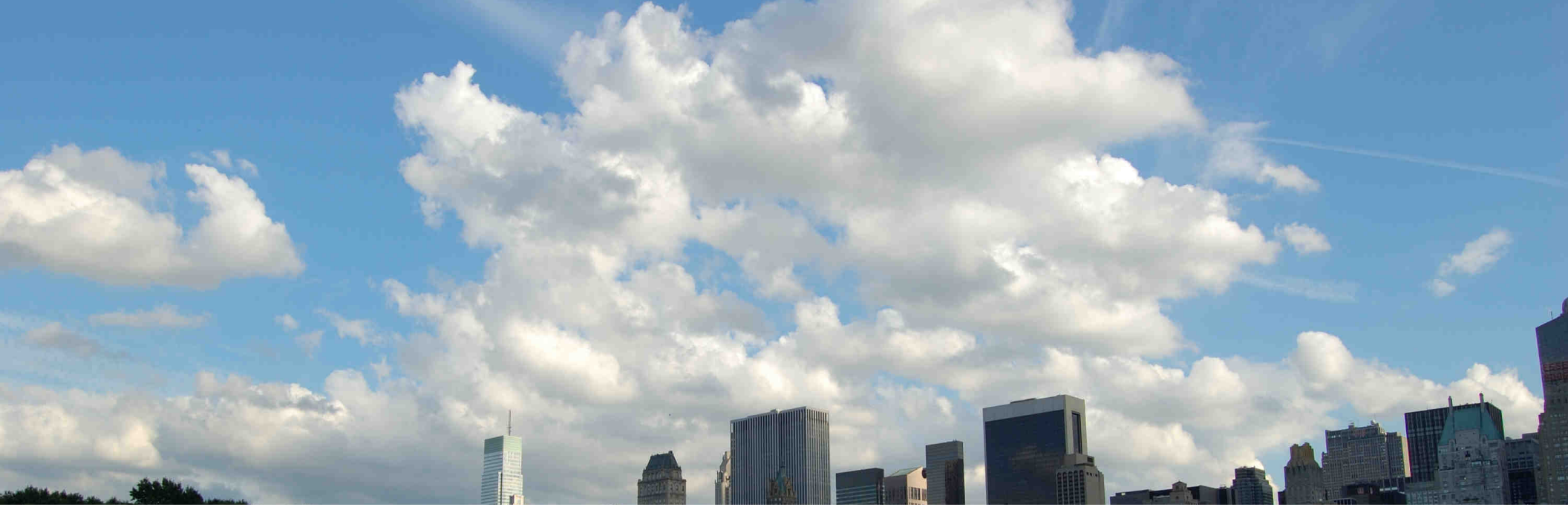

Single Carrier FDMA

: A New Uplink Air Interface in 3GPP Long Term Evolution

WINLAB Seminar, 2007.02.27

Hyung G. Myung, Qualcomm/Flarion

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Outline

Introduction and Background

Overview of SC-FDMA

SC-FDMA Implementation in 3GPP LTE

Peak Power Characteristics of SC-FDMA Signals

Uplink Resource Scheduling in SC-FDMA Systems

Summary and Conclusions

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3GPP Evolution

- Release 99 (Mar. 2000): UMTS/WCDMA
- Rel-5 (Mar. 2002): HSDPA
- Rel-6 (Mar. 2005): HSUPA
- Rel-7 (???, 2007): DL MIMO, IMS (IP Multimedia Subsystem), optimized real-time services (VoIP, gaming, push-to-talk).
- Long Term Evolution (LTE)
  - 3GPP work on the Evolution of the 3G Mobile System started in November 2004.
  - Currently, standardization in progress in the form of Rel-8.
  - Spec scheduled to be finalized by the end of 2007/early 2008.
  - Target deployment in 2010.

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.
- Coverage
  - Performance should be met for 5 km cells with slight degradation for 30 km cells. Up to 100 km cells not precluded.

Requirements of LTE - *cont.*

- Enhanced multimedia broadcast multicast service (E-MBMS)
- Spectrum flexibility
  - 1.25 ~ 20 MHz
- Enhanced support for end-to-end QoS

Key Features of LTE

- Multiple access scheme
  - DL: OFDMA with CP.
  - UL: Single Carrier FDMA (SC-FDMA) with CP.
- Adaptive modulation and coding
  - DL modulations: QPSK, 16QAM, and 64QAM
  - UL modulations: QPSK and 16QAM
  - Rel-6 Turbo code: Coding rate of 1/3, two 8-state constituent encoders, and a contention-free internal interleaver.
- Advanced MIMO spatial multiplexing techniques
  - (2 or 4)x(2 or 4) downlink and uplink supported.
    - Multi-layer transmission with up to four streams.
  - Multi-user MIMO also supported.
- ARQ within RLC sublayer and Hybrid ARQ within MAC sublayer.

Key Features of LTE - *cont.*

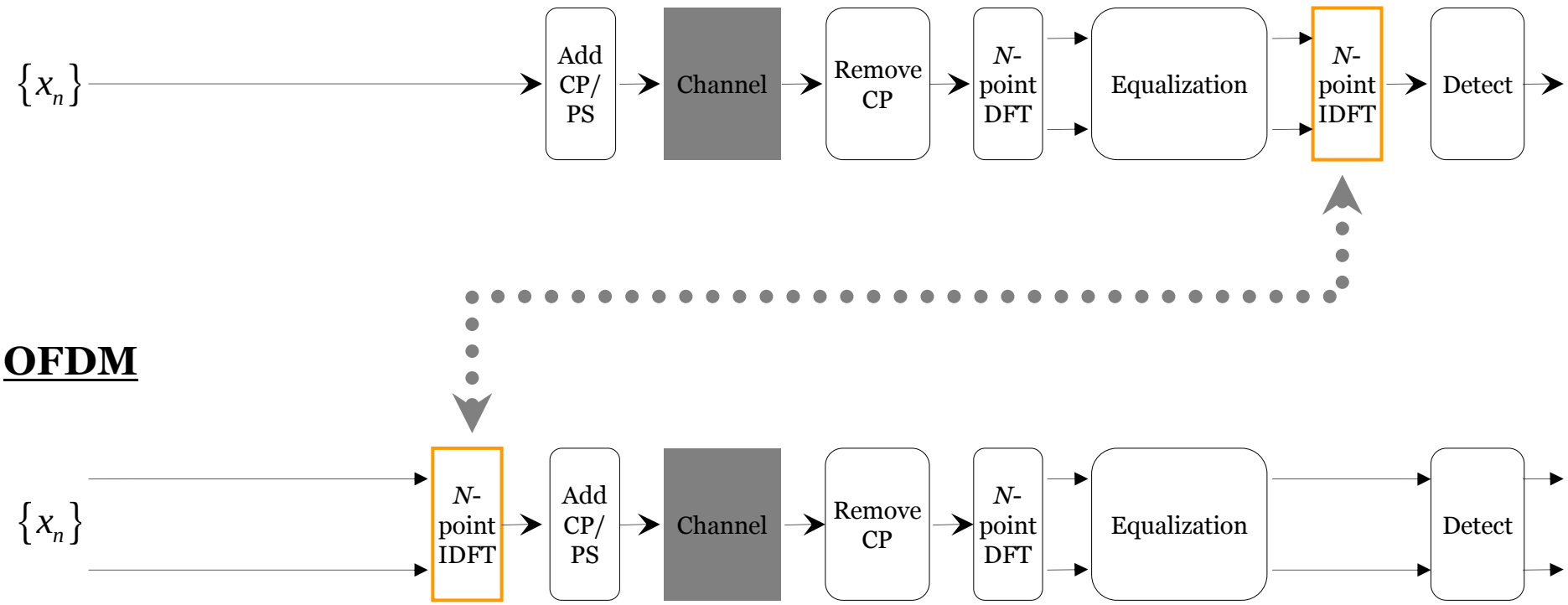
- Power control and link adaptation
- Implicit support for interference coordination
- Support for both FDD and TDD
- Possible support for operating as single frequency network (SFN) to support MBMS
  - Time-synchronized common waveform transmitted from multiple cells.

Broadband Multipath Channel Equalization

- Demand for higher data rate is leading to utilization of wider transmission bandwidth.
- For broadband multipath 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.
- Frequency domain equalization is more practical for such channels.
  - Convert the signal into frequency domain using DFT.

Single Carrier with Frequency Domain Equalization (SC/FDE)

SC/FDE



* CP: Cyclic Prefix, PS: Pulse Shaping

SC/FDE - *cont.*

- 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 due to single carrier modulation at the transmitter.
  - robustness to spectral null.
  - lesser sensitivity to carrier frequency offset.
  - lower complexity at the transmitter which will benefit the mobile terminal in cellular uplink communications.
- Single carrier FDMA (SC-FDMA) is an extension of SC/FDE to accommodate multiple-user access.

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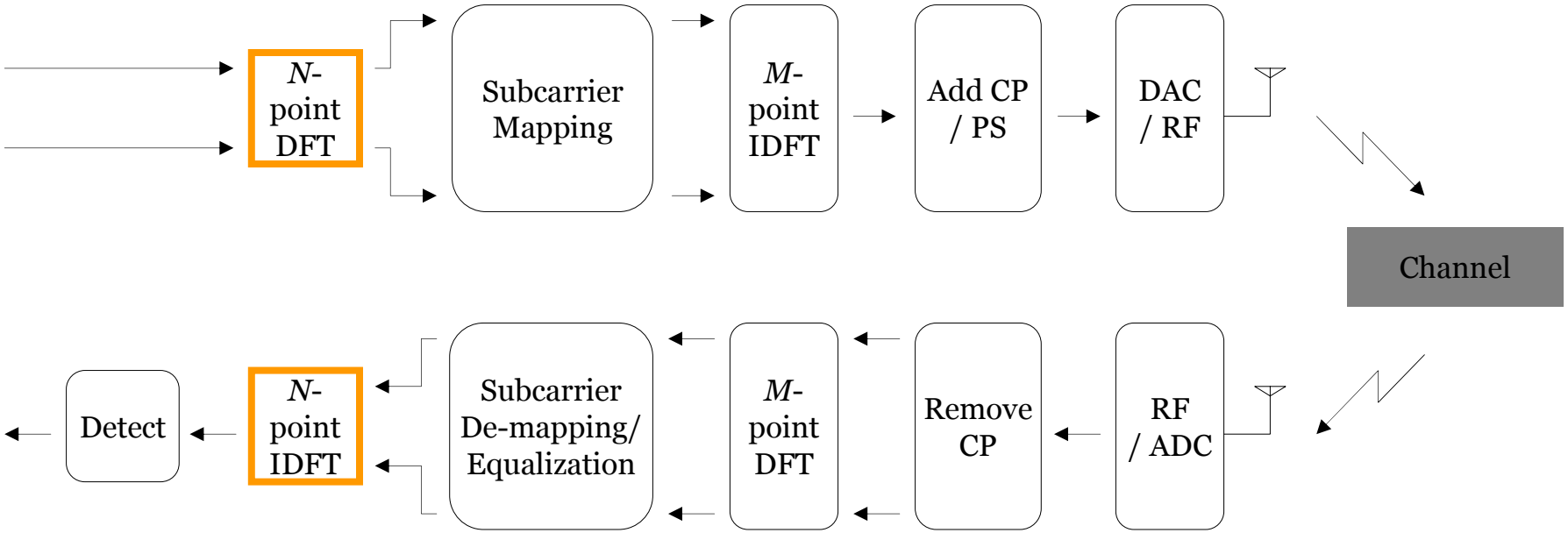
TX & RX structure of SC-FDMA

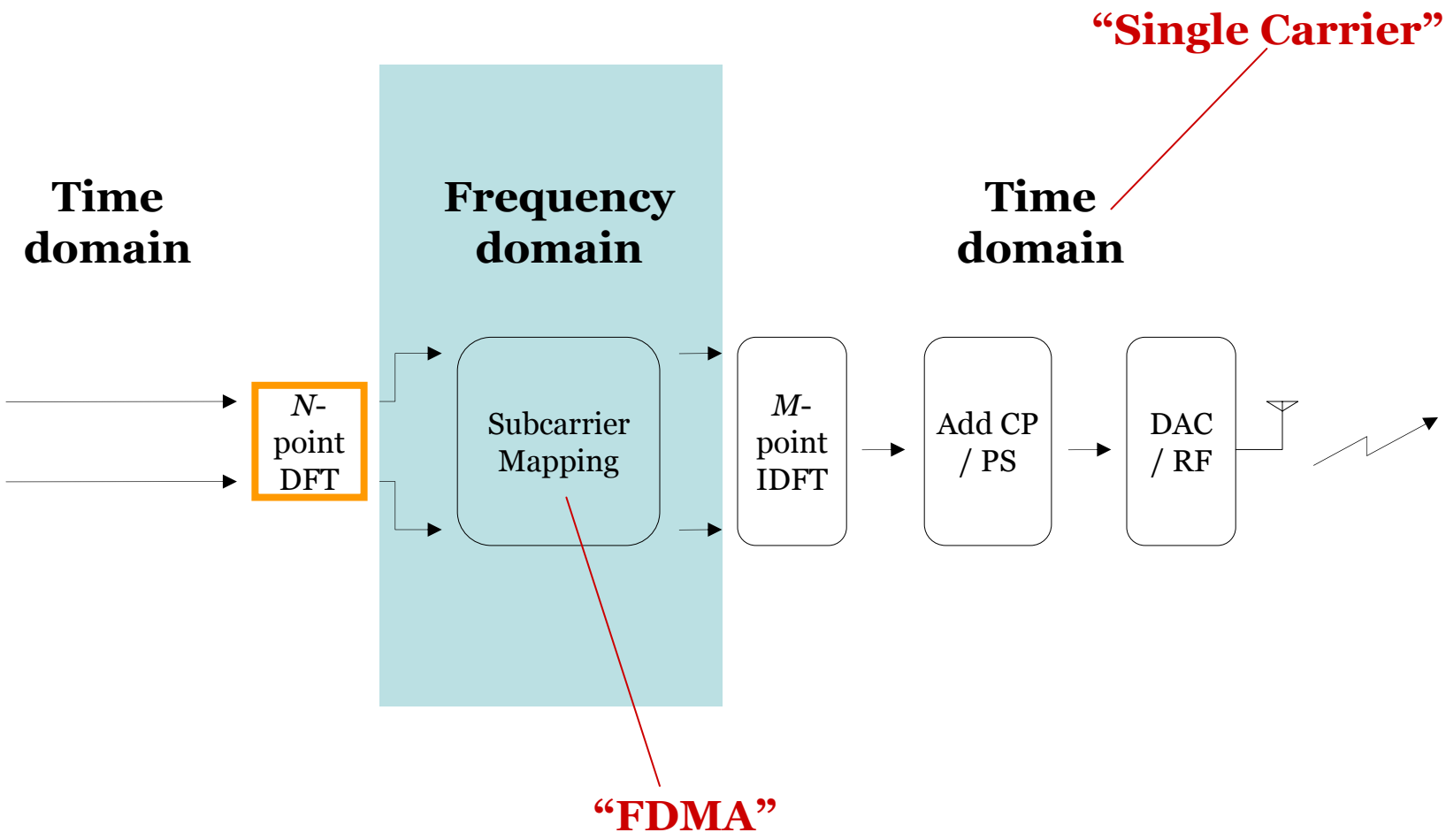


SC-FDMA: □ + □

OFDMA: □

*$N < M$

Why "Single Carrier" "FDMA"?



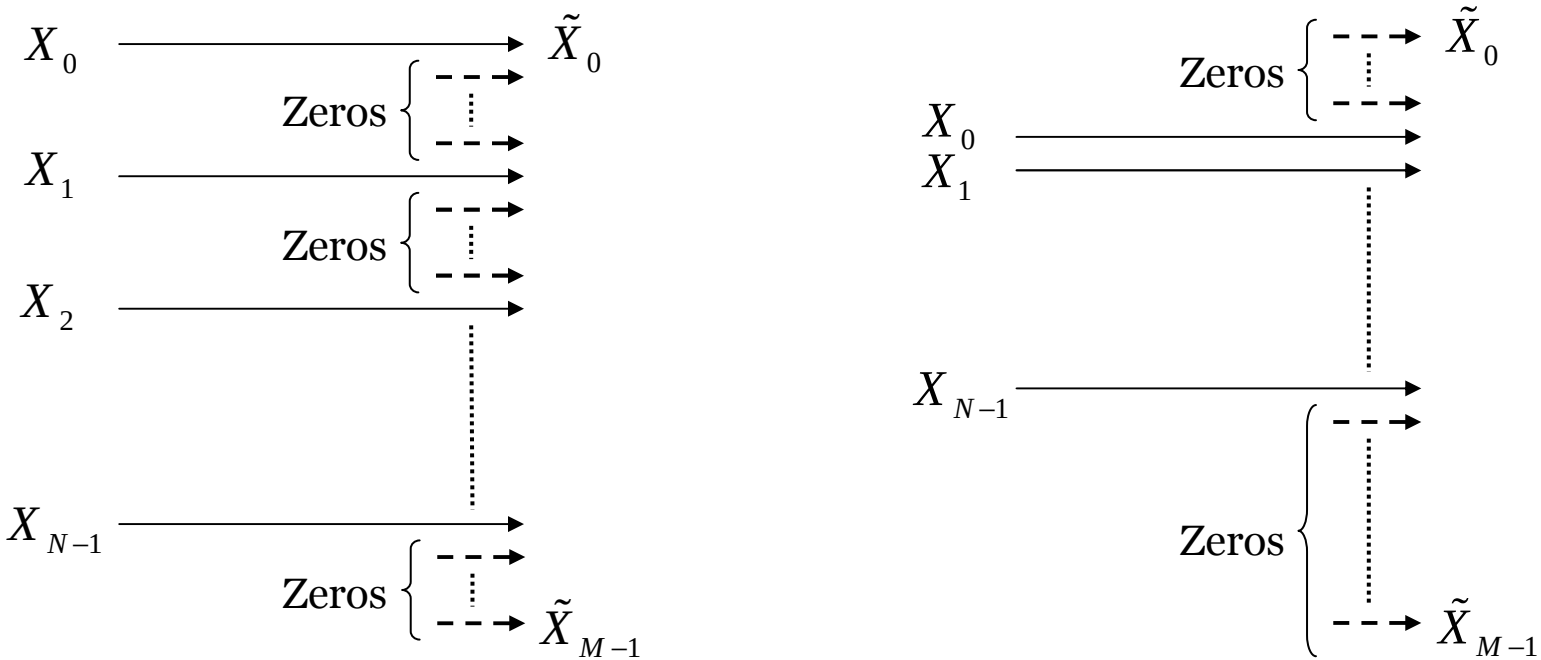
Frequency Domain Equalization

- Most of the time domain equalization techniques can be implemented in the frequency domain.
  - MMSE equalizer, DFE, turbo equalizer, and so on.

- References
  - G. K. Kaleh, "Channel Equalization for Block Transmission Systems," *IEEE J. Select. Areas Commun.*, vol. 13, no. 1, Jan. 1995
  - 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 and J. Hagenauer, "Linear Time and Frequency Domain Turb o Equalization," *Proc. IEEE 53rd Veh. Technol. Conf. (VTC)*, vol. 2, May 2001
  - N. Benvenuto and S. Tomasin, "Iterative Design and Detection of a DFE in the Frequency Domain," *IEEE Trans. Commun.*, vol. 53, no. 11, Nov. 2005
  - F. Pancaldi and G. M. Vitetta, "Block Channel Equalization in the Frequency Domain," *IEEE Trans. Commun.*, vol. 53, no. 3, Mar. 2005

Subcarrier Mapping

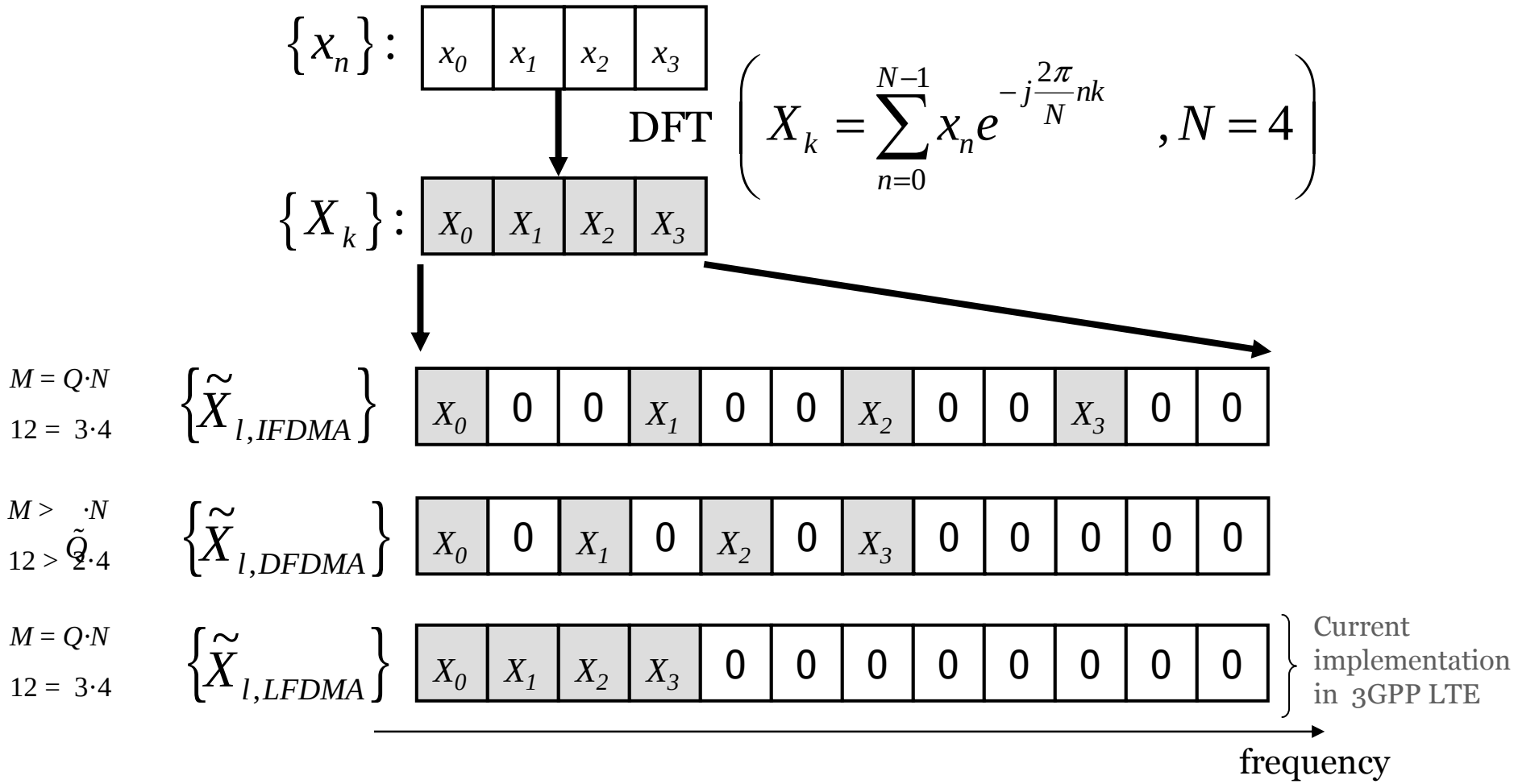
- Two ways to map subcarriers; *distributed* and *localized*.



Distributed **Localized**

- Distributed mapping scheme for (total # of subcarriers) = (data block size)×(bandwidth spreading factor) is called *Interleaved* FDMA (IFDMA).

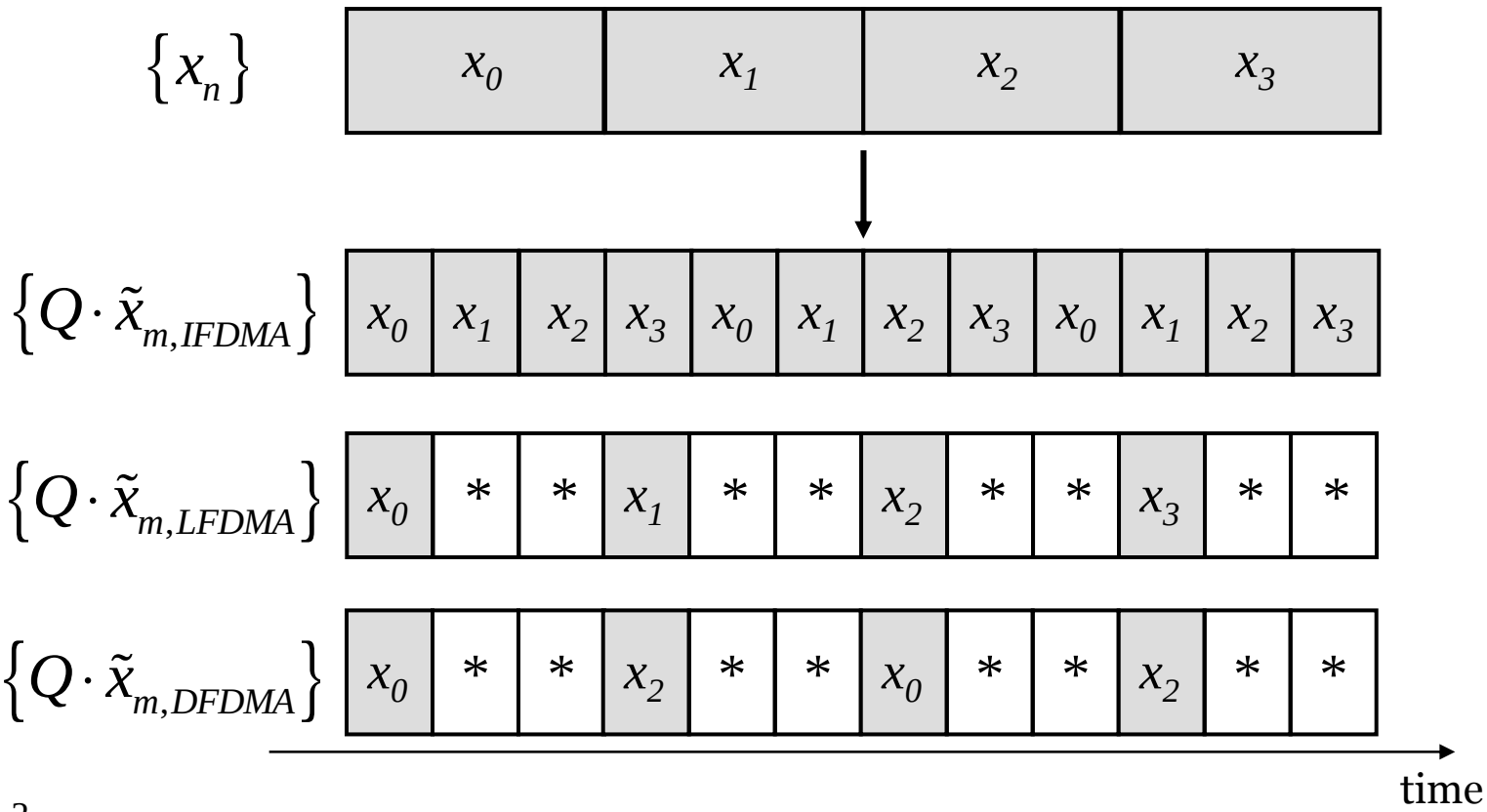
Subcarrier Mapping - *cont.*



*M : Total number of subcarriers, N : Data block size, Q : Bandwidth spreading factor

Time Domain Representation

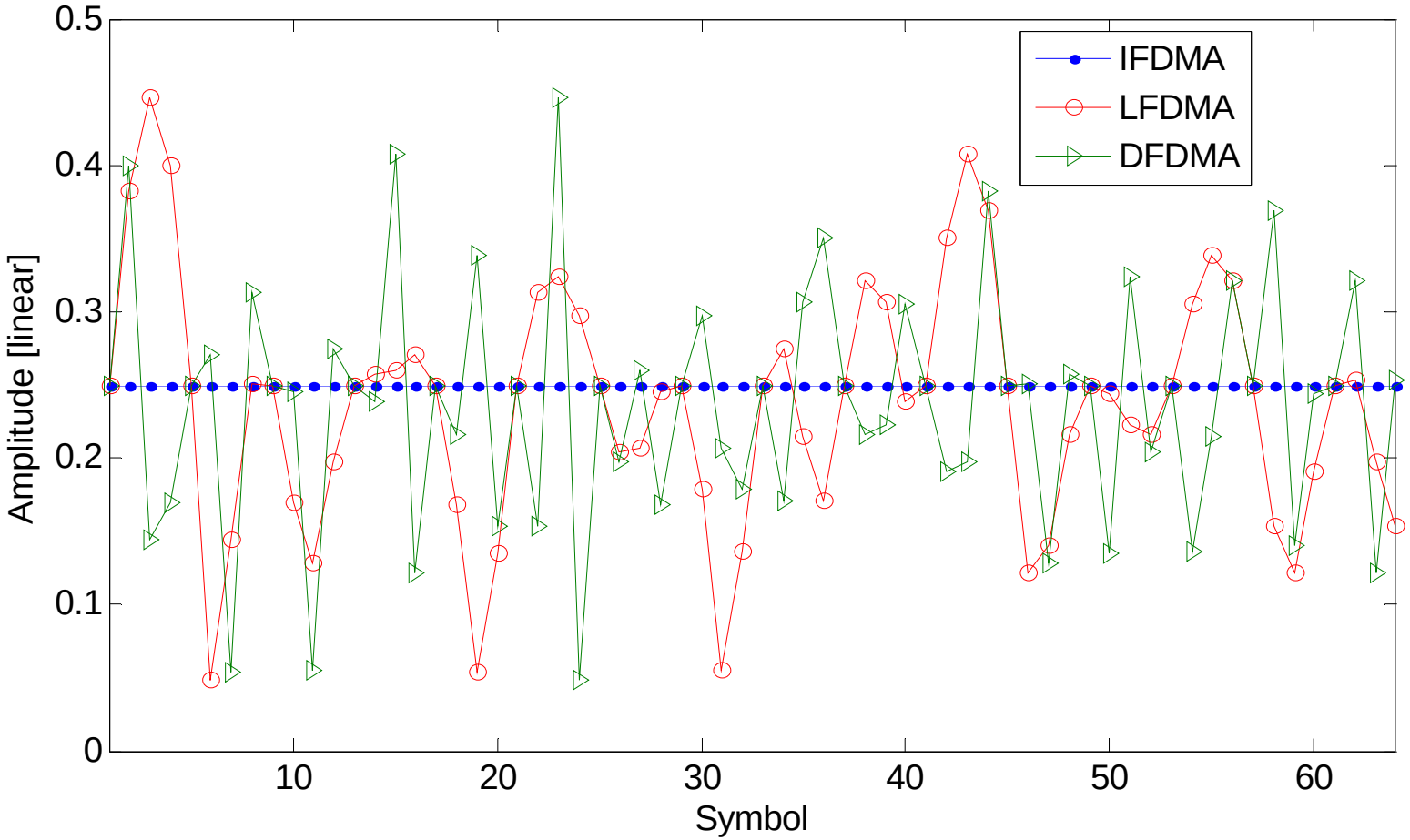
- Example (M = 12, N = 4, Q = 3, $\tilde{Q}$ = 2)



$$* = \sum_{k=0}^{3} c_{k,m} \cdot x_k \quad , c_{k,m} : \text{ complex weight}$$

Amplitude of SC-FDMA Symbols

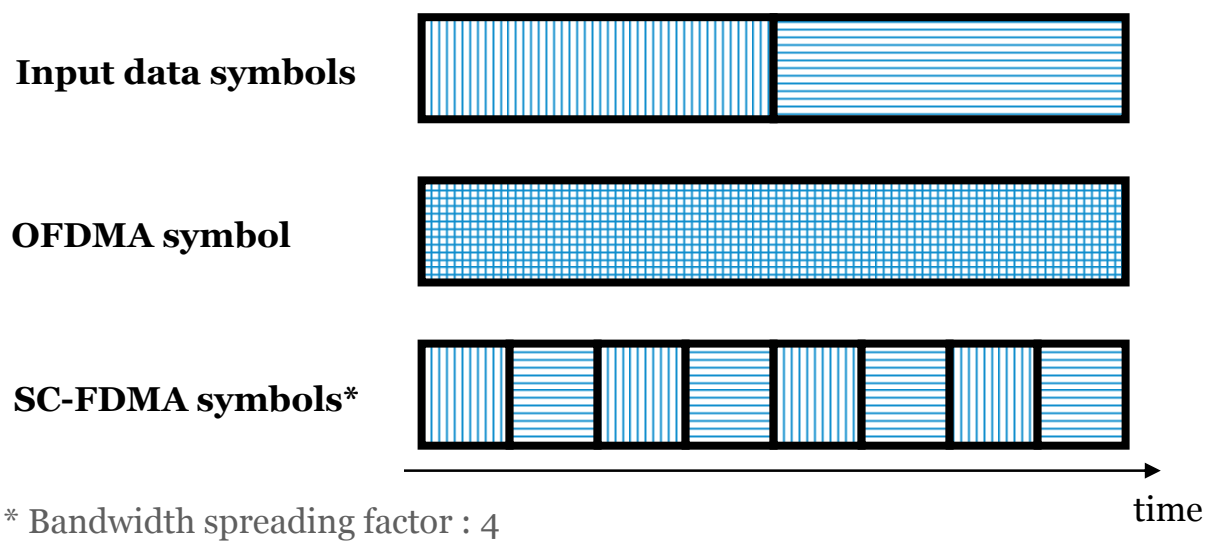
- Example (M = 64, N = 16, Q = 4, $\tilde{Q}$ = 3; QPSK)



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 regarded as DFT-*precoded* or DFT-*spread* OFDMA.

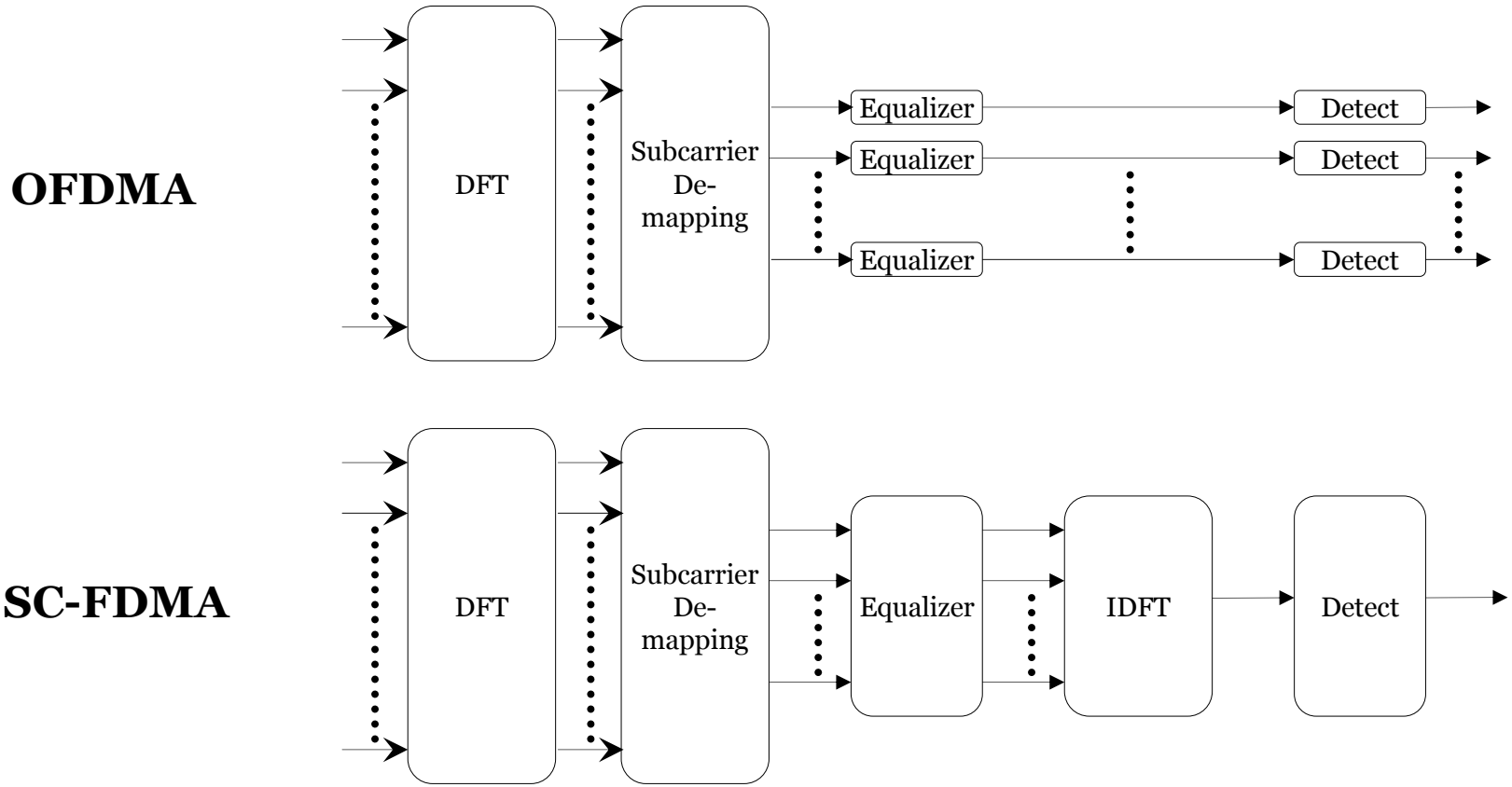
- Difference in time domain signal



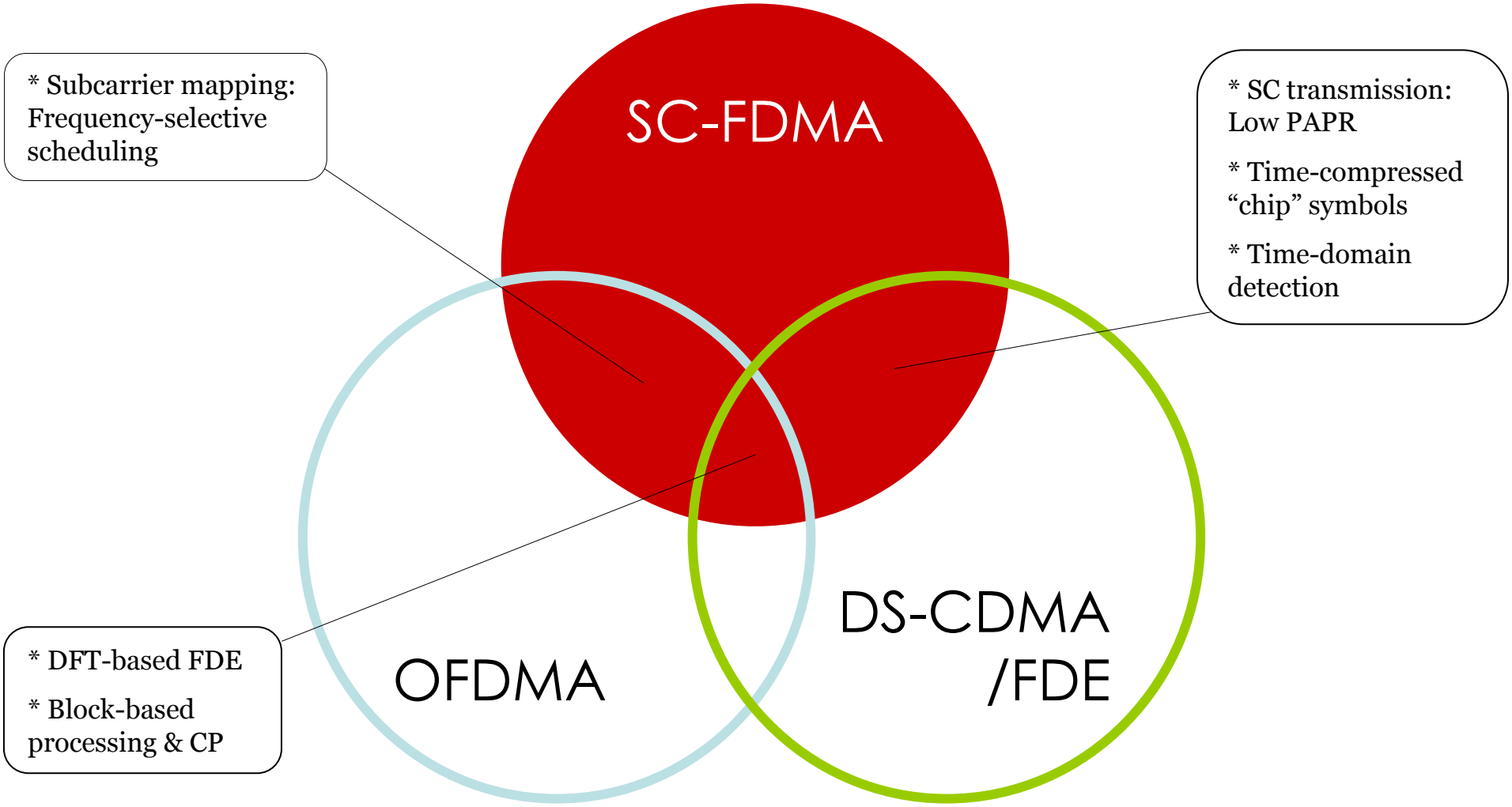
* Bandwidth spreading factor : 4

SC-FDMA and OFDMA

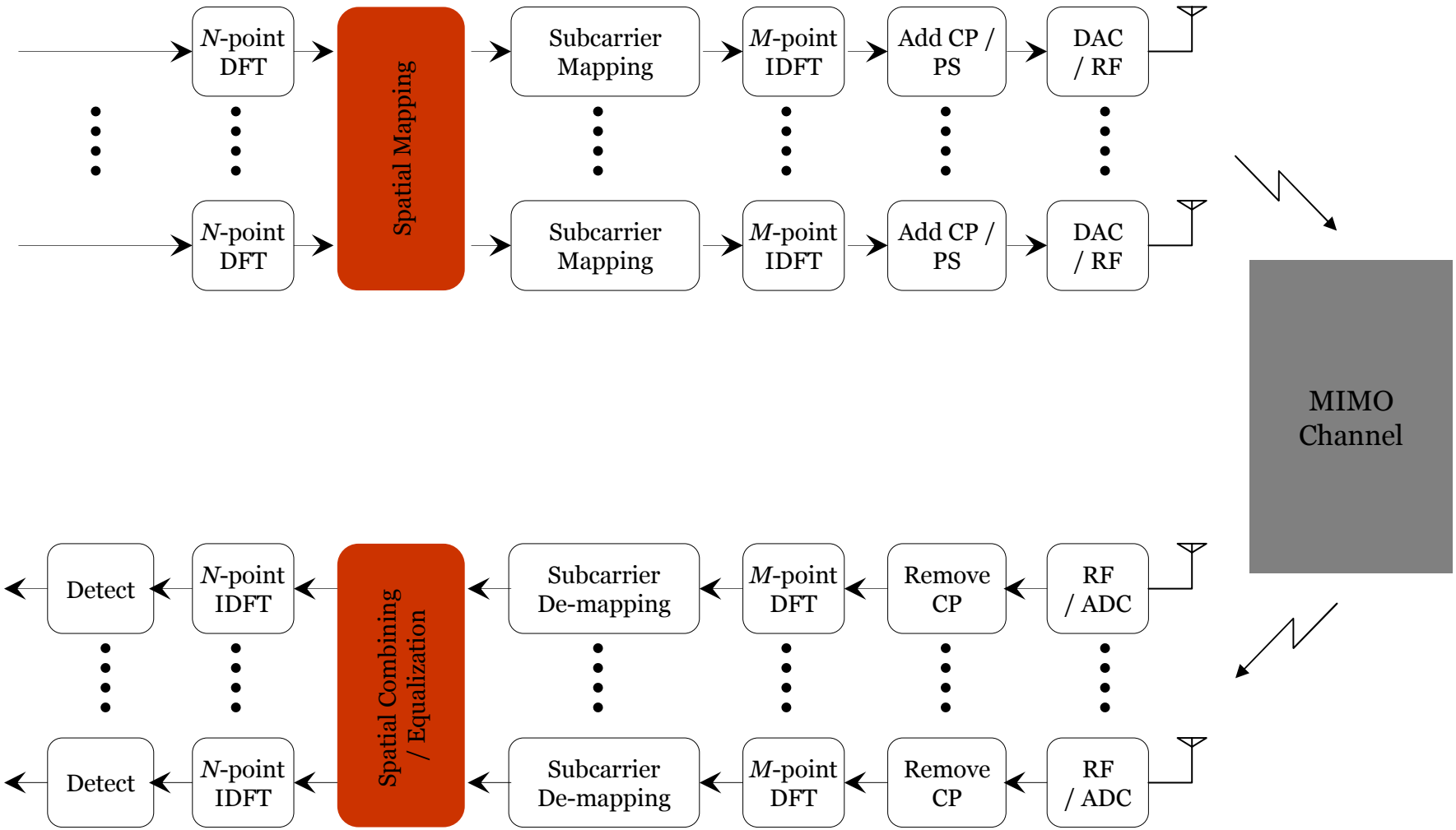
- Different equalization aspects



SC-FDMA and Other Schemes



SC-FDMA MIMO


N-point DFT
N-point DFT
Spatial Mapping
Subcarrier Mapping
Subcarrier Mapping
M-point IDFT
M-point IDFT
Add CP / PS
Add CP / PS
DAC / RF
DAC / RF
MIMO Channel
RF / ADC
RF / ADC
Remove CP
Remove CP
M-point DFT
M-point DFT
Subcarrier De-mapping
Subcarrier De-mapping
Spatial Combining / Equalization
N-point IDFT
N-point IDFT
Detect
Detect

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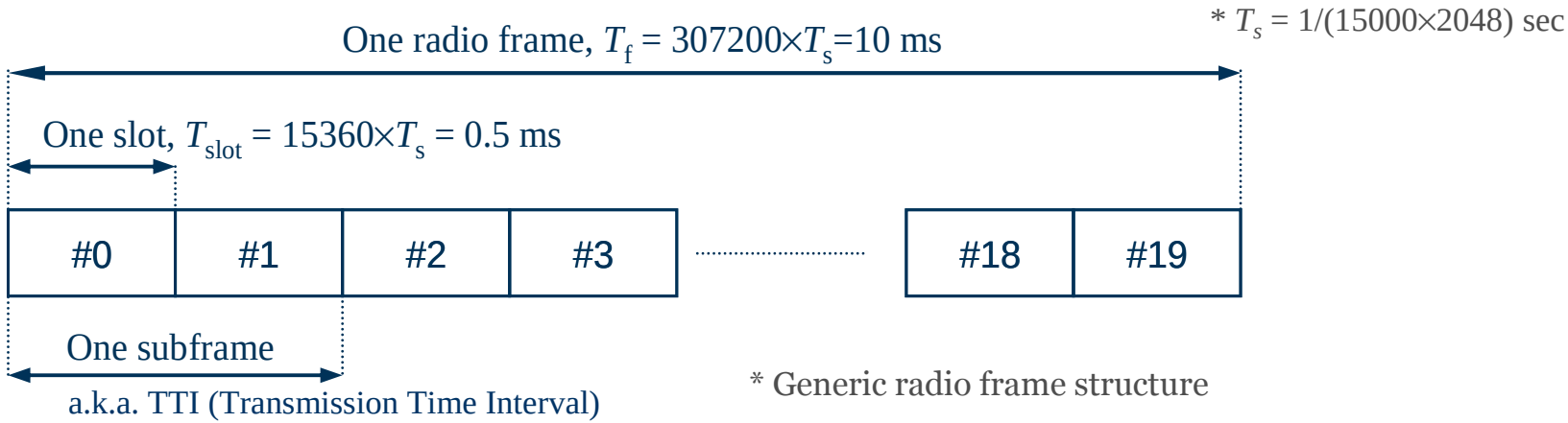
Disclaimer

- 3GPP LTE standardization process is still on-going at current moment.
  ⇒ Many of the technical details presented in this section may change or evolve into different forms.
- For latest updates, refer to the most current specification at http://www.3gpp.org/ftp/Specs/html-info/36-series.htm .

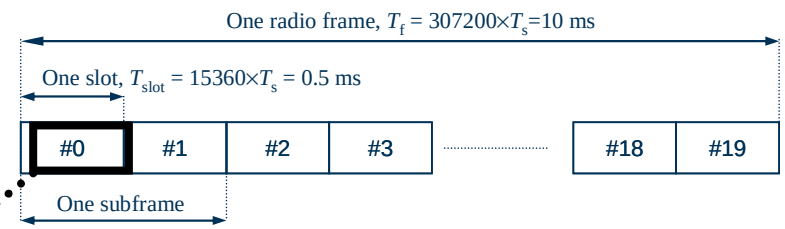
LTE Frame Structure

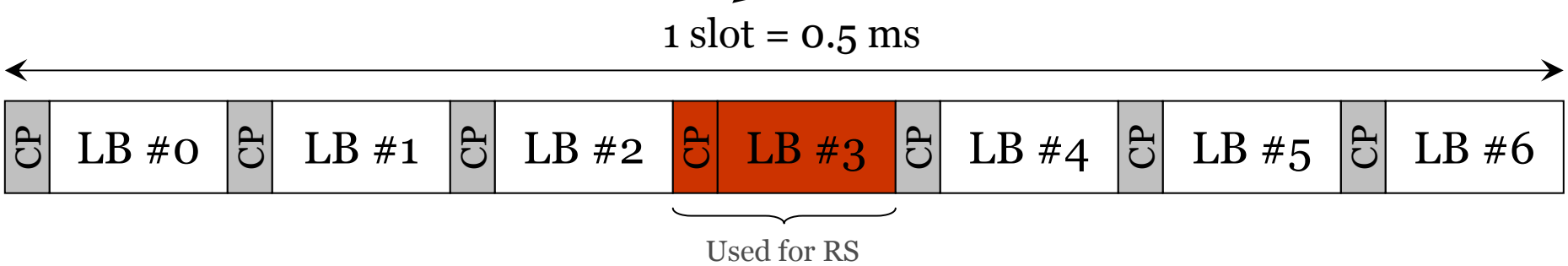
- Two radio frame structures defined.
  - Generic frame structure: FDD and TDD.
  - Alternative frame structure: TDD only.
- Generic radio frame has duration of 10 ms. It consists of 20 slots. A slot has a duration of 0.5 ms. 2 slots comprise a subframe.
- A resource block (RB) spans 12 subcarriers over a slot duration of 0.5 ms. One subcarrier has bandwidth of 15 kHz.



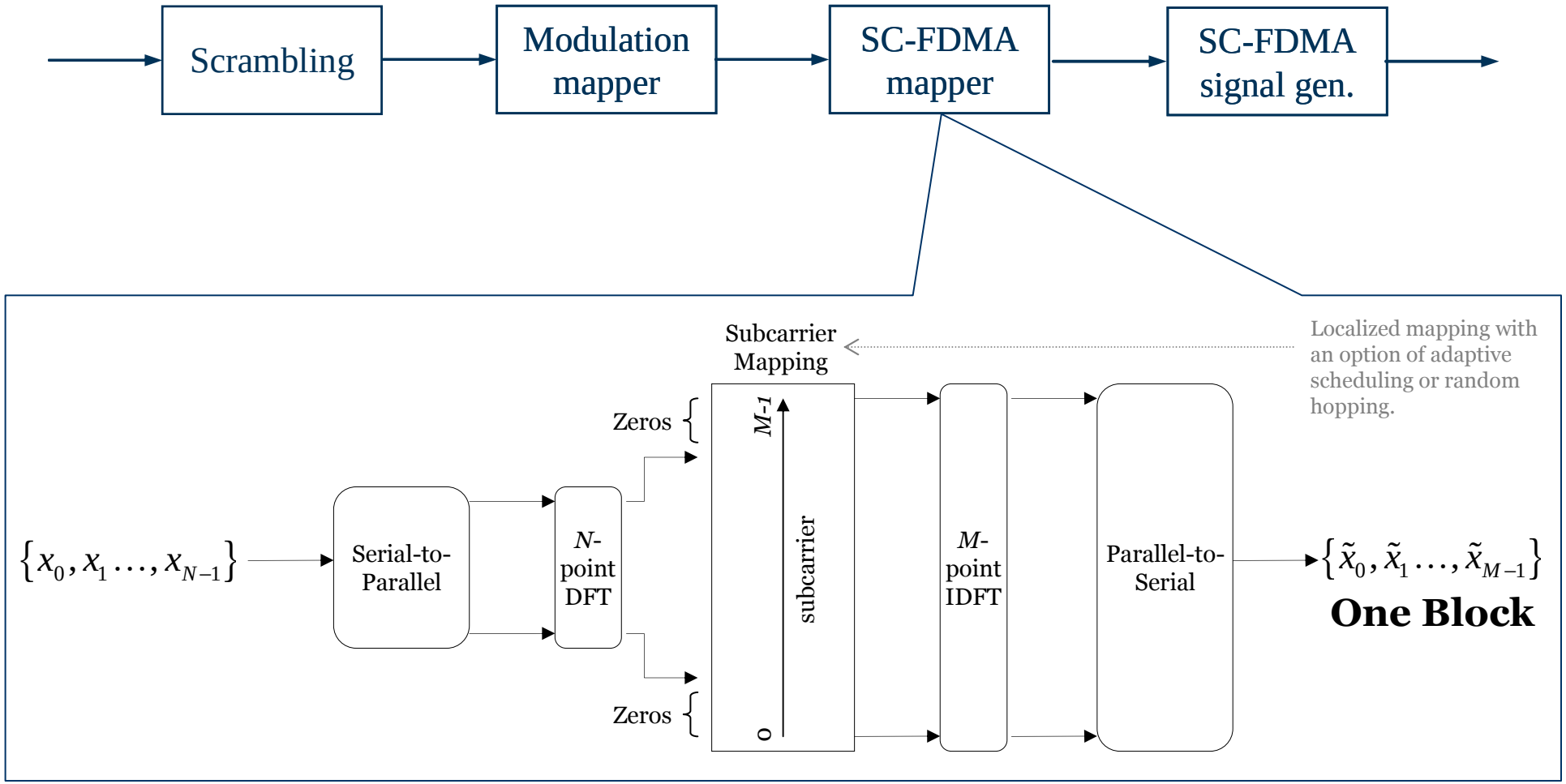
LTE UL Overview

- UL physical channels
  - Physical Uplink Shared Channel (PUSCH)
  - Physical Uplink Control Channel (PUCCH)
- UL physical signals
  - Reference signal (RS)
  - Random access preamble





LTE UL Signal Generation



LTE UL Transmission Parameters

Bandwidth (MHz)	Slot duration (ms)	LB size (μs/# of occupied subcarriers /FFT size)	SB size (μs/# of occupied subcarriers /FFT size)	CP duration (μs/# of subcarriers)
20	0.5	66.67/1200/2048	33.33/600/1024	(4.13/127) or (4.39/135)
15	0.5	66.67/900/1536	33.33/450/768	(4.12/95) or (4.47/103)
10	0.5	66.67/600/1024	33.33/300/512	(4.1/63) or (4.62/71)
5	0.5	66.67/300/512	33.33/150/256	(4.04/31) or (5.08/39)
2.5	0.5	66.67/150/256	33.33/75/128	(3.91/15) or (5.99/23)
1.25	0.5	66.67/75/128	33.33/38/64	(3.65/7) or (7.81/15)

LTE UL Reference Signal

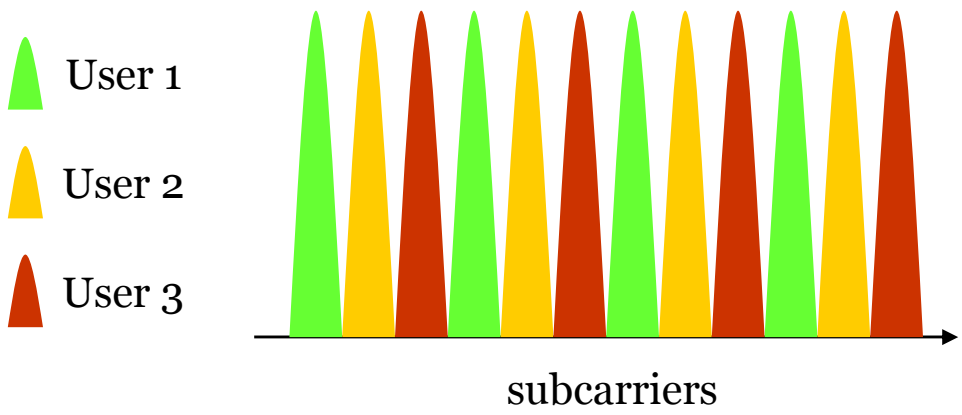
- Two types of UL RS
  - Demodulation (DM) RS ⇒ Narrowband.
  - Sounding RS: Used for UL resource scheduling ⇒ Broadband.
- RS based on Zadoff-Chu CAZAC (Constant Amplitude Zero Auto-Correlation) polyphase sequence
  - CAZAC sequence: Constant amplitude, zero circular auto-correlation, flat frequency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

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

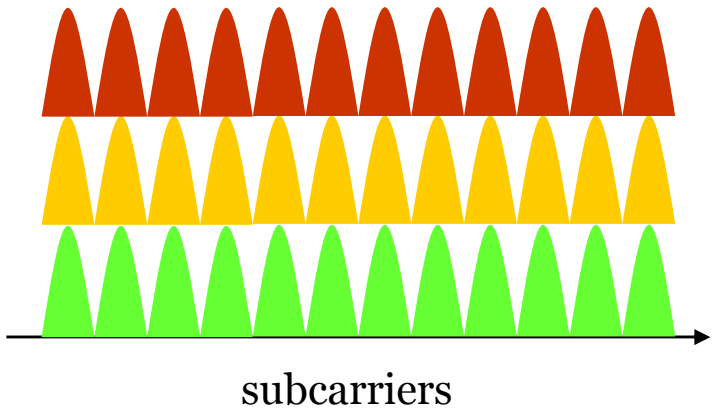
* r is any integer relatively prime with L and q is any integer.

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

LTE UL RS Multiplexing



FDM Pilots



CDM Pilots

LTE UL RS Multiplexing - *cont.*

- DM RS
  - For SIMO: FDM between different users.
  - For SU-MIMO: CDM between RS from each antenna
  - For MU-MIMO: CDM between RS from each antenna
- Sounding RS
  - CDM when there is only one sounding bandwidth.
  - CDM/FDM when there are multiple sounding bandwidths.

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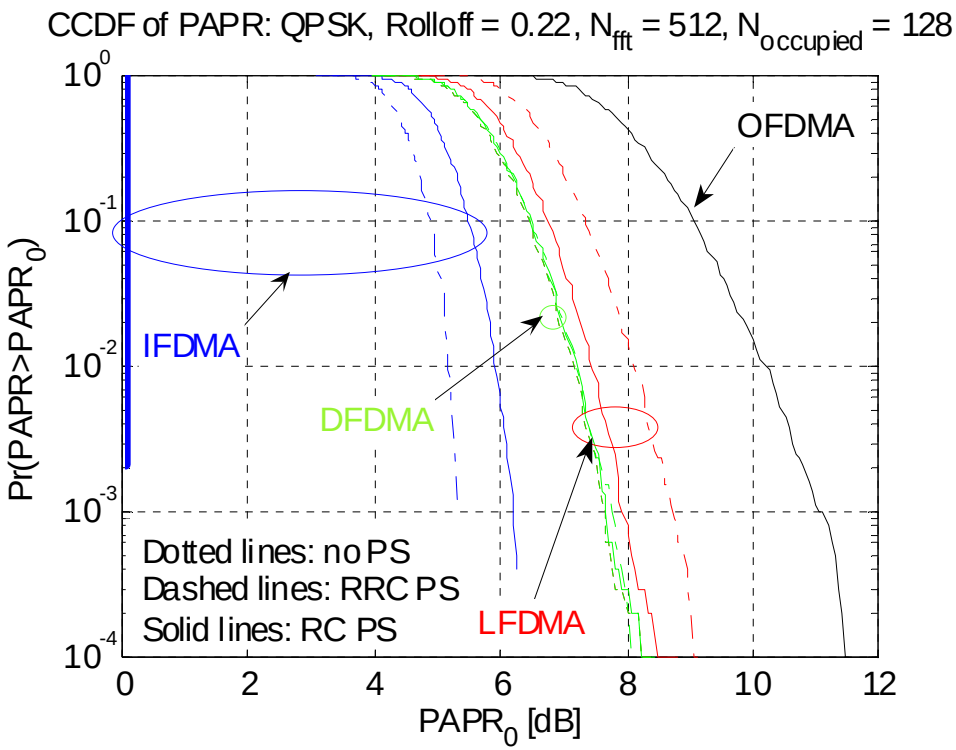
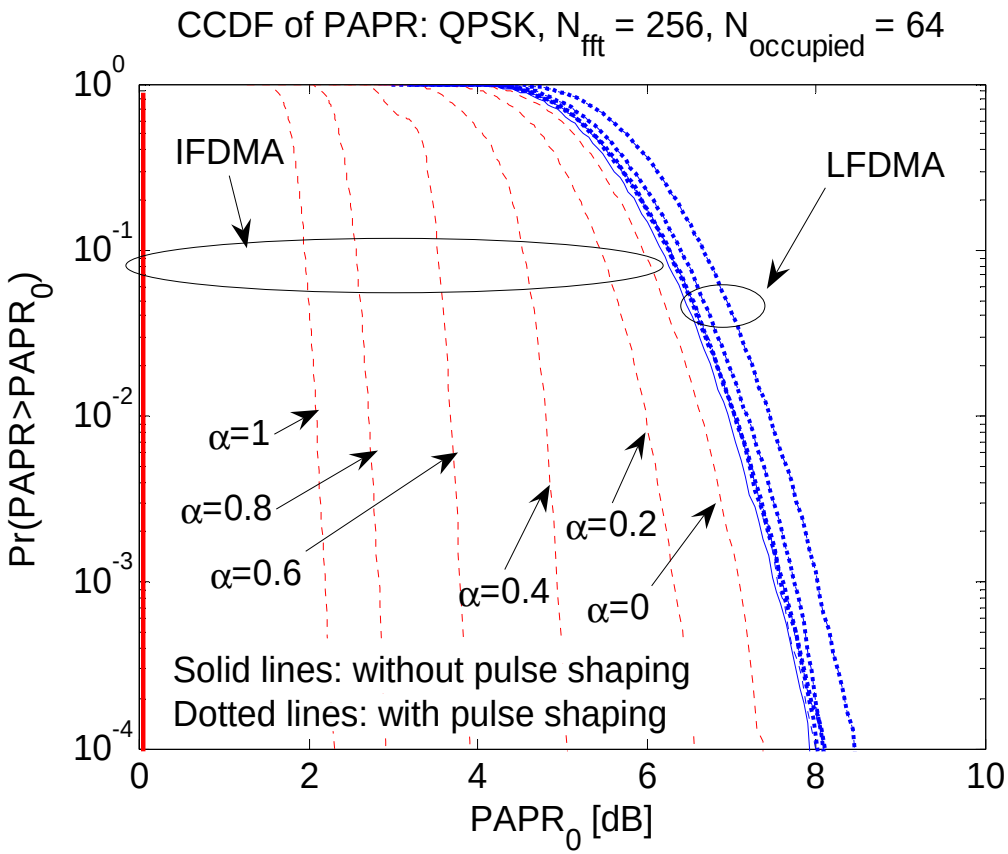
PAPR Characteristics



* Monte Carlo simulations
* Number of iterations: > 10^4
* QPSK
* Time domain pulse shaping with 8-times overs ampling
* N_{fft}: number of total subcarriers = FFT size
* $N_{occupied}$: number of occupied subcarriers = data block size
* RC: raised-cosine, RRC: root raised-cosine
* Rolloff factor of 0.22

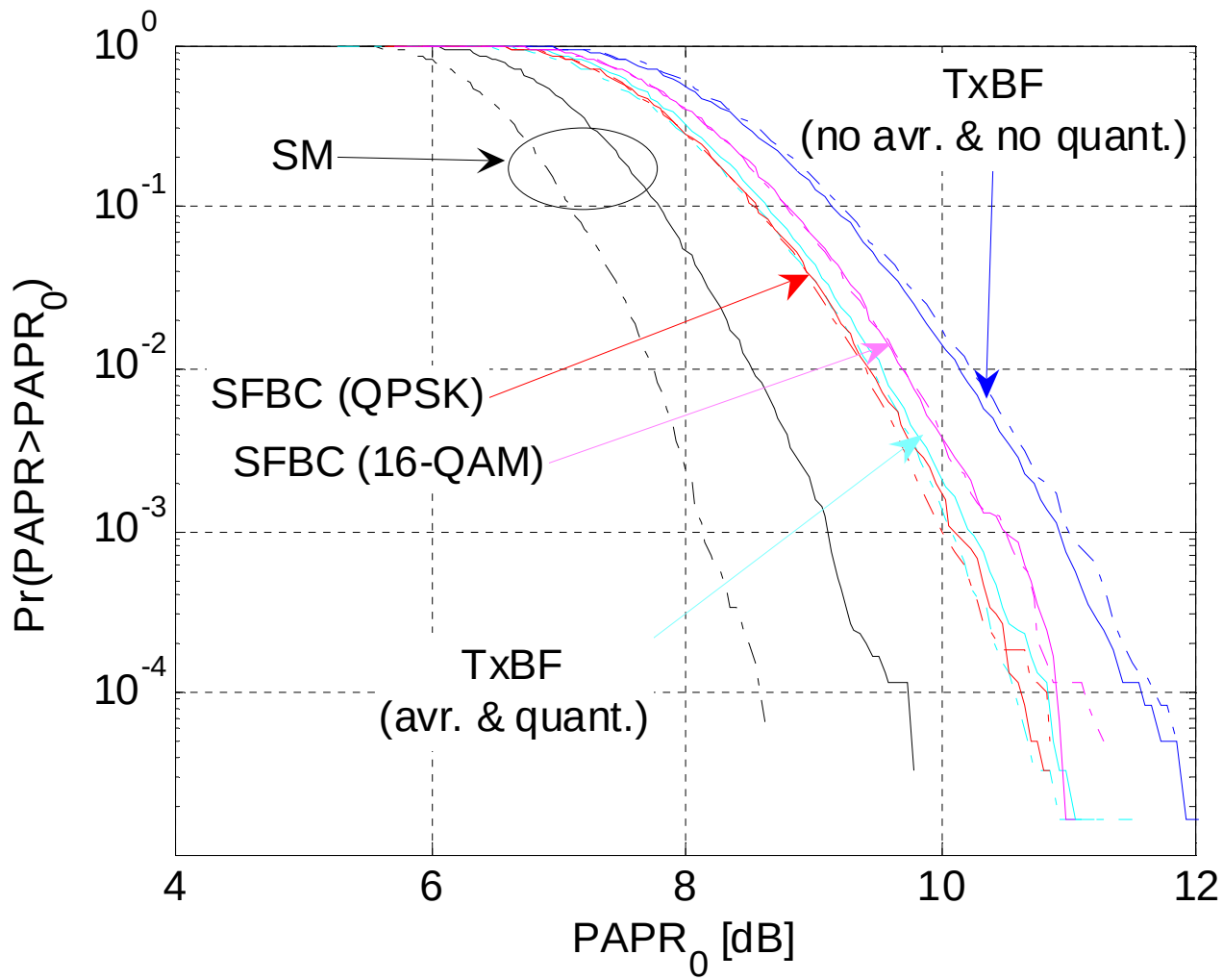
PAPR Characteristics - *cont.*

- PAPR and different rolloff factors



*α: rolloff factor of raised cosine pulse shaping filter

PAPR of SC-FDMA MIMO



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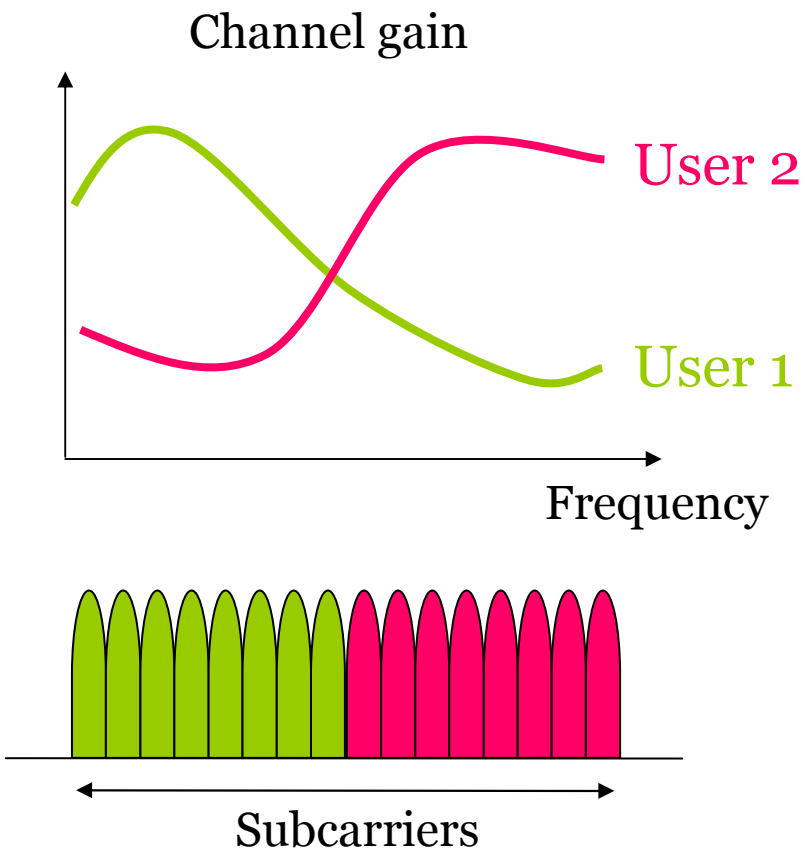
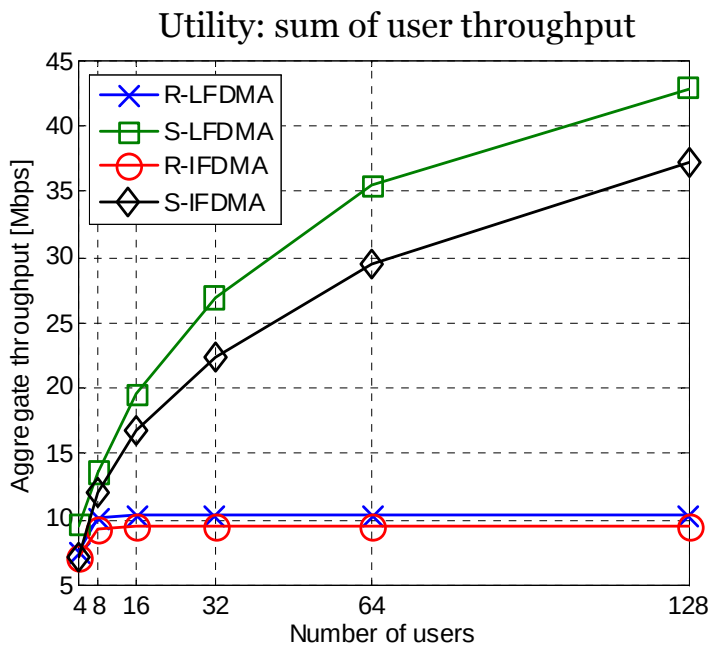
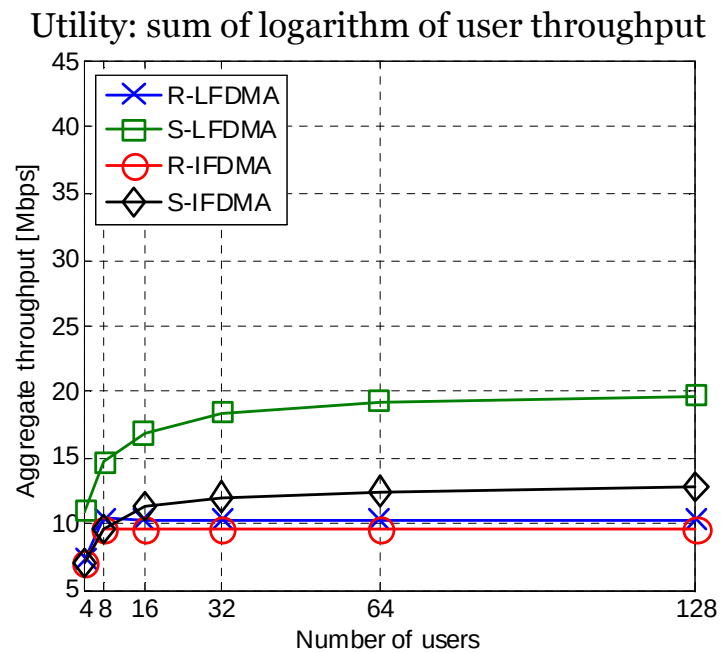
Channel-Dependent Scheduling (CDS)

- Channel-dependent scheduling
  - Assign subcarriers to a user in excellent channel condition.
- Two subcarrier mapping schemes have advantages over each other.
  - Distributed: Frequency diversity.
  - Localized: Frequency selective gain with CDS.



CDS - *cont.*

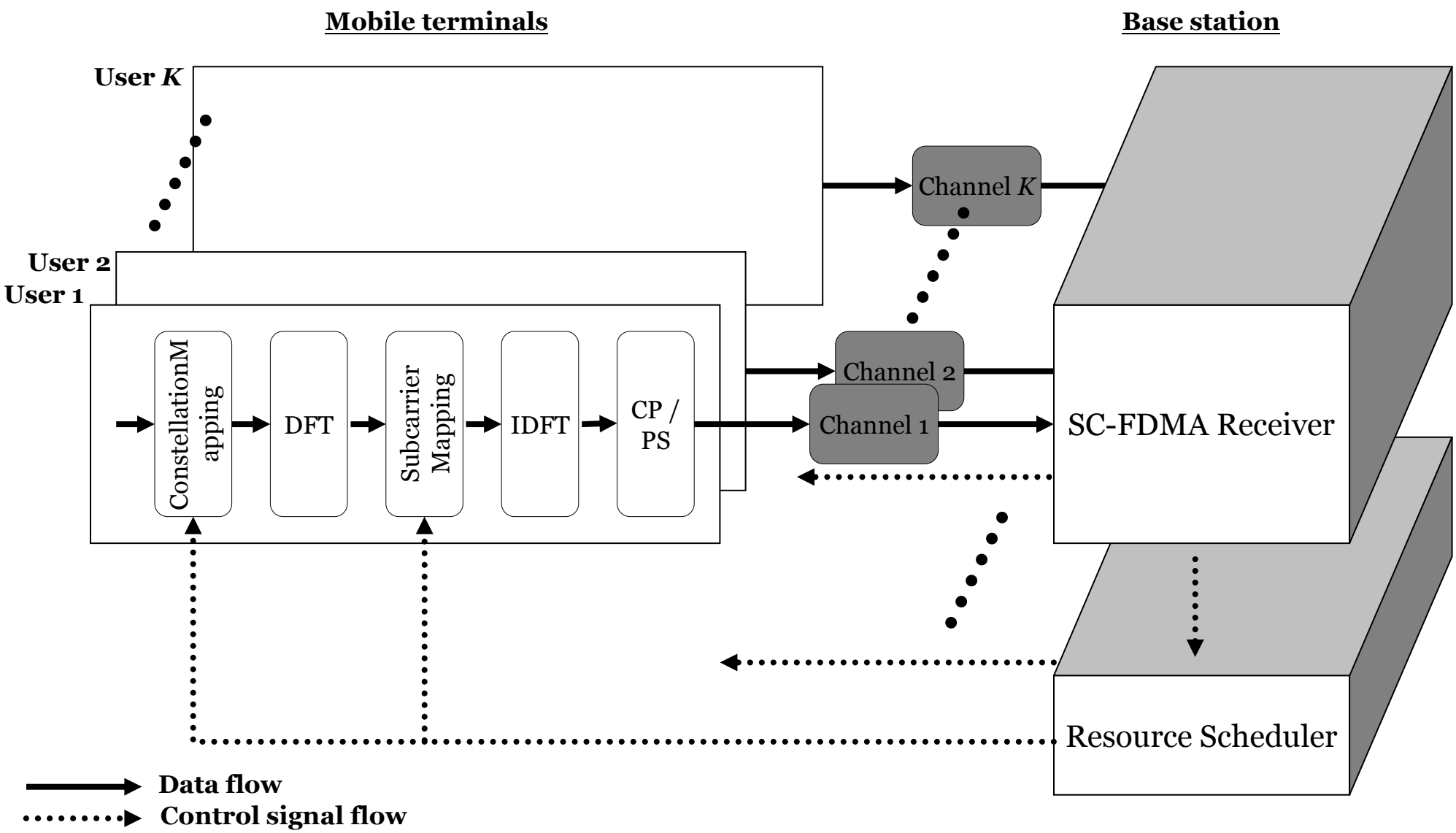




*J. Lim, H. G. Myung, K. Oh, and D. J. Goodman, "Proportional Fair Scheduling of Uplink Single-Carrier FDMA Systems", *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) 2006.*

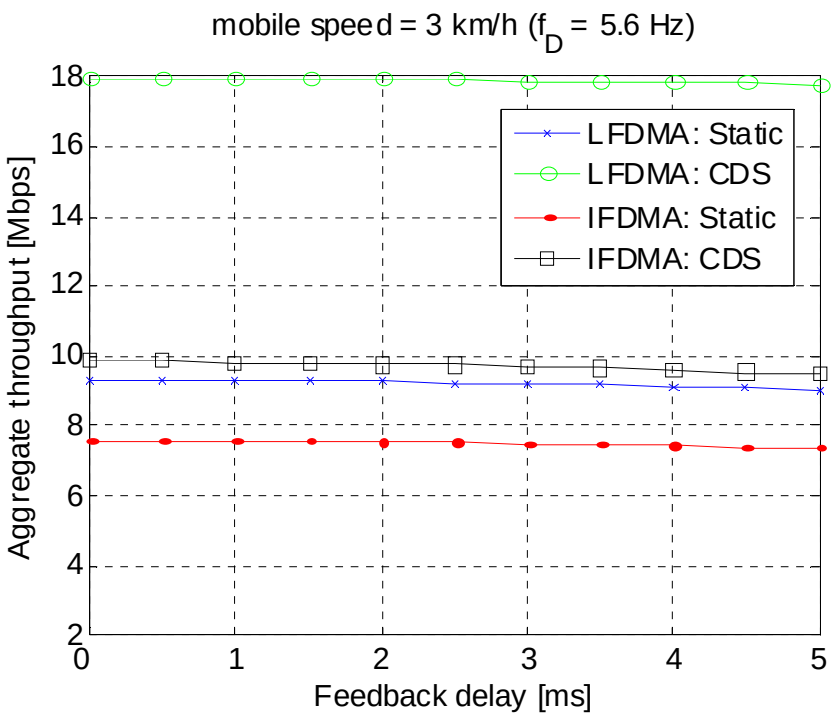
* Capacity based on Shannon's upper bound.
* Time synchronized uplink data transmission.
* Perfect channel knowledge.
* No feedback delay or error.

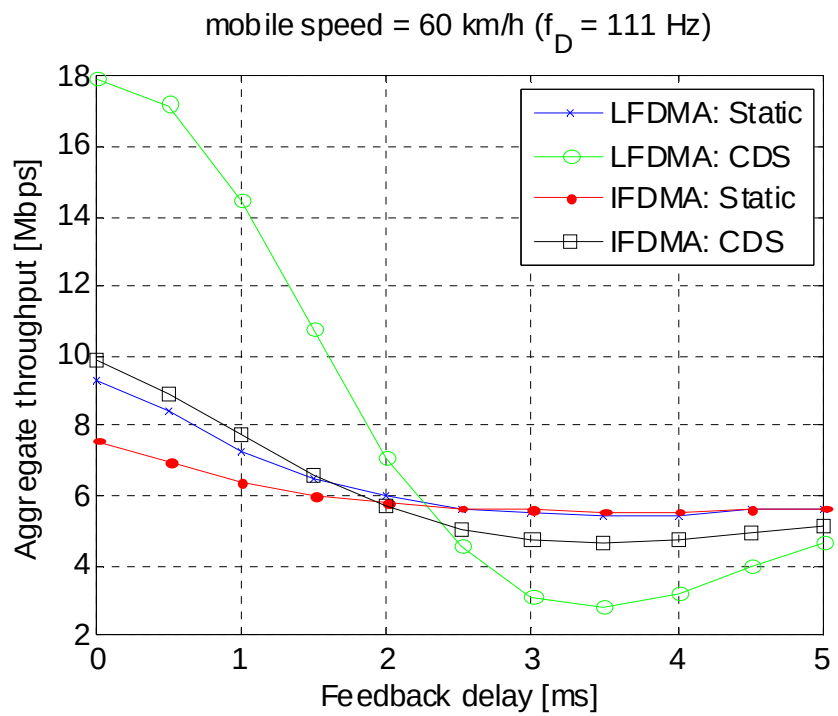
Uplink SC-FDMA with Adaptive Modulation and CDS



Simulation Results

- Aggregate throughput vs. feedback delay





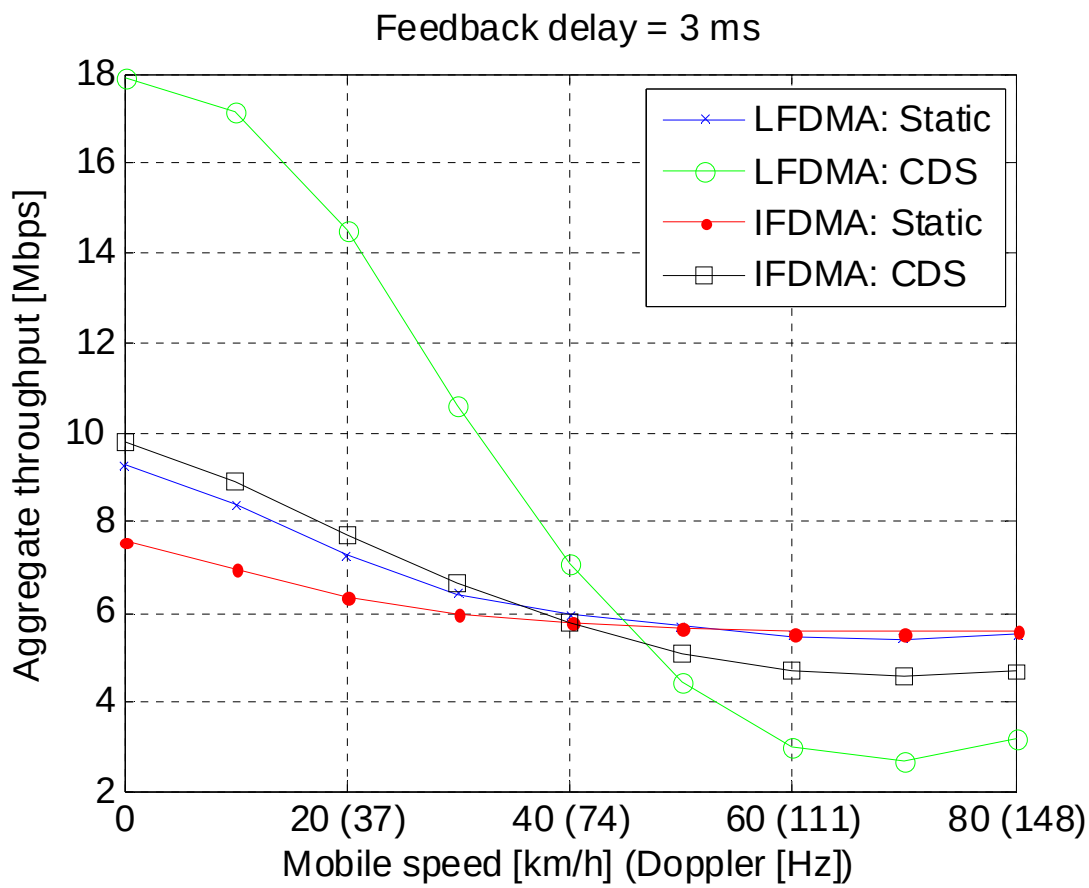
* Carrier frequency = 2 GHz

* K = 64 total number of users, N = 16 subcarriers per chunk, Q = 16 total number of chunks

* Utility: sum of user throughput

Simulation Results - *cont.*

- Aggregate throughput vs. mobile speed



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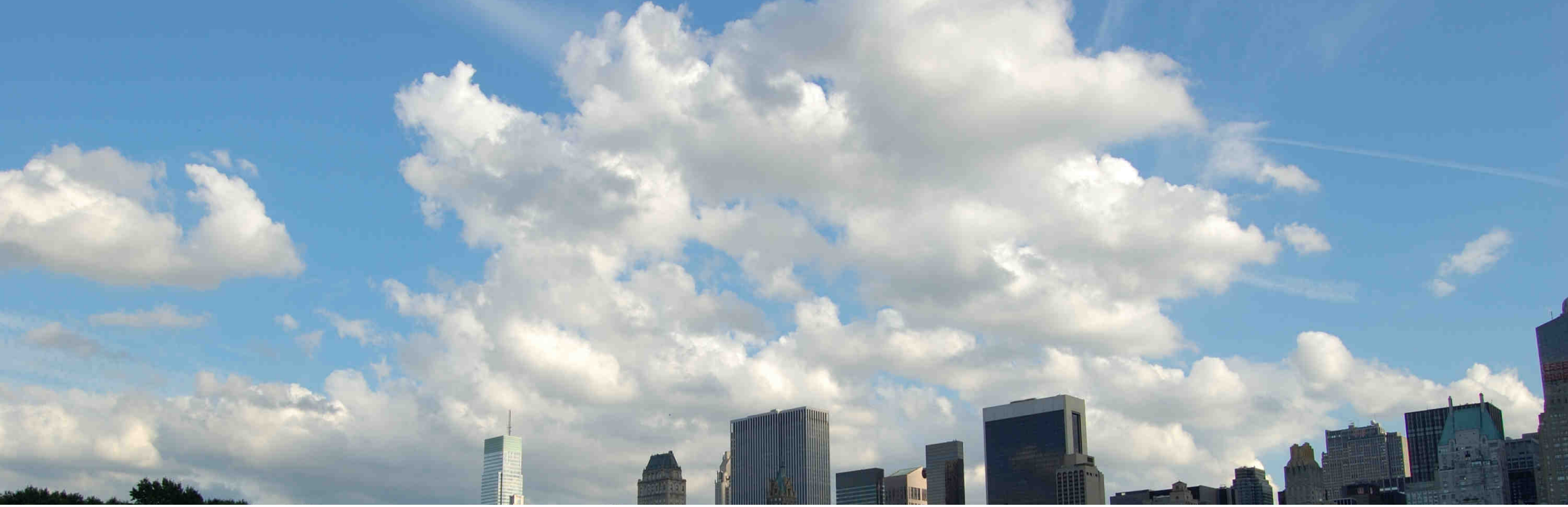
- SC-FDMA is a new single carrier multiple access technique which has similar structure and performance to OFDMA.
  - Currently adopted for uplink multiple access scheme for 3GPP LTE.
- Two types of subcarrier mapping, distributed and localized, give system design flexibility to accommodate either frequency diversity or frequency selective gain.
- A salient advantage of SC-FDMA over OFDM/OFDMA is low PAPR.
  - Efficient transmitter and improved cell-edge performance.
- Pulse shaping as well as subcarrier mapping scheme has a significant impact on PAPR.

References and Resources

- H. G. Myung, J. Lim, & D. J. Goodman, "Single Carrier FDMA for Uplink Wireless Transmission," *IEEE Vehic. Tech. Mag.*, vol. 1, no. 3, Sep. 2006
- H. Ekström *et al.*, "Technical Solutions for the 3G Long-Term Evolution," *IEEE Commun. Mag.*, vol. 44, no. 3, Mar. 2006
- D. Falconer *et al.*, "Frequency Domain Equalization for Single-Carrier Broadband Wireless Systems," *IEEE Commun. Mag.*, vol. 40, no. 4, Apr. 2002
- H. Sari *et al.*, "Transmission Techniques for Digital Terrestrial TV Broadcasting," *IEEE Commun. Mag.*, vol. 33, no. 2, Feb. 1995
- http://singlecarrierfdma.com
- http://www.3gpp.org/ftp/Specs/html-info/36-series.htm

Final Word

SC-FDMA ⇒ Low PAPR



Questions? Thank you!

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