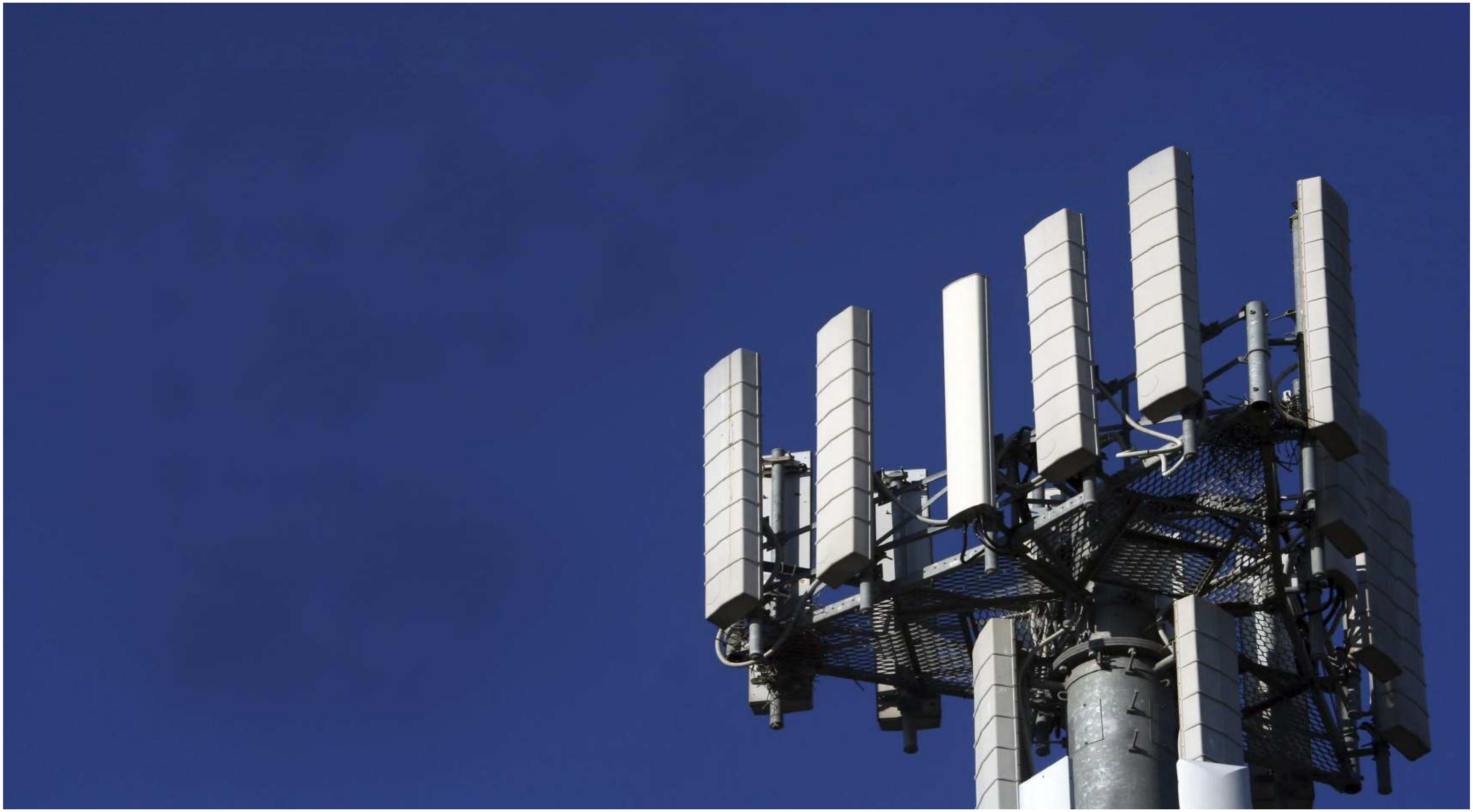


Digital Cellular Wireless
Long Term Evolution (LTE)

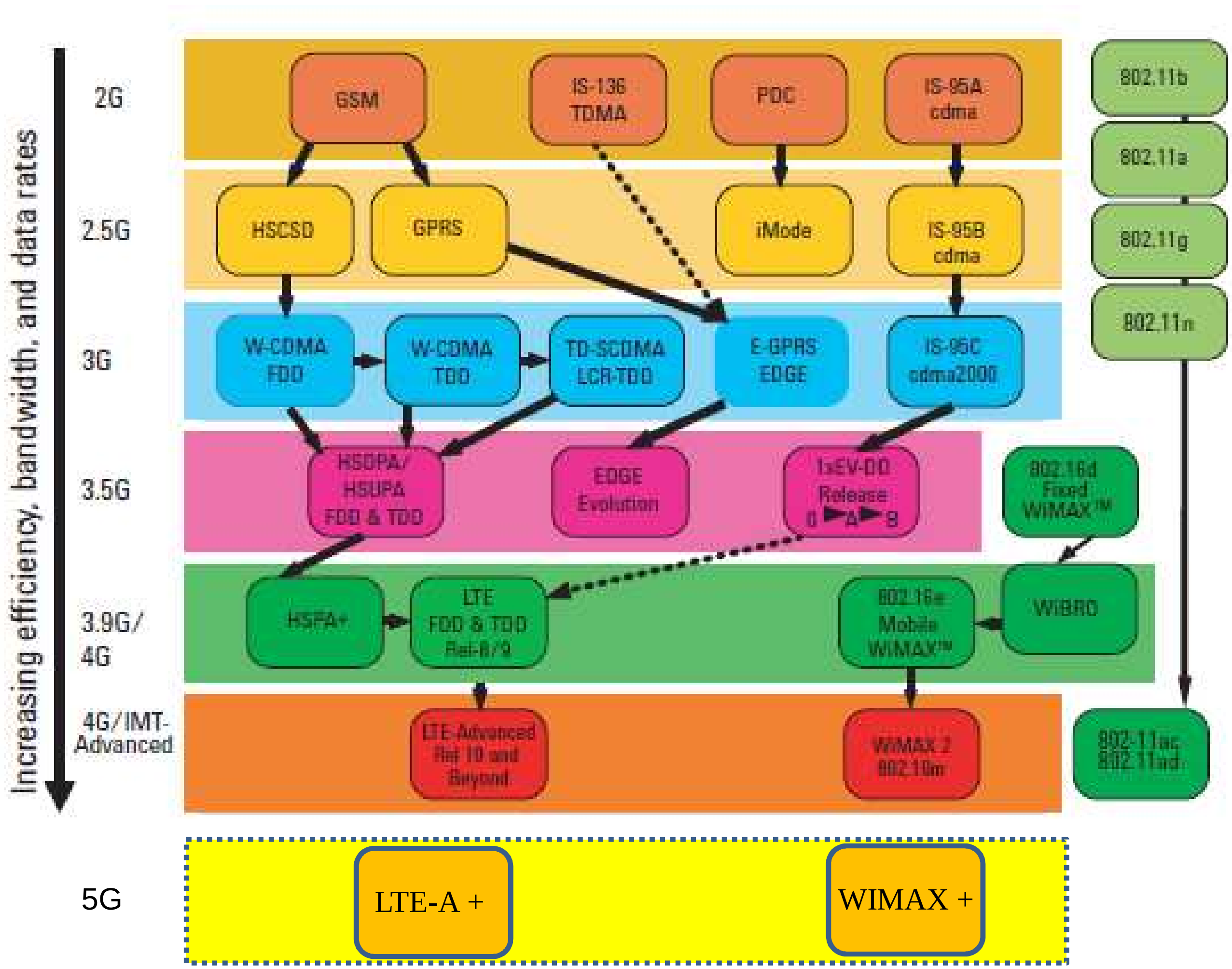
Evolution of Digital Wireless Standards

- Digital wireless communications started with the so-called second generation (2G) systems of the early 1990s, which first introduced digital cellular technology followed by (2.5G) systems.

- Next, third generation (3G) systems with their higher speed data networks were deployed to the much-anticipated fourth generation technology being developed today.

- Only two 4G candidates being actively developed today: 3GPP LTE-Advanced and IEEE 802.16m, which is the evolution of the WiMAX standard known as Mobile WiMAX™ and 5G for the future networks (circa 2020)

Evolution of Digital Wireless Standards - Illustration



Long Term Evolution (LTE)

A common evolution path…

Long Term Evolution (LTE) is the current / next generation broadband wireless technology for 3GPP and 3GPP2 networks

Enabling new applications, lowering cost

- Peer to peer applications requiring high throughput
- Online gaming, HD Video
- Flat fee trend

OFDM

Communication Robustness

MIMO

Increased link capacity

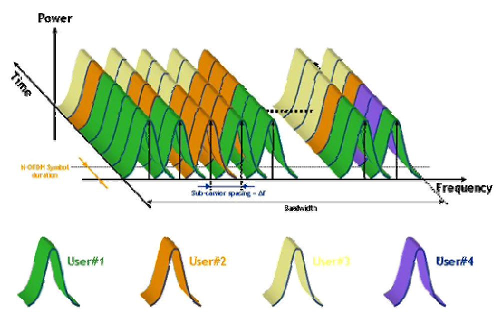
Scalable

Flat & scalable Architecture

LTE Key Principles

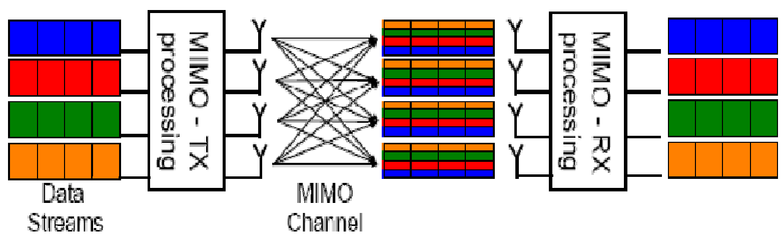
Airlink is OFDMA (DL) **/ SC-FDMA** (UL) **for robust modulation in dense environments**

- Increased spectral efficiency
- Flexibility in scheduling in time & frequency domain
- Scalable → 1.4, 3, 5, 10, 15 & 20 MHz carriers



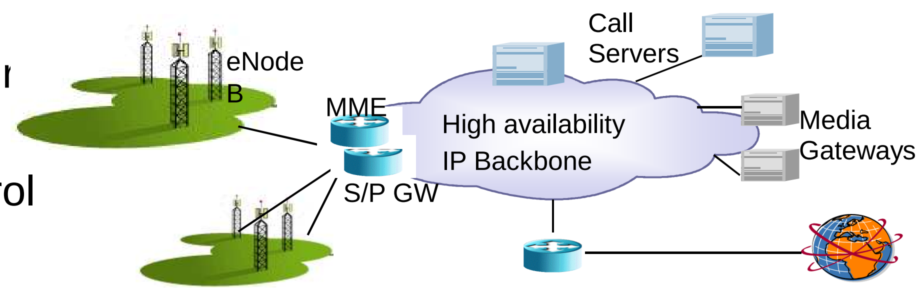
MIMO: Increased link capacity

- Multiple-input, multiple-output UL& DL
- Increased performance & range
- Overcome multi-path interference

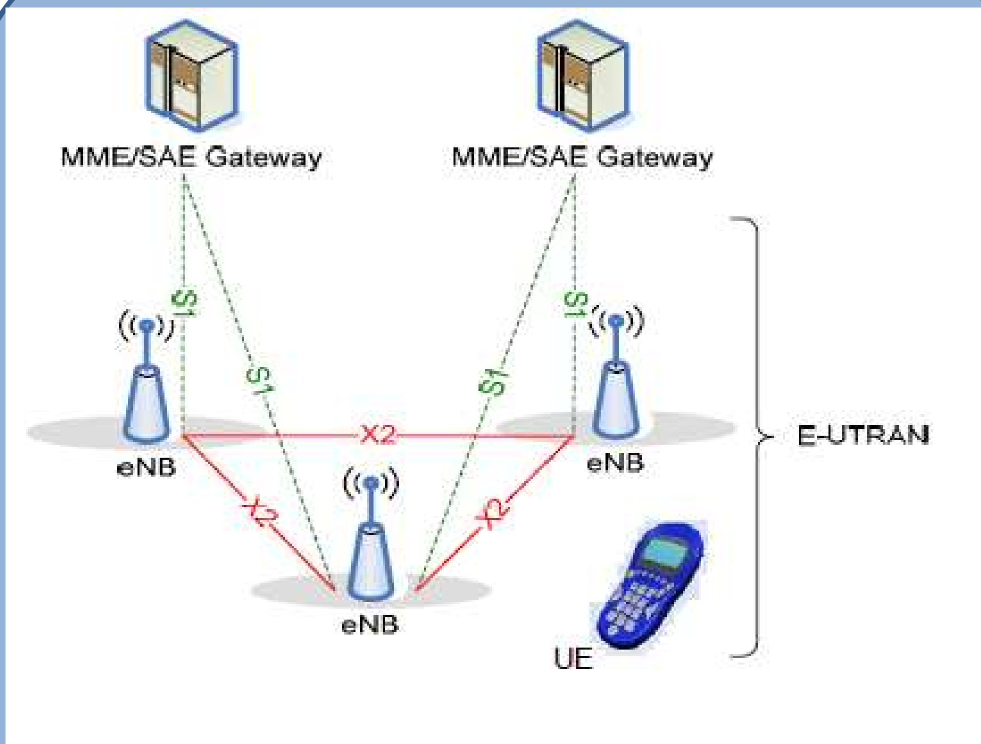


IP Core: flat, scalable

- Simplified packet only network architectur
- Reduction in number of logical nodes
- Clean separation of user plane and control plane



LTE Architecture – Simplified View

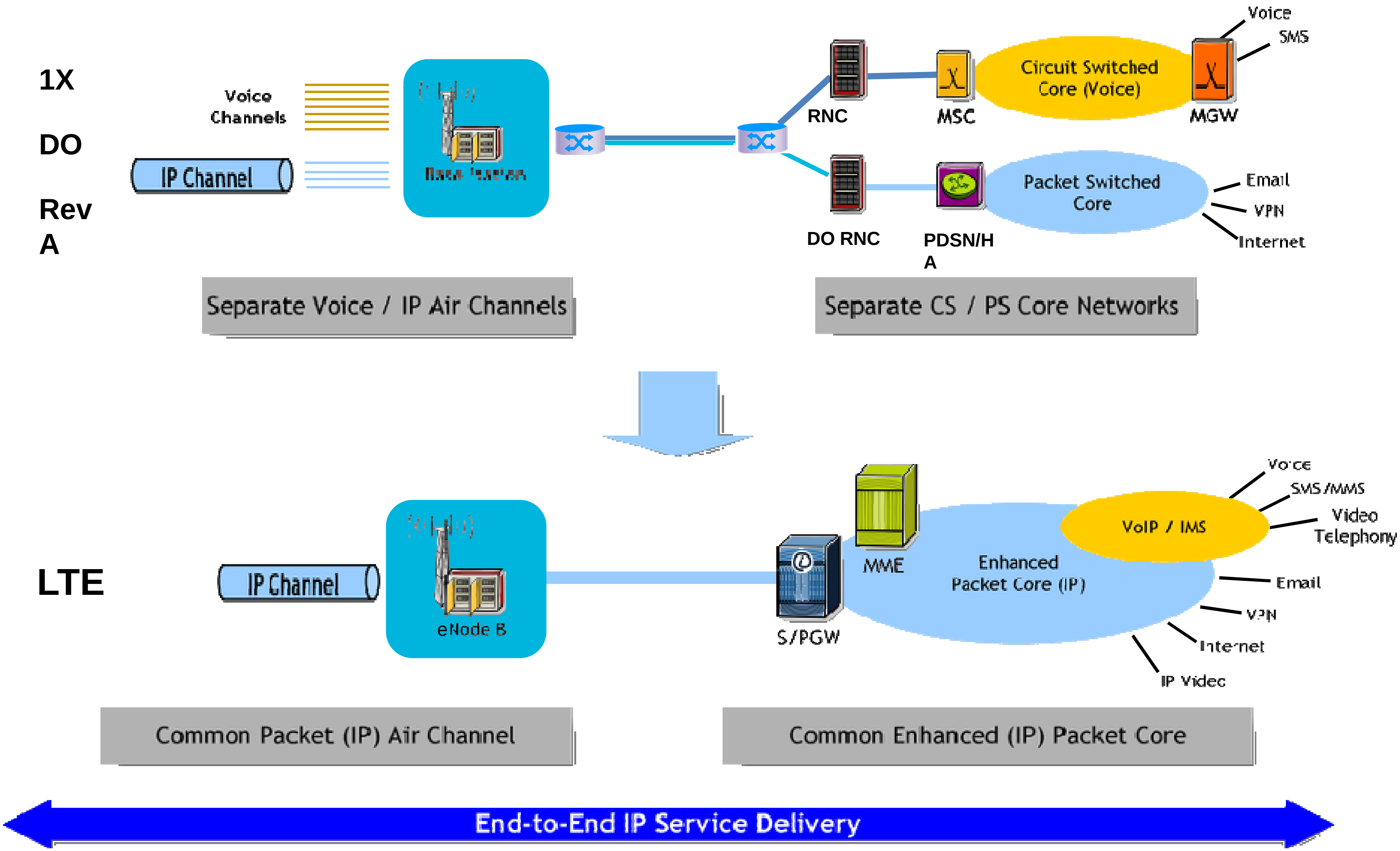


- **eNB**: Enhanced Node B, or base station
- **UE**: User Equipment
- **EPC**: Evolved Packet Core
  - **MME**: Mobility Management Entity (Control Plane)
  - **SAE**: System Architecture Evolved (User Plane)
- **E-UTRAN**: Evolved Universal Terrestrial Radio Access Network

S1 interface – connects eNB to MME/SAE Gateway, handles user traffic and control information

X2 interface – connects eNB in peer to peer fashion to assist handover and provide a means for rapid co-ordination of radio resources

LTE: Evolution Path



2G/3G & 4G Network Functions

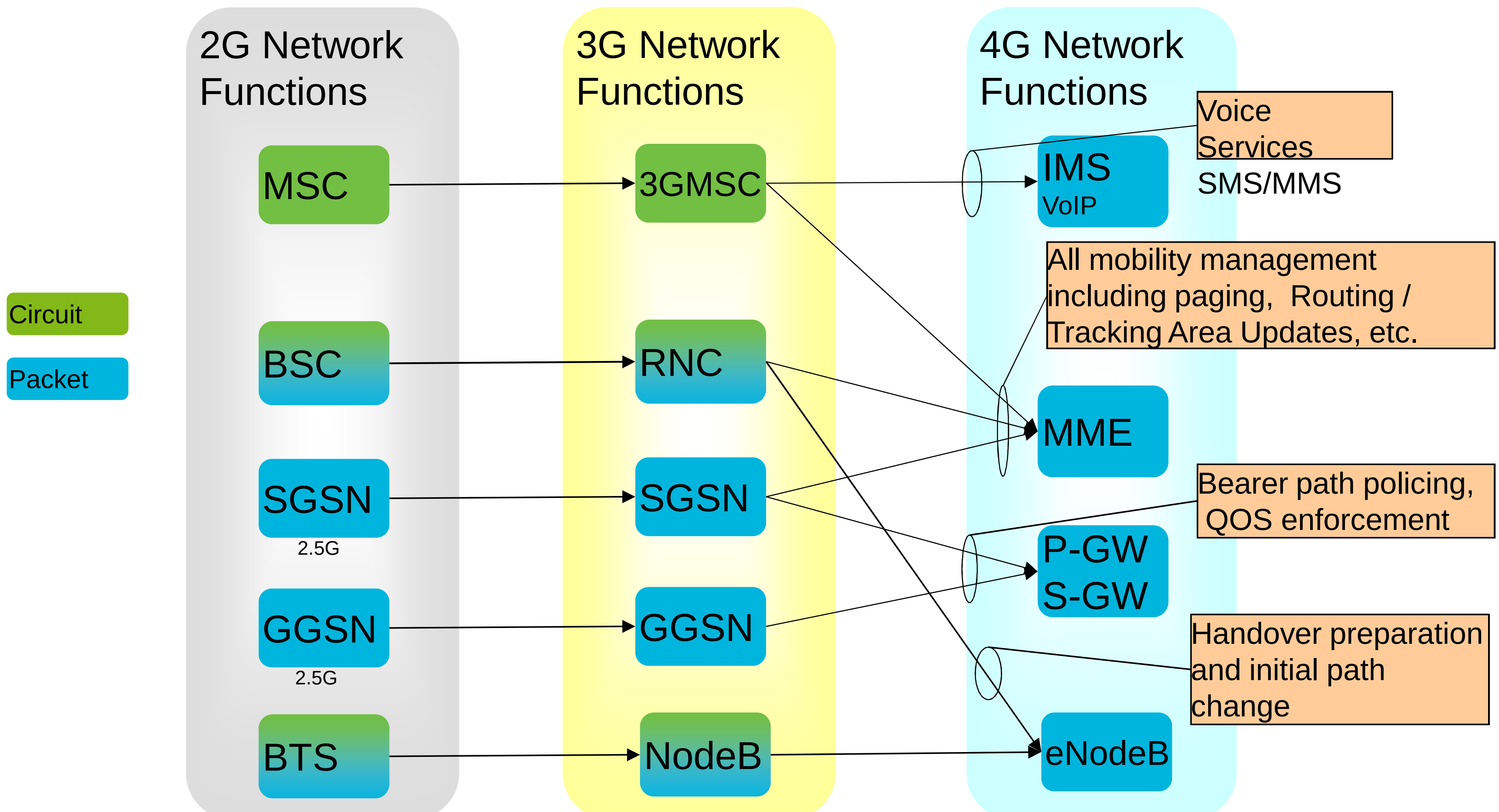
2G Network Functions
MSC – mobile switching center
BSC – base station controller
BTS – base station transceiver system

2G / 3G Network Functions
SGSN – serving GPRS support node
GGSN – gateway GPRS support node

3G Network Functions
3GMSC – 3G mobile switching center
RNC – radio network controller
NodeB -

4G Network Functions
IMS – IP multimedia system
MME – mobility management entity
S-GW – serving gateway
P-GW – packet gateway
eNodeB – evolved NodeB

Core Network Changes between 3G and 4G



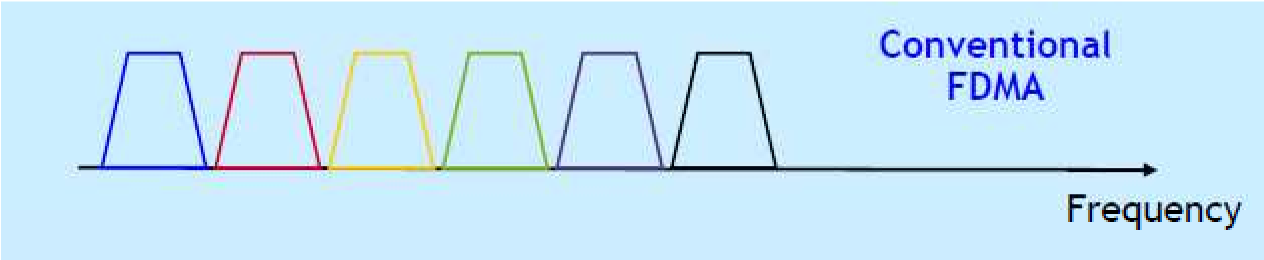
4G LTE introduces radical change in the architecture of the core network.

LTE: Physical Layer

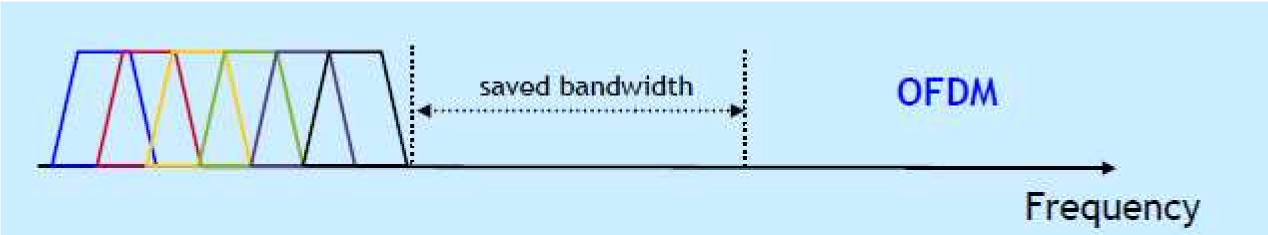
- The LTE physical layer is unique because it has asymmetrical modulation and data rates for uplink and downlink.
- Designed for full-duplex operation, with simultaneous transmission and reception.
- On the downlink, the radio is optimized for performance because the transmitter at the base station has plenty of power.
- On the uplink, the radio is optimized more for power consumption rather than efficiency, because while processing power has increased, mobile device battery power has stayed essentially constant.

OFDM Basics: Concepts

Frequency Division Multiple Access (FDMA)
In FDMA carriers are separated sufficiently in frequency such that there is minimal overlap from the adjacent carrier

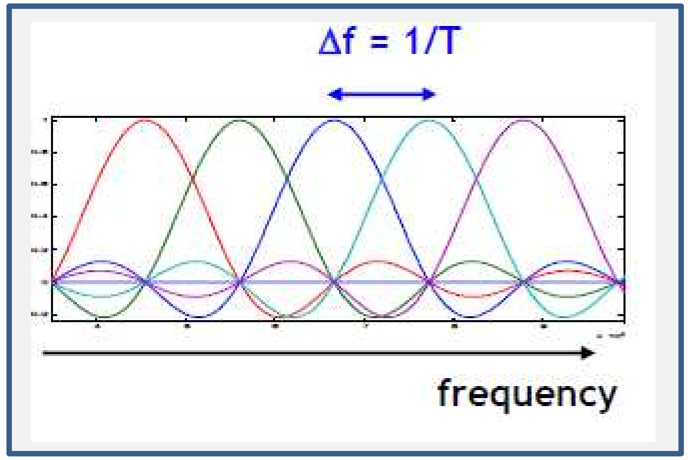


Orthogonal Frequency Division Multiplexing (OFDM)
In OFDM carriers are orthogonal to each other and are overlapped resulting in bandwidth savings (spectrally efficient)

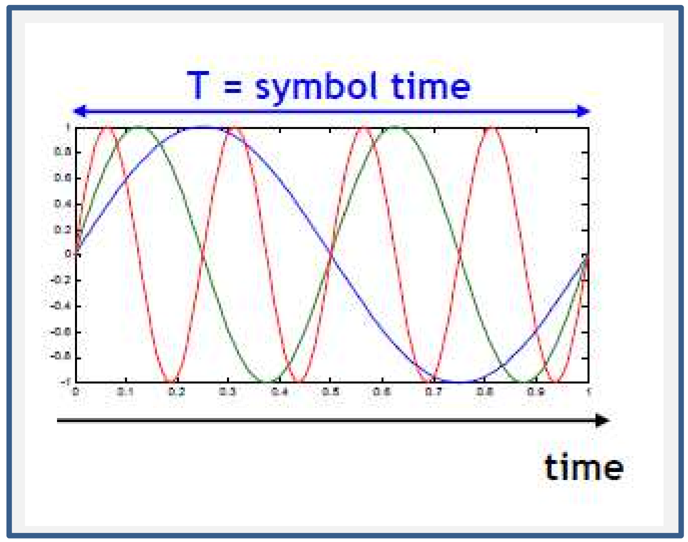


OFDM Basics: Signal View

In Frequency Domain the overlapping carriers are sinc functions referred to as subcarriers with a narrow bandwidth



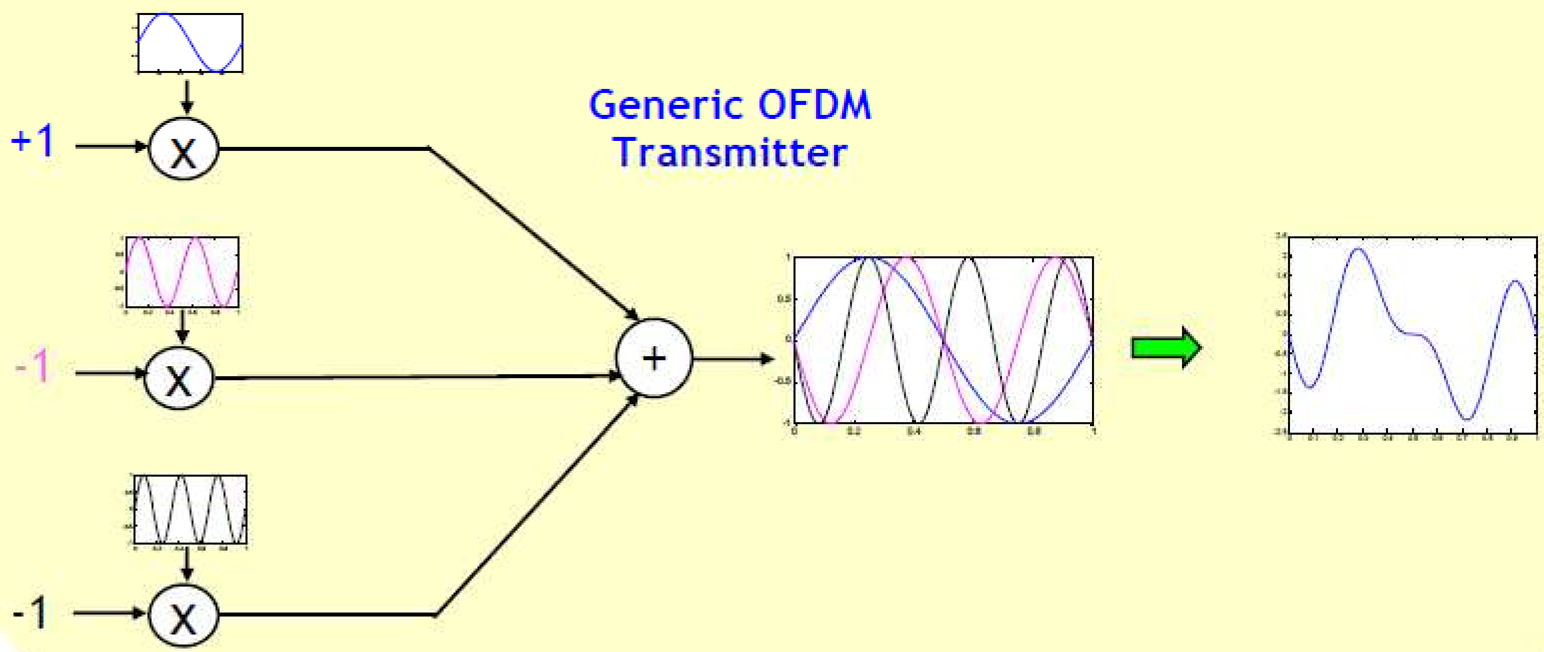
In Time Domain these overlapping carriers are gated sinusoid functions orthogonal to each other and each sinusoid has an integer number of cycles over the symbol time



OFDM Basics: Transmitter

- Because the subcarriers are orthogonal, we can send several symbols in parallel using different subcarriers, and they will not interfere with each other

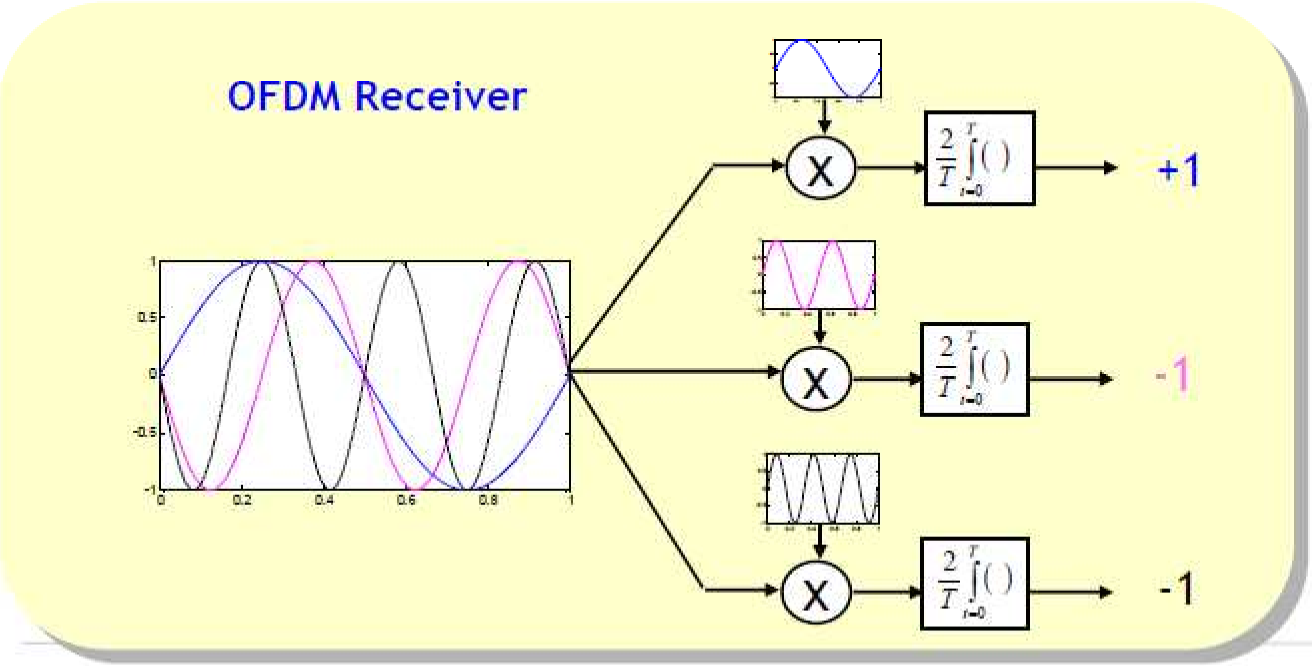
Example: BPSK symbols +1, -1, -1



OFDM Basics: Receiver

- Extracting the individual symbols relies on the orthogonality property of the set of sine waves we are using over the symbol period T

$$\int_{t=0}^{T} \sin\left(\frac{2\pi mt}{T}\right)\sin\left(\frac{2\pi nt}{T}\right)dt = 0 \quad for\ m \neq n$$



OFDM Basics: OFDM Symbol

An OFDM symbol is a set of subcarriers carrying modulation symbols, the sinusoids are represented as complex exponentials and the equation to the generate an OFDM symbol is as follows:

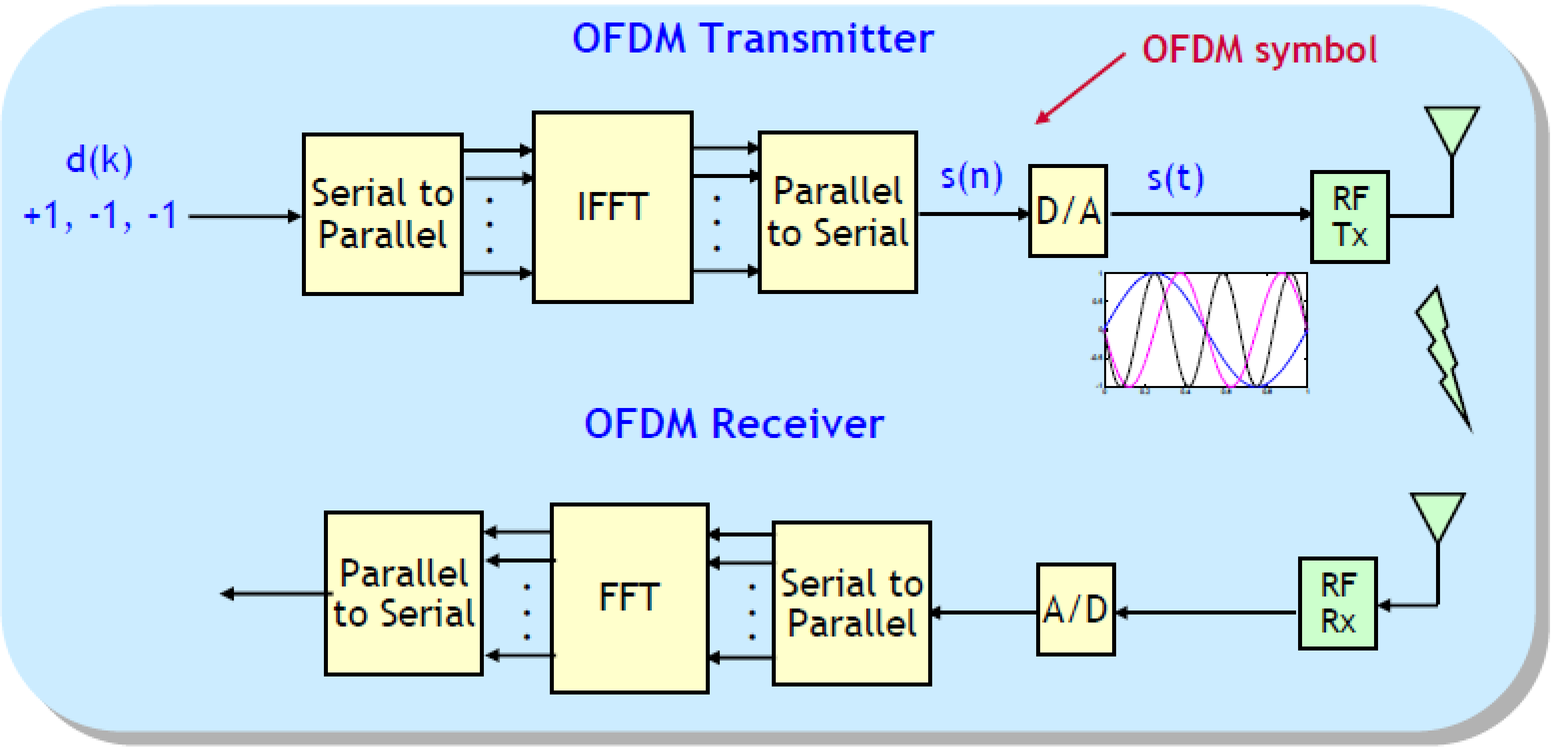
$$s(n)=\sum_{k=0}^{K-1} \underset{\text{Modulation symbols}}{d(k)}\, \underbrace{\exp\left(\frac{j2\pi kn}{N}\right)}_{\text{Sampled sinusoid}}, \quad n=0,..,N-1,\ k=0,..,K-1$$

where N is the number of samples over the symbol period.

It is simply seen as the IDFT of the modulation symbols, which can be implemented   efficiently using IFFT algorithm s(n) = IFFT{d_k}.

OFDM Basics: Use of IFFT / FFT

- It is very efficient to make use of the fast Fourier transform (FFT) algorithm in order to implement the IDFT and DFT operations in the transmitter and receiver



OFDM Basics: Impairments

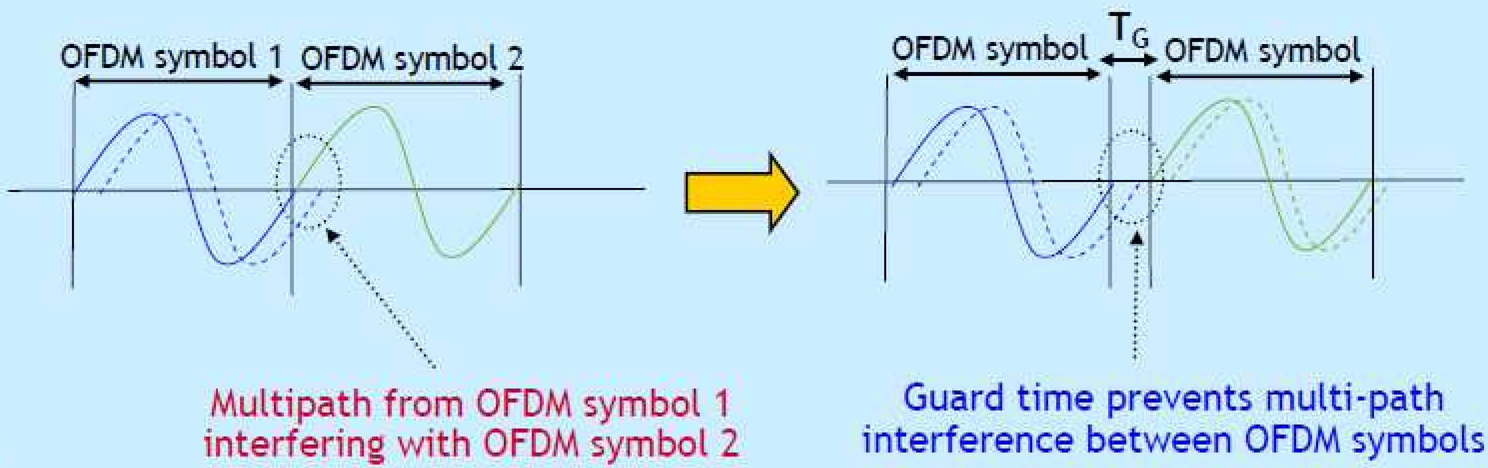
- The interference-free property of OFDM can be lost because of
  - Intra-OFDM symbol interference: effects which cause subcarriers within an OFDM symbol to lose orthogonality
  - Inter-OFDM symbol interference: effects which cause interference between OFDM symbols

- Anything which causes the fundamental orthogonality property to be lost leads to interference → we must have clean sinusoidal tones with an integral number of cycles within the receiver window. Some of the things which can prevent this from happening are:
  - multipath
  - timing offset
  - frequency offset
  - high doppler

OFDM Basics: Multipath - 1

- The OFDM symbol time is chosen to be **much longer** than the expected multi-path delay spread, which helps to minimize inter-OFDM symbol interference

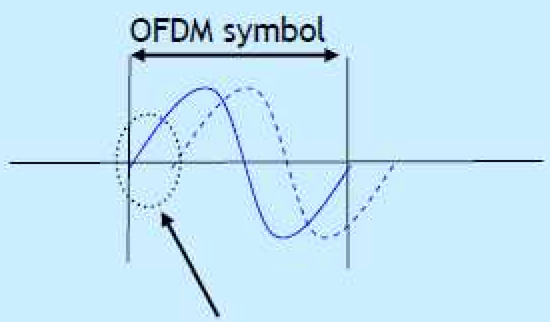
- In order to mitigate ISI between OFDM symbols almost completely, a small **guard time** is inserted between OFDM symbols



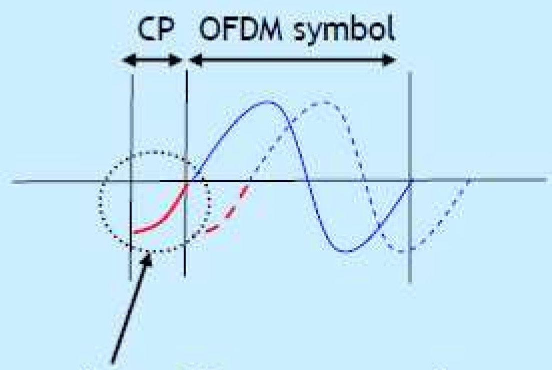
OFDM Basics: Multipath - 2

- Unfortunately, multi-path still is still causing a problem here, not between OFDM symbols anymore (thanks to the guard time), but now **between subcarriers within an OFDM symbol**

- Simply filling the guard time with a Cyclic Prefix (CP) restores orthogonality between the subcarriers within an OFDM symbol, *even in the presence of multipath. Also, sensitivity to timing offset is reduced!*



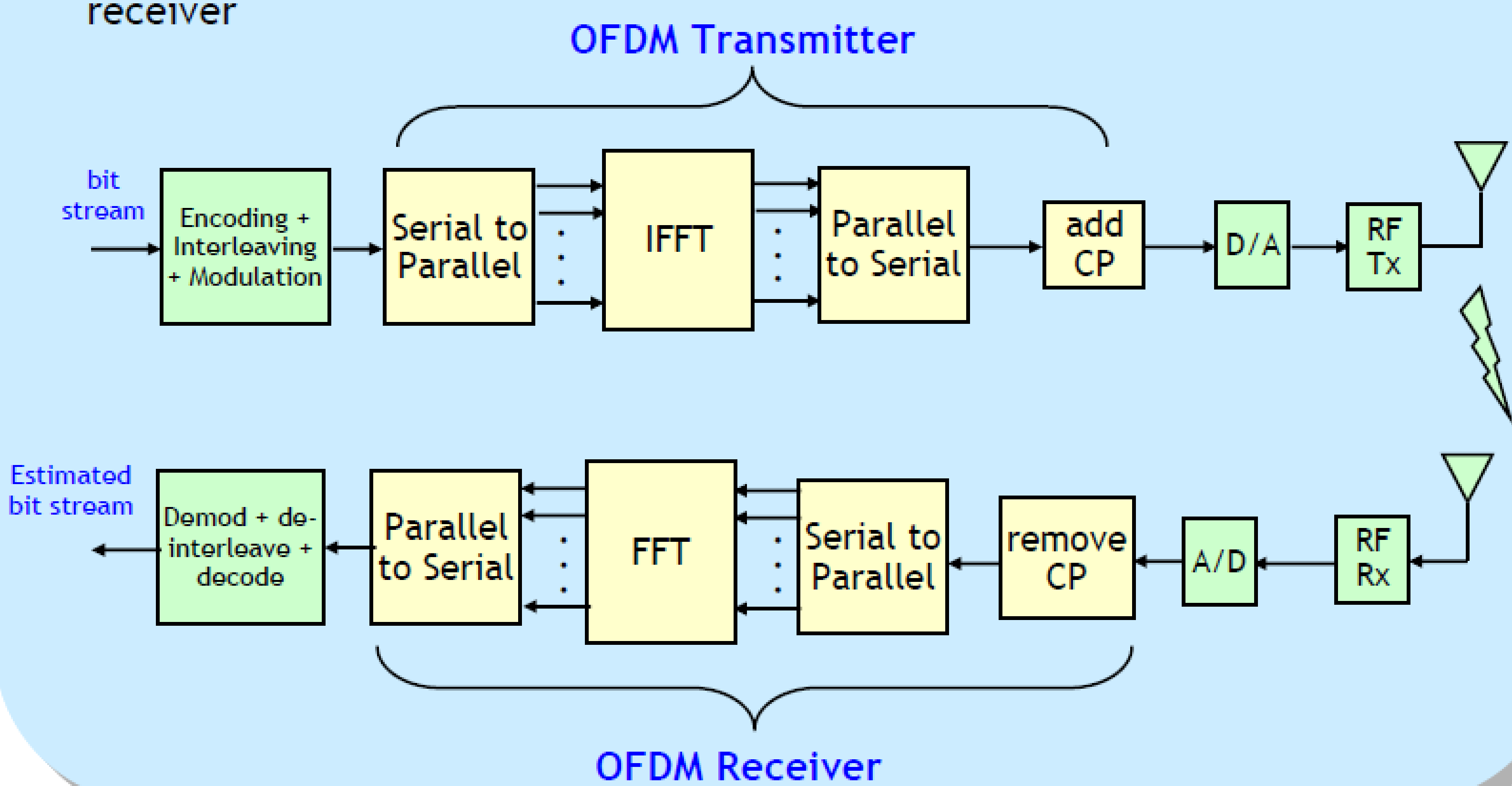
Multi-path adds a sinusoid component without a complete cycle in the receiver window →this will not be orthogonal to the other subcarriers



Appending a CP ensures we have a complete cycle of the sinusoid, as long as the CP length is larger than the worst case delay spread

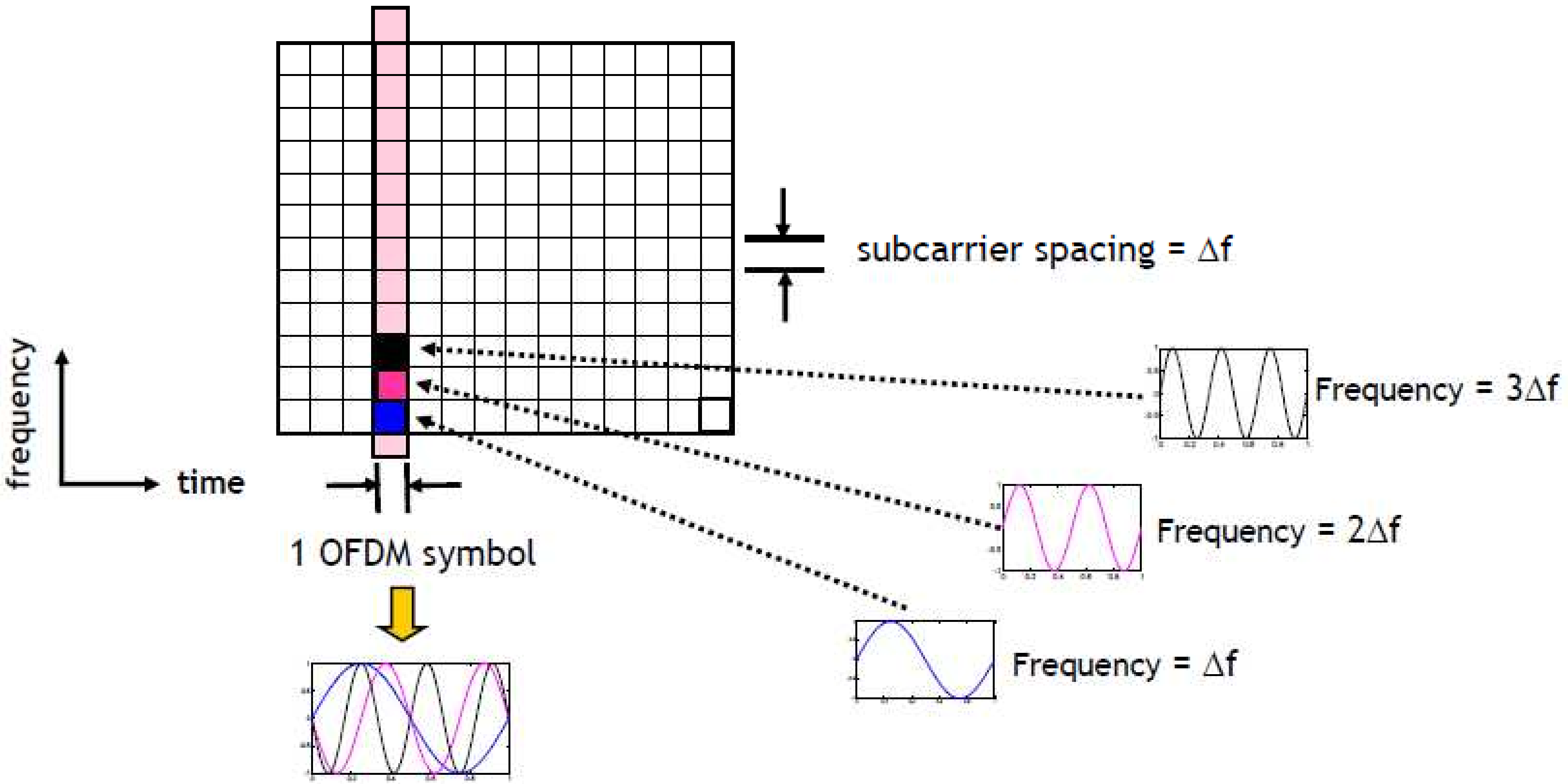
OFDM Basics: OFDM Transceiver

- It is very efficient to make use of the fast Fourier transform (FFT) algorithm in order to implement the IDFT and DFT operations in the transmitter and receiver



OFDM Basics: Time Frequency Grid

- Often a time-frequency grid is used to depict a set of OFDM symbols
  - Each square represents one subcarrier of an OFDM symbol



OFDM Basics: Scalable

- With scalable OFDM, the subcarrier spacing stays fixed at 15 kHz (hence symbol time is fixed to 66.6 μs) regardless of the operating bandwidth (1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz)

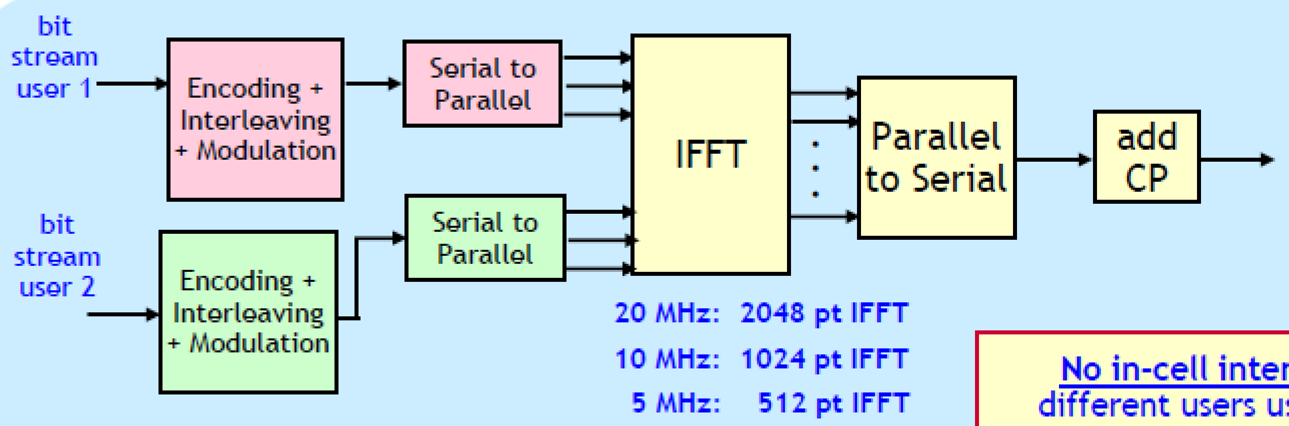
- The total number of subcarriers is varied in order to operate in different bandwidths

  - This is done by specifying different FFT sizes (i.e. 512 point FFT for 5 MHz, 2048 point FFT for 20 MHz)

- Advantage of scalable OFDM: influence of delay spread, Doppler due to user mobility, timing accuracy, etc. remain the *same* as the system bandwidth is changed, given that the symbol time and CP length are constant → robust design

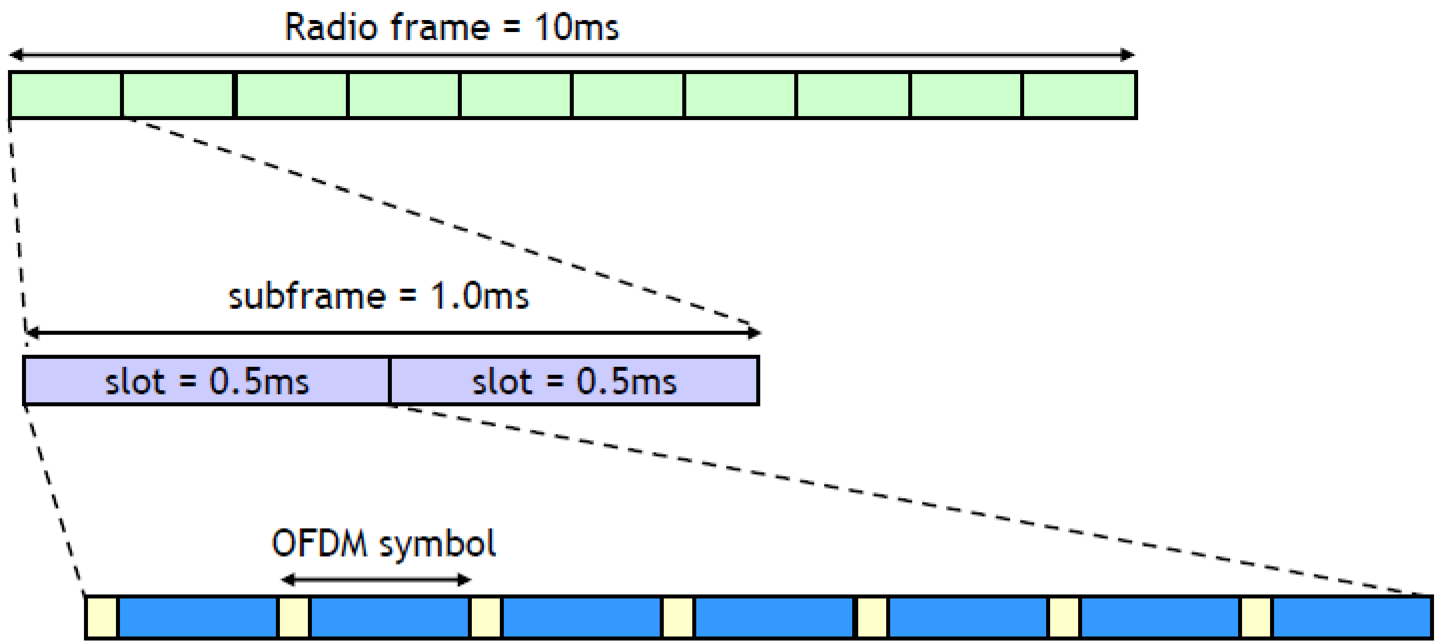
LTE Downlink: Scalable OFDMA

- The LTE downlink uses scalable OFDMA
  - Fixed subcarrier spacing of 15 kHz for unicast
    - symbol time fixed at T = 1/15kHz = 66.67 μs
  - Different UEs are assigned different sets of subcarriers so that they remain orthogonal to each other (except MU-MIMO)



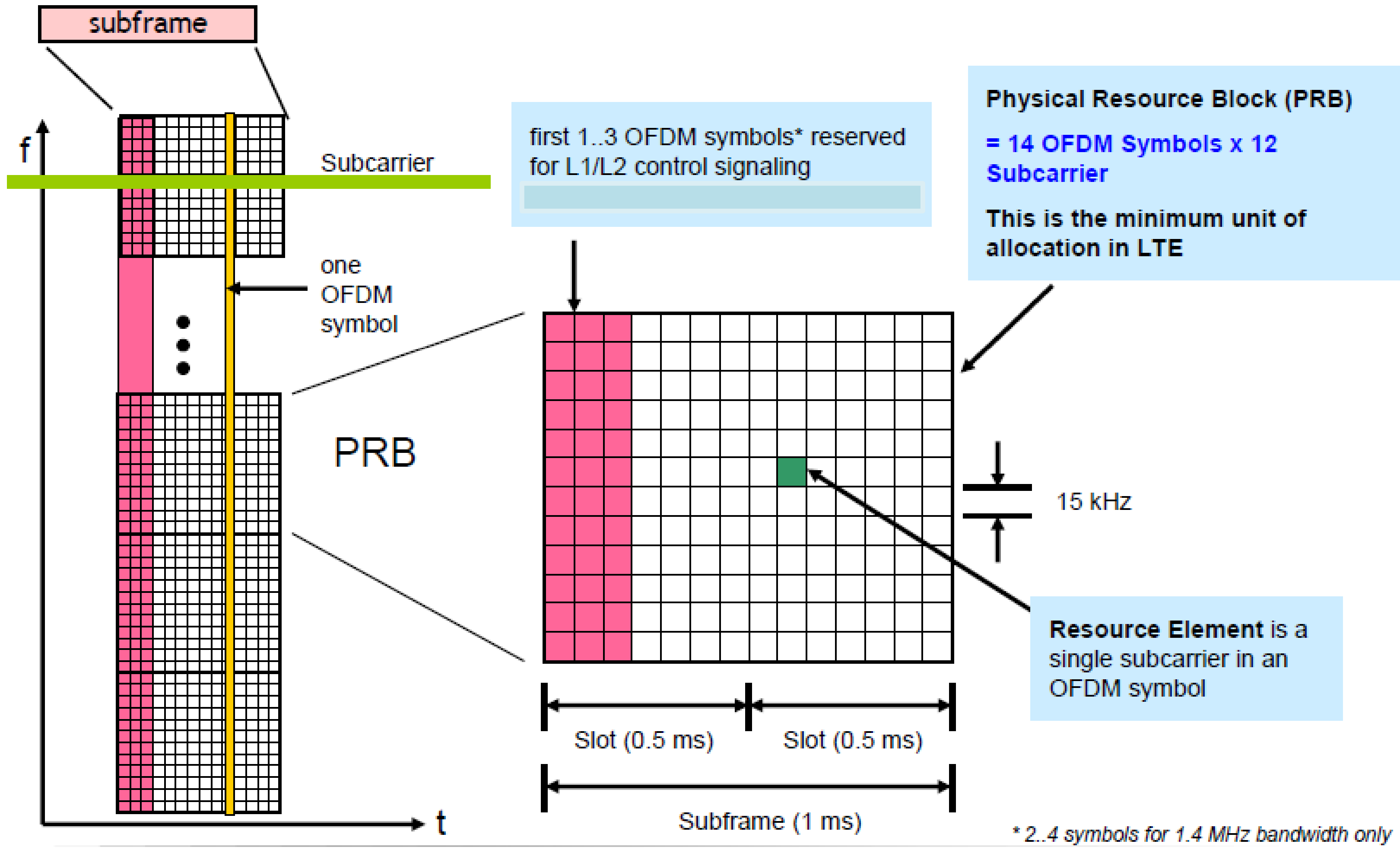
No in-cell interference - different users use different subcarriers

LTE Downlink: Frame Format

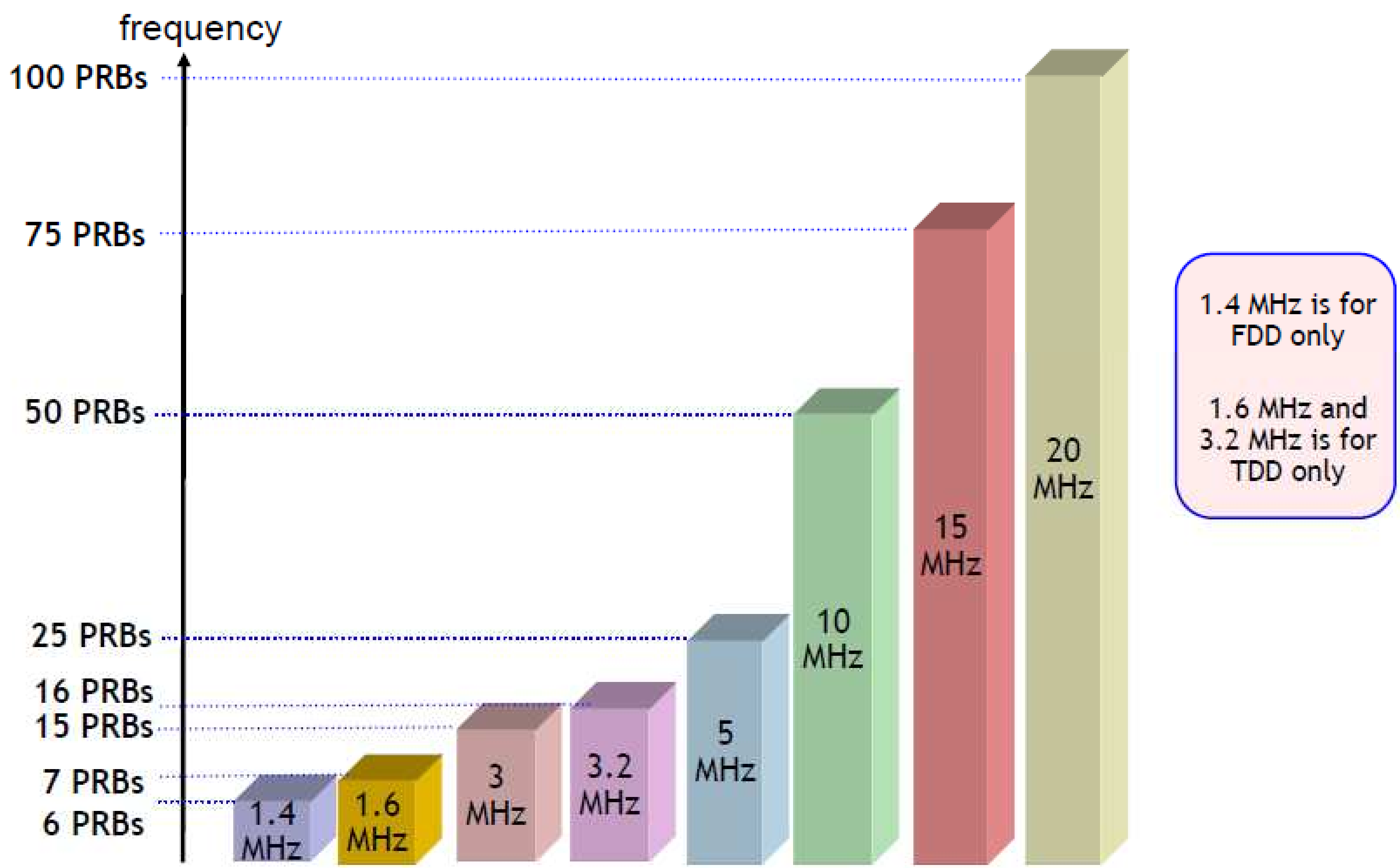


- Subframe length is 1ms
  - consists of two 0.5ms slots
- 7 OFDM symbols per 0.5ms slot → 14 OFDM symbols per 1ms subframe

LTE Downlink: Channel Structure



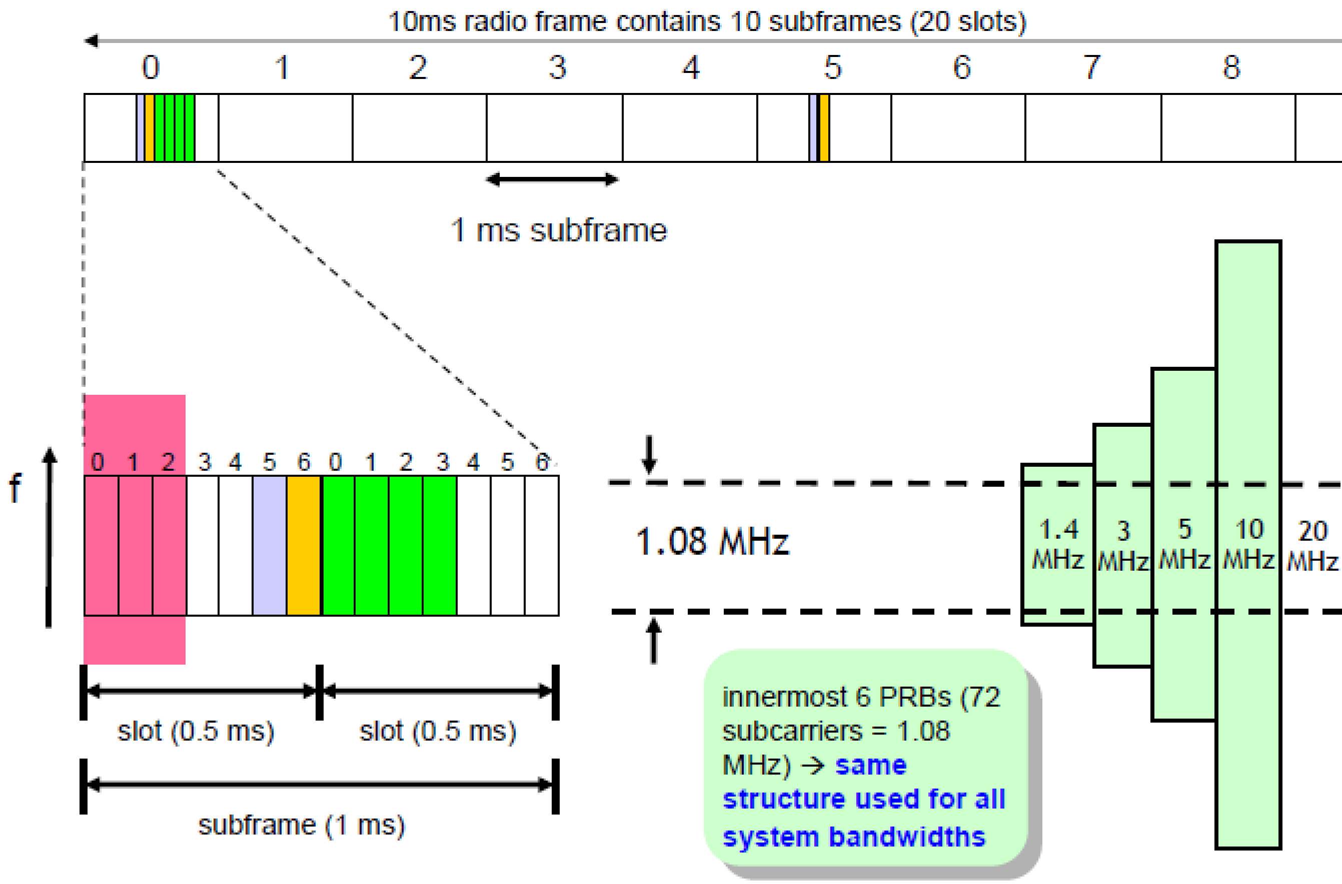
LTE Downlink: Maximum number of Resource Blocks



LTE Downlink: FFT Size / Bandwidth

	FFT Size	Sampling Frequency	Number of Usable Subcarriers*	Occupied BW
1.4 MHz	128	1.92 MHz	72	1.08 MHz
3 MHz	256	3.84 MHz	180	2.7 MHz
5 MHz	512	7.68 MHz	300	4.5 MHz
10 MHz	1024	15.36 MHz	600	9 MHz
15 MHz	1536	23.04 MHz	900	13.5 MHz
20 MHz	2048	30.72 MHz	1200	18 MHz

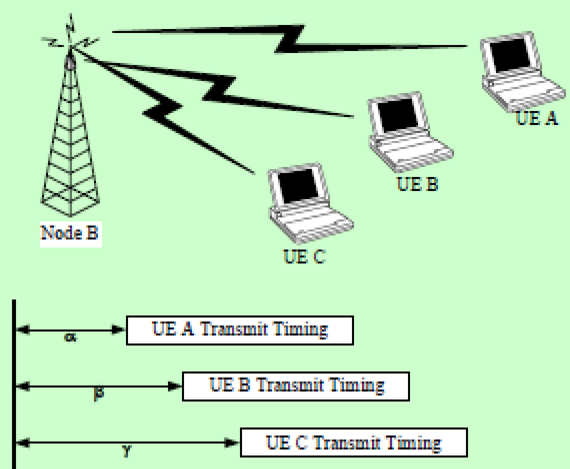
LTE Downlink: Frame / Sub-frames



LTE uplink: Multiple Access Schemes

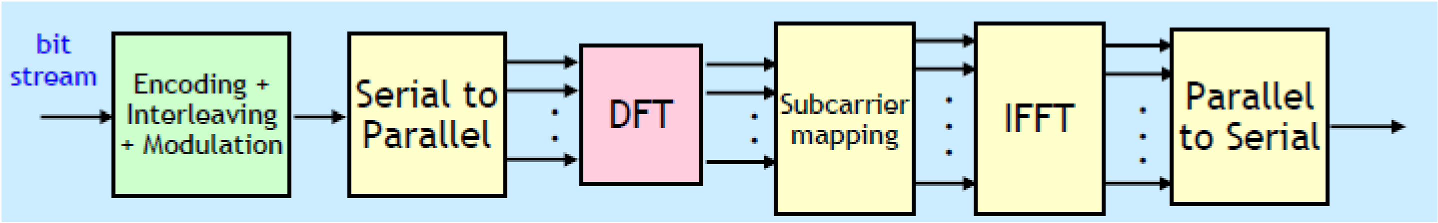
- To facilitate efficient power amplifier design in the UE, 3GPP chose single carrier frequency domain multiple access (SC-FDMA) in favor of OFDMA for uplink multiple access
- SC-FDMA improves the peak-to-average power ratio (PAPR) compared to OFDM
  - ~4 dB improvement for QPSK, ~2 dB improvement for 16-QAM
  - Reduced power amplifier cost for mobile
  - Reduced power amplifier back-off → improved coverage

- SC-FDMA is still an orthogonal multiple access scheme
  - UEs are orthogonal in frequency
  - Synchronous in the time domain through the use of timing advance (TA) signaling
    - Only need to be synchronous within a fraction of the CP length
    - TA command sent as a MAC control element with 0.52 µs timing resolution



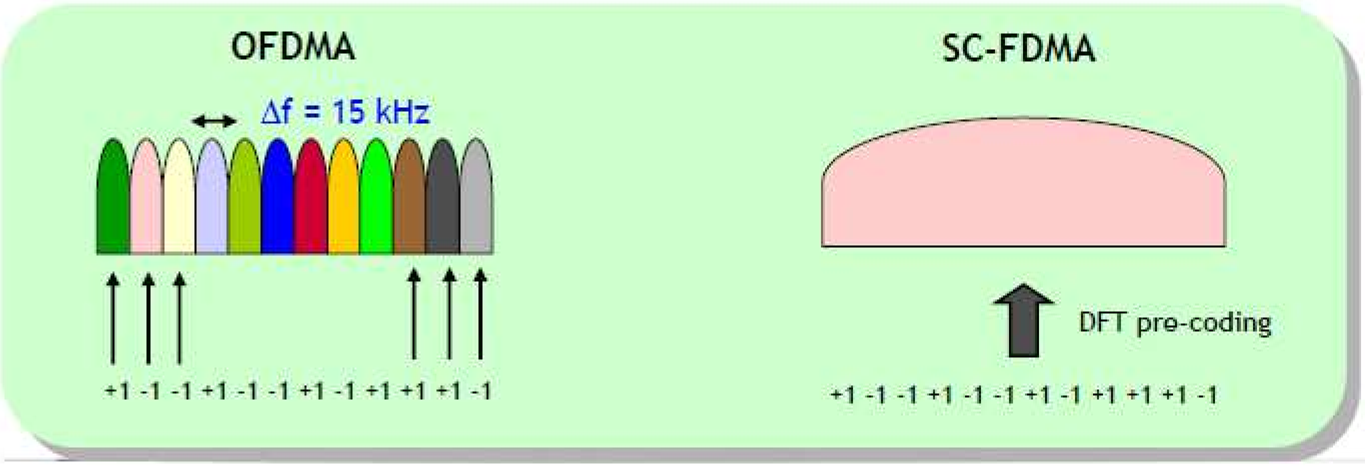
LTE uplink: SC-FDMA

- SC-FDMA implemented using an OFDMA front-end and a DFT pre-coder, this is referred to as DFT-spread OFDMA (DFT-SOFDMA)
    - Advantage is that numerology (subcarrier spacing, symbol times, FFT sizes, etc.) can be shared between uplink and downlink
    - Allocation of variable bandwidth in units of 12 subcarriers (same as downlink)

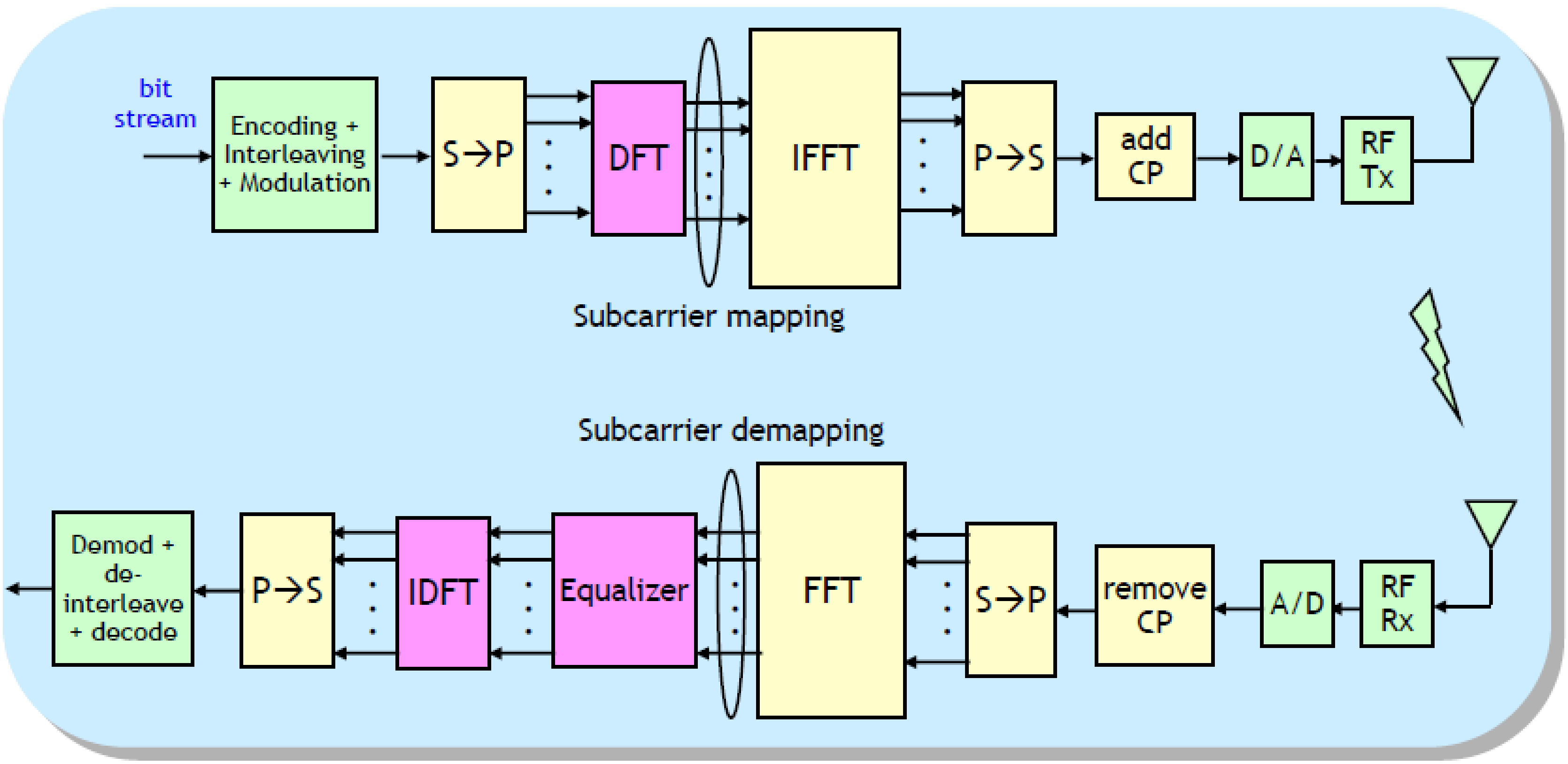


LTE uplink: SC-FDMA

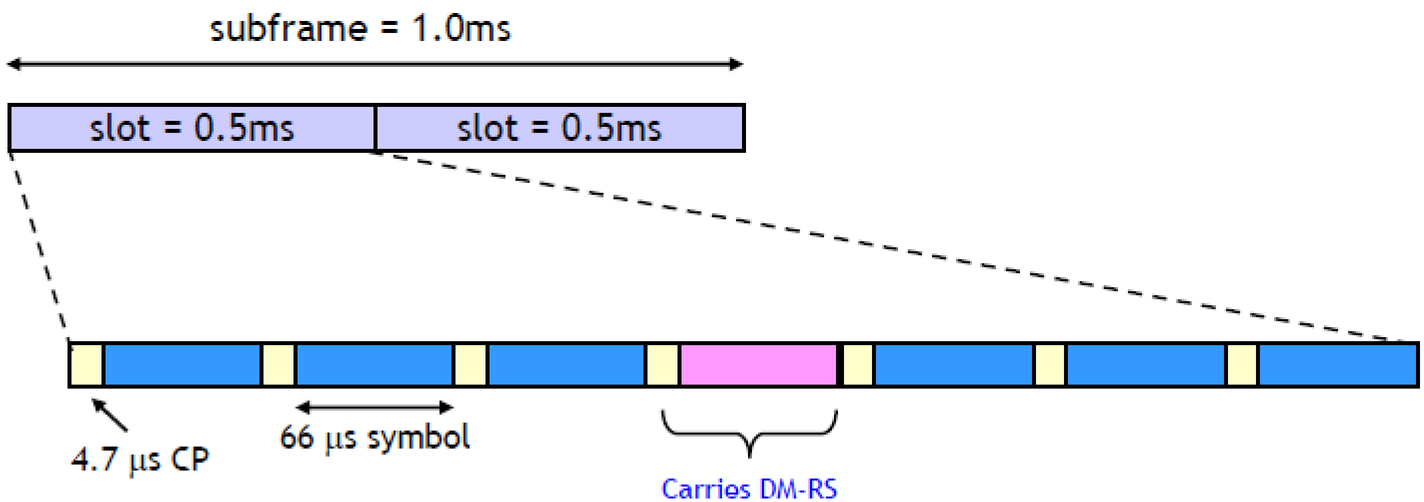
- DFT spreading of modulation symbols reduces PAPR, but also leads to the possibility of inter-symbol interference (ISI)
  - In OFDM, each modulation symbols “sees” a single 15 kHz subcarrier (flat channel)
  - In DFT-SOFDM, each modulation symbol “sees” a wider bandwidth (i.e. m x 180 KHz) → if channel is frequency selective within allocated bandwidth the we get ISI
    - Equalization is required in the SC-FDMA receiver
    - Simple one-tap frequency domain equalization facilitated by use of CP



LTE uplink: SC-FDMA Transceiver



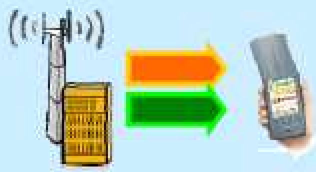
LTE uplink: Frame Format



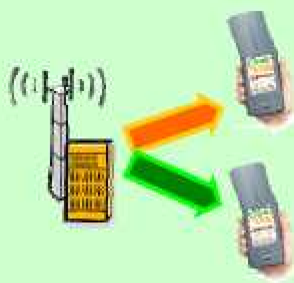
- Subframe length is 1 ms
  - 1ms subframe consists of two 0.5ms slots (can hop on slot boundaries)
- 7 SC-FDMA symbols per 0.5 ms slot
  - 6 SC-FDMA symbols used to carry data
  - center SC-FDMA symbol used for the data demodulation reference signal (DM-RS)

LTE : MIMO

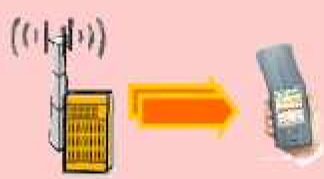
- Spatial Multiplexing (SM) → SU-MIMO
  - Multiple data streams sent to the same user (max 2 codewords)
  - Significant throughput gains for UEs in high SINR conditions



- Spatial Division Multiple Access (SDMA) or Beamforming
  - Different data streams sent to different users on same resource
  - Improves throughput even in low SINR conditions (cell-edge)
  - Works even for single antenna mobiles
  - User-specific RS (dedicated RS) supported to facilitate beamforming; used for demodulation of PDSCH

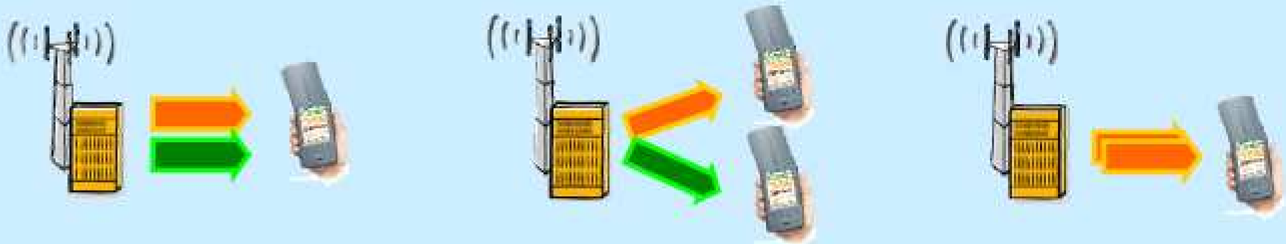


- Transmit Diversity
  - Improves reliability on a single data stream; space-frequency block coding (SFBC), cyclic delay diversity (CDD)
  - Fall back scheme if channel conditions do not allow SM; useful to improve reliability on common control channels

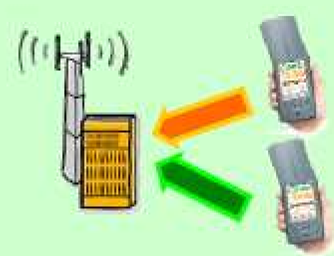


LTE : Downlink / Uplink MIMO Support

- **Downlink MIMO**
  - Supports Spatial Multiplexing, MU-MIMO, and Transmit Diversity

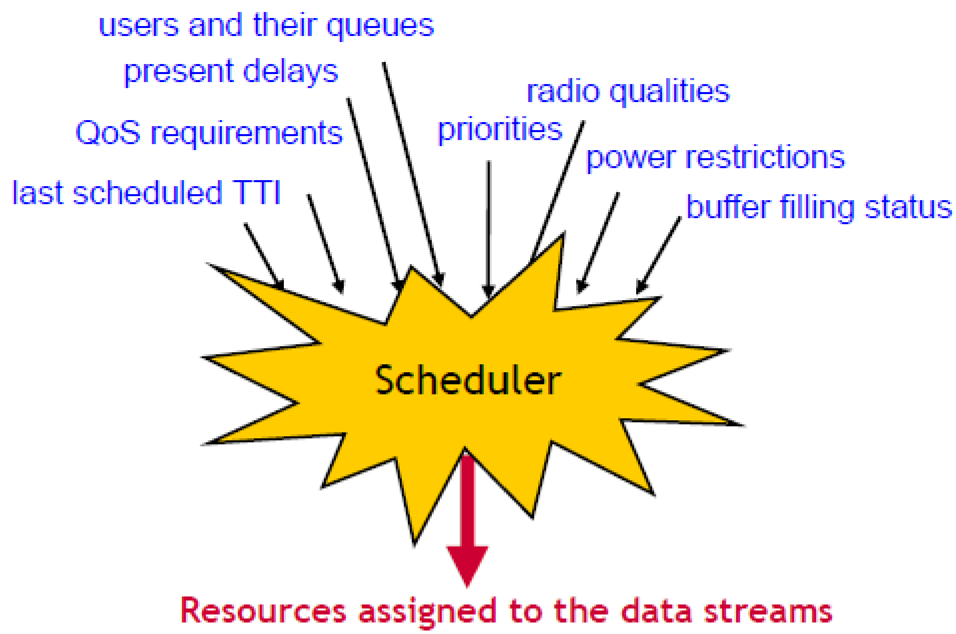


- **Uplink MIMO**
  - Initial release of LTE will only support MU-MIMO with a single PA at the UE → desire to avoid multiple PAs at UE
  - Cyclic-shift orthogonal pilots used in the uplink to facilitate MU-MIMO operation



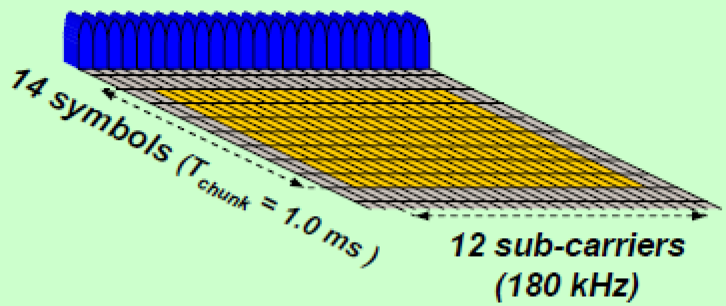
LTE Scheduling and Resource Allocation

- LTE makes heavy use of the uplink and downlink shared channel (DL-SCH and UL-SCH) for user data, system broadcast, and paging
- LTE provides several mechanism to allow for high performance user scheduling and resource allocation algorithms



LTE Physical Resource Block

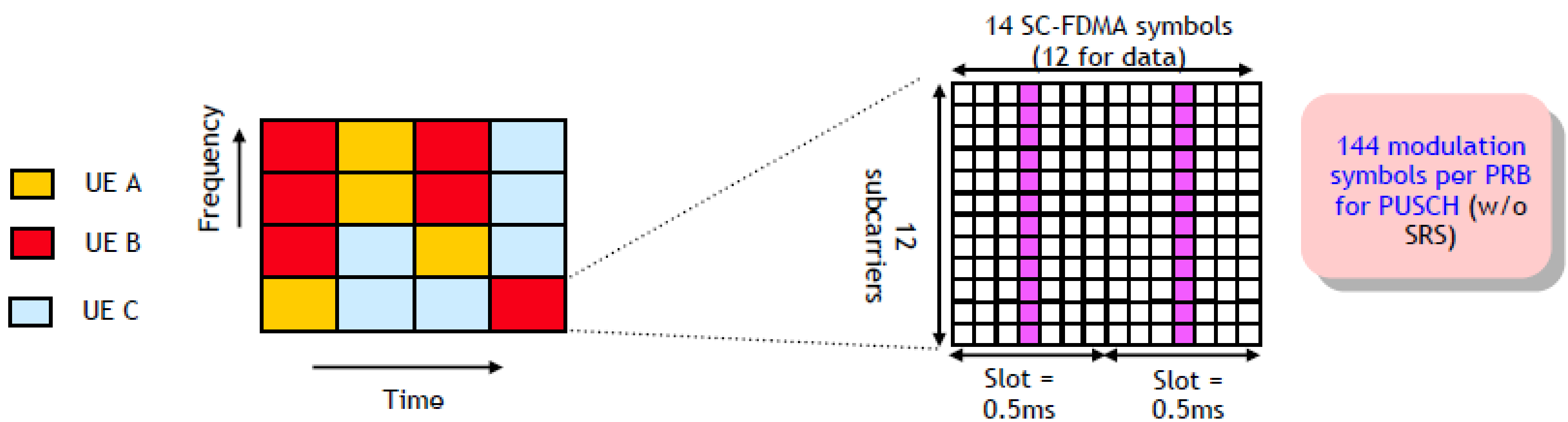
- Basic unit of allocation is called a Physical Resource Block (PRB)
  - 12 subcarriers in frequency (= 180 kHz)
  - 1 sub-frame in time (= 1 ms, = 14 OFDM symbols)
  - Multiple resource blocks can be allocated to a user in a given subframe



- The total number of PRBs available depends on the operating bandwidth
  - 6 PRBs for 1.4 MHz up to 100 PRBs in 20 MHz

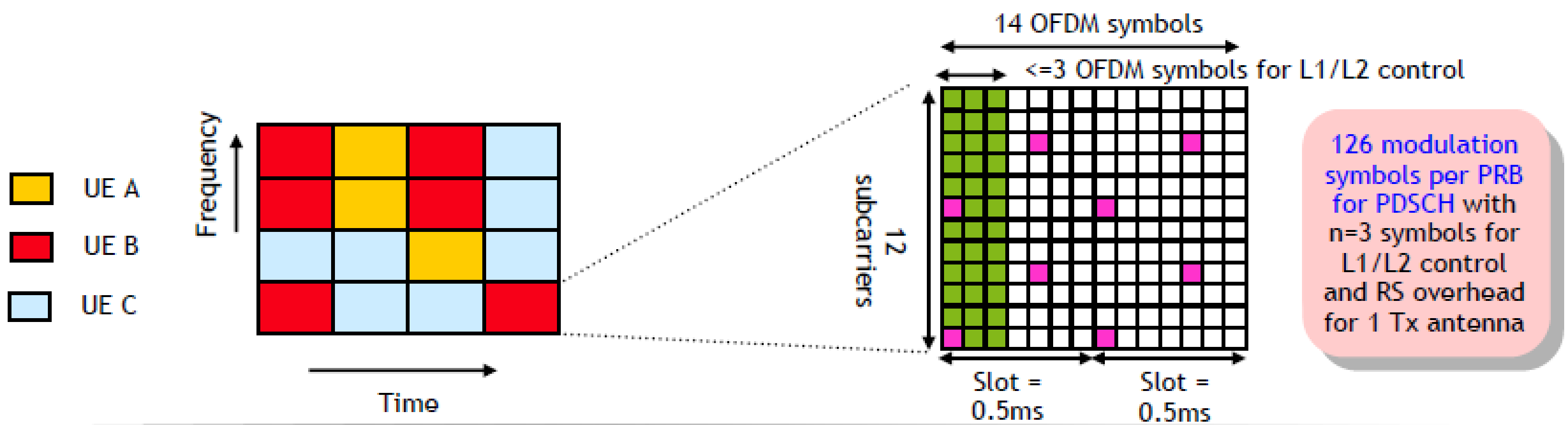
LTE Uplink Scheduling and Resource Allocation

- Channel dependent scheduling in both time and frequency enabled through the use of the sounding reference signal (SRS)
- Scheduler selects bandwidth, modulation, use of MU-MIMO, and PC parameters
- PRBs assigned for a particular UE must be contiguous in the uplink (SC-FDMA)
- To reduce UE complexity, restriction placed on # of PRBs that can be assigned
    - Number of allocated subcarriers must have largest prime factor less than or equal to 5 → can use radix-2,3,5 FFT for DFT-precoding (i.e., cannot assign 7, 11, 13, 17,... PRBs)



LTE Downlink Scheduling and Resource Allocation

- Channel dependent scheduling is supported in both time and frequency domain → enables two dimensional flexibility
  - CQI feedback can provide both wideband and frequency selective feedback
  - PMI and RI feedback allow for MIMO mode selection
  - Scheduler chooses bandwidth allocation, modulation, MIMO mode, and power allocation
- HARQ operation is asynchronous and adaptive
- Assigned PRBs need not be contiguous for a given user in the downlink



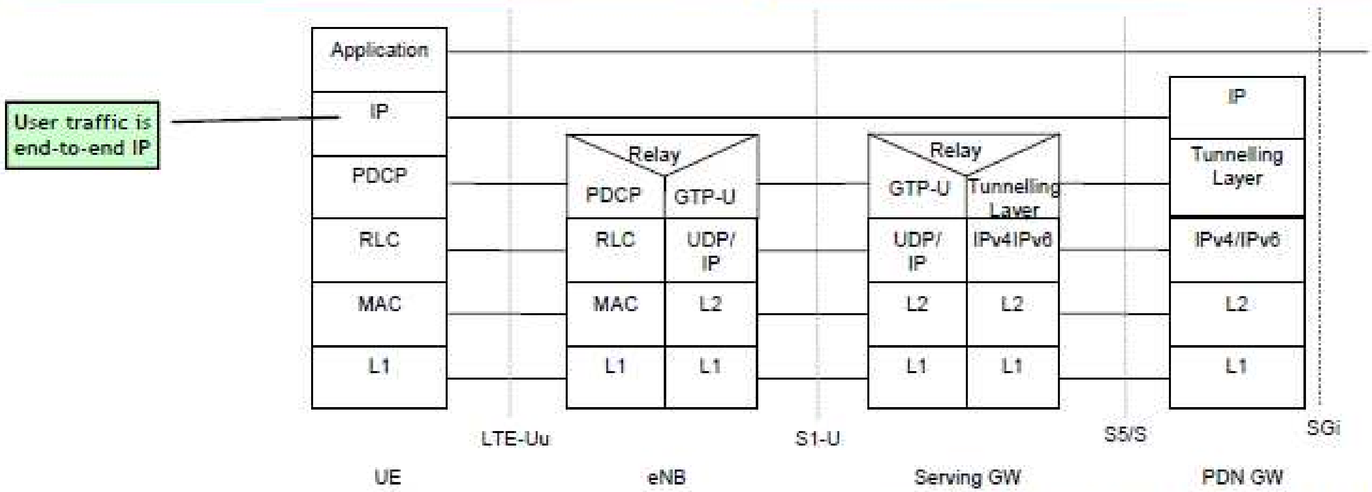
Serving & Packet Data Network Gateway

S-GW is the <u>local mobility anchor</u>

- Terminates (S1-U) interface towards E-UTRAN
- Local anchor point for inter-eNB handover & inter-3GPP mobility
- Support ECM-idle mode DL packet buffering & network-initiated service request
- (IP) packet routing & forwarding functions

PDN-GW is the <u>IP anchor</u> for bearers

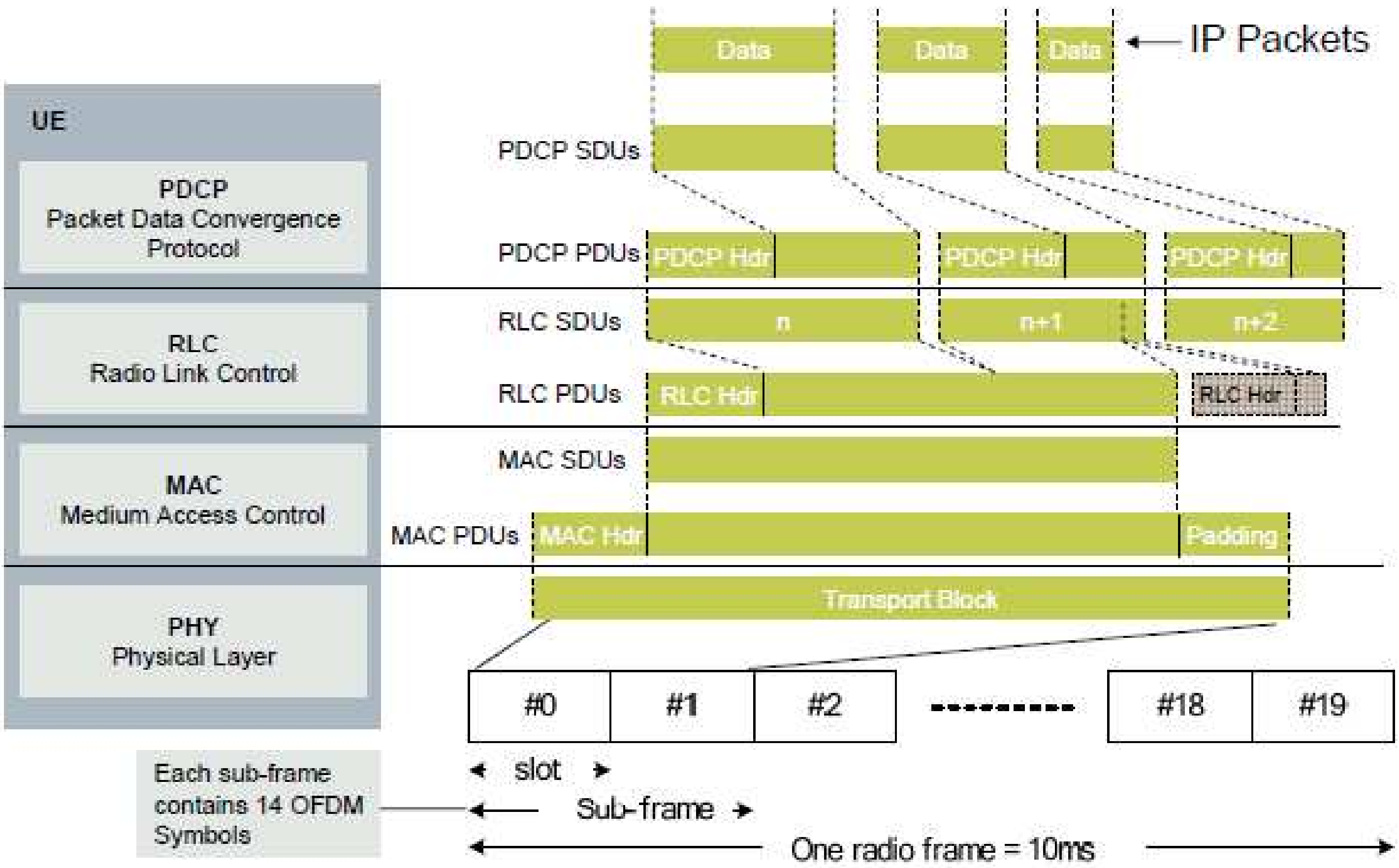
- Terminates the (SGi) interface towards the PDN
- Provides UE IP address management (allocation)
- Provide Policy & Charging Enforcement Function (PCEF)
- Per-SDF based packet filtering



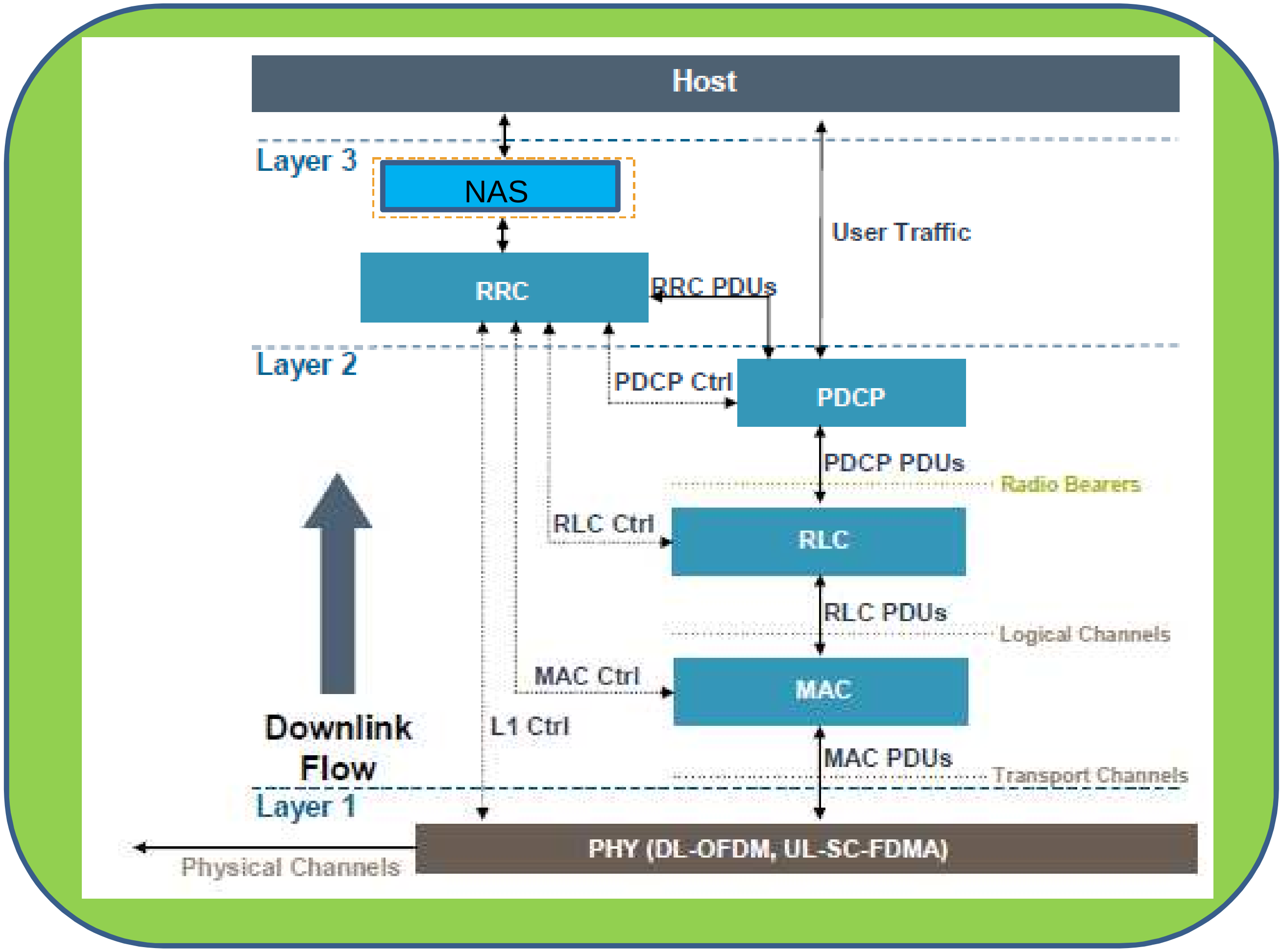
* S5/S8 reference point between S-GW & PDN-GW can also be GTP based

The Key Role of the S-GW and PDN-GW is to manage the User plane bearer traffic

LTE Downlink – Frames / Packets Time Domain View

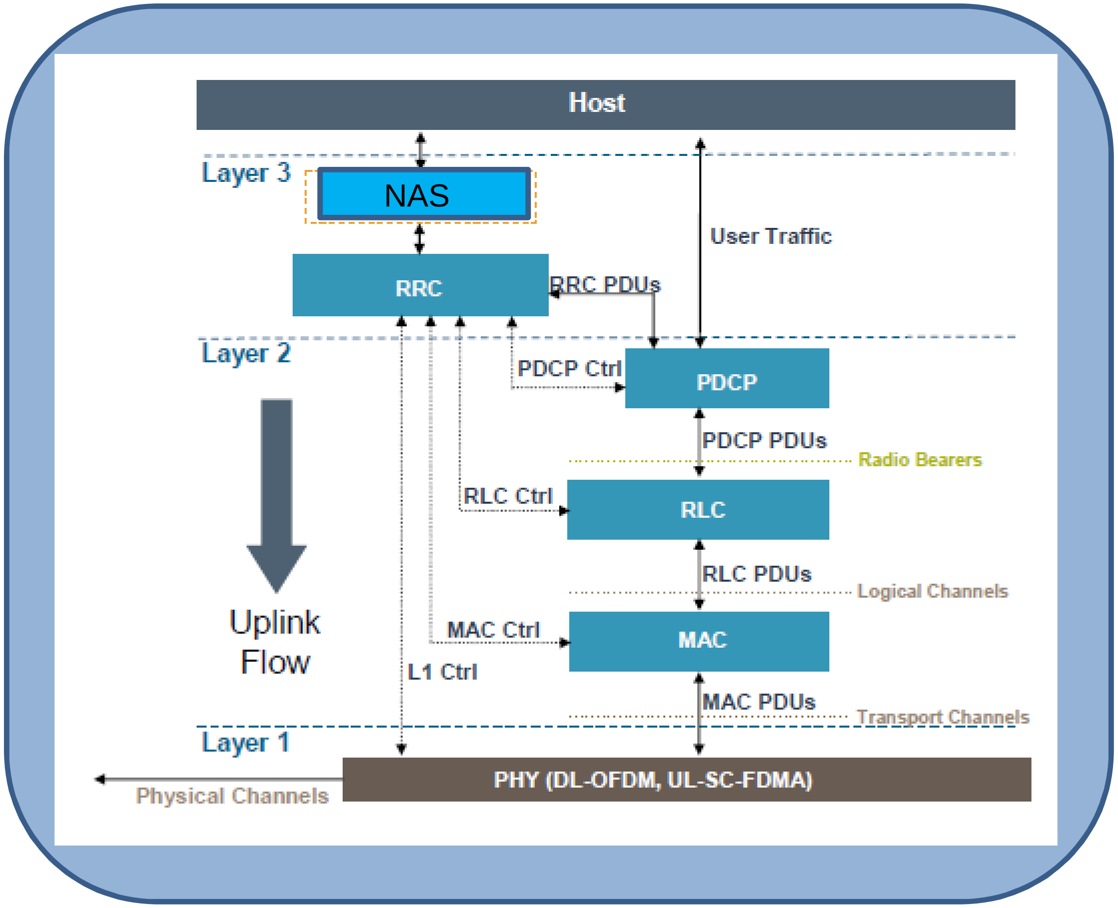


LTE Downlink – Data Flow



Information decoding consists of converting the transport blocks to IP packets

LTE Uplink – Data Flow



PHY uses SC-FDMA, for power efficient transmission in the uplink

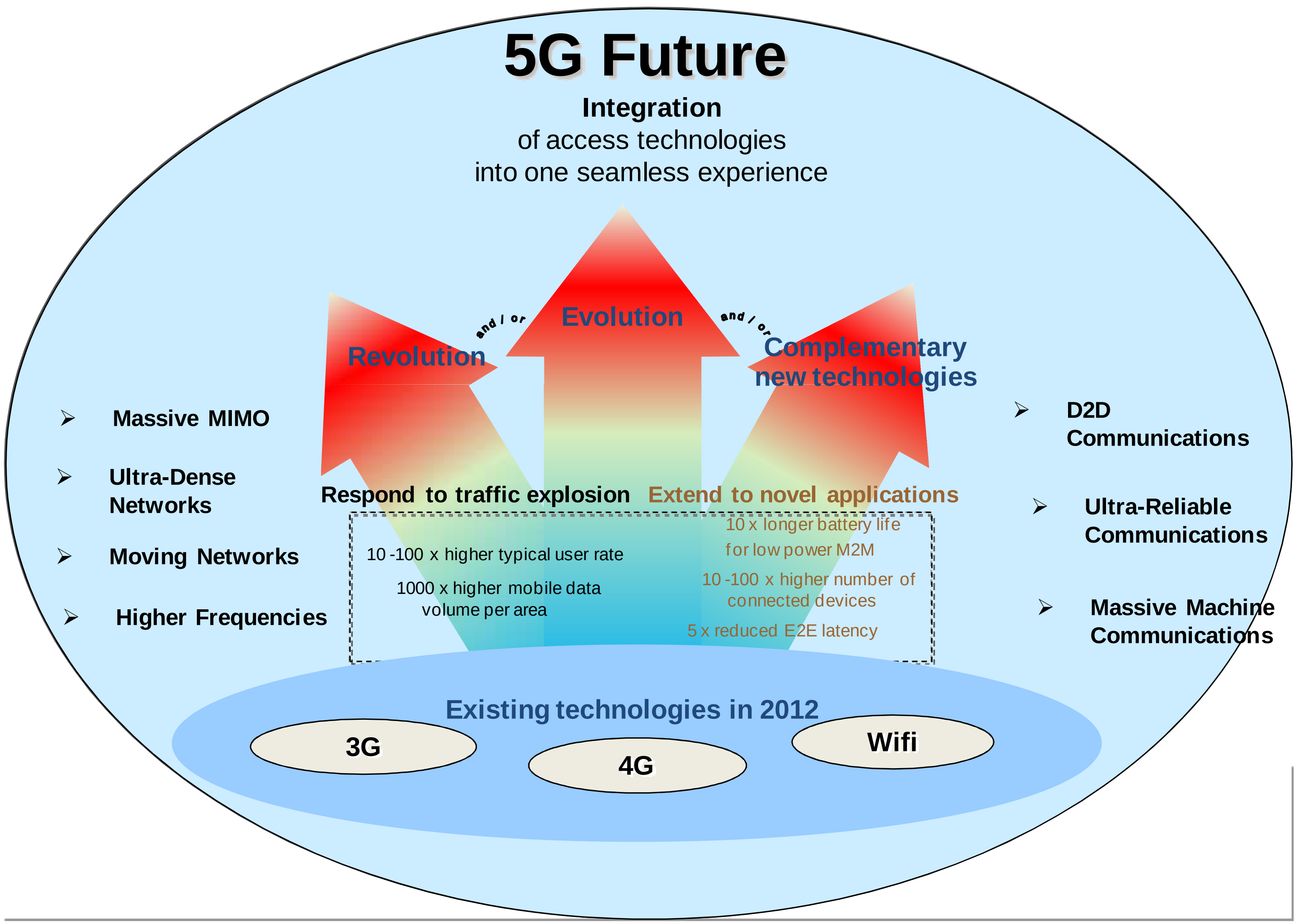
LTE - Summary

- The Long Term Evolution project was initiated in 2004 .
- The motivation for LTE included the desire for a reduction in the cost per bit, the addition of lower cost services with better user experience, the flexible use of new and existing frequency bands, a simplified and lower cost network with open interfaces, and a reduction in terminal complexity with an allowance for reasonable power consumption.
- Reduced latency for packets, and spectral efficiency improvements high speed packet access (HSPA).
- Flexible channel bandwidths— 1.4, 3, 5, 10, 15, and 20 MHz in both the uplink and the downlink.

LTE Advanced – Key Features

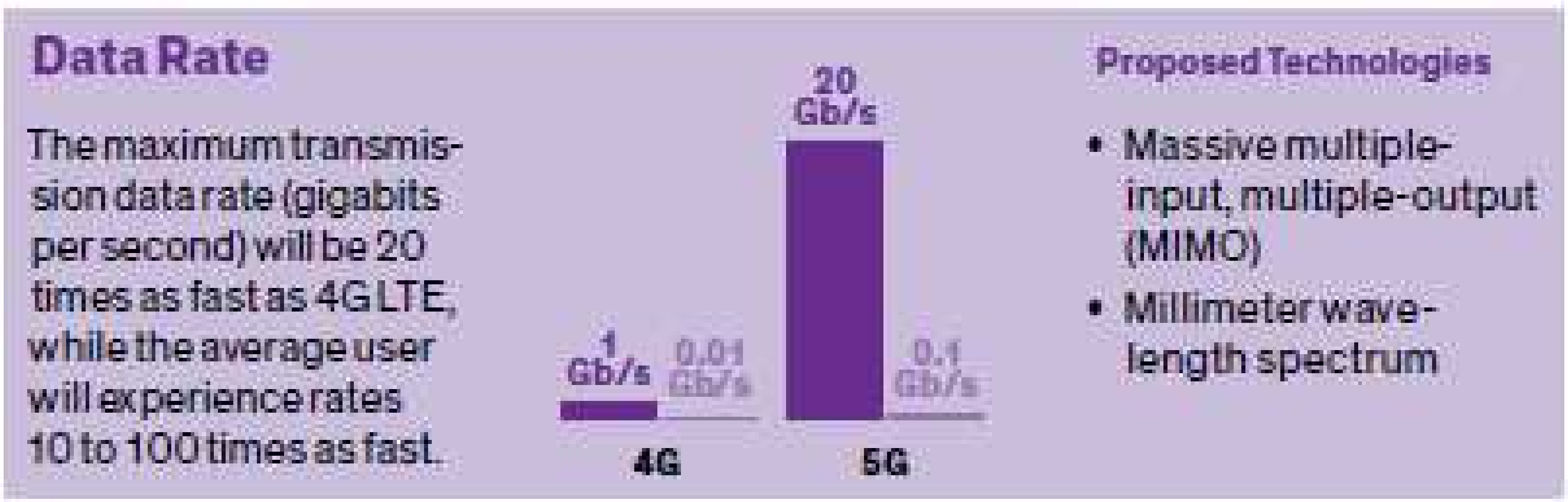
- **Carrier Aggregation:** Increases effective bandwidth and data rates by logically grouping multiple carrier frequencies.
- **Enhanced MIMO:** Support for 8x8 SU-MIMO in the downlink and 4x4 SU-MIMO in the uplink.
- **Self Organizing Networks (SONs):** Automatic configuration by the discovery of cell sites and network components, establish connections and co-ordinate activities without an operator.
- **Coordinated Multipoint (CoMP):** Simultaneous transmit / receive of same data over multiple cells in the downlink.
- **Relay and Heterogeneous Networks (HetNets):** Improve cell-edge performance and network capacity by extending radio coverage beyond what is provided by traditional cells

5G – Vision



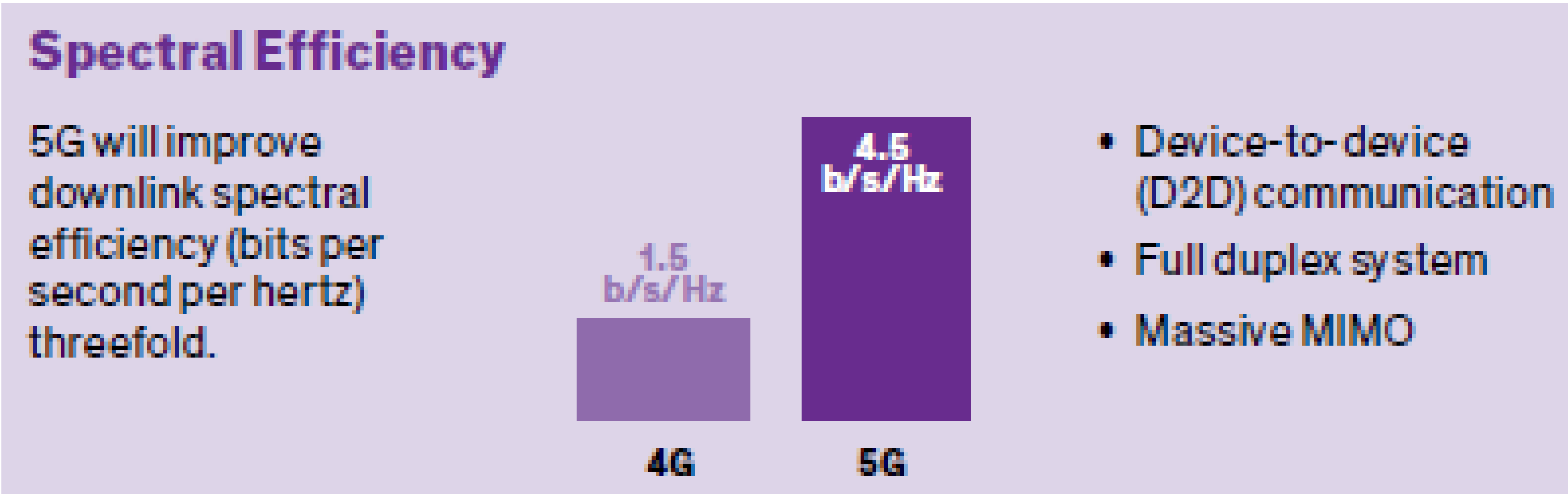
5G Future
Integration
of access technologies
into one seamless experience
Revolution
and / or
Evolution
and / or
Complementary
new technologies
Massive MIMO
Ultra-Dense
Networks
Moving Networks
Higher Frequencies
D2D
Communications
Ultra-Reliable
Communications
Massive Machine
Communications
Respond to traffic explosion
Extend to novel applications
10 -100 x higher typical user rate
1000 x higher mobile data
volume per area
10 x longer battery life
for low power M2M
10 -100 x higher number of
connected devices
5 x reduced E2E latency
Existing technologies in 2012
3G
4G
Wifi

5G – Key Features



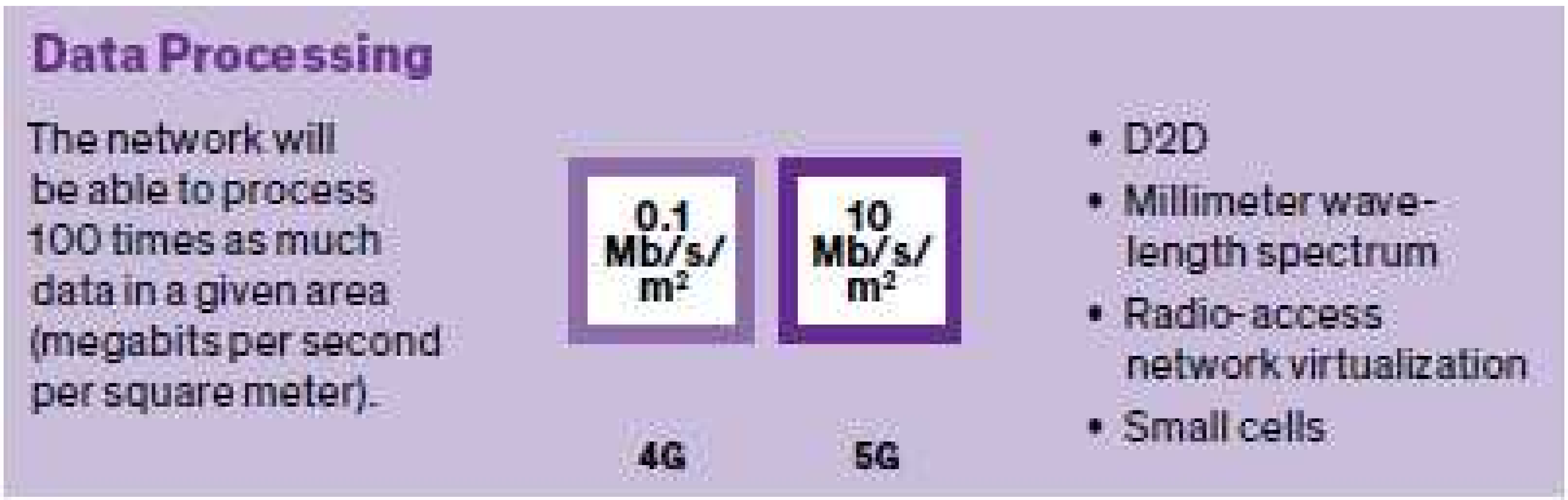
Millimeter wavelength spectrum (30 GHz – 300 GHz) will expand the amount of cellular spectrum beyond the limited ultra high frequency band used today enabling higher data rates in greater than 1 gigabit / second

5G – Key Features



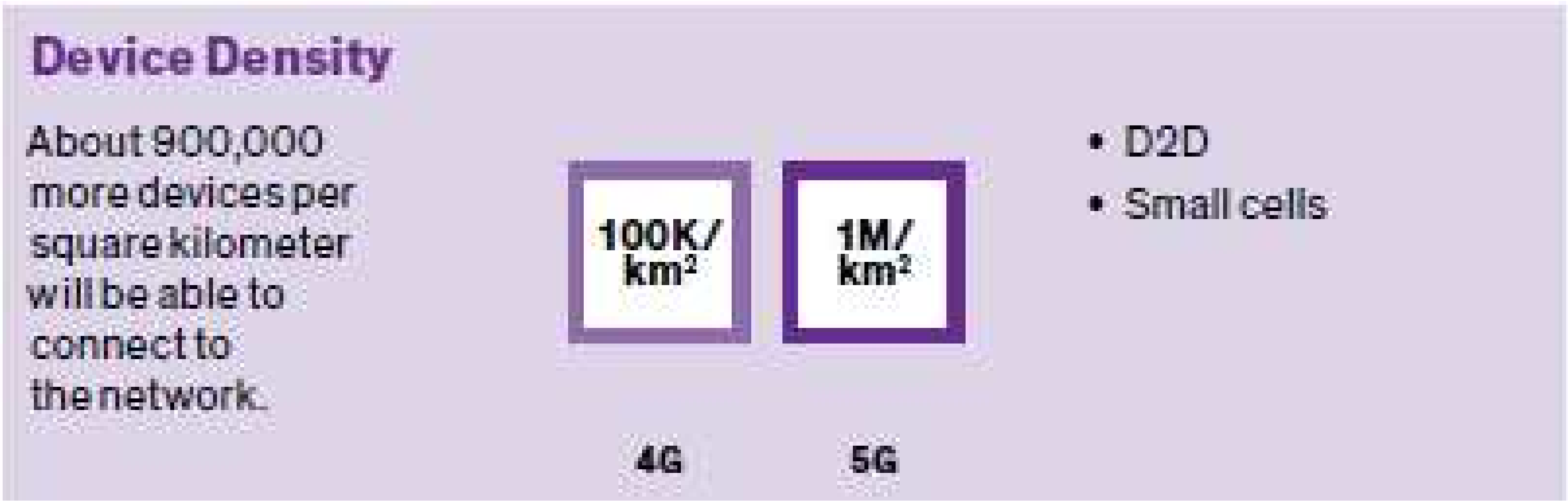
Device to Device (D2D) will allow direct communication between devices in close proximity without network assistance by skipping the base station which means one less step in getting information to devices.

5G – Key Features



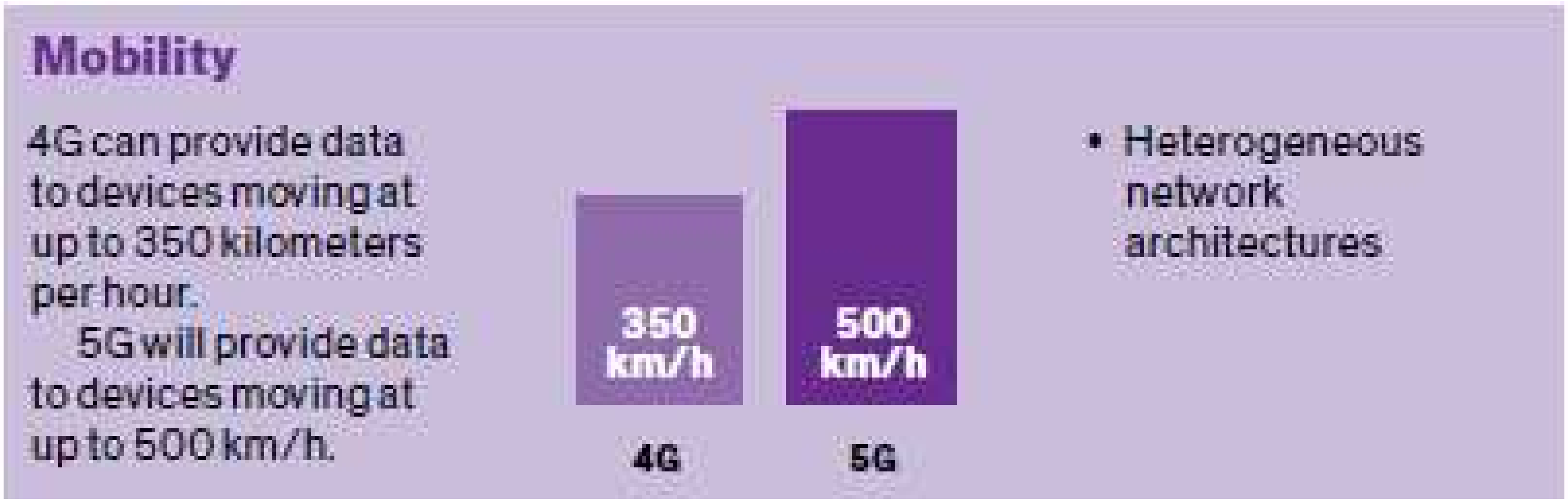
Radio-access network virtualization means that radio-access network processor functions will be virtualized into the cloud virtualizing the network, multiple service providers can physically share the same data center platform without any impact on connection strength.

5G – Key Features



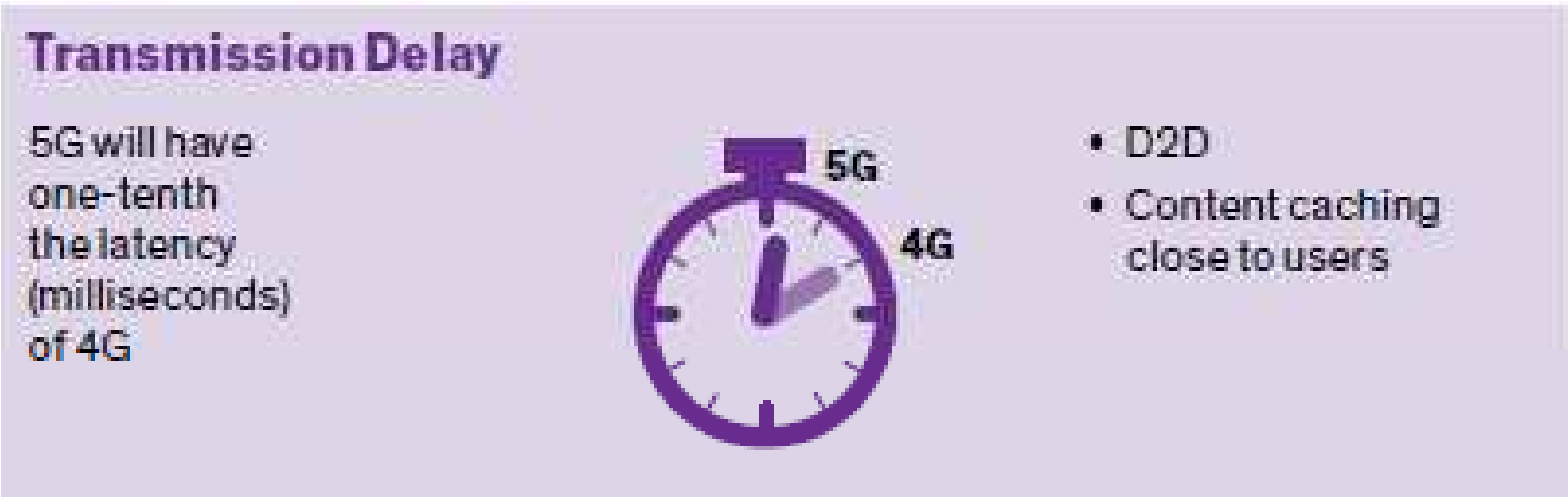
Small cells will increase the number of small cell base-stations thereby increase in the bandwidth providing enough capacity for devices to consume hundreds of megabits per second

5G – Key Features



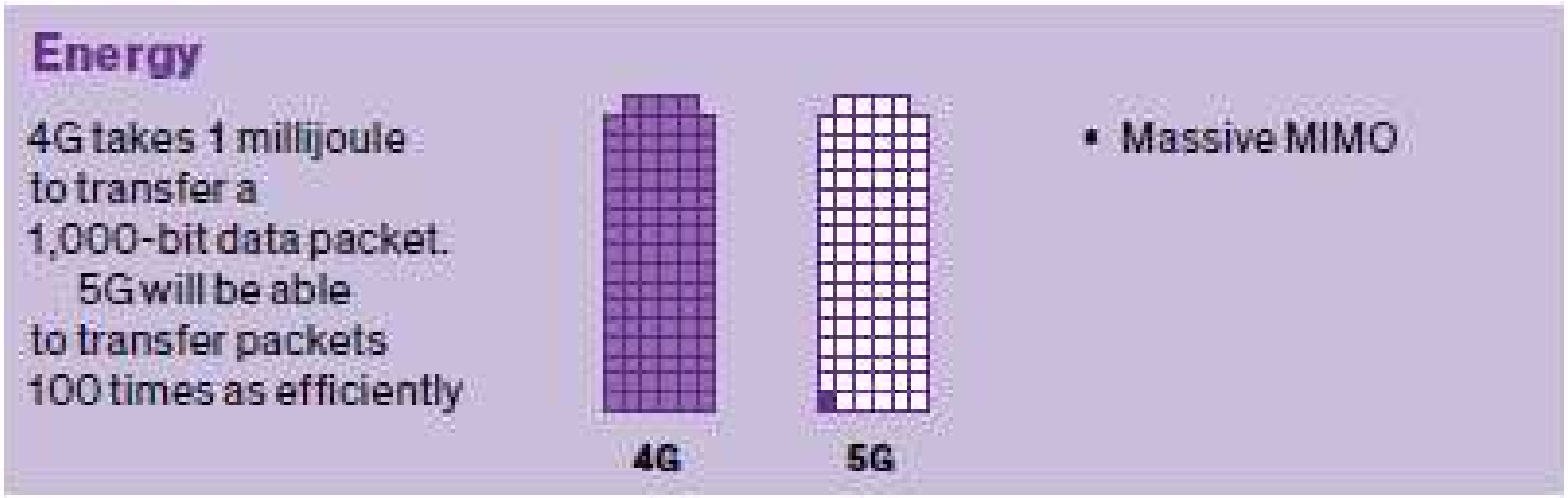
Heterogeneous network architectures are made of a combination of pico cells, small cells, macro cells, and different layers, these networks will provide appropriate coverage as the distance between a device and a base station changes, supporting real-time location tracking and quick handoffs between base stations

5G – Key Features



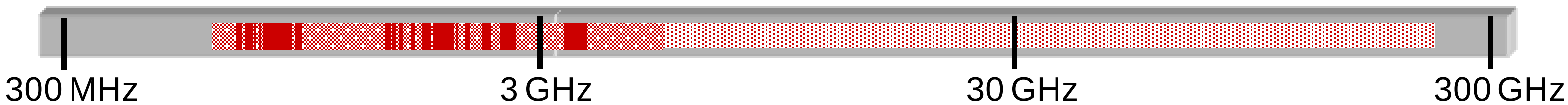
Content caching close to users brings information that is accessed frequently by caching it closer to the user so that it takes less time to get the data

5G – Key Features

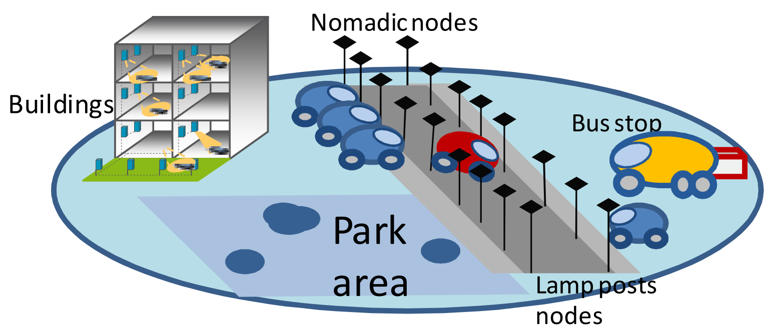


Massive multiple input, multiple out (MIMO) uses a huge array of antennas to steer and finely focus a radio beam so that it spotlights the intended receiver.

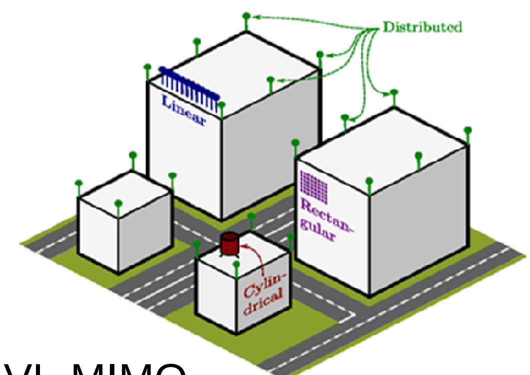
5G – Some Technology Components



New spectrum bands and access methods

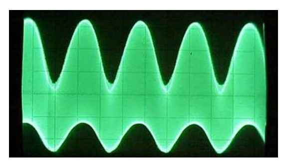


Dense and moving networks
Multi-hop wireless backhaul

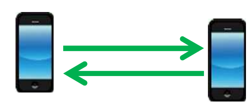


VL-MIMO
Massive multi-antenna systems

Context-aware interference and mobility management



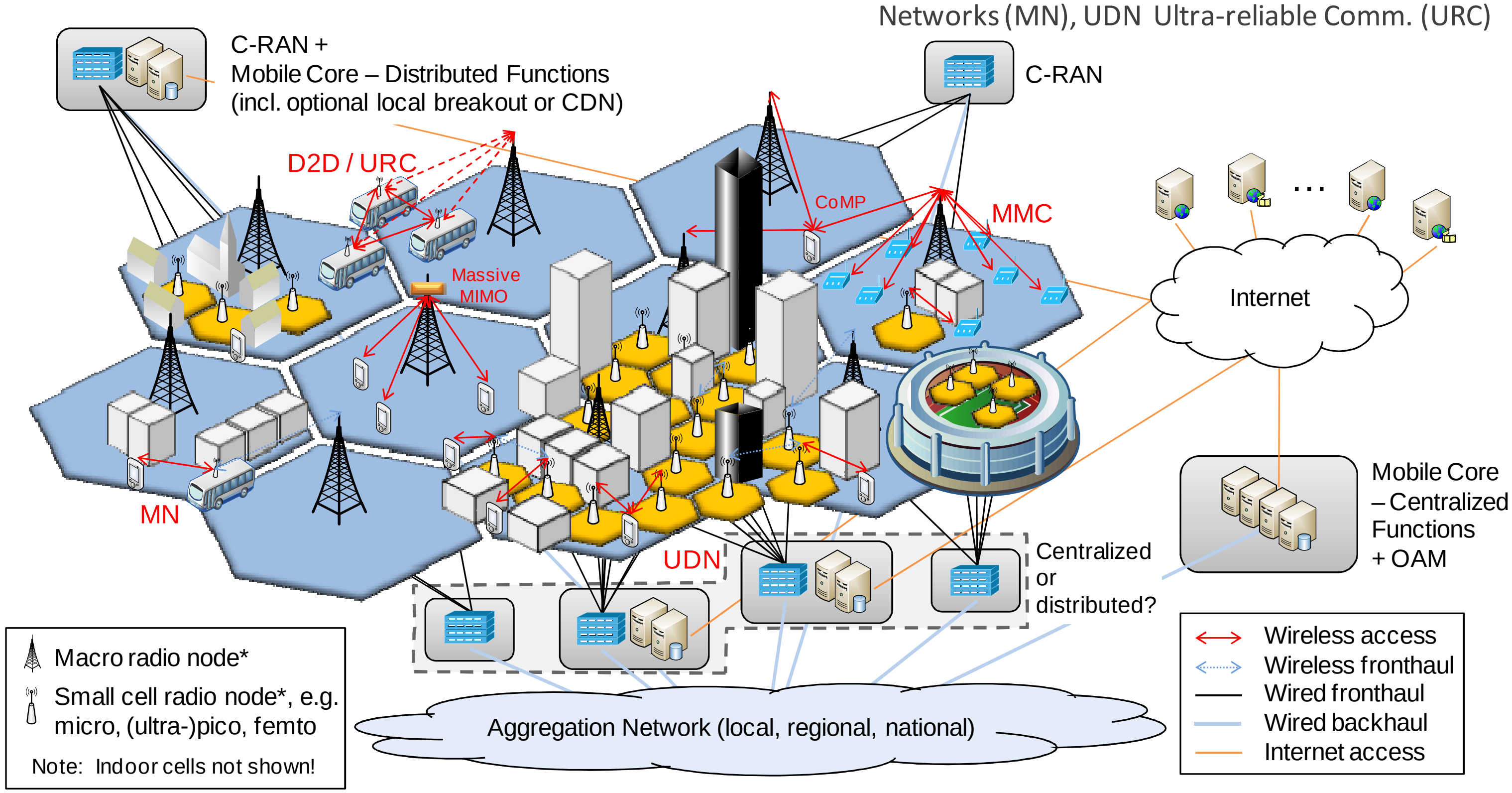
Air interfaces for new applications and reduced signaling



Mobile
Device-to-device

5G – Network Architecture

- Amazingly Fast scenario
  - high data rates & network capacities
- Ultra-Dense Networks (UDN)
  - ISD about 10 m
  - >= 1 radio nodes per room
- Local break out & Distributed mobile core functions
- Accelerated content delivery
- Tech. Dependent
  - D2D, MMC (Massive Machine Comm.), Moving Networks (MN), UDN Ultra-reliable Comm. (URC)



* Only Remote Radio Units (RRUs) assumed.

Resources

References

Lecture compiled from LTE fundamentals (Alcatel-Lucent internal) and other selected presentations.

Textbook

Fundamentals of LTE: Arunabha Ghosh, Jun Zhang, Jeffrey G. Andrews, Rias Muhamed, Prentice Hall.