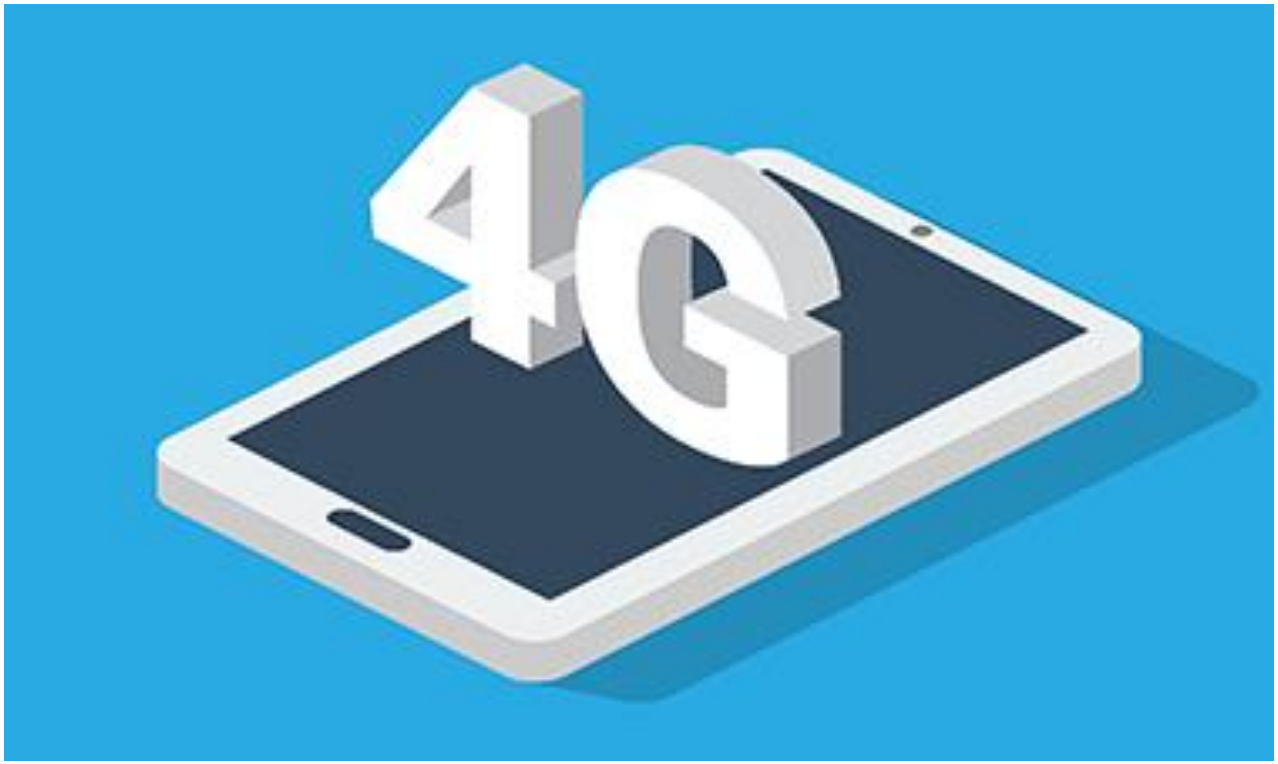
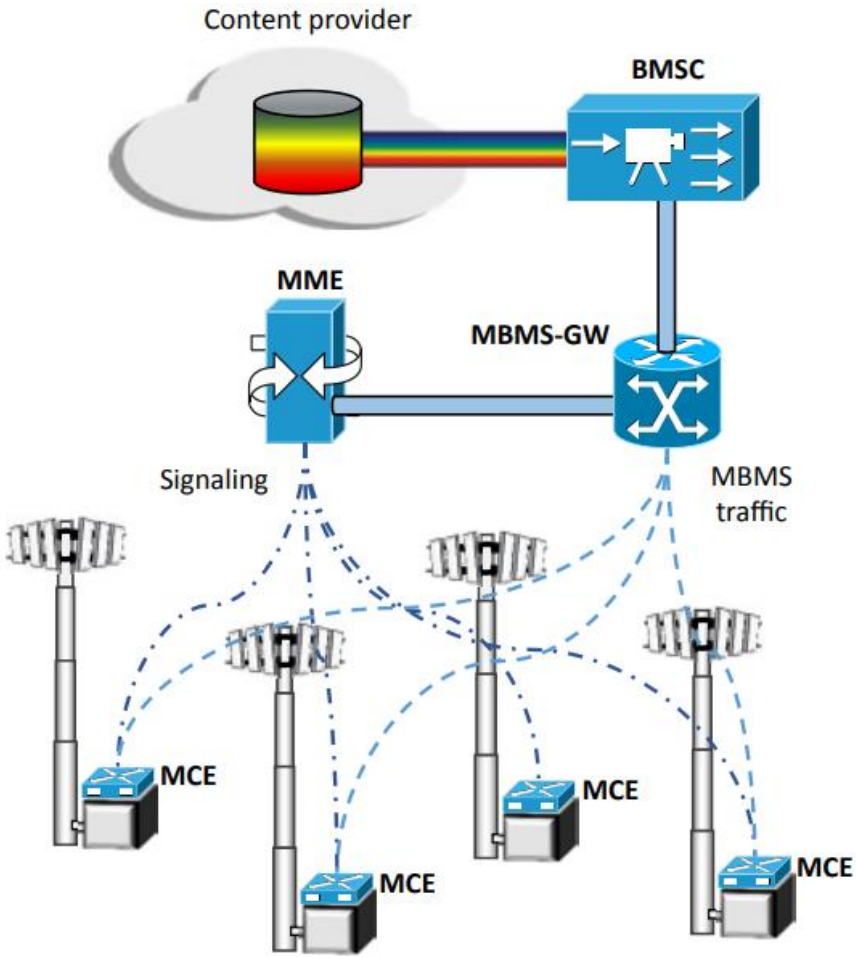


Long Term Evolution (LTE)
Long Term Evolution – Advanced (LTE-A)

Evolved Multimedia Broadcast Multicast Services (eMBMS)

Evolved Multimedia Broadcast Multicast Services (eMBMS)



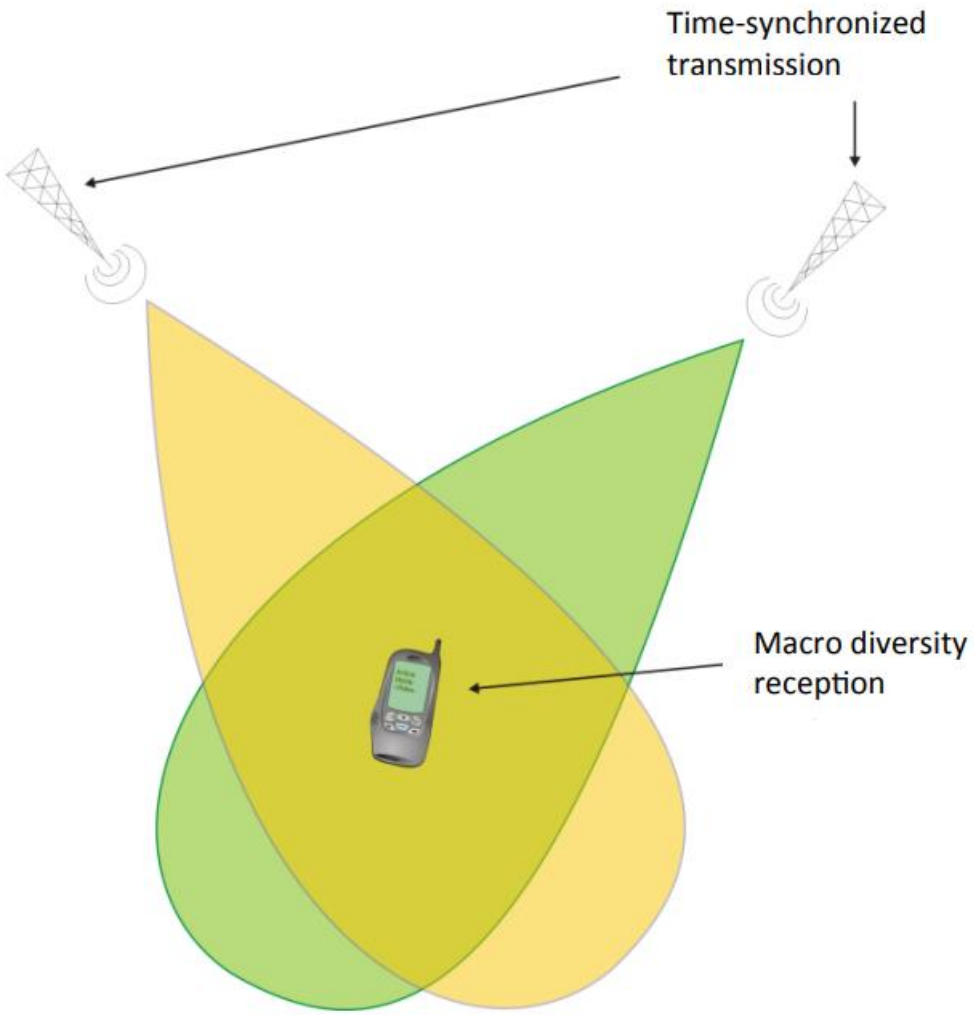
Broadcast Multicast Service Center (BMSC)
Interface with content providers including billing and the content to be transmitted.

MBMS Gateway (MBMS-GW)
Delivers MBMS traffic using IP-multicast reaching multiple cells

Multi-cell/multicast Coordination Entity (MCE)
Administration of radio resources for MBMS

Mobility Management Entity (MME)
Session control signaling (start, update, and stop, QoS)

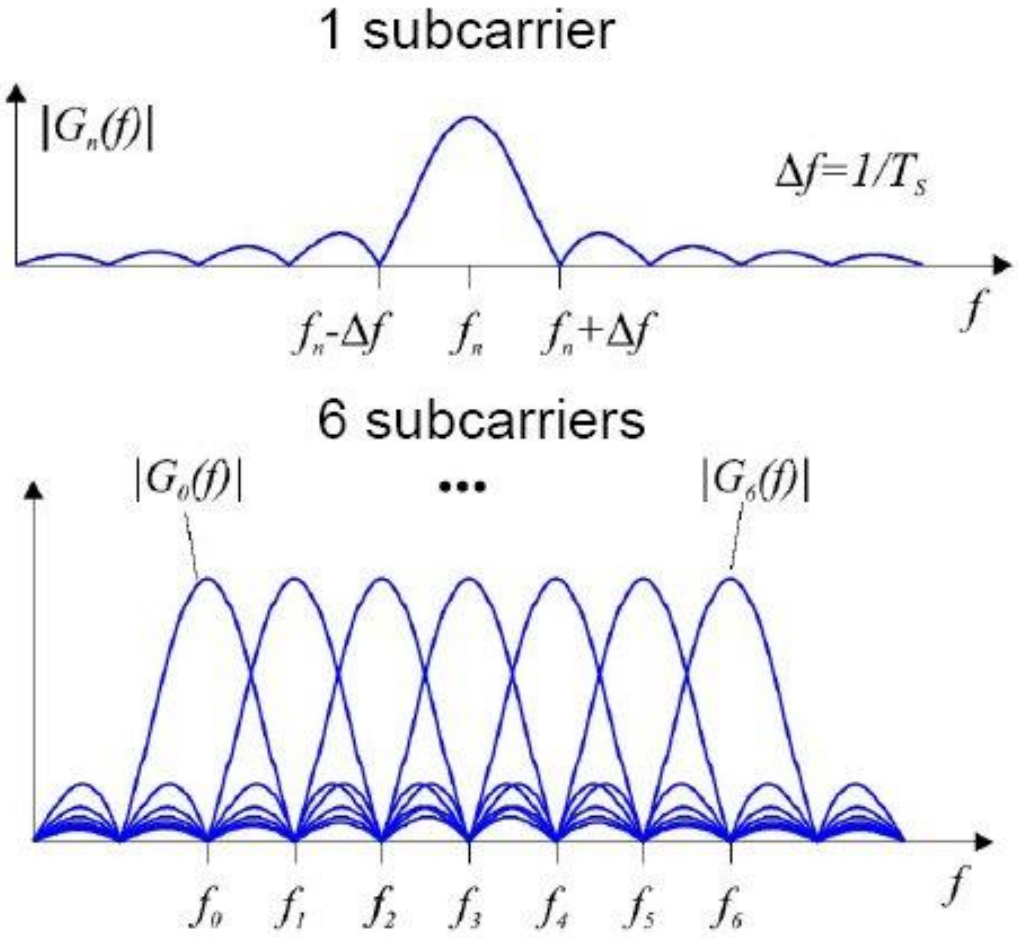
MBMS single-frequency network (MBSFN)



LTE Transmission Techniques

- LTE employs Orthogonal Frequency Division Multiple Access (OFDMA) for downlink data transmission and Single Carrier FDMA (SC-FDMA) for uplink transmission

LTE-Downlink (OFDM)



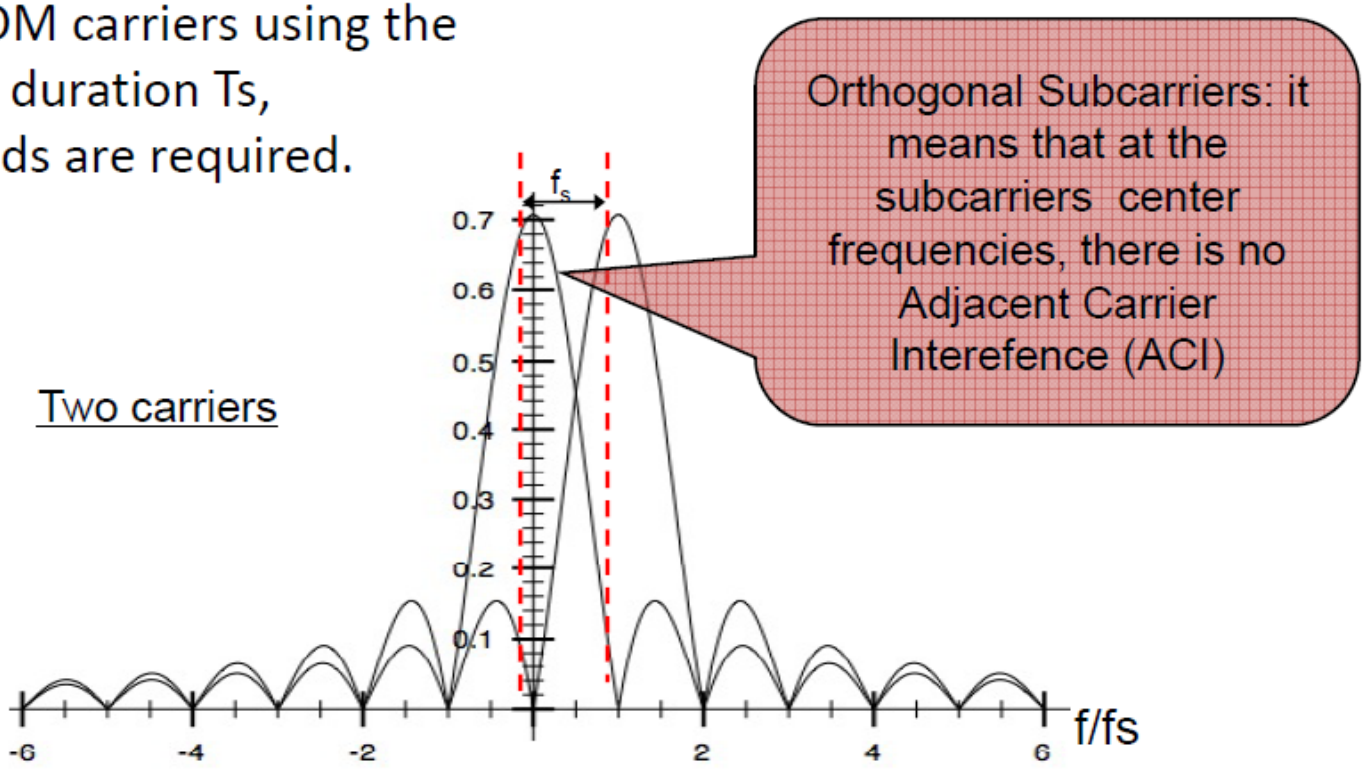
- Improved spectral efficiency
- Reduce ISI effect by multipath
- Against frequency selective fading

OFDM: Orthogonal Frequency Division Multi-Carrier

Thus OFDM simply places the next carrier exactly in the first null point of the previous one.

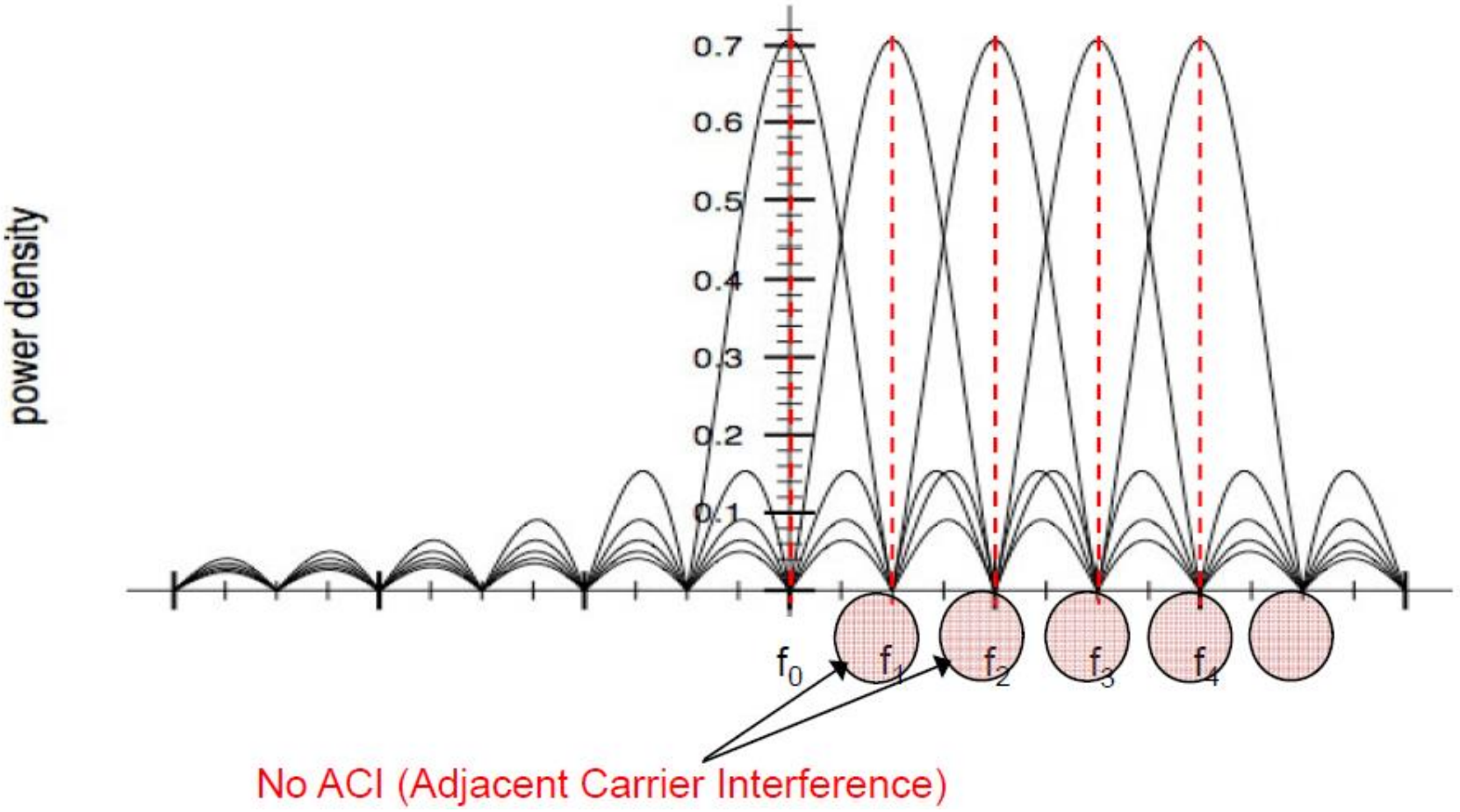
With this we don't need any pulse-shaping.

Between OFDM carriers using the same symbol duration Ts, no guard bands are required.



Spectrum Overlapping of multiple OFDM carriers

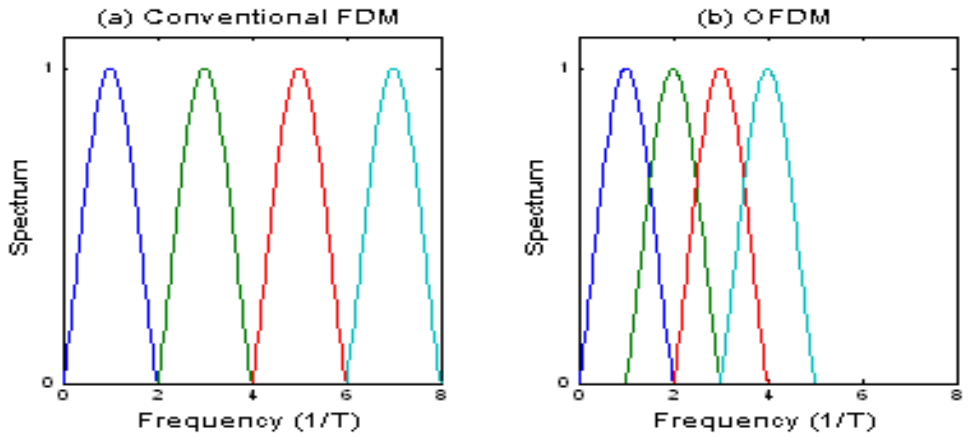
$$f_n = f_0 + nf_s = f_0 + n\frac{1}{T_s} \qquad n = \ldots -1, 0, 1, 2 \ldots.$$



OFDM pros and cons

Pros

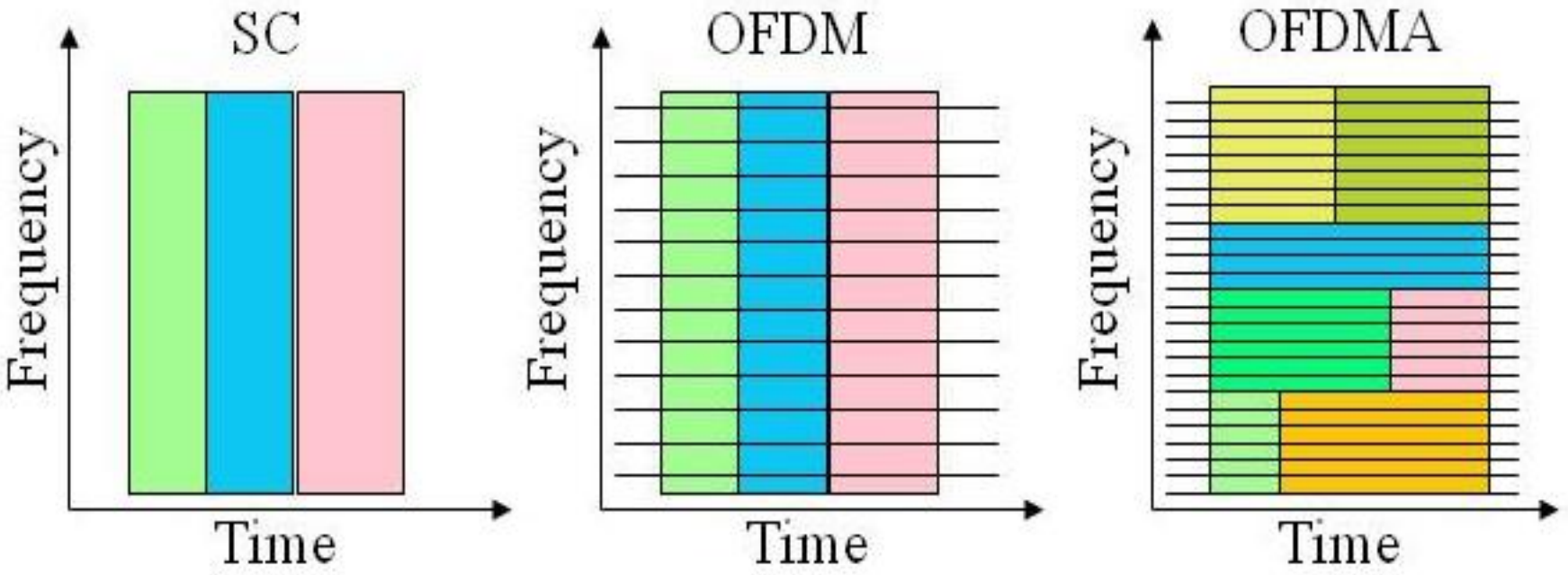
- Spectral efficiency
- Robust against narrow-band co-channel interference
- Higher throughput in the same frequency band (more subcarriers)



Cons

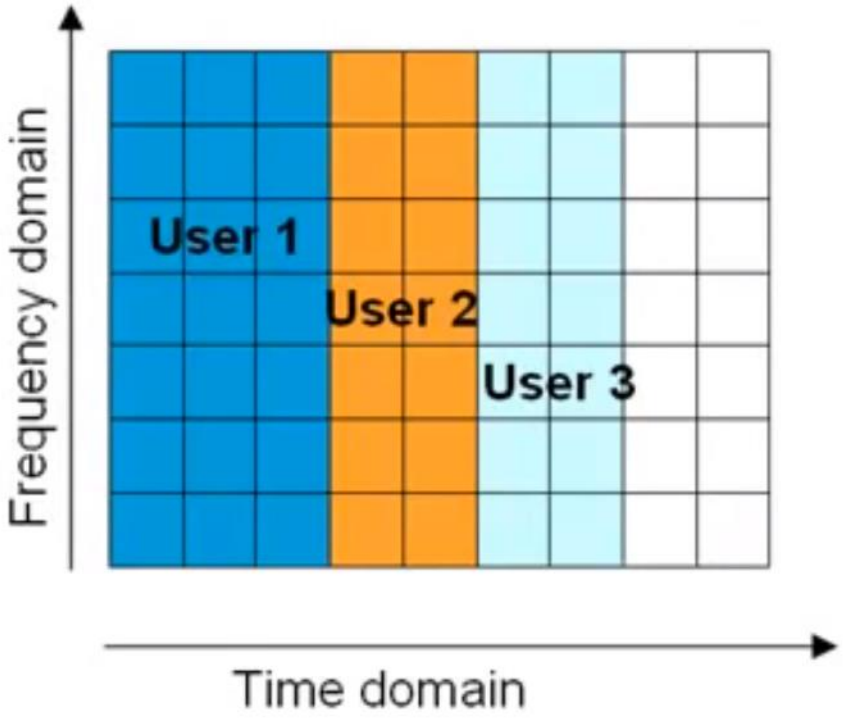
- It is more sensitive to carrier frequency offsets
- More energy requirements due to high peak-to-average power ratio (PAPR)

SC/OFDM/OFDMA

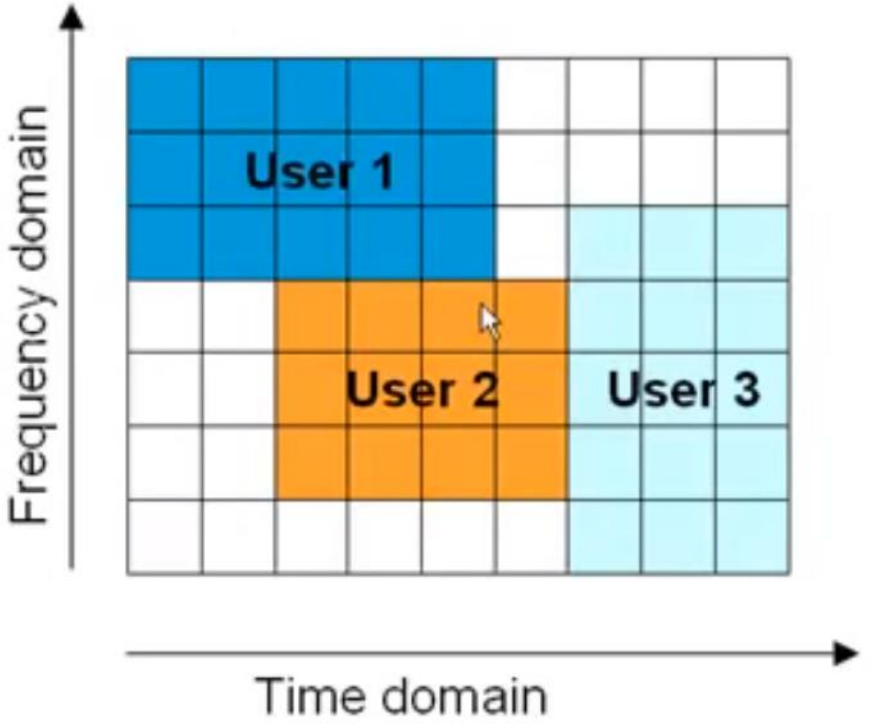


OFDMA allocation

I OFDM allocates users in time domain only



I OFDMA allocates users in time and frequency domain



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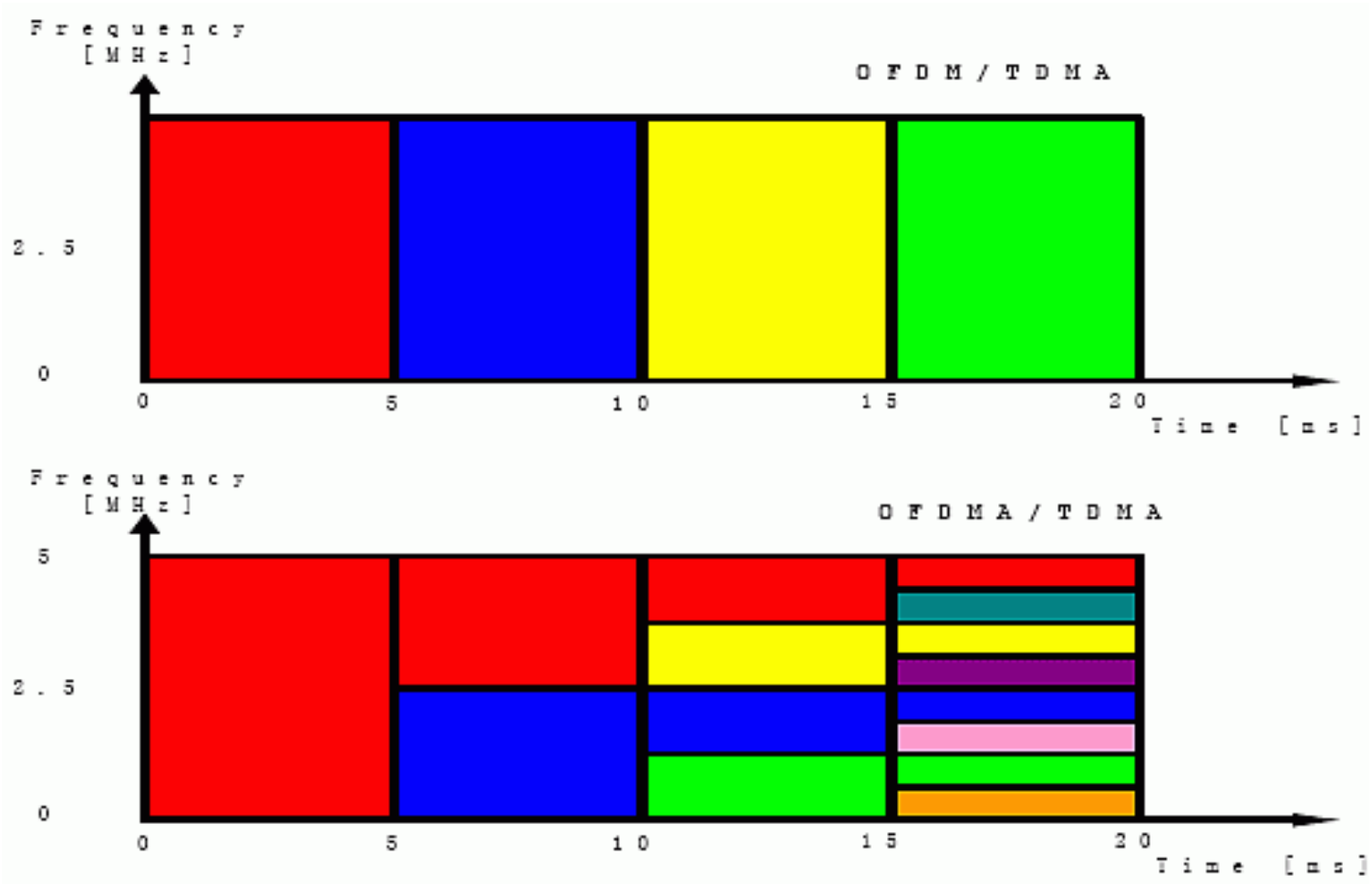
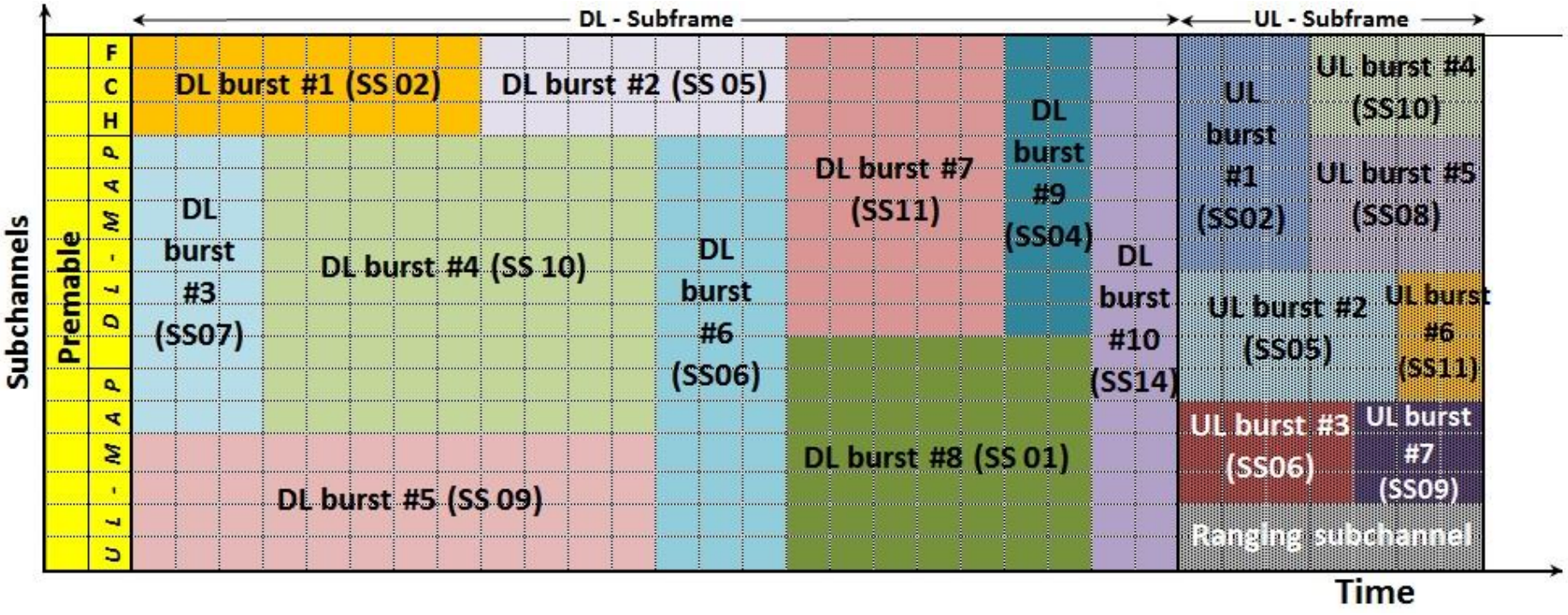


OFDMA/TDD structure



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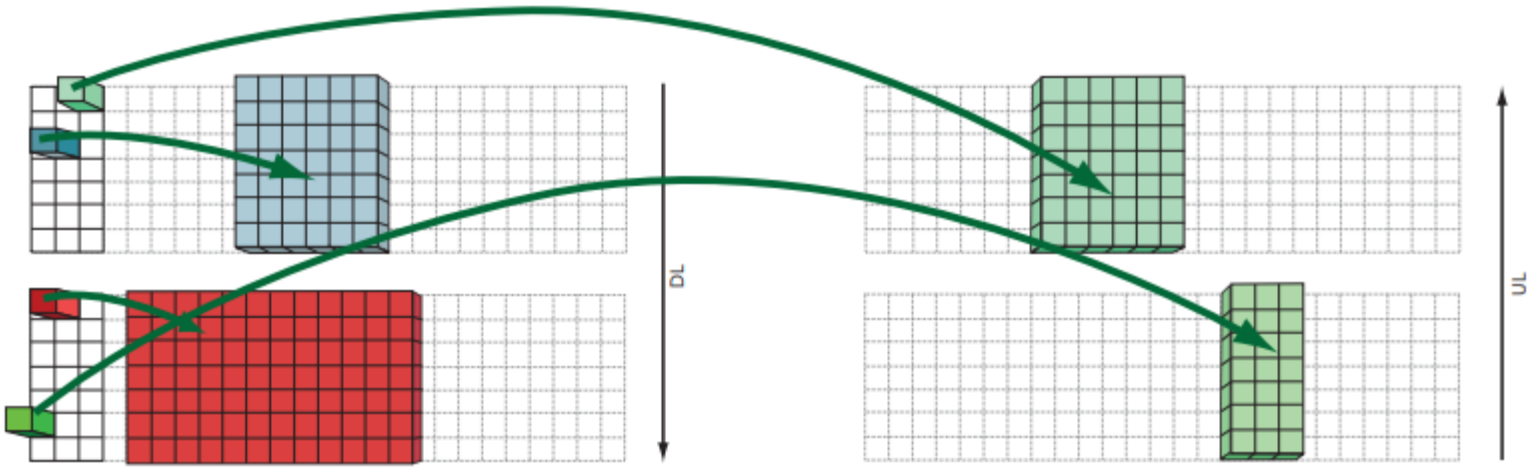

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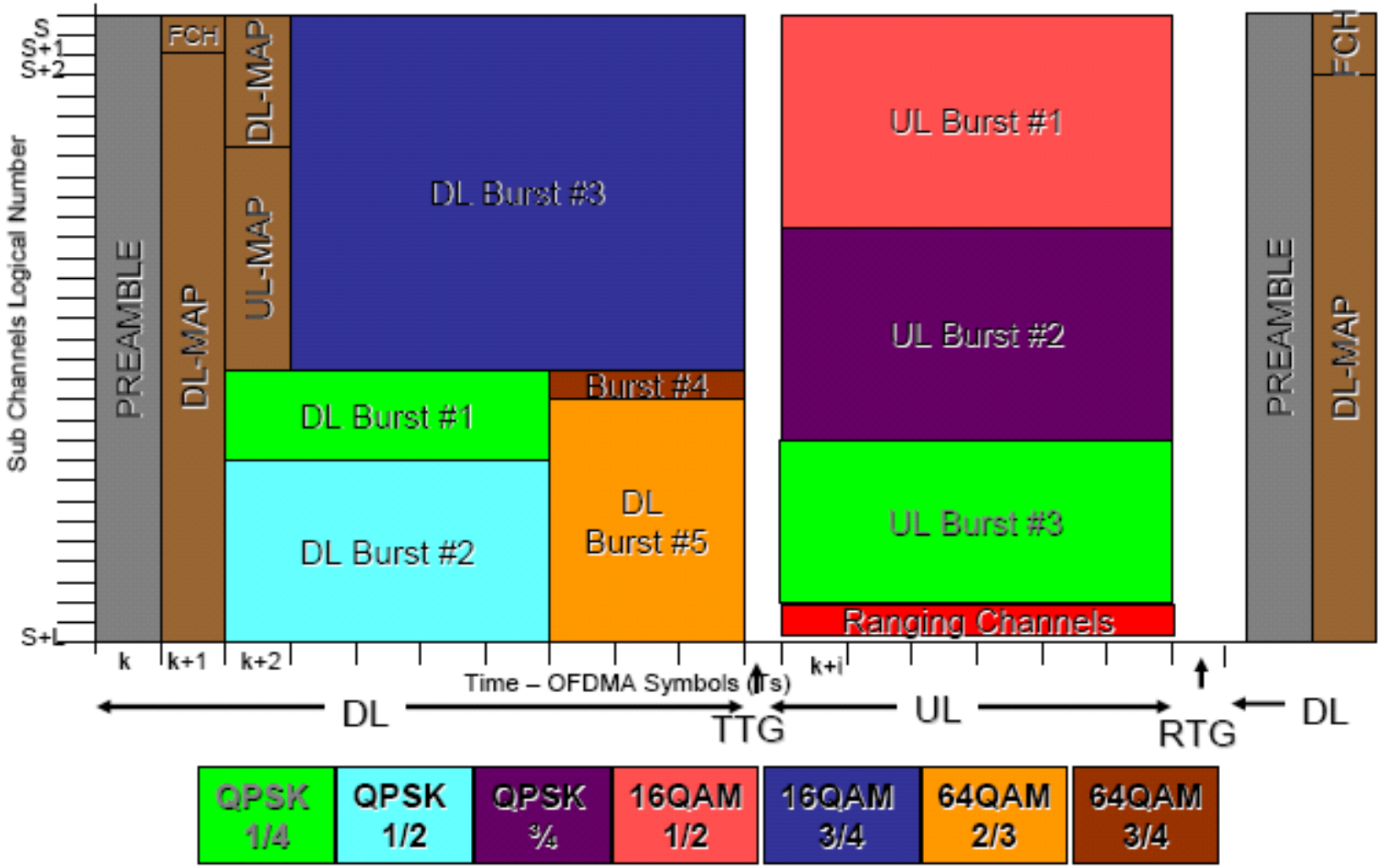
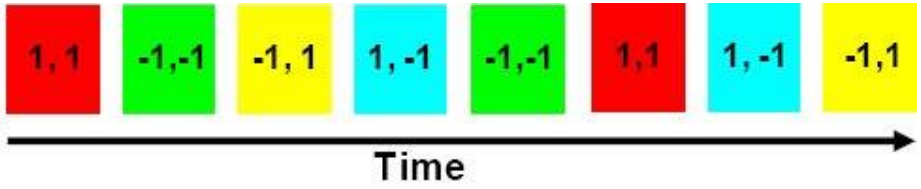
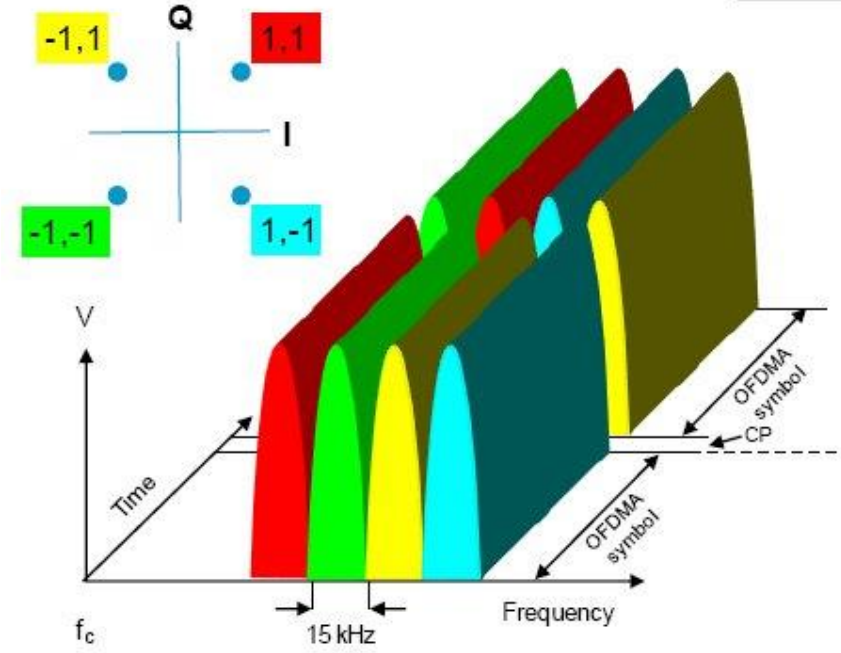


OFDMA vs SC-FDMA

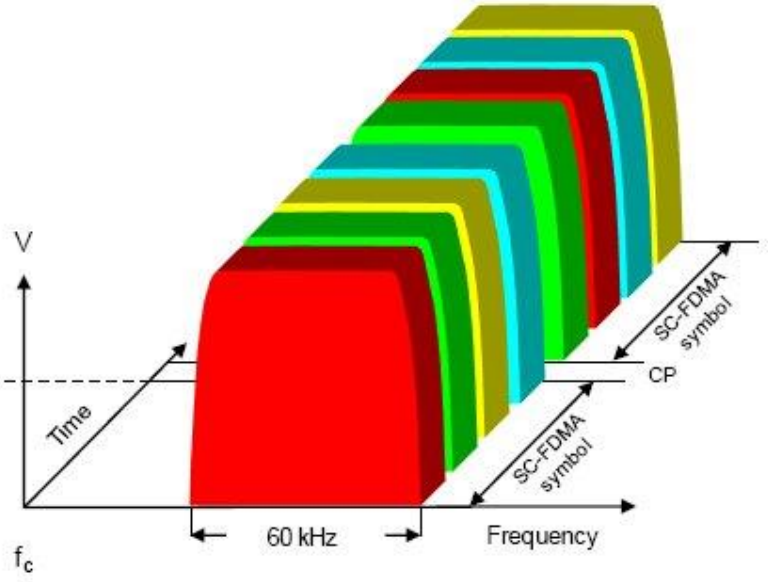
The following graphs show how a sequence of eight QPSK symbols is represented in frequency and time





OFDMA

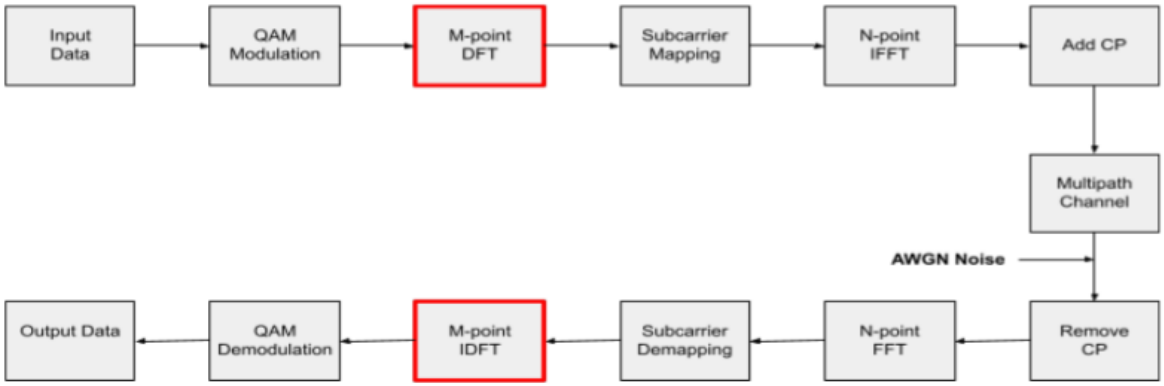
Data symbols occupy 15 kHz for one OFDMA symbol period



SC-FDMA

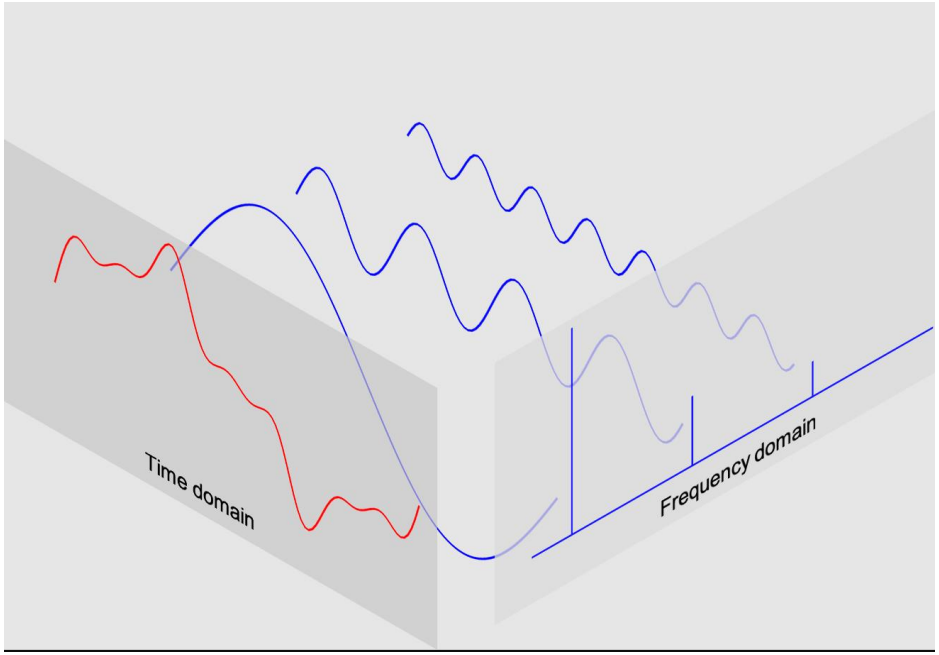
Data symbols occupy M*15 kHz for 1/M SC-FDMA symbol periods

OFDMA vs SC-FDMA

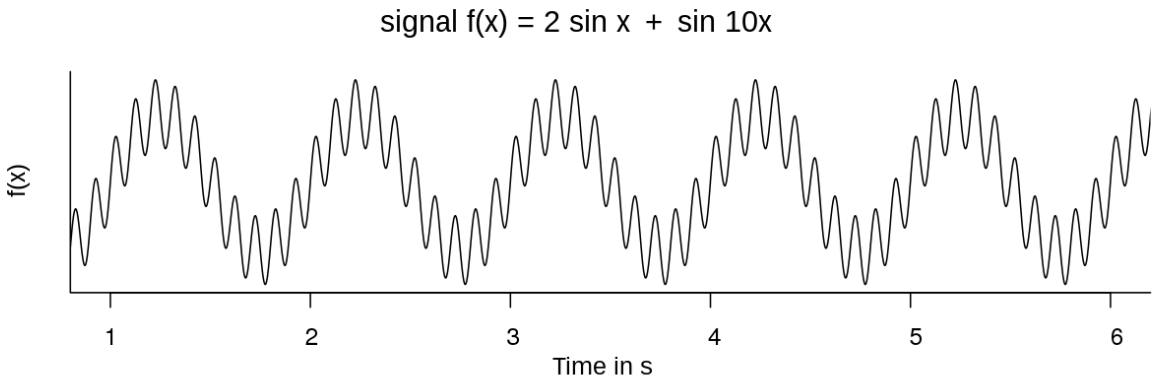


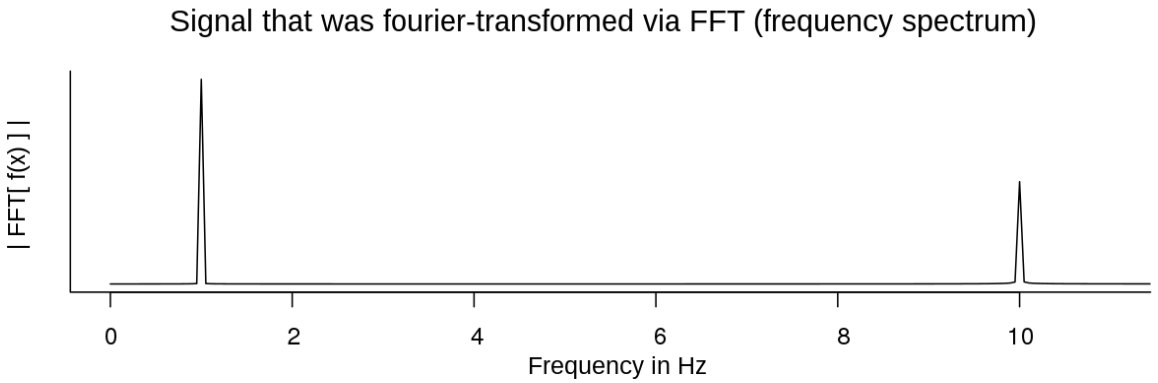
OFDMA :

SC-FDMA : +

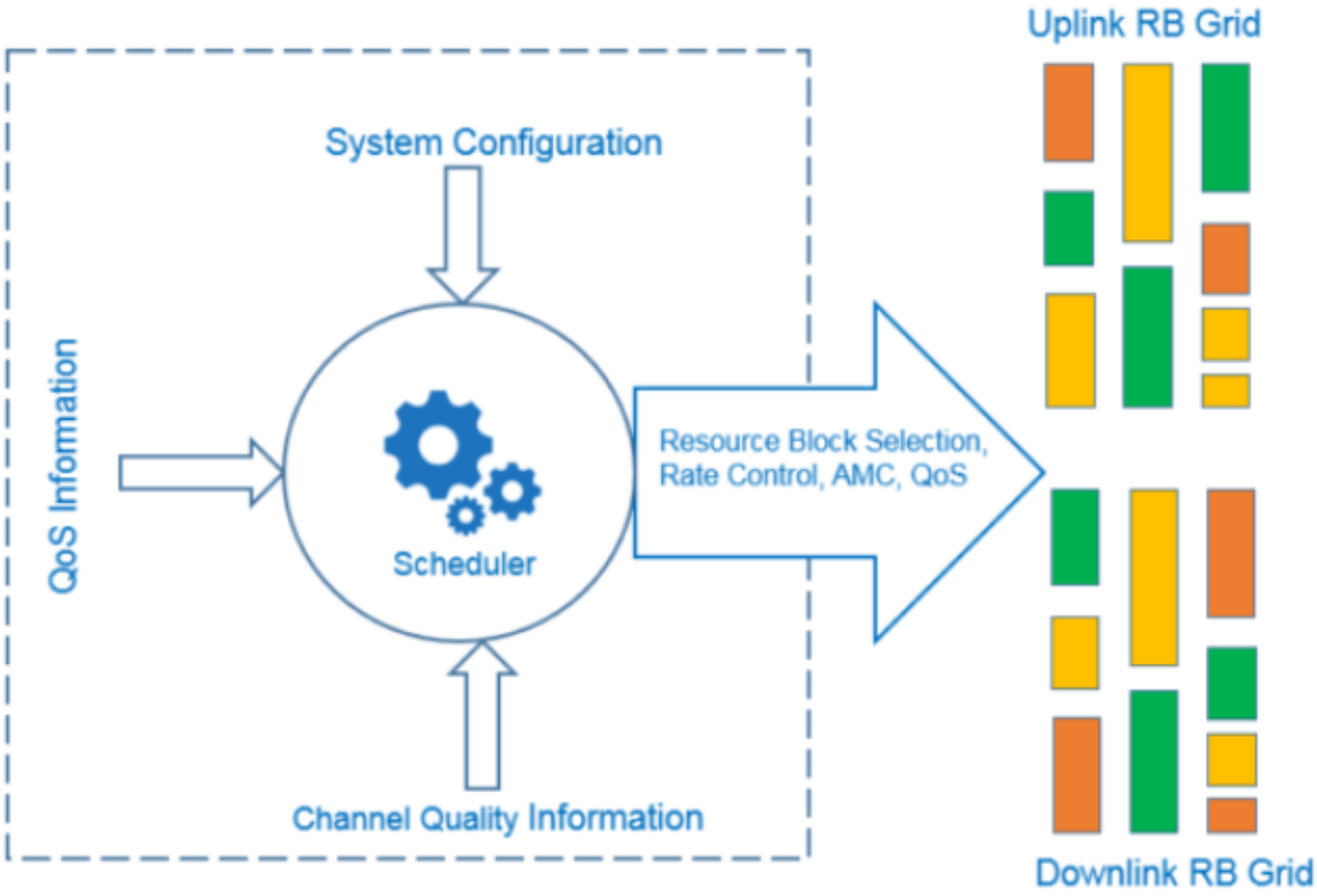


Fast Fourier Transform

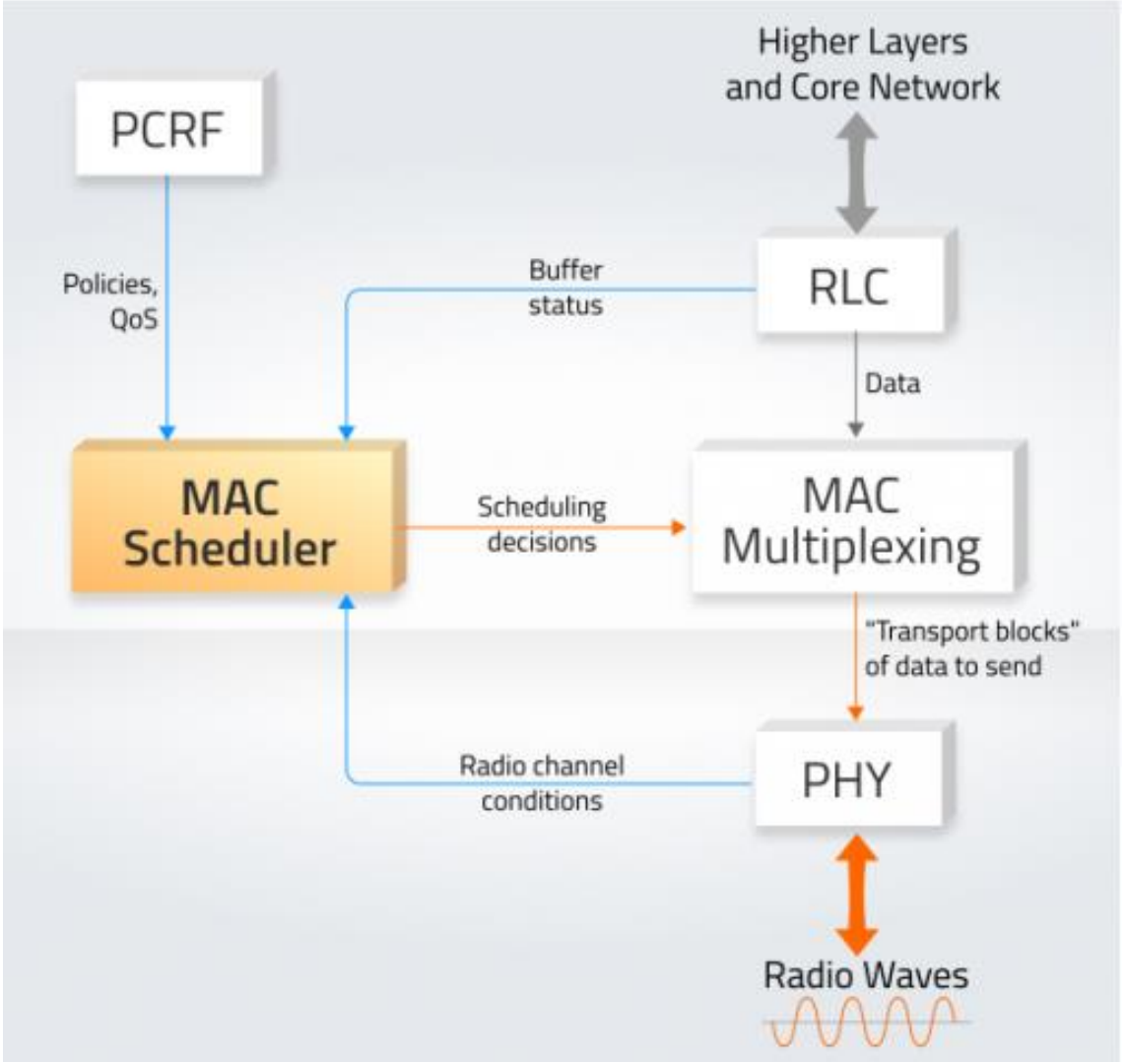




Traffic Scheduling

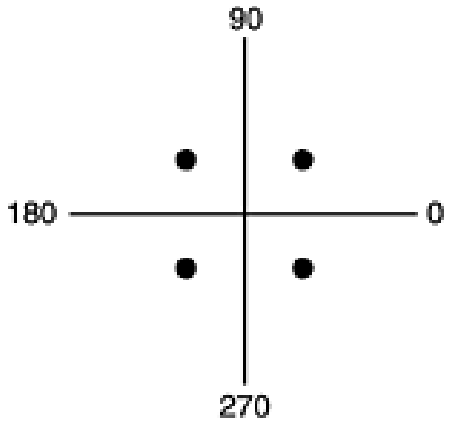


Traffic Scheduling

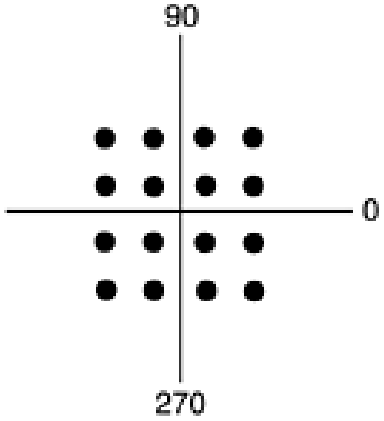


Multiple Modulations

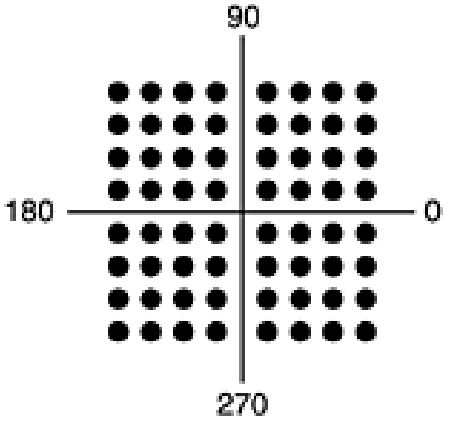
- QPSK (Quadrature Phase Shift Keying) = 4 phase shifts, 1 amplitude level, 2 bits/symbol
- QAM-16 = 4 phase shifts, 4 amplitude levels, 4 bits/symbol
- QAM-64 = 4 phase shifts, 16 amplitude levels, 6 bits/symbol



QPSK

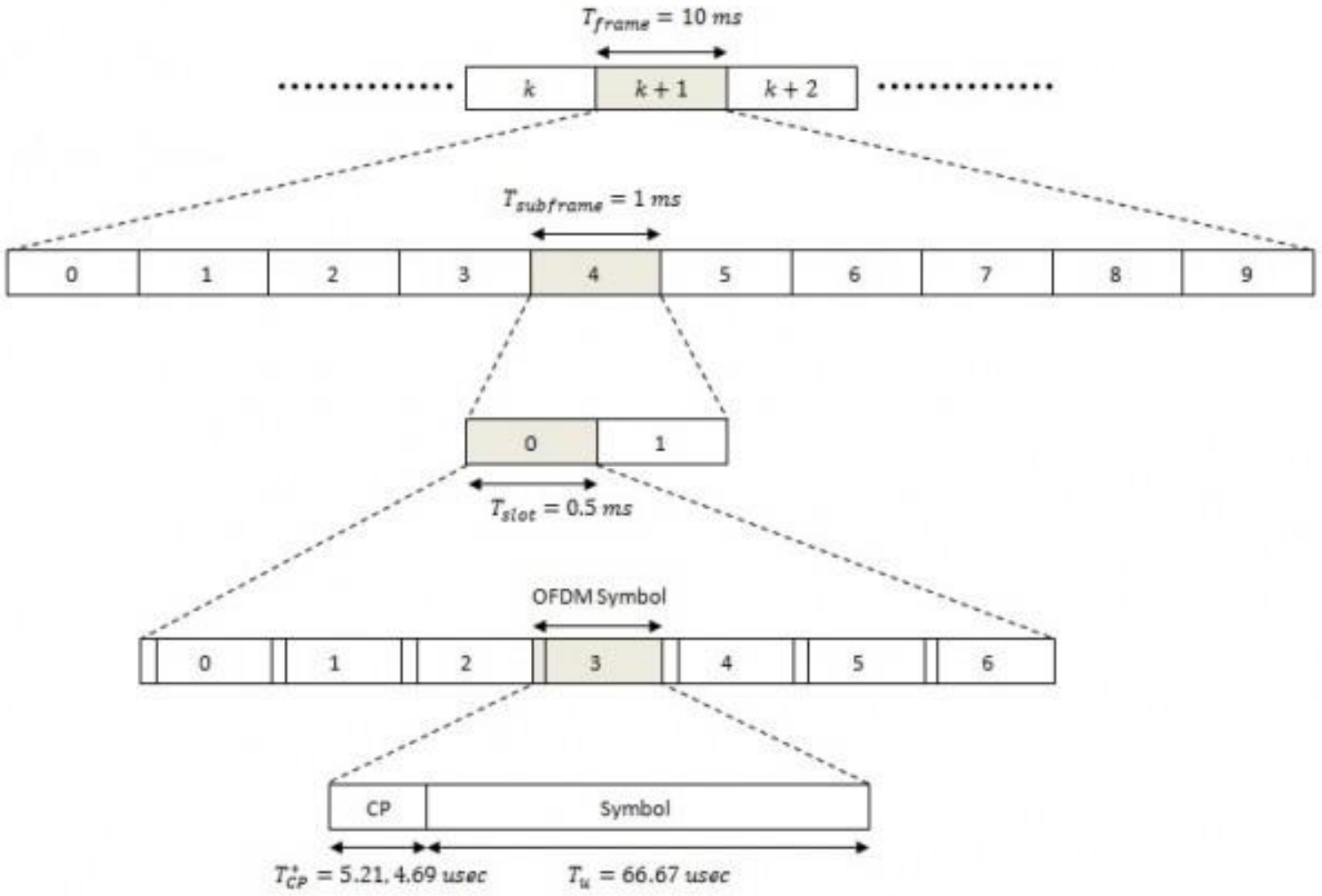


QAM-16

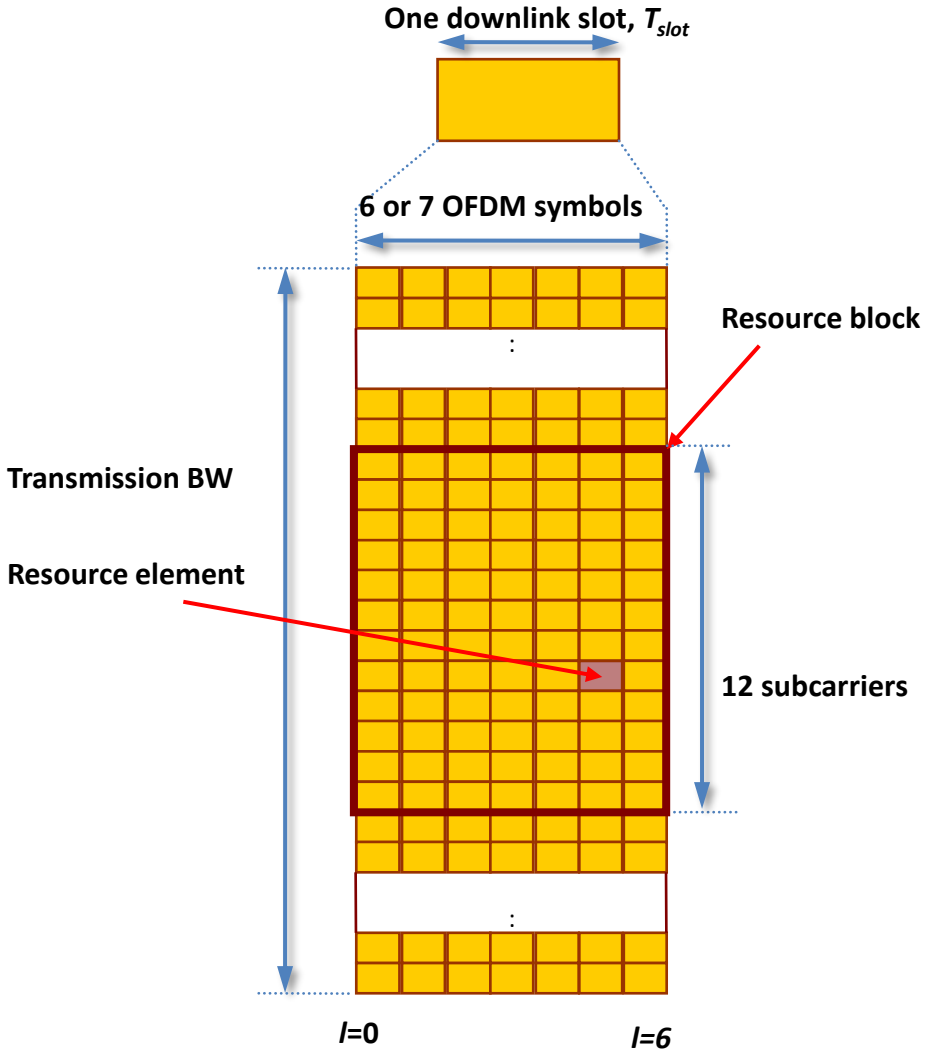


QAM-64

Generic Frame Structure

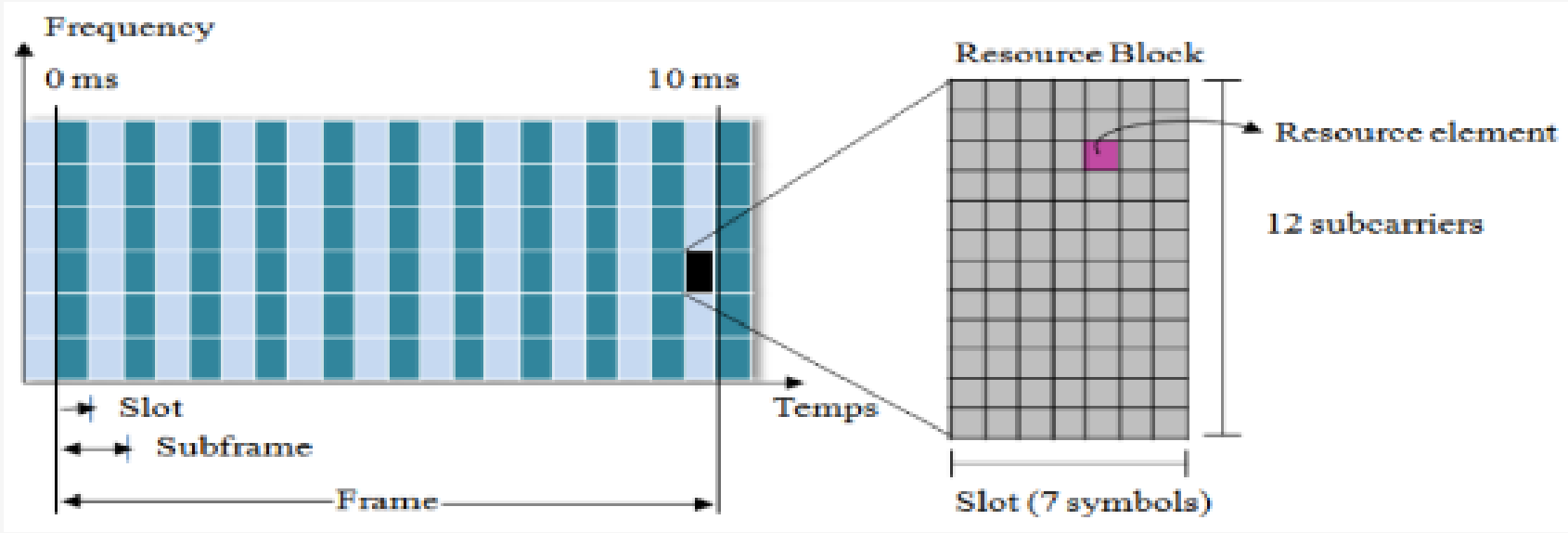


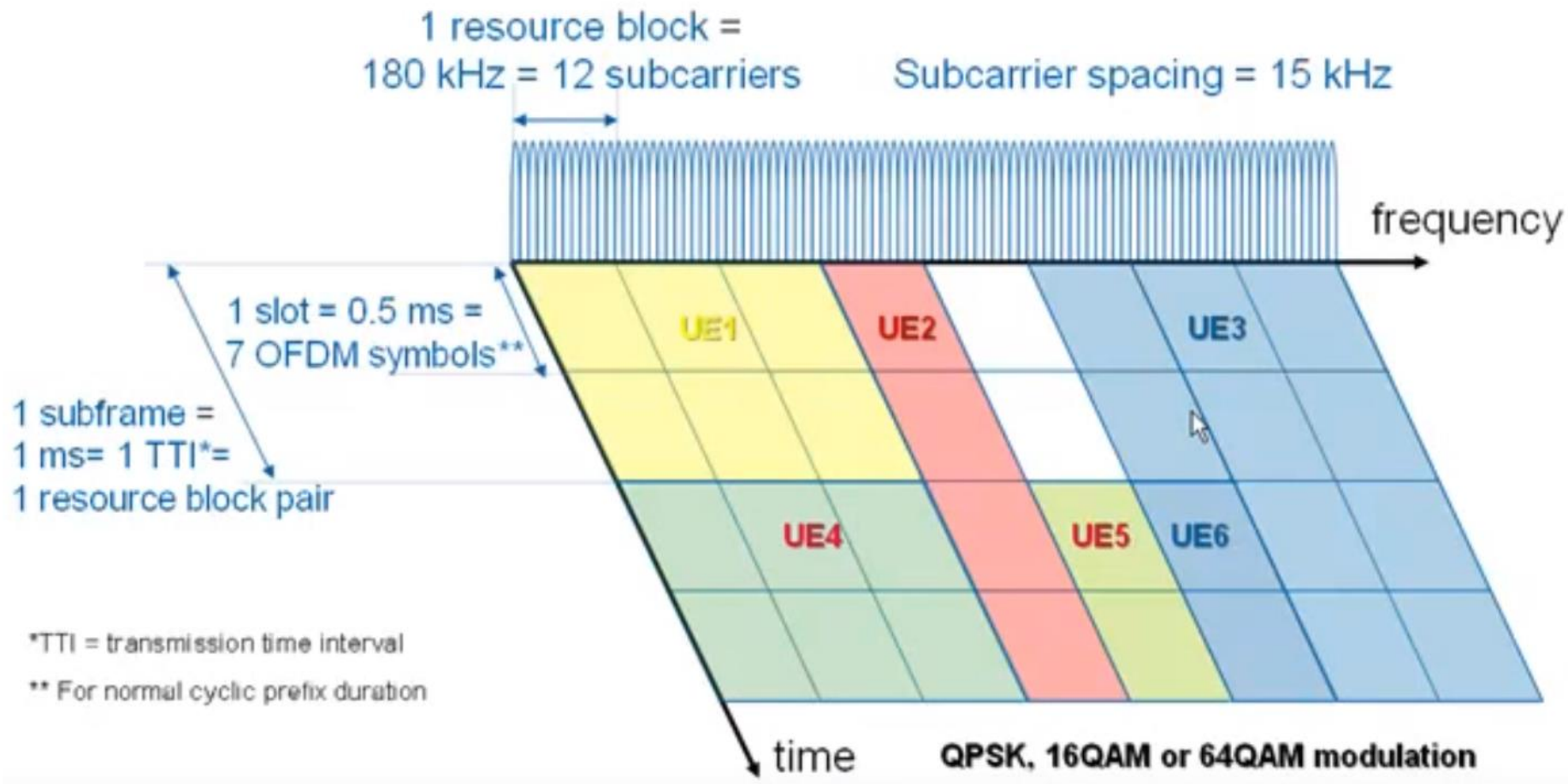
Resource Grid



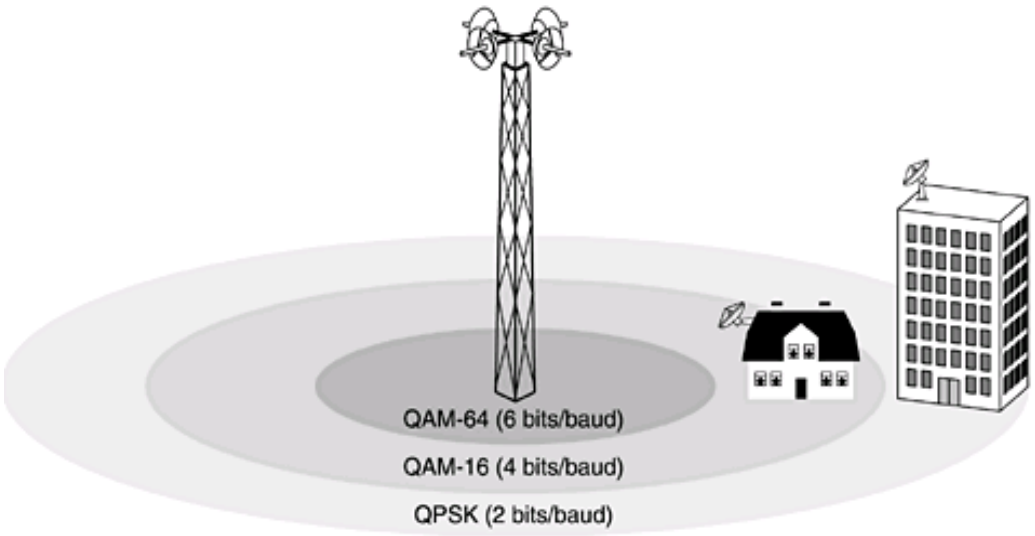
- 6 or 7 OFDM symbols in 1 slot
- Subcarrier spacing = 15 kHz
- Block of 12 SCs in 1 slot = 1 RB
  - *0.5 ms x 180 kHz*
  - Smallest unit of allocation

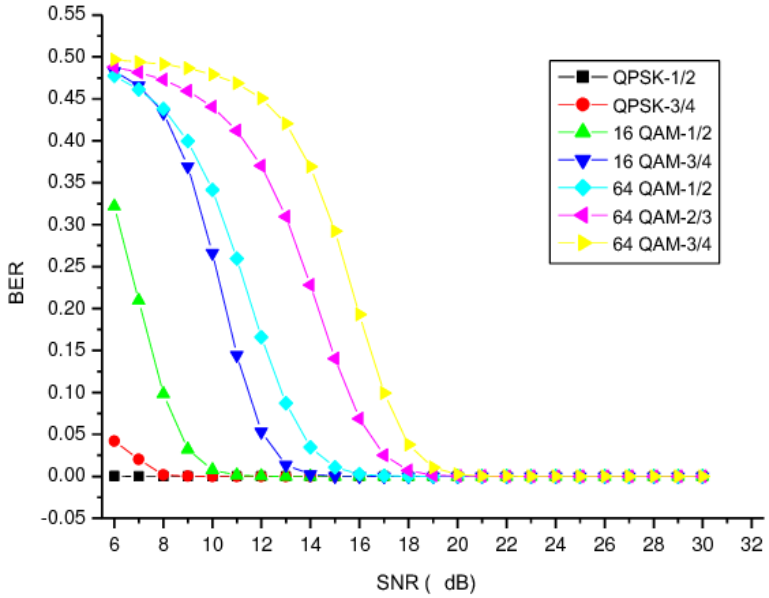
Resource Grid

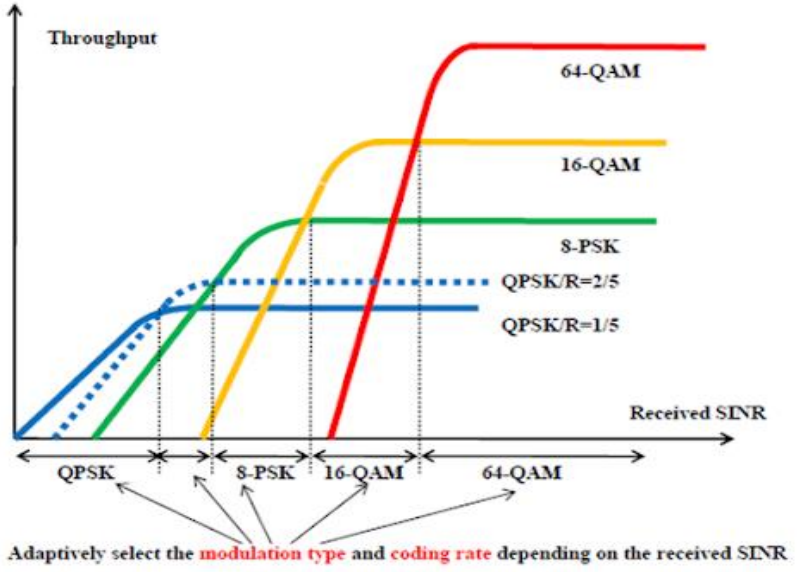



1 resource block =
180 kHz = 12 subcarriers
Subcarrier spacing = 15 kHz
frequency
1 slot = 0.5 ms =
7 OFDM symbols**
1 subframe =
1 ms= 1 TTI*=
1 resource block pair
UE1
UE2
UE3
UE4
UE5
UE6
*TTI = transmission time interval
** For normal cyclic prefix duration
time
QPSK, 16QAM or 64QAM modulation

Adaptive modulation



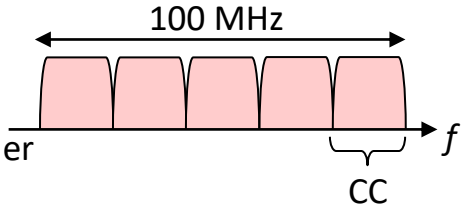




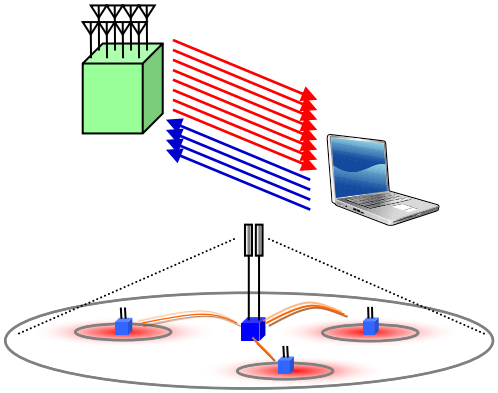
	WCDMA (UMTS)	HSPA HSDPA / HSUPA	HSPA+	LTE	LTE ADVANCED (IMT ADVANCED)
Max downlink speed (bps)	384k	14 M	28 M	100 M	1 G
Max uplink speed (bps)	128 k	5.7 M	11 M	50 M	500 M
Latency round trip time (approx.)	150 ms	100 ms	50 ms (max)	~10 ms	Less than 5 ms
3GPP releases	Rel 99/4	Rel 5/6	Rel 7	Rel 8/9	Rel 10
Approx years of initial roll out	2003/4	2005/6 HSDPA 2007/8 HSUPA	2008/9	2009/10	
Access methodology	CDMA	CDMA	CDMA	OFDMA/SC-FDMA	OFDMA/SC-FDMA

LTE-A main features

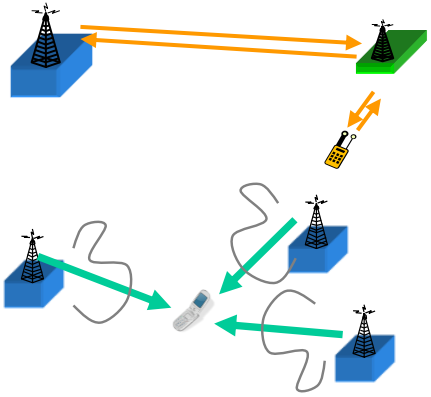
- Support of Wider Bandwidth(Carrier Aggregation)
  - Use of multiple component carriers(CC) to extend bandwidth up to 100 MHz
  - Common physical layer parameters between component carrier and LTE Rel-8 carrier
  - ➔ Improvement of peak data rate, backward compatibility with LTE Rel-8



- Advanced MIMO techniques
  - Extension to up to 8-layer transmission in downlink
  - Introduction of single-user MIMO up to 4-layer transmission in uplink
  - Enhancements of multi-user MIMO
  - ➔ Improvement of peak data rate and capacity



- Heterogeneous network and eICIC (enhanced Inter-Cell Interference Coordination)
  - Interference coordination for overlaid deployment of cells with different Tx power
  - ➔ Improvement of cell-edge throughput and coverage



- Relay
  - Supports radio backhaul and creates a separate cell and appear as Rel. 8 LTE eNB to Rel. 8 LTE UEs
  - ➔ Improvement of coverage and flexibility of service area extension

- Coordinated Multi-Point transmission and reception (CoMP)
  - Support of multi-cell transmission and reception
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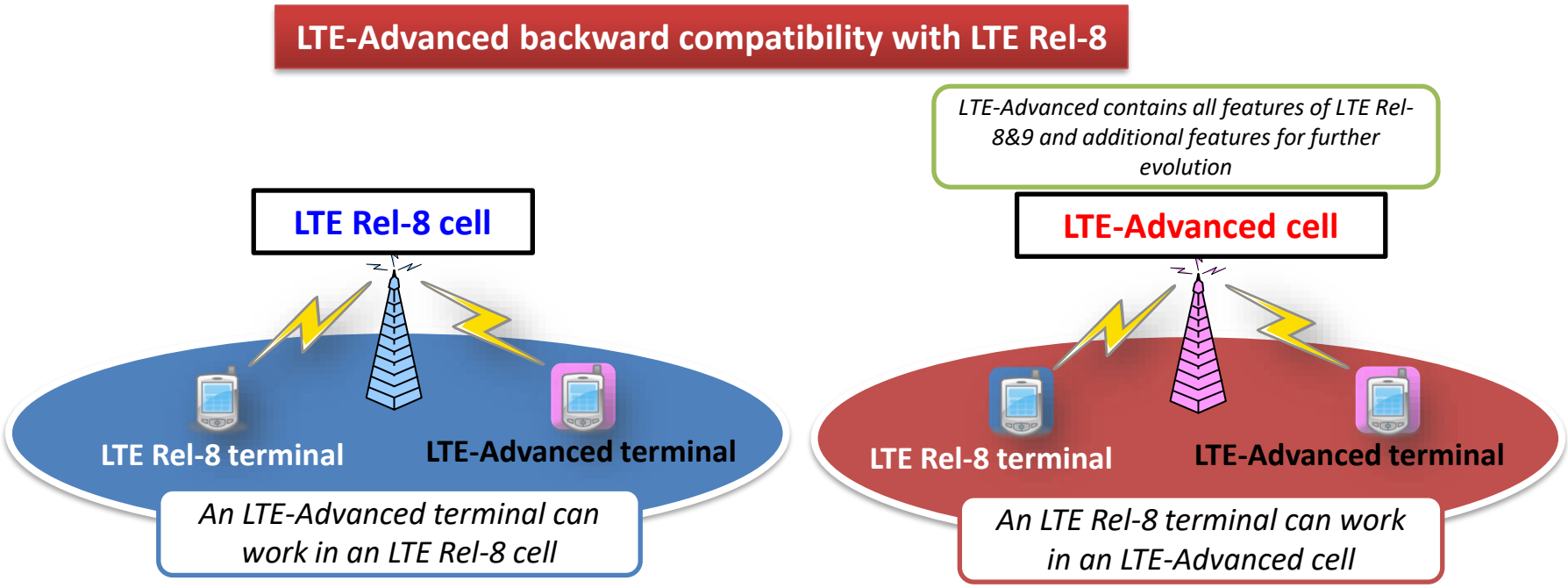
Backward compatibility



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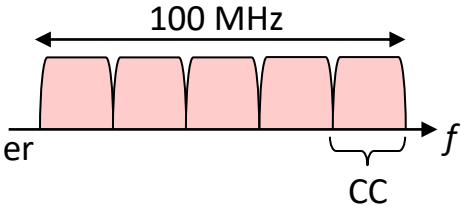

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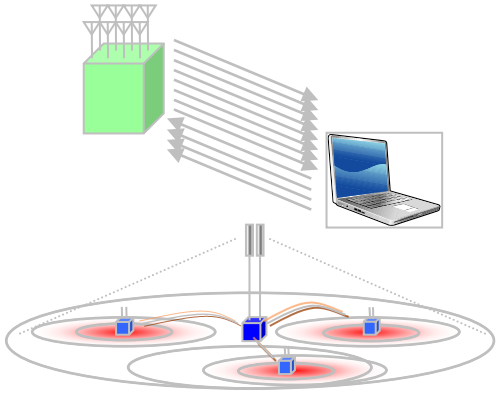

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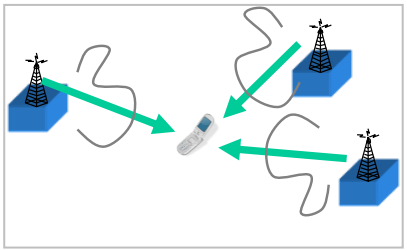
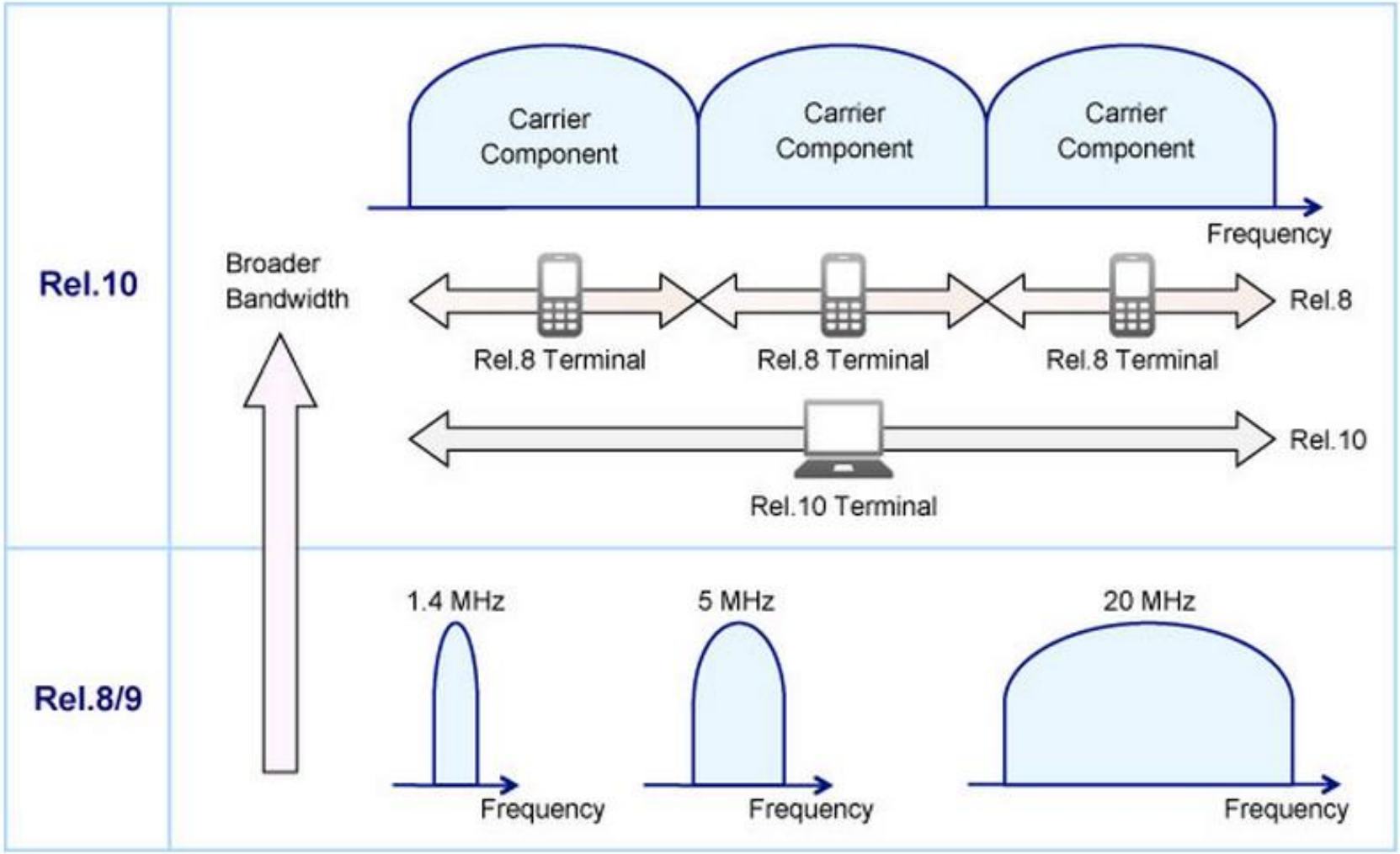


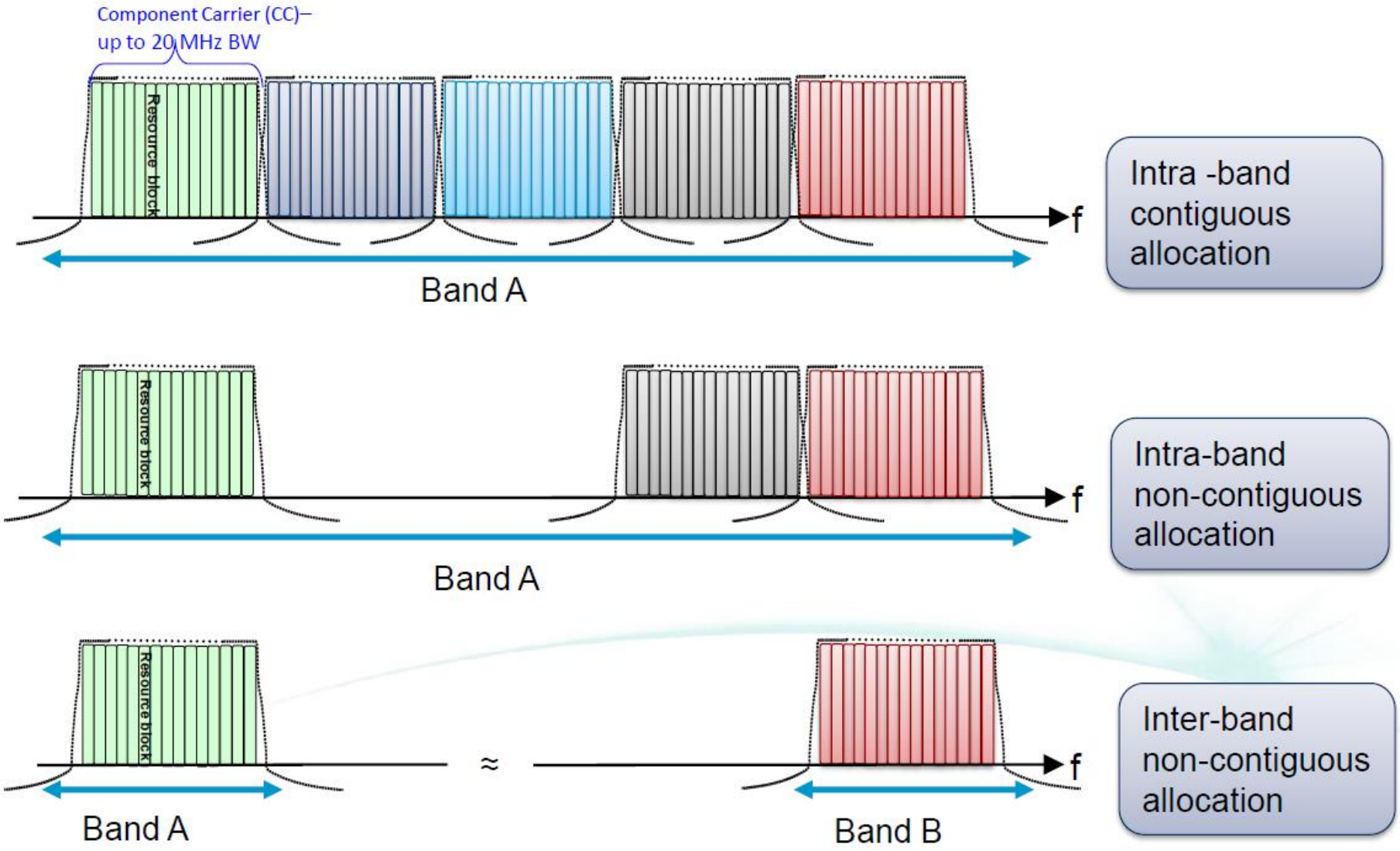
Carrier aggregation

- Extends the maximum transmission bandwidth, up to 100MHz, by aggregating up to five LTE carriers – also known as component carriers (CCs)
- Lack of sufficient contiguous spectrum forces use of carrier aggregation to meet peak data rate targets:
  - 1 Gbps in the downlink and 500 Mbps in the uplink
- Motivation:
  - Achieve wide bandwidth transmissions
  - Facilitate efficient use of fragmented spectrum
  - Efficient interference management for control channels in heterogeneous networks

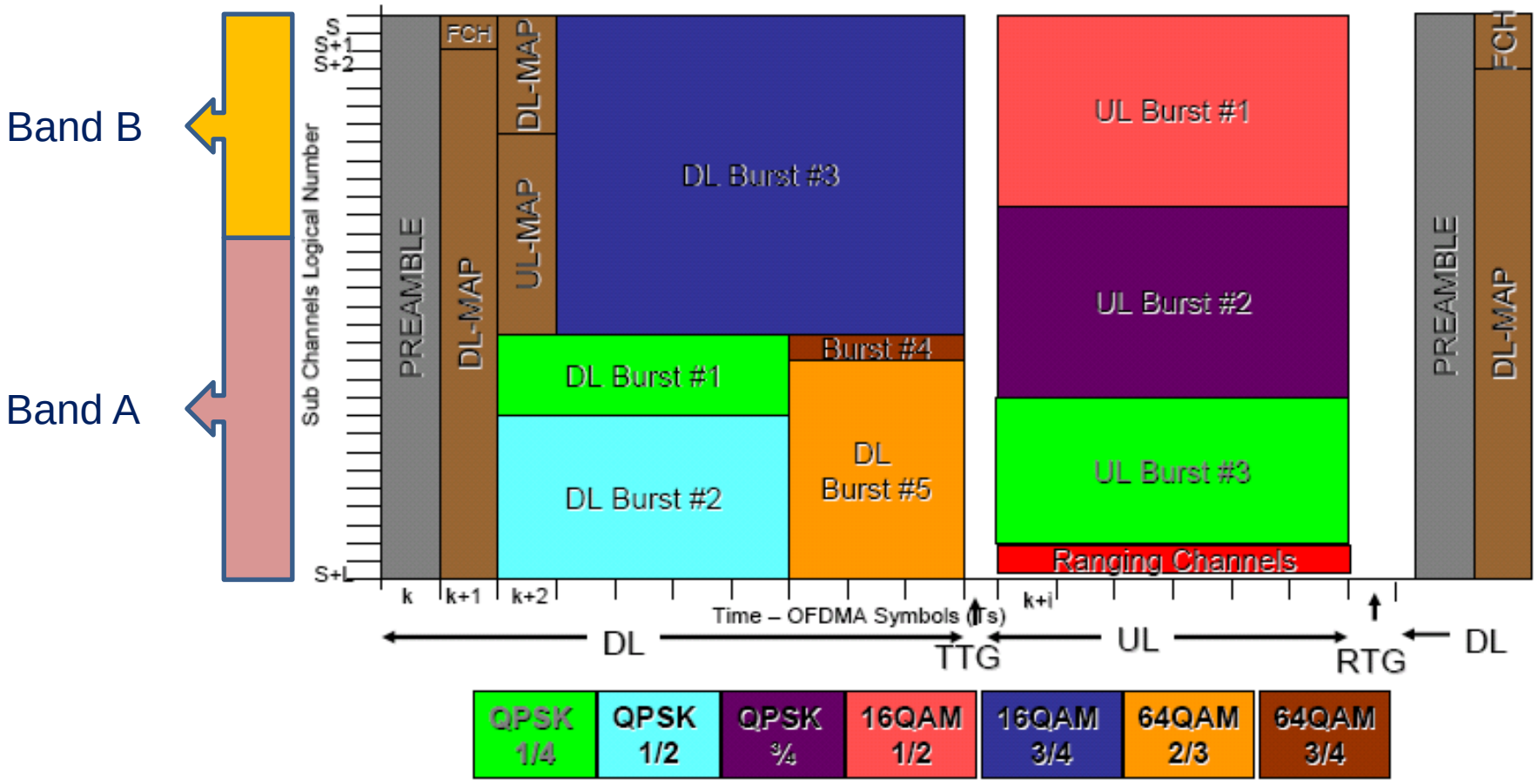
Carrier aggregation



Carrier aggregation modes



OFDMA/TDD structure



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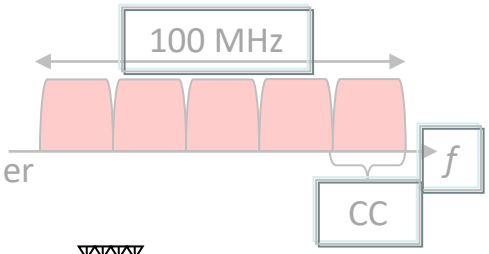

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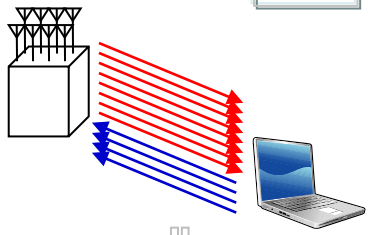

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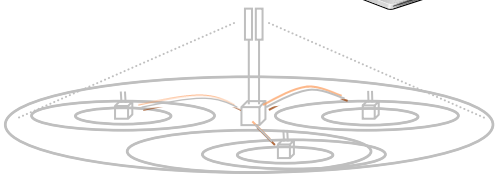

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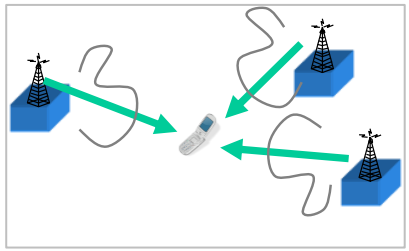
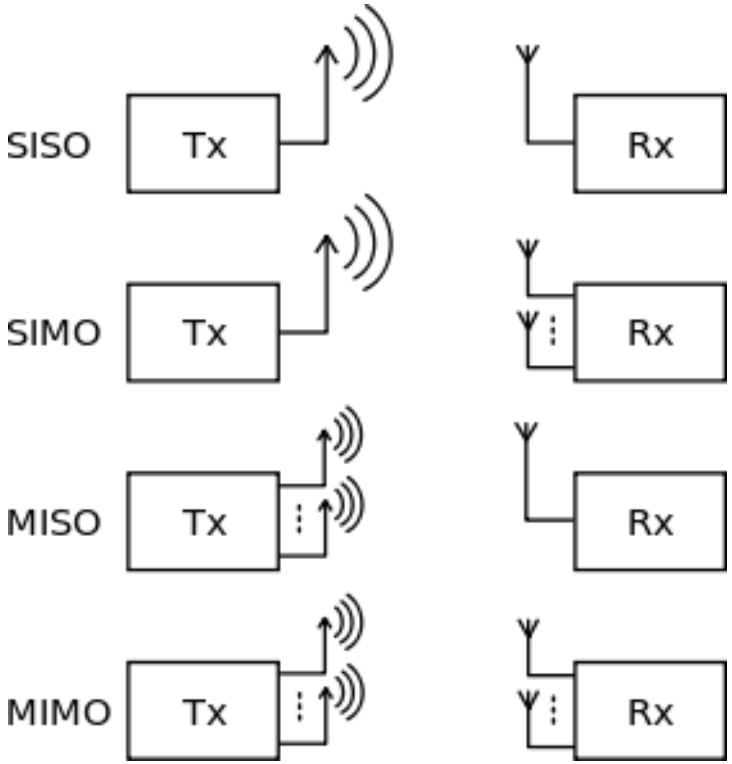
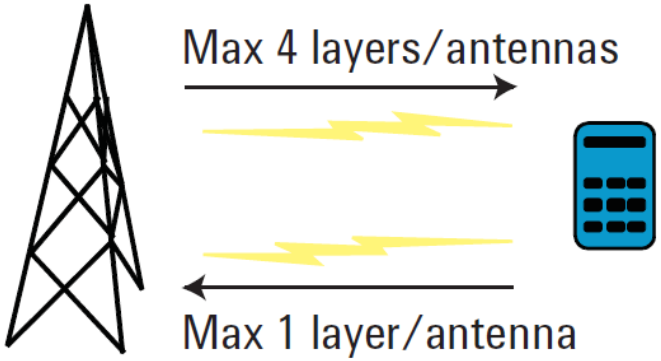
  - Support of multi-cell transmission and reception
  - ➔ Improvement of cell-edge throughput and coverage

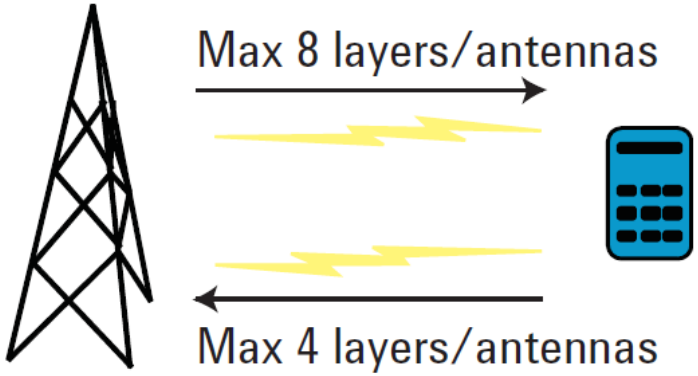


MIMO capabilities



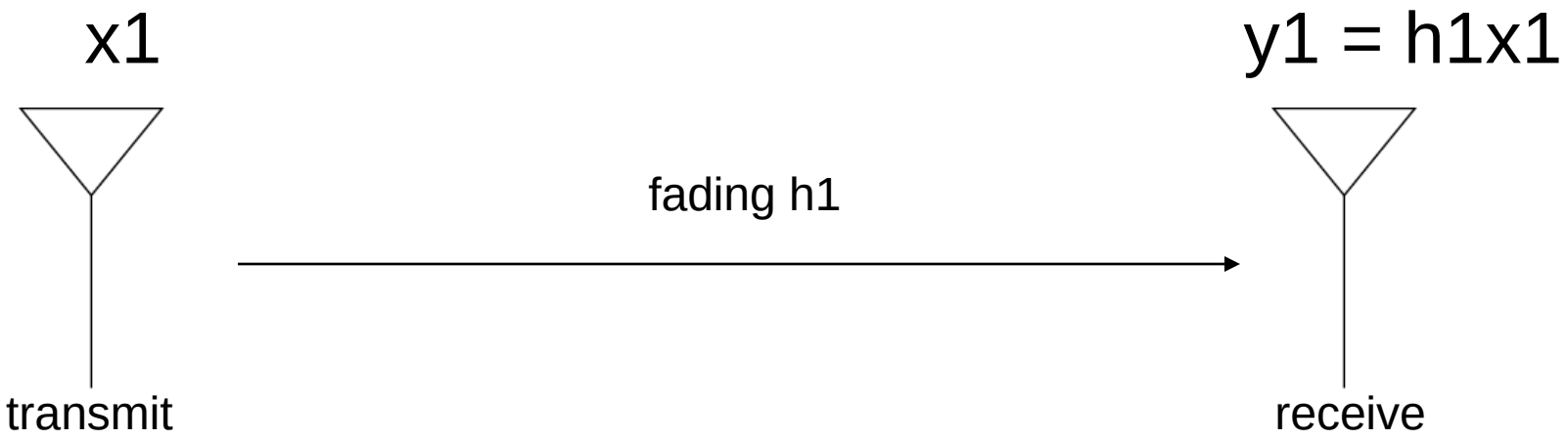


LTE

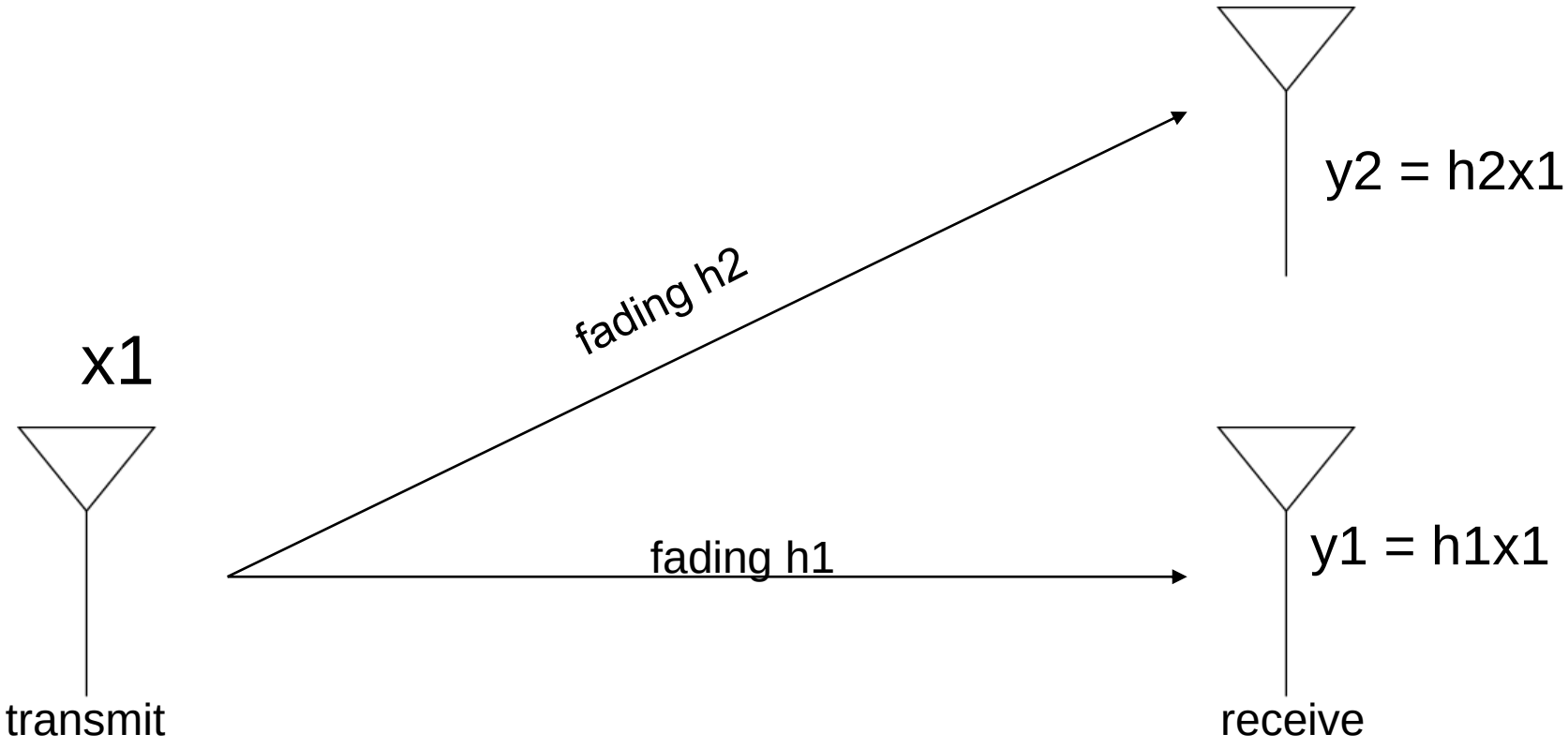


LTE-A

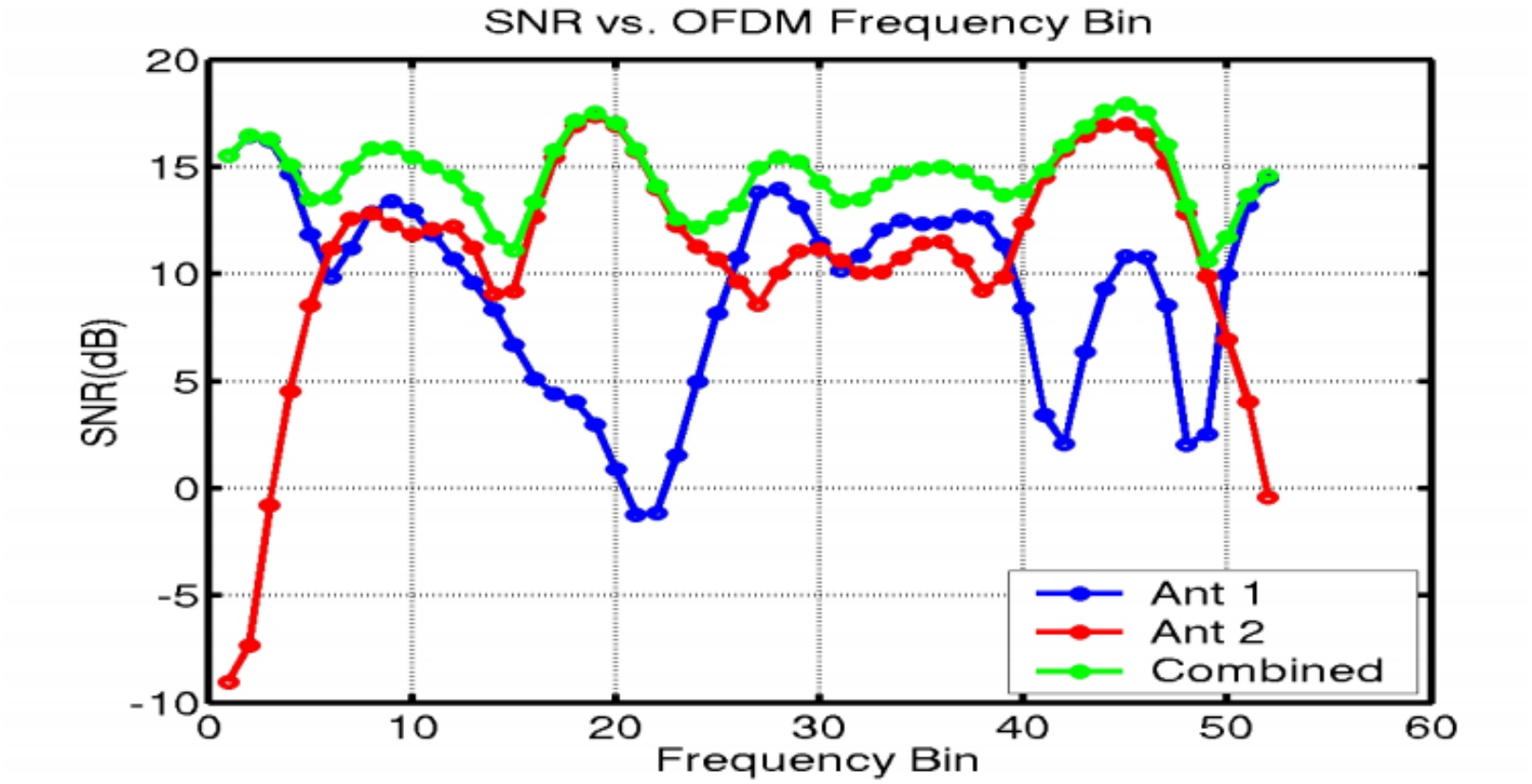
SISO Single Input Single Output



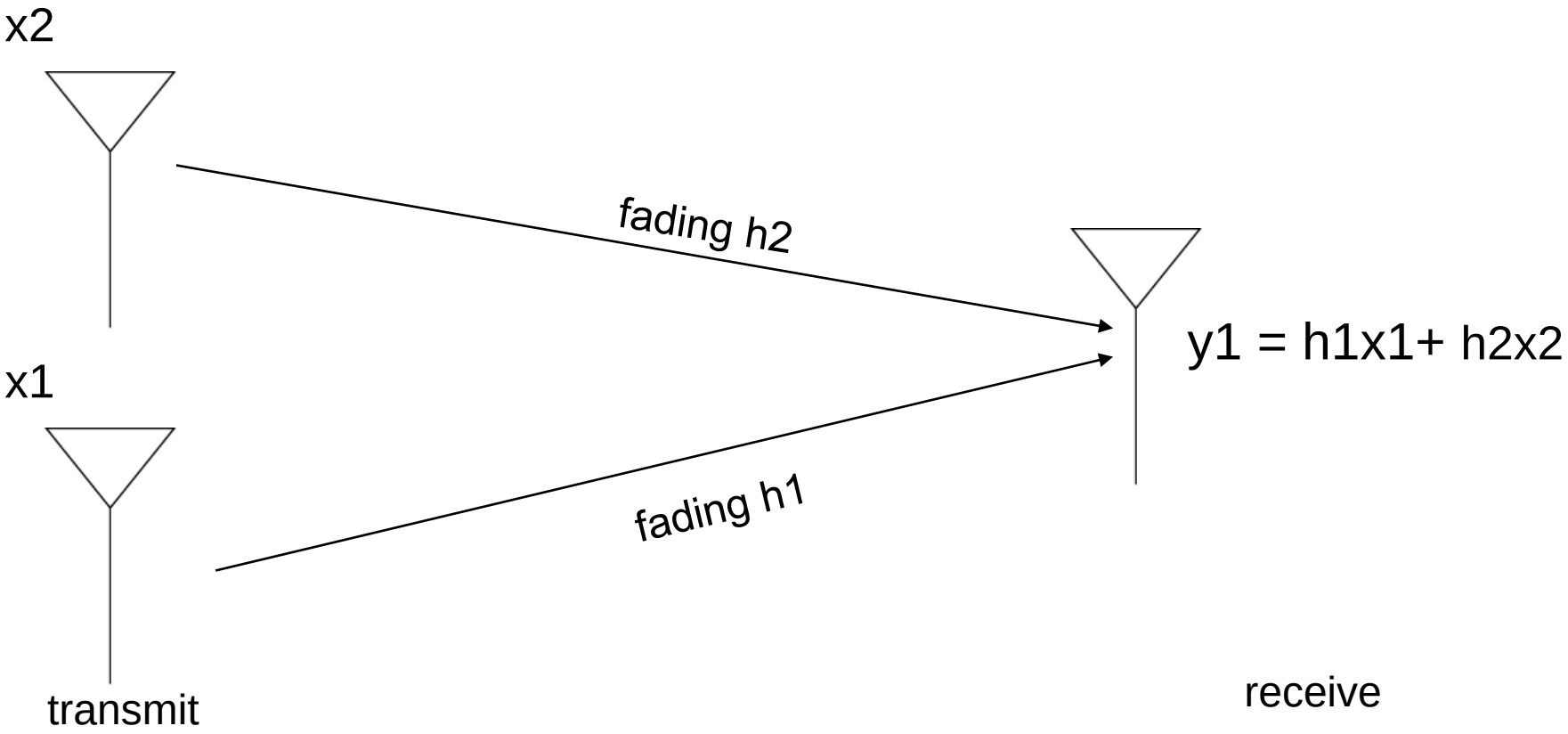
SIMO Single Input Multiple Output



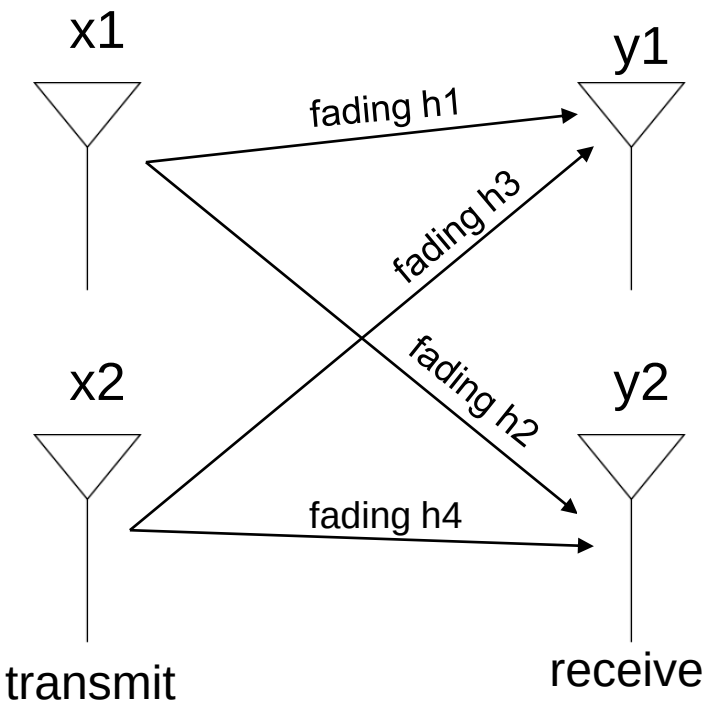
Mitigating fading with receiver diversity



MISO Multiple Input Single Output



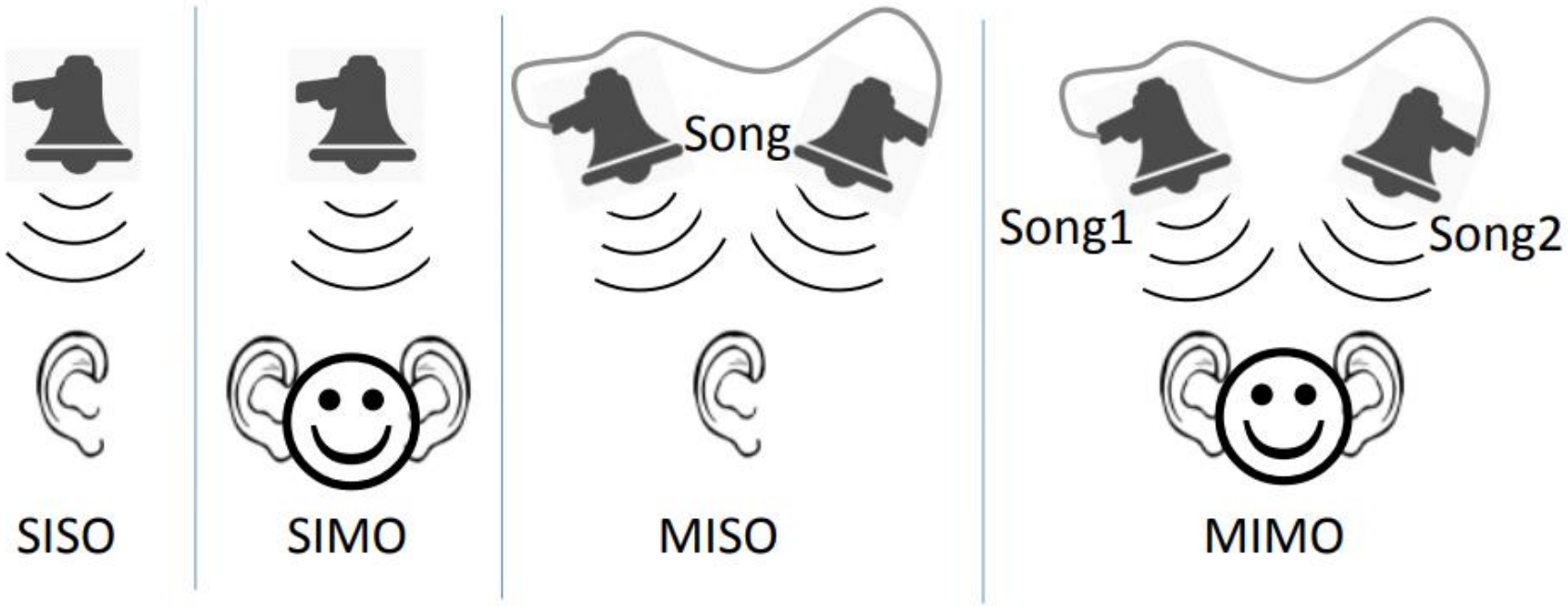
MIMO Multiple Input Multiple Output

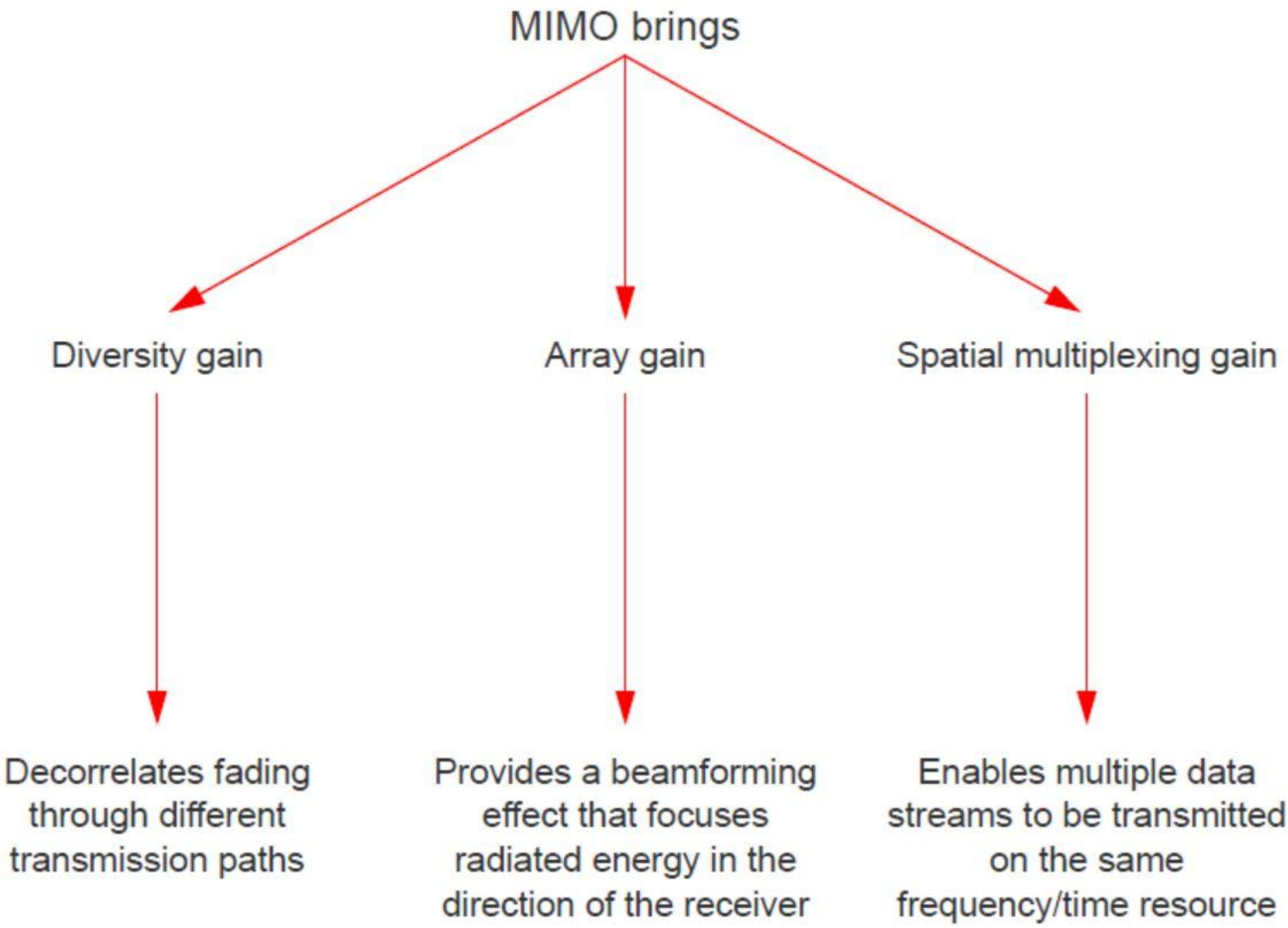


$y1 = h1x1 + h2x2$

$y2 = h3x1 + h4x2$

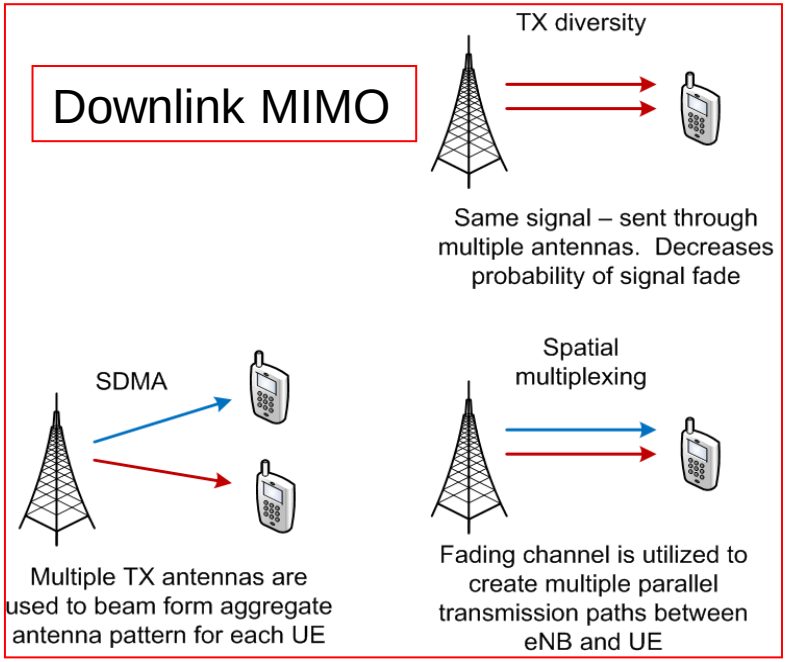
An audio metaphor

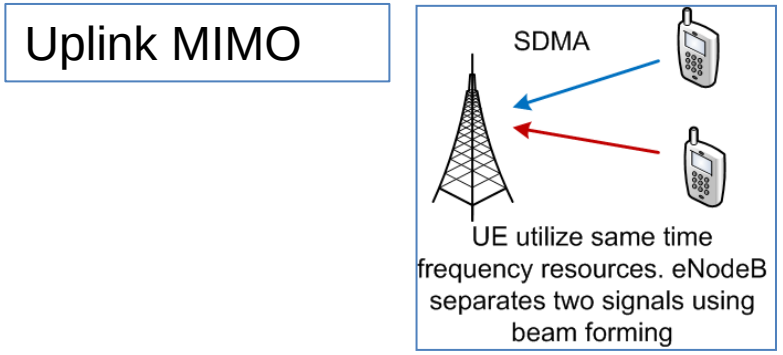



MIMO brings
Diversity gain
Array gain
Spatial multiplexing gain
Decorrelates fading through different transmission paths
Provides a beamforming effect that focuses radiated energy in the direction of the receiver
Enables multiple data streams to be transmitted on the same frequency/time resource

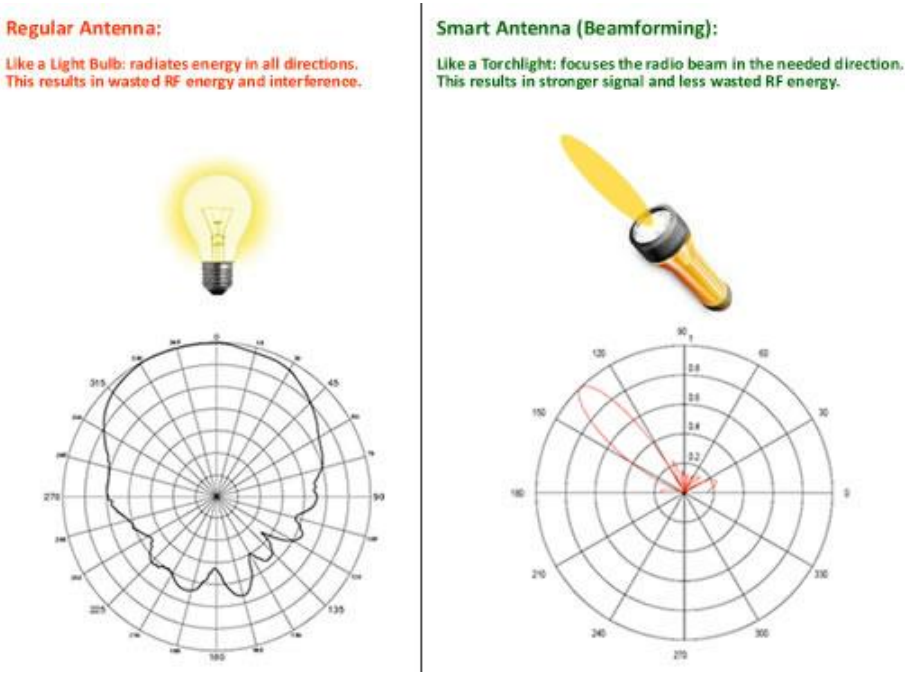
Multi antenna configuration

- LTE uses of multiple antennas at both communication ends
- LTE-A standard supports for
  - 8 antennas at the eNodeB
  - 4 antennas at the UE
- Multiple antennas may be used in three principle ways
  - Reception/transmission diversity
  - Beam forming
  - Spatial multiplexing (MIMO antenna processing)
- Downlink MIMO
  - TX diversity
  - Beam forming
  - Spatial multiplexing
- Uplink MIMO
  - Multi user MIMO (SDMA)





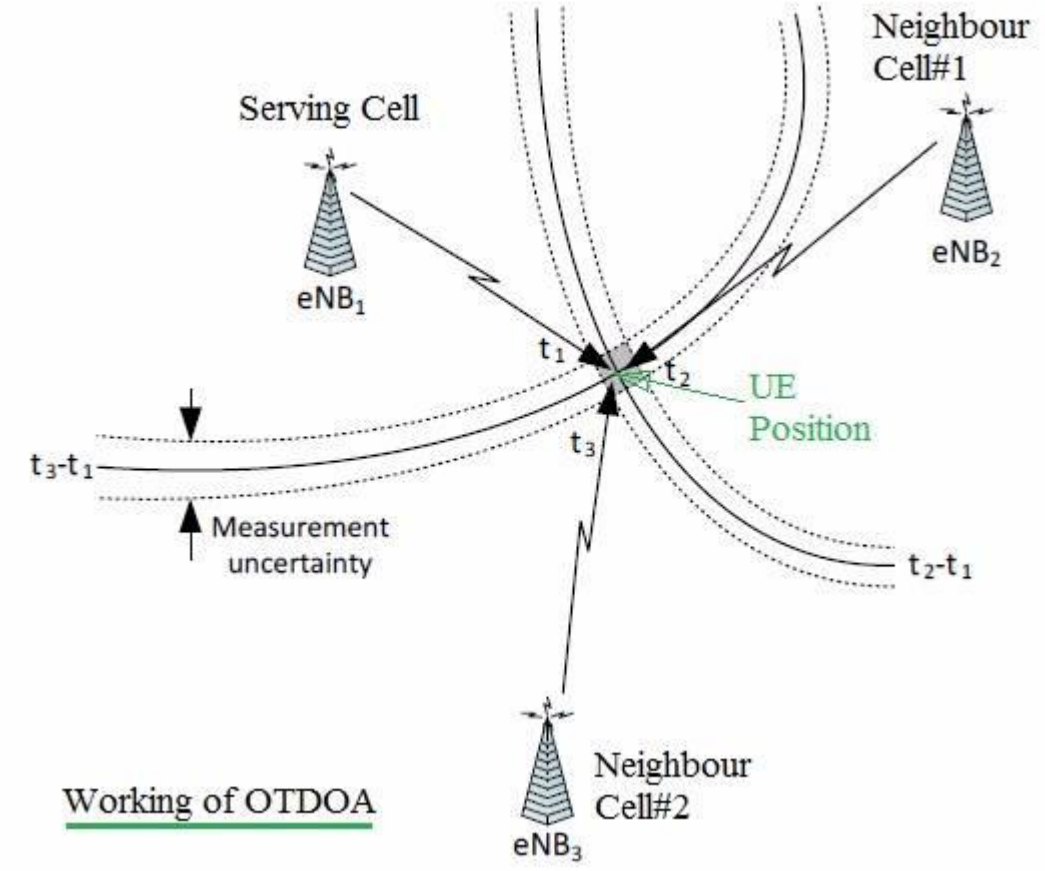
Beamforming



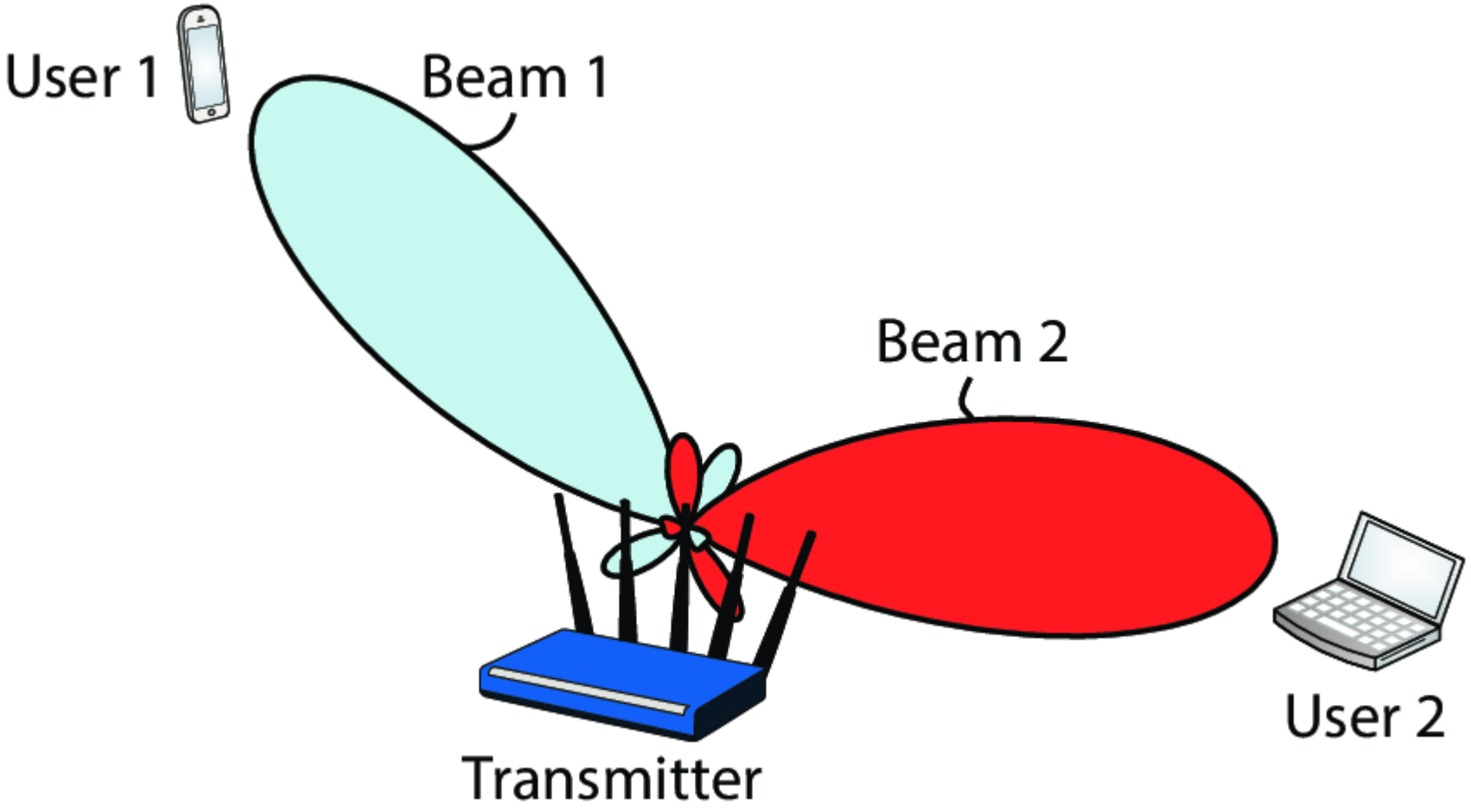
- Transmitter detects the positions of reception devices and transmits focused point-to-point signals with directionality
- Mitigates interference and reinforces signal of interest
- Strong stable transmission covering longer range

Positioning in LTE

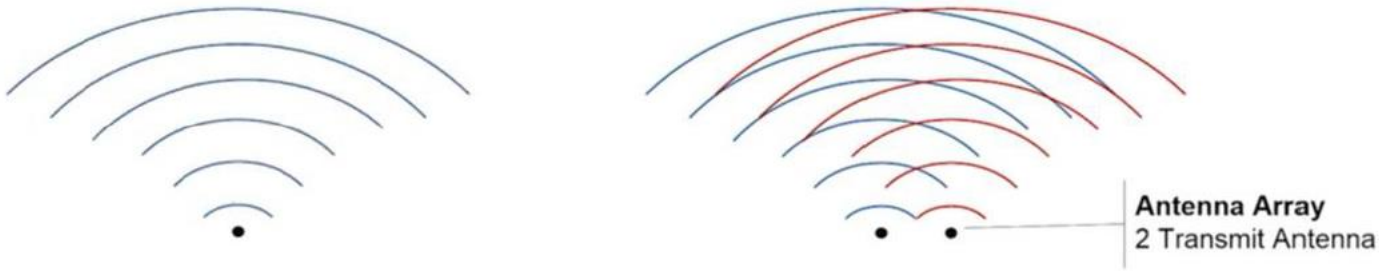
- OTDOA (**Observed Time Difference of Arrival**)

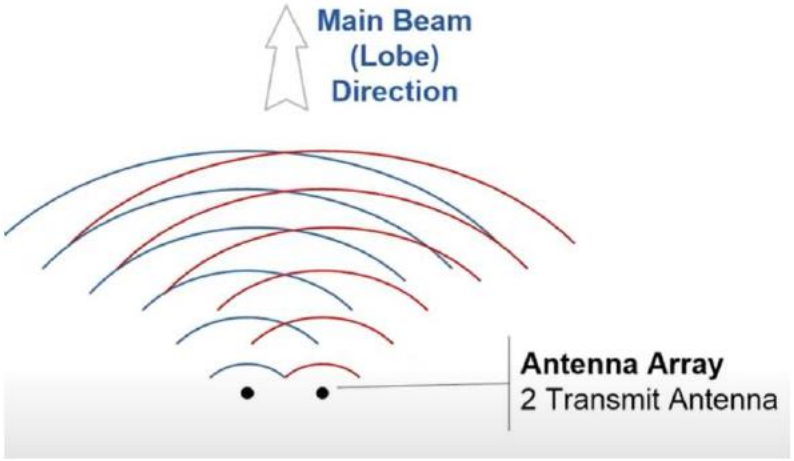


Beamforming

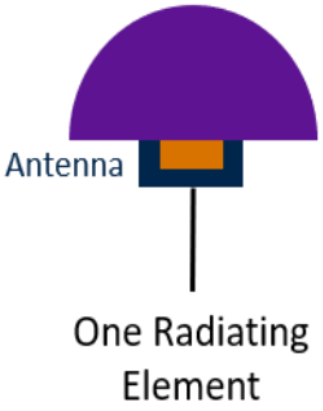


Beamforming

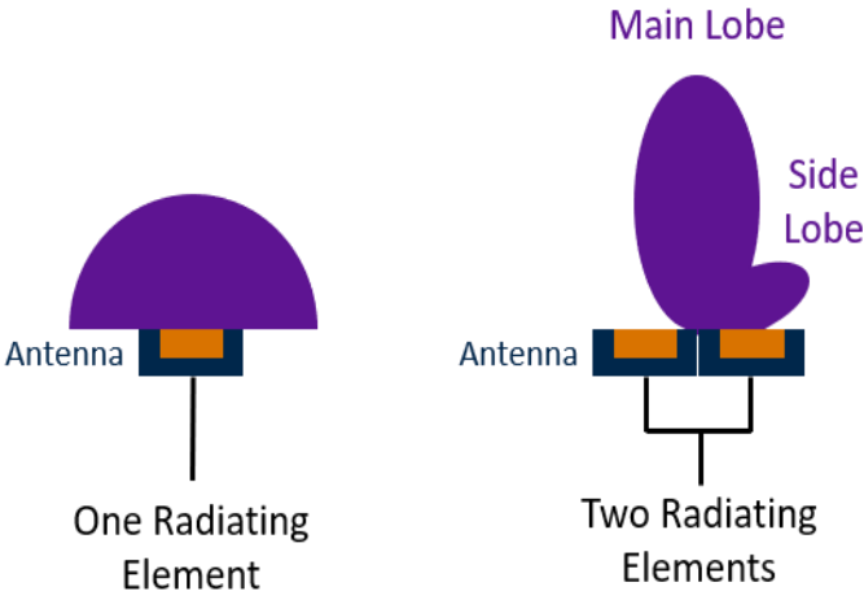




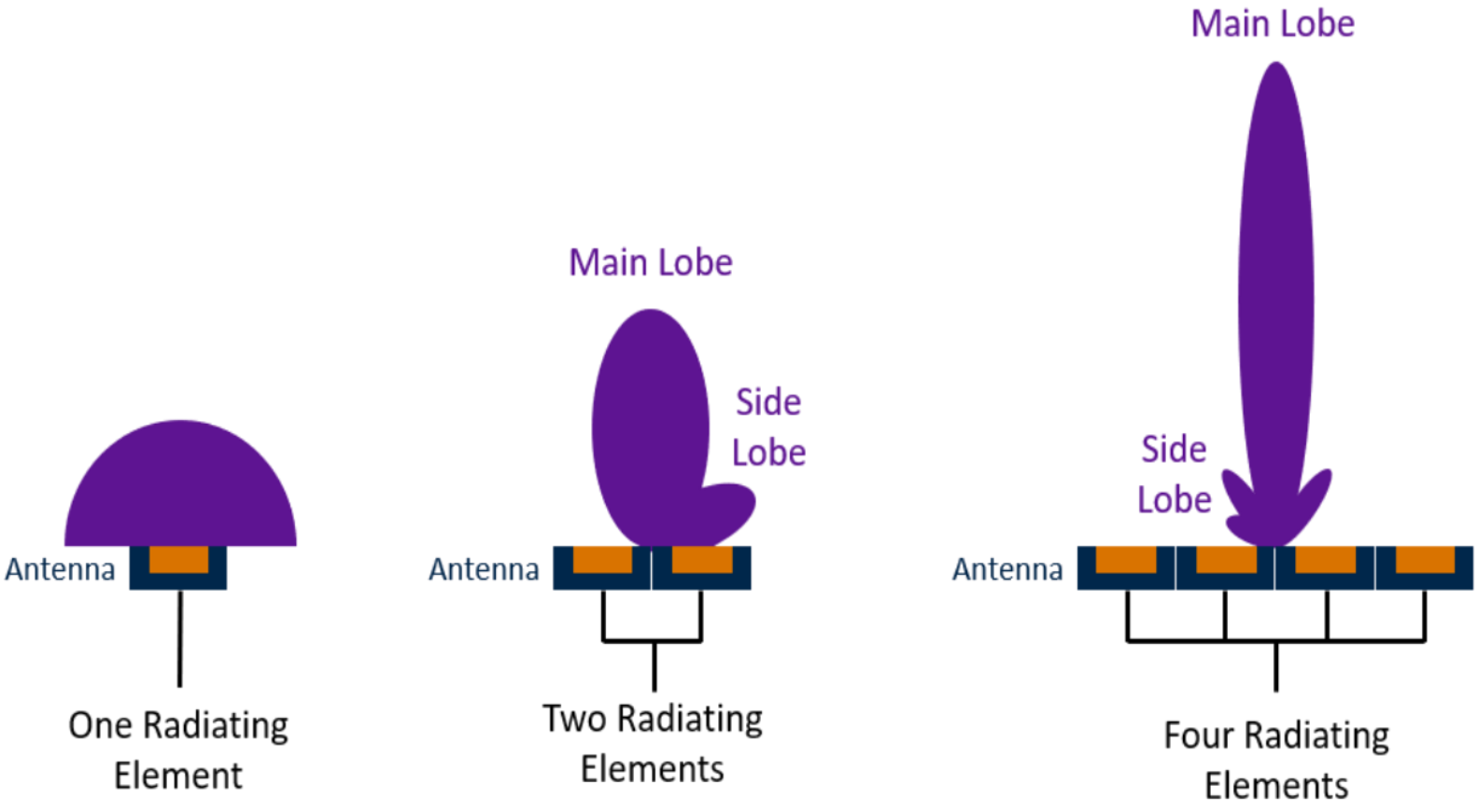
Radiating Elements and Antennas



Radiating Elements and Antennas

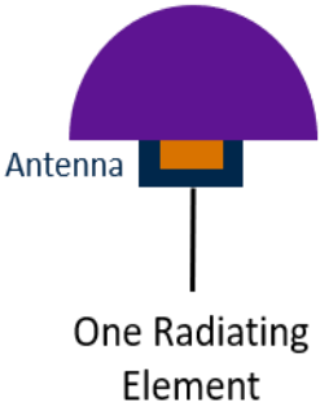


Radiating Elements and Antennas

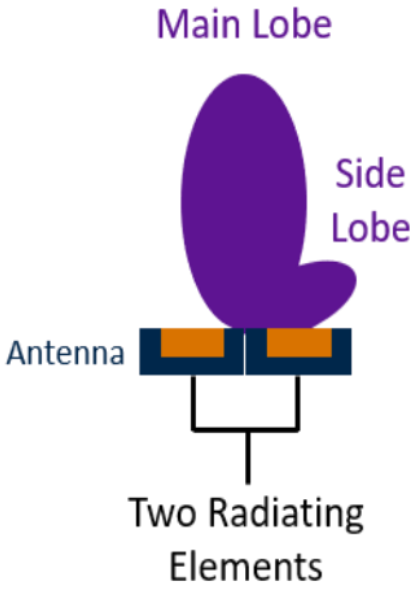


Antenna Gain (dB) = Element Gain + 10 $\log_{10}$(N)
N = number of array Elements

Antenna Gain = 0 dB

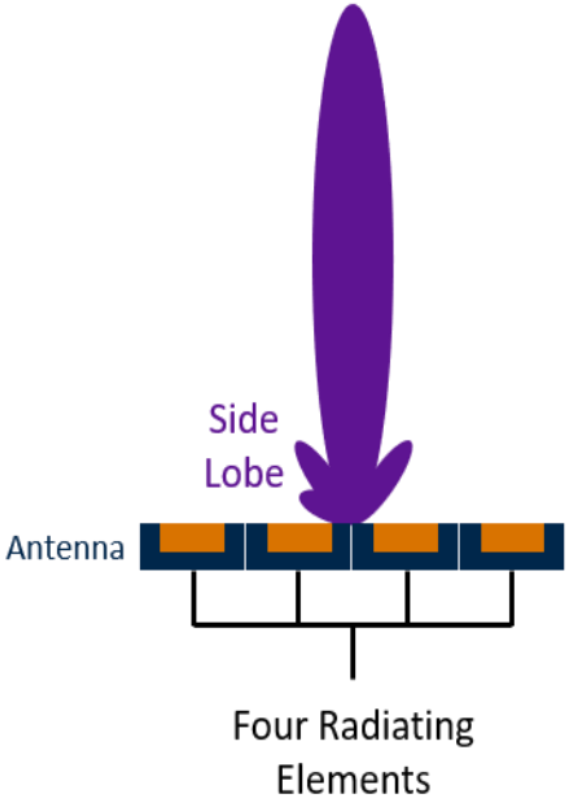


Antenna Gain = 3 dB



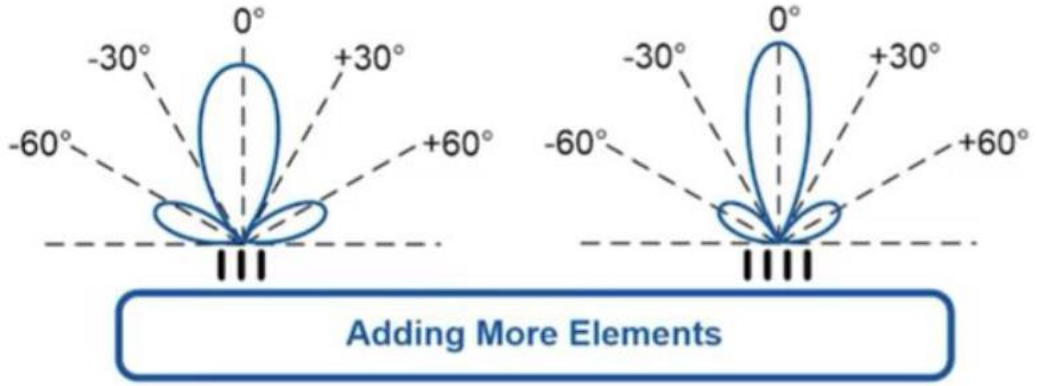
Two times stronger

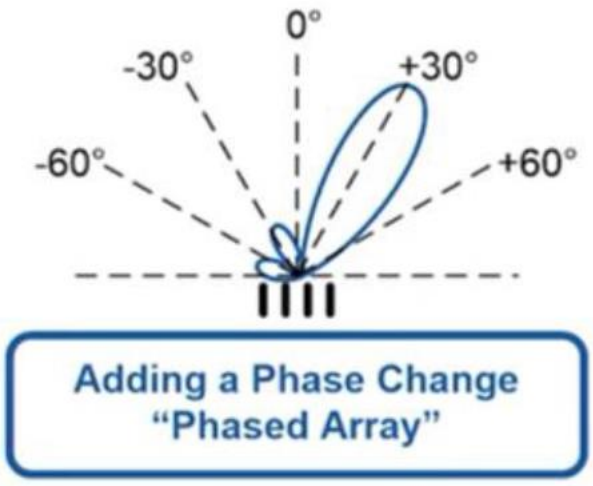
Antenna Gain = 6 dB

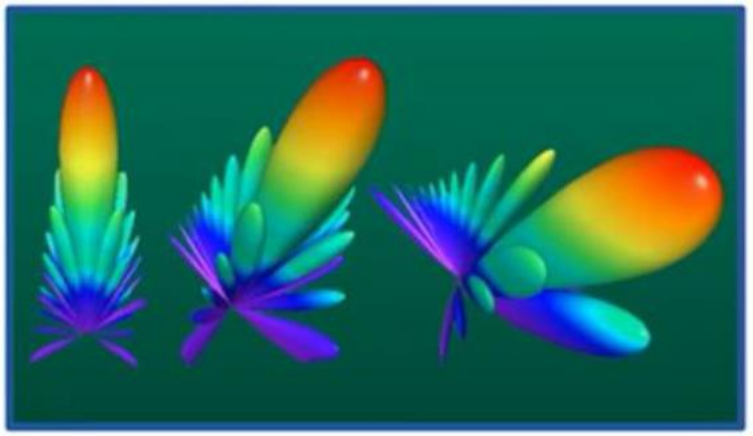


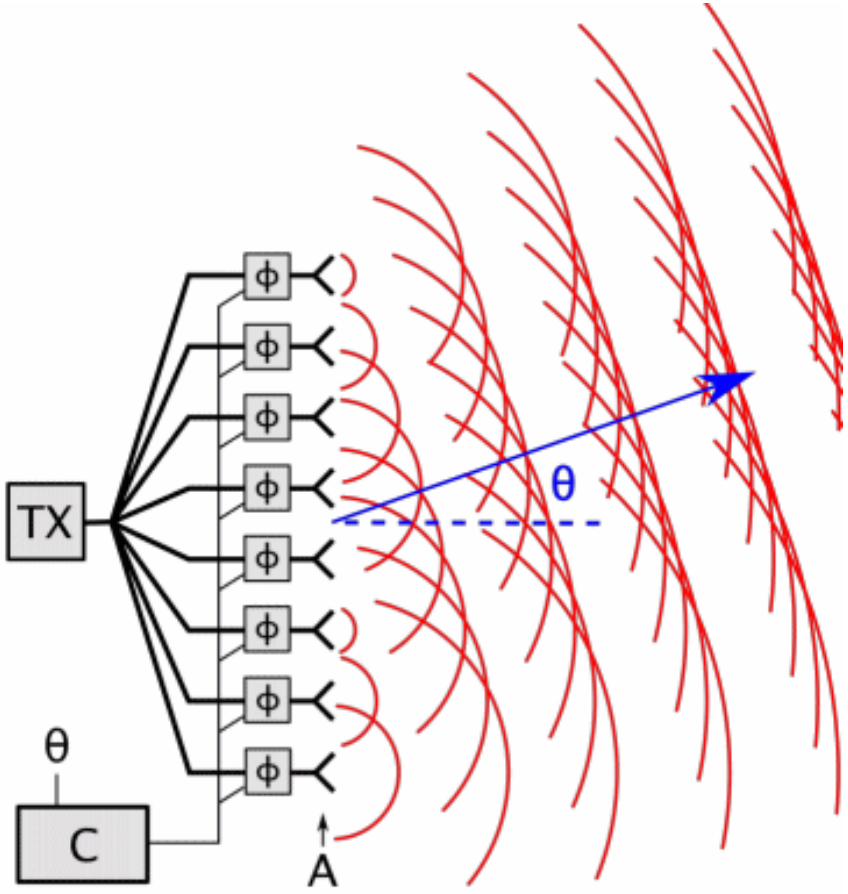
Four times stronger

Beamforming

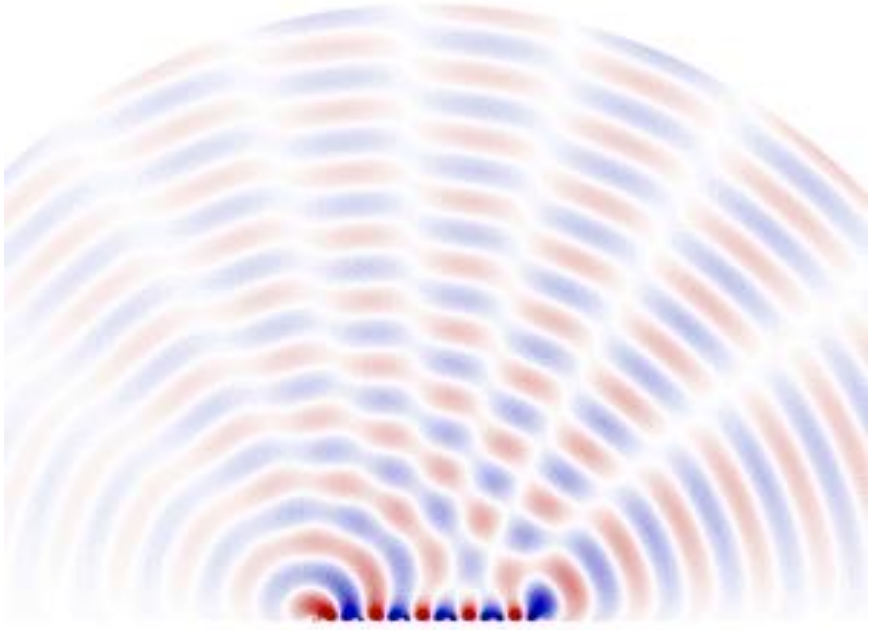








Visual representation of Phased Array

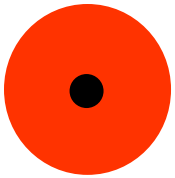


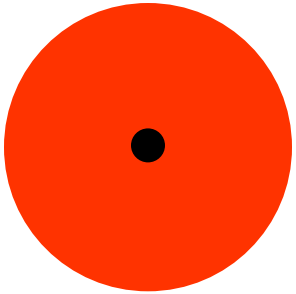
Visual representation of Phased Array

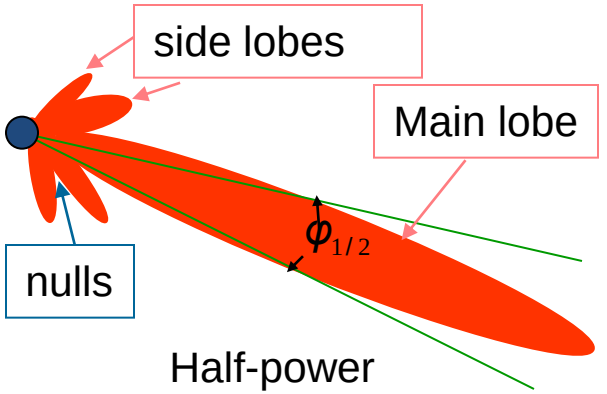
Patterns, beamwidth & Gain

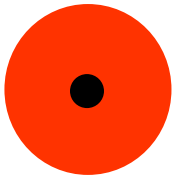
top view(horizontal)

side view(vertical)

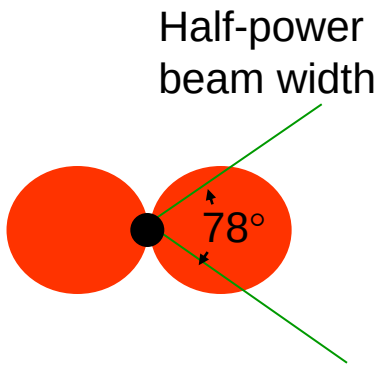




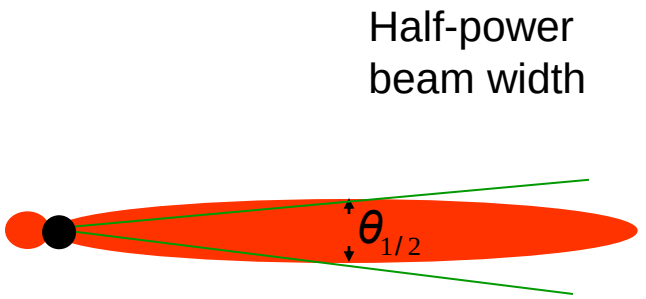




Isotropic dipole

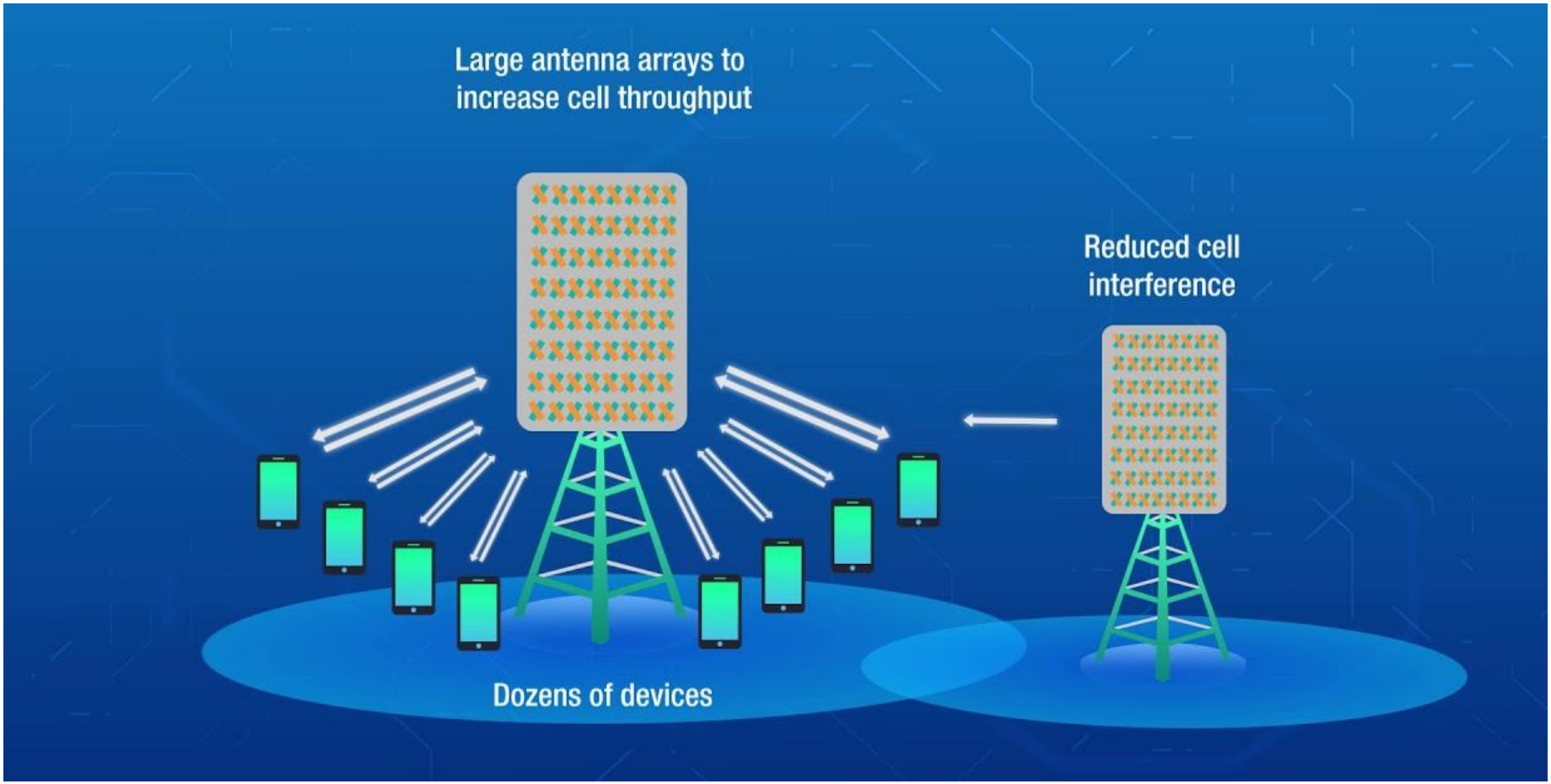


half-wave dipole

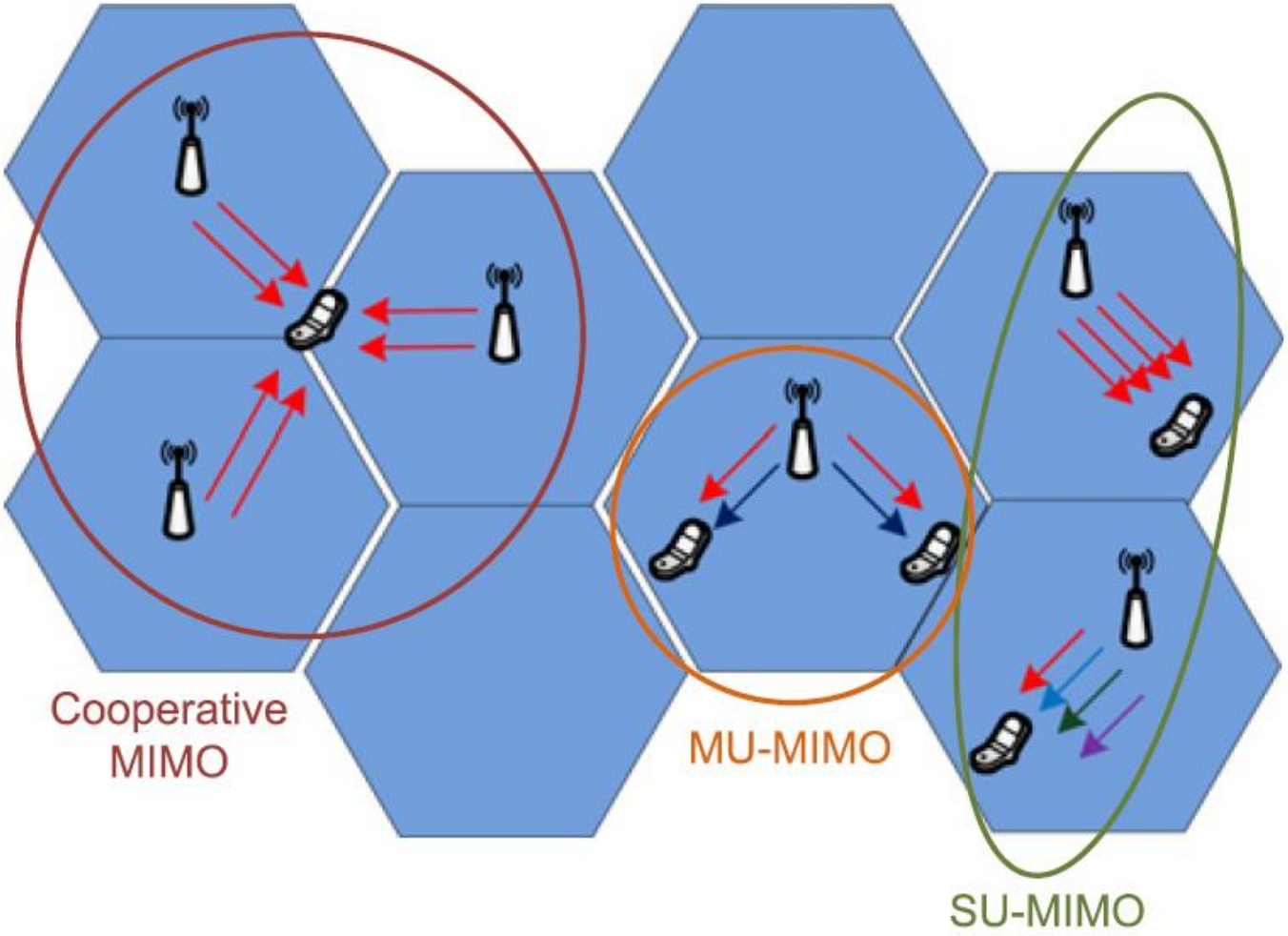


beamformer

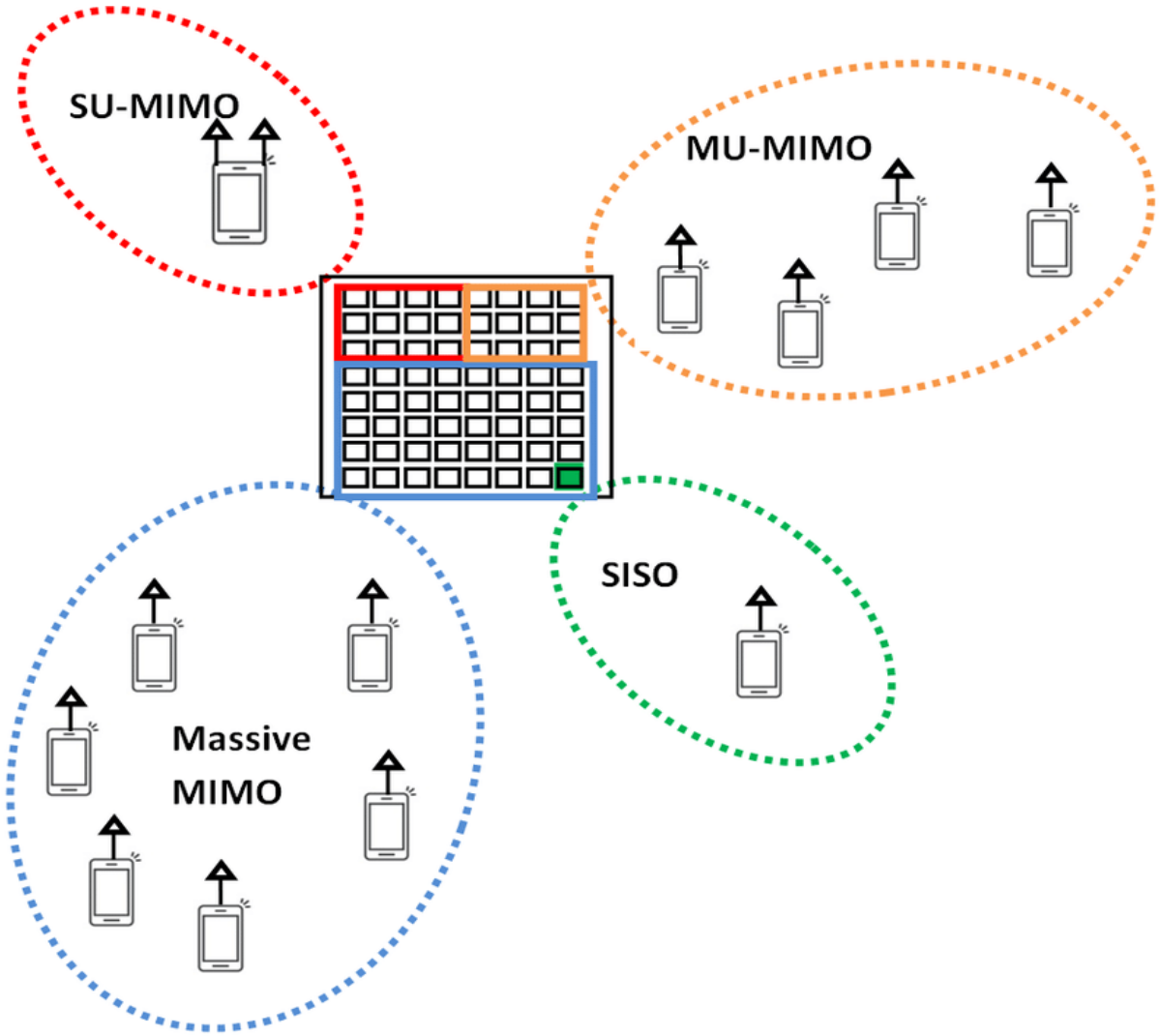
Towards 5G: Massive MIMO and beamforming



Different MIMO capabilities

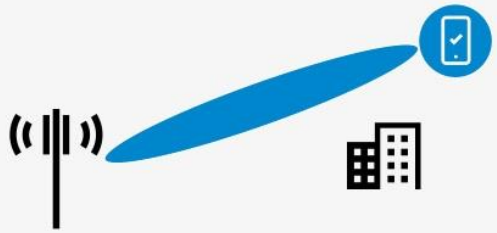


Different MIMO capabilities



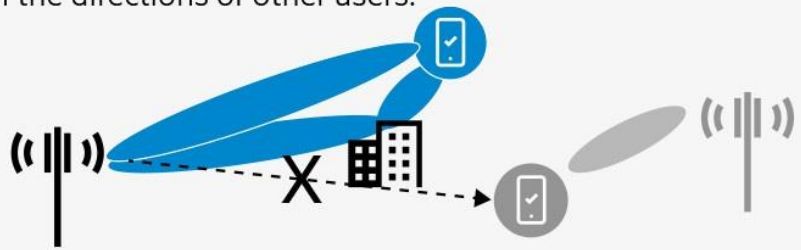
A. Beamforming

Serve single users by directing the energy toward the user.



B. Generalized beamforming

Serve single users by sending the same data stream in different directions and possibly forming zero (nulls) in the directions of other users.

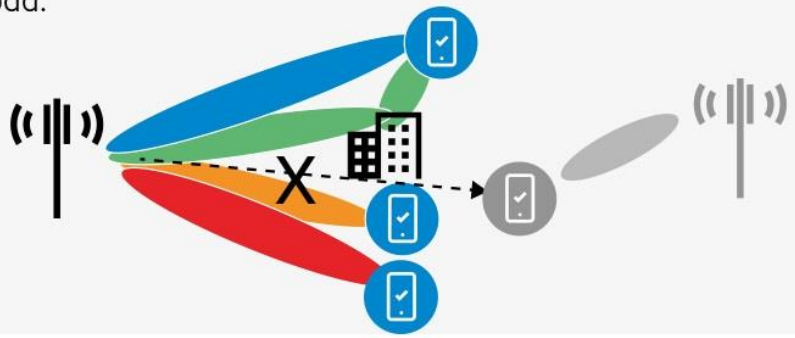


C. SU-MIMO

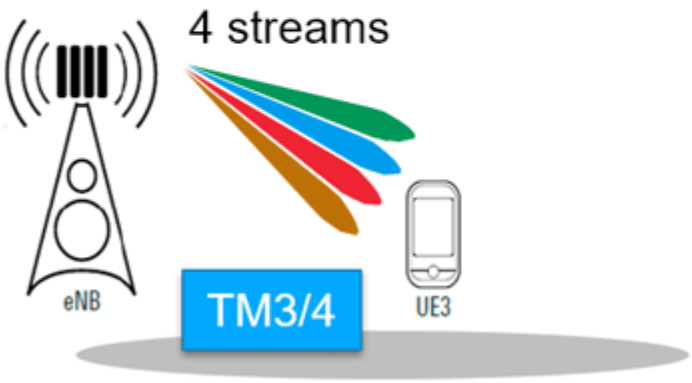
Increase data rates by transmitting several data streams to a user.

D. MU-MIMO

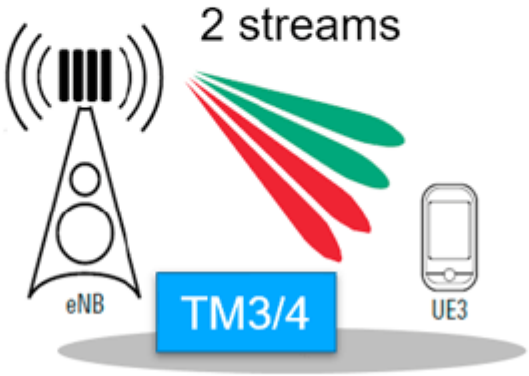
At high load, serve more users simultaneously at high load.



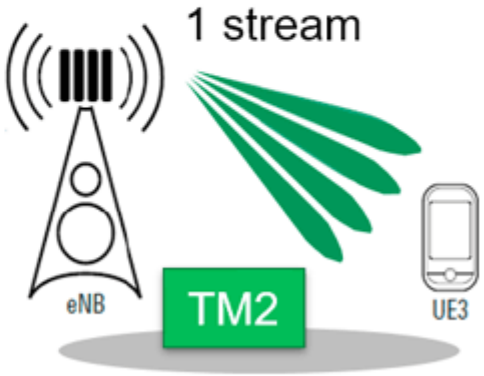
SU MIMO: (cell center)
4 Tx, Rank 4



SU MIMO: (mid cell)
4 Tx, Rank 2



SU MIMO: (cell edge)
4 Tx, Rank 1



Transmission modes

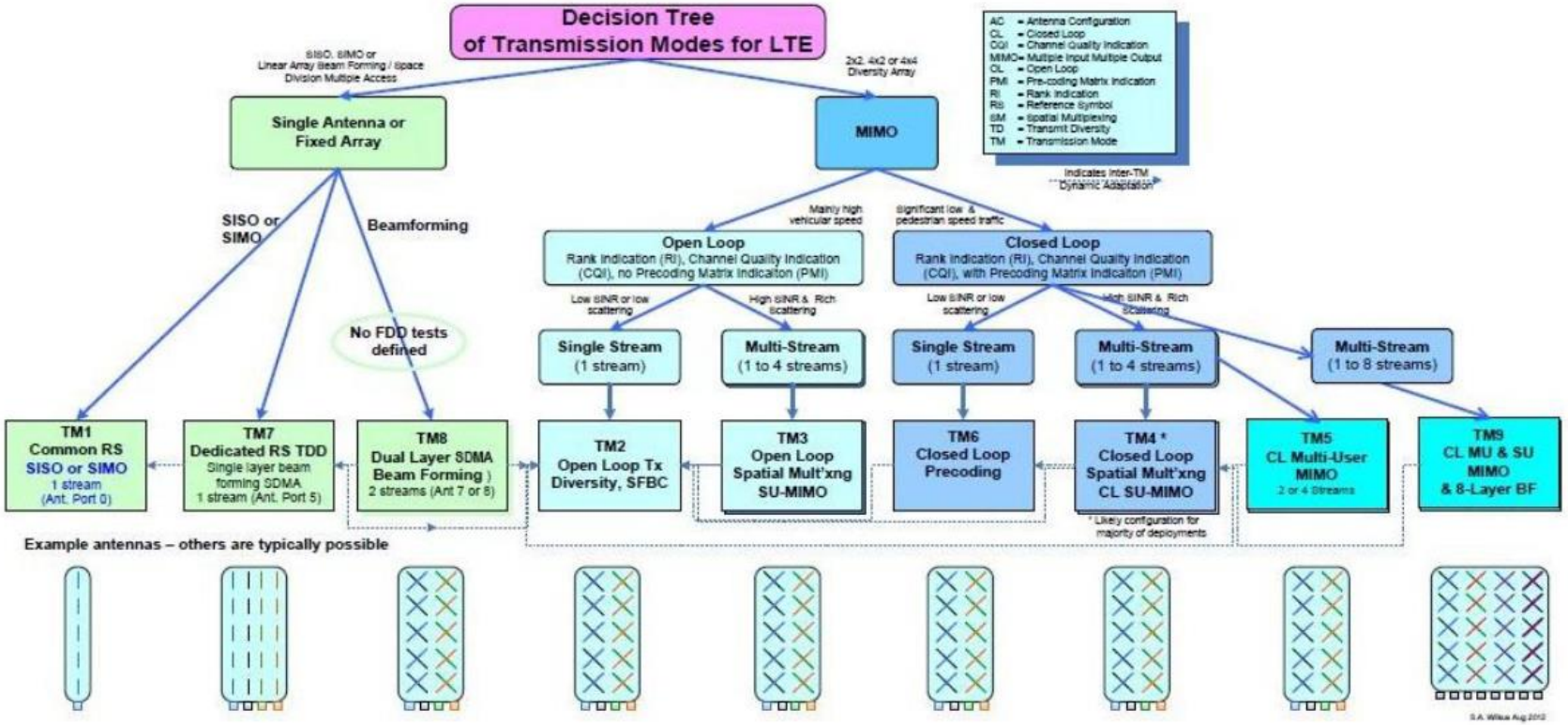
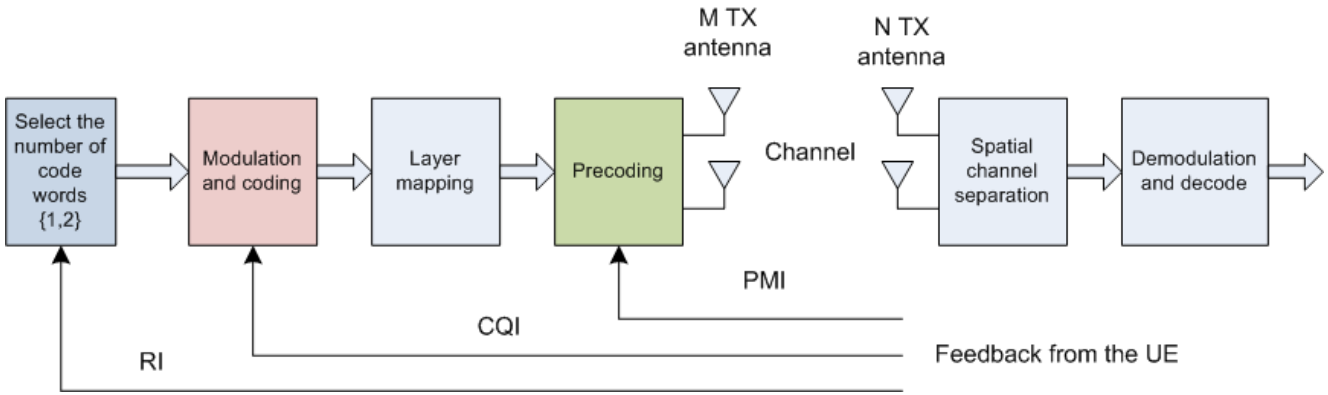


Figure 3 – Taxonomy of smart antenna processing algorithms in LTE Release 10. Shadows behind blocks indicate that they are capable of transmitting multiple streams. (LTE Release 11 recently added Transmit Mode 10 with explicit support for CoMP (Coordinated MultiPoint Transmission Reception) use which is not shown.)

Spatial multiplexing in LTE

- Two types
  - Open loop (used high speed scenarios)
    - Large delay Cyclic Delay Diversity (CDD)
  - Closed loop (used in low speed scenarios)
    - Mobile provides channel feedback to eNode B

Feedback	Closed loop spatial multiplexing	Open loop spatial multiplexing
PMI (Pre-coded matrix indicator)	PMI feedback from UE based on instantaneous channel state	No feedback from UE. Fixed pre-coding at eNode B implementing cyclic delay diversity (CDD)
CQI (Channel quality indicator)	Separate CQI for each code word	Aggregate CQI (one value)
RI (Rank indicator)	Based on the rank of estimated channel matrix (indicates number of spatial channels)	Based on the rank of estimated channel matrix when SFBCs are used



Closed loop spatial multiplexing

Antenna configurations (LTE)

- LTE defines 7 transmission modes
- Decision on transmission mode – scheduler at eNode B
- Implementation equipment vendor dependent
- Later LTE releases added more MIMO modes

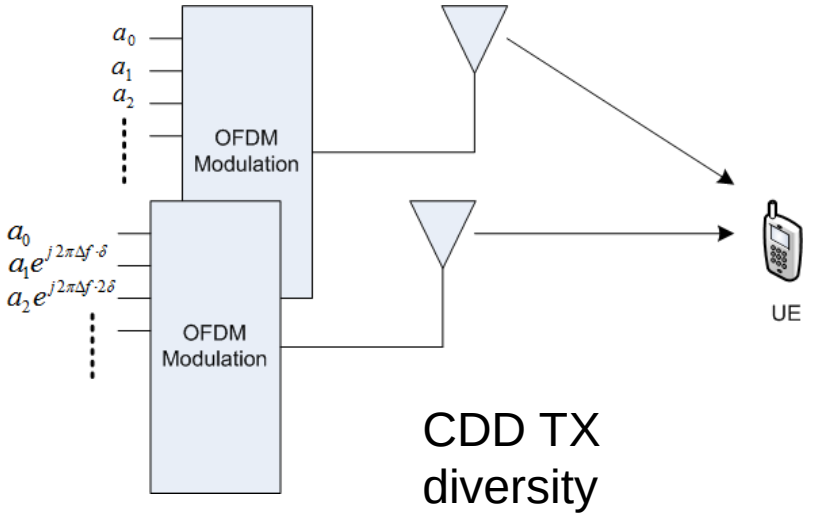
Transmission modes	Description	Comments
1	Single antenna (Port 0)	Used for SISO and SIMO transmission
2	Transmit diversity	Used in low SNR and high mobility
3	Open loop spatial multiplexing	Beneficial in high SNR and rich multipath environment
4	Closed loop spatial multiplexing	Beneficial in high SNR and rich multipath environment
5	Multi-user MIMO	Beneficial in high SNR environment for interference reduction
6	Closed loop	Beneficial in low SNR environments
7	Single antenna port	Used for beam forming of antenna arrays

TM1: SIMO mode

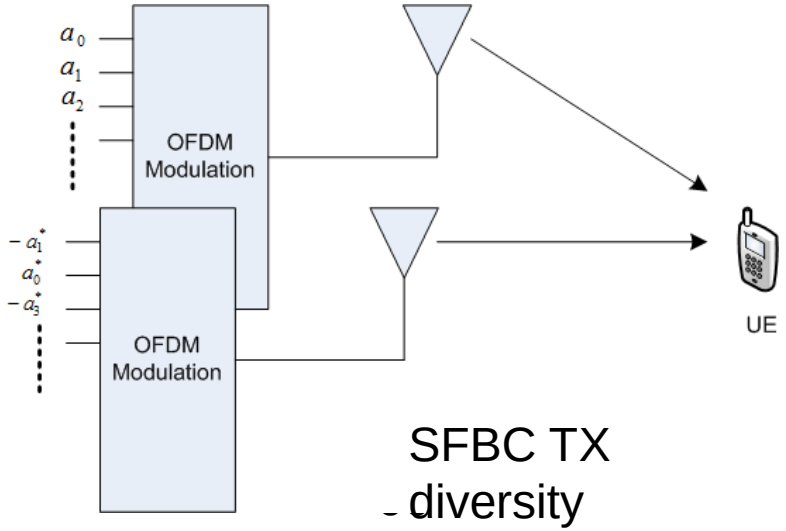
- Default transmission mode
- Every other mode – explicit signaling
- Assumes one TX port (i.e. one antenna)
- Mobile still may use diversity reception
- Not used often – limits the performance of DL
- Typical uses:
  - eNode B with one physical antenna
  - Simple UE with a very low traffic requirements
  - M2M communication (simplified signaling)
  - Limited coverage area

TM 2: DL transmit diversity

- Two implementations
  - Cyclic Delay Diversity (CDD)
  - Space-Time Transmit Diversity (STTD)
- CDD
  - Multiple antenna elements are used to introduce additional versions of the signal that are cyclically delayed
  - UE perceives these signals as additional multi-paths
  - Assuming low correlations between TX antennas –created "multi-paths" fade independently – source of diversity
- STTD
  - Uses Space-Frequency Block Codes
  - Special encoding (SFBC) makes the channel matrix unitary (full rank)
  - Reference symbols are used to estimate and invert channel matrix



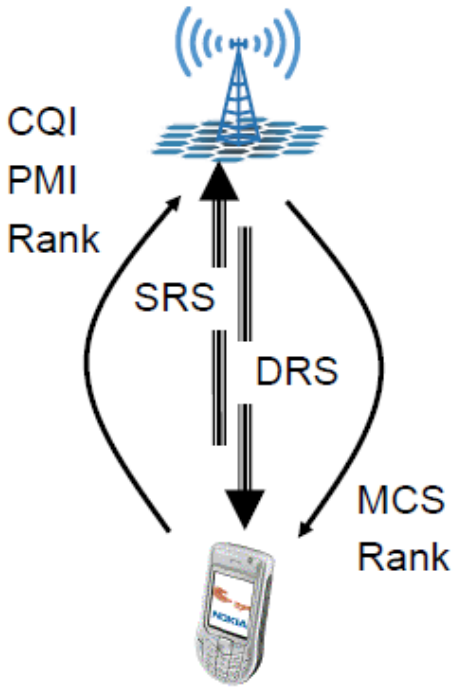
CDD TX diversity



SFBC TX diversity

TM 3/4: Open/Closed loop spatial multiplexing

- Open loop = no PMI, CQI and Rank are still provided
- Closed loop = PMI, CQI and Rank provided by UE
- 2 layers with different information on each layer
- Rank of channel is 2
- May use 2 or 4 ports (antennas)
- If four antennas are used CDD is used on the same layer
- No PMI, eNodeB cycles through a pre-defined sequence of PMIs (TM3)
- PMI present = eNode B uses the UE recommended PMI (TM4)



PDSCH Channel estimation based on DRS

Note 1: UE recommends transmission mode configuration; UEs of different capabilities easily accommodated

Note 2: PMI estimates only valid for slow moving mobiles

TM 5/6: MU-MIMO/Closed Loop

TM 5

- Users are multiplexed in spatial domain
- Scheduling for multiple users
  - Same frequency resources
  - Different layers
- Requires very precise channel estimation
- Not used much in practice

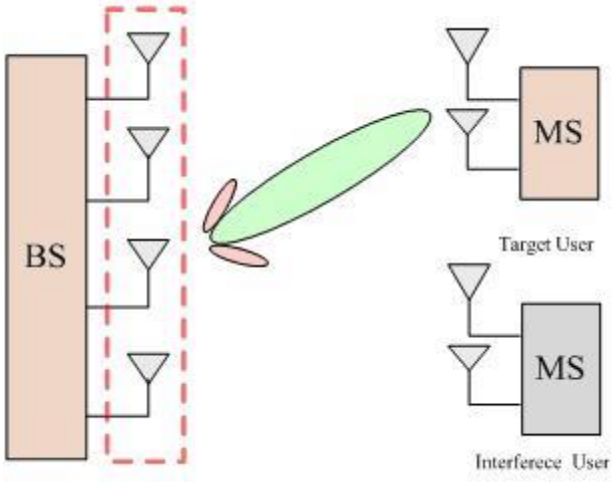
TM 6

- One layer (i.e. one code word)
- PMI selected by the UE
- Appropriate for slow moving mobiles
- Not used much in practice

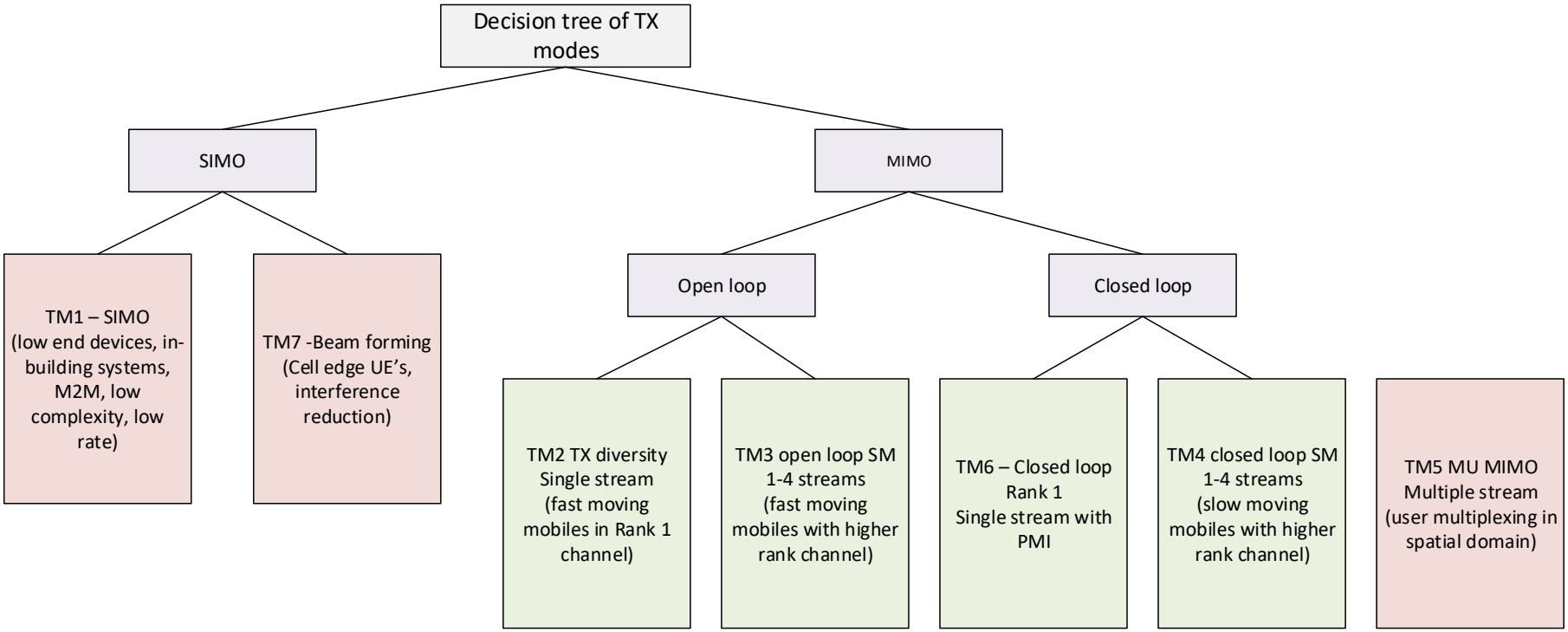
TM 7: Beam forming

- Transmission mode used for beamforming
- Multiple antennas are used to form a higher gain beam towards the mobile
- This is accomplished through phase and amplitude scaling of individual ports
- This is rank 1 technique, i.e. it does not support spatial multiplexing
- Used predominantly as means to help UE's at cell edge

Note: transmission uses multiple antennas that are combined to act as a single high gain antenna



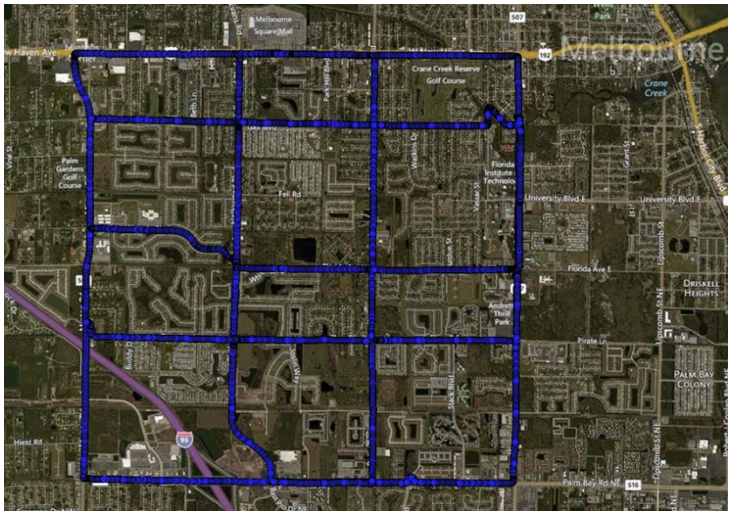
MIMO mode selection in LTE

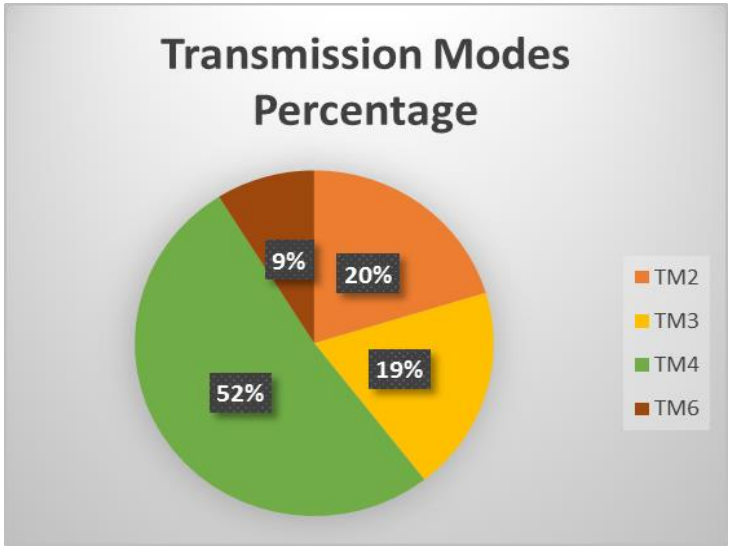


Note: "Green" modes are used more frequently than "red" modes.

Typical distribution of MIMO modes

- Use of MIMO mode – scheduler decision
- Most useful modes:
  - TM4 (spatial multiplexing over rank 2 channel with precoding)
  - TM3 (spatial multiplexing over rank 2 channel without pre-coding)
  - TM2 (transmit diversity)
  - TM6 (closed loop MIMO over Rank 1 channel)

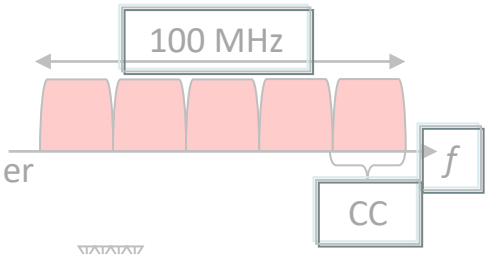




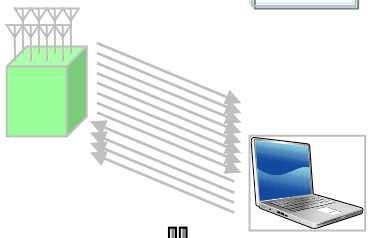
Example of an area and MIMO mode distribution

LTE-A main features

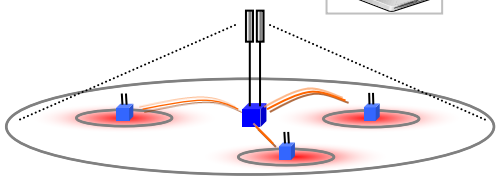
- Support of Wider Bandwidth(Carrier Aggregation)
  - Use of multiple component carriers(CC) to extend bandwidth up to 100 MHz
  - Common physical layer parameters between component carrier and LTE Rel-8 carrier
  - ➔ Improvement of peak data rate, backward compatibility with LTE Rel-8



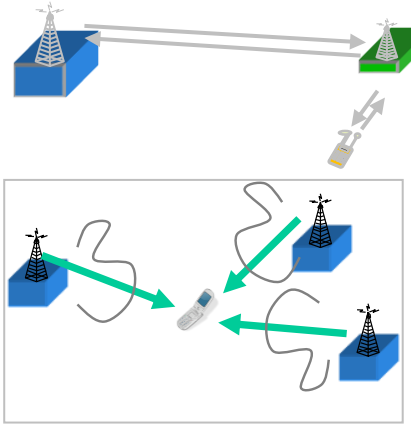
- Advanced MIMO techniques
  - Extension to up to 8-layer transmission in downlink
  - Introduction of single-user MIMO up to 4-layer transmission in uplink
  - Enhancements of multi-user MIMO
  - ➔ Improvement of peak data rate and capacity



- Heterogeneous network and eICIC (enhanced Inter-Cell Interference Coordination)
  - Interference coordination for overlaid deployment of cells with different Tx power
  - ➔ Improvement of cell-edge throughput and coverage



- Relay
  - Supports radio backhaul and creates a separate cell and appear as Rel. 8 LTE eNB to Rel. 8 LTE UEs
  - ➔ Improvement of coverage and flexibility of service area extension



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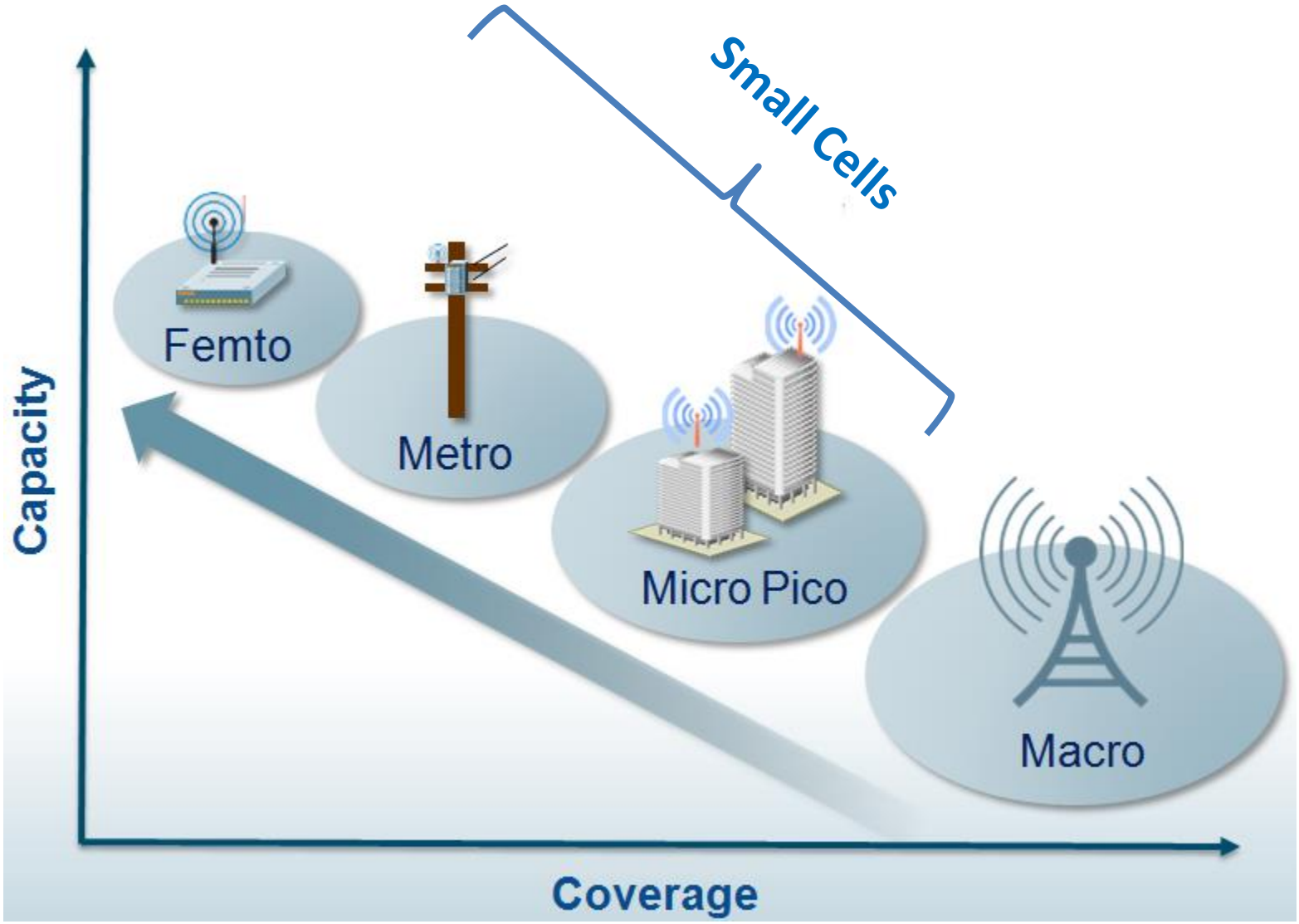
Heterogeneous networks in LTE-A



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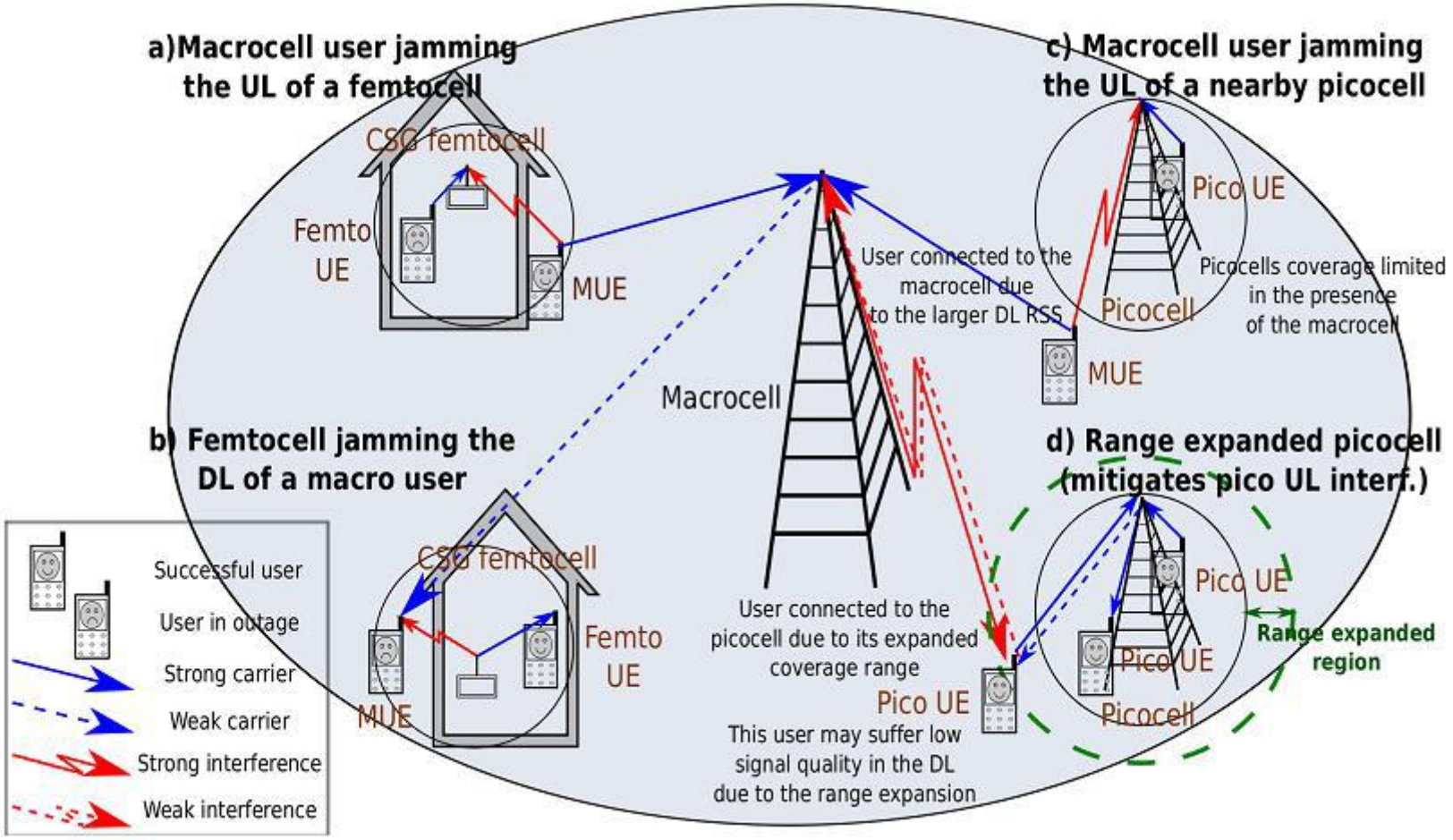
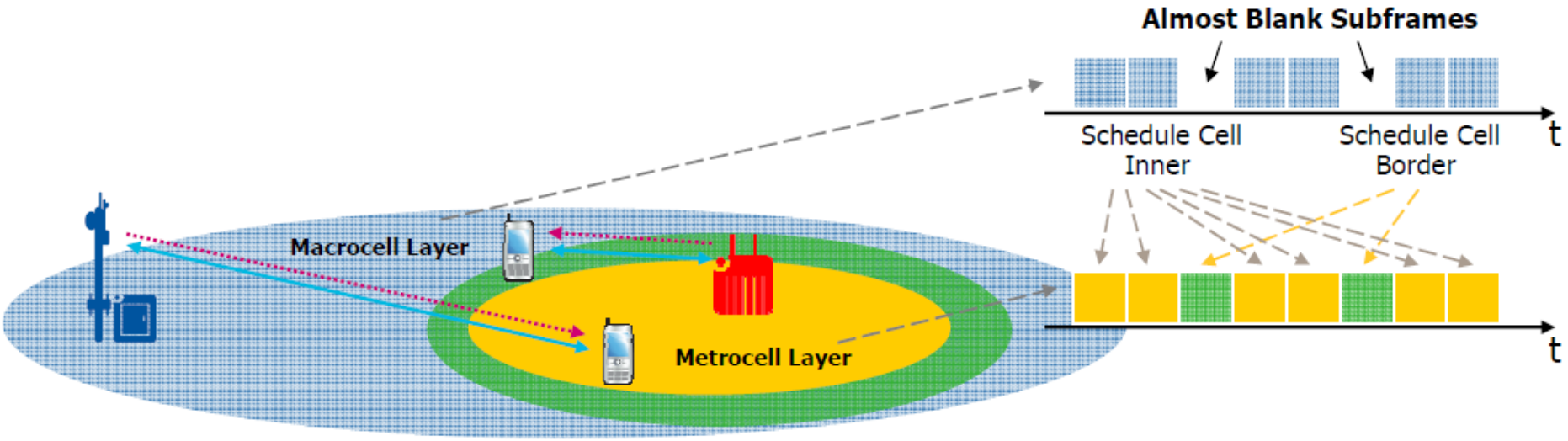


enhanced Inter-Cell Interference Coordination (eICIC)

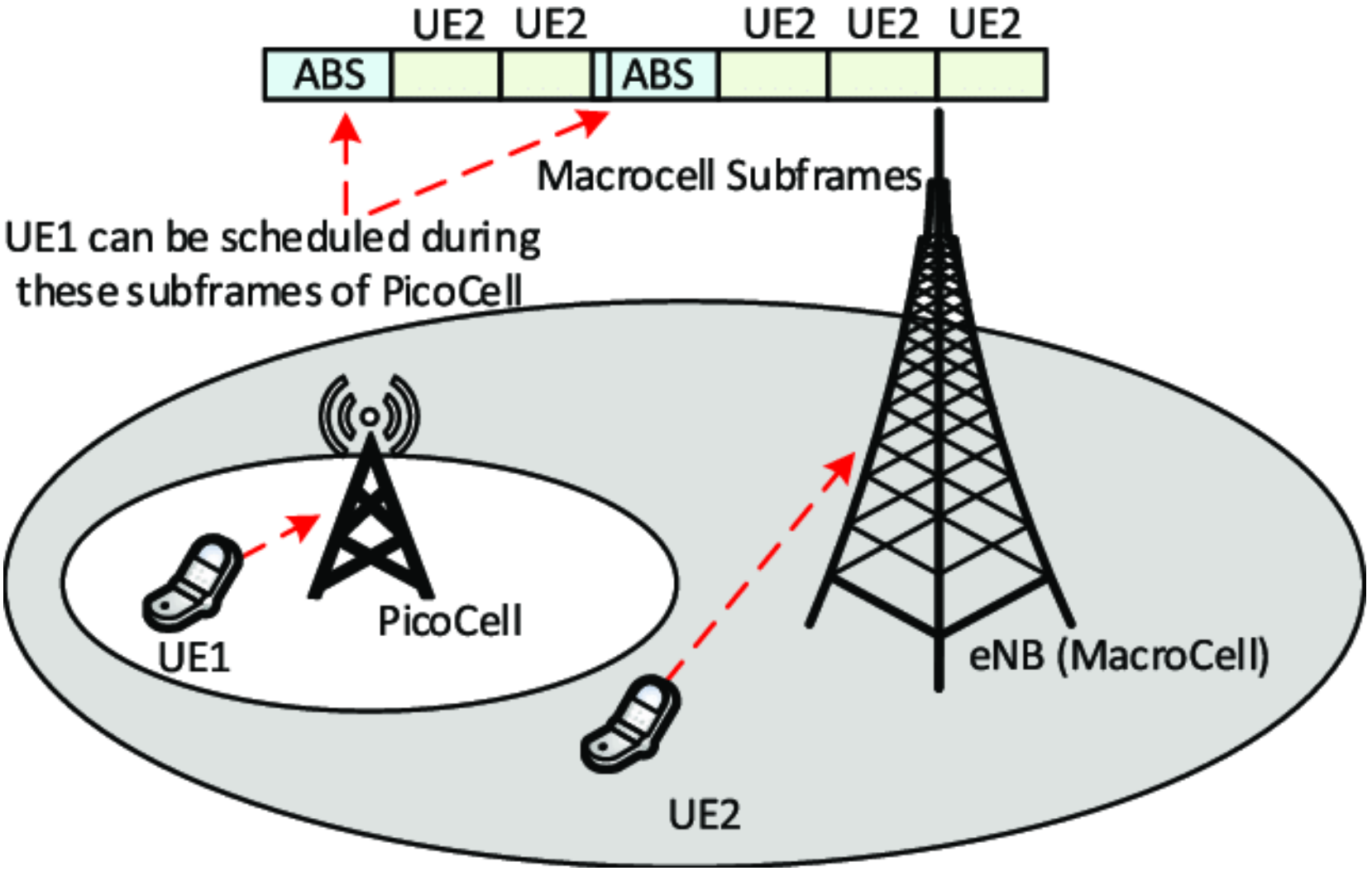
- Coordination between eNBs at different tiers (e.g. femto-marco) to mitigate interference
- Three categories
  - Time-domain: Almost Blank Subframes (ABSFs) at macrocells, where no control or data signals are transmitted.
  - Frequency-domain: Select different frequency channels for victim users in macro and femto
  - Power-domain: Reduce power in femtocell to mitigate interference to macrocell

Almost Blank Subframes



- **Increased coverage**
- **Higher spectral efficiency**
- **Significant improvement in capacity and cell edge performance**

Almost Blank Subframes



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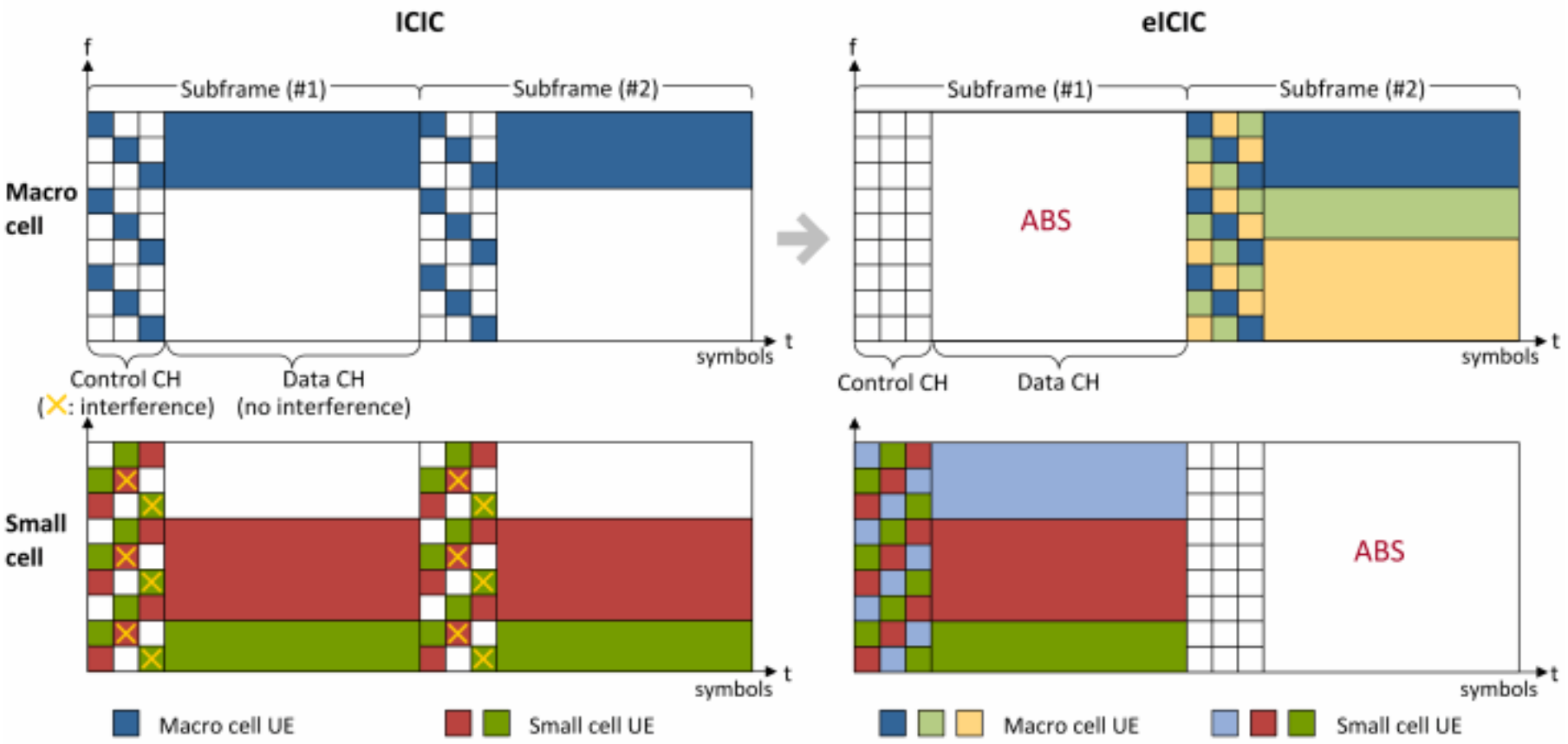

Release 8 (LTE)

Release 10 (LTE-A)

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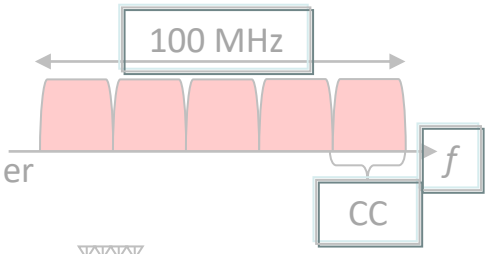

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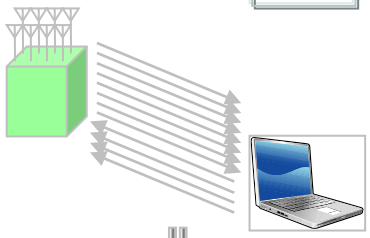

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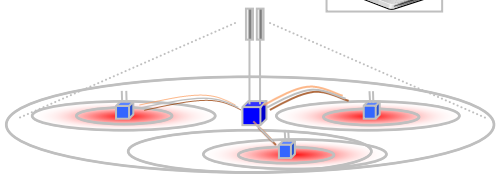

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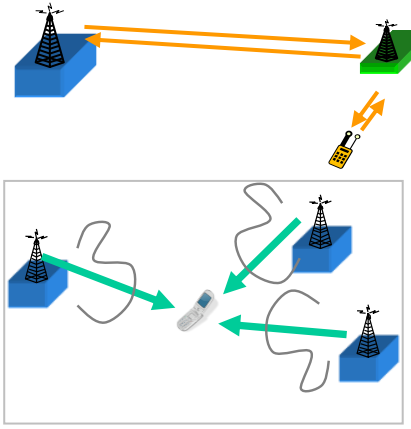

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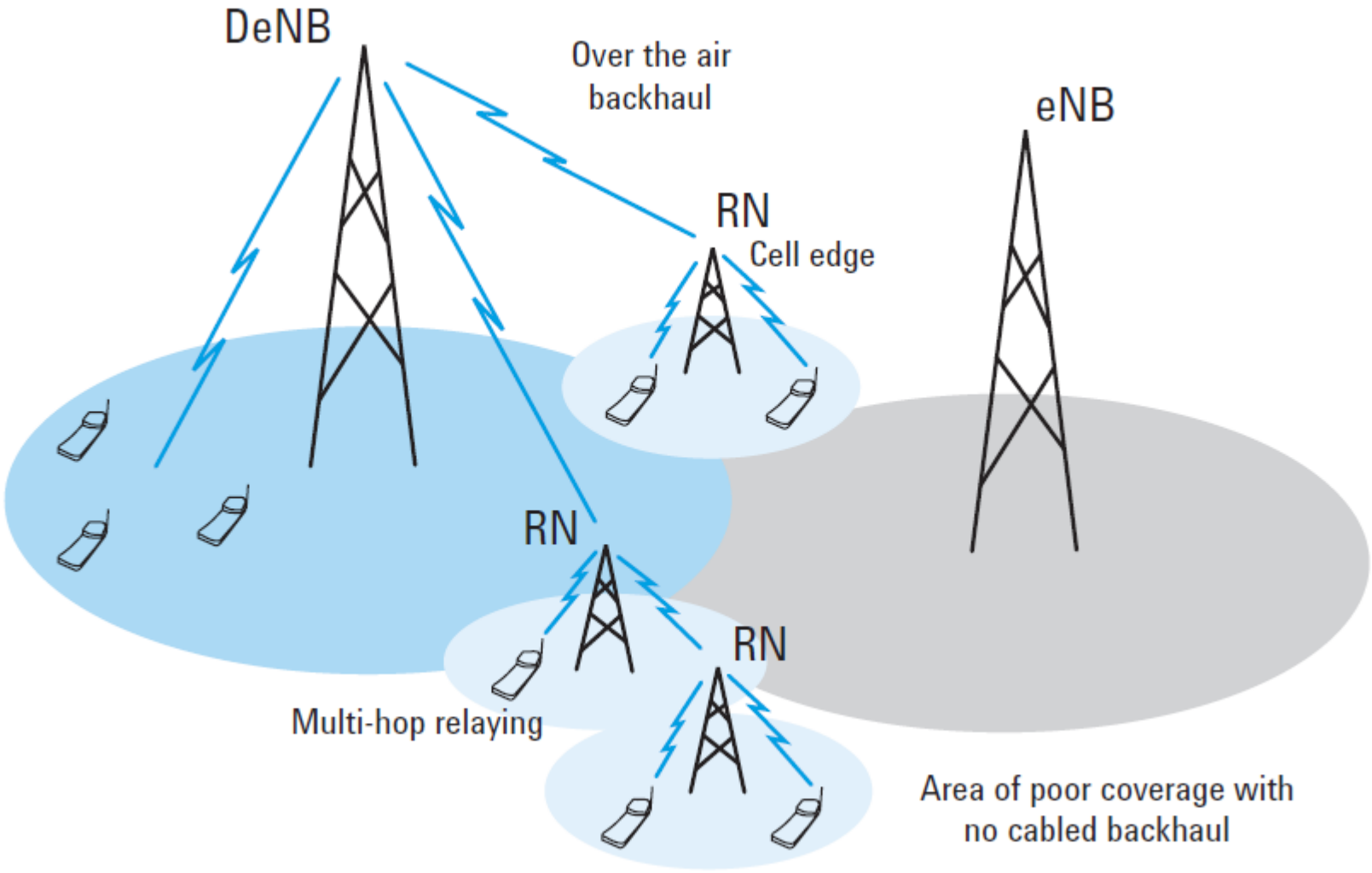
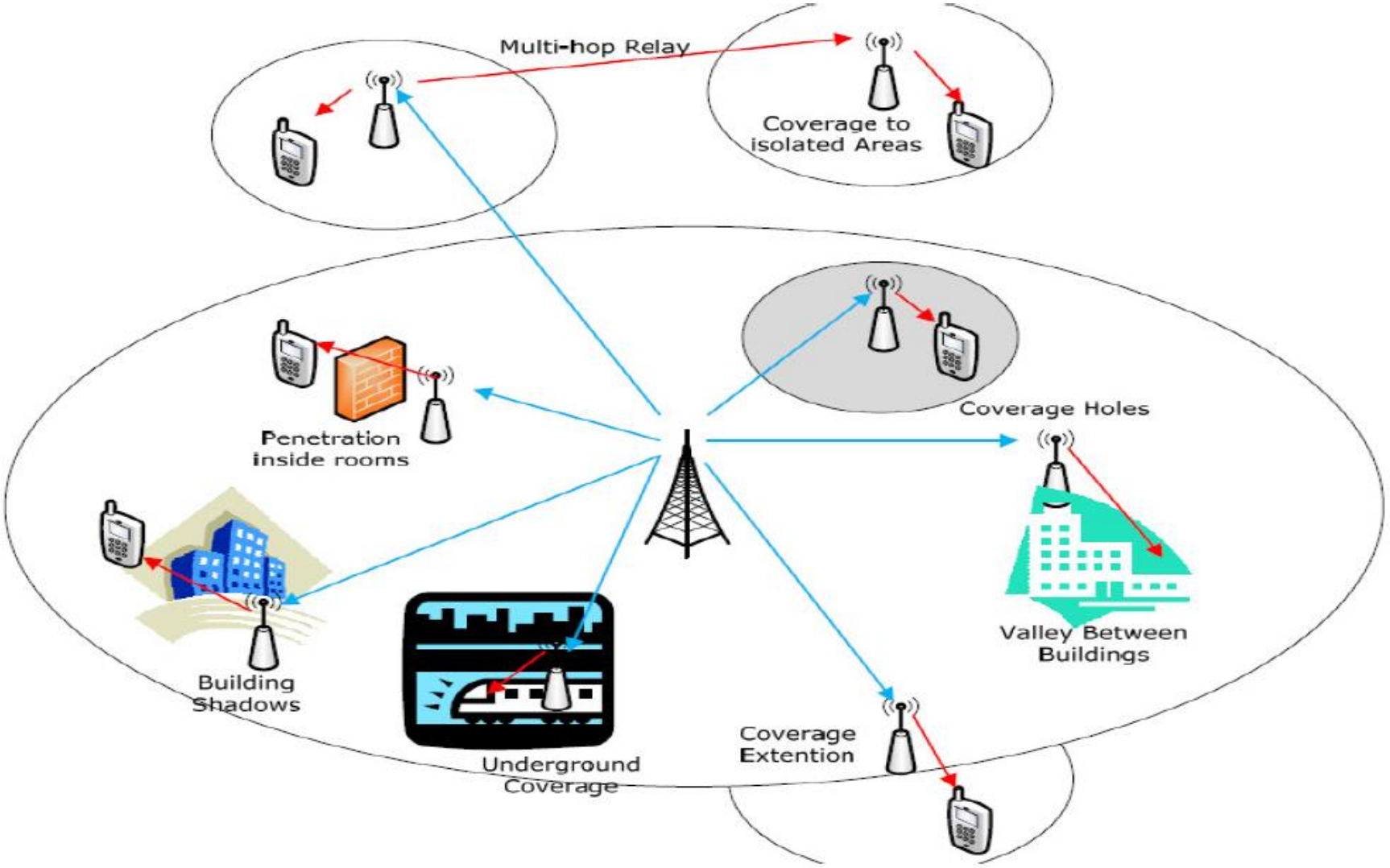
Relaying in LTE-A



Where to use relaying



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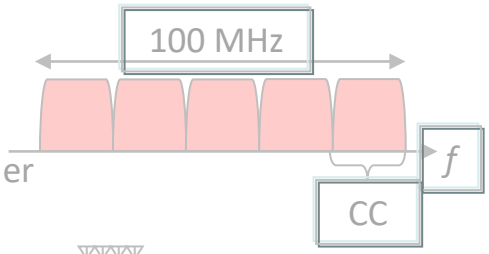

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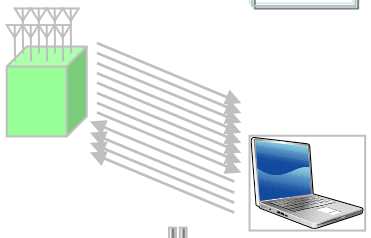

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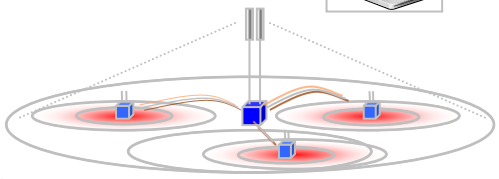

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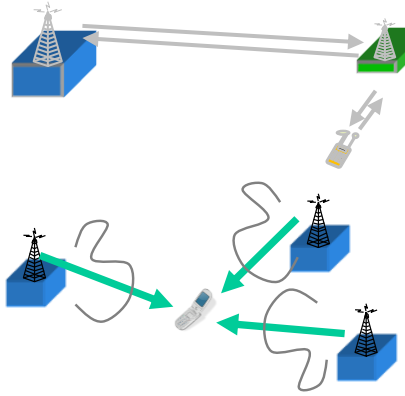

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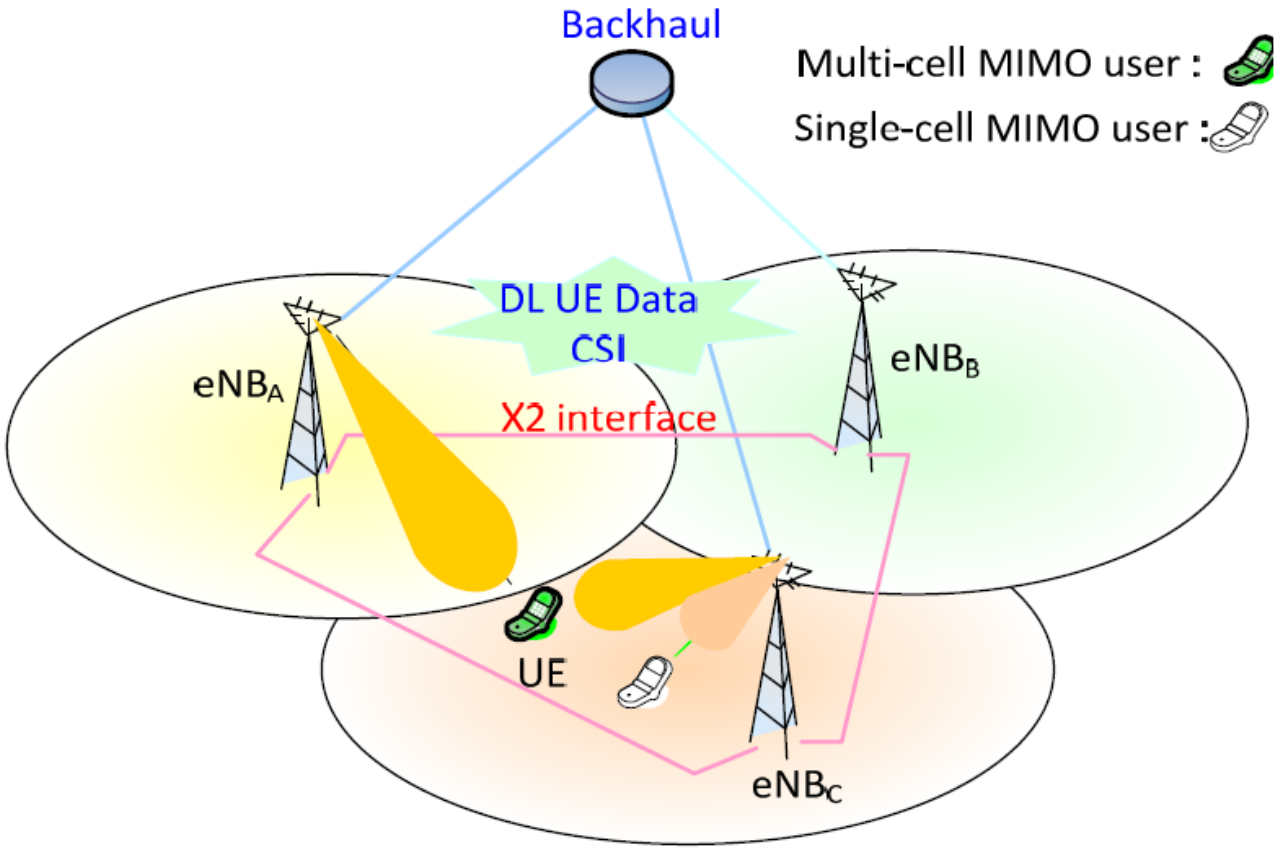
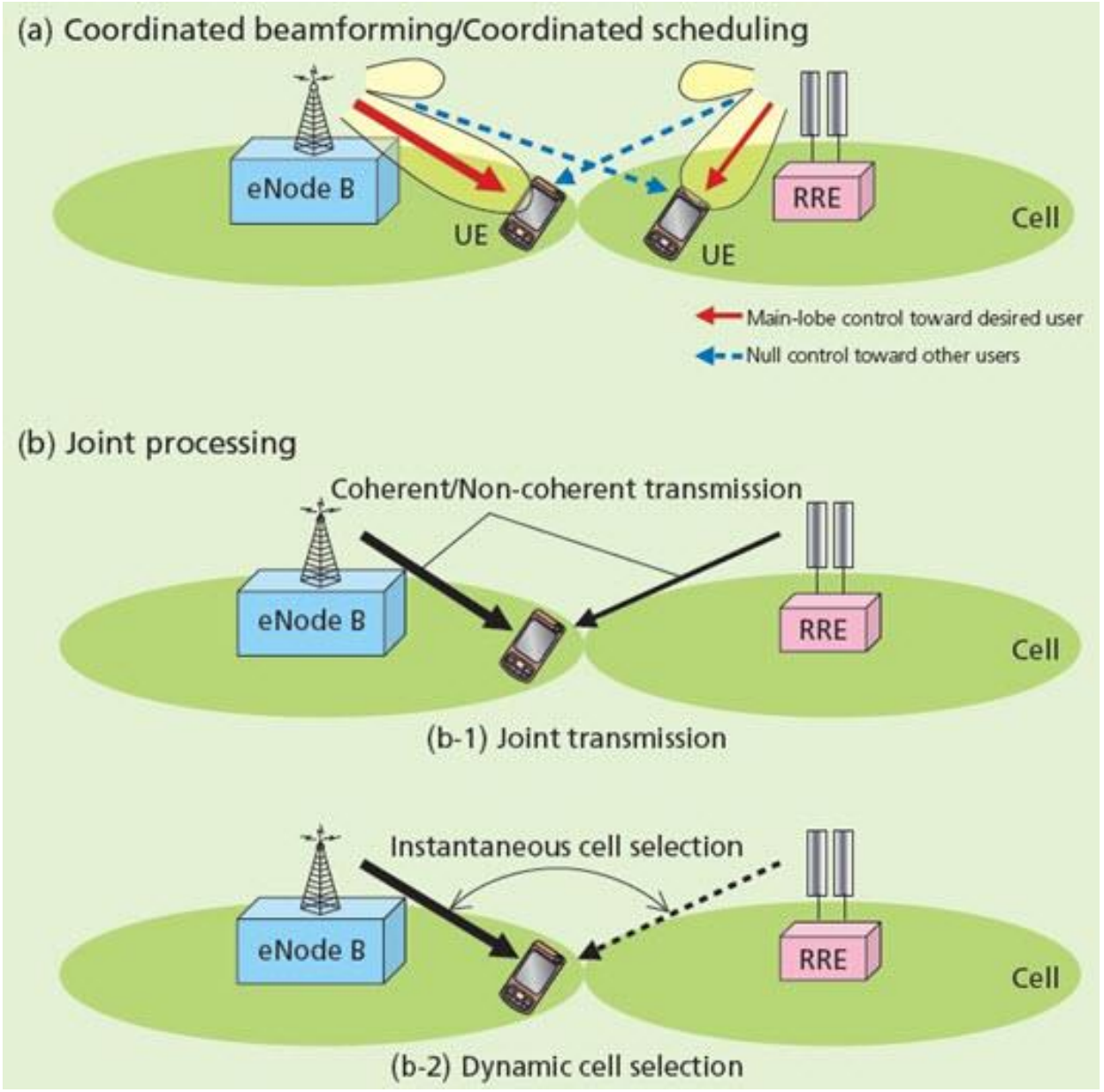
Co-ordinated Multipoint

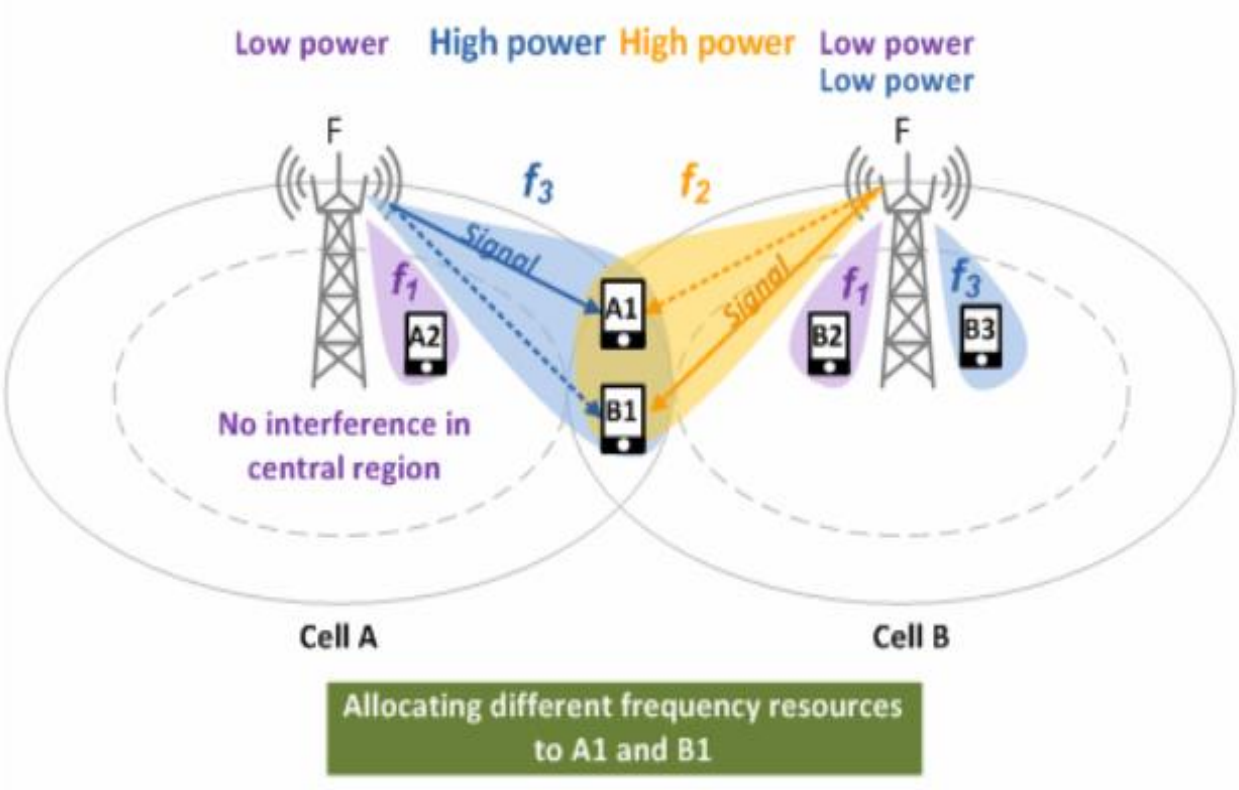
- **CoMP**
  - Stands for Coordinated Multipoint Transmission and Reception
  - Generally known as distributed MIMO or network MIMO



Co-ordinated Multipoint



CoMP – Coordinated scheduling



- Cell A and Cell B cooperate with each other to allocate different frequency resources (f_3, f_2) to A1 and B1 at cell edge, avoiding interference.
- A1 and B1 receive data, only from their respective serving cells, Cell A and Cell B.

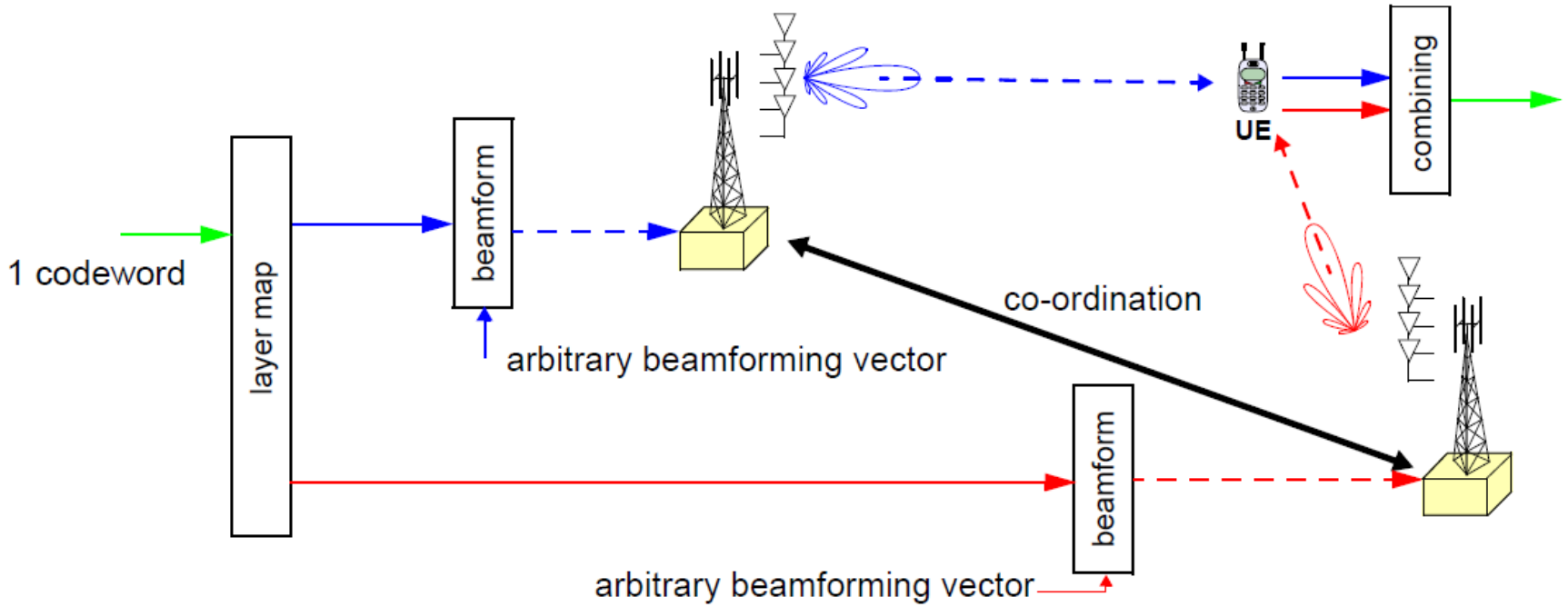
$F = \{f_1, f_2, \ldots, f_N\}$

f_i : RBs or sub-carriers

RB: Resource Block

CoMP – Joint transmission

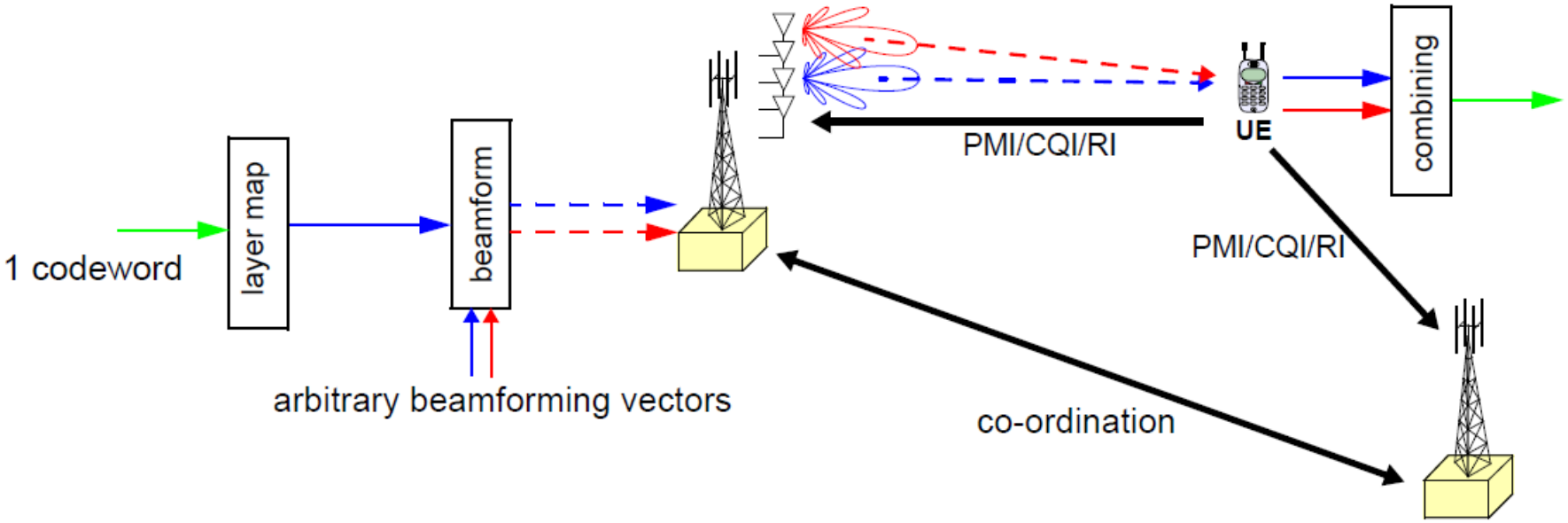
- Multiple eNBs transmit to one UE using UE-specific reference signals:



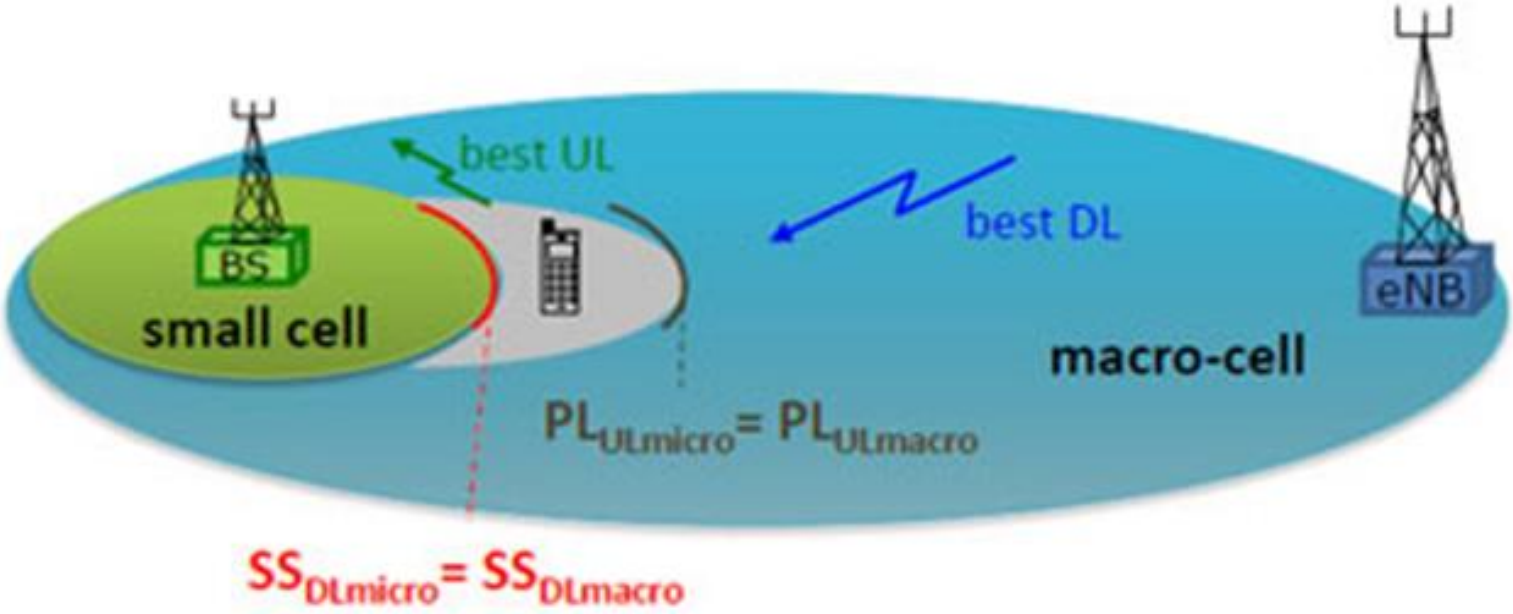
- eNB selection per transmission (UE connected to multiple eNB).

CoMP – Dynamic cell selection

- Data only available at one eNB;
- eNBs jointly decide scheduling of transmission in time, frequency and space:

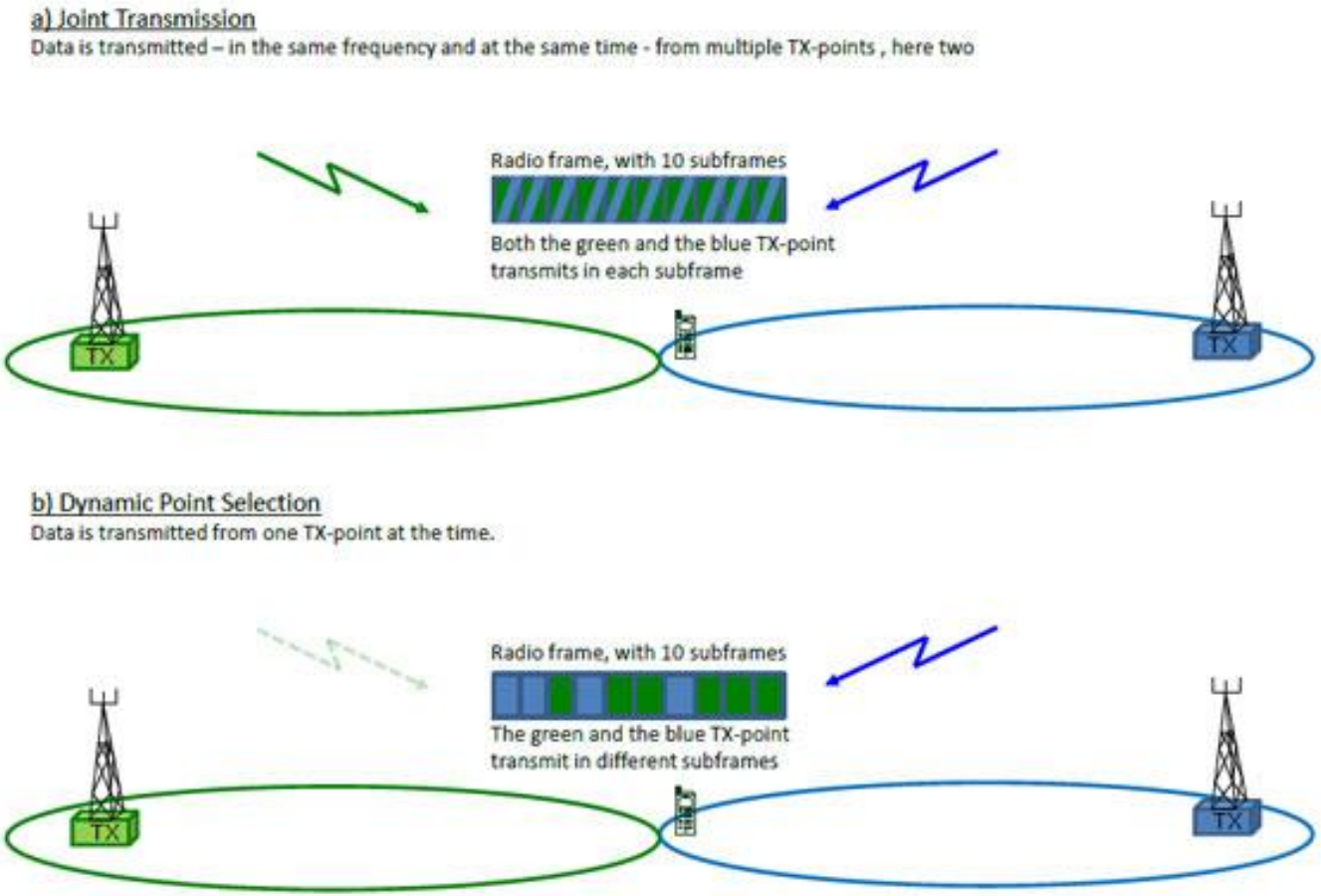


Example of CoMP



- Using CoMP it is possible for the UE in the grey area to have both the best DL from the macro-eNB and the best UL to the base station of the the small cell

Example of DL CoMP



a) Joint Transmission: two TX-points transmit to one UE in the same radio resource

b) Dynamic Point Selection: two TX points are ready to transmit, but only one will be scheduled in each subframe

LTE-Advanced Improvements

- **A schematic view on LTE-Advanced improvements**