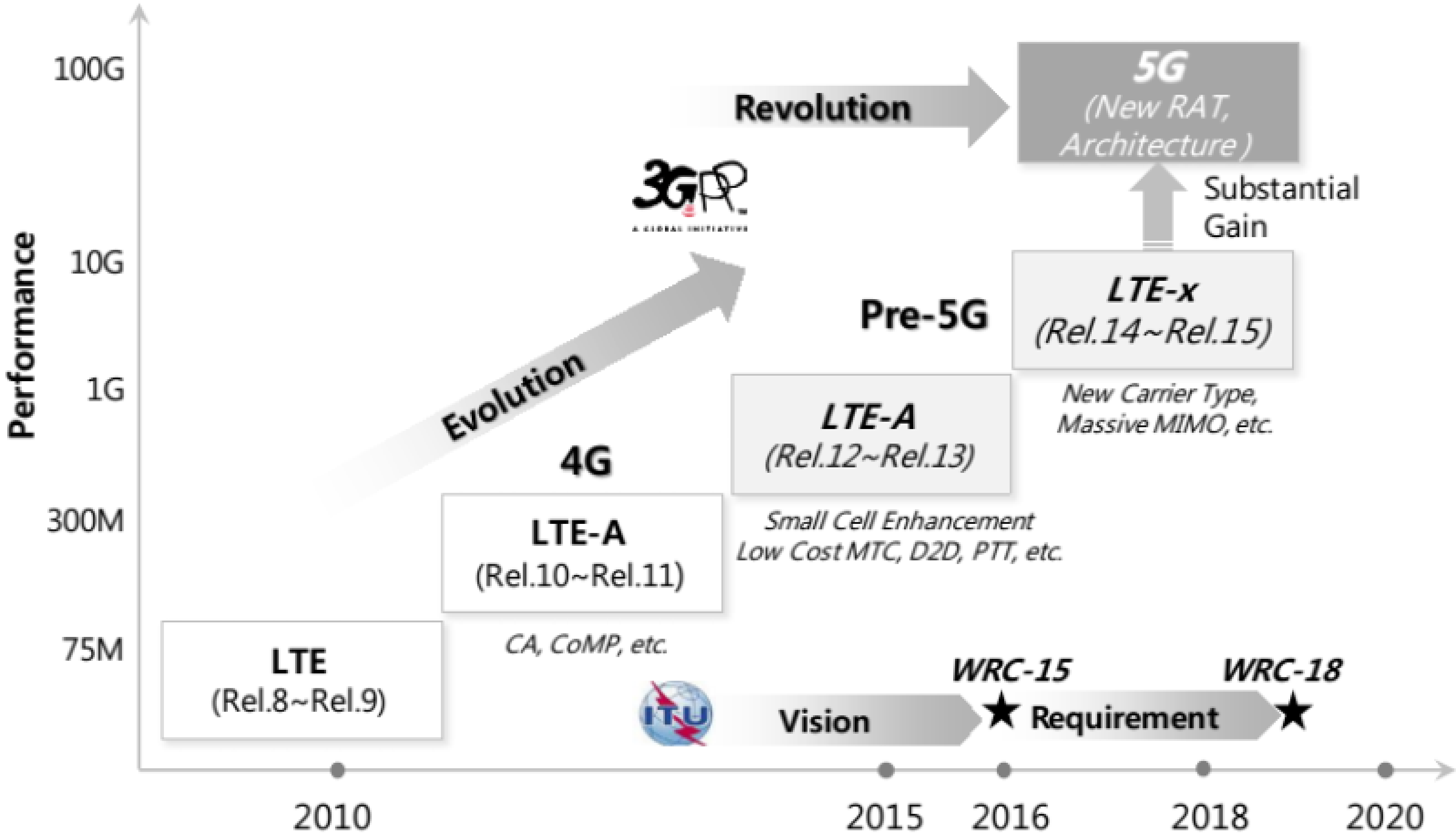
Evolution of Cellular Standards



Evolution of Cellular Standards

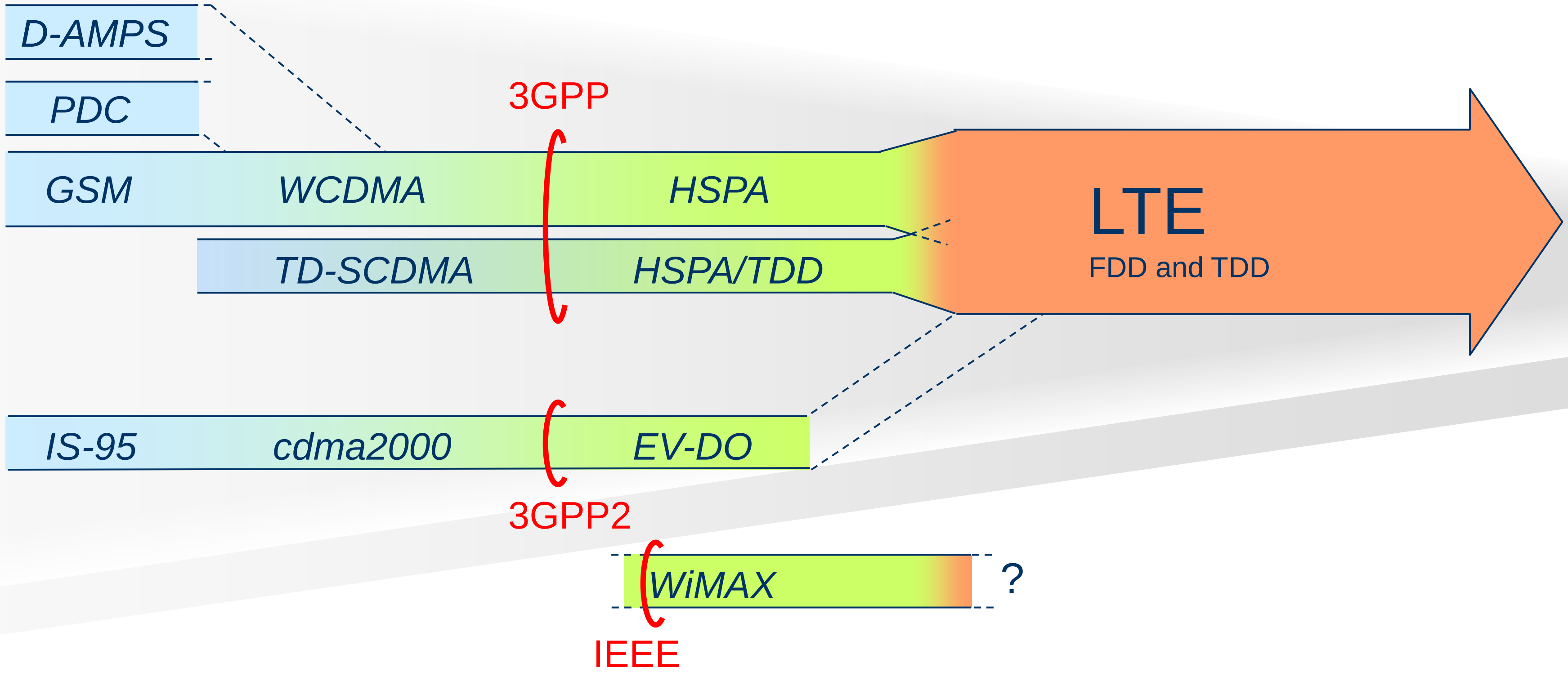


Evolution of Cellular Standards

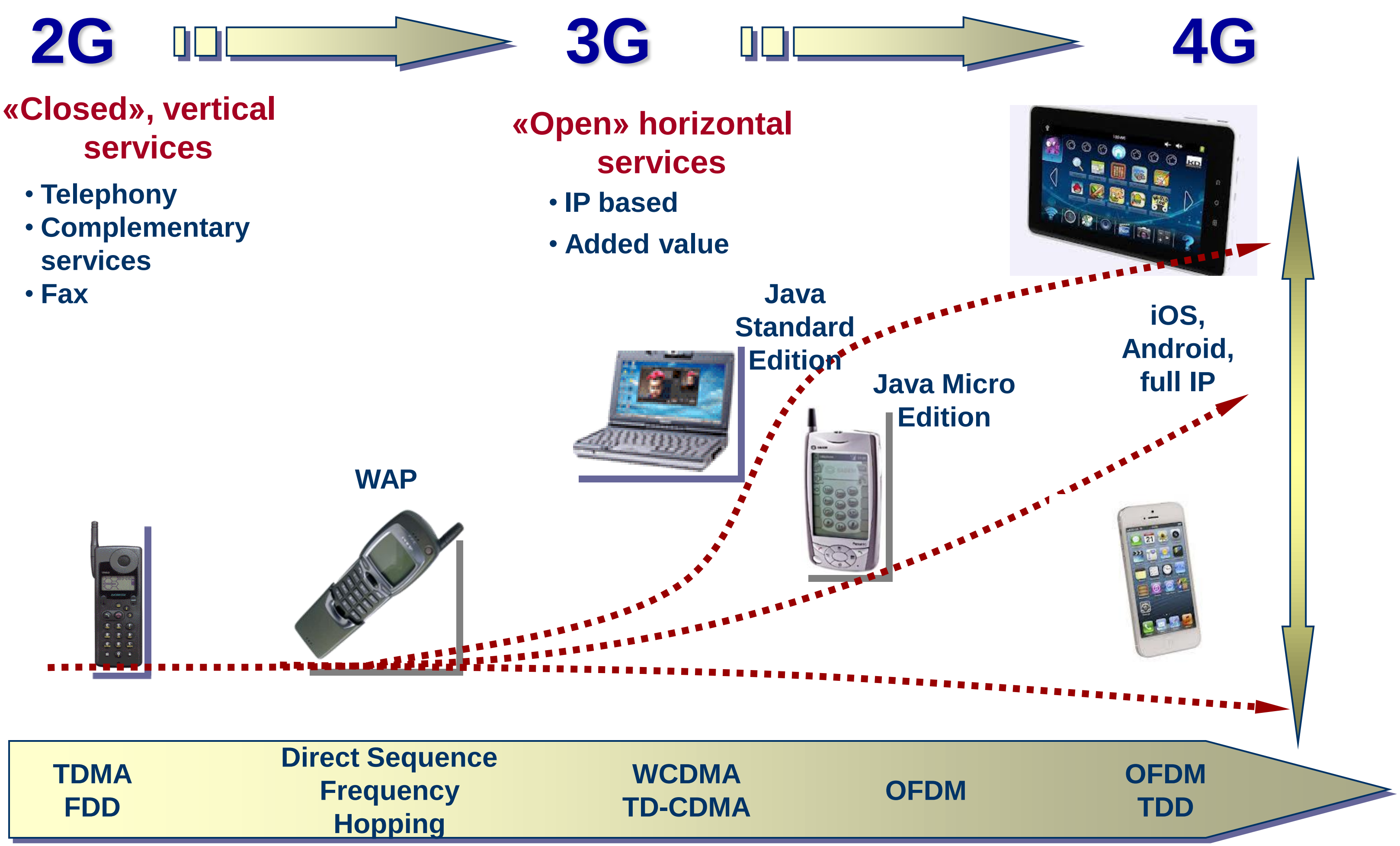


Global Convergence

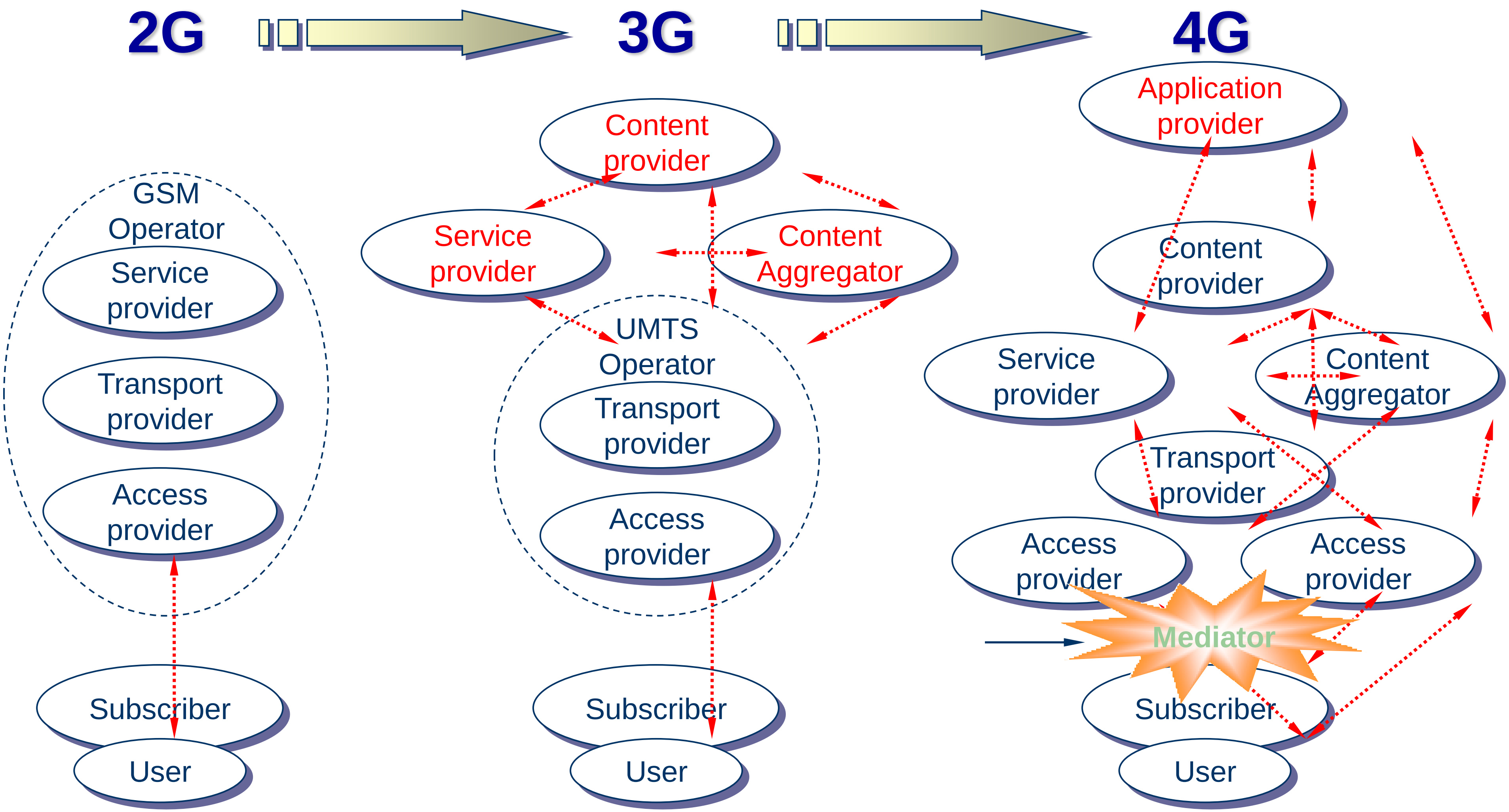
- LTE is the major technology for mobile broadband communications
  - Convergence of 3GPP and 3GPP2 technology tracks
  - Convergence of FDD and TDD into a single technology track



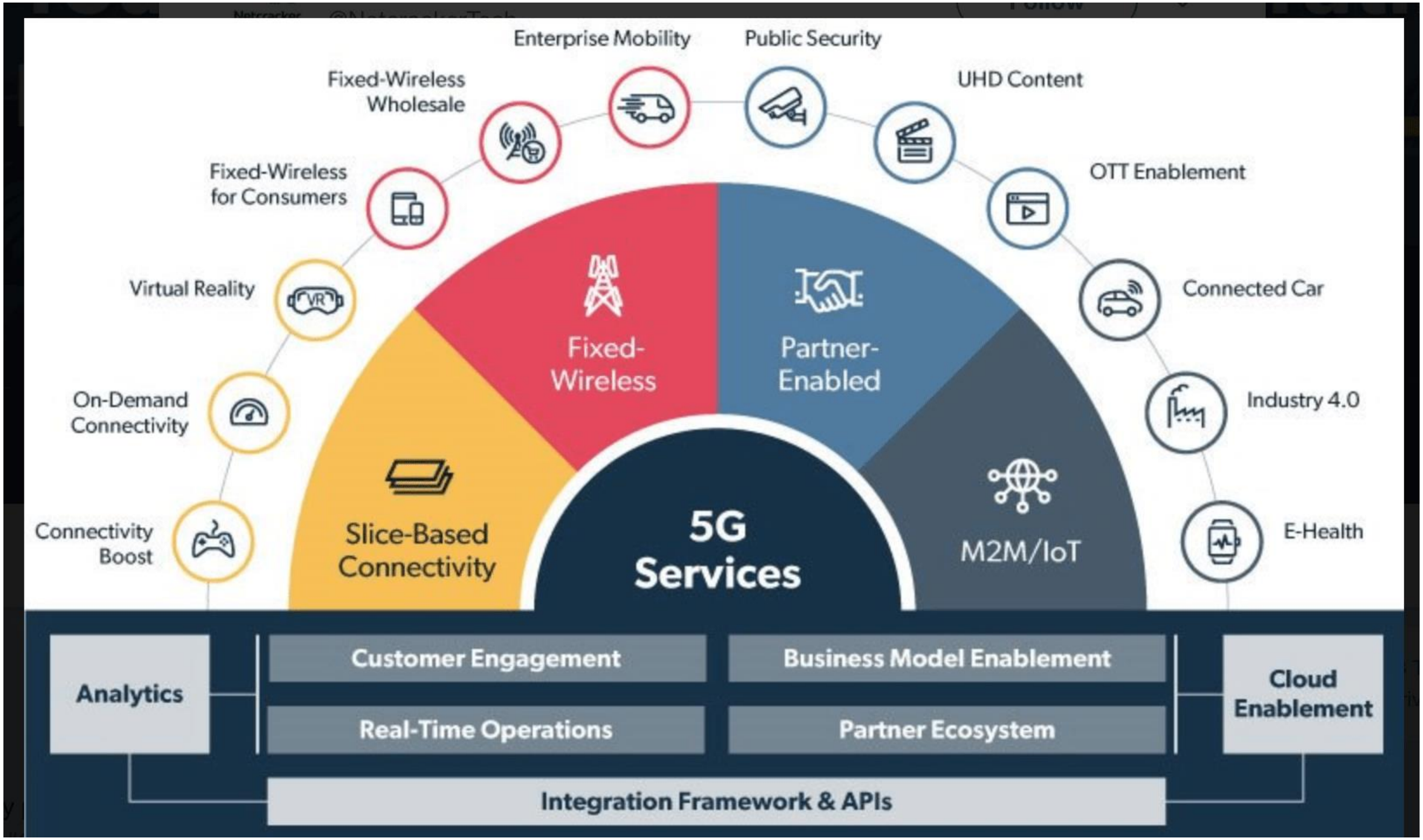
Evolution of terminals and services



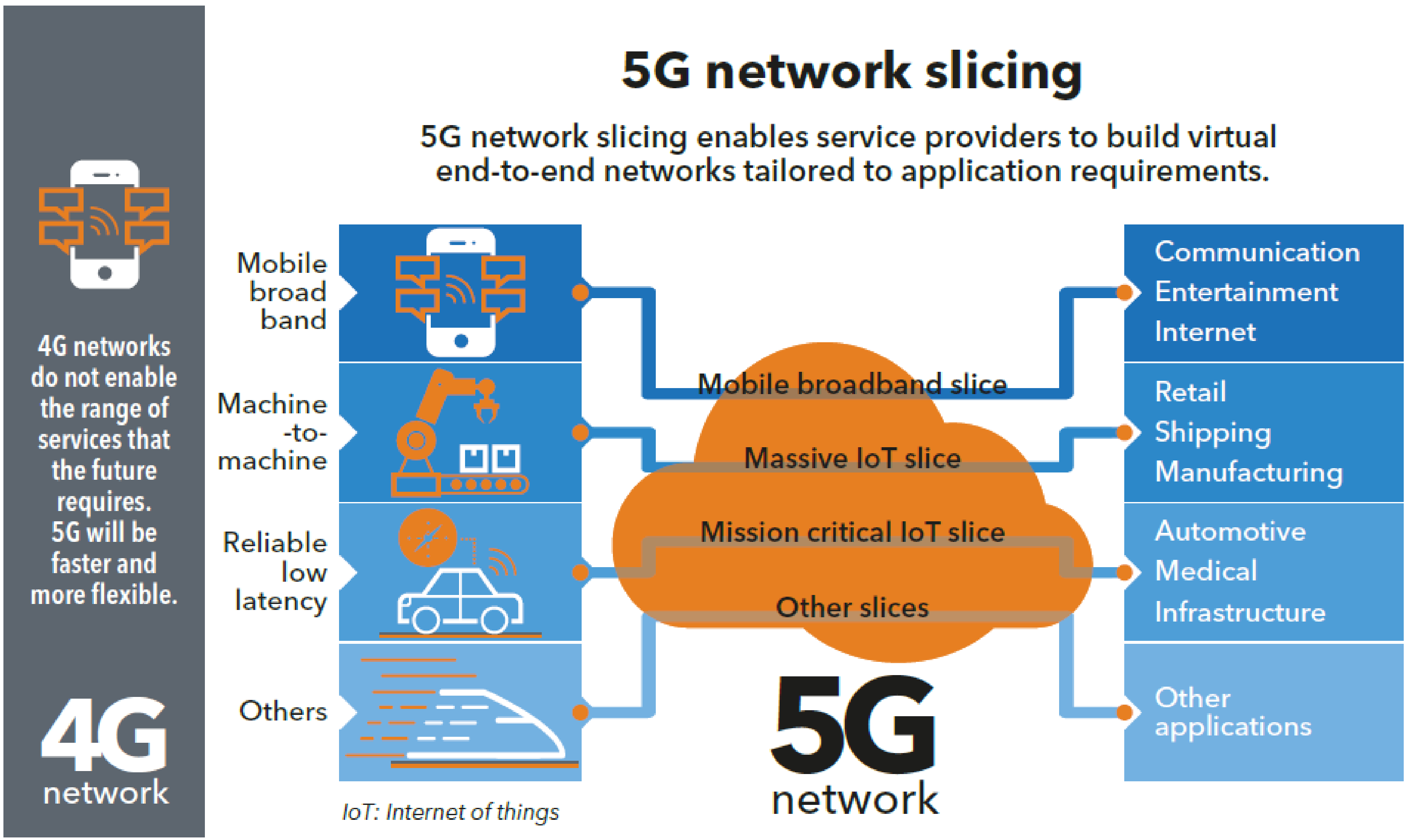
Business model evolution



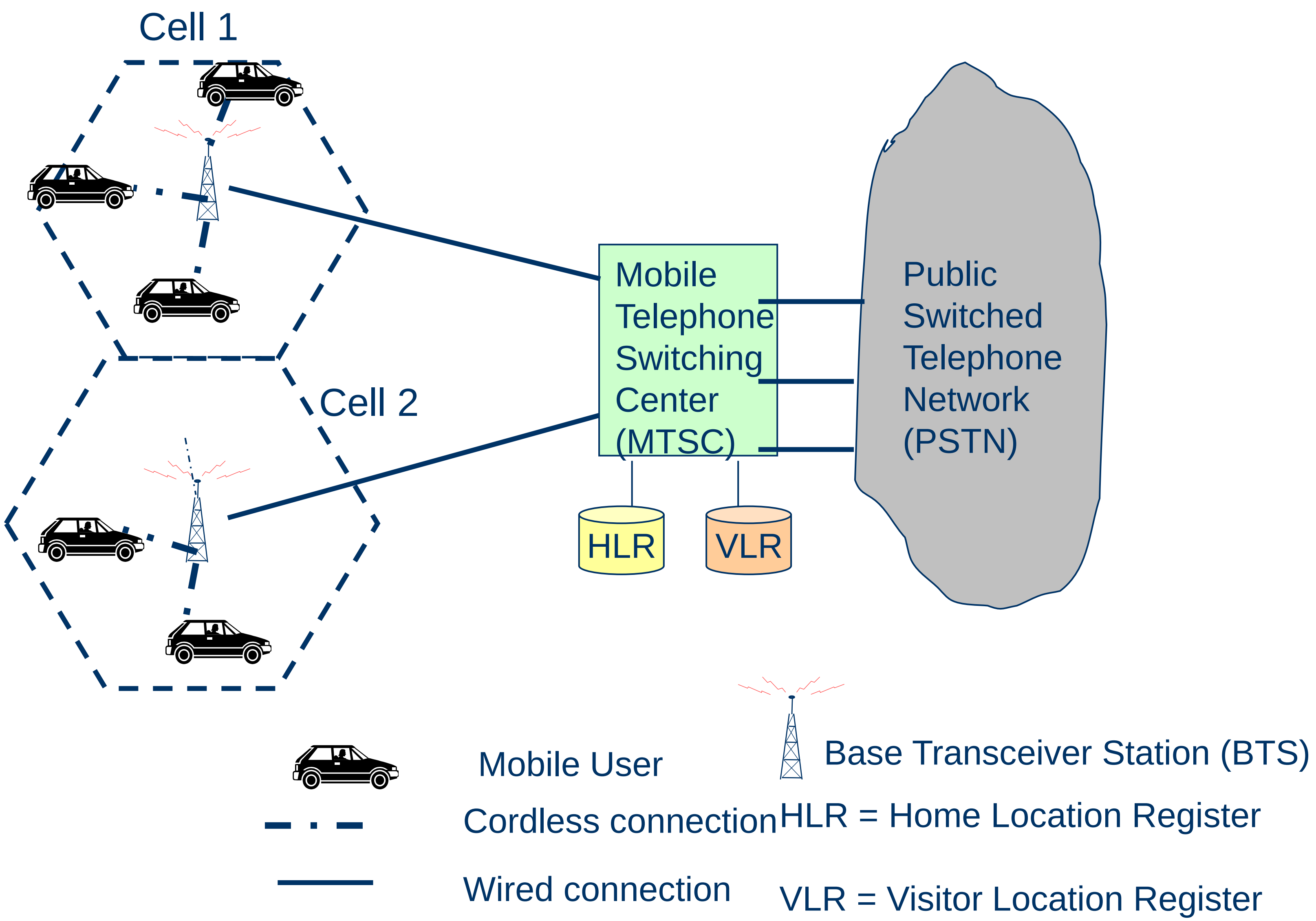
Business model evolution



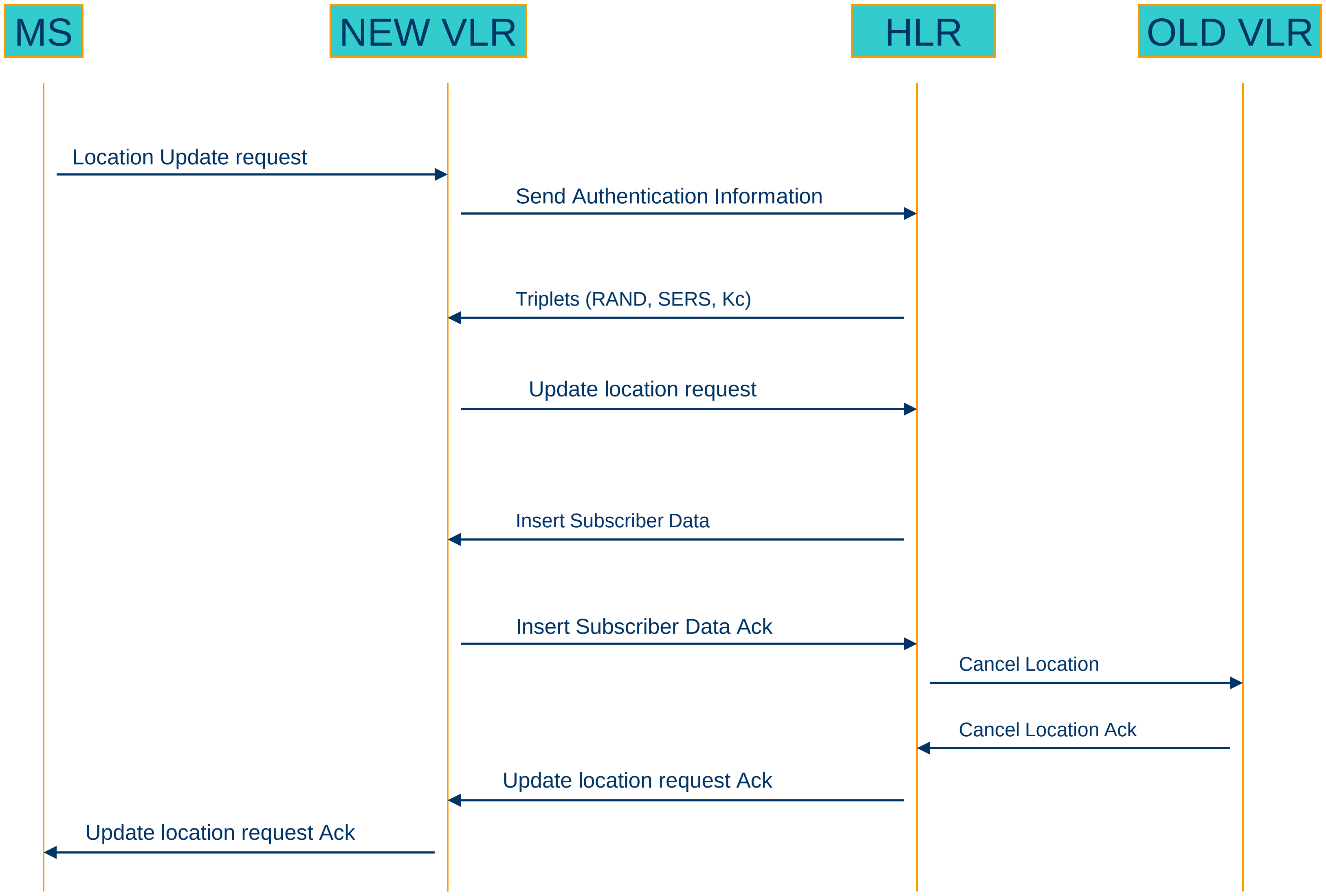
Business model evolution



A cellular network



LOCATION UPDATE



GSM

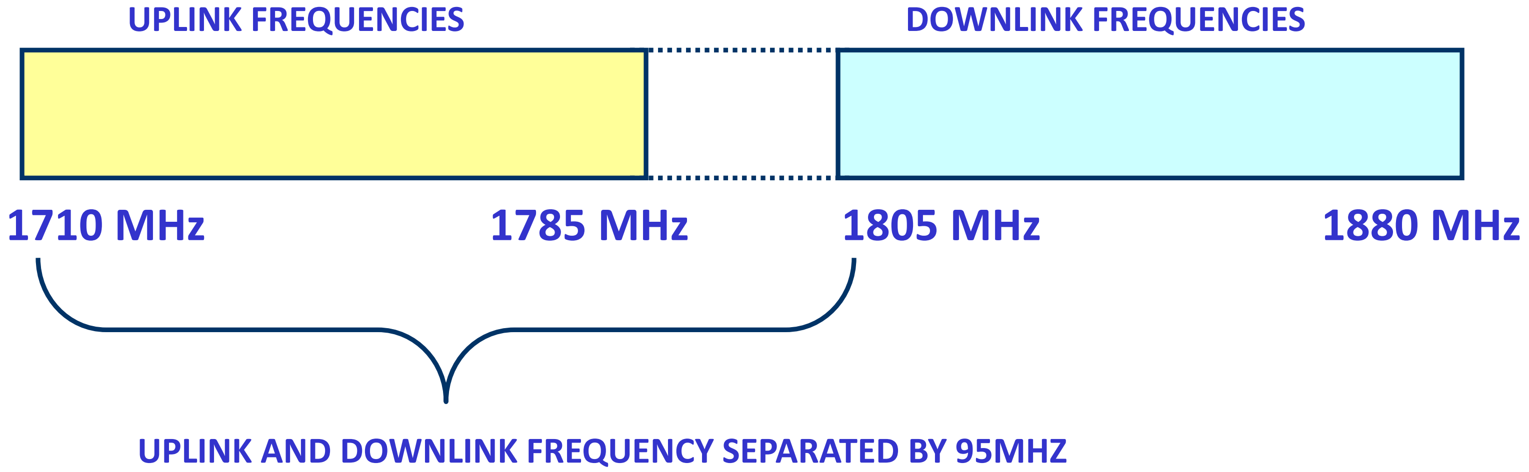
- Abbreviation for Global System for Mobile Communications
- In the mid 1980's, most of Europe didn't have a cellular network
  - They weren't committed to analog
- After many years of research, GSM was proposed around 1990
  - Covered Germany, France, England, and Scandinavia
  - In Greece GSM started in 1993
- Goals:
  - Roaming throughout all of Europe
  - Low power and inexpensive devices
  - All digital to offer 64kbps throughput
    - Never achieved

GSM Services

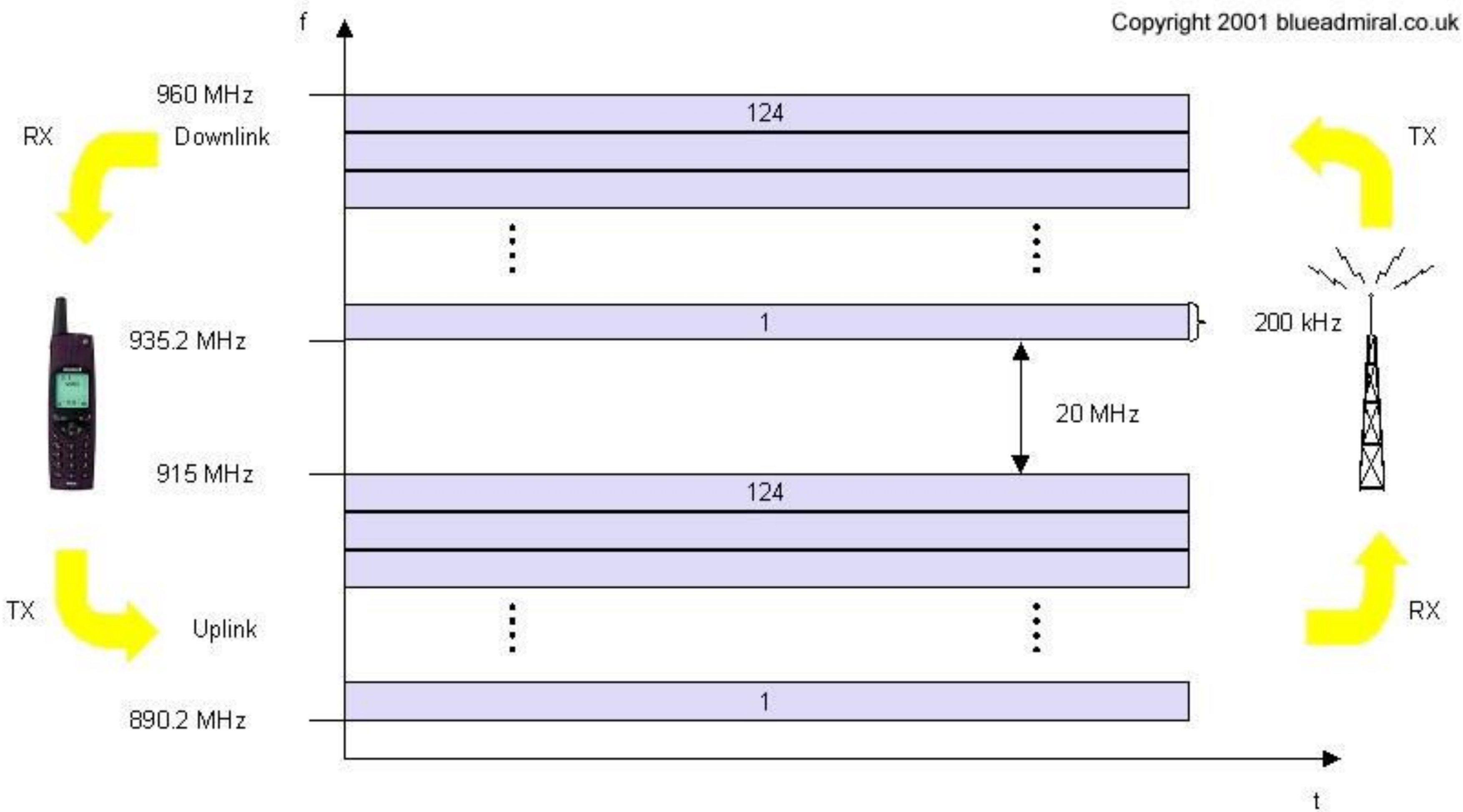
- Voice, 3.1 kHz
- Some data transmission is possible with very low speeds (originally 9.6kbps) – e.g. fax.
- Short Message Service (SMS)
  - 1985 GSM standard that allows messages of at most 160 chars (incl. spaces) to be sent between handsets and other stations
  - SMS was for years the most widely used data application in the world, with 3.6 billion active users, or 78% of all mobile phone subscribers (2011).

GSM Frequencies

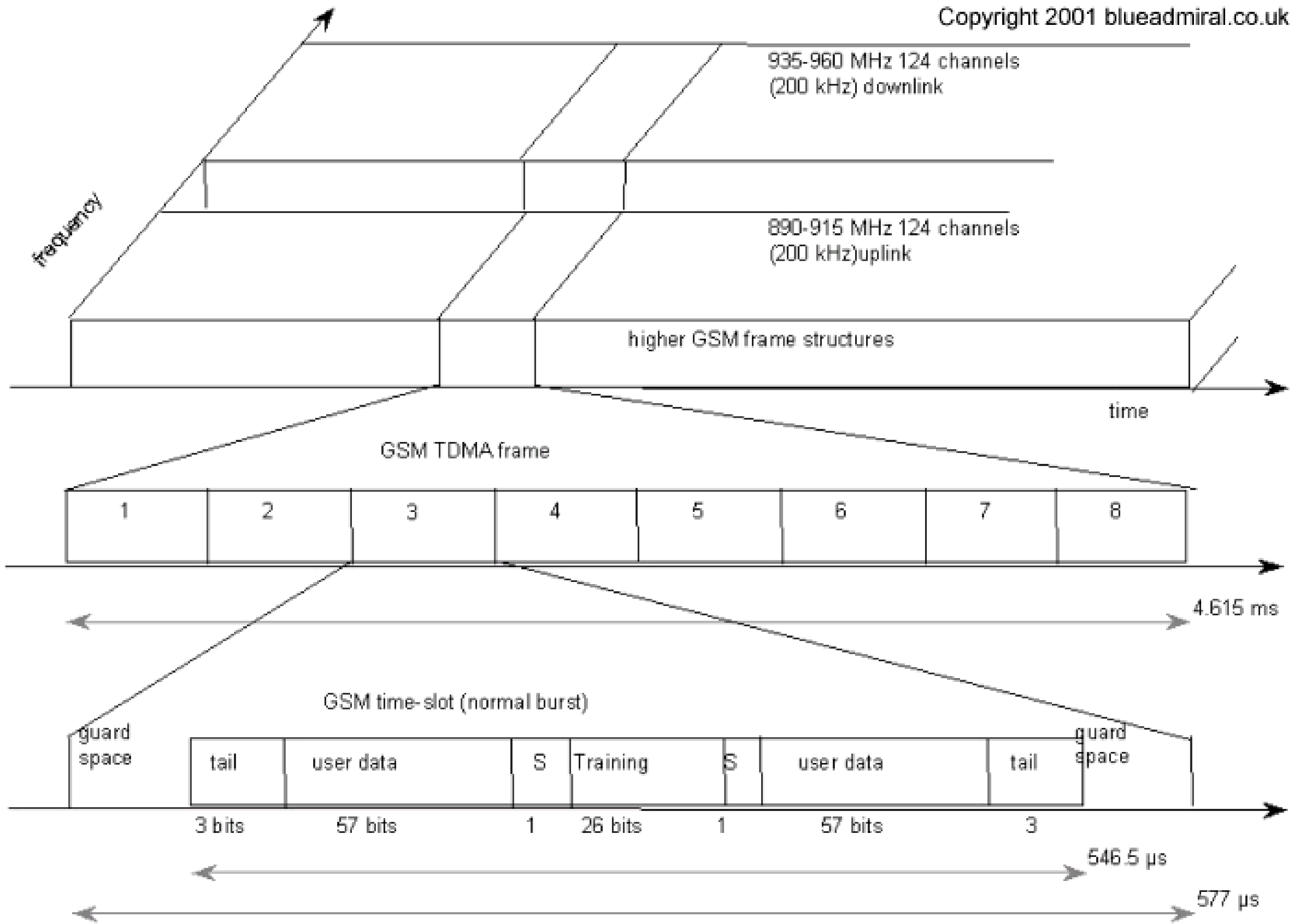
- Originally designed on 900MHz range, later available on 800MHz, 1800MHz and 1900 MHz ranges.
- Separate Uplink and Downlink frequencies
  - One example channel on the 1800 MHz frequency band, where RF carriers are spaced every 200 kHz



Uplink/Downlink frequency channels



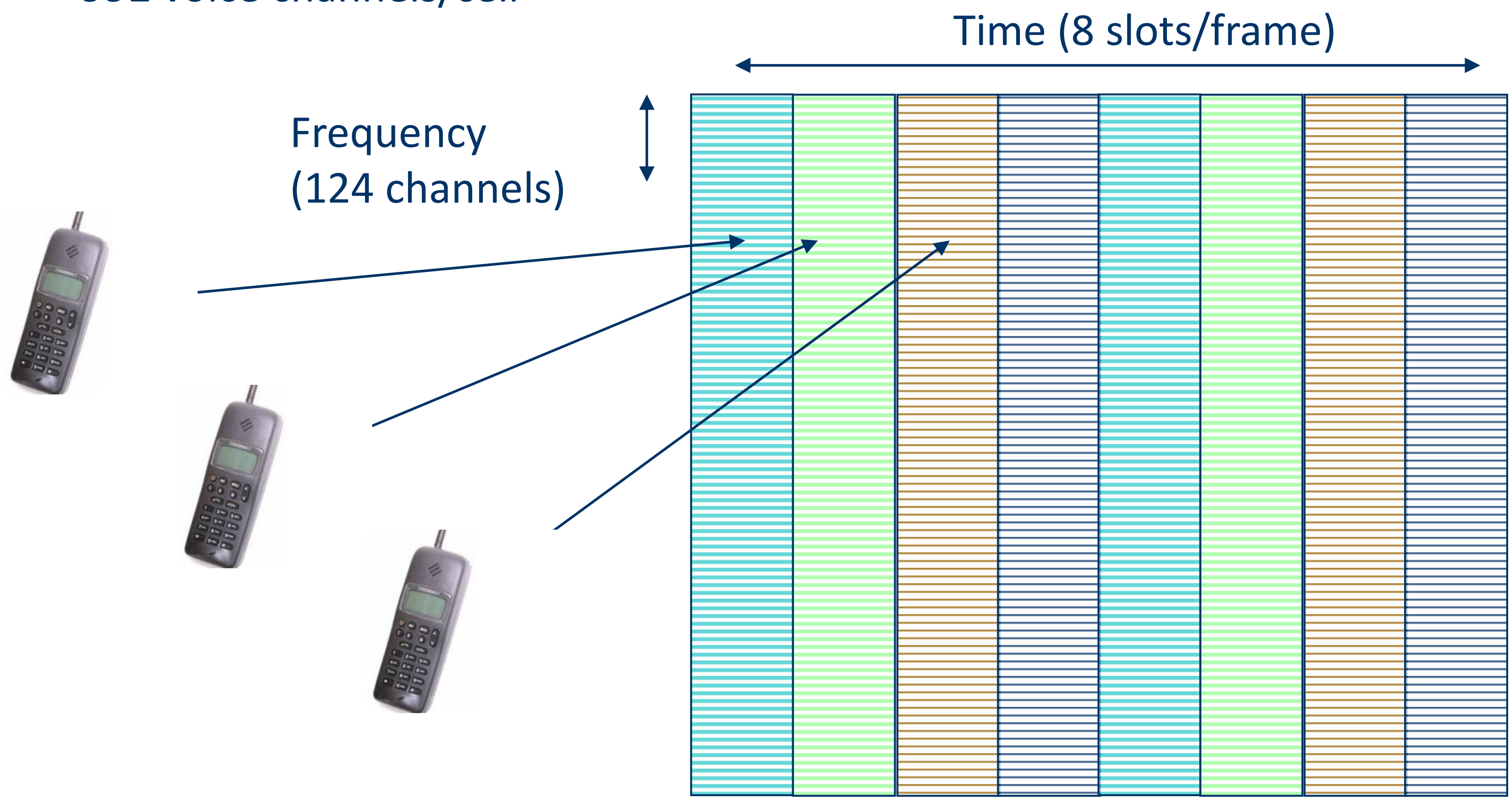
GSM resource allocation



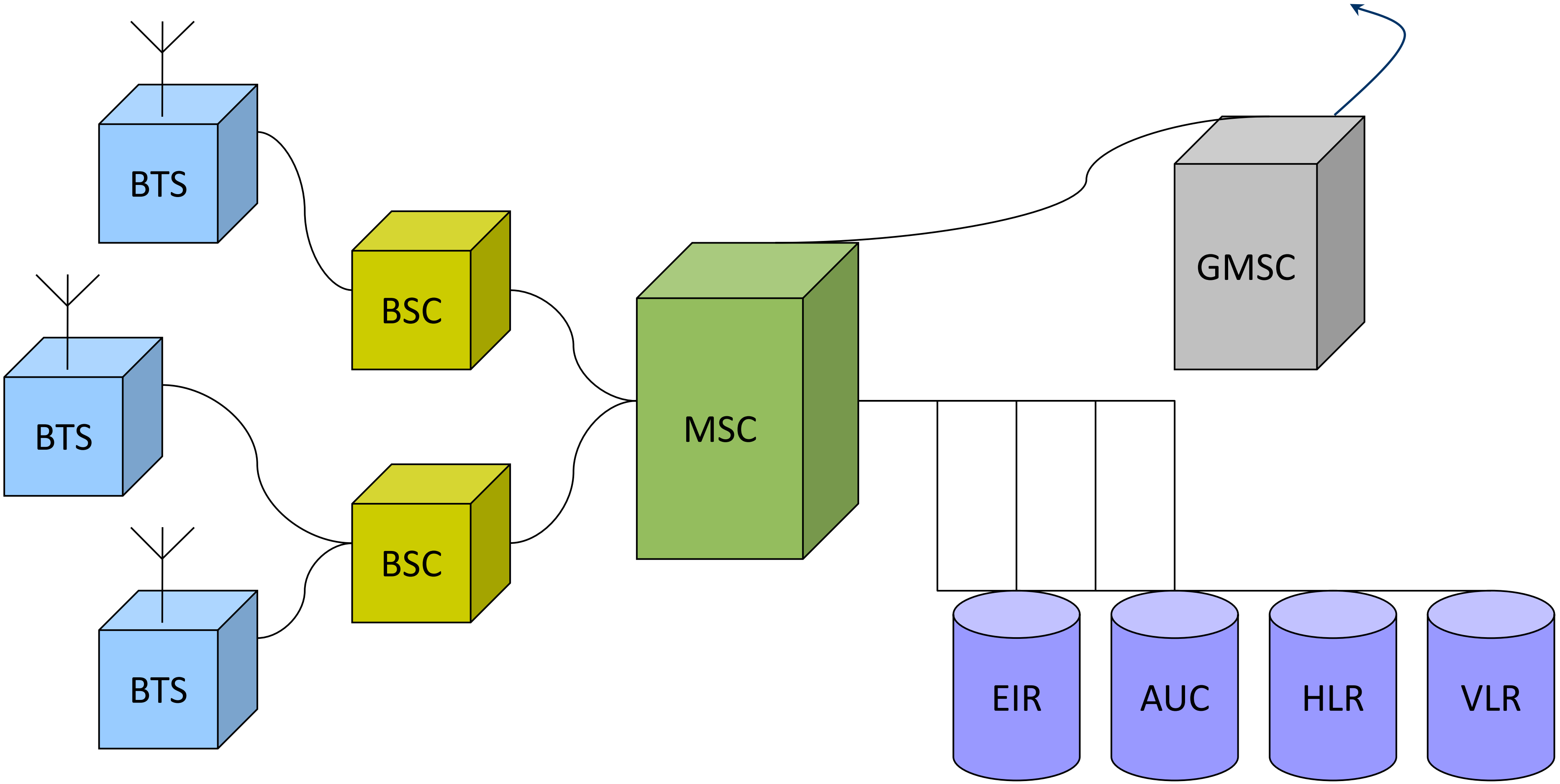
GSM System – Multiple Access

Time Division Multiple Access (TDMA)

992 voice channels/cell



GSM architecture



GSM main components

Base Transceiver Station (BTS): Encodes, encrypts, multiplexes, modulates and feeds the RF signals to the antenna.

Base Station Controller (BSC): Manages Radio resources for BTSs, assigns frequency and time slots for all mobile terminals in its area.

Mobile Switching Center (MSC): Heart of the network, call setup function and basic switching, call routing , billing information and collection, mobility management.

Home/Visiting Location Registers (HLR/VLR): permanent/temporary database about mobile subscribers in a large service area.

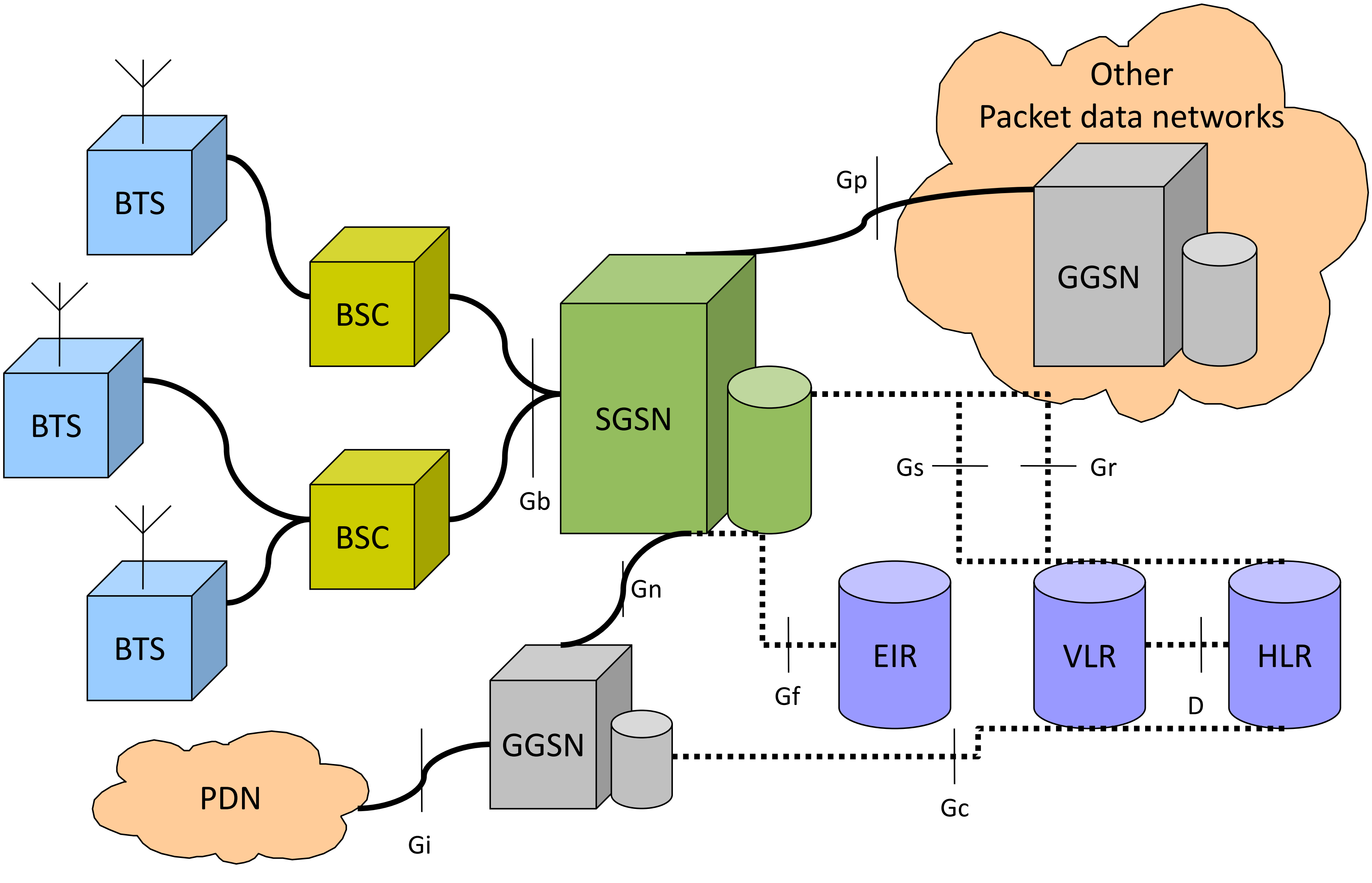
Authentication Center (AUC): Protects against intruders in air interface, maintains authentication keys and algorithms.

Equipment Identity Register (EIR): Database that is used to track handsets using the IMEI (International Mobile Equipment Identity).

GPRS (General Packet Radio Service)

- GSM upgrade that provides IP-based packet data transmission up to 171 kbps (never allowed)
- Users can "simultaneously" make calls and send data
- GPRS provides "always on" Internet access and the Multimedia Messaging Service (MMS)
- Performance degrades as number of users increase
- GPRS is an example of 2.5G telephony

GPRS Architecture

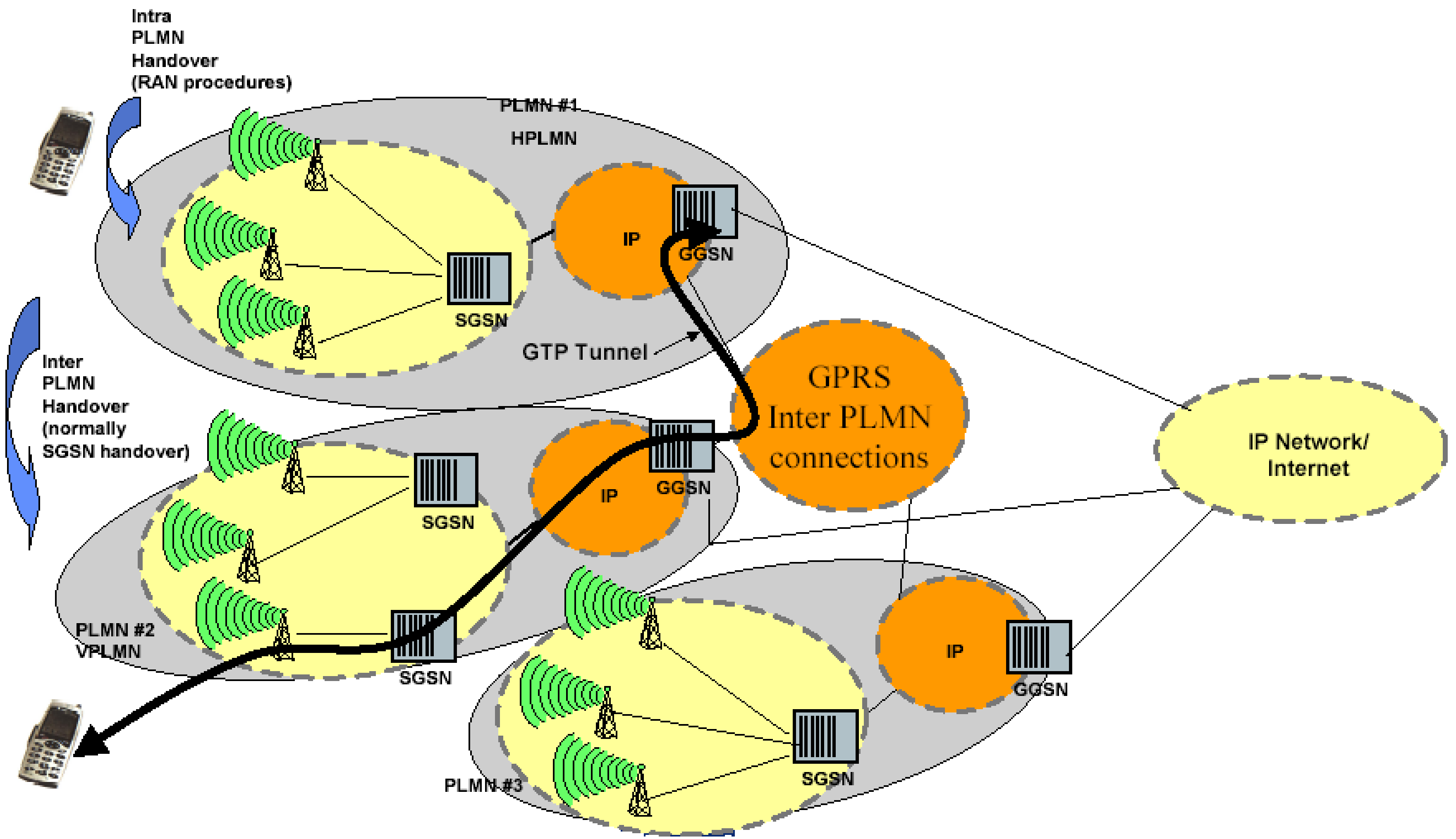


Main difference with GSM

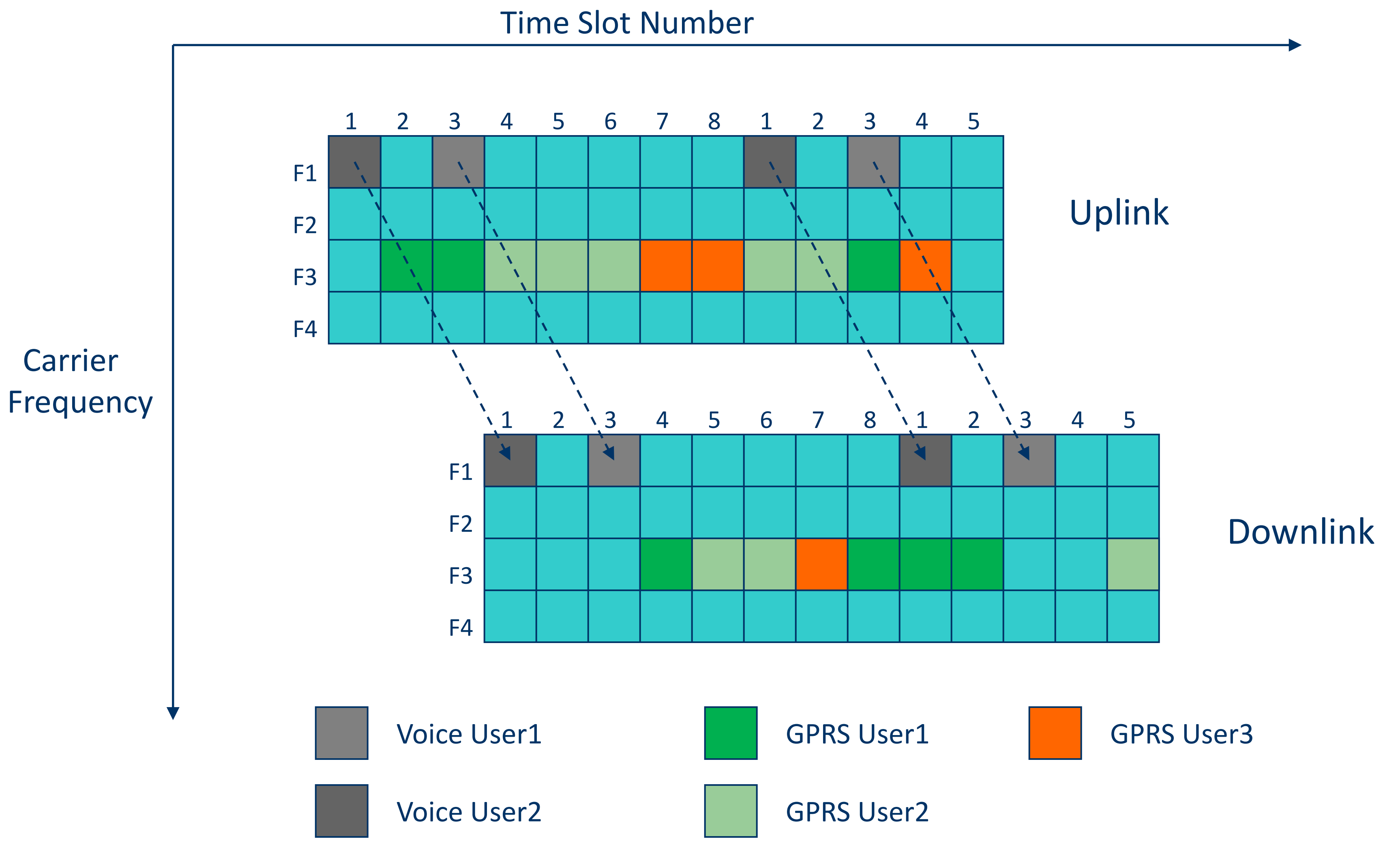
SGSN (Serving GPRS Support Node): Packet switching with mobility management capabilities. Responsible for the delivery of data packets from and to the mobile stations within its geographical service area.

GGSN (Gateway GPRS Support Node): Packet switch interworking with other data networks (Internet). Converts the GPRS packets coming from the SGSN into the appropriate packet data protocol format (e.g., IP)

Routing in GPRS



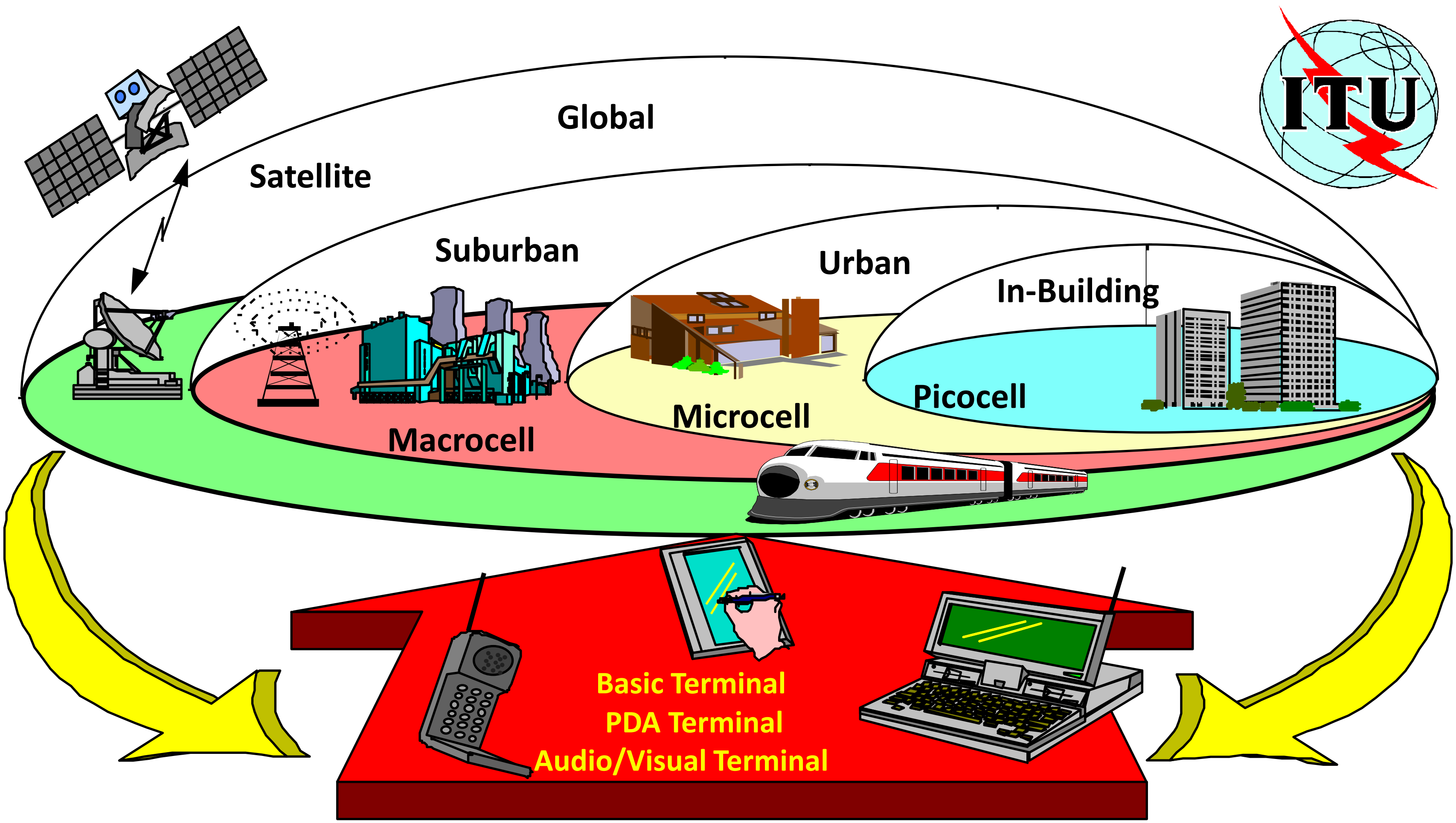
GPRS System – Multiple Access



3G

- 3G refers to a set of standards that comply to IMT-2000 specifications by ITU
- The following standards are typically branded 3G:
  - the UMTS system, first offered in 2001, standardized by 3GPP, used primarily in Europe
  - the CDMA2000 system, first offered in 2002, standardized by 3GPP2, used especially in North America

IMT-2000 Vision Includes LAN, WAN and Satellite Services

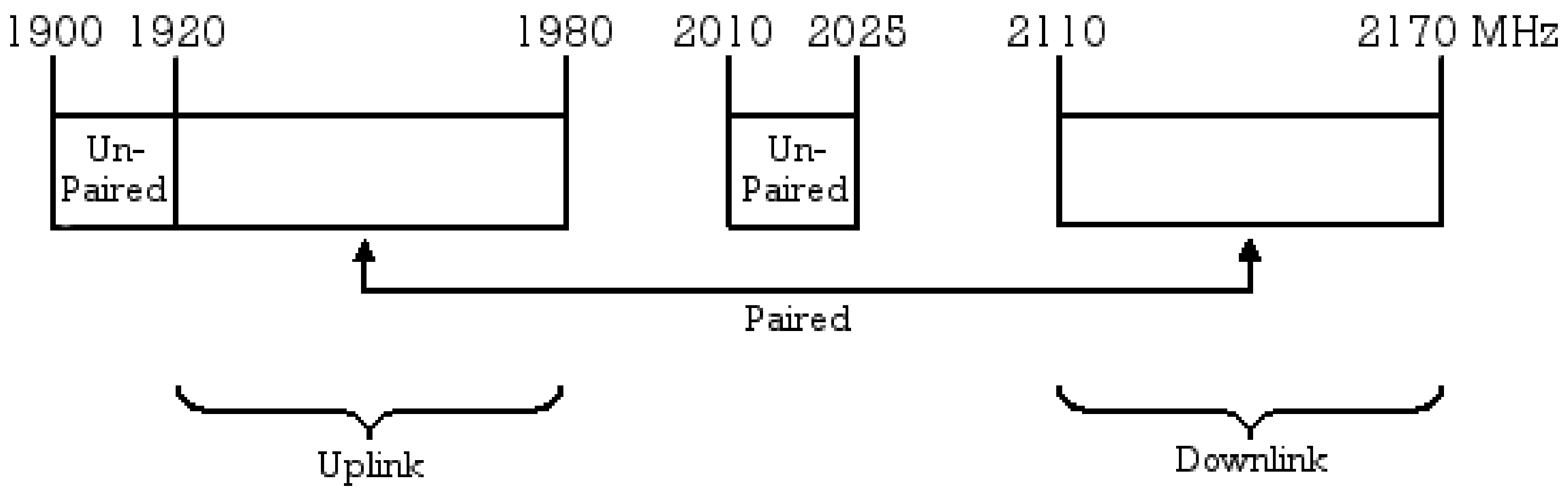


UMTS (Universal Mobile Telecommunications System)

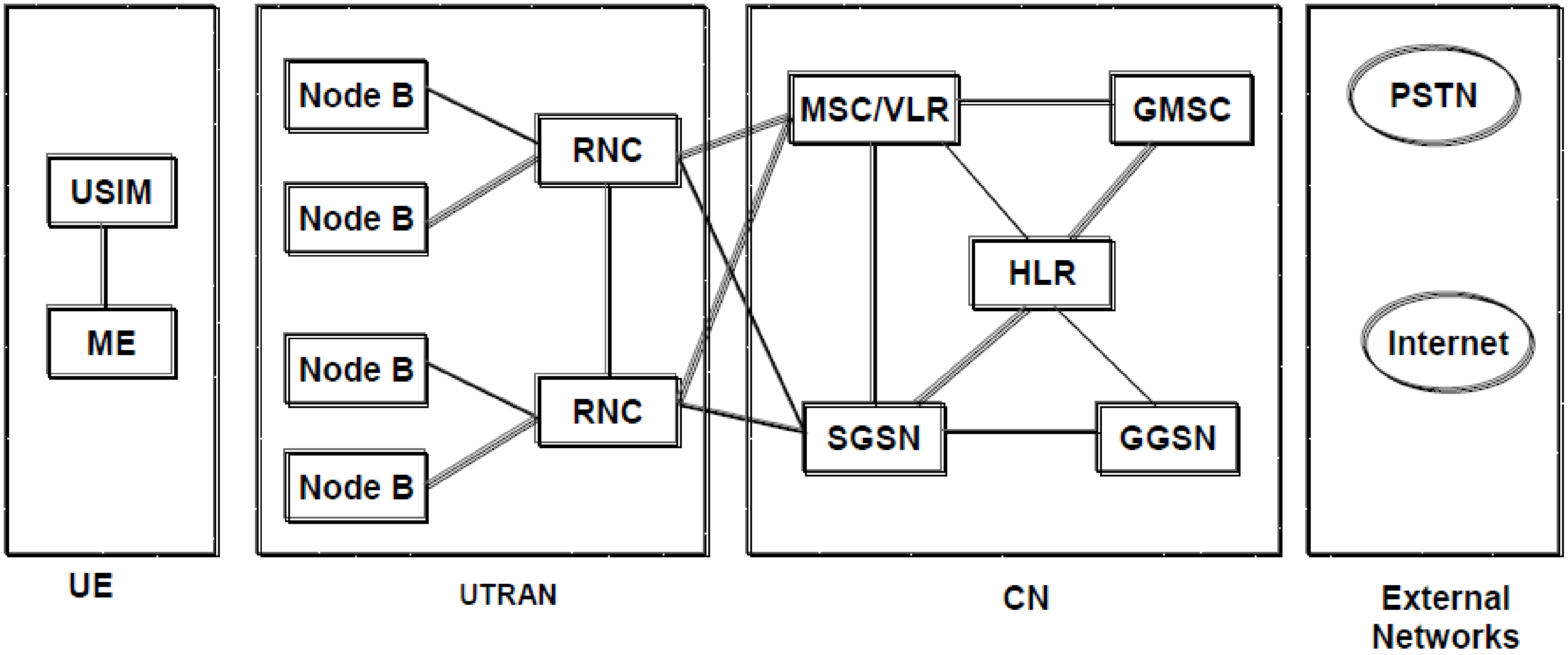
- Voice quality comparable to the public switched telephone network
- 144 Kbps/user in high-speed motor vehicles
- 384 Kbps/pedestrian standing or moving slowly over small areas
- Up to 2 Mbps for fixed applications like office use
- Symmetrical/asymmetrical data transmission rates
- Support for both packet switched and circuit switched data services like Internet Protocol (IP) traffic and real time video

UMTS Frequency Spectrum

- UMTS Band
  - 1900-2025 MHz and 2110-2200 MHz for 3G transmission
  - In the US, 1710–1755 MHz and 2110–2155 Mhz is used instead, as the 1900 MHz band was already used.



UMTS Architecture



- UE (User Equipment) that interfaces with the user
- UTRAN (UMTS Terrestrial Radio Access Network) handles all radio related functionality – WCDMA is radio interface standard here.
- CN (Core Network) is responsible for transport functions such as switching and routing calls and data, tracking users

UMTS Network Architecture

- UMTS network architecture consists of three domains
  - **Core Network (CN):** Provide switching, routing and transit for user traffic
  - **UMTS Terrestrial Radio Access Network (UTRAN):** Provides the air interface access method for user equipment.
  - **User Equipment (UE):** Terminals work as air interface counterpart for base stations.

UMTS QoS Classes

Traffic class	**Conversational class**	**Streaming class**	**Interactive class**	**Background**
Fundamental characteristics	Preserve time relation between information entities of the stream Conversational pattern (stringent and low delay)	Preserve time relation between information entities of the stream	Request response pattern Preserve data integrity	Destination is not expecting the data within a certain time Preserve data integrity
Example of the application	Voice, videotelephony, video games	Streaming multimedia	Web browsing, network games	Background download of emails

UMTS QoS Classes

Conversational	Streaming	Interactive	Background
low delay low delay variation	reasonably low delay	low round-trip delay	delay is not critical

basic QoS requirements

Conversational	Streaming	Interactive	Background
speech video telephony/ conferencing	video streaming audio streaming	www applications	store-and-forward applications (e-mail, SMS) file transfer

basic applications

UMTS QoS Classes

Conversational	Streaming	Interactive	Background

- low delay (< 400 ms) and low delay variation
- BER requirements not so stringent
- in the radio network => real-time (RT) connections

- speech (using AMR = Adaptive Multi-Rate speech coding)
- video telephony / conferencing:

  ITU-T Rec. H.324 (over circuit switched connections)

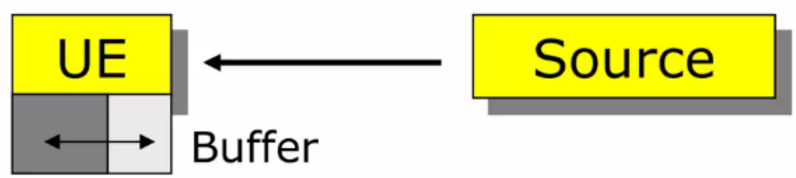
  ITU-T Rec. H.323 or IETF SIP (over packet switched connections)

UMTS QoS Classes

Conversational	Streaming	Interactive	Background

- reasonably low delay and delay variation
- BER requirements quite stringent
- traffic management important (variable bit rate)
- in the radio network => real-time (RT) connections

- video streaming
- audio streaming



video or audio information is buffered in the UE,
large delay => buffer is running out of content!

UMTS QoS Classes

Conversational	Streaming	Interactive	Background

- low round-trip delay (< seconds)
- delay variation is not important
- BER requirements stringent
- in the radio network => non-real-time (NRT) connections

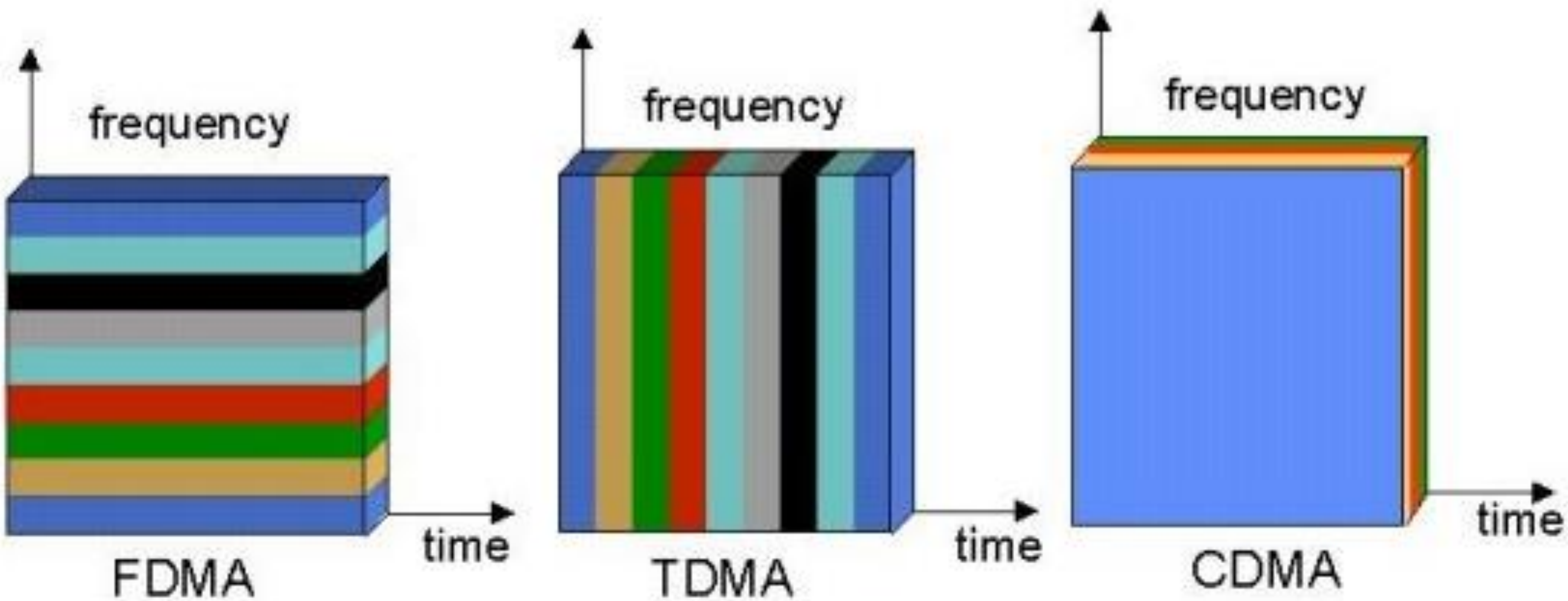
- web browsing
- interactive games
- location-based services (LCS)

UMTS QoS Classes

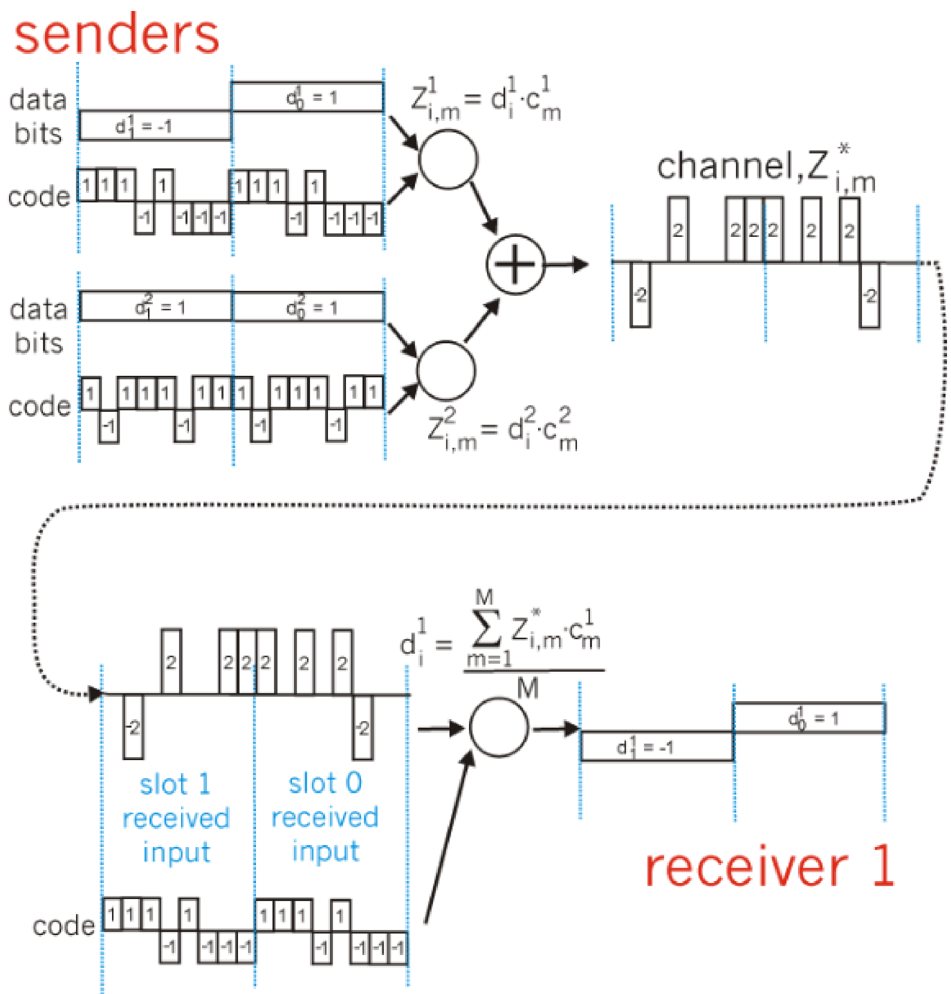
Conversational	Streaming	Interactive	Background

- delay / delay variation is not an important issue
- BER requirements stringent
- in the radio network => non-real-time (NRT) connections

- SMS (Short Message Service) and other more advanced messaging services (EMS, MMS)
- e-mail notification, e-mail download
- file transfer

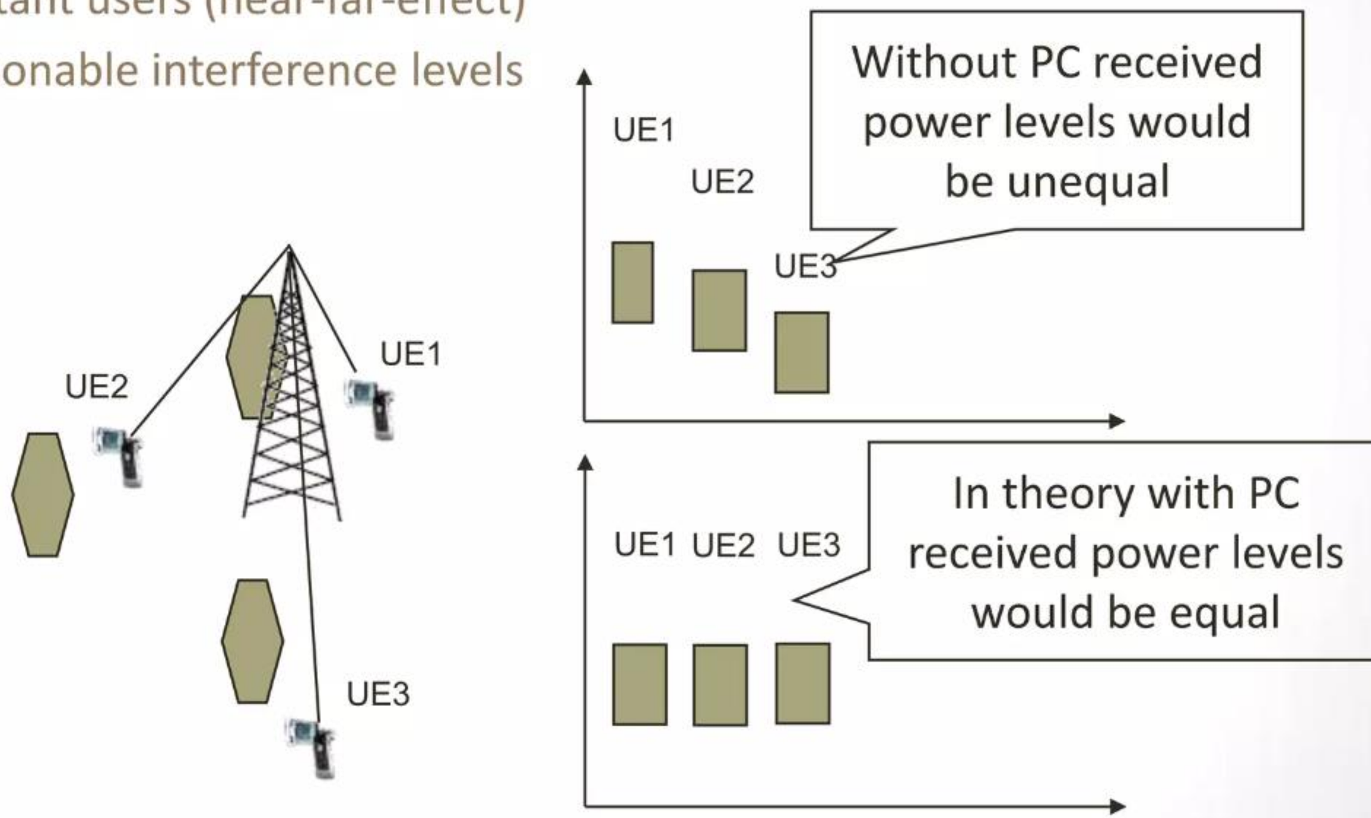

frequency
time
FDMA
frequency
time
TDMA
frequency
time
CDMA

Code Division Multiple Access (CDMA)



Power control in WCDMA

- The purpose of power control (PC) is to ensure that each user receives and transmits just enough energy to prevent:
  - Blocking of distant users (near-far-effect)
  - Exceeding reasonable interference levels



3.5G (HSPA)

High Speed Packet Access (HSPA) is an amalgamation of two mobile telephony protocols, High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA), that extends and improves the performance of existing WCDMA protocols

3.5G introduces many new features that enhance the UMTS technology. These include:

- Adaptive Modulation and Coding
- Fast Scheduling
- Backward compatibility with 3G
- Enhanced Air Interface

Service Roadmap