



# Towards 4G

: Technical Overview of LTE and LTE-Advanced

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# Outline

## Wireless Background

4G Enabling Technologies

Long Term Evolution (LTE)

LTE-Advanced

Summary and References

# Wireless Background

- Fundamental limits
- Multiple access schemes
- Broadband wireless channel basics
- Cellular system

# Fundamental Constraints

- Shannon's capacity upper bound
  - Achievable data rate is fundamentally limited by bandwidth and signal-to-noise ratio (SNR).

$$C = BW \cdot \log_2 \left( 1 + \frac{S}{N} \right) \text{ [bits per second]}$$

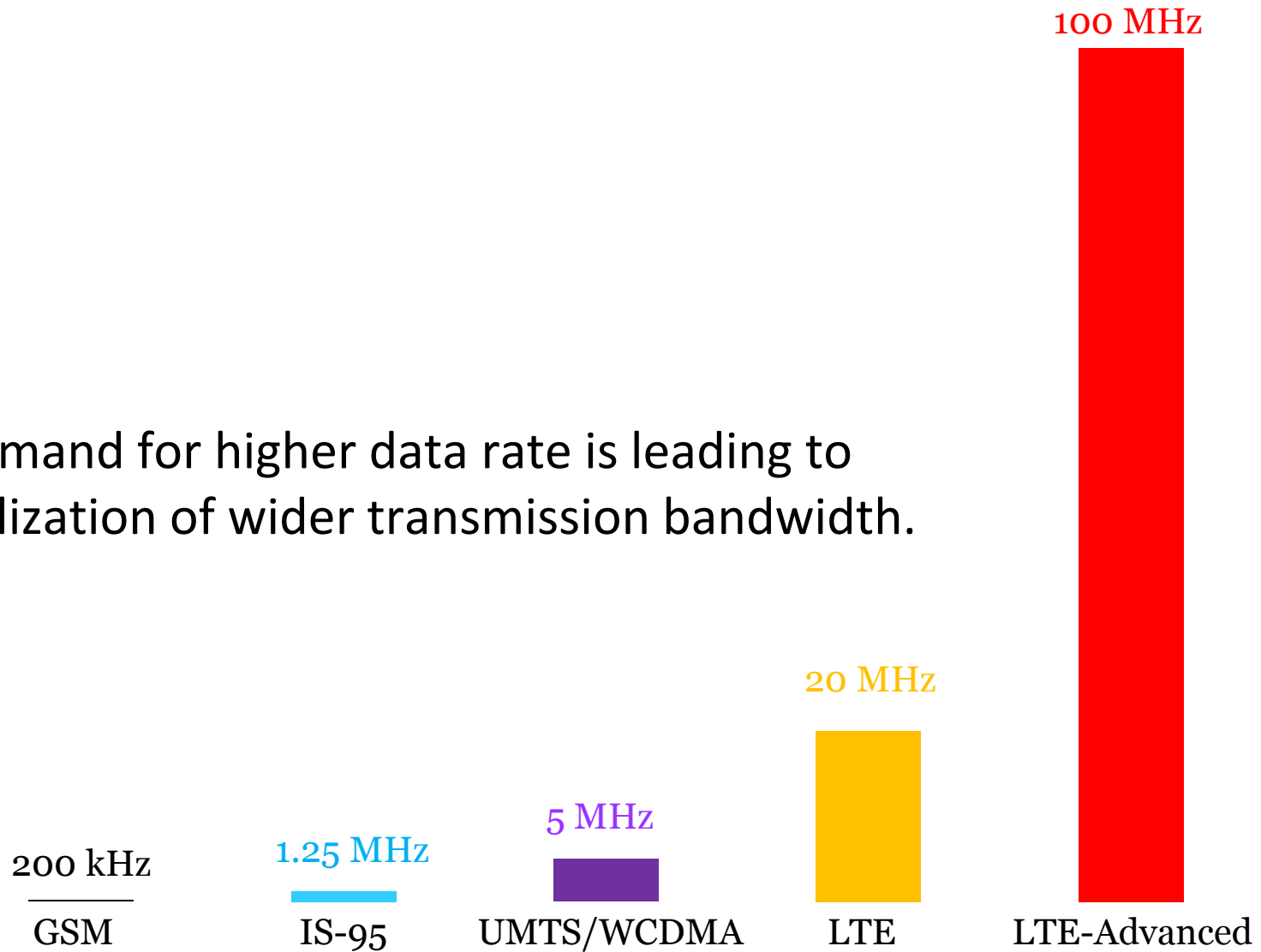
*Channel bandwidth* (pointing to  $BW$ )

*Signal power* (pointing to  $S$ )

*Noise power* (pointing to  $N$ )

# Wider Bandwidth

- Demand for higher data rate is leading to utilization of wider transmission bandwidth.

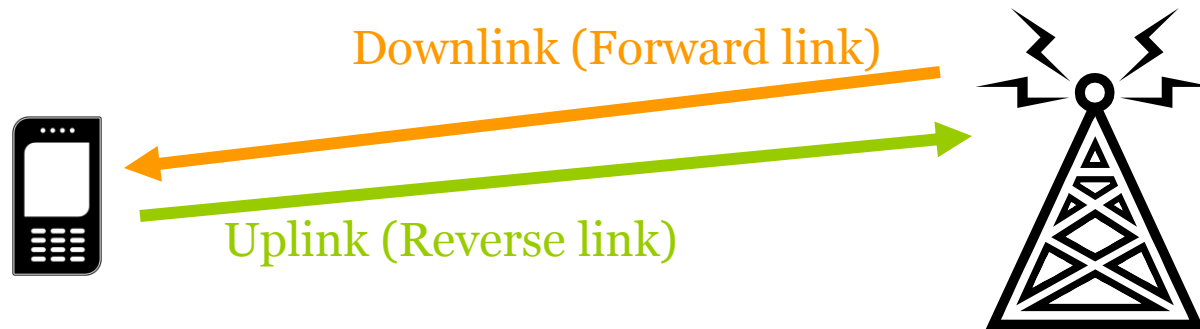


# Challenges of Wireless Communications

- Multipath radio propagation
- Spectrum limitations
- Limited energy
- User mobility
- Resource management

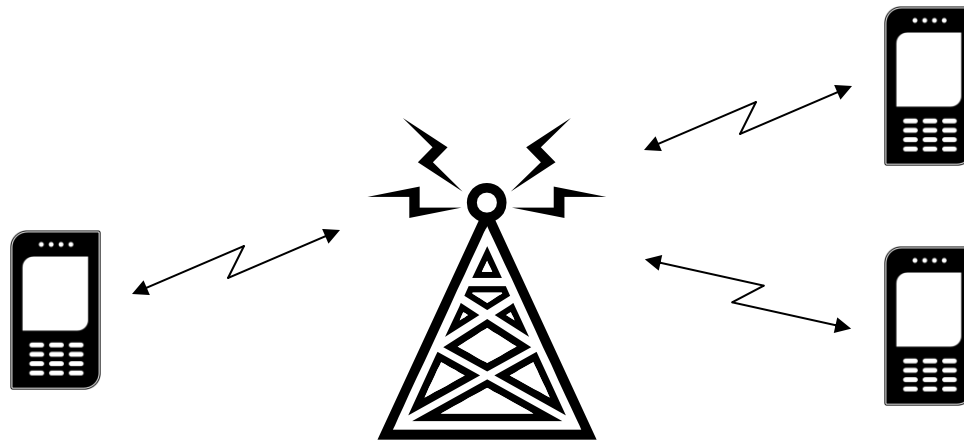
# Duplexing

- Two ways to duplex downlink (base station to mobile) and uplink (mobile to base station)
  - Frequency division duplexing (FDD)
  - Time division duplexing (TDD)



# Multiple Access Schemes

- Multiple devices communicating to a single base station.
  - How do you resolve the problem of sharing a common communication resource?





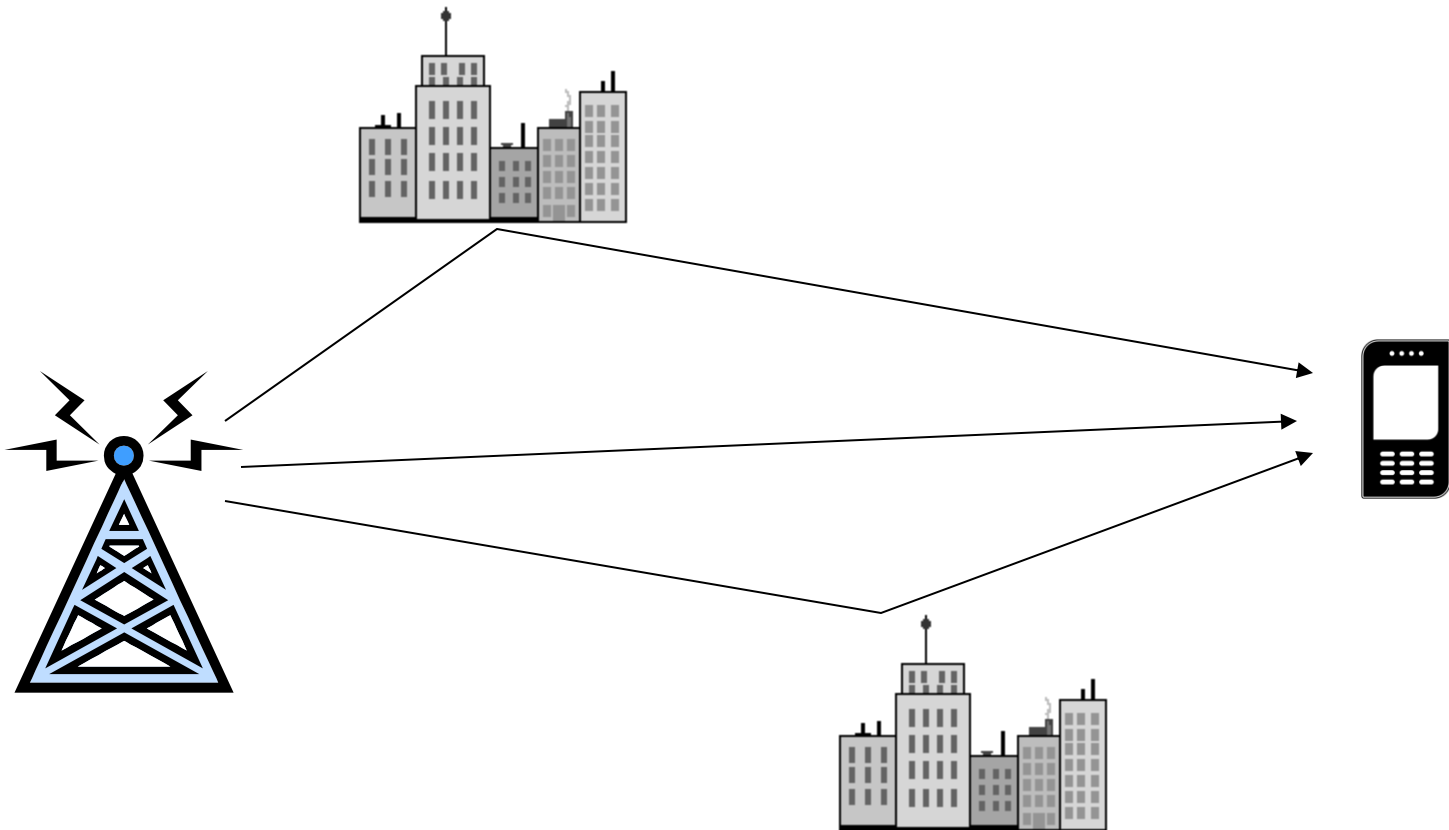
# Multiple Access Schemes

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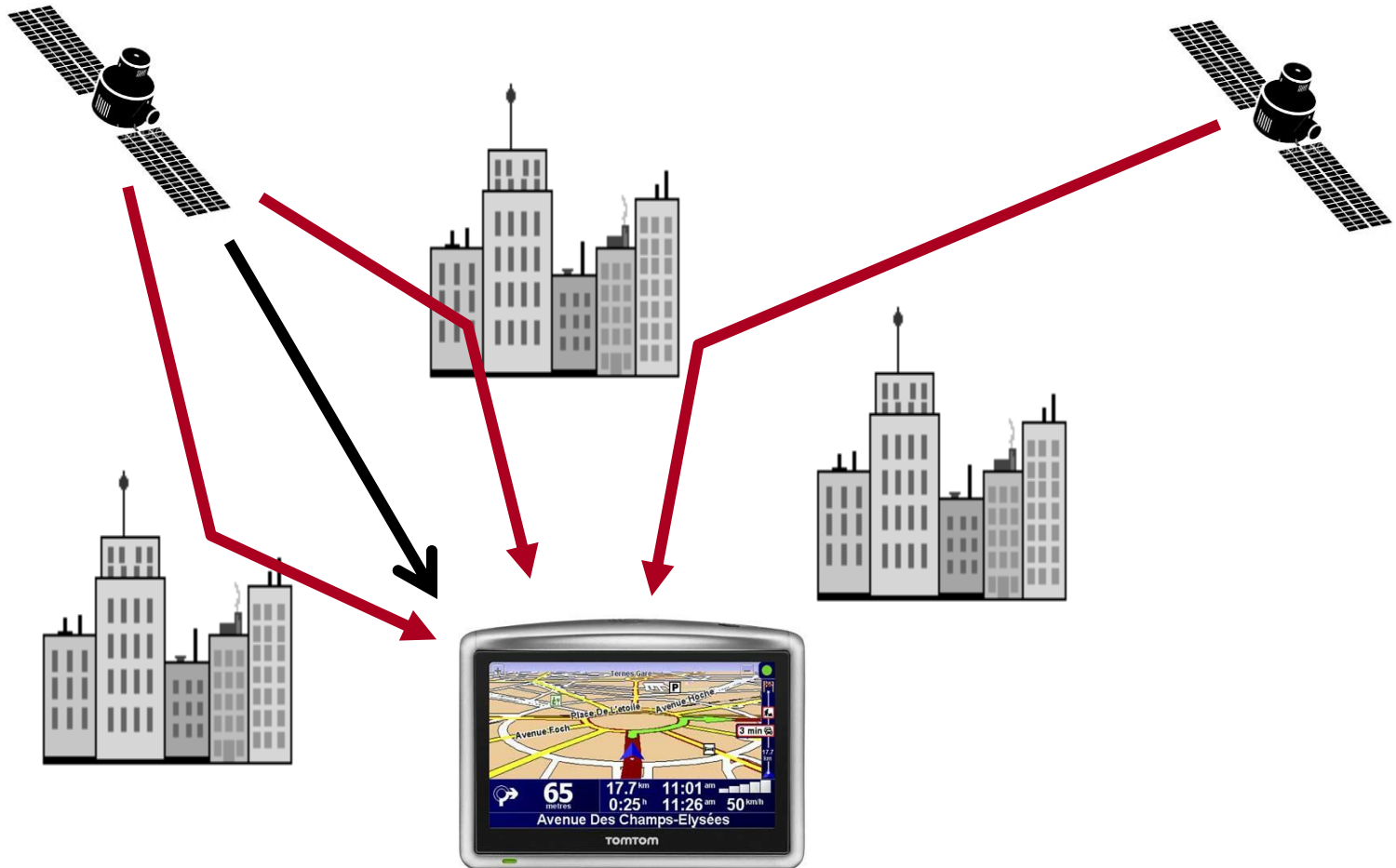
- Access resources can be shared in time, frequency, code, and space.
  - Time division multiple access (TDMA): GSM
  - Frequency division multiple access (FDMA): AMPS
  - Code division multiple access (CDMA): IS-95, UMTS
  - Spatial division multiple access (SDMA): iBurst

# Wireless Channel

- Wireless channel experiences multi-path radio propagation.

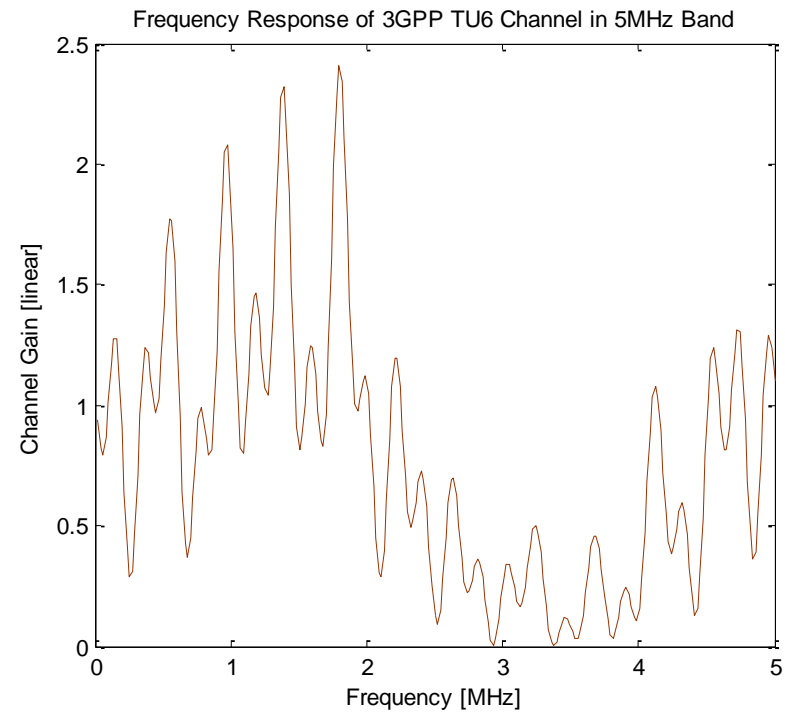
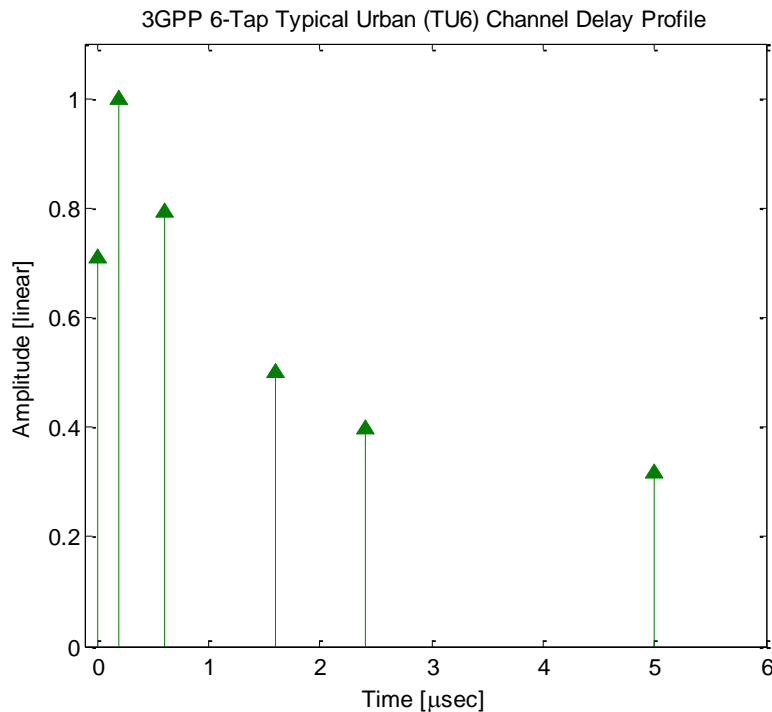


# Multipath Radio Propagation



# Multi-Path Channel

- Multi-path channel causes:
  - Inter-symbol interference (ISI) and fading in the time domain.
  - Frequency-selectivity in the frequency domain.



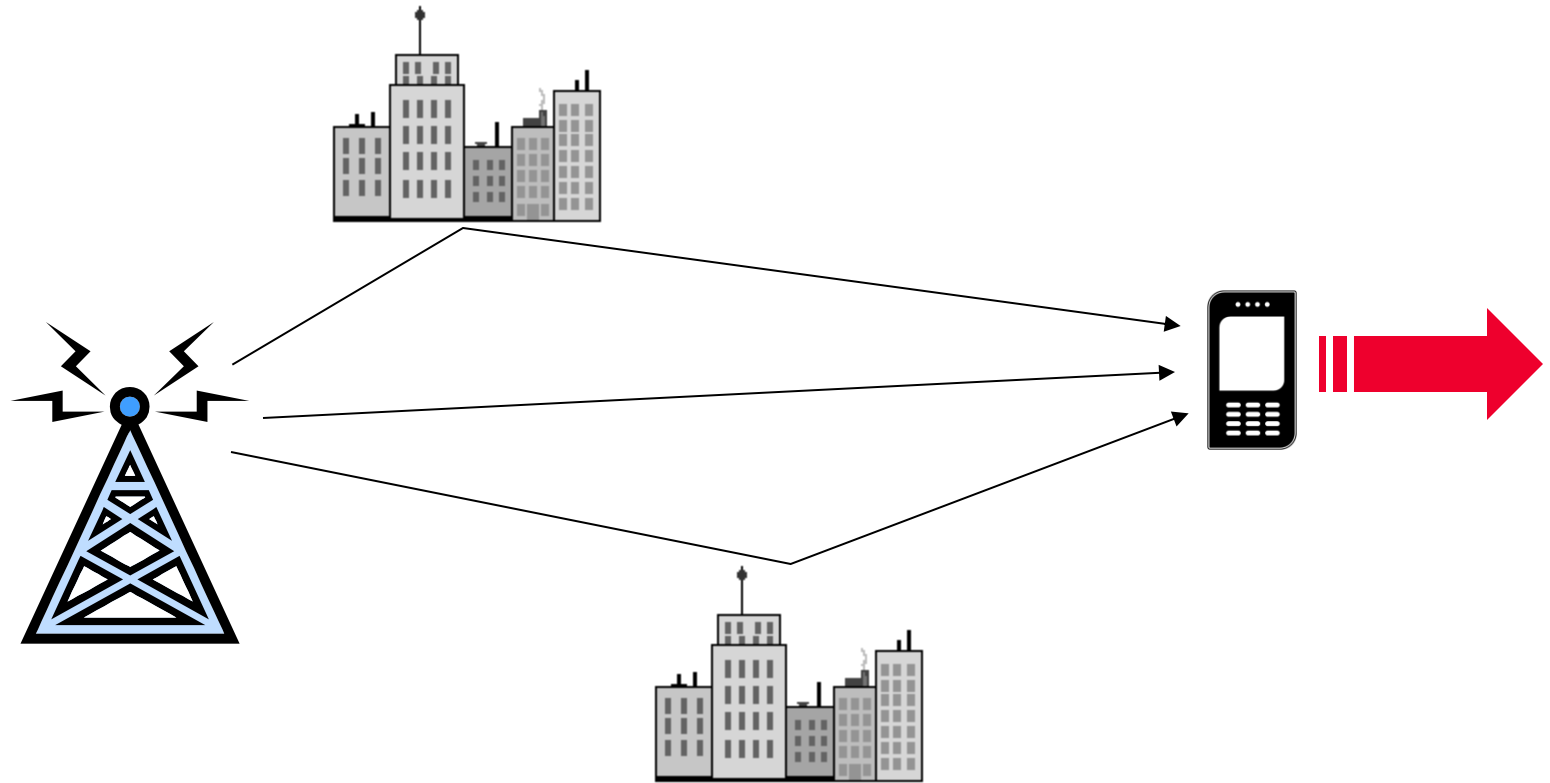
# Multi-Path Channel

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- For broadband wireless channel, ISI and frequency-selectivity become severe.
- To resolve the ISI and the frequency-selectivity in the channel, various measures are used.
  - Channel equalization in the time domain or frequency domain
  - Multi-carrier multiplexing
    - Orthogonal frequency division multiplexing (OFDM)
  - Frequency hopping
  - Channel-adaptive scheduling
  - Channel coding
  - Automatic repeat request (ARQ) and hybrid ARQ (H-ARQ)

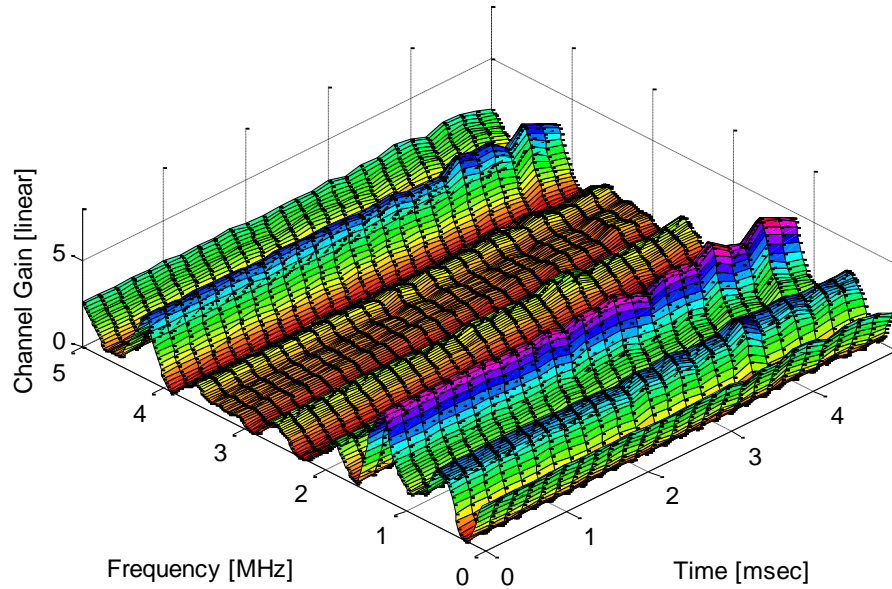
# Mobile User

- When the user is mobile, the channel becomes time-varying.
- There is also Doppler shift in the carrier frequency.

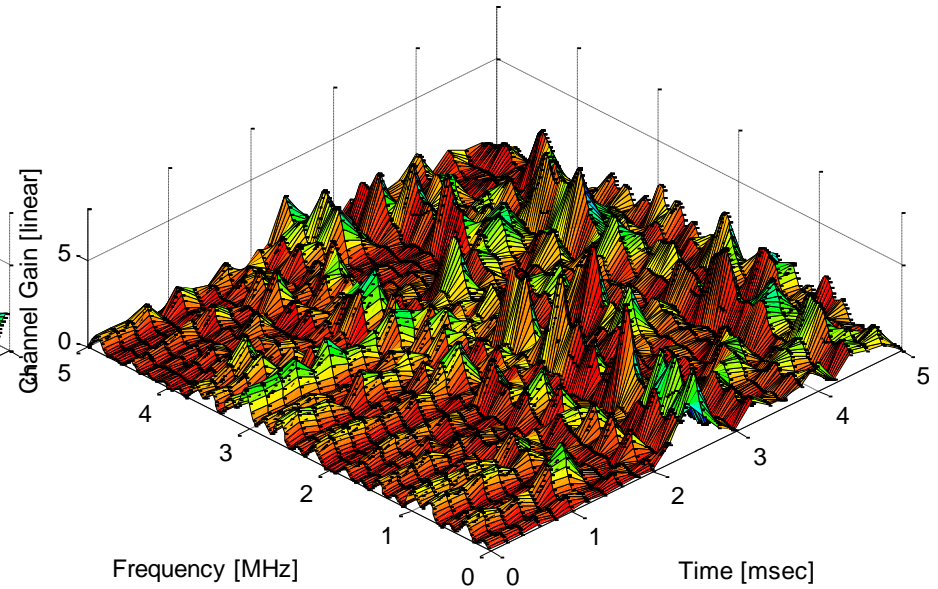


# Time-Varying Multi-path Channel

Mobile speed = 3 km/h (5.6 Hz doppler)



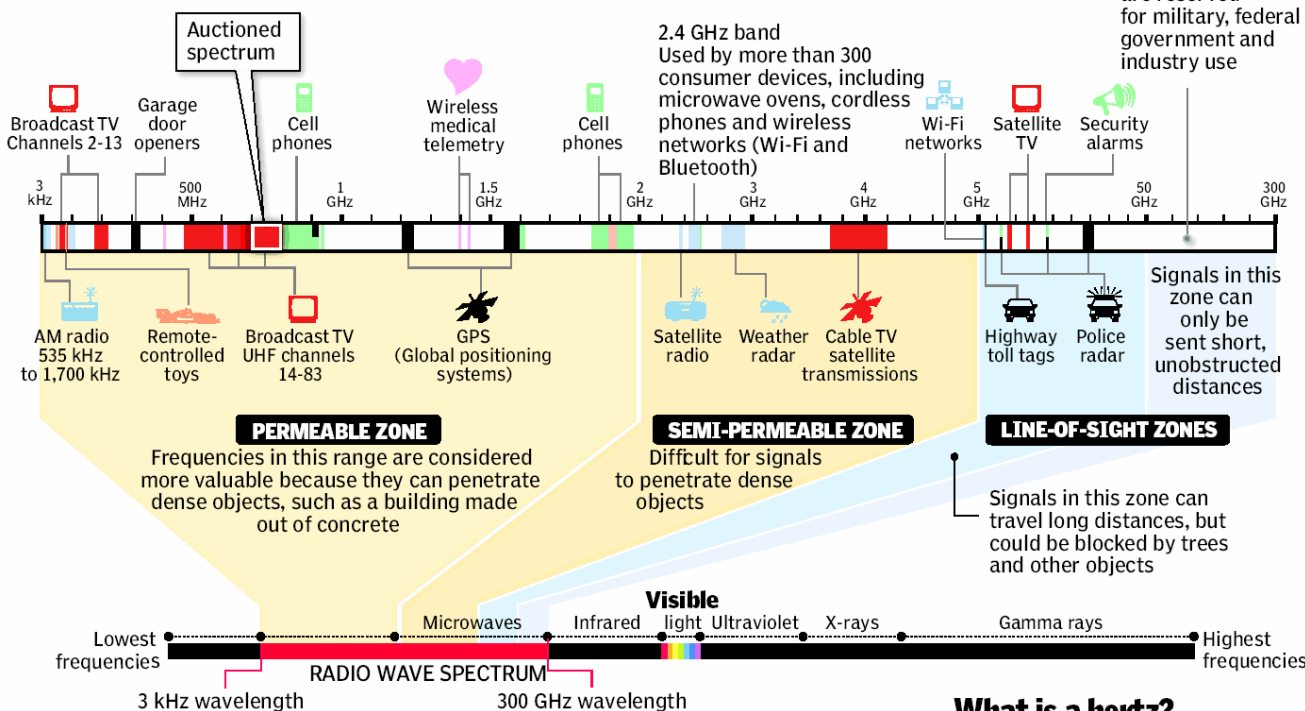
Mobile speed = 60 km/h (111 Hz doppler)



# Wireless Spectrum

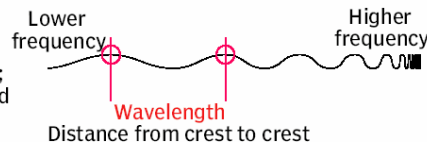
## Inside the radio wave spectrum

Almost every wireless technology – from cell phones to garage door openers – uses radio waves to communicate. Some services, such as TV and radio broadcasts, have exclusive use of their frequency within a geographic area. But many devices share frequencies, which can cause interference. Examples of radio waves used by everyday devices are reserved for military, federal government and industry use



## The electromagnetic spectrum

Radio waves occupy part of the electromagnetic spectrum, a range of electric and magnetic waves of different lengths that travel at the speed of light; other parts of the spectrum include visible light and x-rays; the shortest wavelengths have the highest frequency, measured in hertz



## What is a hertz?

One hertz is one cycle per second. For radio waves, a cycle is the distance from wave crest to crest

1 kilohertz (kHz) = 1,000 hertz

1 megahertz (MHz) = 1 million hertz

1 gigahertz (GHz) = 1 billion hertz

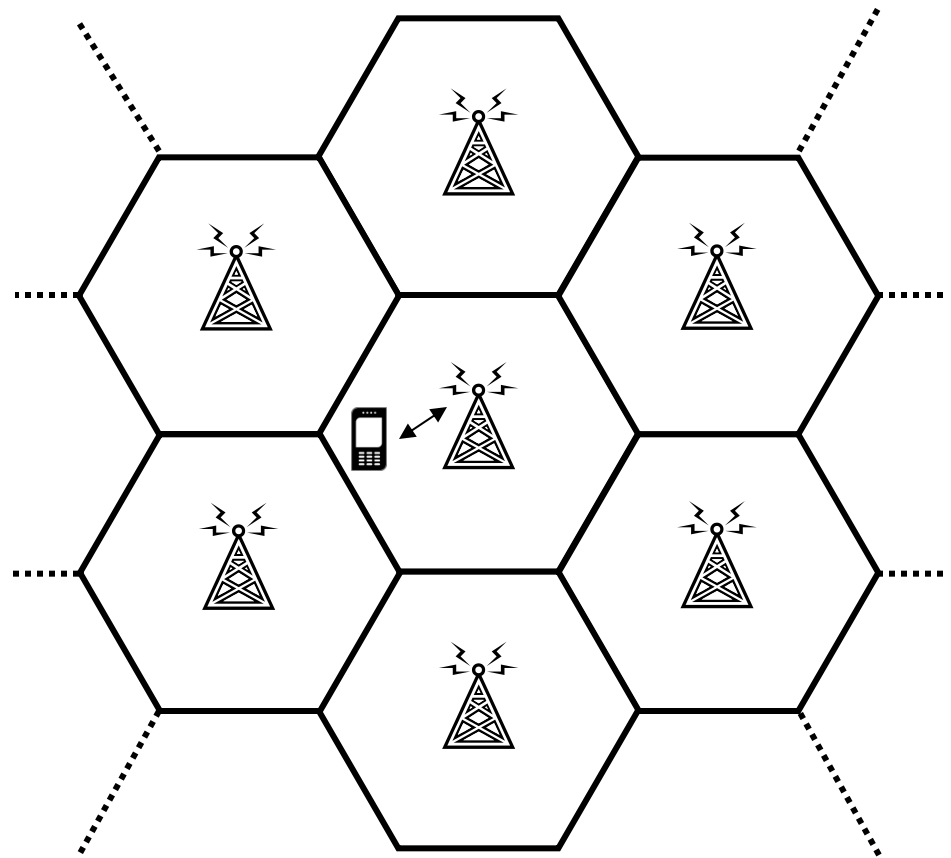
Source: New America Foundation, MCT, Howstuffworks.com  
Graphic: Nathaniel Levine, Sacramento Bee

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# Cellular Wireless System

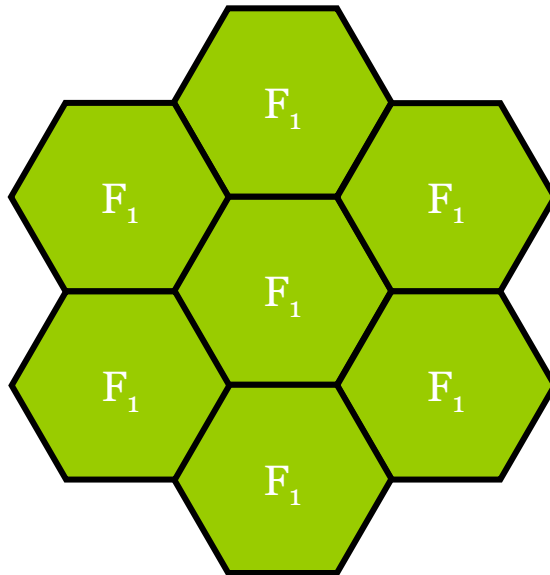
- A large geographical region is segmented into smaller “cell”s.
  - Transmit power limitation
  - Facilitates frequency spectrum re-use
- Cellular network design issues
  - Inter-cell synchronization
  - Handoff mechanism
  - Frequency planning



# Cellular Wireless System

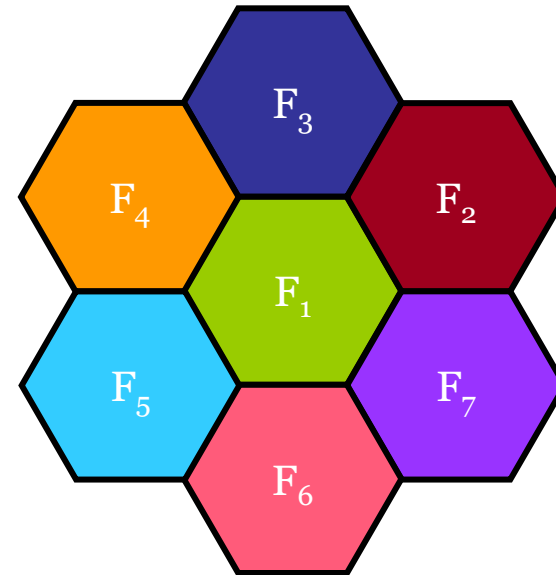
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- Frequency re-use



**Frequency re-use = 1**

- Higher spectral efficiency
- Higher interference for cell-edge users



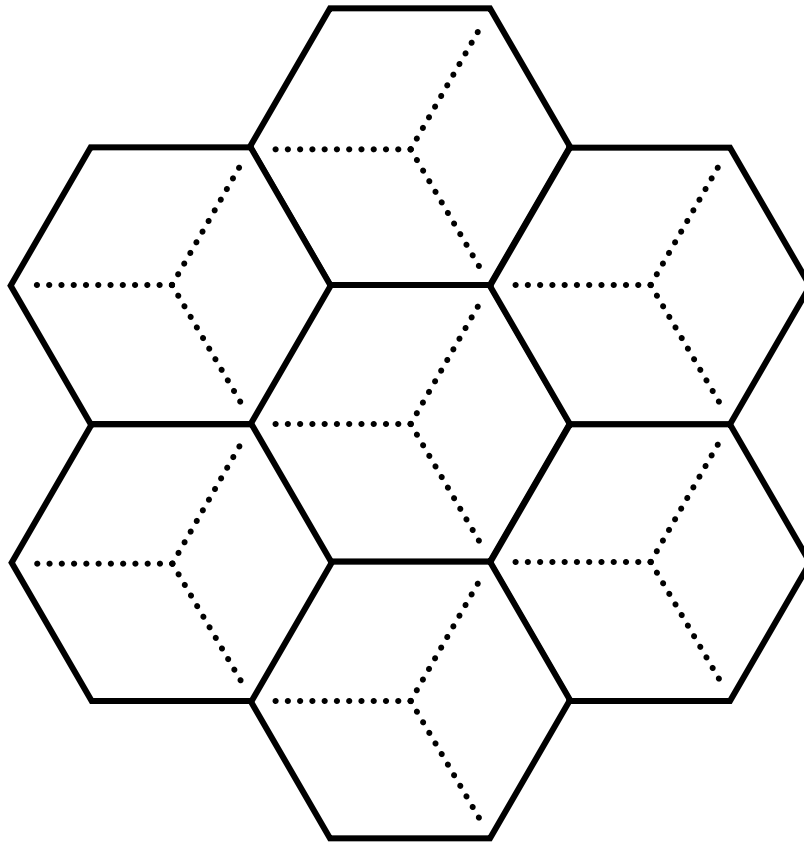
**Frequency re-use = 7**

- Lower interference for cell-edge users
- Lower spectral efficiency

# Cellular Wireless System

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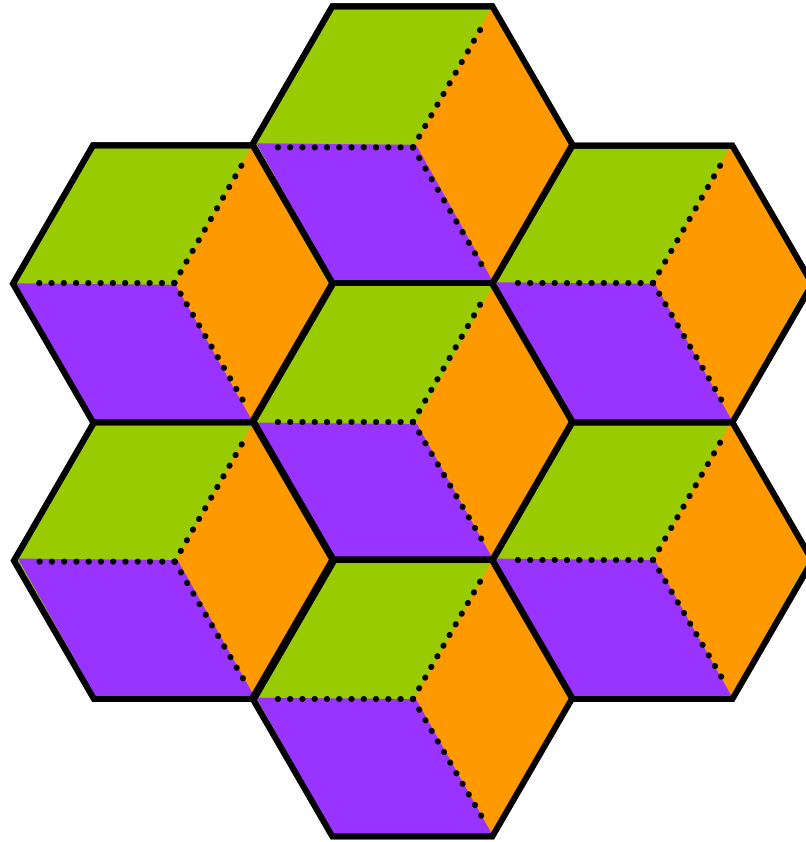
- Sectorized cells



# Cellular Wireless System

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- Frequency re-use = 3



# Outline

Wireless Background

**4G Enabling Technologies**

Long Term Evolution (LTE)

LTE-Advanced

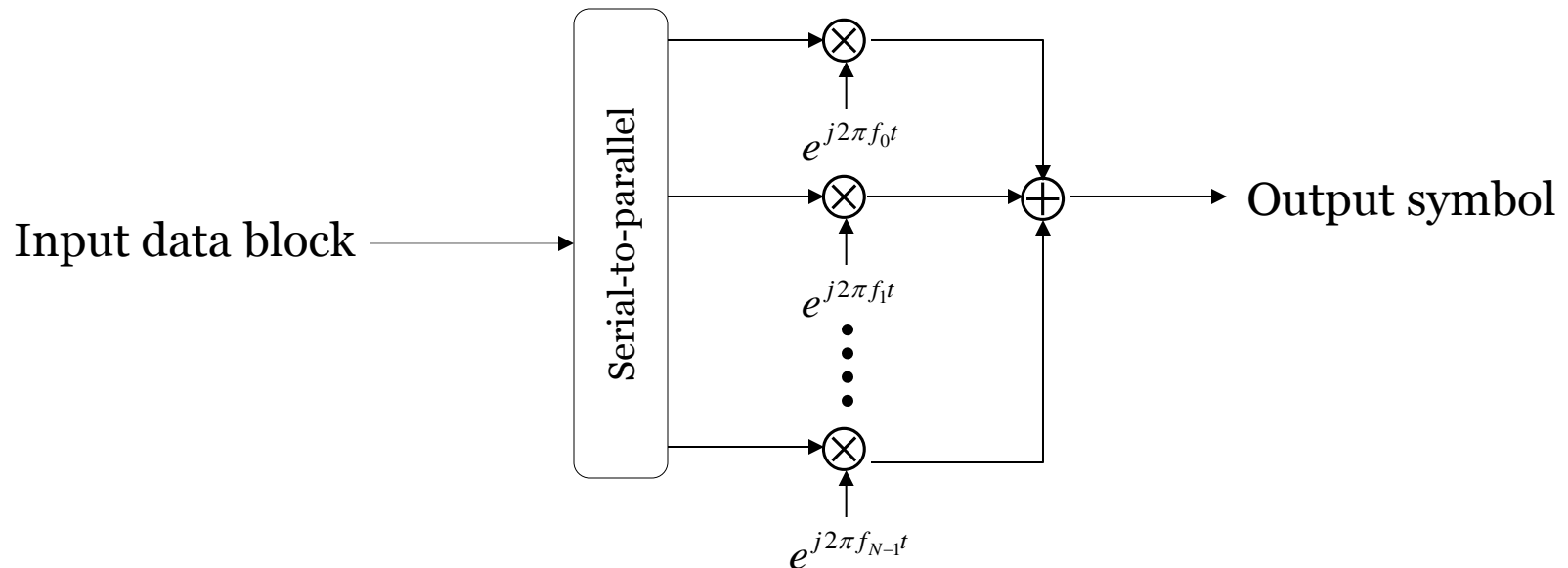
Summary and References

# 4G Enabling Technologies

- OFDM/OFDMA
- Frequency domain equalization
- SC-FDMA
- MIMO
- Fast channel-dependent resource scheduling

# Orthogonal Frequency Division Multiplexing

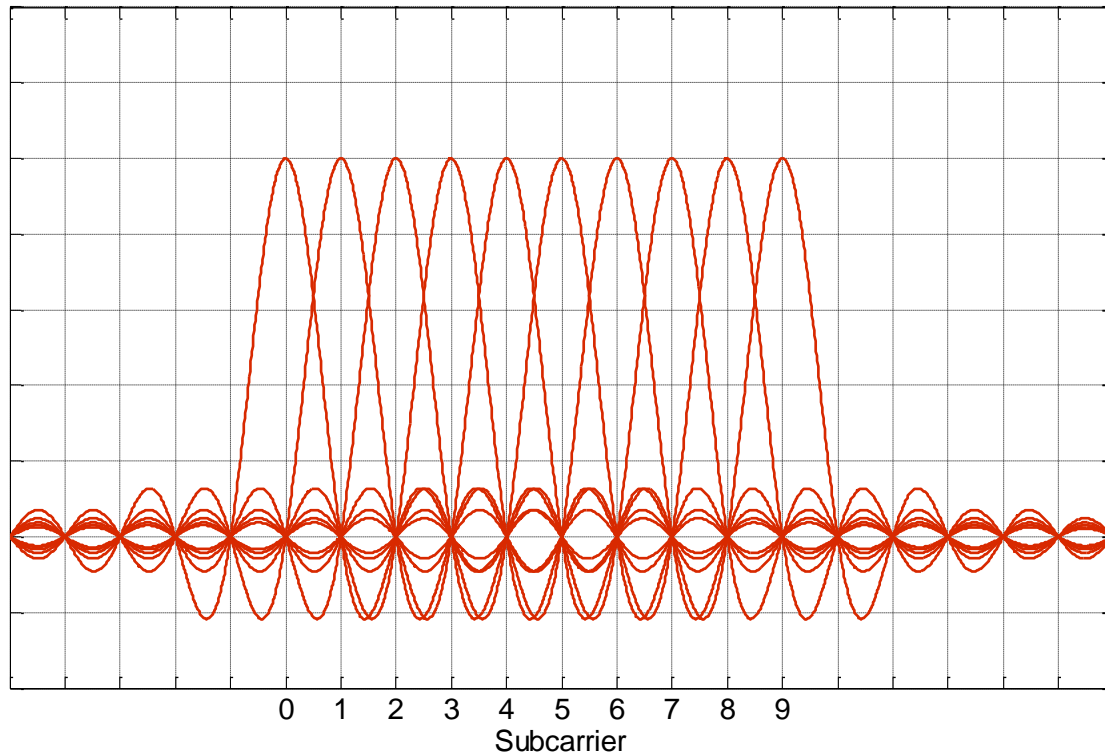
- OFDM can be viewed as a form of frequency division multiplexing (FDM).
  - Divides the transmission bandwidth into narrower equally spaced tones, or subcarriers.
  - Individual information symbols are conveyed over the subcarriers.



# OFDM

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- Use of orthogonal subcarriers makes OFDM spectrally efficient.
  - Because of the orthogonality among the subcarriers, they can overlap with each other.

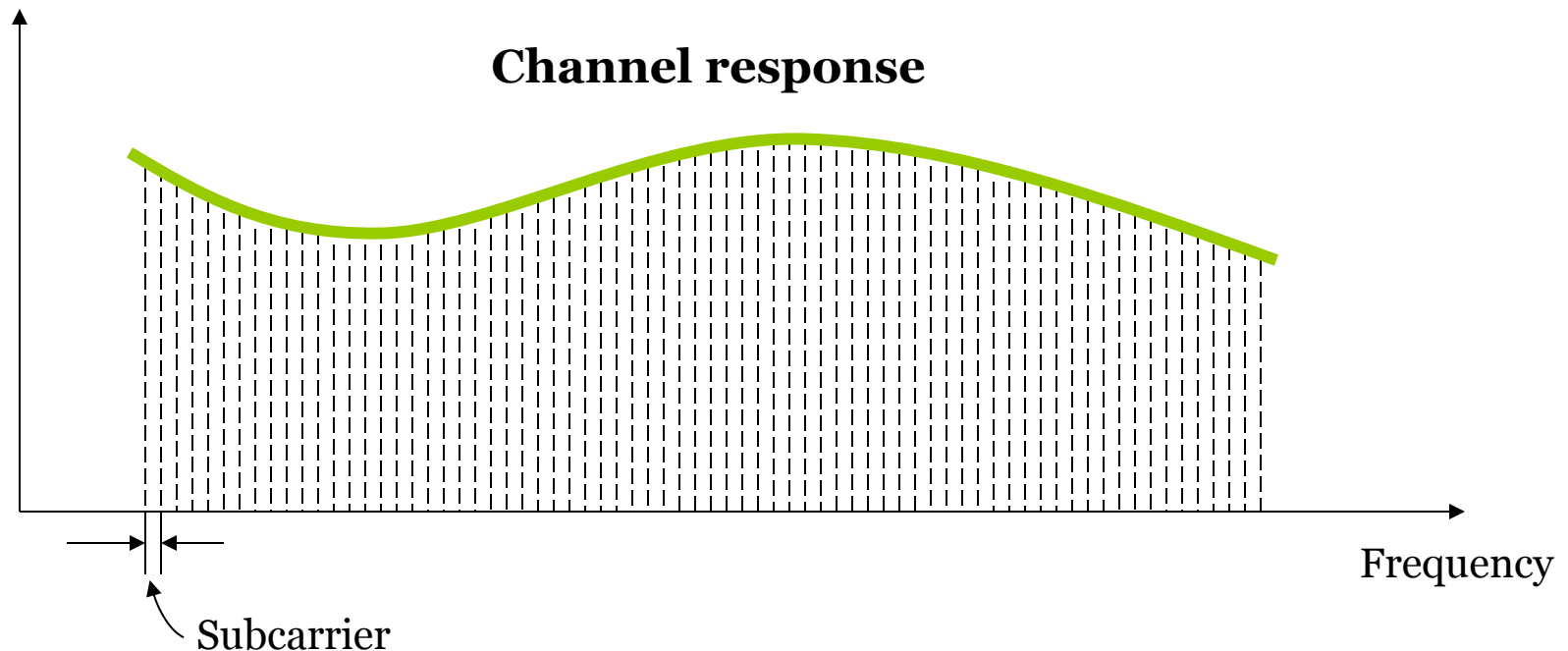




# OFDM

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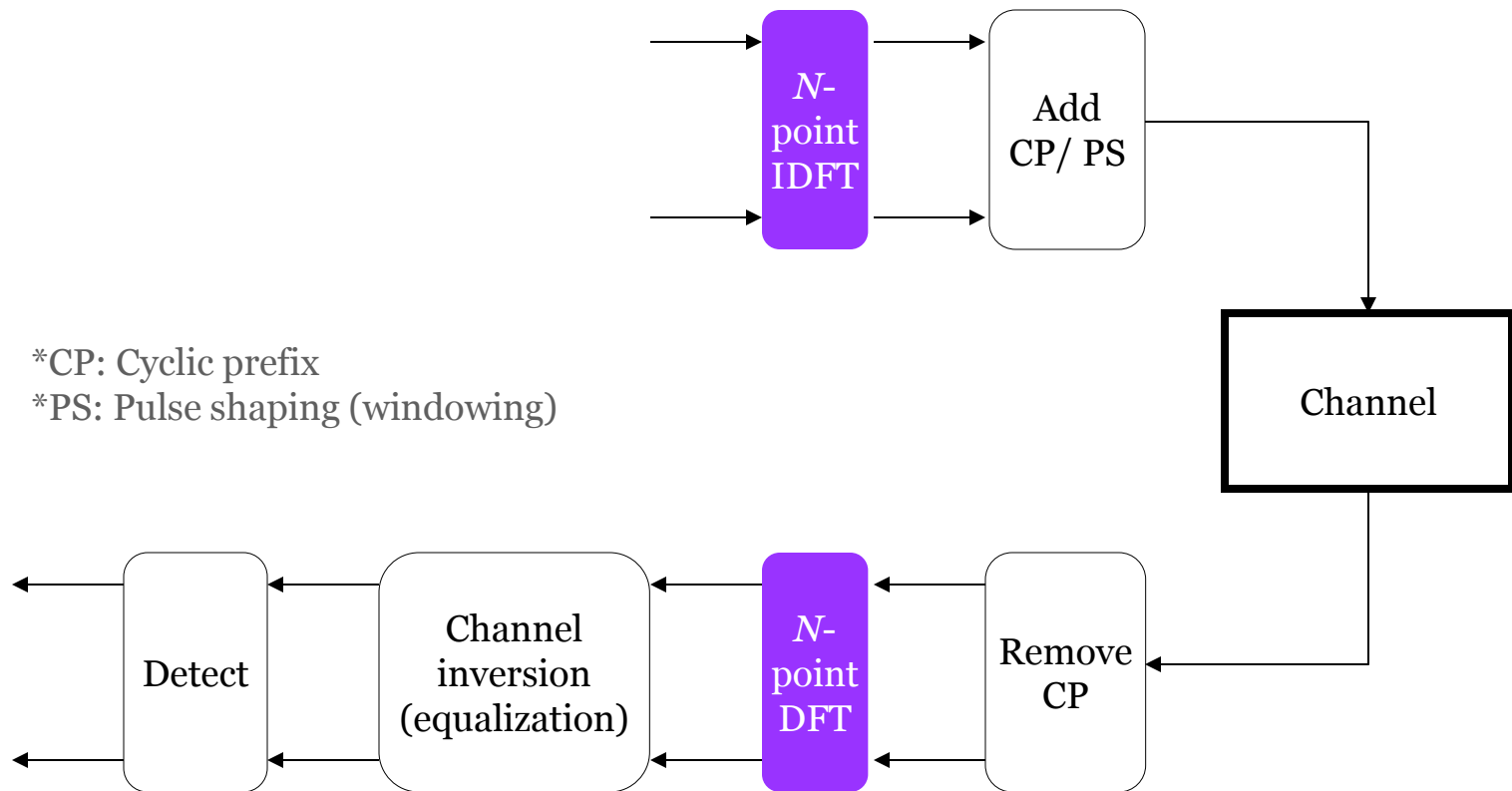
- Since the bandwidth of each subcarrier is much smaller than the coherence bandwidth of the transmission channel, each subcarrier sees flat fading.



# OFDM

- cont.

- OFDM implementation using discrete Fourier transform (DFT)

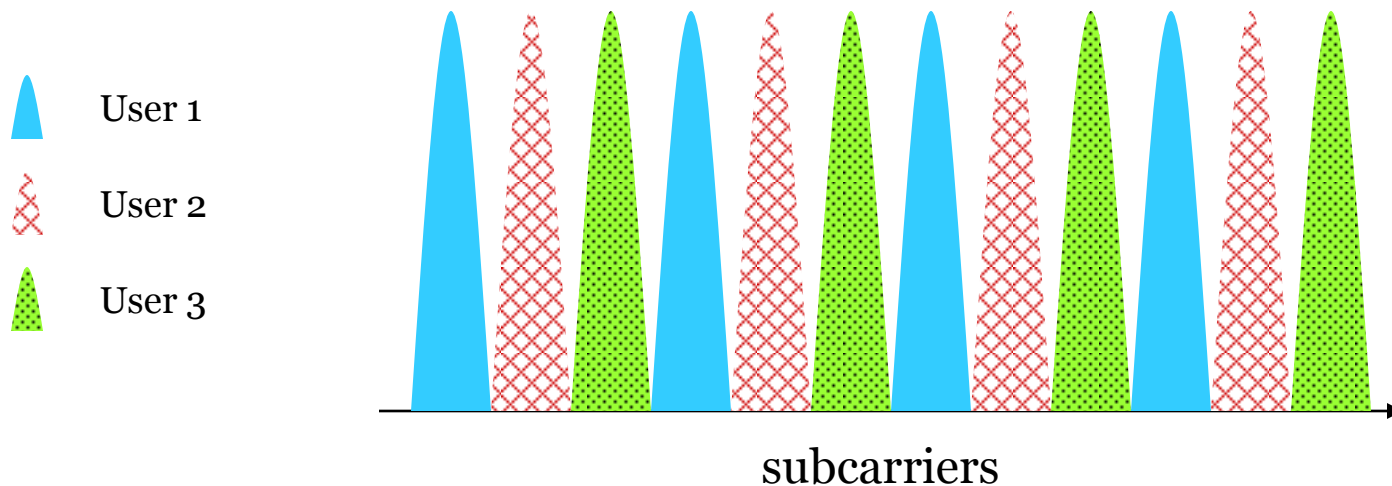


- Design issues of OFDM

- **Cyclic prefix (CP):** To maintain orthogonality among subcarriers in the presence of multi-path channel, CP longer than the channel impulse response is needed. Also CP converts linear convolution of the channel impulse response into a circular one.
- **High peak-to-average power ratio (PAPR):** Since the transmit signal is a composition of multiple subcarriers, high peaks occur.
- **Carrier frequency offset:** Frequency offset breaks the orthogonality and causes inter-carrier interference.
- **Adaptive scheme or channel coding** is needed to overcome the spectral null in the channel.

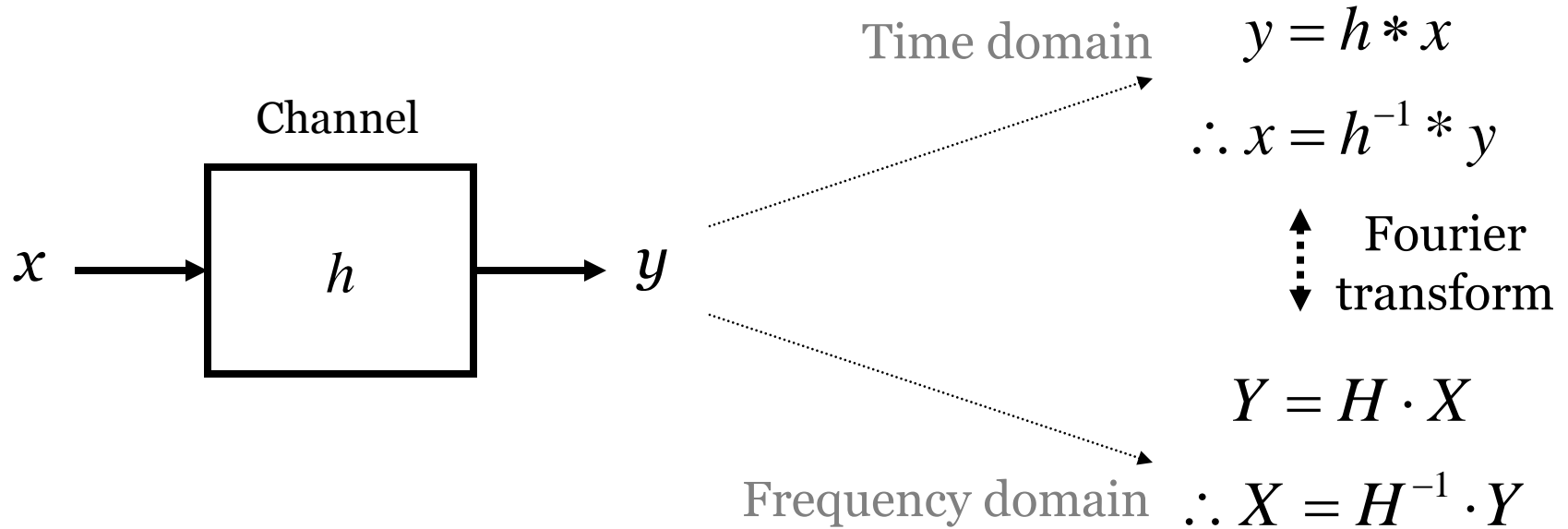
# Orthogonal Frequency Division Multiple Access

- OFDMA is a multi-user access scheme using OFDM.
  - Each user occupies a different set of subcarriers.
  - Scheduler can exploit frequency-selectivity and multi-user diversity.



# Frequency Domain Equalization

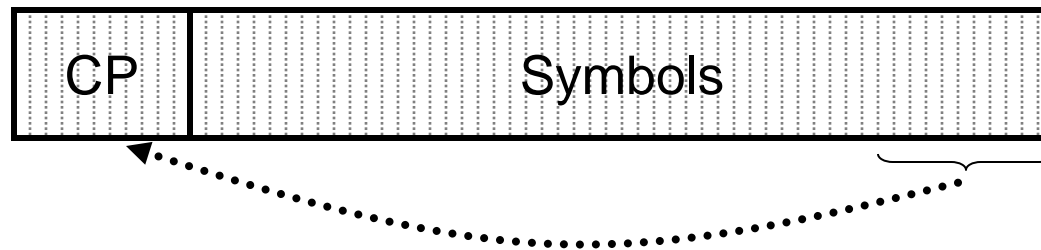
- For broadband multi-path channels, conventional time domain equalizers are impractical because of complexity.
  - Very long channel impulse response in the time domain.
  - Prohibitively large tap size for time domain filter.
- Using discrete Fourier transform (DFT), equalization can be done in the frequency domain.
- Because the DFT size does not grow linearly with the length of the channel response, the complexity of FDE is lower than that of the equivalent time domain equalizer for broadband channel.



# FDE

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- In DFT, frequency domain multiplication is equivalent to time domain circular convolution.
- Cyclic prefix (CP) longer than the channel response length is needed to convert linear convolution to circular convolution.

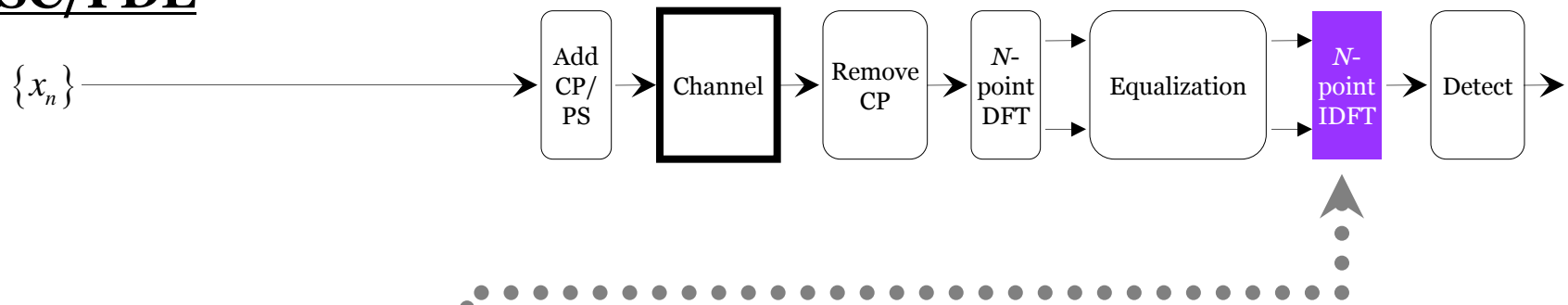


- Most of the time domain equalization techniques can be implemented in the frequency domain.
  - MMSE equalizer, DFE, turbo equalizer, and so on.
- References
  - M. V. Clark, “Adaptive Frequency-Domain Equalization and Diversity Combining for Broadband Wireless Communications,” *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, Oct. 1998
  - M. Tüchler *et al.*, “Linear Time and Frequency Domain Turbo Equalization,” *Proc. IEEE 53rd Veh. Technol. Conf. (VTC)*, vol. 2, May 2001
  - F. Pancaldi *et al.*, “Block Channel Equalization in the Frequency Domain,” *IEEE Trans. Commun.*, vol. 53, no. 3, Mar. 2005

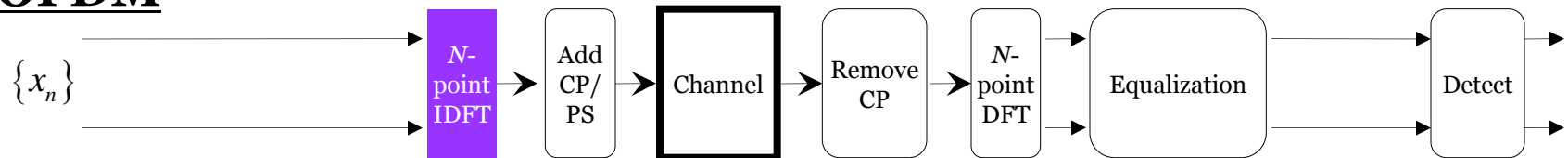


# Single Carrier with FDE

## SC/FDE



## OFDM



\* CP: Cyclic Prefix, PS: Pulse Shaping

- SC/FDE delivers performance similar to OFDM with essentially the same overall complexity, even for long channel delay.
- SC/FDE has advantage over OFDM in terms of:
  - Low PAPR.
  - Robustness to spectral null.
  - Less sensitivity to carrier frequency offset.
- Disadvantage to OFDM is that channel-adaptive subcarrier bit and power loading is not possible.

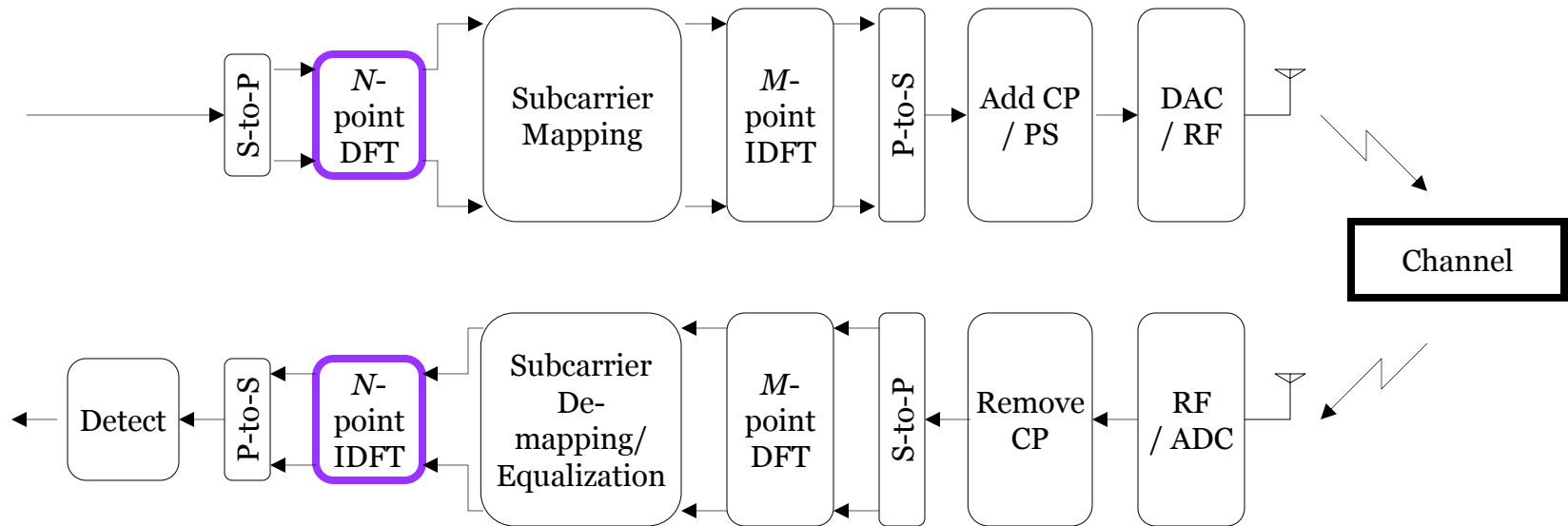
- References

- H. Sari *et al.*, “Transmission Techniques for Digital Terrestrial TV Broadcasting,” *IEEE Commun. Mag.*, vol. 33, no. 2, Feb. 1995, pp. 100-109.
  - D. Falconer *et al.*, “Frequency Domain Equalization for Single-Carrier Broadband Wireless Systems,” *IEEE Commun. Mag.*, vol. 40, no. 4, Apr. 2002, pp. 58-66.
- Single carrier FDMA (SC-FDMA) is an extension of SC/FDE to accommodate multiple-user access.

# Single Carrier FDMA

- SC-FDMA is a new multiple access technique.
  - Utilizes *single carrier modulation*, *DFT-spread orthogonal frequency multiplexing*, and *frequency domain equalization*.
- It has similar structure and performance to OFDMA.
- SC-FDMA is currently adopted as the uplink multiple access scheme in 3GPP LTE.

# TX & RX structure of SC-FDMA



SC-FDMA: ☐ + ☒

OFDMA: ☐

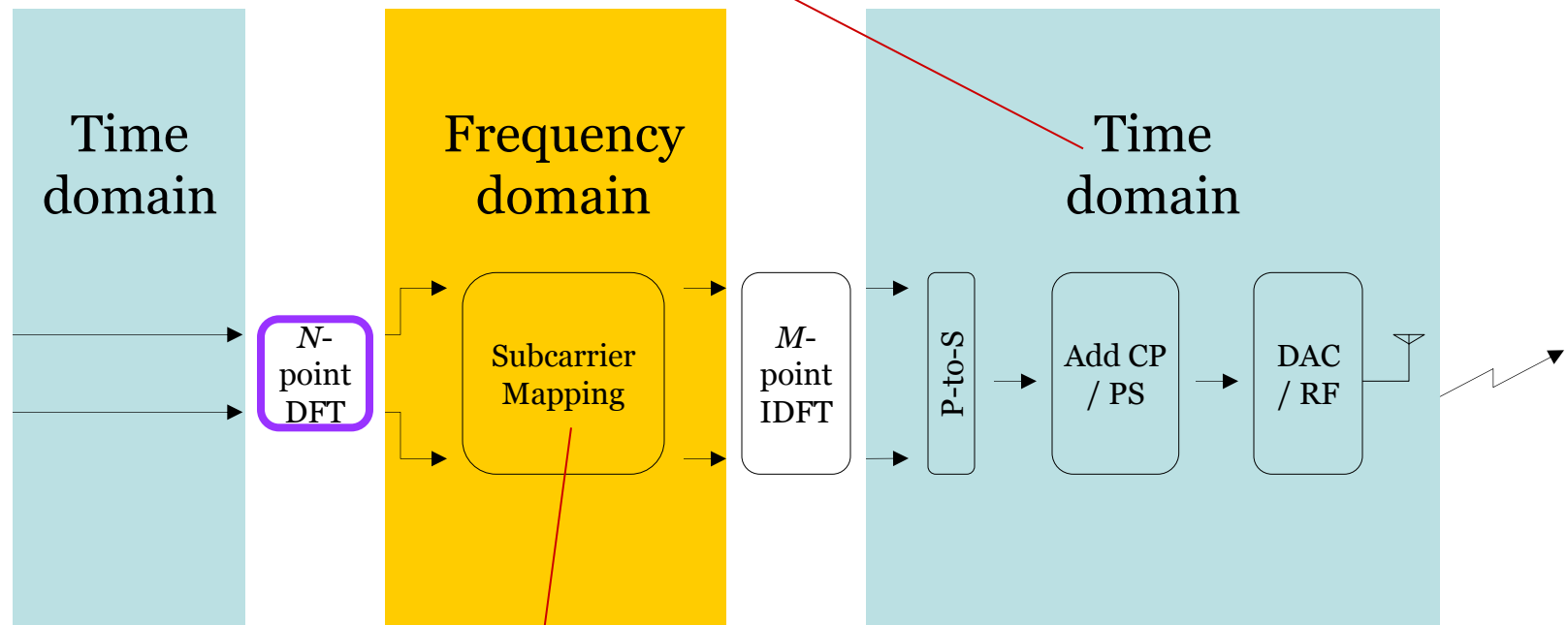
\*  $N < M$

\* S-to-P: Serial-to-Parallel

\* P-to-S: Parallel-to-Serial

# Why “Single Carrier” “FDMA”?

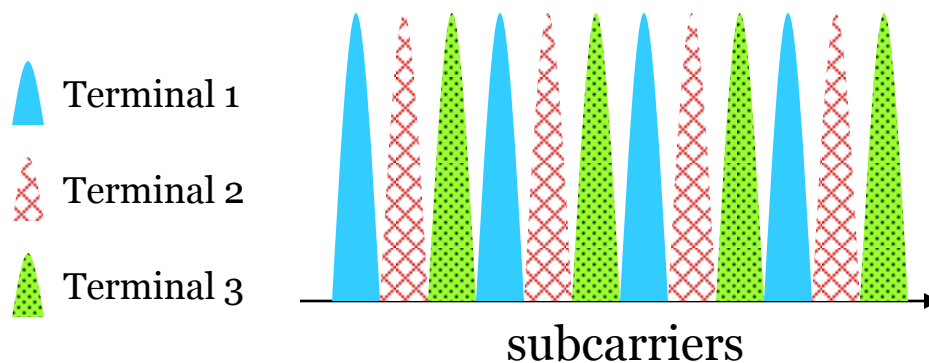
**“Single Carrier”**: Sequential transmission of the symbols over a single frequency carrier.



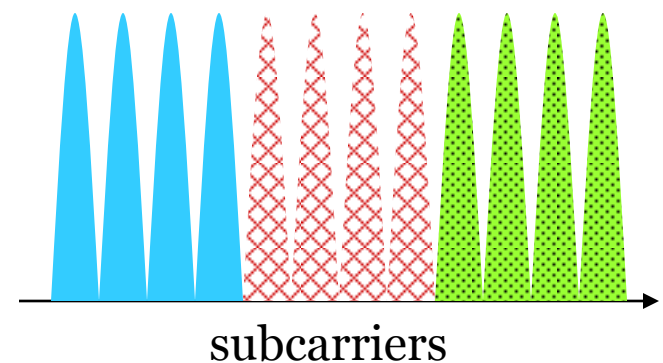
**“FDMA”**: User multiplexing in the frequency domain.

# Subcarrier Mapping

- Data block size ( $N$ ) = 4, Number of users ( $Q$ ) = 3, Number of subcarriers ( $M$ ) = 12.



**Distributed Mode**



**Localized Mode**

# SC-FDMA and OFDMA

- Similarities

- Block-based modulation and use of CP.
- Divides the transmission bandwidth into smaller subcarriers.
- Channel inversion/equalization is done in the frequency domain.
- SC-FDMA is regarded as *DFT-precoded* or *DFT-spread* OFDMA.

- Dissimilarities

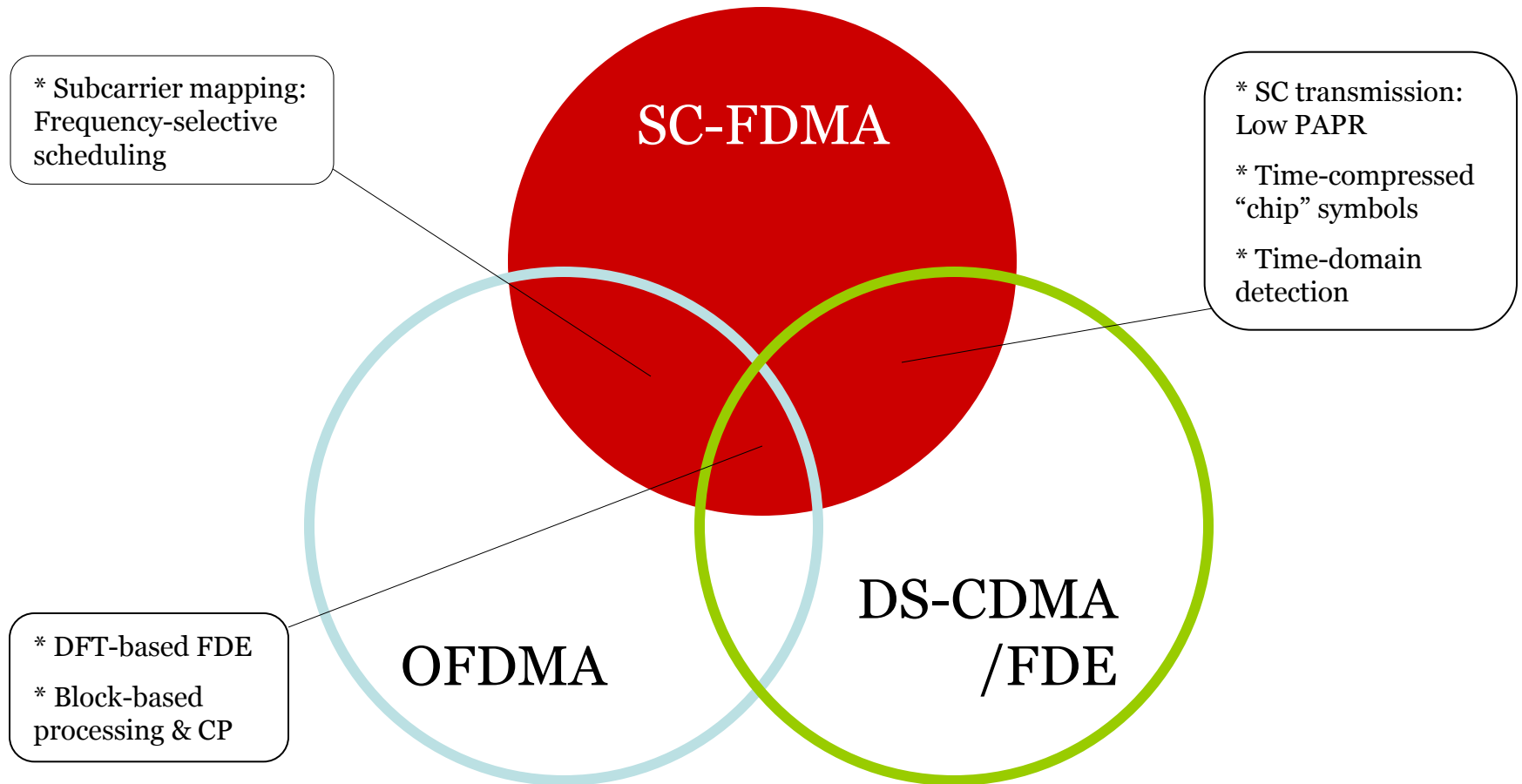
- Lower transmit peak power.
- Equalization performance.
- Multi-carrier MIMO receiver algorithm.



# SC-FDMA and DS-CDMA

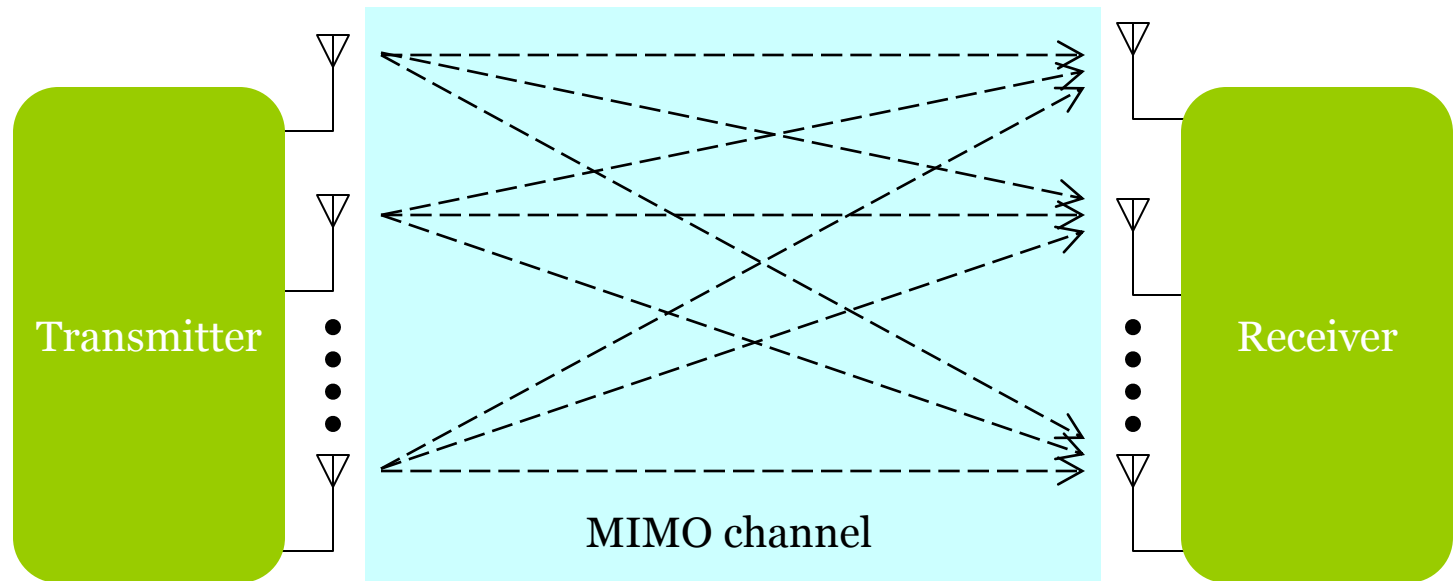
- In terms of bandwidth expansion, SC-FDMA is very similar to DS-CDMA system using orthogonal spreading codes.
  - Both spread narrowband data into broader band.
  - Time symbols are compressed into “chips” after modulation.
  - Spreading gain (processing gain) is achieved.

# SC-FDMA: Comparison



# MIMO

- Multiple input multiple output (MIMO) technique improves communication link quality and capacity by using multiple transmit and receive antennas.
- Two types of gain; **spatial diversity** gain and **spatial multiplexing** gain.



- Spatial diversity

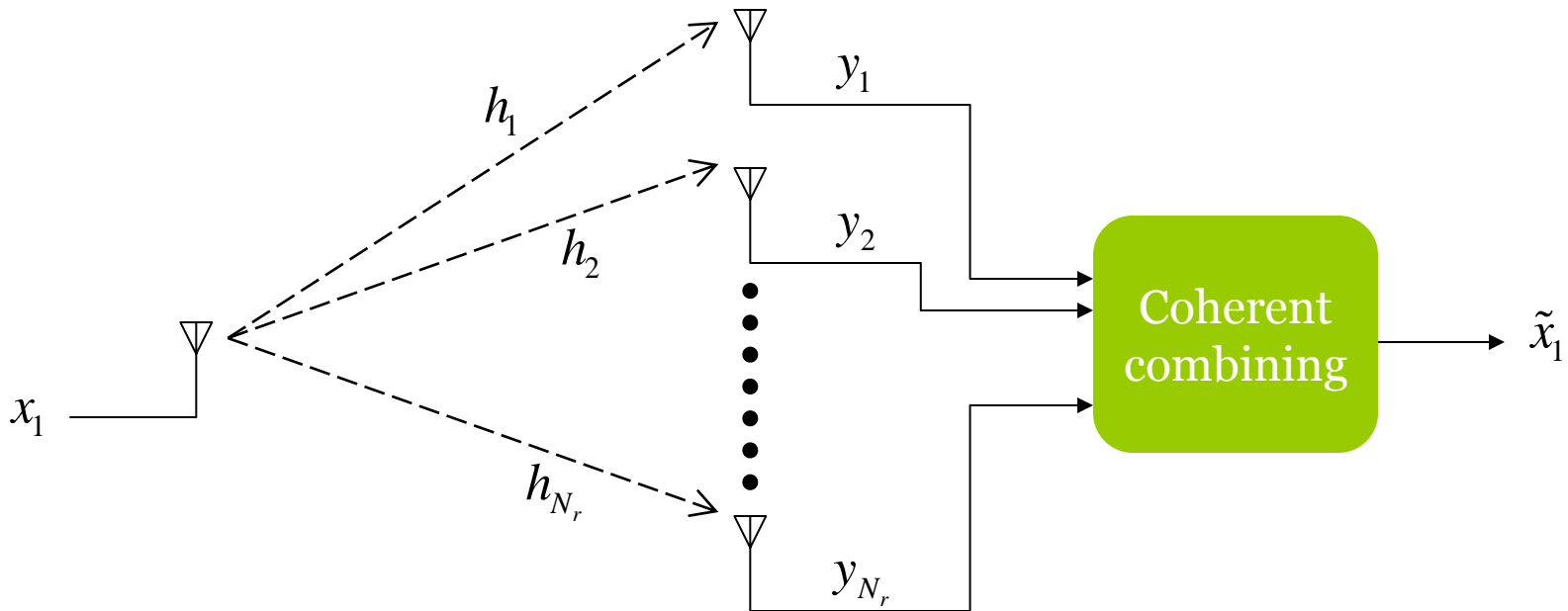
- Improves link quality (SNR) by combining multiple independently faded signal replicas.
- With  $N_t$  Tx and  $N_r$  Rx antennas,  $N_t \times N_r$  diversity gain is achievable.
- Smart antenna, Alamouti transmit diversity, and space-time coding.

- Spatial multiplexing

- Increases data throughput by sending multiple streams of data through parallel spatial channels.
- With  $N_t$  Tx and  $N_r$  Rx antennas,  $\min(N_t, N_r)$  multiplexing gain is achievable.
- BLAST (Bell Labs Space-Time Architecture) and unitary precoding.

# Basic Idea of Spatial Diversity

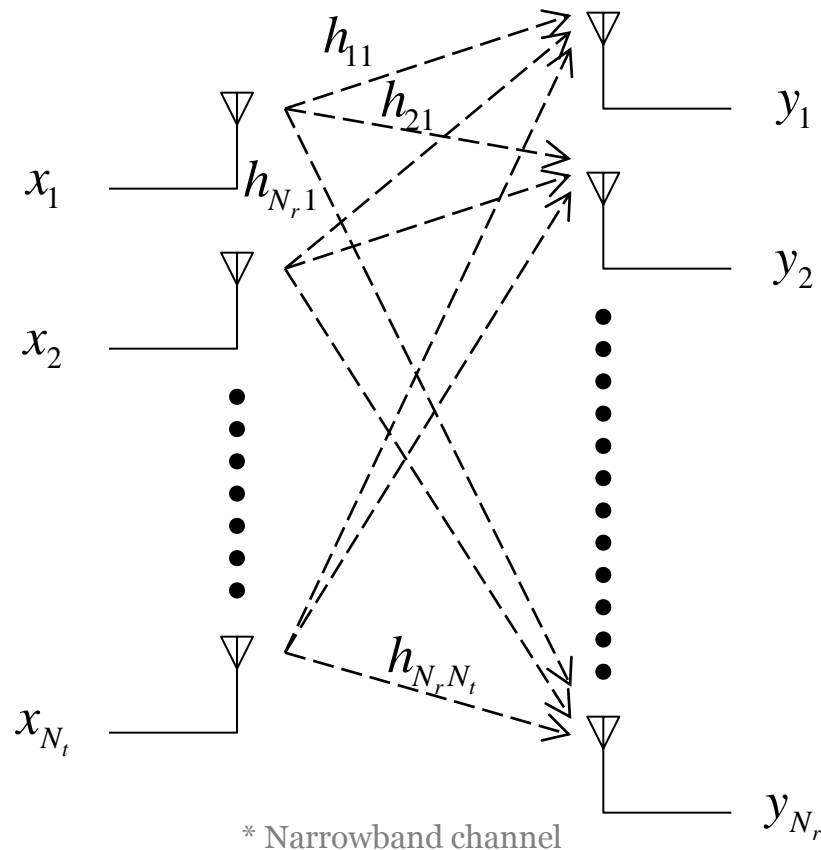
- Coherent combining of multiple copies



\* Narrowband channel

# Basic Idea of Spatial Multiplexing

- Parallel decomposition of a MIMO channel



# Basic Idea of Spatial Multiplexing

- cont.

$$\begin{pmatrix} y_1 \\ \vdots \\ y_{N_r} \end{pmatrix} = \begin{pmatrix} h_{11} & \cdots & h_{1N_t} \\ \vdots & \ddots & \vdots \\ h_{N_r 1} & \cdots & h_{N_r N_t} \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ \vdots \\ x_{N_t} \end{pmatrix} + \begin{pmatrix} n_1 \\ \vdots \\ n_{N_r} \end{pmatrix}$$

$$\Rightarrow \underline{y} = \underline{H} \cdot \underline{x} + \underline{n}$$

← Singular value decomposition (SVD)

$$\underline{H} = \underline{U} \underline{D} \underline{V}^H \Rightarrow \underline{y} = \underline{U} \underline{D} \underline{V}^H \underline{x} + \underline{n}$$

$$\underline{U}^H \underline{y} = \underbrace{\underline{U}^H \underline{U}}_{=I} \underline{D} \underline{V}^H \underline{x} + \underline{U}^H \underline{n}$$

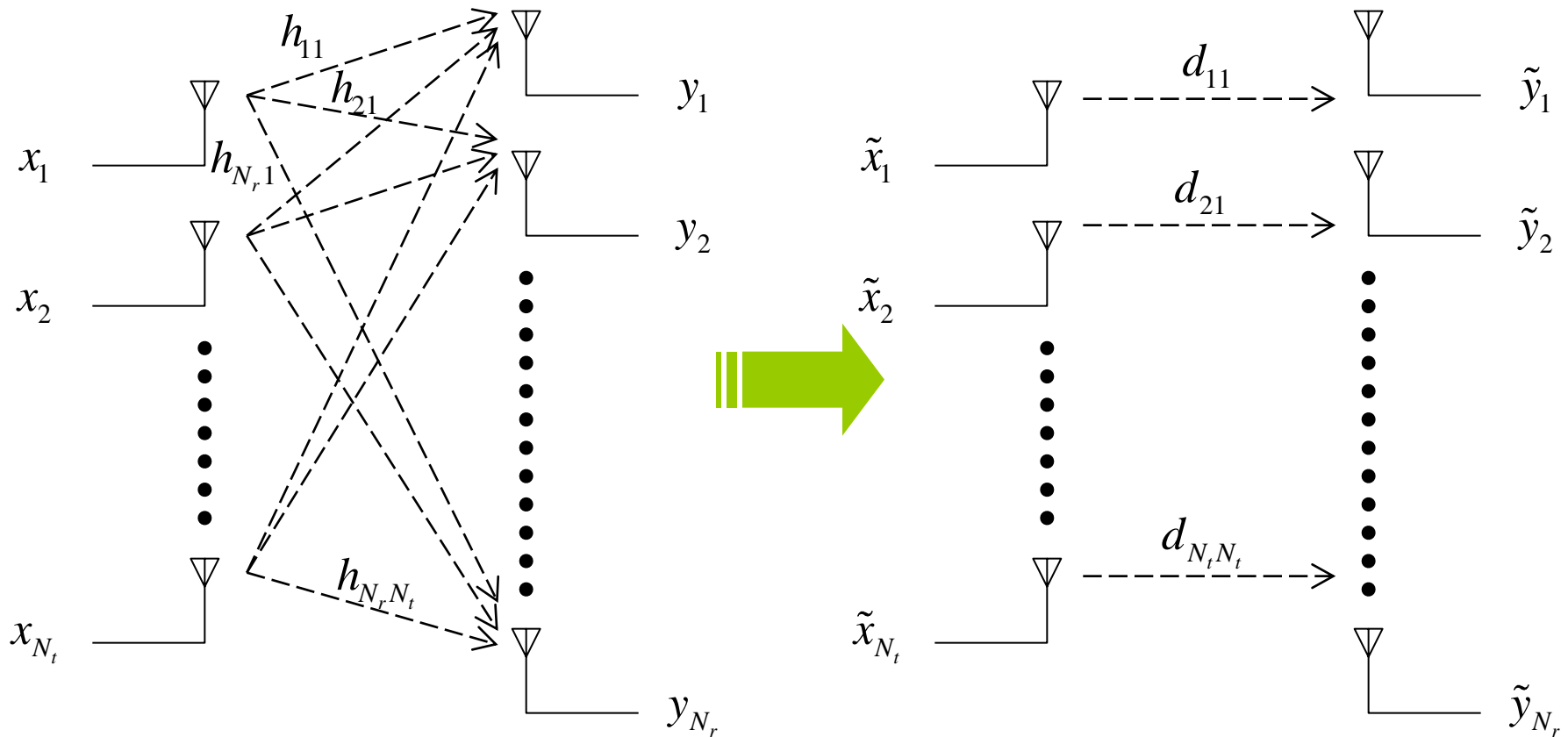
$$\underbrace{\underline{U}^H \underline{y}}_{\tilde{\underline{y}}} = \underline{D} \underbrace{\underline{V}^H \underline{x}}_{\tilde{\underline{x}}} + \underbrace{\underline{U}^H \underline{n}}_{\tilde{\underline{n}}}$$

$$\tilde{\underline{y}} = \underline{D} \tilde{\underline{x}} + \tilde{\underline{n}}$$

← Diagonal matrix

# Basic Idea of Spatial Multiplexing

- cont.



\*  $N_t < N_r$



# Multicarrier MIMO Spatial Multiplexing

- Frequency domain for  $k^{\text{th}}$  subcarrier

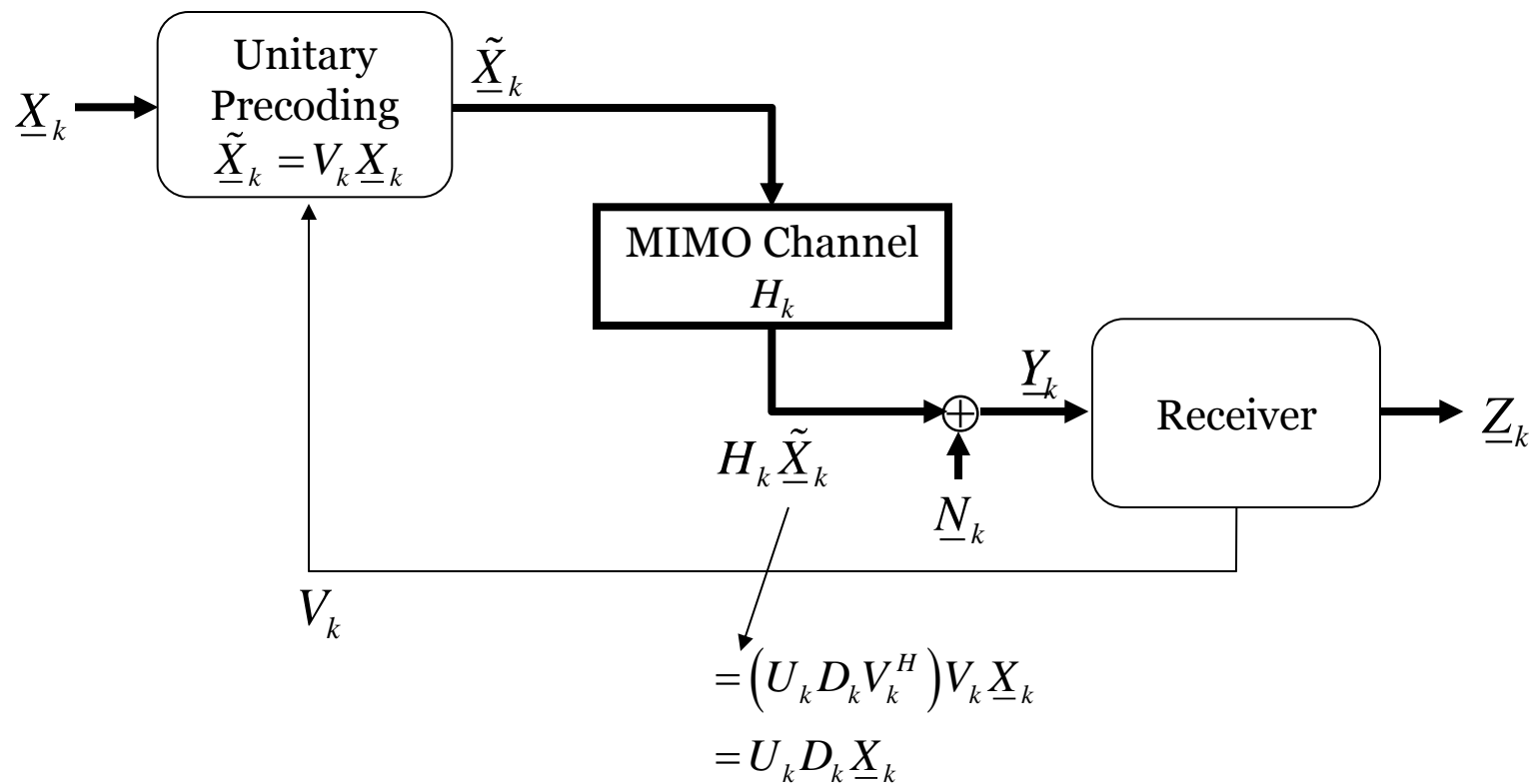
$$\underbrace{\begin{pmatrix} Y_{1,k} \\ \vdots \\ Y_{N_r,k} \end{pmatrix}}_{=\underline{Y}_k} = \underbrace{\begin{pmatrix} H_{11,k} & \cdots & H_{1N_t,k} \\ \vdots & \ddots & \vdots \\ H_{N_r1,k} & \cdots & H_{N_rN_t,k} \end{pmatrix}}_{=H_k} \cdot \underbrace{\begin{pmatrix} X_{1,k} \\ \vdots \\ X_{N_t,k} \end{pmatrix}}_{=\underline{X}_k} + \underbrace{\begin{pmatrix} N_{1,k} \\ \vdots \\ N_{N_r,k} \end{pmatrix}}_{=\underline{N}_k}$$

$$\Rightarrow \underline{Y}_k = H_k \cdot \underline{X}_k + \underline{N}_k$$

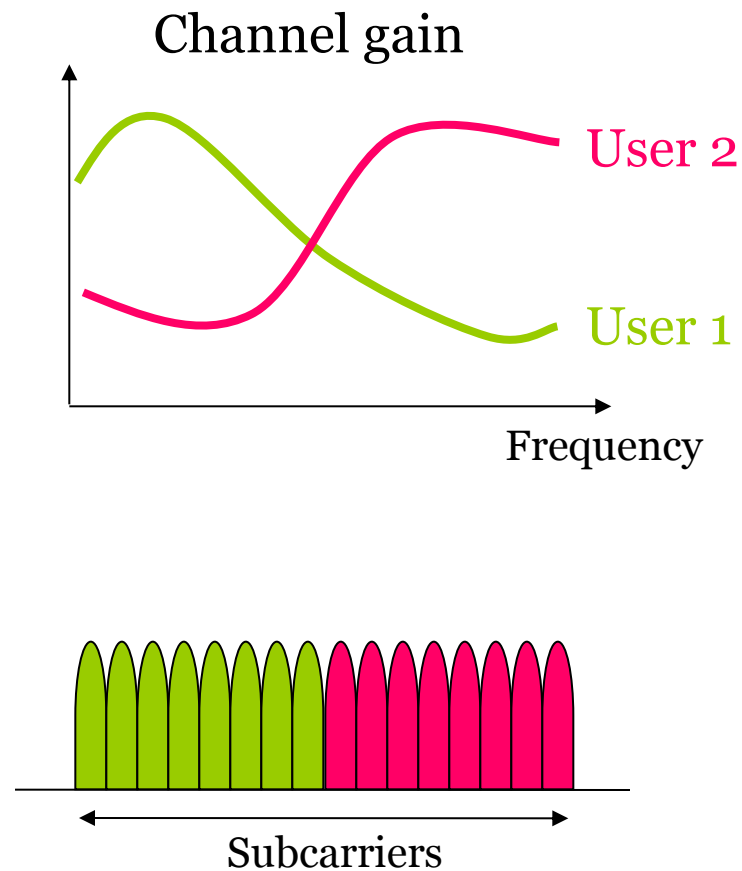
$$\Rightarrow \tilde{\underline{Y}}_k = D_k \tilde{\underline{X}}_k + \tilde{\underline{N}}_k$$

$$\begin{cases} \tilde{\underline{Y}}_k = U_k^H \underline{Y}_k \\ \tilde{\underline{X}}_k = V_k^H \underline{X}_k \\ \tilde{\underline{N}}_k = U_k^H \underline{N}_k \end{cases}$$

# Unitary Precoding



# Channel-Dependent Scheduling



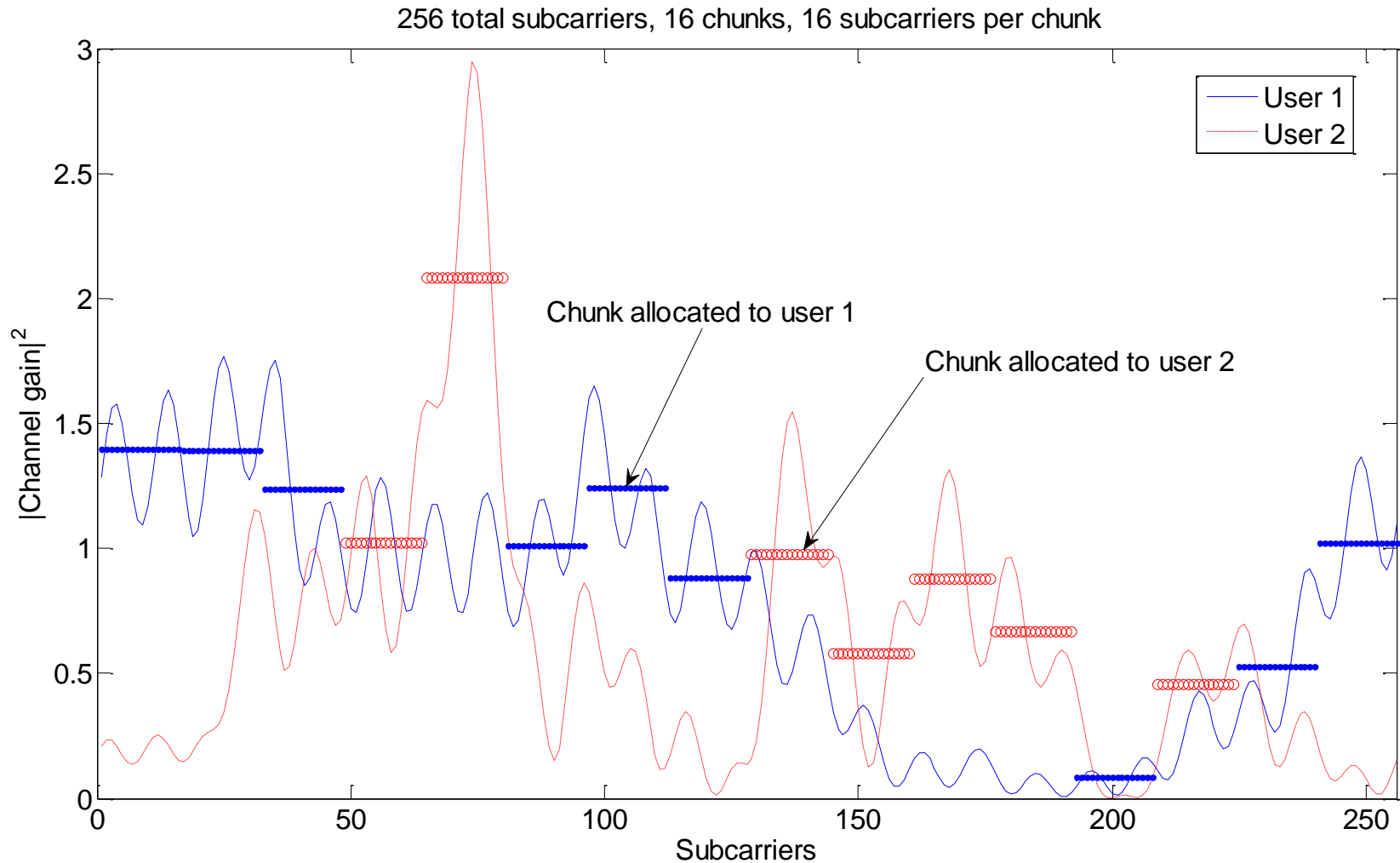
# Channel-Dependent Scheduling

- cont.

- Assign subcarriers to a user in good channel condition.
- Two subcarrier mapping schemes have advantages over each other.
  - Distributed: Frequency diversity.
  - Localized: Frequency selective gain with CDS.
- CDS is a scheme to find an optimal set of subcarriers that are allocated to each user that maximizes some utility based on each user's channel response.

# Channel-Dependent Scheduling

- cont.



# Outline

Wireless Background

4G Enabling Technologies

**Long Term Evolution (LTE)**

LTE-Advanced

Summary and References

# LTE: Long Term Evolution

- Standardized by 3GPP (3rd Generation Partnership Project).
- 3GPP is a partnership of 6 regional standards organizations.
  - ARIB (Japan)
  - ATIS (USA)
  - CCSA (China)
  - ETSI (Europe)
  - TTA (South Korea)
  - TTC (Japan)



A GLOBAL INITIATIVE

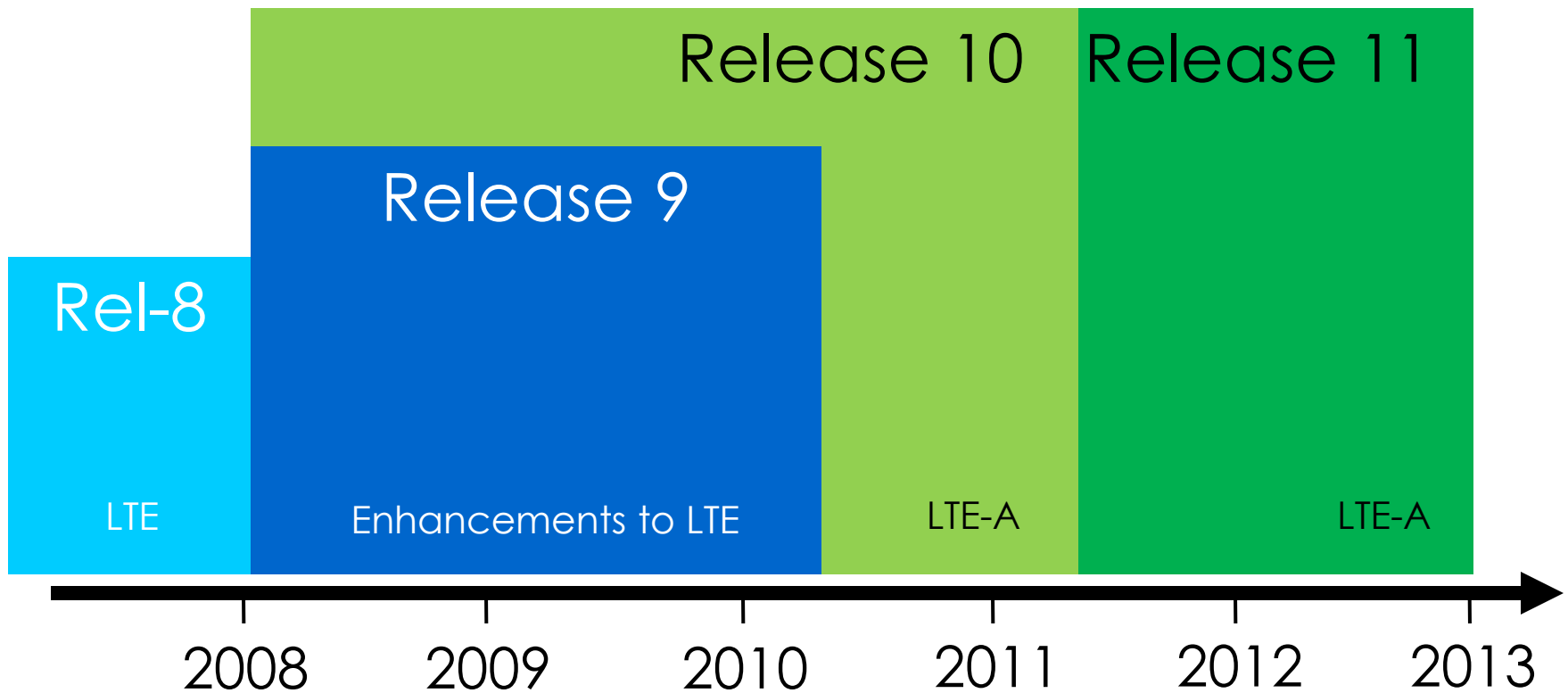
# 3GPP Evolution

- Release 99 (2000): UMTS/WCDMA
- Rel-5 (2002): HSDPA
- Rel-6 (2005): HSUPA
- Rel-7 (2007) and beyond: HSPA+
- **Long Term Evolution (LTE)**
  - 3GPP work on the Evolution started in November 2004.
  - Standardized in the form of Rel-8 (Dec. 2008).
- **LTE-Advanced (LTE-A)**
  - More bandwidth (up to 100 MHz) and backward compatible with LTE.
  - Standardized in the form of Rel-10 (Mar. 2011).
  - Meets IMT-Advanced requirements: Real '4G'.





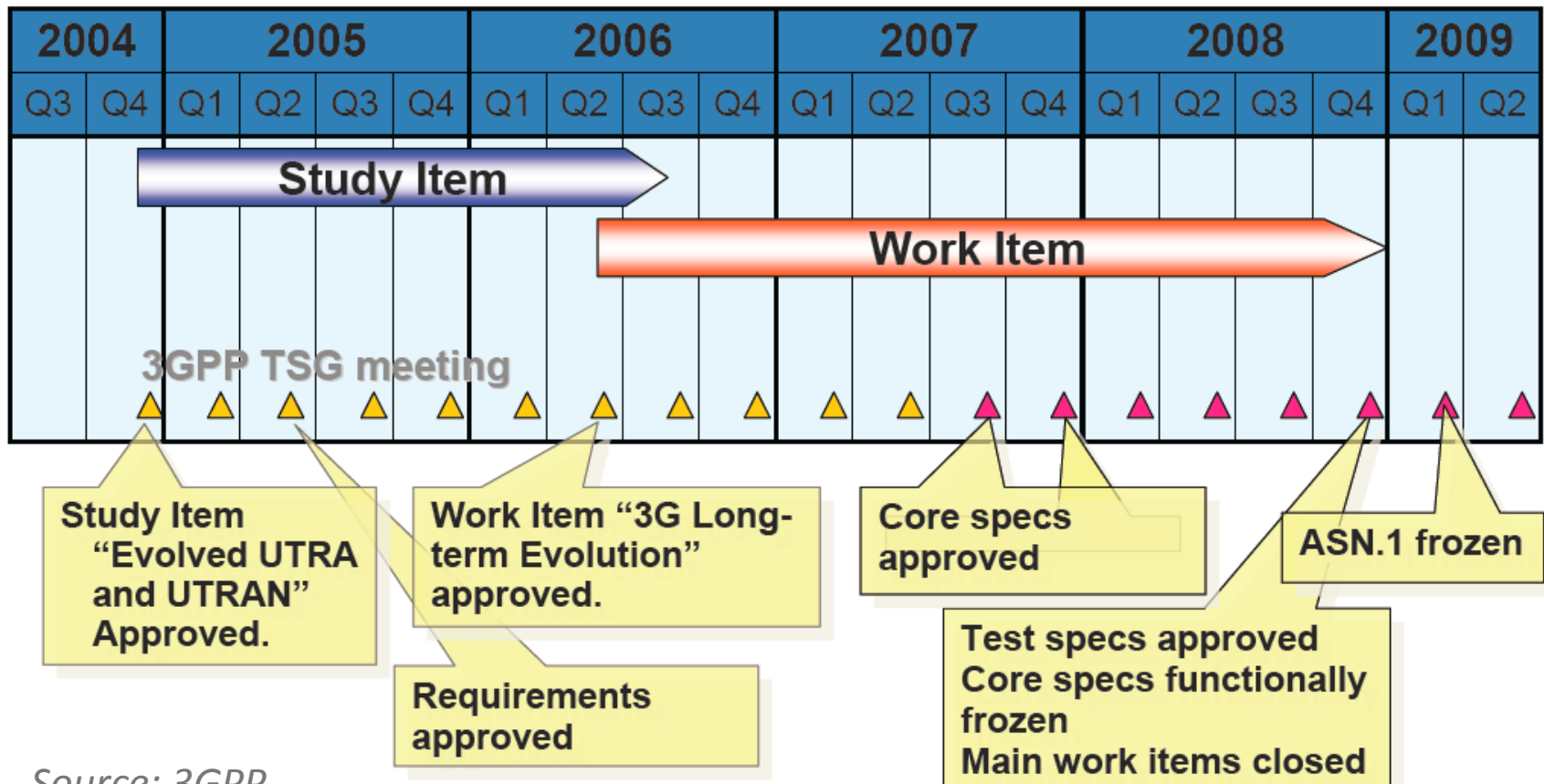
# LTE Standardization Status



Source: 3GPP

# Detailed LTE Standardization Process

## LTE Release 8 Standardisation History



Source: 3GPP

# Commercialization Status

- 156 commercial LTE networks (GSA, Mar. 19, 2013)
  - TeliaSonera: World's first commercial LTE network launched in Dec. 2009 in Stockholm and Oslo.
    - 36.1Mbps avg DL, 23ms avg latency in real world measurement (Eptiro )
  - Verizon Wireless: US commercial LTE network launched in Dec. 2010 in 38 cities and 60 airports.
    - 500,000 subscribers at the end of Q1, 2011
    - Sold 1.2 million LTE devices during Q2, 2011
  - NTT DOCOMO: Launched in Dec. 24, 2010 in the Tokyo, Nagoya, & Osaka areas.

# Requirements of LTE

- Peak data rate
  - 100 Mbps DL/ 50 Mbps UL within 20 MHz bandwidth.
- Up to 200 active users in a cell (5 MHz)
- Less than 5 ms user-plane latency
- Mobility
  - Optimized for 0 ~ 15 km/h.
  - 15 ~ 120 km/h supported with high performance.
  - Supported up to 350 km/h or even up to 500 km/h.
- Enhanced multimedia broadcast multicast service (E-MBMS)
- Spectrum flexibility: 1.25 ~ 20 MHz
- Enhanced support for end-to-end QoS

# Key Features of LTE (Rel-8)

- Spectrum flexibility: 1.25 ~ 20 MHz (100 MHz for LTE-A)
- Multicarrier-based radio air interface
  - OFDM/OFDMA and SC-FDMA
- Support for both FDD and TDD spectrums
- Active interference avoidance and coordination
- Peak data rate (theoretical max., TR 25.912)
  - Downlink (DL): **326.4 Mbps** (20 MHz, 4x4 MIMO, 64-QAM)
  - Uplink (UL): **86.4 Mbps** (20 MHz, no MIMO, 64-QAM)

# LTE Device Category

Category		1	2	3	4	5
Peak rate (Mbps)	DL	10	50	100	150	300
	UL	5	25	50	50	75
RF bandwidth		20 MHz				
Modulation	DL	QPSK, 16-QAM, 64-QAM				
	UL	QPSK, 16-QAM				QPSK, 16-QAM, 64-QAM
2 Rx diversity		Assumed in performance requirements.				
2x2 MIMO (DL)		X	O			
4x4 MIMO (DL)		X				O

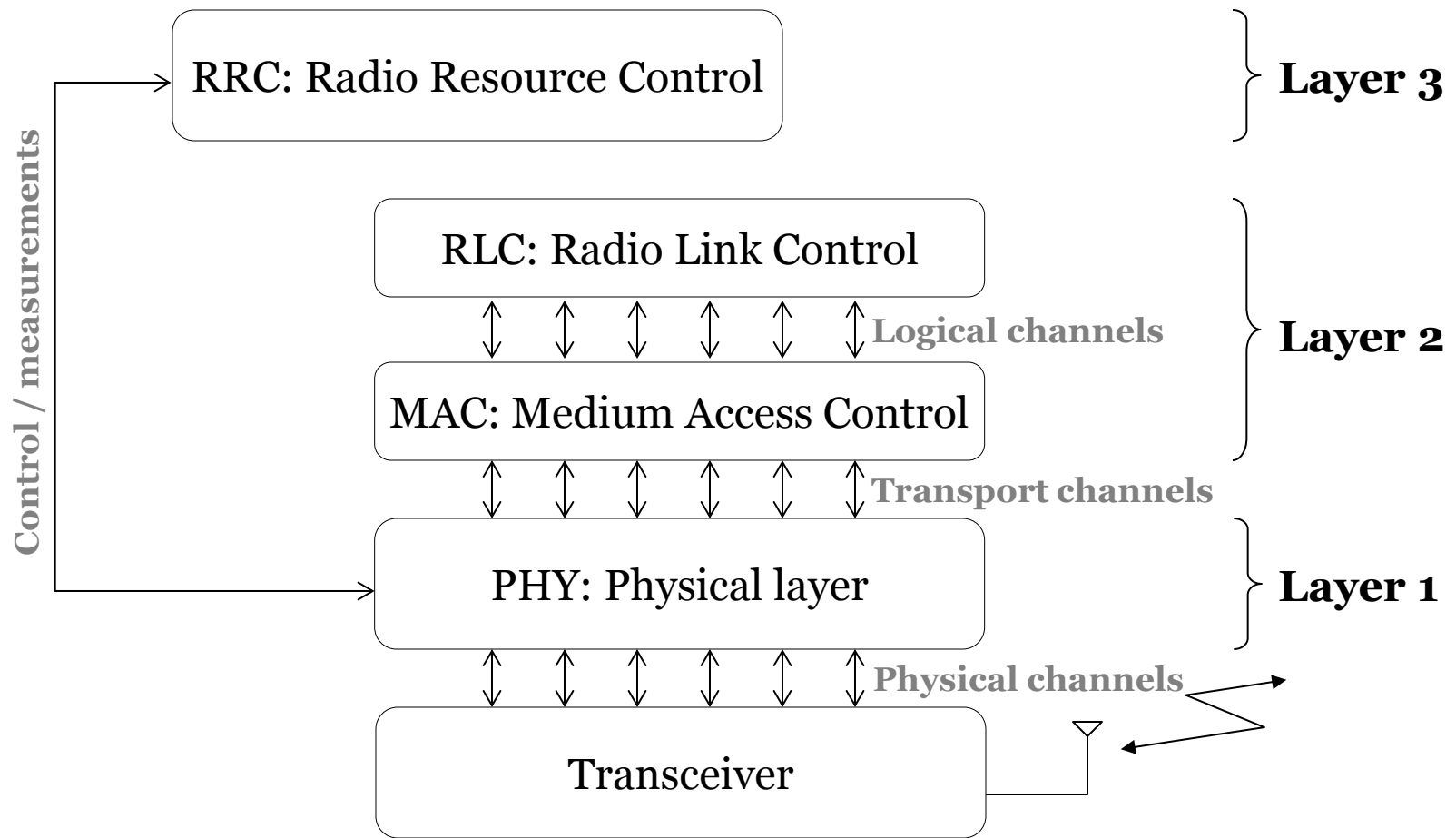
Source: 3GPP

# LTE Standard Specifications

- Freely downloadable from <http://www.3gpp.org/ftp/Specs/html-info/36-series.htm>

Specification index	Description of contents
TS 36.1xx	Equipment requirements: Terminals, base stations, and repeaters.
TS 36.2xx	Physical layer.
TS 36.3xx	Layers 2 and 3: Medium access control, radio link control, and radio resource control.
TS 36.4xx	Infrastructure communications including base stations and mobile management entities.
TS 36.5xx	Conformance testing.

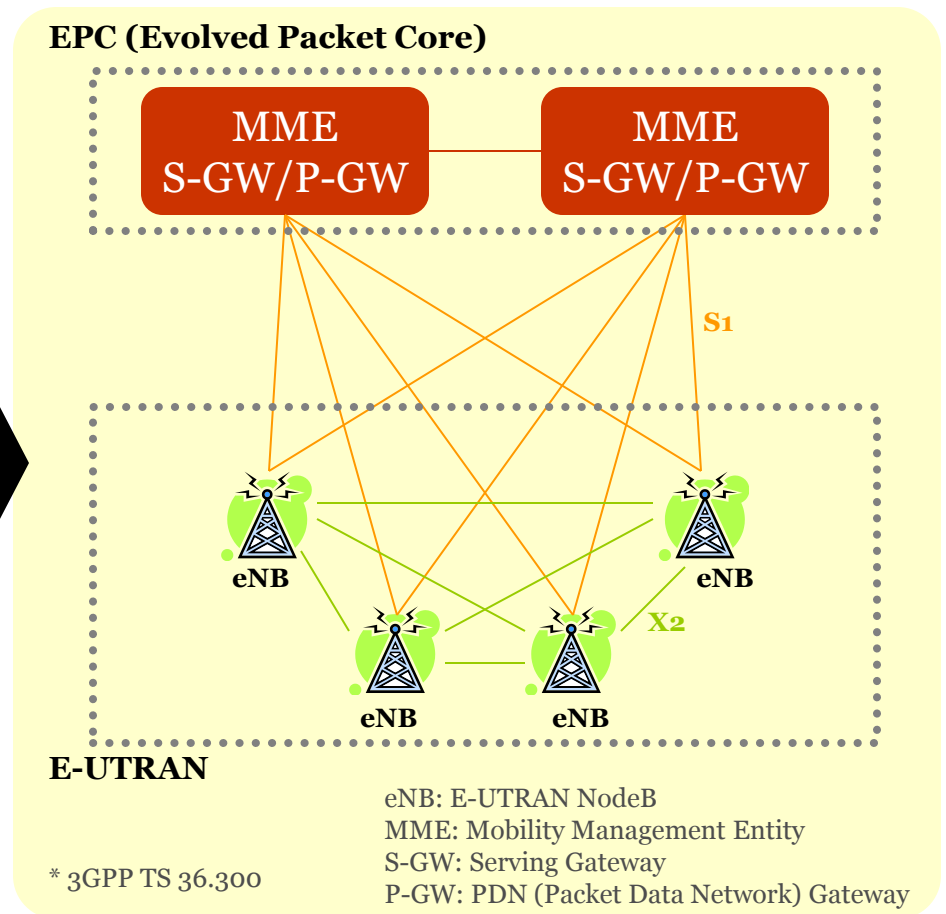
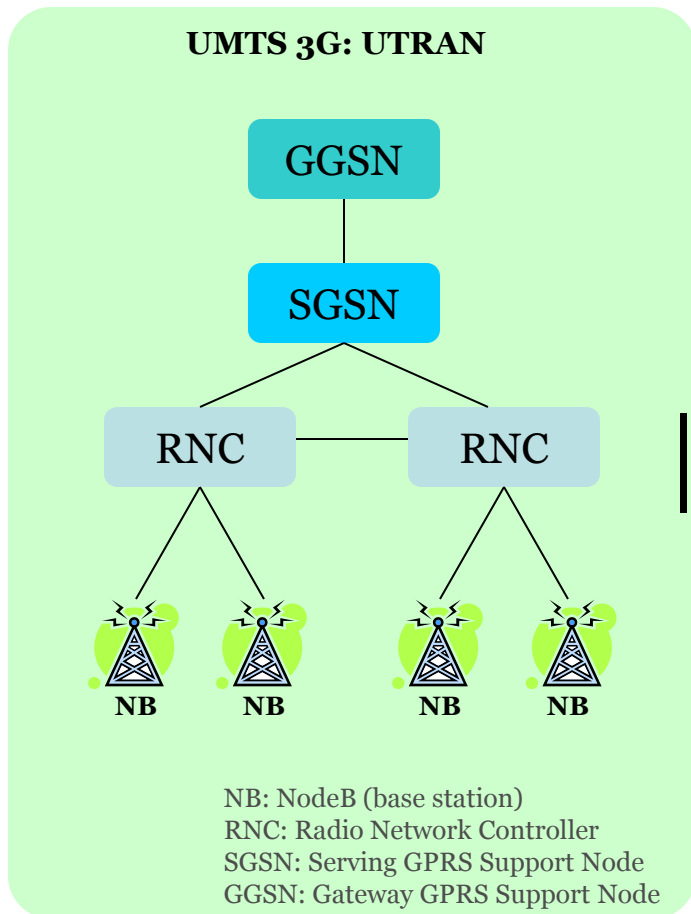
# Protocol Architecture





# LTE Network Architecture

- E-UTRAN (Evolved Universal Terrestrial Radio Access Network)

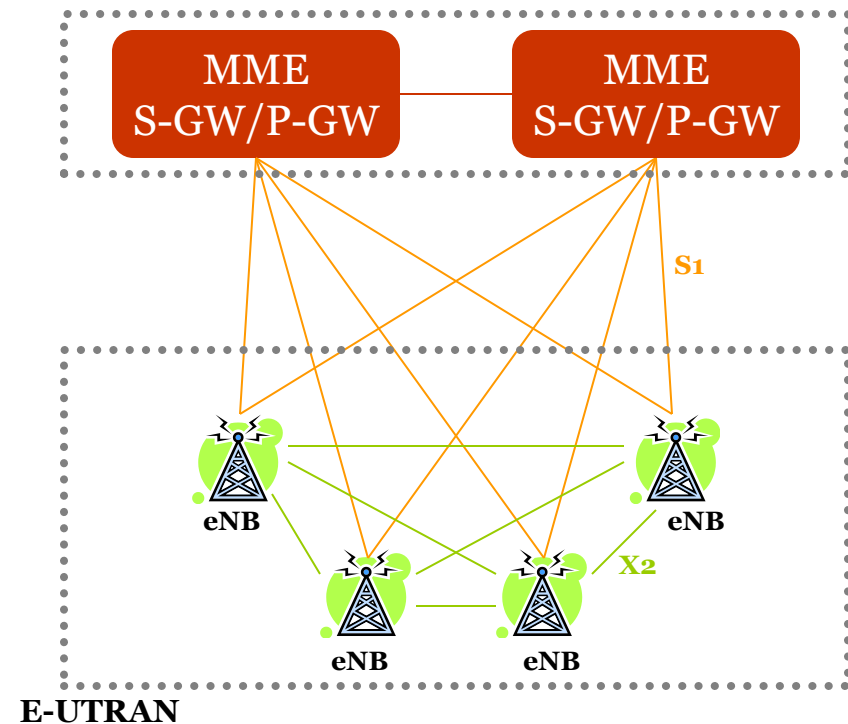


# LTE Network Architecture

- cont.

- eNB
  - All radio interface-related functions
- MME
  - Manages mobility, UE identity, and security parameters.
- S-GW
  - Node that terminates the interface towards E-UTRAN.
- P-GW
  - Node that terminates the interface towards PDN.

## EPC (Evolved Packet Core)

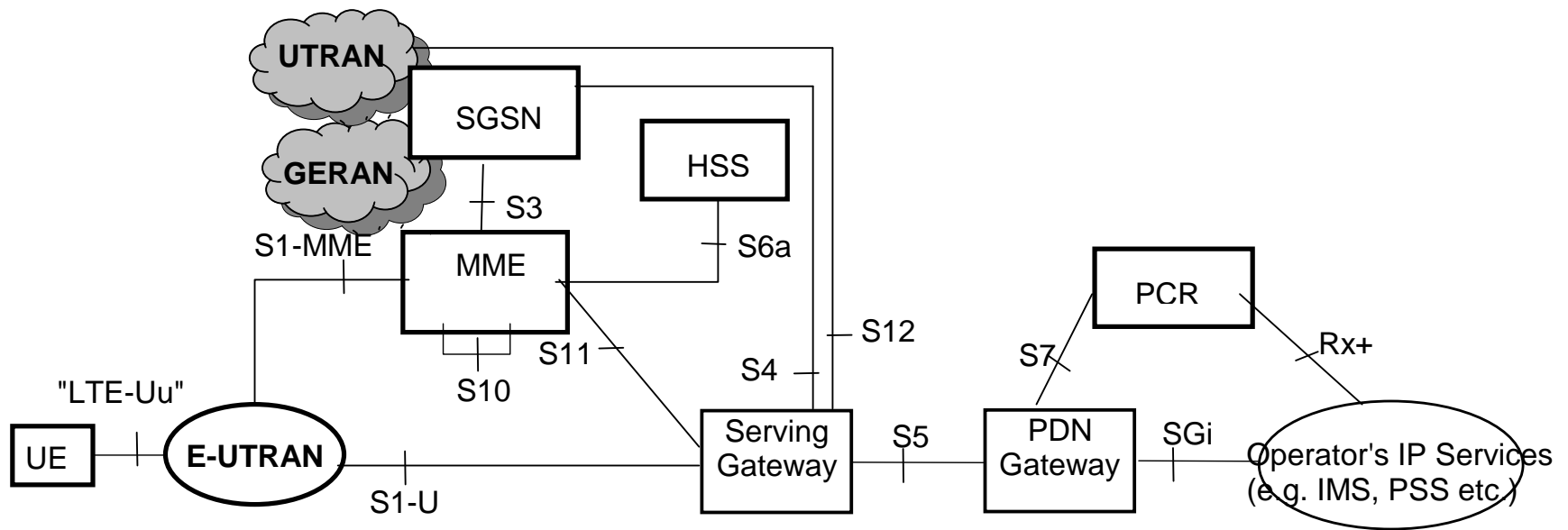


\* 3GPP TS 36.300

eNB: E-UTRAN NodeB  
MME: Mobility Management Entity  
S-GW: Serving Gateway  
P-GW: PDN (Packet Data Network) Gateway

# LTE Network Architecture

- cont.



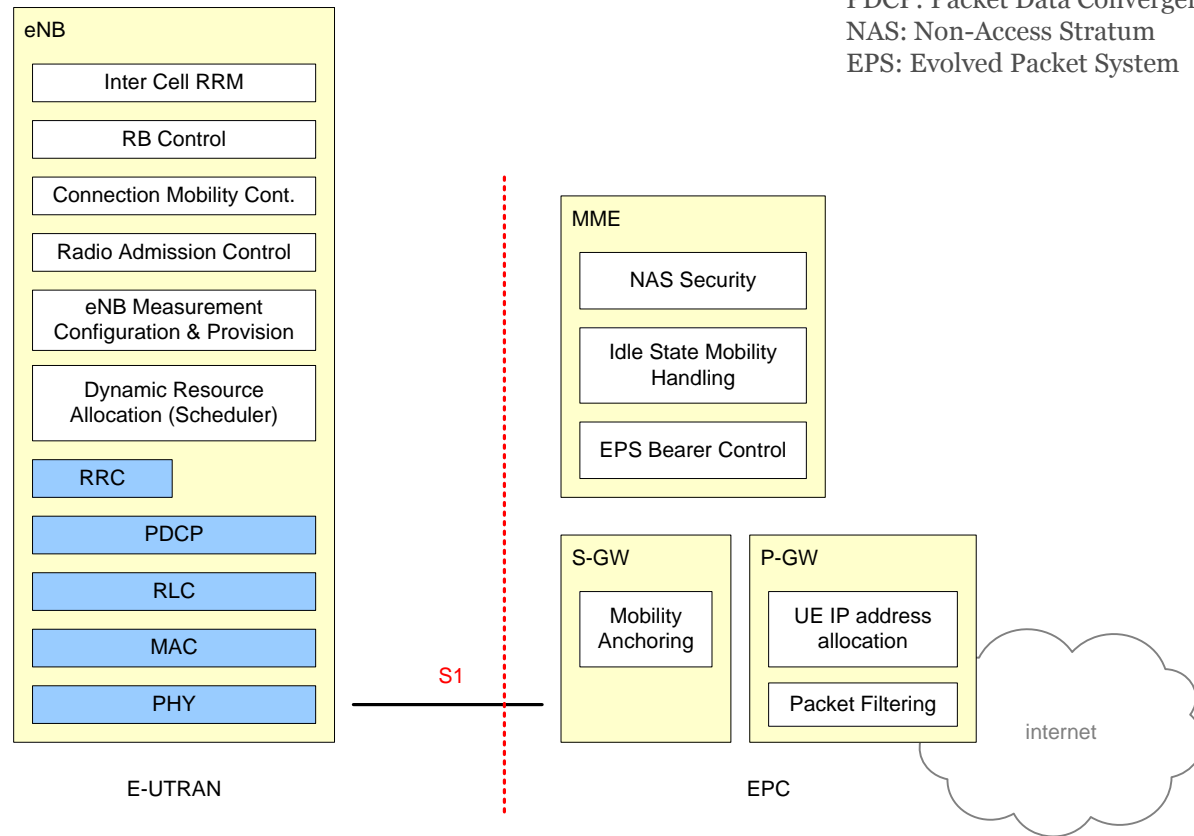
\* Non-roaming architecture

\* 3GPP TS 23.401

# LTE Network Architecture

- cont.

RRM: Radio Resource Management  
RB: Radio Bearer  
RRC: Radio Resource Control  
PDCP: Packet Data Convergence Protocol  
NAS: Non-Access Stratum  
EPS: Evolved Packet System

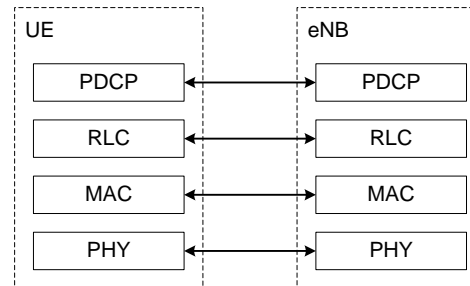


\* 3GPP TS 36.300

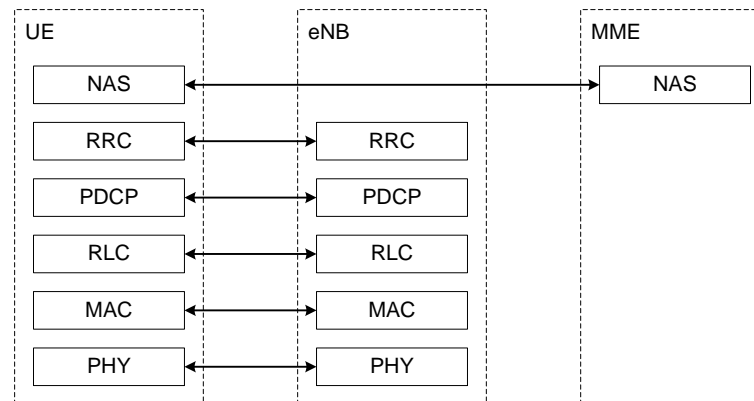
# LTE Network Architecture

- cont.

## User-Plane Protocol Stack



## Control-Plane Protocol Stack



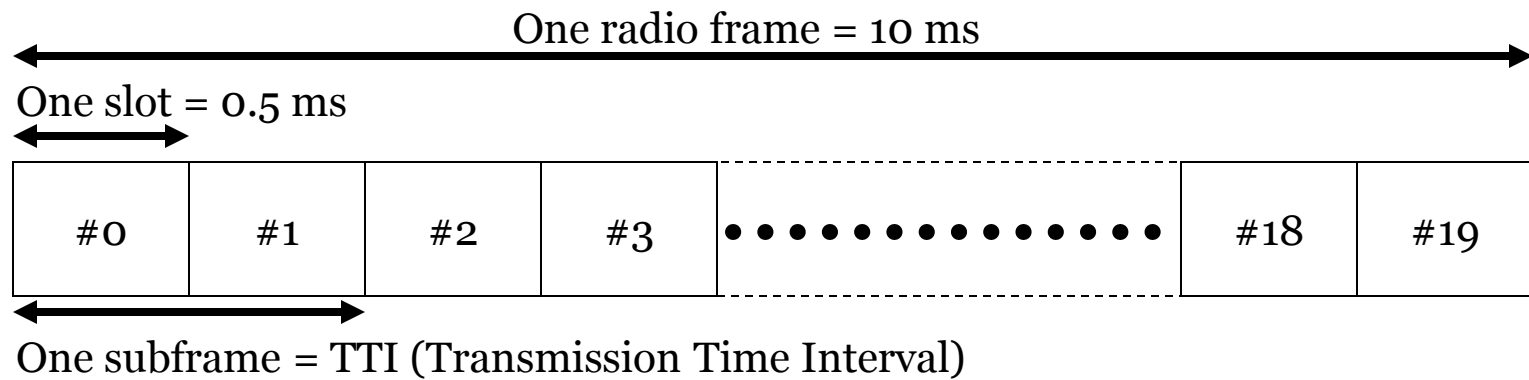
\* 3GPP TS 36.300

# Frame Structure

- Two radio frame structures defined.
  - Frame structure type 1 (FS1): FDD.
  - Frame structure type 2 (FS2): TDD.
- A radio frame has duration of 10 ms.
- A resource block (RB) spans 12 subcarriers over a slot duration of 0.5 ms. One subcarrier has bandwidth of 15 kHz, thus 180 kHz per RB.

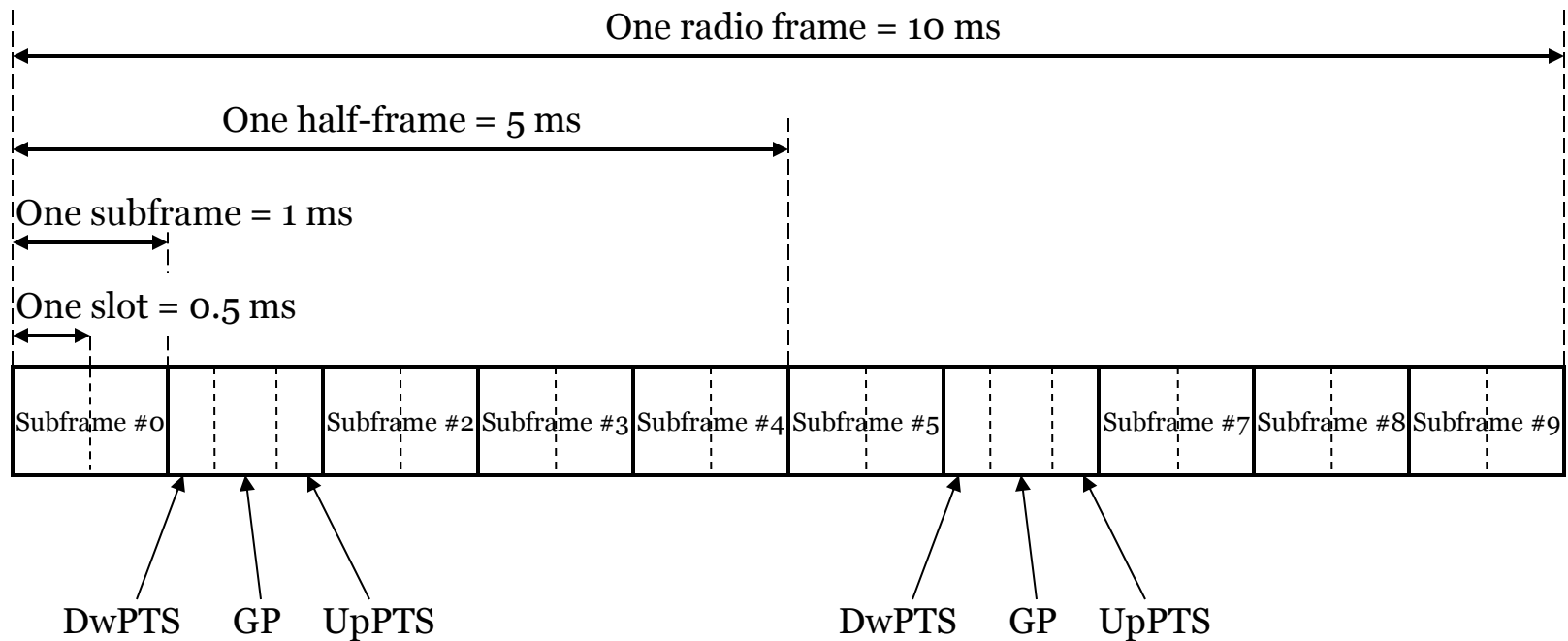
# Frame Structure Type 1

- FDD frame structure



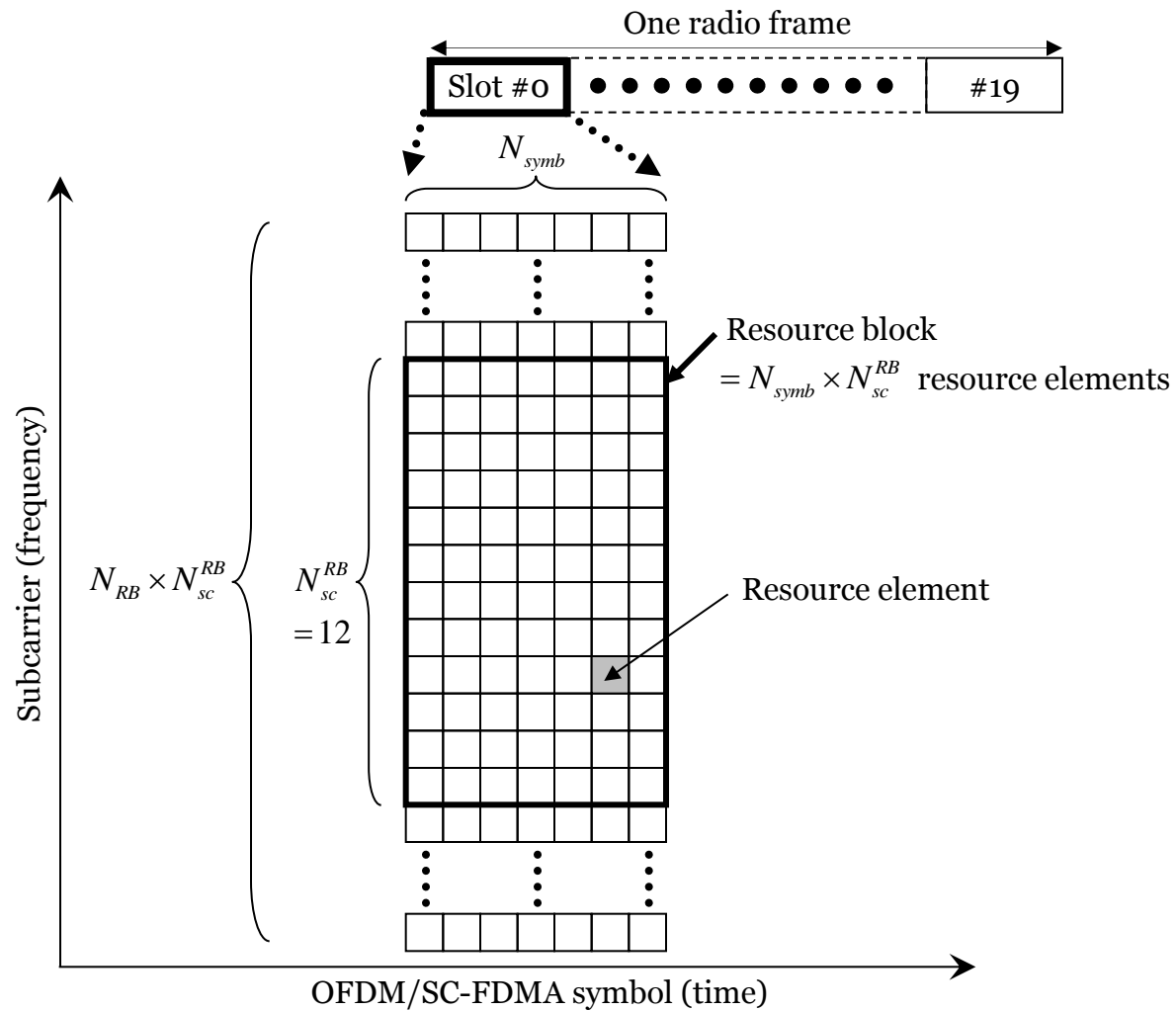
# Frame Structure Type 2

- TDD frame structure





# Resource Grid



# Length of CP

Configuration	$N_{\text{symb}}$
Normal CP	7
Extended CP	6
Extended CP ( $\Delta f = 7.5$ kHz) <sup>†</sup>	3

Configuration	CP length $N_{\text{CP},l}$ [samples]
Normal CP	160 ( $\approx 5.21$ $\mu\text{s}$ ) for $l = 0$ 144 ( $\approx 4.69$ $\mu\text{s}$ ) for $l = 1, 2, \dots, 6$
Extended CP	512 ( $\approx 16.67$ $\mu\text{s}$ ) for $l = 0, 1, \dots, 5$
Extended CP ( $\Delta f = 7.5$ kHz) <sup>†</sup>	1024 ( $\approx 33.33$ $\mu\text{s}$ ) for $l = 0, 1, 2$

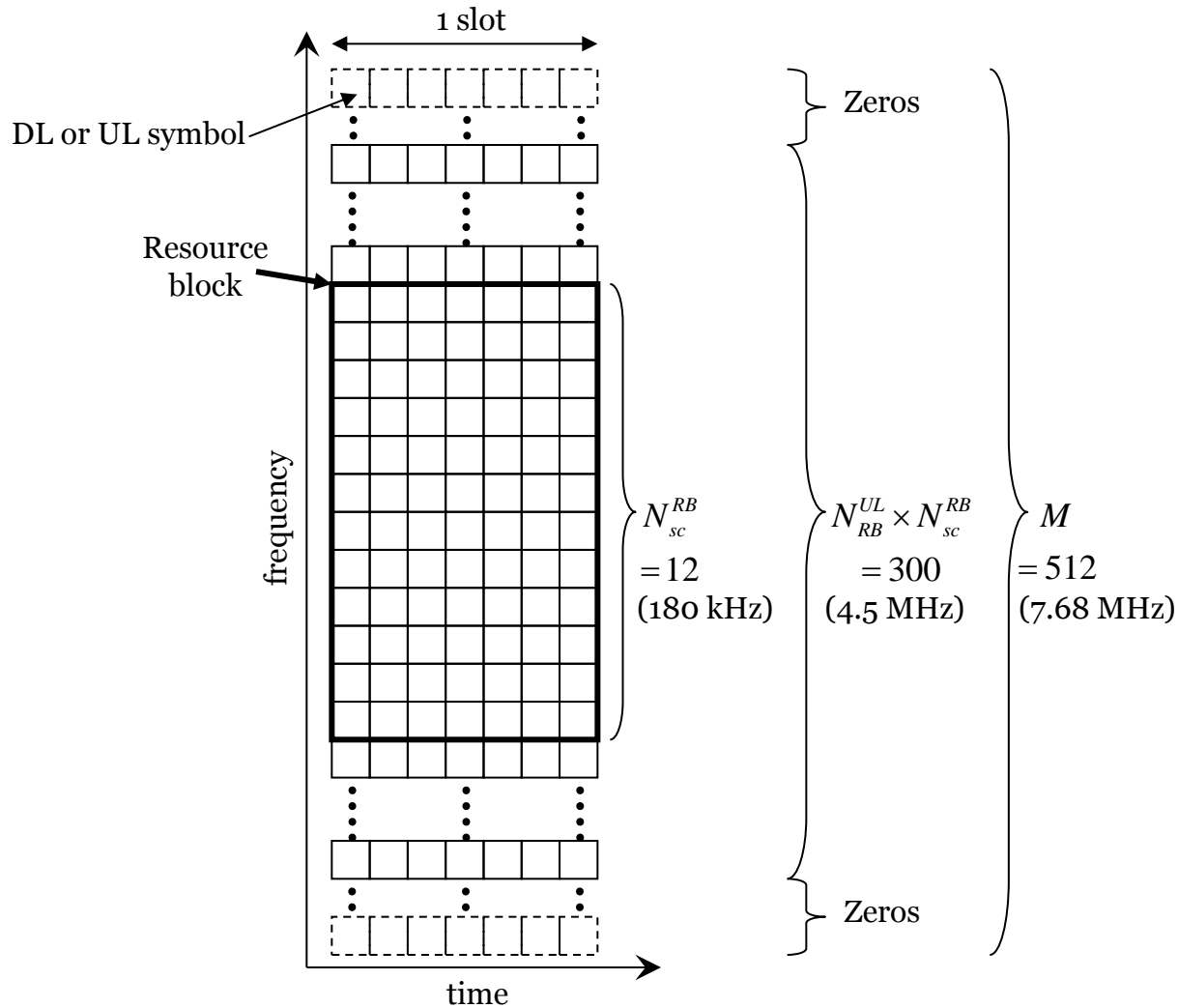
<sup>†</sup> Only in downlink

# LTE Bandwidth/Resource Configuration

<b>Channel bandwidth [MHz]</b>	1.4	3	5	10	15	20
<b>Number of resource blocks (<math>N_{RB}</math>)</b>	6	15	25	50	75	100
<b>Number of occupied subcarriers</b>	72	180	300	600	900	1200
<b>IDFT(Tx)/DFT(Rx) size</b>	128	256	512	1024	1536	2048
<b>Sample rate [MHz]</b>	1.92	3.84	7.68	15.36	23.04	30.72
<b>Samples per slot</b>	960	1920	3840	7680	11520	15360

\*3GPP TS 36.104

# Bandwidth Configuration



\* 5 MHz system with frame structure type 1

# LTE Physical Channels

- DL

- Physical Downlink Shared Channel (PDSCH)
- Physical Broadcast Channel (PBCH)
- Physical Multicast Channel (PMCH)
- Physical Control Format Indicator Channel (PCFICH)
- Physical Downlink Control Channel (PDCCH)
- Physical Hybrid ARQ Indicator Channel (PHICH)

- UL

- Physical Uplink Shared Channel (PUSCH)
- Physical Uplink Control Channel (PUCCH)
- Physical Random Access Channel (PRACH)

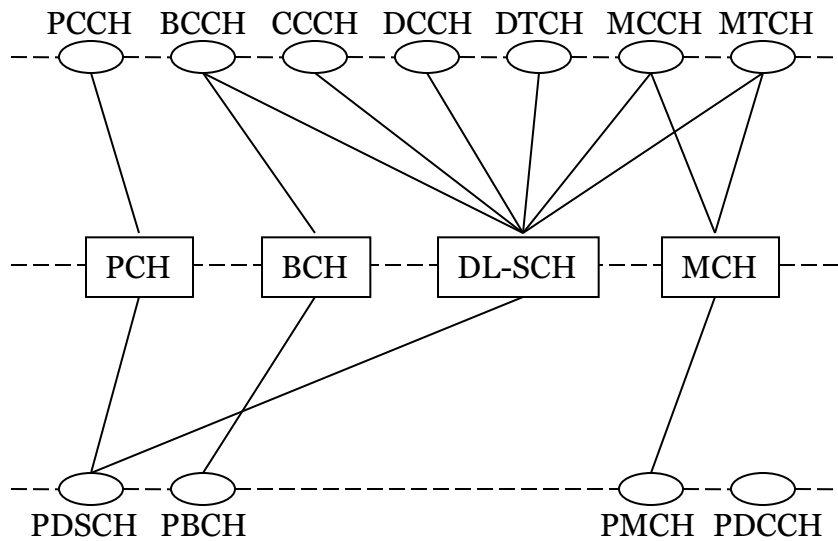
# LTE Transport Channels

- Physical layer transport channels offer information transfer to medium access control (MAC) and higher layers.
- DL
  - Broadcast Channel (BCH)
  - Downlink Shared Channel (DL-SCH)
  - Paging Channel (PCH)
  - Multicast Channel (MCH)
- UL
  - Uplink Shared Channel (UL-SCH)
  - Random Access Channel (RACH)

# LTE Logical Channels

- Logical channels are offered by the MAC layer.
- Control Channels: Control-plane information
  - Broadcast Control Channel (BCCH)
  - Paging Control Channel (PCCH)
  - Common Control Channel (CCCH)
  - Multicast Control Channel (MCCH)
  - Dedicated Control Channel (DCCH)
- Traffic Channels: User-plane information
  - Dedicated Traffic Channel (DTCH)
  - Multicast Traffic Channel (MTCH)

# Channel Mappings

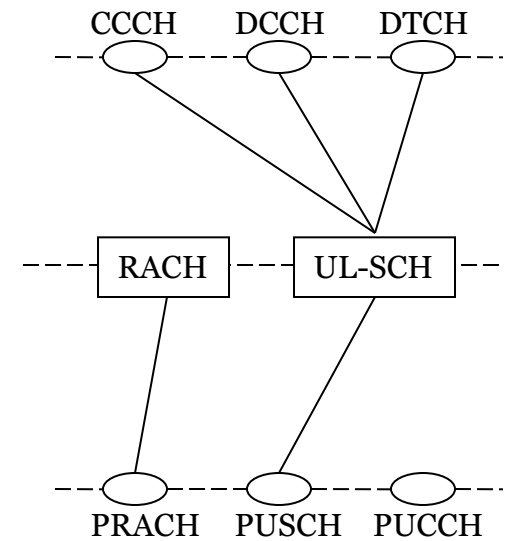


***Downlink***

**Logical  
channels**

**Transport  
channels**

**Physical  
channels**

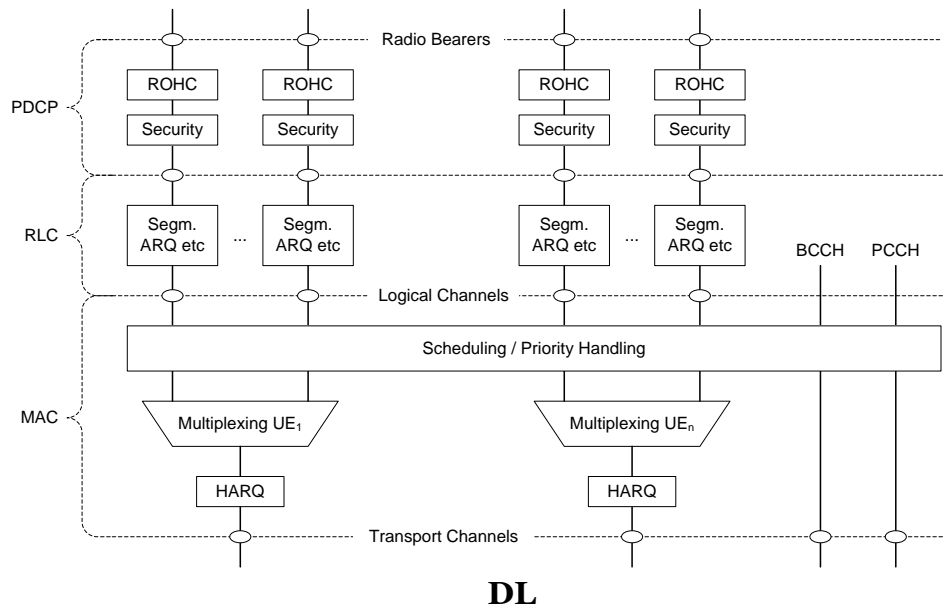


***Uplink***

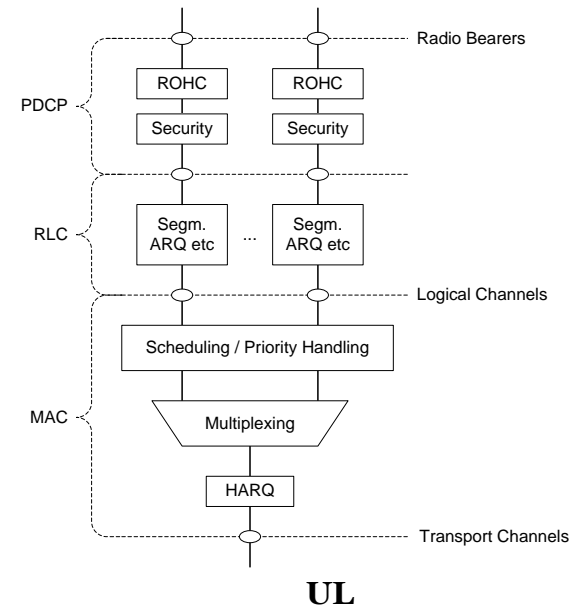


# LTE Layer 2

- Layer 2 has three sublayers
  - MAC (Medium Access Control)
  - RLC (Radio Link Control)
  - PDCP (Packet Data Convergence Protocol)



**DL**



**UL**

ROHC: Robust Header Compression

\* 3GPP TS 36.300

# RRC Layer

- Terminated in eNB on the network side.
- Functions
  - Broadcast
  - Paging
  - RRC connection management
  - RB (Radio Bearer) management
  - Mobility functions
  - UE measurement reporting and control
- RRC states
  - RRC\_IDLE
  - RRC\_CONNECTED

# Resource Scheduling of Shared Channels

- Dynamic resource scheduler resides in eNB on MAC layer.
- Radio resource assignment based on radio condition, traffic volume, and QoS requirements.
- Radio resource assignment consists of:
  - Physical Resource Block (PRB)
  - Modulation and Coding Scheme (MCS)

# Radio Resource Management

- Radio bearer control (RBC)
- Radio admission control (RAC)
- Connection mobility control (CMC)
- Dynamic resource allocation (DRA) or packet scheduling (PS)
- Inter-cell interference coordination (ICIC)
- Load balancing (LB)

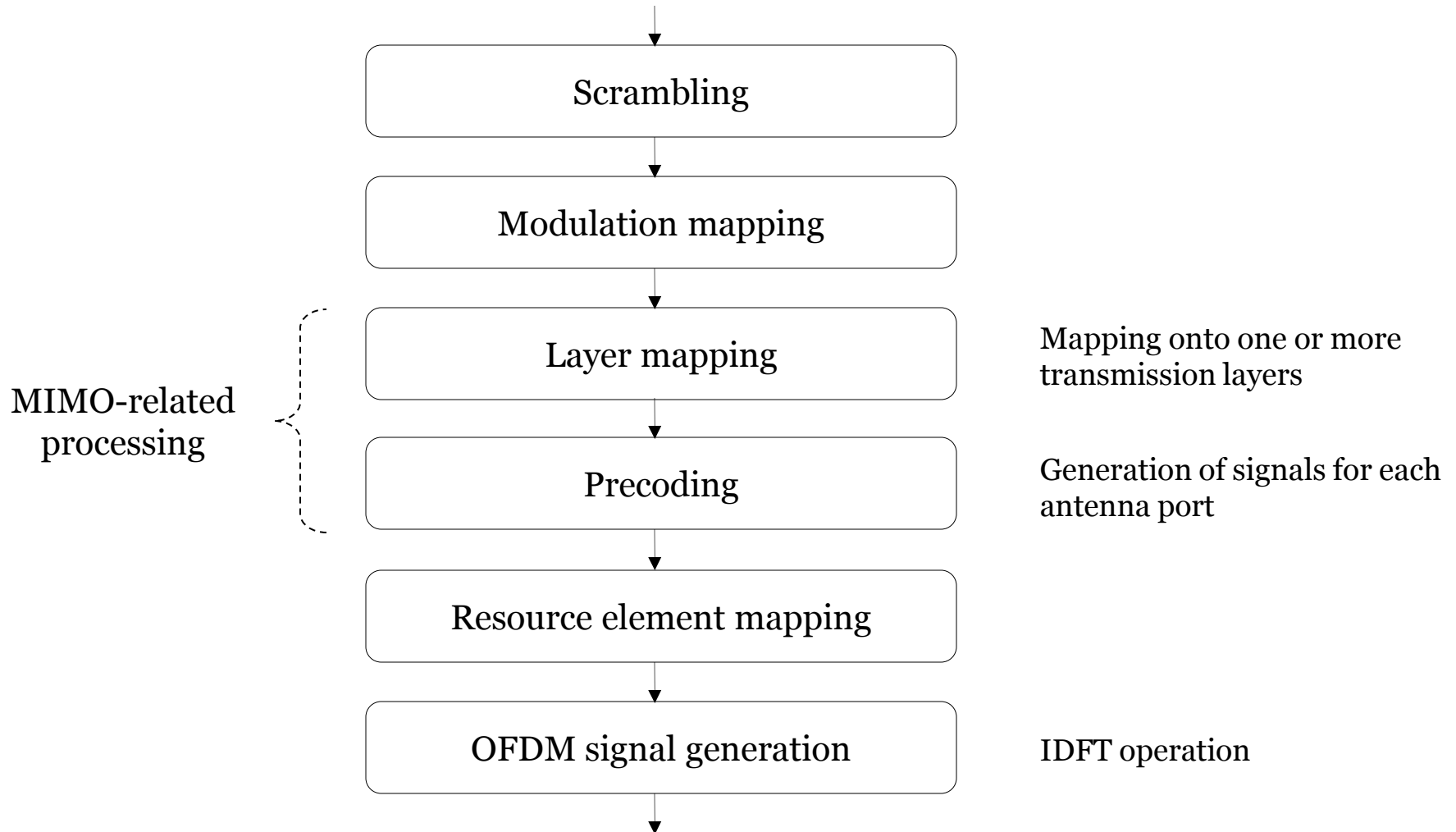
# Other Features

- ARQ (RLC) and H-ARQ (MAC)
- Mobility
- Rate control
- DRX (Discontinuous Reception)
- MBMS
- QoS
- Security

# DL Overview

- DL physical channels
  - Physical Downlink Shared Channel (PDSCH)
  - Physical Broadcast Channel (PBCH)
  - Physical Multicast Channel (PMCH)
  - Physical Control Format Indicator Channel (PCFICH)
  - Physical Downlink Control Channel (PDCCH)
  - Physical Hybrid ARQ Indicator Channel (PHICH)
- DL physical signals
  - Reference signal (RS)
  - Synchronization signal
- Available modulation for data channel
  - QPSK, 16-QAM, and 64-QAM

# DL Physical Channel Processing



# DL Reference Signal

- Three types of DL reference signals
  - Cell-specific reference signals
    - Associated with non-MBSFN transmission
  - MBSFN reference signals
    - Associated with MBSFN transmission
  - UE-specific reference signals



# DL Reference Signal

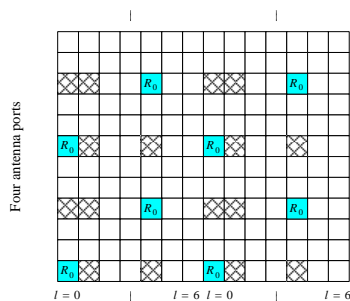
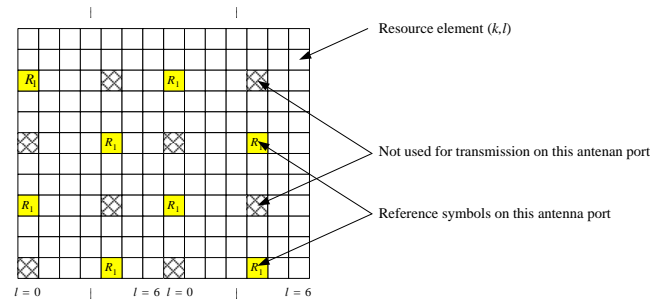
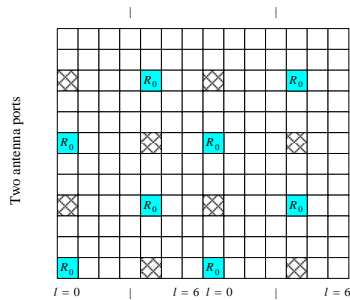
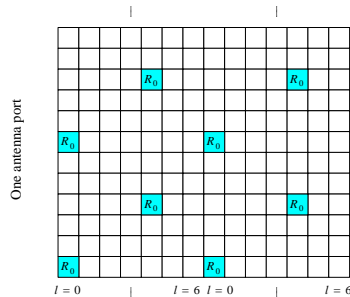
– cont.

- Cell-specific 2D RS sequence is generated as the symbol-by-symbol product of a 2D orthogonal sequence (OS) and a 2D pseudo-random sequence (PRS).
  - 3 different 2D OS and ~170 different PRS.
  - Each cell (sector) ID corresponds to a unique combination of one OS and one PRS  $\Rightarrow$  ~510 unique cell IDs.
- CDM of RS for cells (sectors) of the same eNodeB (BS)
  - Use complex orthogonal spreading codes.
- FDM of RS for each antenna in case of MIMO

# DL Reference Signal

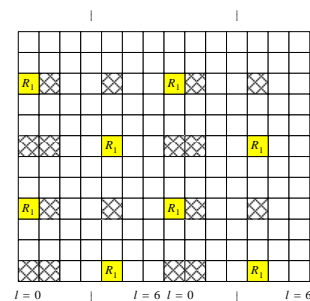
- cont.

\*With normal CP  
\*3GPP TS 36.211



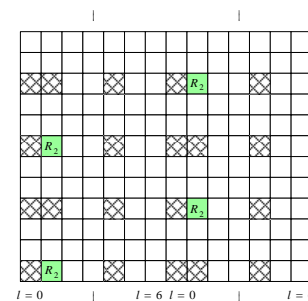
← even-numbered slots → odd-numbered slots →

Antenna port 0



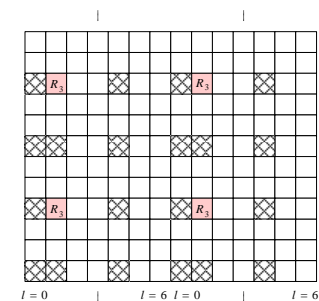
← even-numbered slots → odd-numbered slots →

Antenna port 1



← even-numbered slots → odd-numbered slots →

Antenna port 2



← even-numbered slots → odd-numbered slots →

Antenna port 3

# DL MIMO

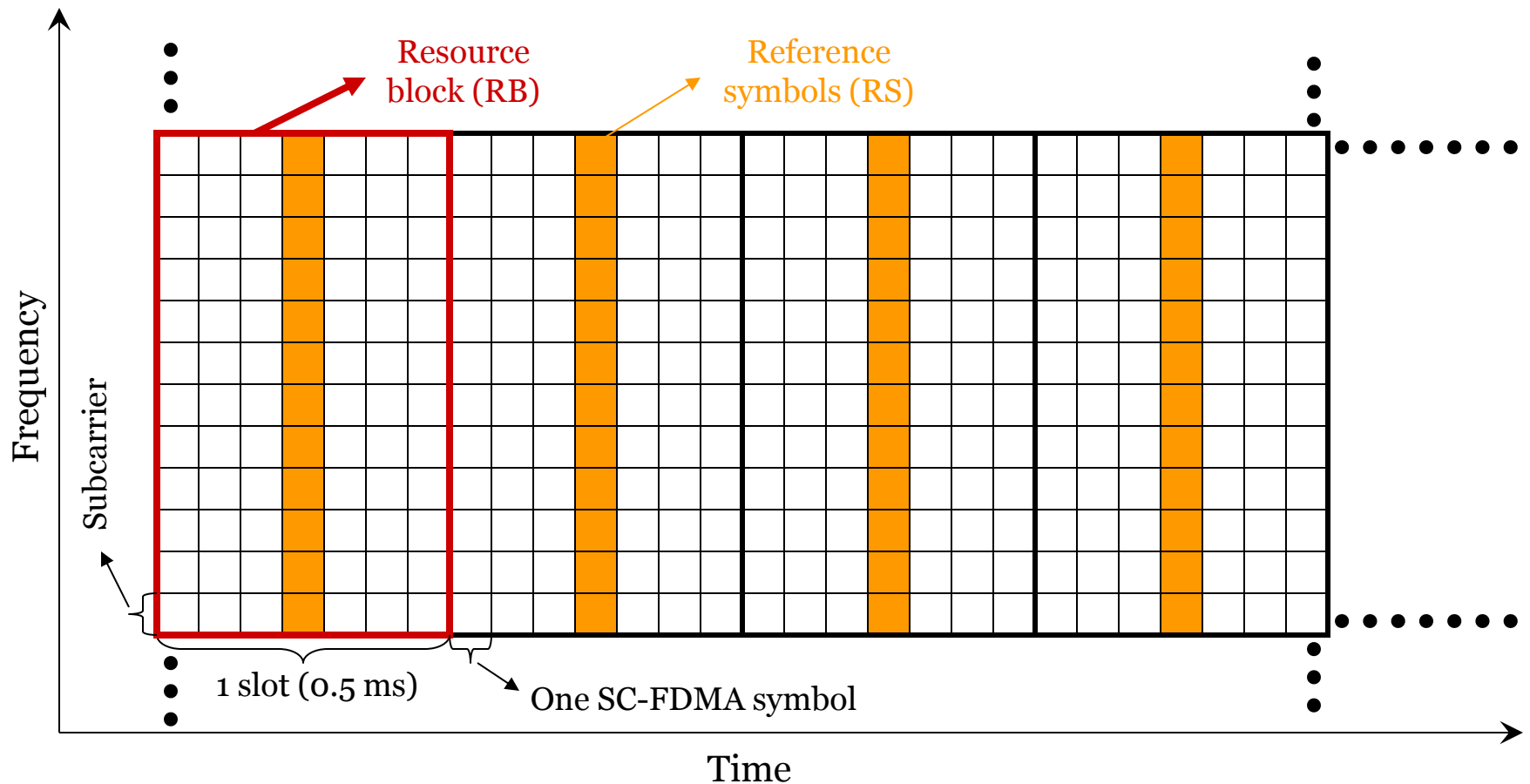
- Supported up to 4x4 configuration.
- Support for both spatial multiplexing (SM) and Tx diversity (TxD).
  - SM
    - Unitary precoding based scheme with codebook based feedback from user.
    - Multiple codewords (up to two).
  - TxD: SFBC and CDD (Cyclic Delay Diversity).
- MU-MIMO supported.
- 3G Americas, “MIMO Transmission Schemes for LTE and HSPA Networks,” Jun. 2009, available at <http://3gamericas.org>

# UL Overview

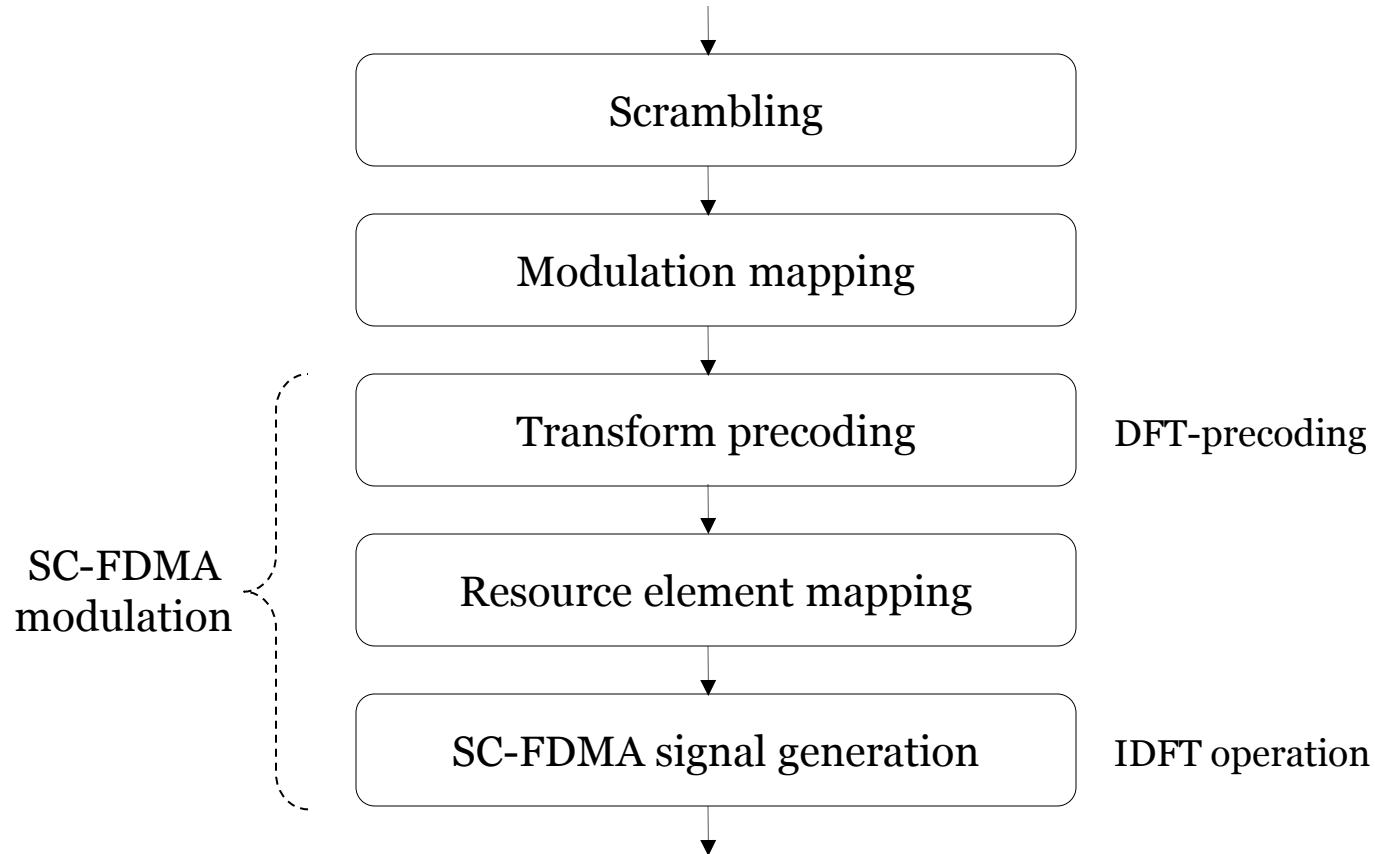
- UL physical channels
  - Physical Uplink Shared Channel (PUSCH)
  - Physical Uplink Control Channel (PUCCH)
  - Physical Random Access Channel (PRACH)
- UL physical signals
  - Reference signal (RS)
- Available modulation for data channel
  - QPSK, 16-QAM, and 64-QAM
- Single user MIMO not supported in Release 8.
  - But it is addressed in Release 10.
  - Multi-user collaborative MIMO supported.

# UL Resource Block

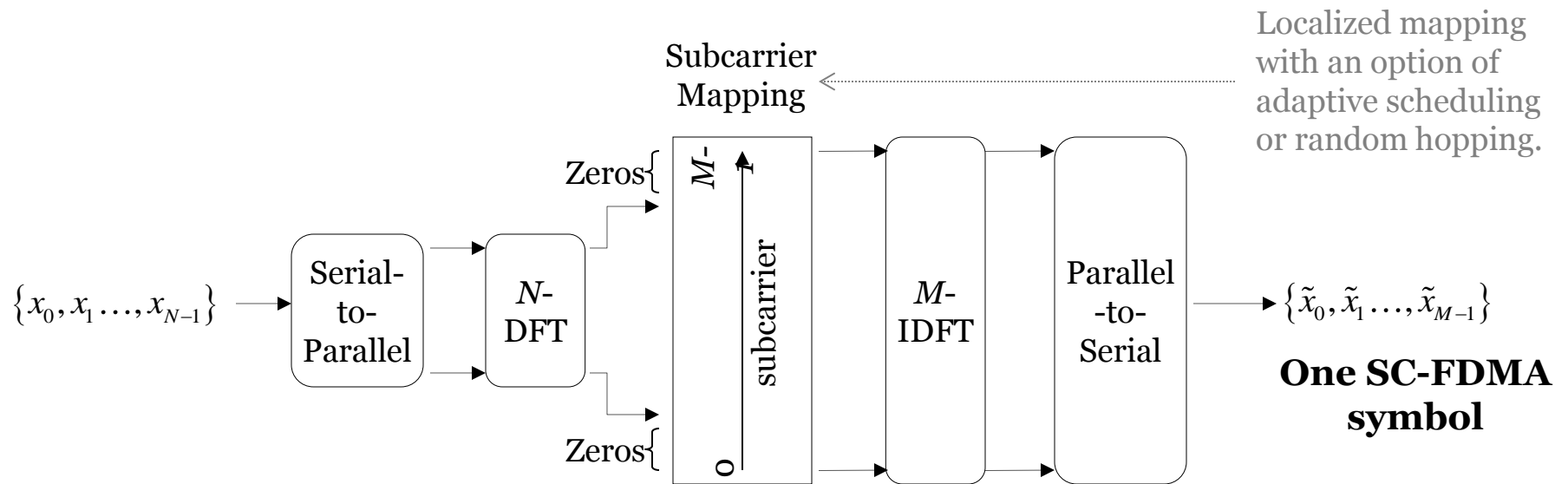
\*PUSCH with normal CP



# UL Physical Channel Processing



# SC-FDMA Modulation in LTE UL



# UL Reference Signal

- Two types of UL RS
  - Demodulation (DM) RS  $\Rightarrow$  Narrowband.
  - Sounding RS: Used for UL resource scheduling  $\Rightarrow$  Broadband.
- RS based on Zadoff-Chu CAZAC (Constant Amplitude Zero Auto-Correlation) polyphase sequence
  - CAZAC sequence: Constant amplitude, zero circular auto-correlation, flat frequency response, and low circular cross-correlation between two different sequences.

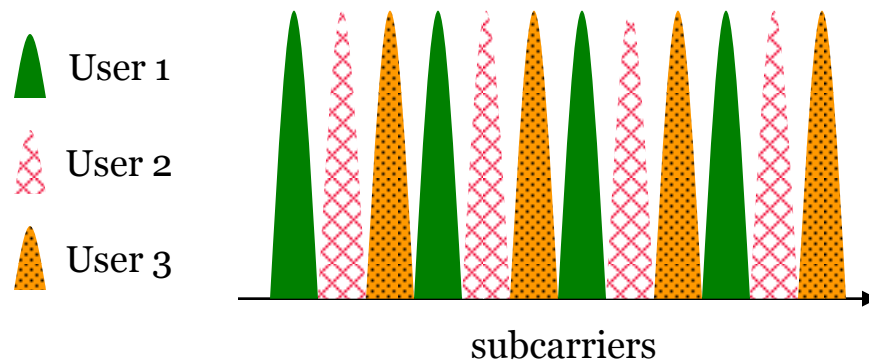
$$a_k = \begin{cases} e^{-j2\pi \frac{r}{L} \left( \frac{k^2}{2} + qk \right)} & , \quad k=0,1,2,\dots,L-1; \text{ for } L \text{ even} \\ e^{-j2\pi \frac{r}{L} \left( \frac{k(k+1)}{2} + qk \right)} & , \quad k=0,1,2,\dots,L-1; \text{ for } L \text{ odd} \end{cases}$$

\*  $r$  is any integer relatively prime with  $L$  and  $q$  is any integer.

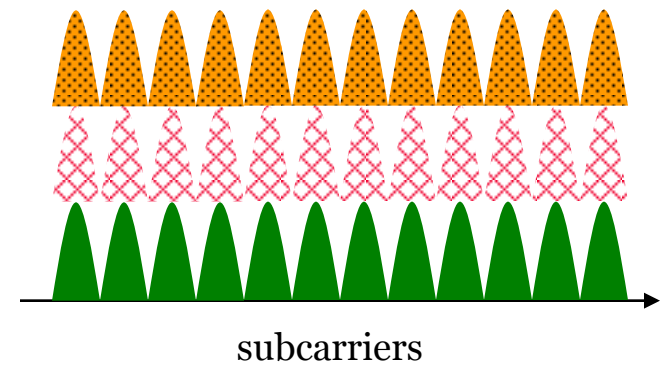
B. M. Popovic, "Generalized Chirp-like Polyphase Sequences with Optimal Correlation Properties," *IEEE Trans. Info. Theory*, vol. 38, Jul. 1992, pp. 1406-1409.



# UL RS Multiplexing



**FDM Pilots**



**CDM Pilots**

# UL RS Multiplexing

- cont.

- DM RS: Associated with PUSCH or PUCCH
  - For SIMO: FDM between different users.
  - For MU-MIMO: CDM between RS from each antenna
- Sounding RS: Not associated with PUSCH or PUCCH
  - CDM when there is only one sounding bandwidth.
  - CDM/FDM when there are multiple sounding bandwidths.

# Radio Procedures

- Cell search
- Random access
- Power control
- Uplink synchronization and uplink timing control
- Hybrid ARQ related procedures

# LTE Release 9

- Completed in Mar. 2010.
- Enhancements to Release 8
  - Enhanced DL beamforming (dual layer)
  - Vocoder rate adaptation
  - Self-organizing network (SON)
  - Multimedia broadcast/multicast service (MBMS)
  - Circuit-switched (CS) domain services
  - UE positioning
  - IMS emergency

# Outline

Wireless Background

4G Enabling Technologies

Long Term Evolution (LTE)

**LTE-Advanced**

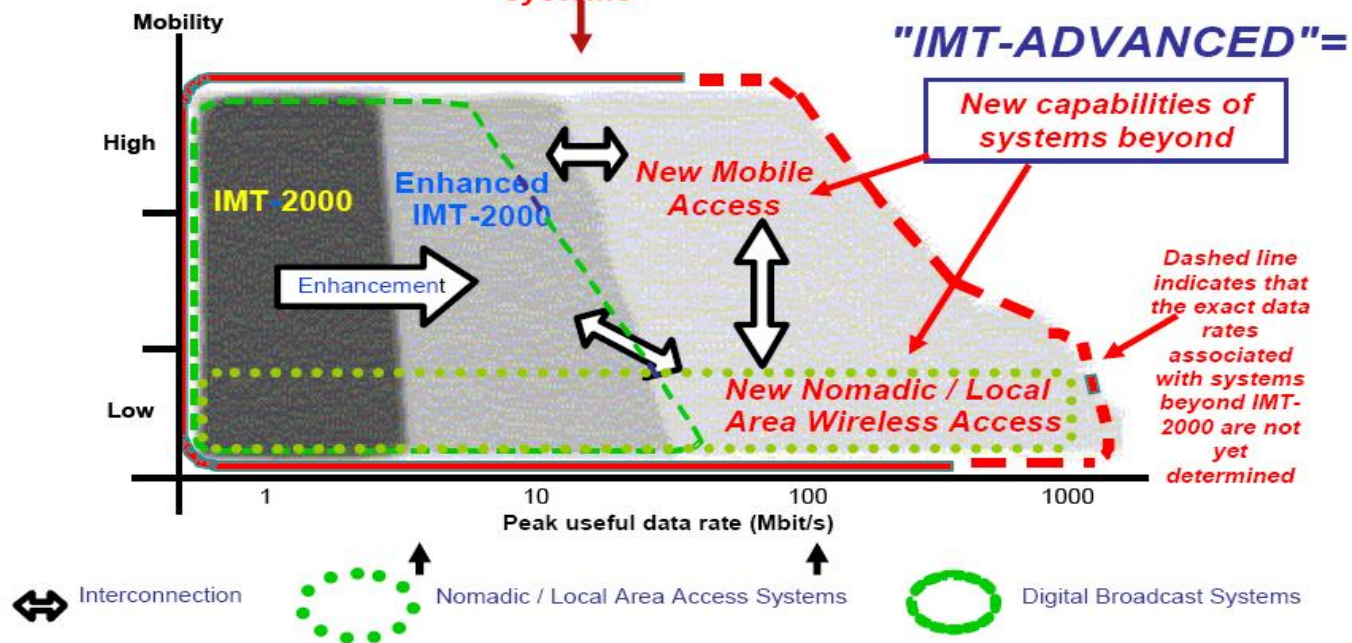
Summary and References

# 4G: IMT-Advanced



## The "VAN diagram"...

Recommendation ITU-R M.1645



Source: 3G Americas, "Defining 4G: Understanding the ITU Process for the Next Generation of Wireless Technology", Aug. 2008

# LTE-Advanced Requirements

- Peak data rate:
  - 1 Gbps DL and 500 Mbps UL
- Latency
  - Less than 10 ms within Connected mode
  - Less than 50 ms from Idle to Connected mode
- Spectrum
  - Up to 100 MHz bandwidth
  - Support for non-consecutive bands (spectrum aggregation)
- Peak spectrum efficiency
  - 30 bps/Hz DL and 15 bps/Hz UL

# LTE-A Features

- Release 10 (Completed in Mar. 2011)
  - Carrier aggregation
    - Spectrum bonding
  - Enhanced MIMO
  - Heterogeneous network (HetNet)
    - Macro-cell + small-cell
  - Relaying
- Release 11 (Completed in Sep. 2012)
  - Coordinated multi-point (CoMP) transmission and reception
  - Advanced inter-cell interference coordination (ICIC)
  - Enhanced PDCCH
- [http://www.3gpp.org/ftp/Information/WORK PLAN/Description Releases/](http://www.3gpp.org/ftp/Information/WORK_PLAN/Description_Releases/)

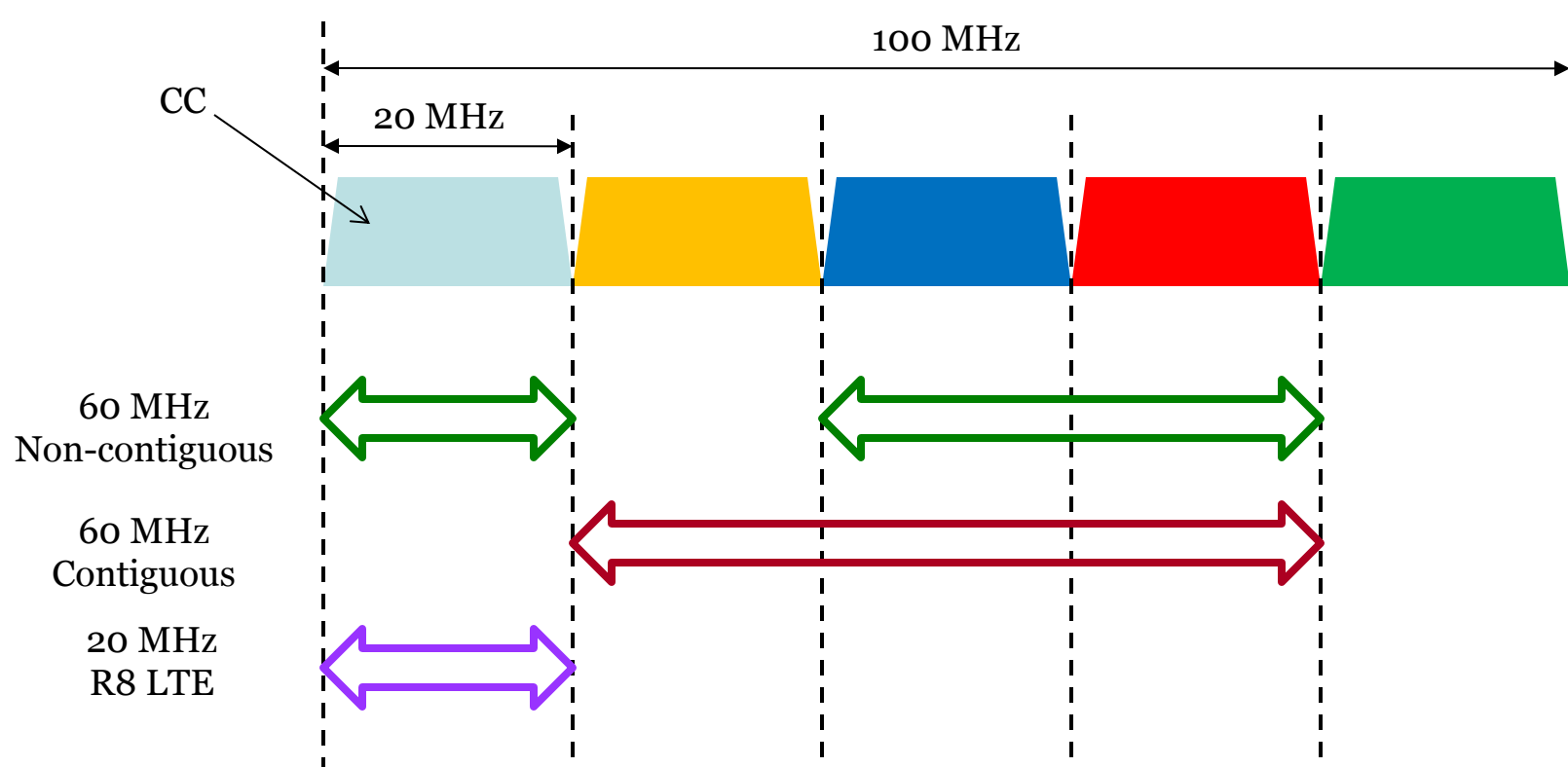


# LTE-A: Carrier Aggregation

- In order to support up to 100 MHz bandwidth, two or more component carriers aggregated
  - Component carrier (CC): Basic frequency block which comply with R8 LTE numerology
  - Each CC is limited to 20 MHz bandwidth (110 resource blocks).
  - Maintains backward compatibility with R8 LTE.
- Supports both contiguous and non-contiguous spectrum.
- Also supports asymmetric bandwidth for FDD.

# LTE-A: Carrier Aggregation

- cont.



# LTE-A: Carrier Aggregation

- cont.

- Spectrum aggregation scenarios
  - Intra-band adjacent
  - Intra-band non-adjacent
  - Inter-band
- Asymmetric bandwidth for FDD
  - Number of DL CC  $\geq$  Number of UL CC

# LTE-A: Carrier Aggregation

- cont.

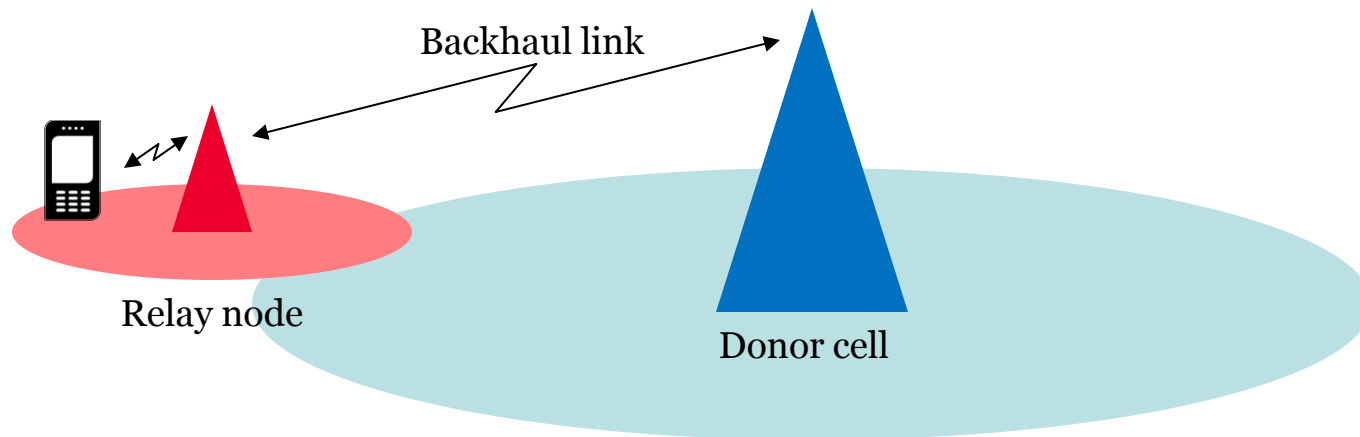
- Downlink multiple access scheme
  - OFDMA with CC-based structure: Re-use R8 spec for low cost & fast development
  - One transport block is mapped within one CC.
- Uplink multiple access scheme
  - N-times DFT-spread OFDM: Clustered DFT spreading

# LTE-A: Enhanced MIMO

- Downlink MIMO
  - Up to 8x8 (8 layer) configuration
  - Additional RS: CSI-RS and UE-specific DM RS
  - Support for MU-MIMO
  - Enhancements to CSI feedback
- Uplink MIMO
  - Introduction of UL transmit diversity
  - Introduction of up to 4x4 SU-MIMO
  - Use of turbo serial interference canceller

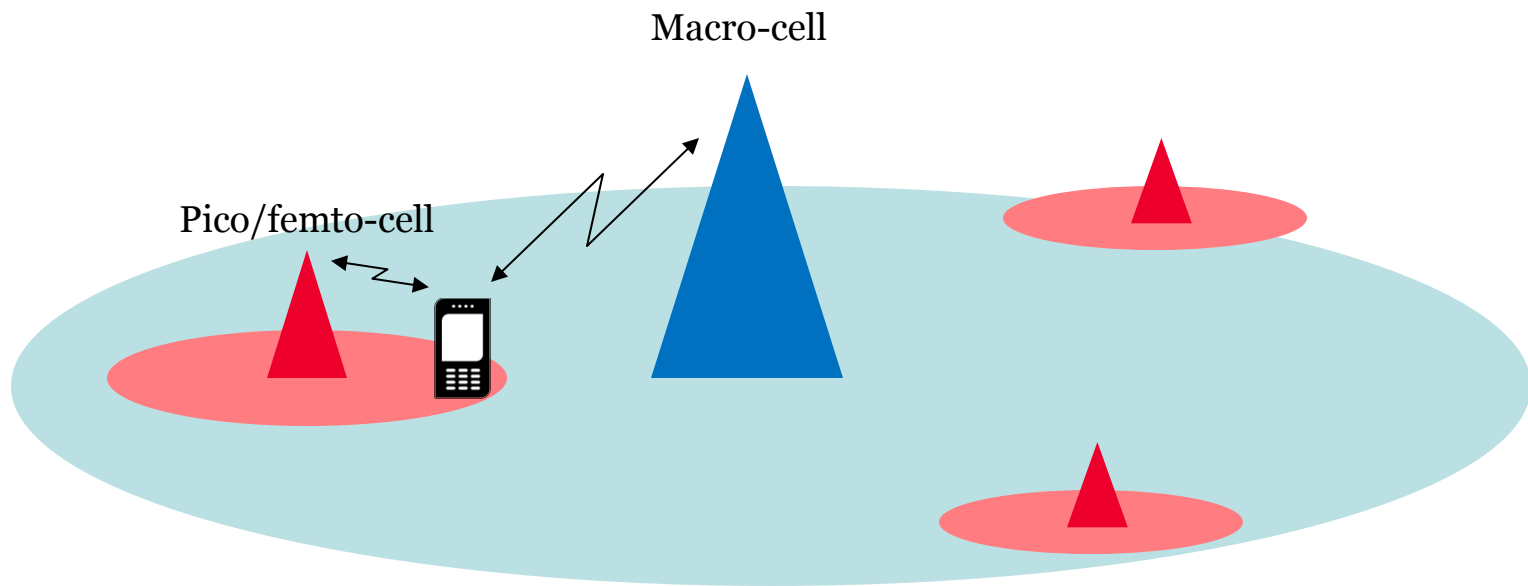
# LTE-A: Relaying

- Improves coverage and cell-edge performance.
- Relay node is wirelessly connected to RAN via a donor cell.



# Heterogeneous Network Support

- Heterogeneous network (HetNet): Low power nodes/cells are placed throughout a macro-cell deployment as an underlay.
  - Low power cell: Pico/femto-cell, relay, remote radio head (RRH), etc.



# HetNet Support

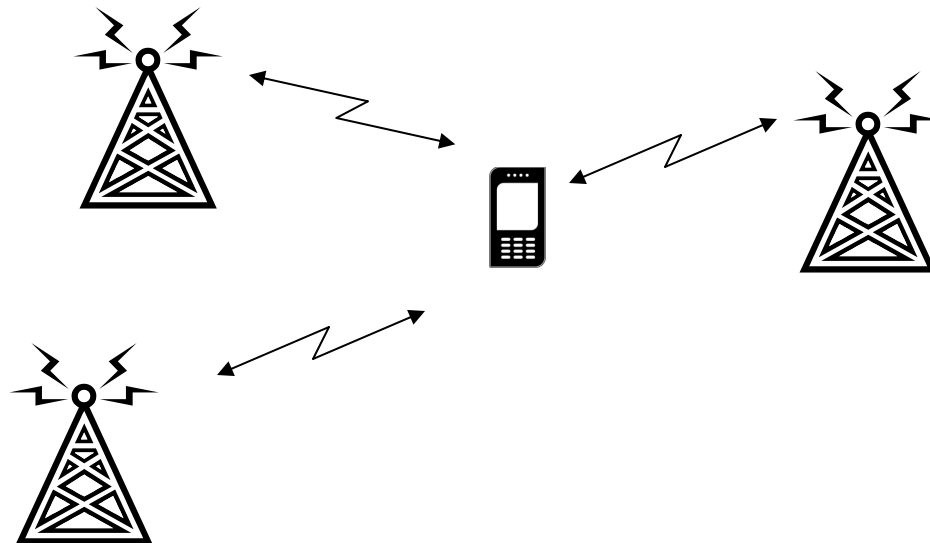
- cont.

- Supports interference coordination for both CA-based and non-CA-based HetNets.
- Ways to coordinate interference
  - Time domain coordination
    - Introduction of ABS (Almost Blank Subframe)
    - Coordinated CSI-RS
    - Backhaul coordination between macro and underlay cells
  - Power control
- Release 11 will add more enhancements.



# LTE-A: CoMP TX & RX

- Release 11 feature
- Improves coverage, cell-edge performance, and system throughput
  - DL: Joint processing, coordinated scheduling/beamforming
  - UL: Multi-point reception



# Release 12

- Target specification freeze date of Jun. 2014.
- Work items
  - Enhancements to LTE-A features, new carrier type (NCT), ...
- New study items
  - Mobile relay, small cell enhancements, device-to-device (D2D) proximity services, 3D MIMO, energy saving enhancement, interference cancellation, WLAN/3GPP radio interworking, ...

# Release 12

- cont.

- 3GPP, “Overview of 3GPP Release 12”
  - [http://www.3gpp.org/ftp/Information/WORK PLAN/Description Releases/Rel-12 description 20130317.zip](http://www.3gpp.org/ftp/Information/WORK_PLAN/Description_Releases/Rel-12_description_20130317.zip)
- Further references
  - <http://www.3gpp.org/Release-12>

# Outline

Wireless Background

4G Enabling Technologies

Long Term Evolution (LTE)

LTE-Advanced

**Summary and References**

# Summary

- Key technologies of 4G systems
  - Multicarrier-based radio air interface
    - OFDM/OFDMA and SC-FDMA
  - Frequency domain equalization
  - IP-based flat network architecture
  - Multi-input multi-output (MIMO)
  - Active interference avoidance and coordination
  - Fast multi-carrier frequency-selective resource scheduling

# Summary

- cont.

- Key features of LTE
  - OFDM/SC-FDMA air interface
  - Flexible 1.25 ~ 20 MHz bandwidth (up to 100 MHz in LTE-Advanced)
  - Support for both FDD and TDD
  - Advanced MIMO
  - Peak data rate (20MHz): DL - 326.4 Mbps (4x4 MIMO), UL - 86.4 Mbps
  - Low latency

# References and Resources

- 4G enabling technologies
  - OFDM/OFDMA
    - R. van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*, Artech House, 2000.
  - Frequency domain equalization
    - D. Falconer *et al.*, “Frequency Domain Equalization for Single-Carrier Broadband Wireless Systems,” *IEEE Commun. Mag.*, vol. 40, no. 4, Apr. 2002, pp. 58-66.
    - H. Sari *et al.*, “Transmission Techniques for Digital Terrestrial TV Broadcasting,” *IEEE Commun. Mag.*, vol. 33, no. 2, Feb. 1995, pp. 100-109.
  - SC-FDMA
    - H. G. Myung & D. Goodman, *Single Carrier FDMA: A New Air Interface for Long Term Evolution*, John Wiley & Sons, Nov. 2008
    - H. G. Myung *et al.*, “Single Carrier FDMA for Uplink Wireless Transmission,” *IEEE Vehicular Technology Mag.*, vol. 1, no. 3, Sep. 2006.

# References and Resources

– cont.

## – MIMO

- A. Paulraj *et al.*, *Introduction to Space-Time Wireless Communications*, Cambridge University Press, May 2003.
- G. L. Stüber *et al.*, “Broadband MIMO-OFDM Wireless Communications,” *Proceedings of the IEEE*, Feb. 2004, vol. 92, no. 2, pp. 271-294.

## – Multicarrier scheduling


- G. Song and Y. Li, “Utility-based Resource Allocation and Scheduling in OFDM-based Wireless Broadband Networks,” *IEEE Commun. Mag.*, vol. 43, no. 12, Dec. 2005, pp. 127-134.



# References and Resources

- cont.

- LTE
  - Spec
    - <http://www.3gpp.org/ftp/Specs/html-info/36-series.htm>
  - 4G Americas
    - <http://4gamericas.org>
  - LTE books
    - [http://www.wiley.com/WileyCDA/Section/id-WILEY2\\_SEARCH\\_RESULT.html?query=lte](http://www.wiley.com/WileyCDA/Section/id-WILEY2_SEARCH_RESULT.html?query=lte)
  - <http://www.LTEwatch.com>



Questions? Thank you!

 **WCNC**  
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