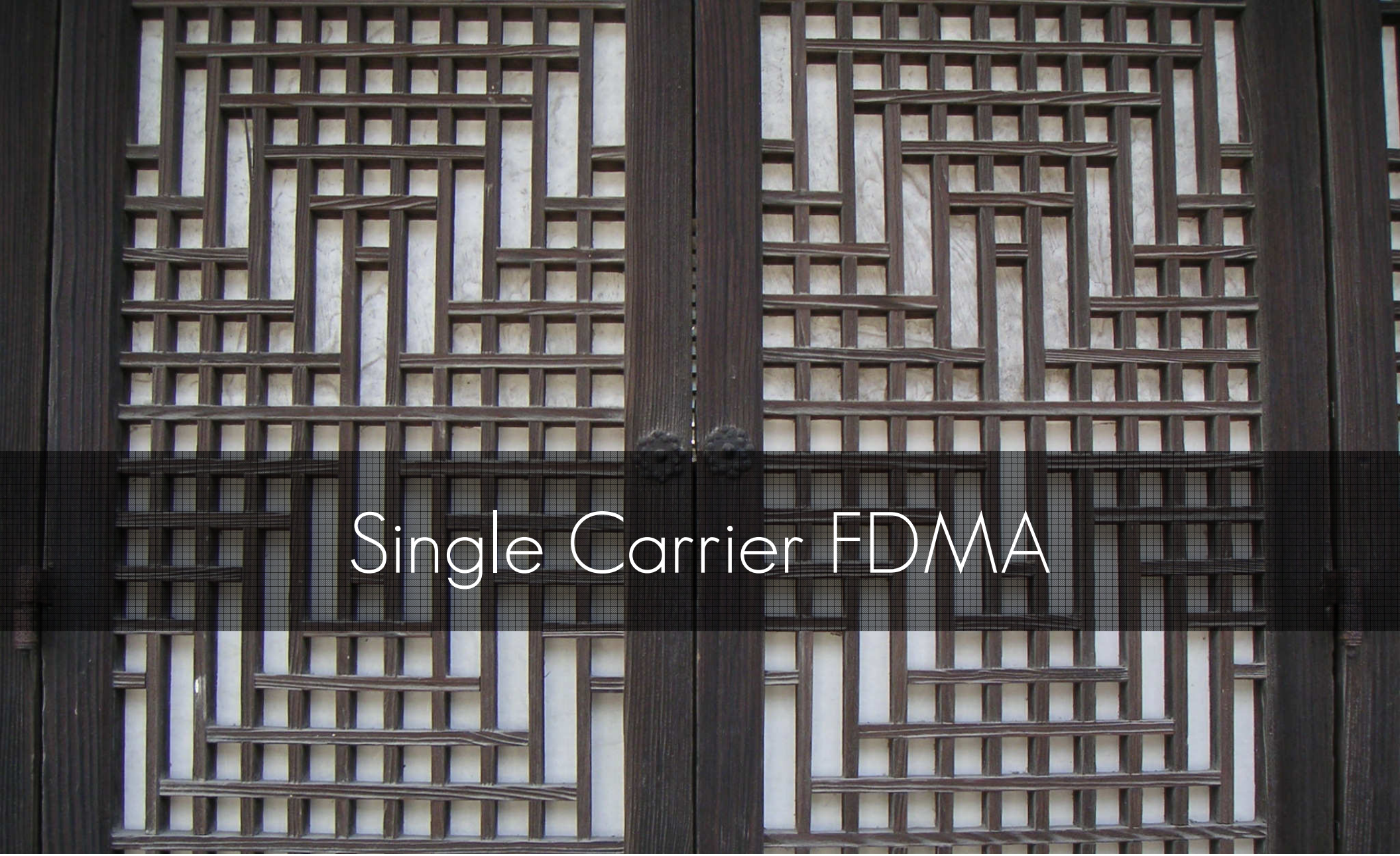


Single Carrier FDMA

May 18, 2008

Hyung G. Myung (hgmyung@ieee.org)

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

Introduction and Background

Overview of SC-FDMA

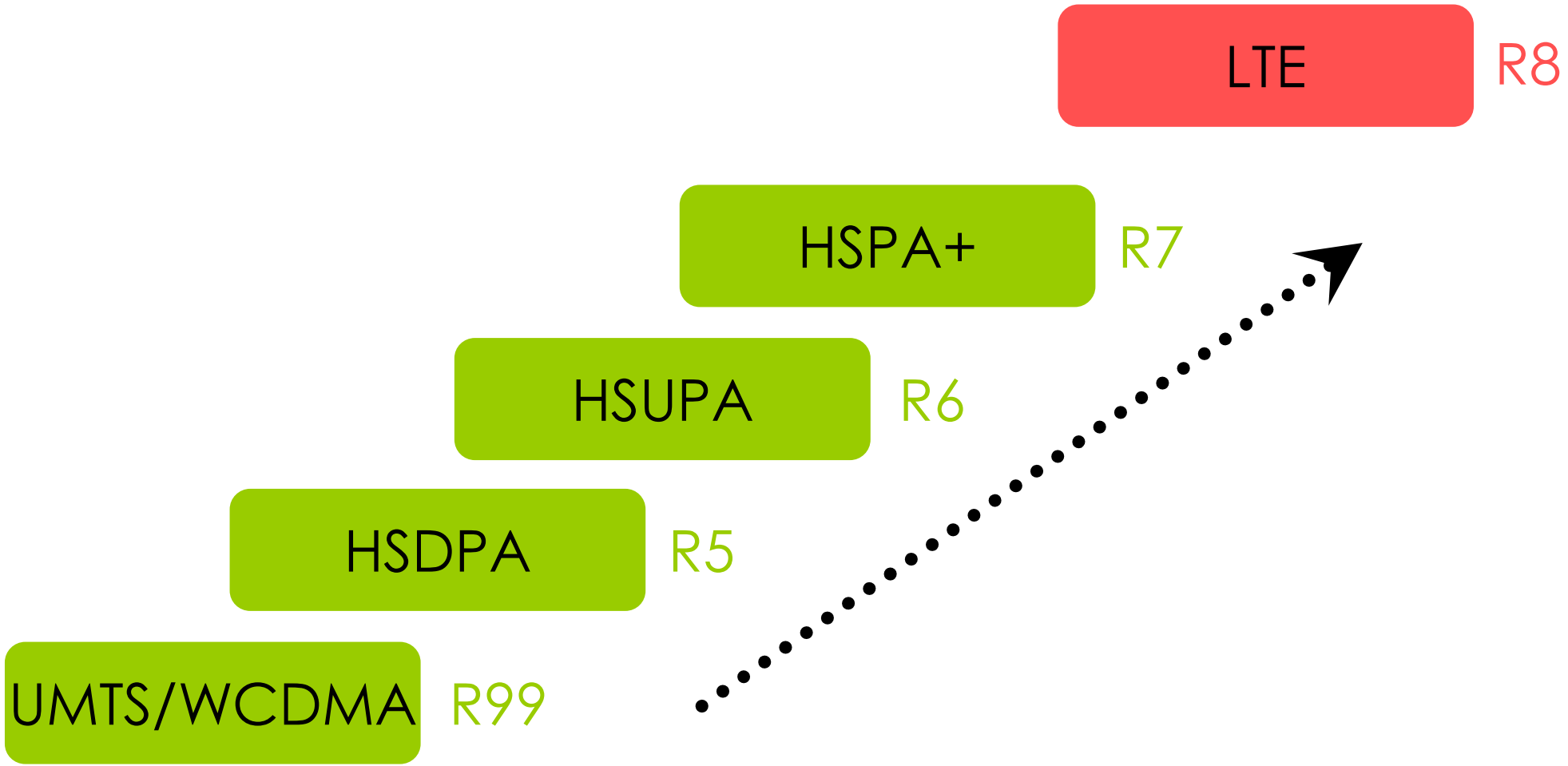
SC-FDMA Implementation in 3GPP LTE

Peak Power Characteristics of SC-FDMA Signals

Uplink Resource Scheduling in SC-FDMA Systems

Summary and Conclusions

3GPP Evolution



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.

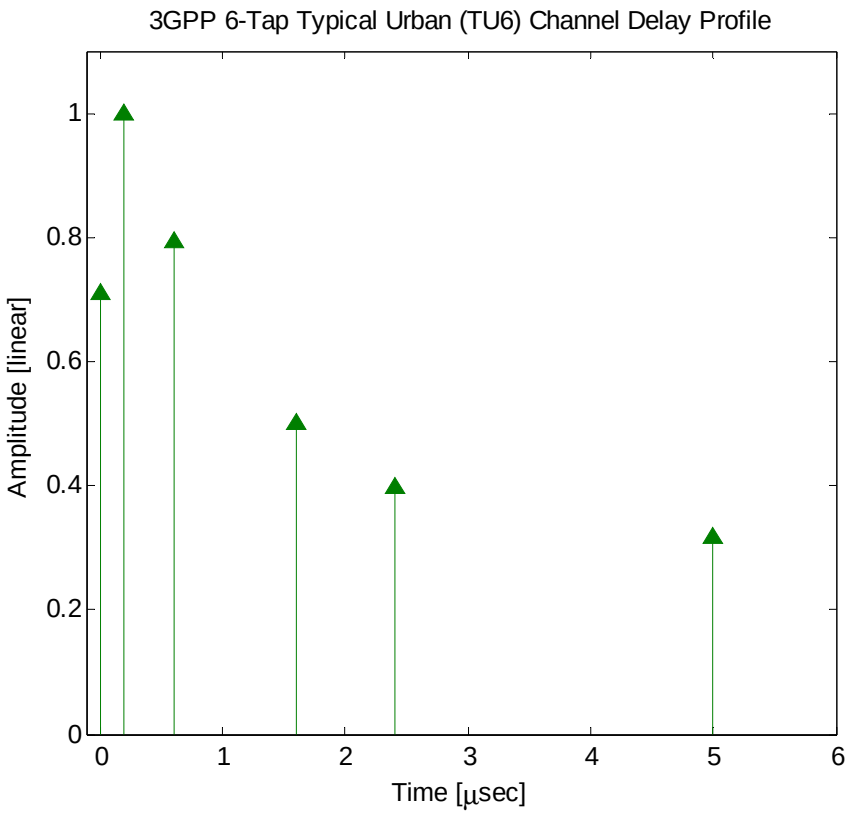
Broadband Multipath Channel

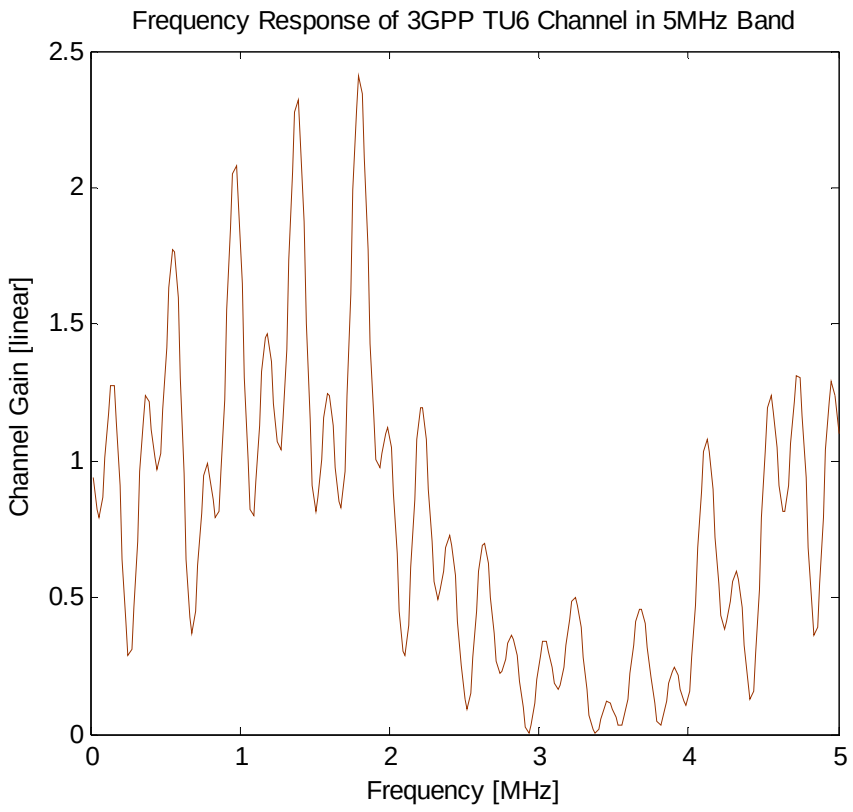
- Demand for higher data rate is leading to utilization of wider transmission bandwidth.

	Standard	Transmission bandwidth
2G	GSM	200 kHz
	IS-95 (CDMA)	1.25 MHz
3G	WCDMA	5 MHz
	cdma2000	5 MHz
3.5~4G	LTE, UMB, WiMAX	Up to 20 MHz

Broadband Multipath Channel - cont.

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



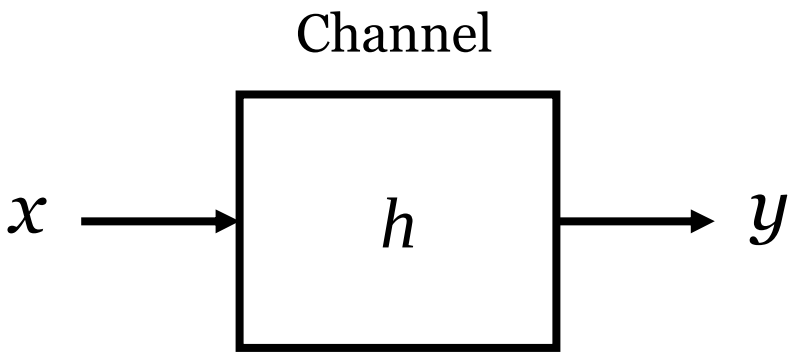


Frequency Domain Equalization

- 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

- cont.



Time domain $y = h * x$

$\therefore x = h^{-1} * y$

Fourier transform

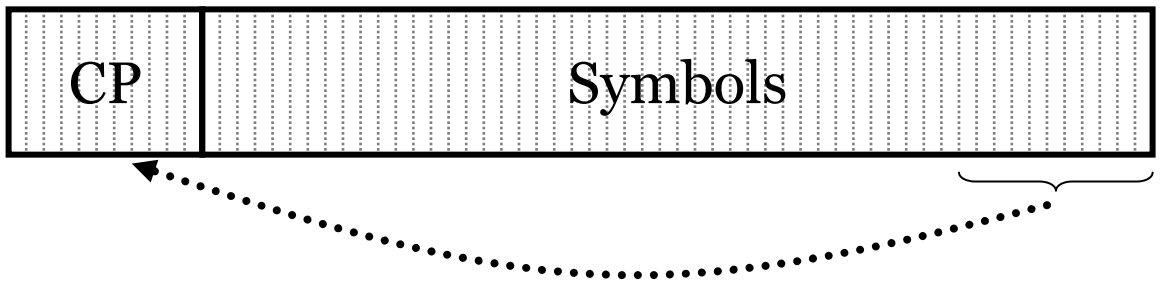
$Y = H \cdot X$

Frequency domain $\therefore X = H^{-1} \cdot Y$

FDE

- cont.

- 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.



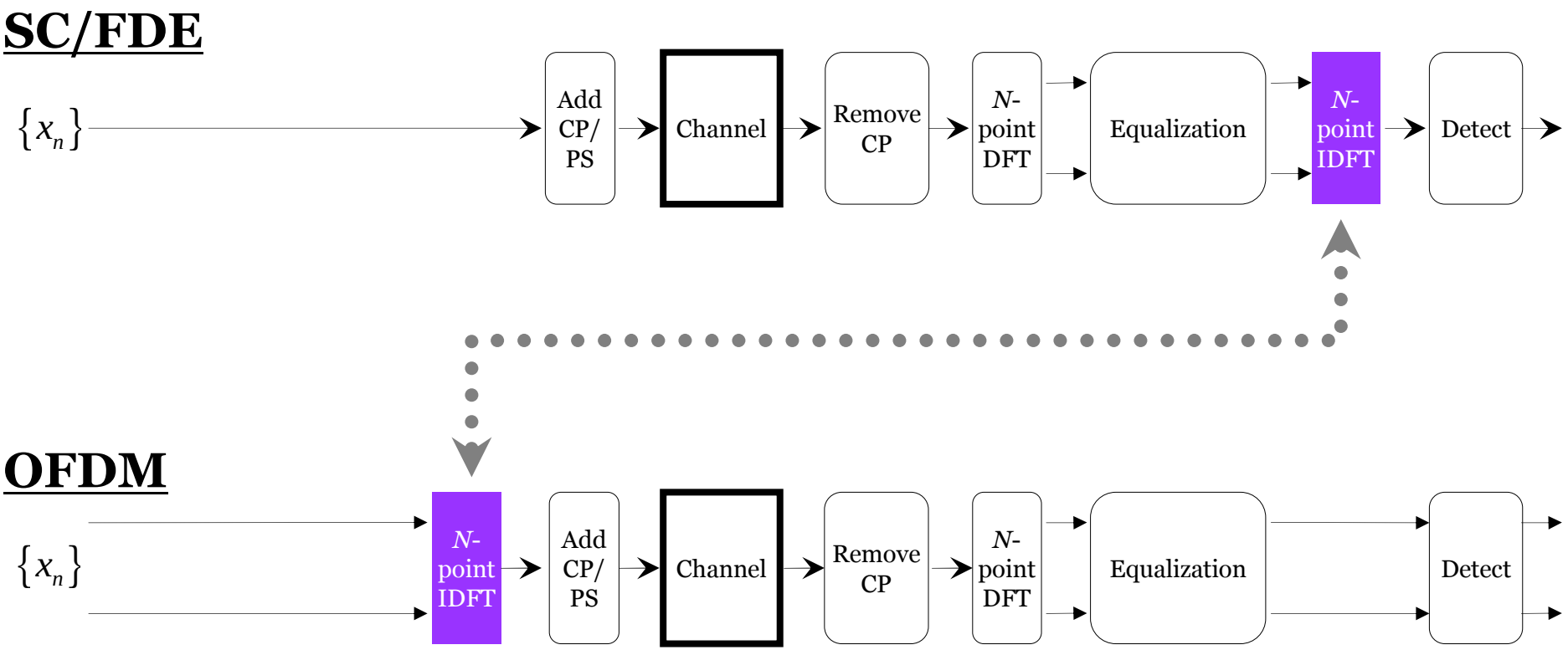
FDE

- cont.

- 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



* 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.
  - 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.

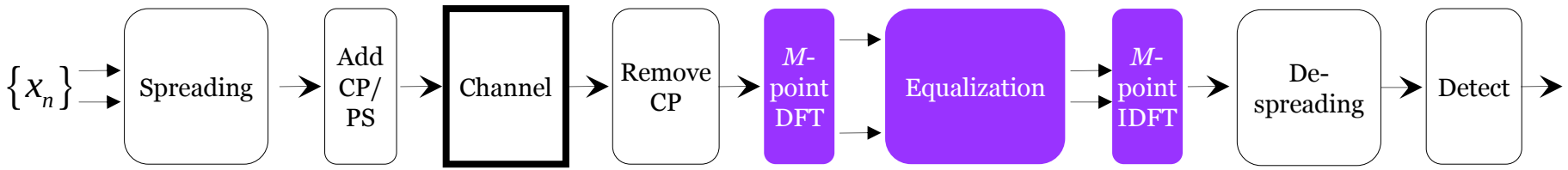
SC/FDE

– cont.

- 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.

CDMA with FDE

- Instead of a RAKE receiver, use frequency domain equalization for channel equalization.
- Reference
  - F. Adachi *et al.*, "Broadband CDMA Techniques," *IEEE Wireless Comm.*, vol. 12, no. 2, Apr. 2005, pp. 8-18.



Introduction and Background

Overview of SC-FDMA

SC-FDMA Implementation in 3GPP LTE

Peak Power Characteristics of SC-FDMA Signals

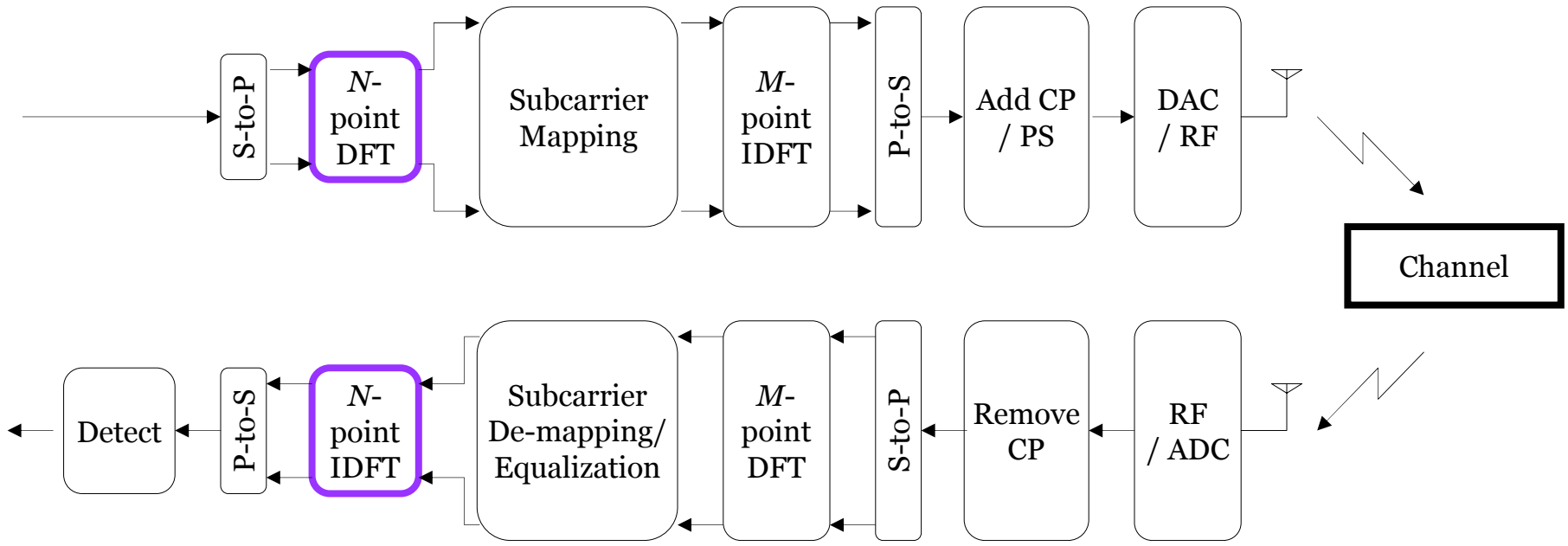
Uplink Resource Scheduling in SC-FDMA Systems

Summary and Conclusions

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.
  - A variant of SC-FDMA using code spreading is used in 3GPP2 UMB uplink.
  - 802.16m also considering it for uplink.

TX & RX Structure of SC-FDMA



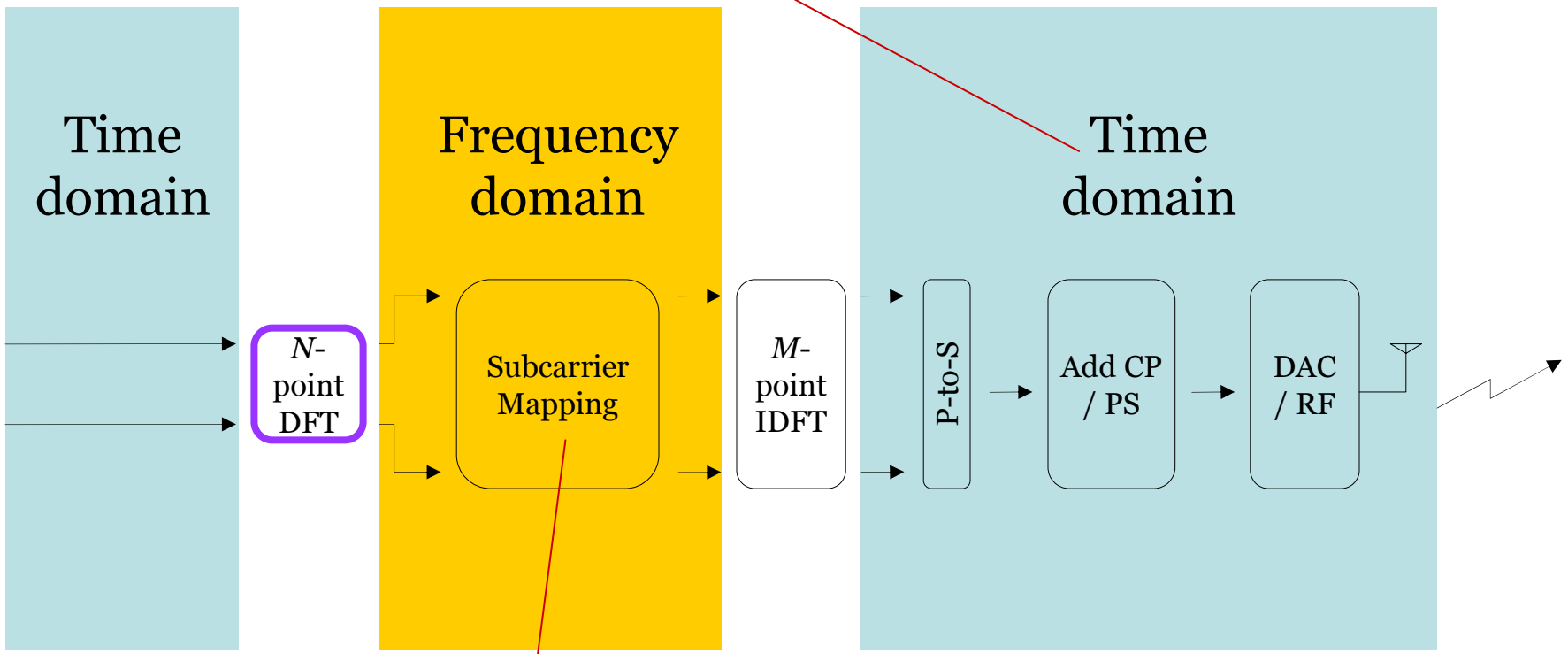
SC-FDMA: □ + □

OFDMA: □

* $N < M$
* S-to-P: Serial-to-Parallel
* P-to-S: Parallel-to-Serial

Why "Single Carrier" "FDMA"?

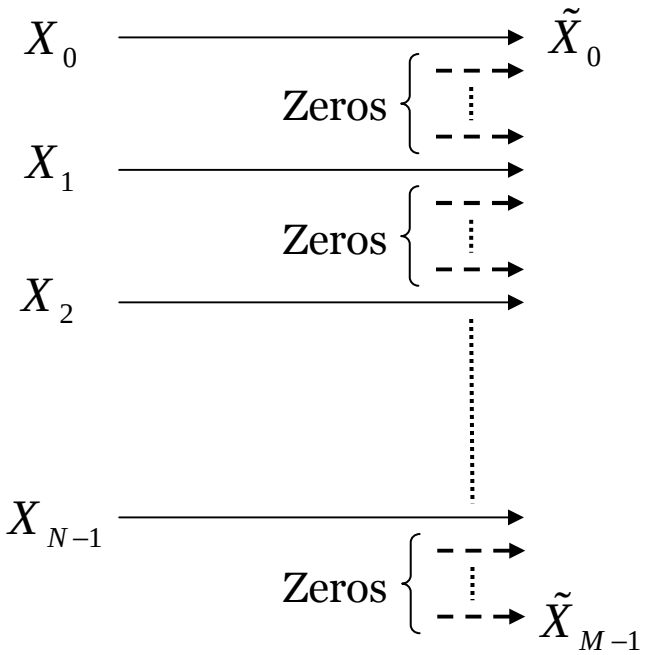
"Single Carrier" : Sequential transmission of the symbols over a single frequency carrier.



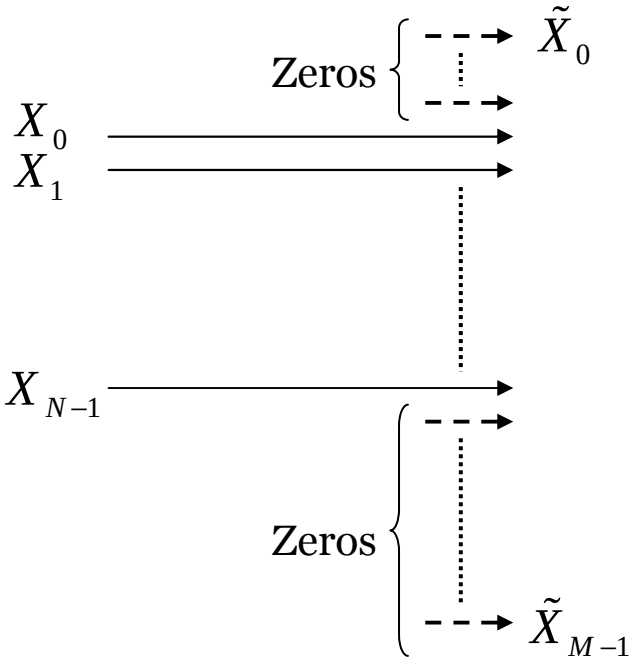
"FDMA" : User multiplexing in the frequency domain.

Subcarrier Mapping

- Two ways to map subcarriers; distributed and localized.
- Distributed mapping scheme for (total # of subcarriers) = (data block size) × (bandwidth spreading factor) is called **Interleaved FDMA (IFDMA)**.



Distributed

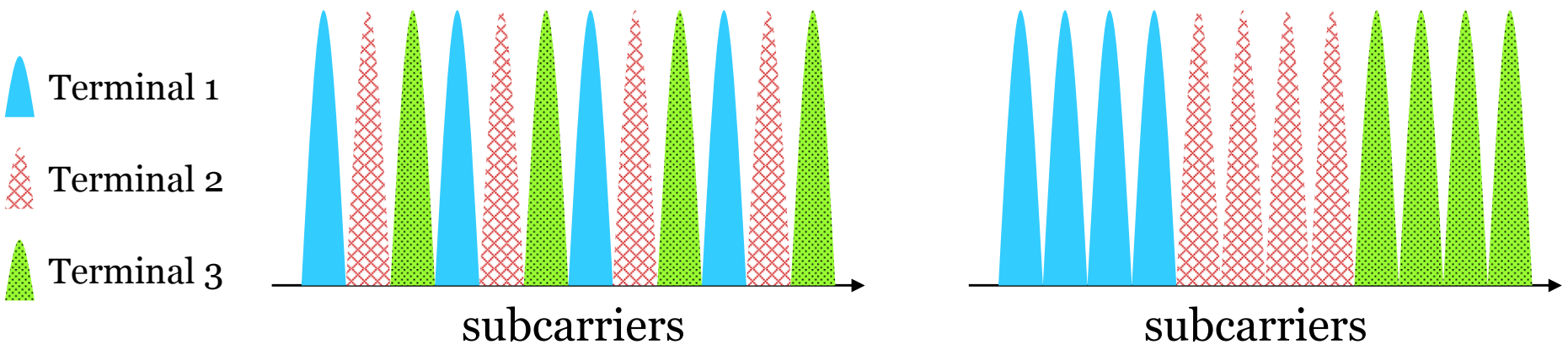


Localized

Subcarrier Mapping

- cont.

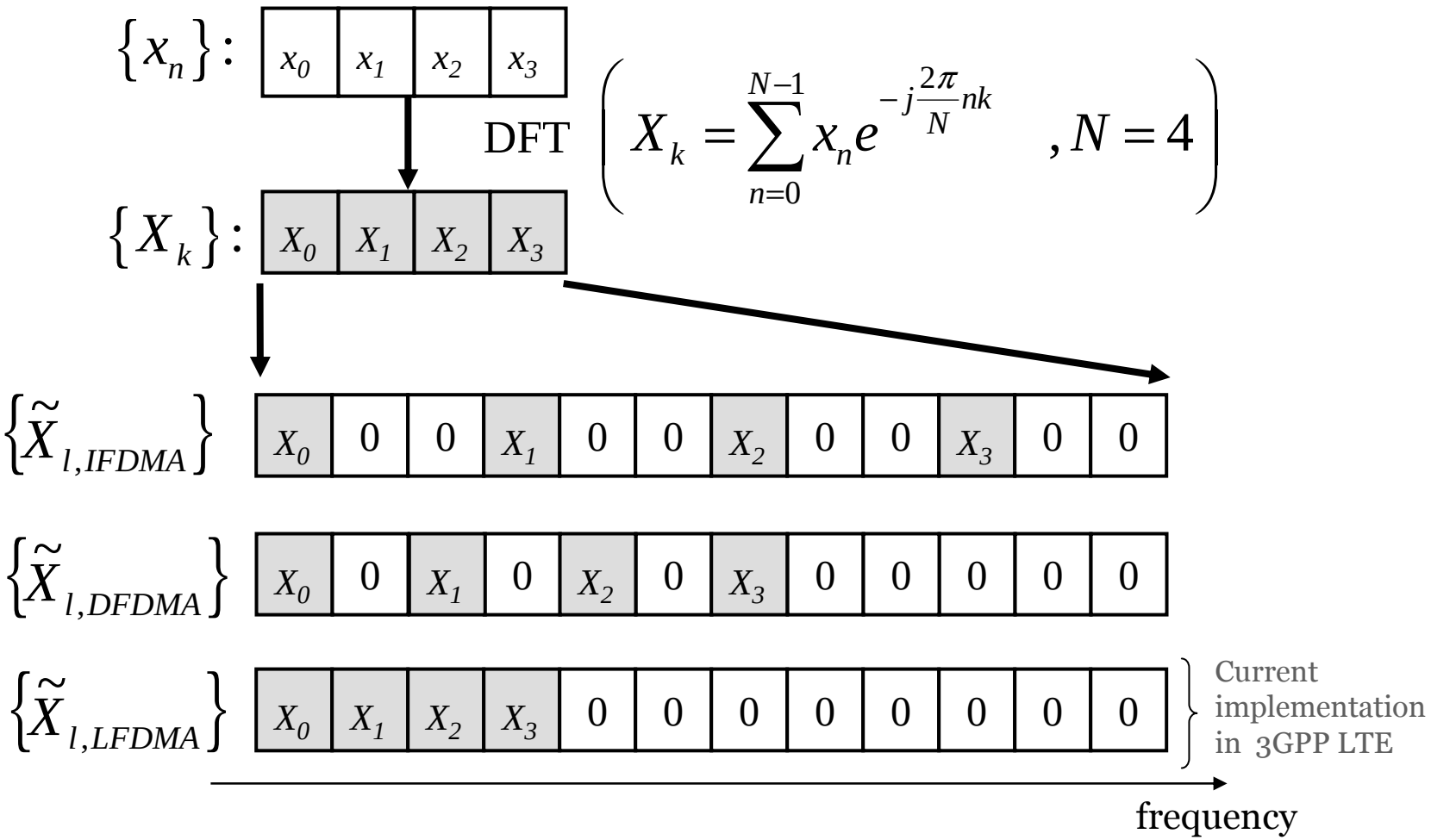
- Data block size (N) = 4, Number of users (Q) = 3, Number of subcarriers (M) = 12.



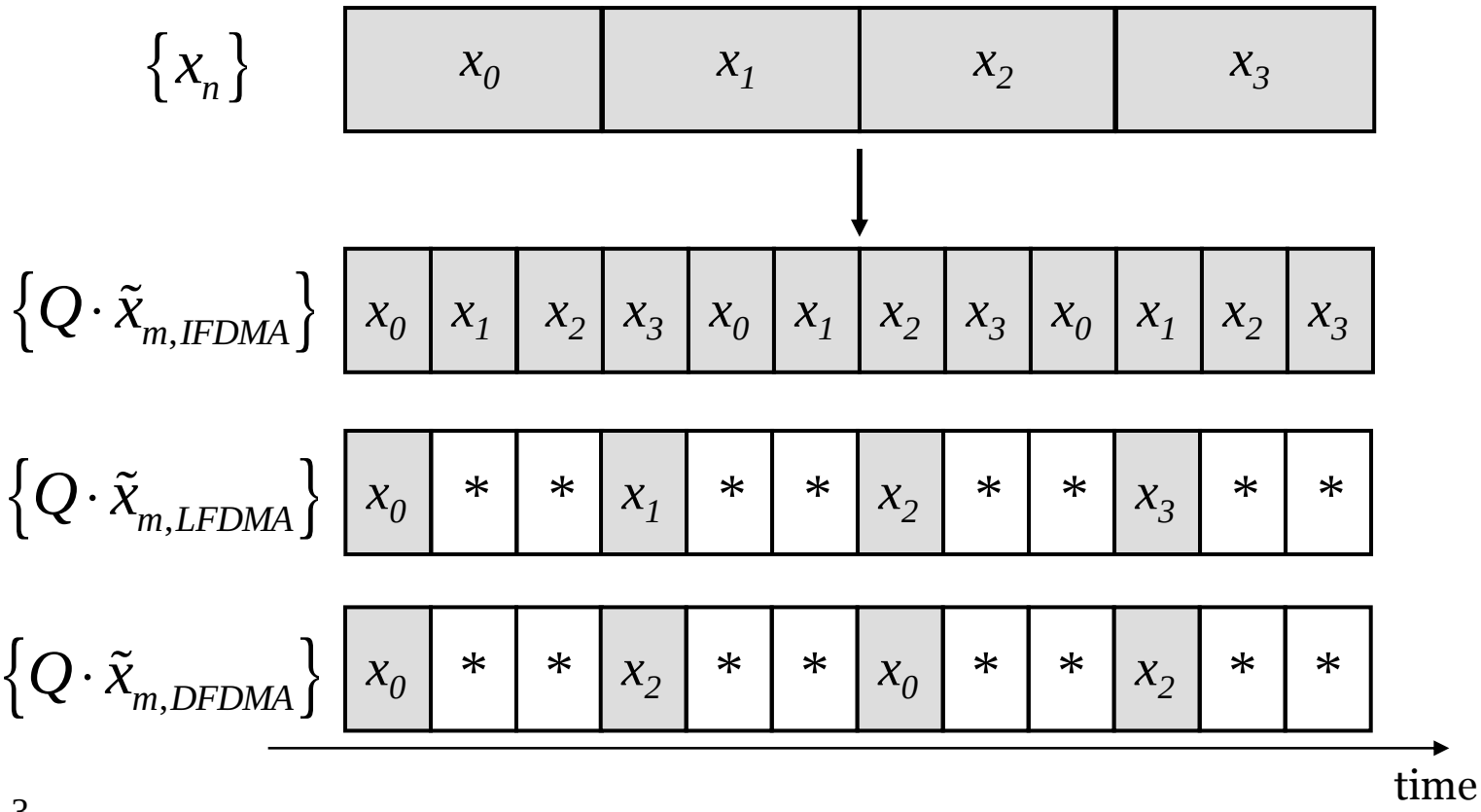
Distributed Mode **Localized Mode**

Subcarrier Mapping

- cont.

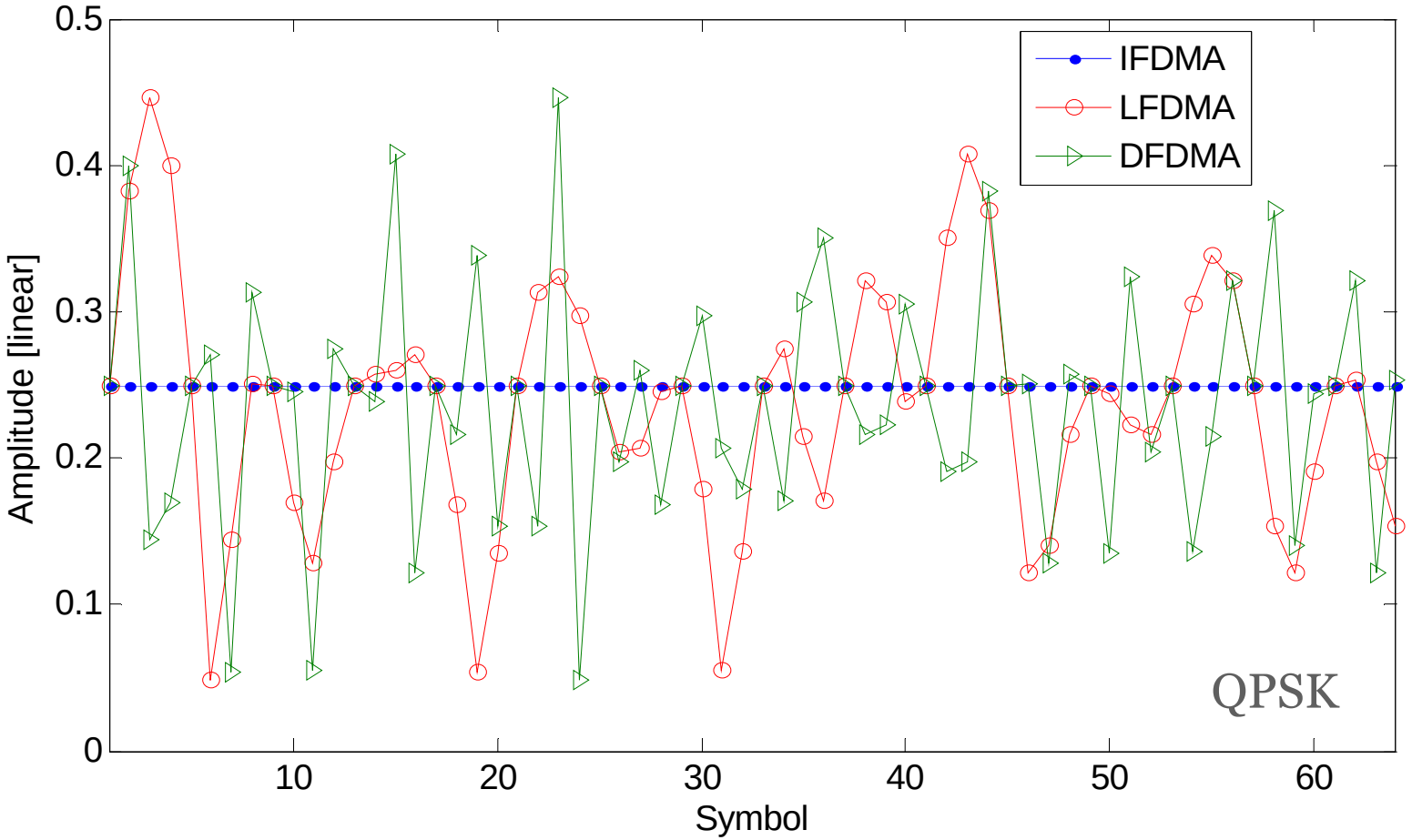


Time Domain Representation



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

Amplitude of SC-FDMA Symbols



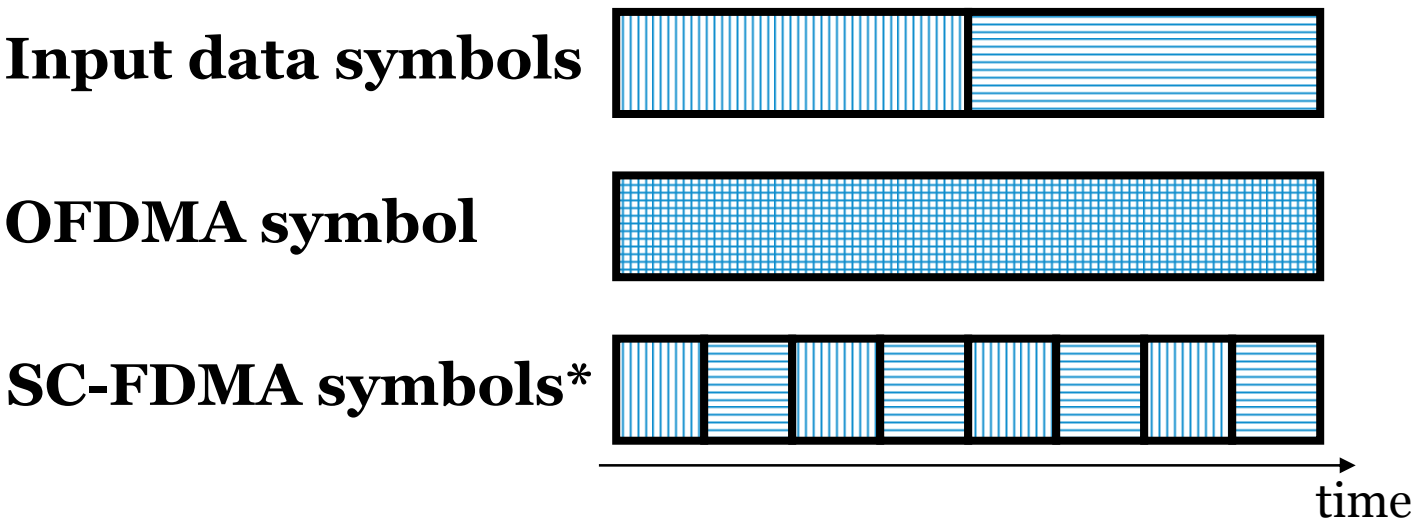
SC-FDMA and OFDMA

- 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.

SC-FDMA and OFDMA

- cont.

- Difference in time domain signal



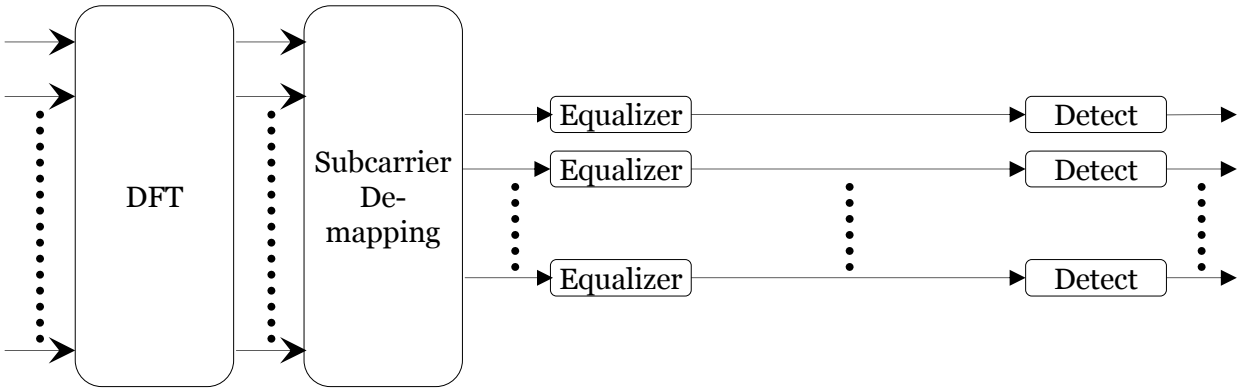
* Bandwidth spreading factor : 4

SC-FDMA and OFDMA

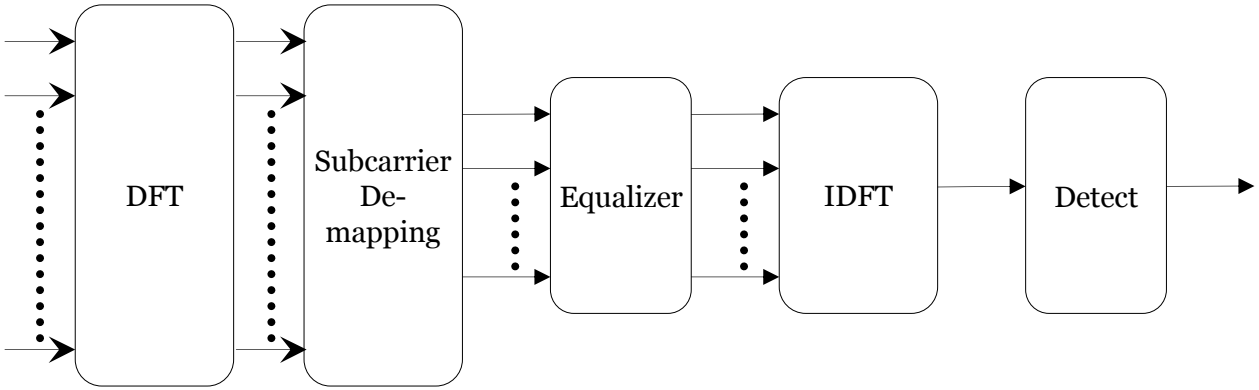
- cont.

- Different equalization/detection aspects

OFDMA



SC-FDMA



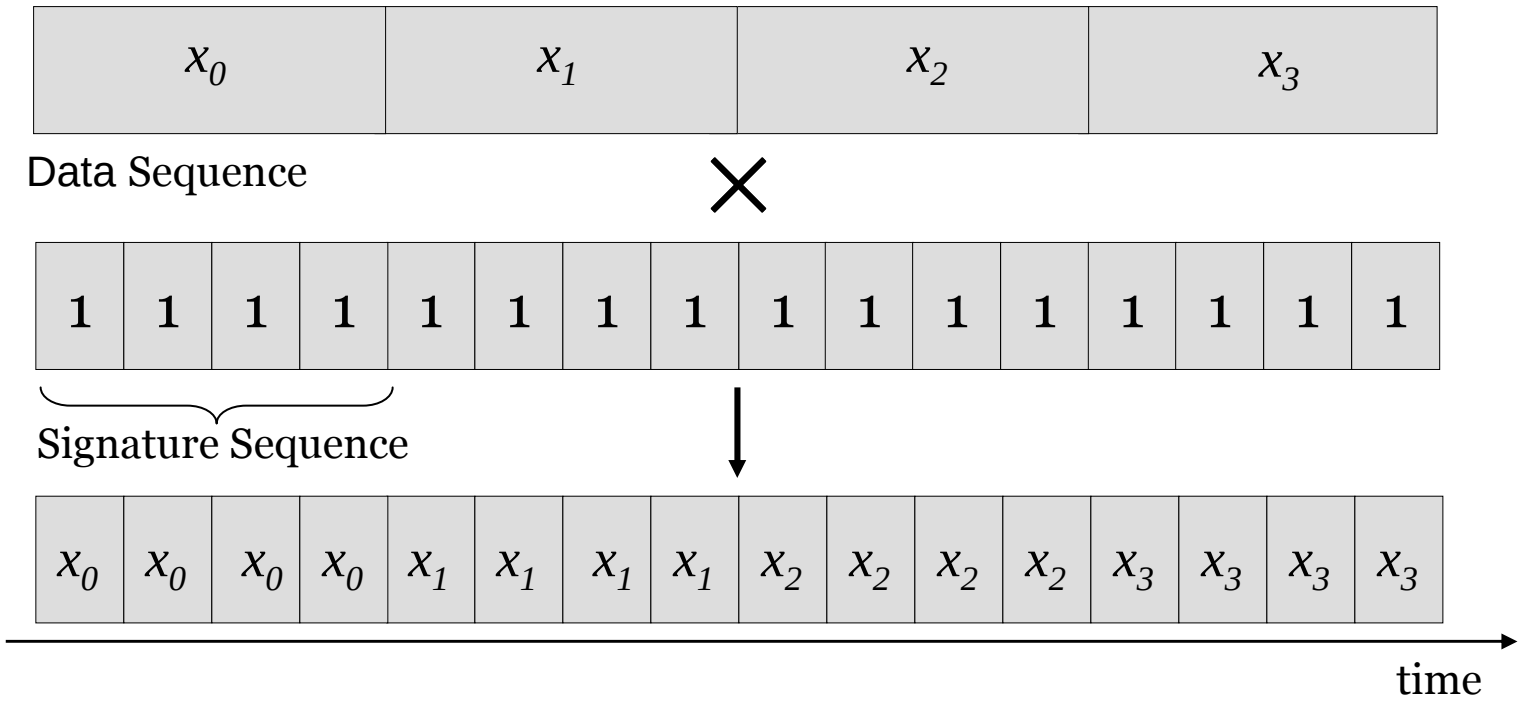
SC-FDMA and DS-CDMA

- 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 and DS-CDMA

– cont.

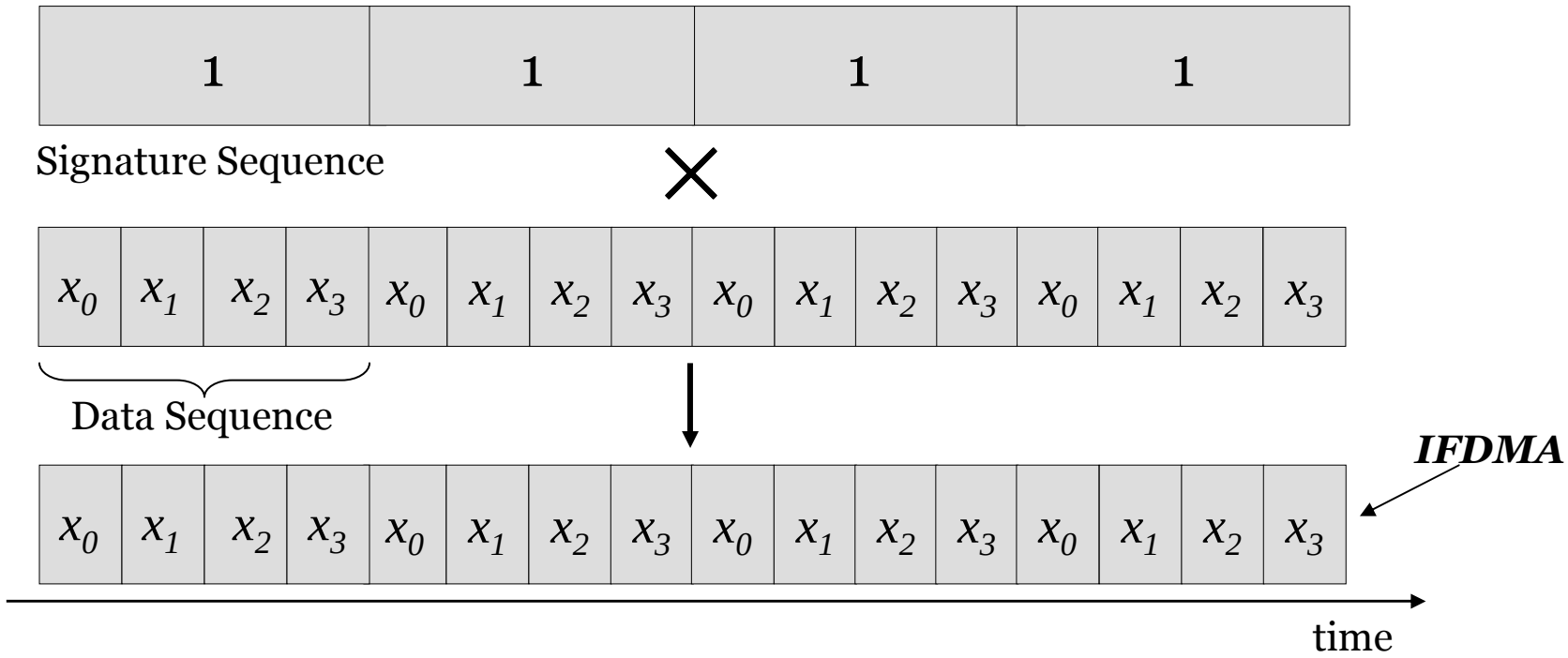
- Conventional spreading



SC-FDMA and DS-CDMA

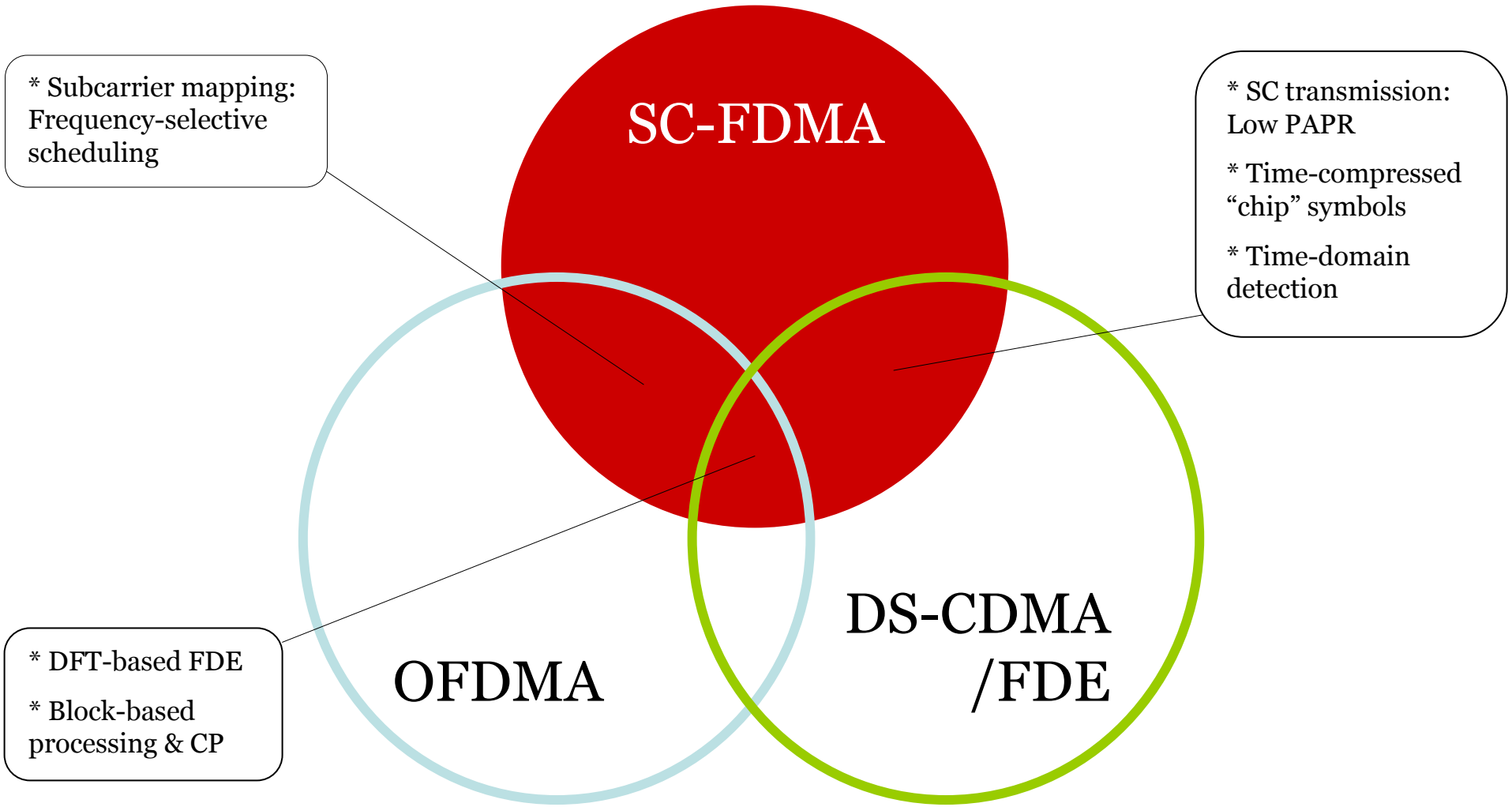
– cont.

- Exchanged spreading

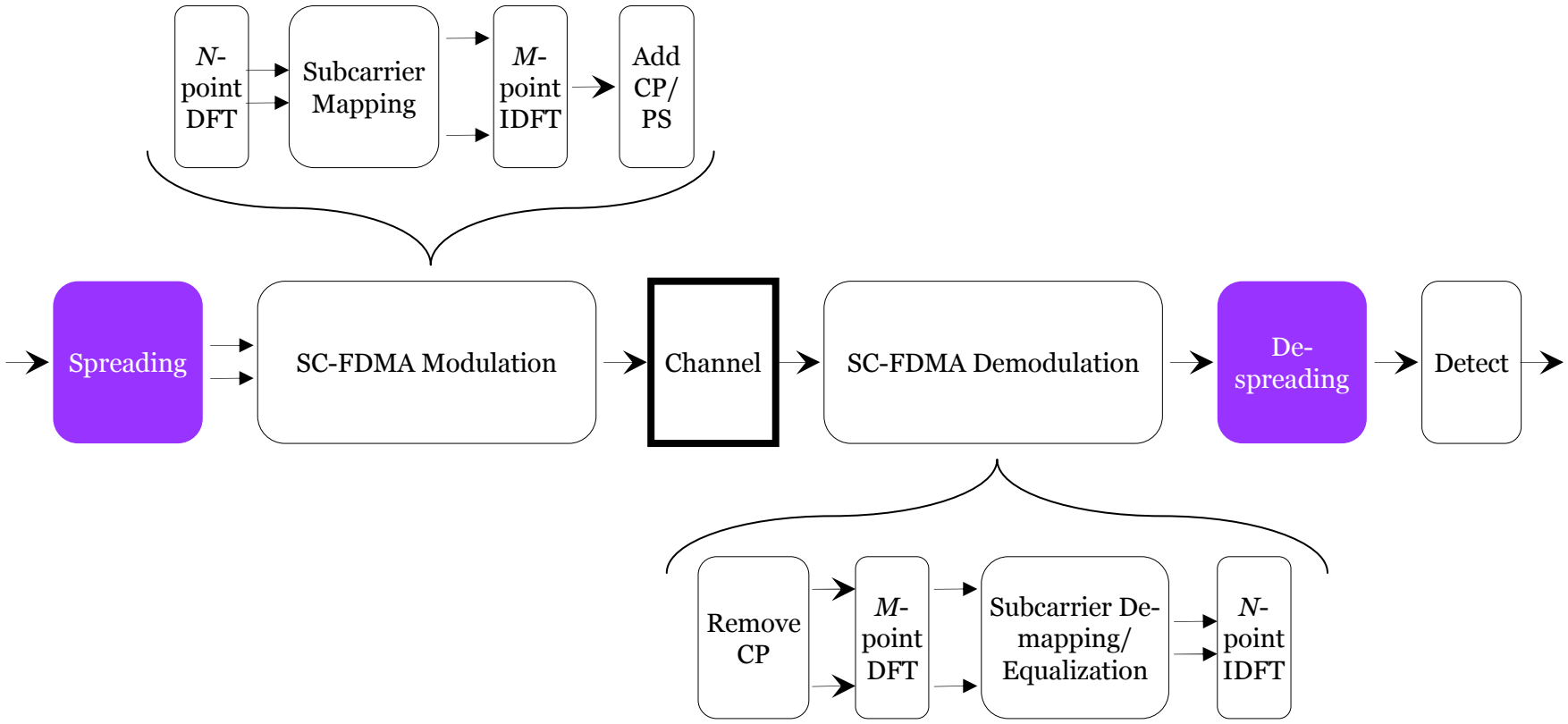


*C. Chang, and K. Chen, "Frequency-Domain Approach to Multiuser Detection over Frequency-Selective Slowly Fading Channels," IEEE PIMRC 2002, Lisboa, Portugal, Sep., 2002, pp. 1280-1284

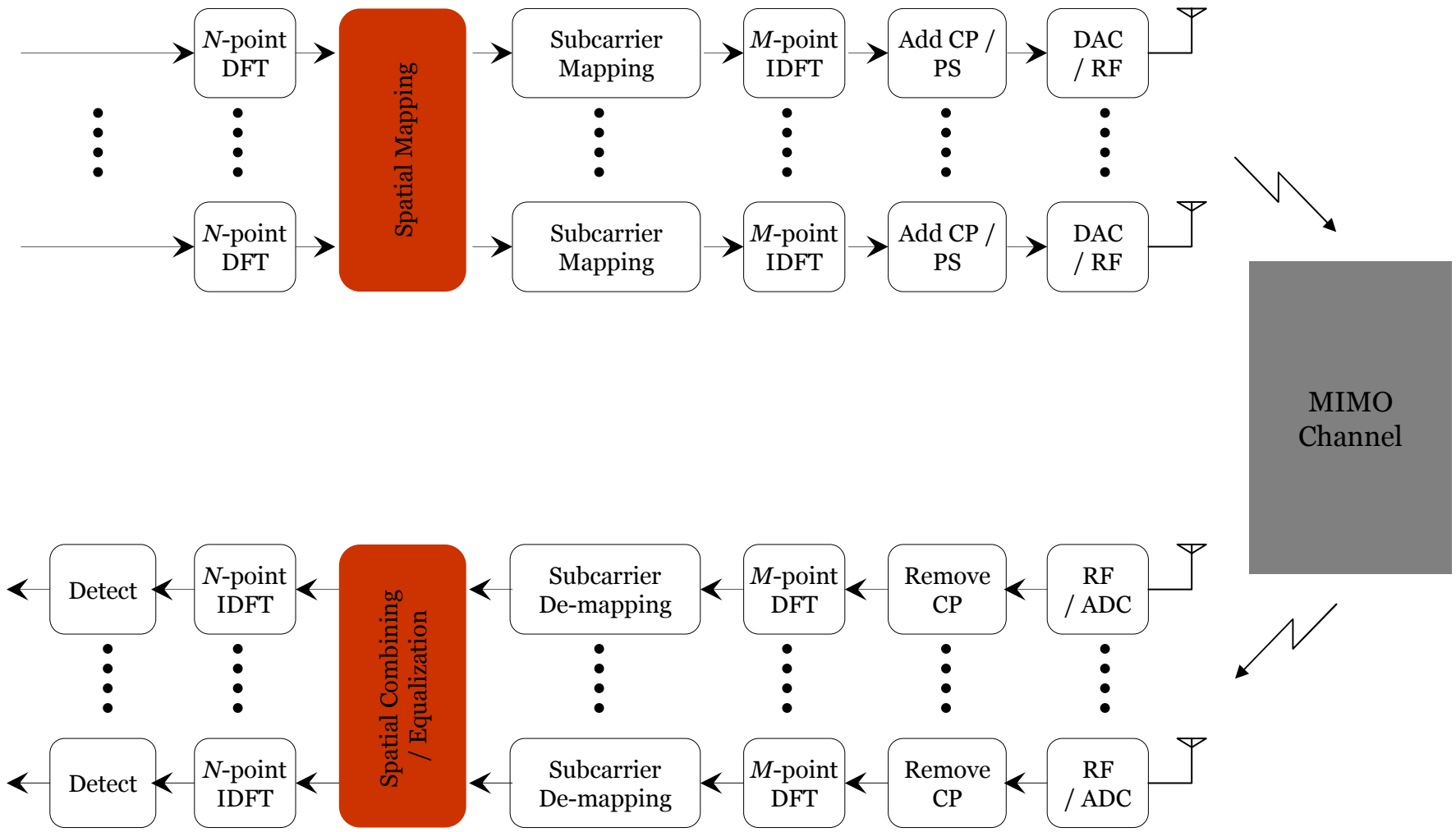
SC-FDMA and Other Schemes



SC-FDMA with Code Spreading



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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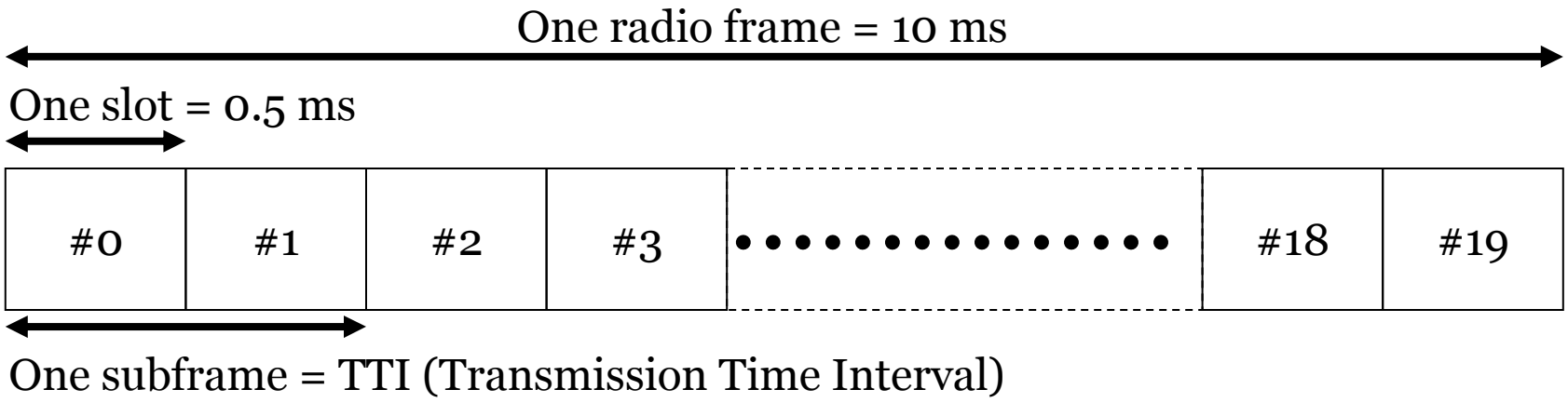
Summary and Conclusions

LTE 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.

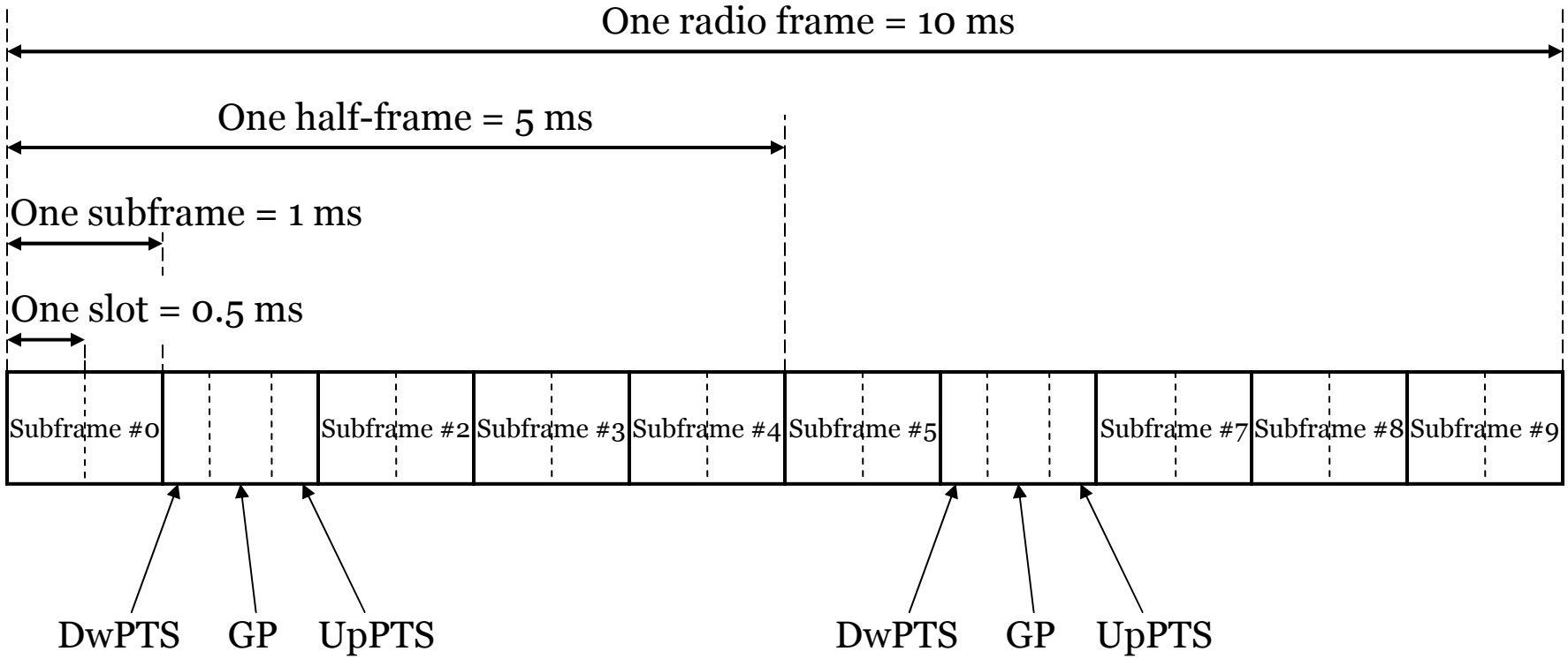
LTE Frame Structure Type 1

- FDD frame structure

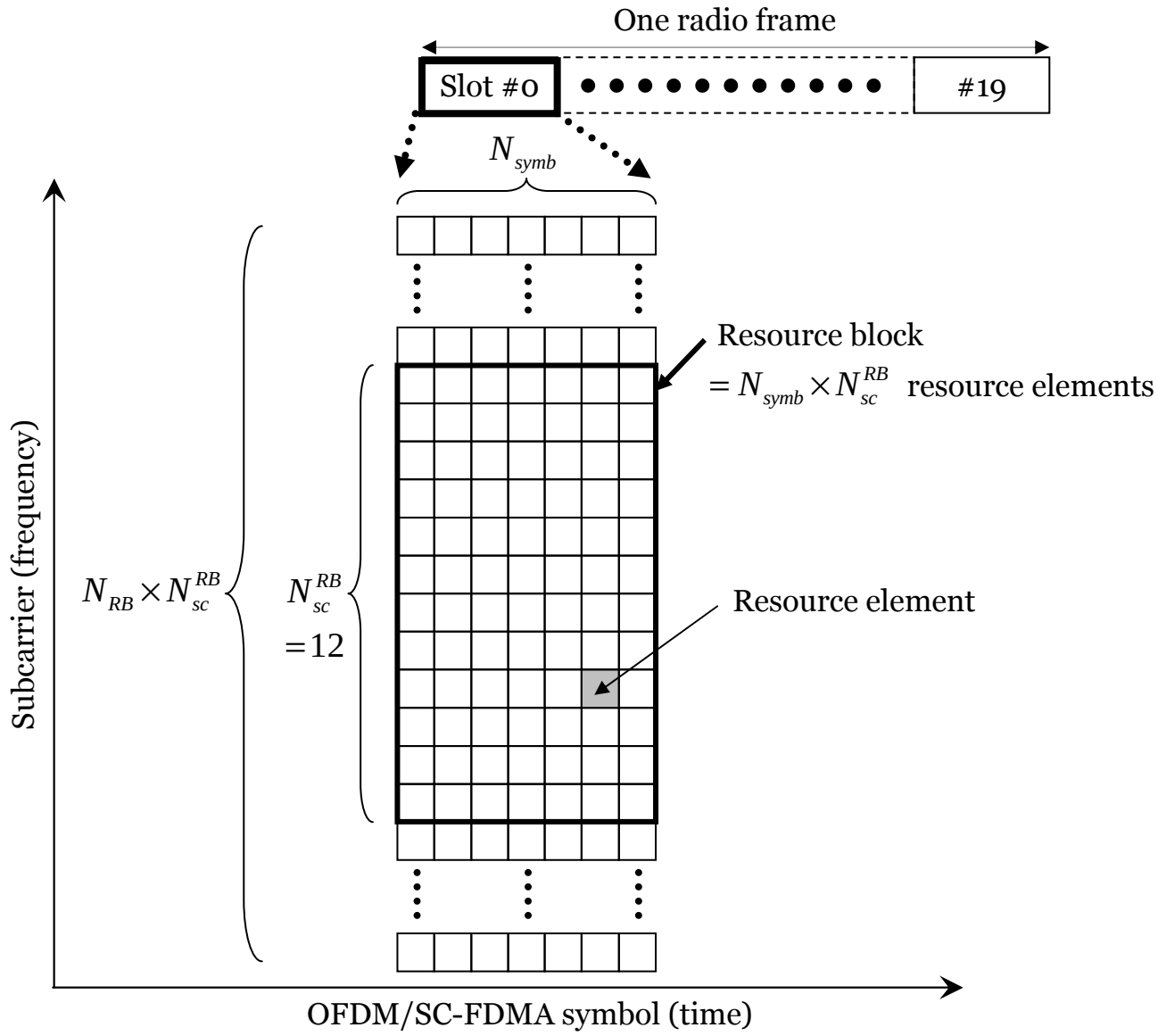


LTE Frame Structure Type 2

- TDD frame structure



LTE Resource Grid



Length of CP

Configuration	N_{symb}
Normal CP	7
Extended CP	6
Extended CP (Δf = 7.5 kHz)†	3

Configuration	CP length $N_{CP,l}$ [samples]
Normal CP	160 (≈ 5.21 μs) for l = 0 144 (≈ 4.69 μs) for l = 1, 2, …, 6
Extended CP	512 (≈ 16.67 μs) for l = 0, 1, …, 5
Extended CP (Δf = 7.5 kHz) †	1024 (≈ 33.33 μs) for l = 0, 1, 2

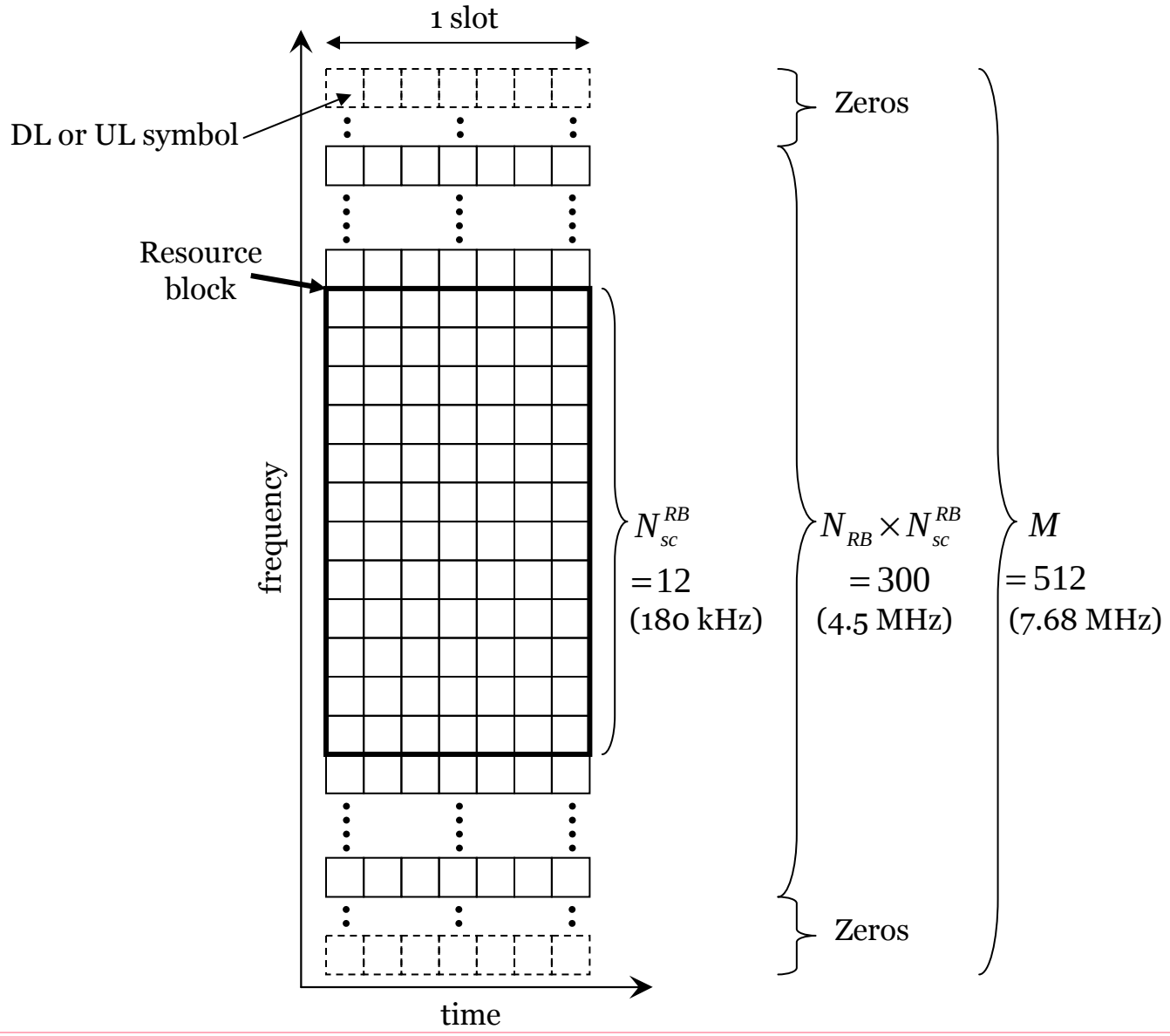
† Only in downlink

LTE Bandwidth/Resource Configuration

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

*3GPP TS 36.104

LTE Bandwidth Configuration

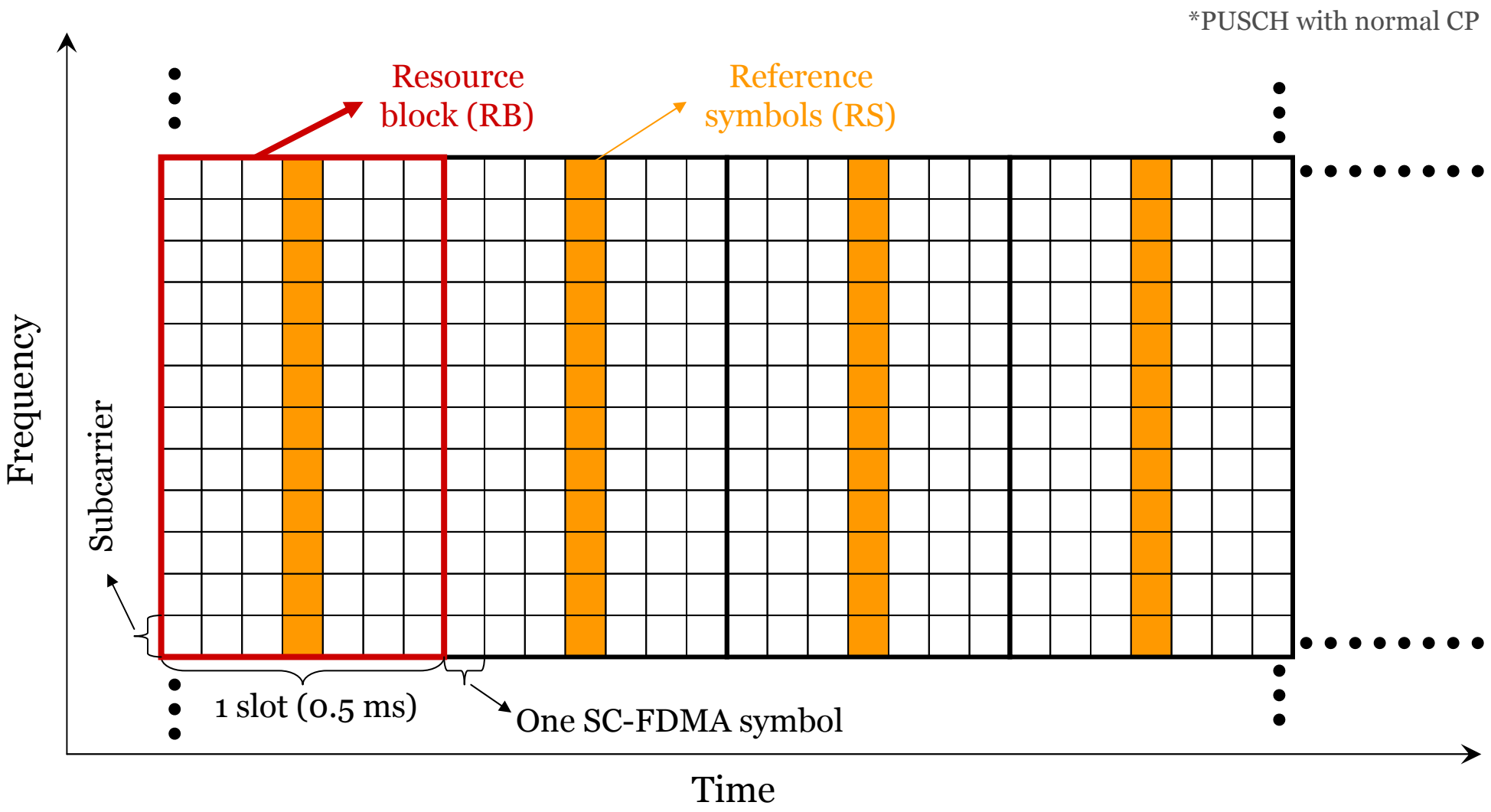


* 5 MHz system with frame structure type 1

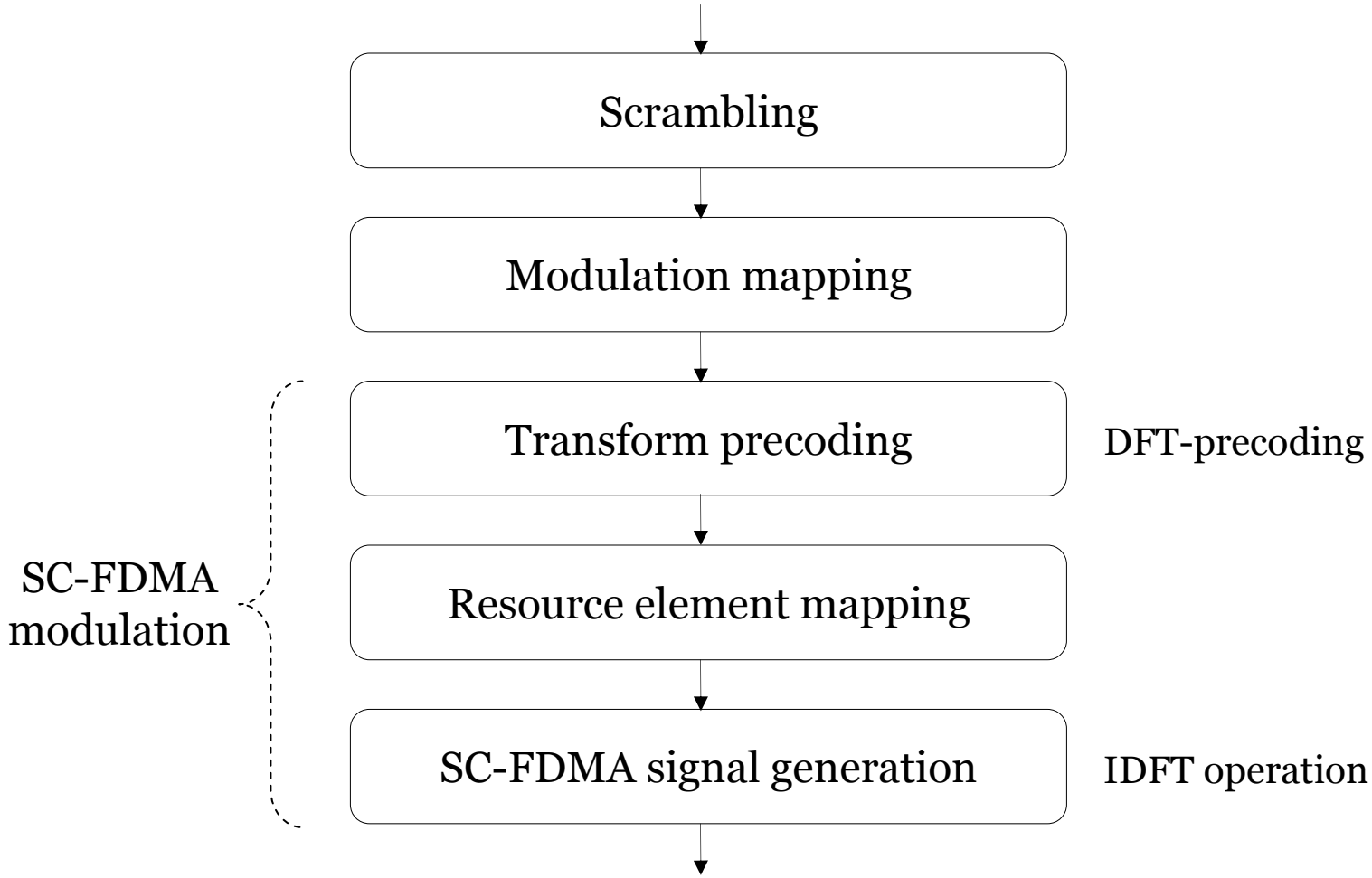
UL Overview

- 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 current release.
  - But it will be addressed in the future release.
  - Multi-user collaborative MIMO supported.

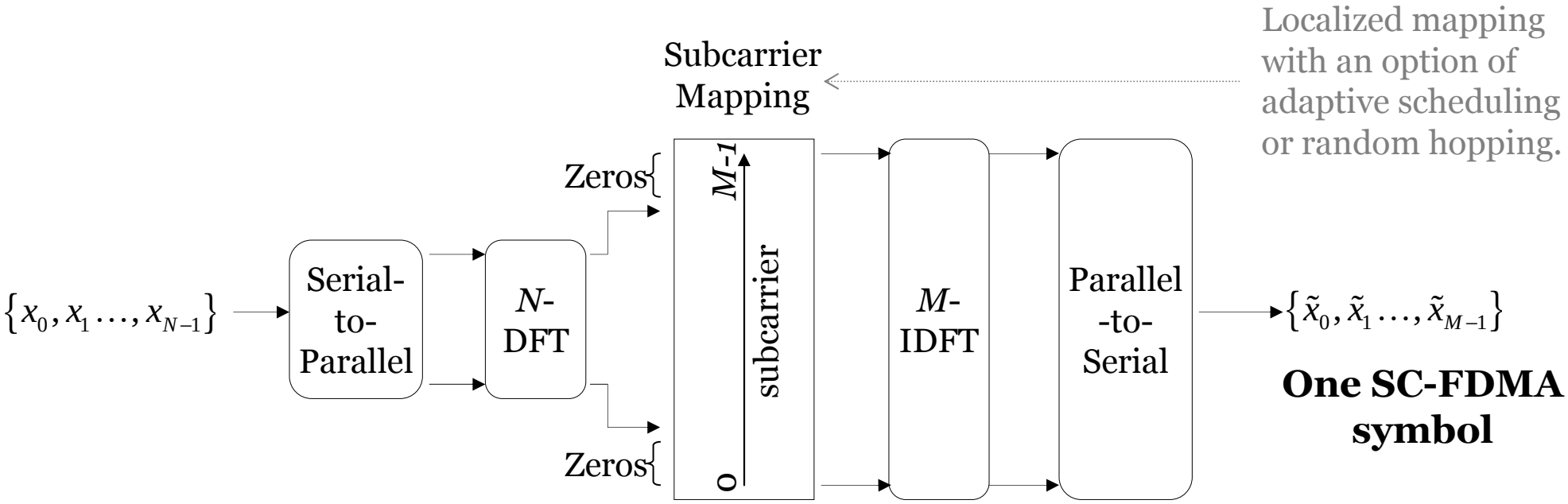
UL Resource Block



UL Physical Channel Processing



SC-FDMA Modulation in LTE UL



UL Reference Signal

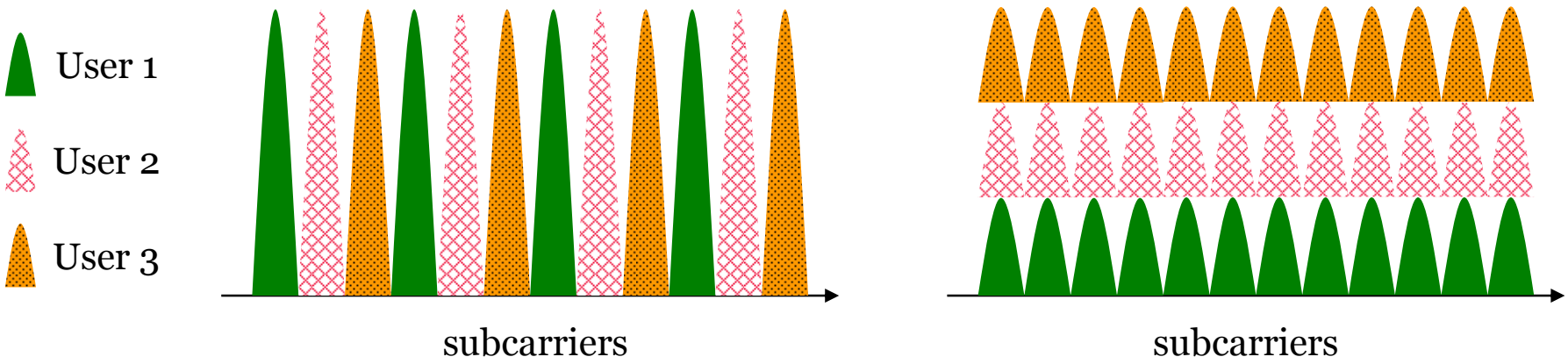
- Two types of UL RS
  - Demodulation (DM) RS ⇒ Narrowband.
  - Sounding RS: Used for UL resource scheduling ⇒ Broadband.
- RS based on Zadoff-Chu CAZAC (Constant Amplitude Zero Auto-Correlation) polyphase sequence
  - CAZAC sequence: Constant amplitude, zero circular auto-correlation, flat frequency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

UL RS Multiplexing



FDM Pilots

CDM Pilots

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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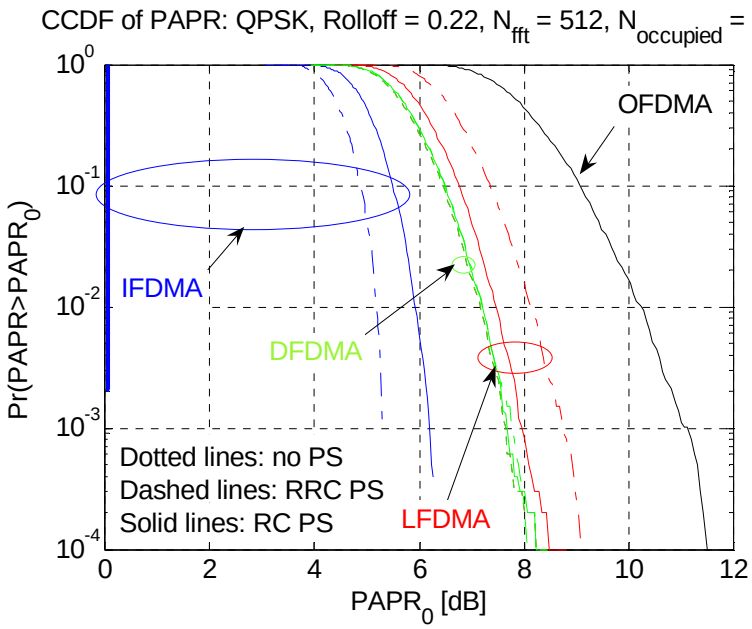
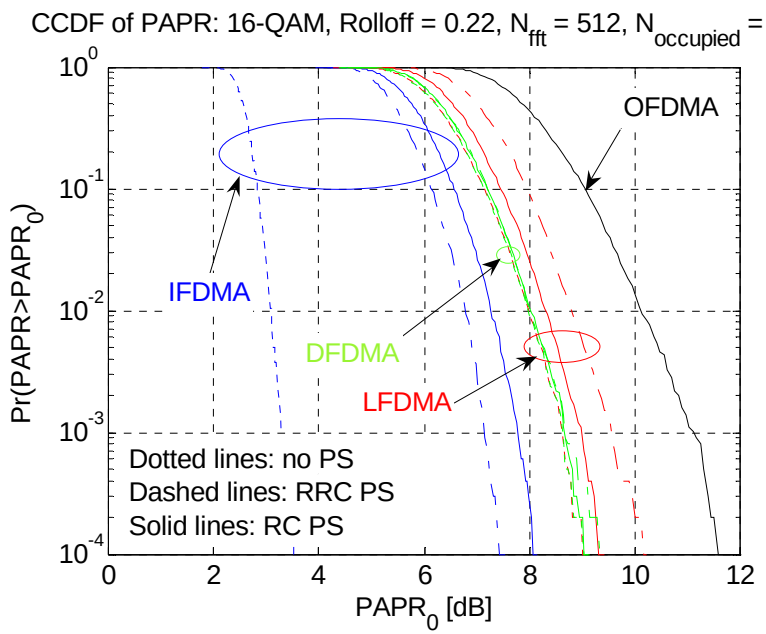
PAPR Characteristics



(a) QPSK



(b) 16-QAM

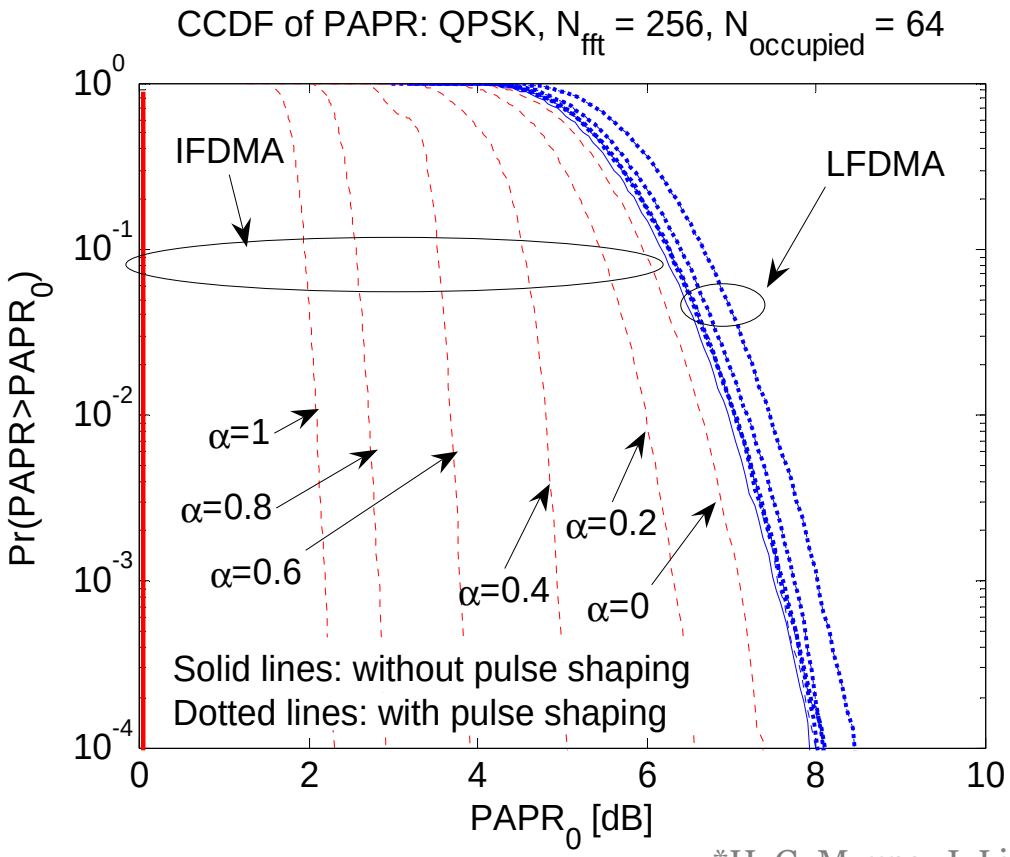
* Monte Carlo simulations (Number of iterations: > 10^4)
* Time domain pulse shaping with 8-times oversampling
* N_{fft}: number of total subcarriers = FFT size
* $N_{occupied}$: number of occupied subcarriers = data block size
* RC: raised-cosine, RRC: root raised-cosine
* Rolloff factor of 0.22

*H. G. Myung, J. Lim, and D. J. Goodman, "Peak-to-Average Power Ratio of Single Carrier FDMA Signals with Pulse Shaping," *IEEE PIMRC '06*, Helsinki, Finland, Sep. 2006

PAPR Characteristics

– cont.

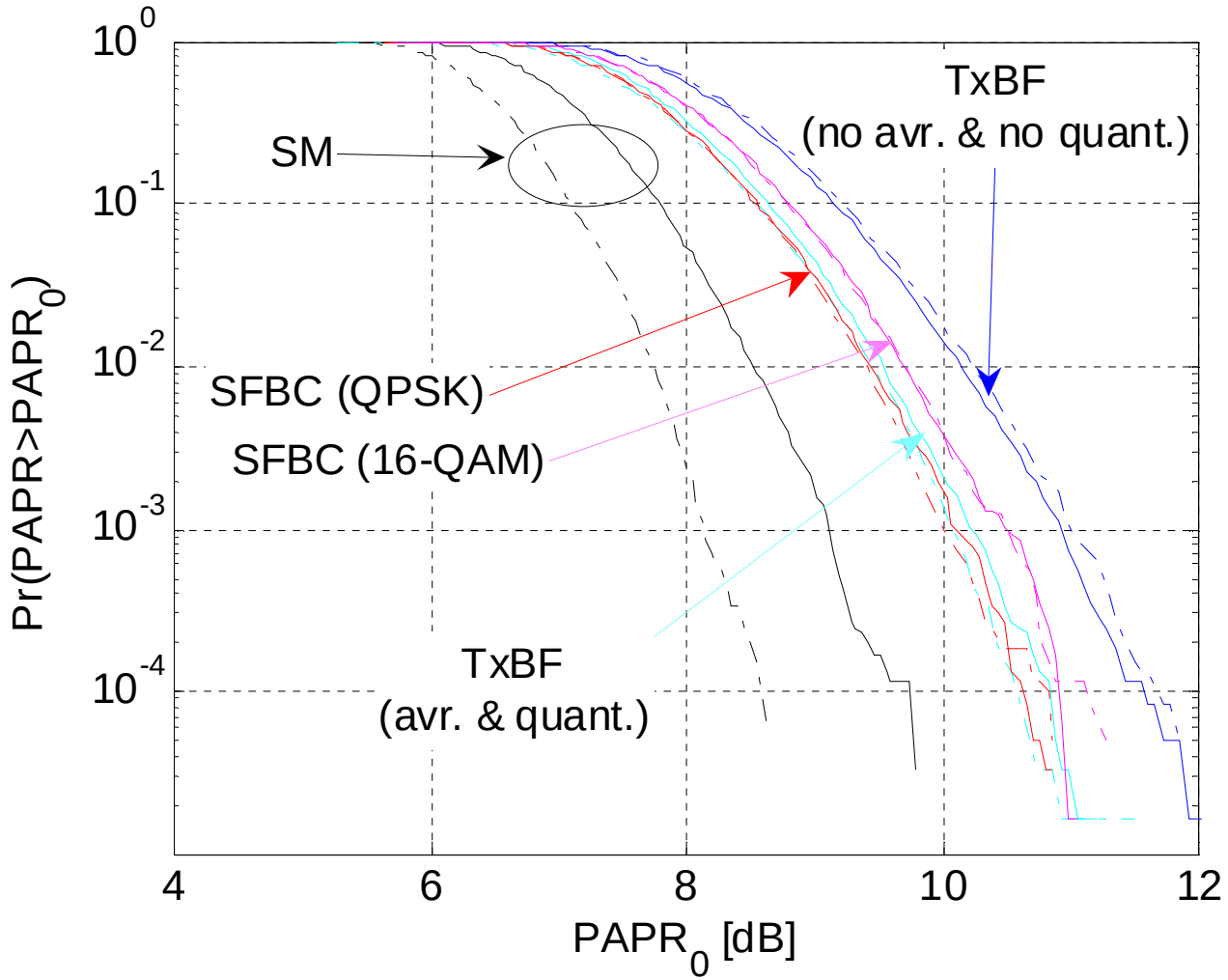
- PAPR and different rolloff factors



*α: rolloff factor of raised cosine pulse shaping filter

*H. G. Myung, J. Lim, and D. J. Goodman, "Peak-to-Average Power Ratio of Single Carrier FDMA Signals with Pulse Shaping," *IEEE PIMRC'06*, Helsinki, Finland, Sep. 2006

PAPR of SC-FDMA MIMO



*H. G. Myung, J.-L. Pan, R. Olesen, and D. Grieco, "Peak Power Characteristics of Single Carrier FDMA MIMO Precoding System", *IEEE VTC 2007 Fall*, Baltimore, USA, Oct. 2007

Introduction and Background

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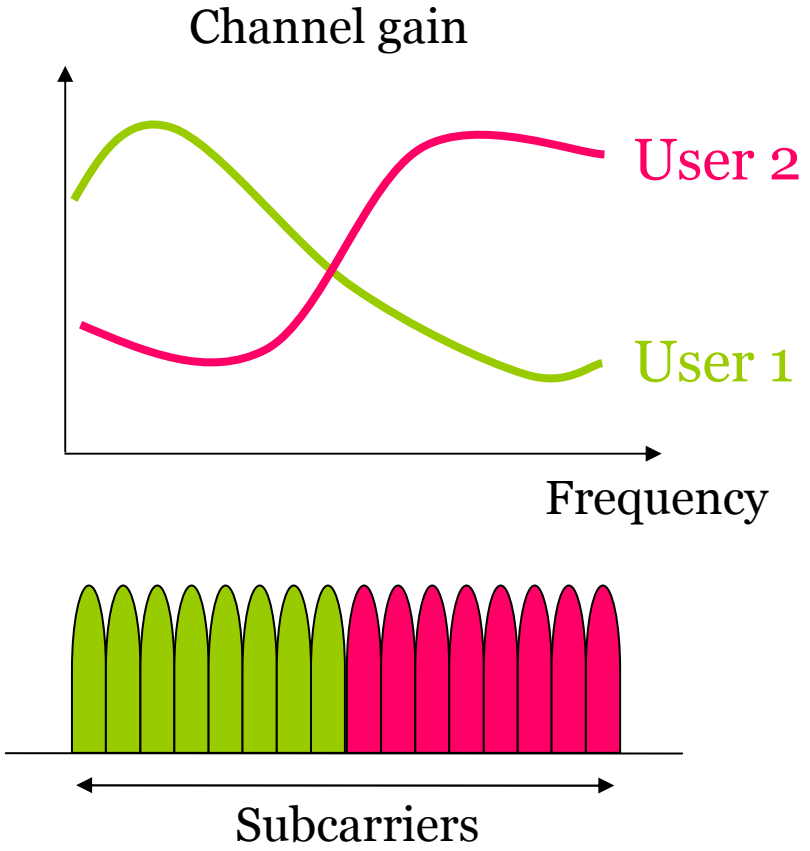
Summary and Conclusions

Channel-Dependent Scheduling (CDS)

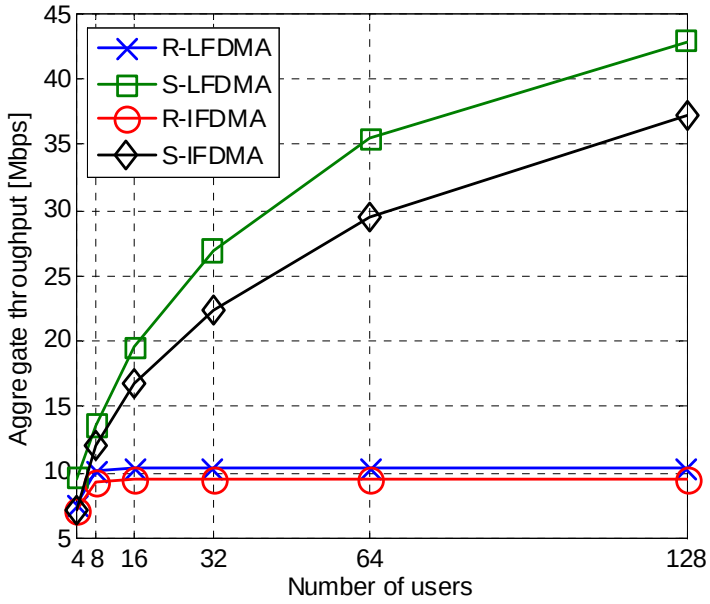
- Channel-dependent scheduling
  - Assign subcarriers to a user in excellent channel condition.
- Two subcarrier mapping schemes have advantages over each other.
  - Distributed: Frequency diversity.
  - Localized: Frequency selective gain with CDS.



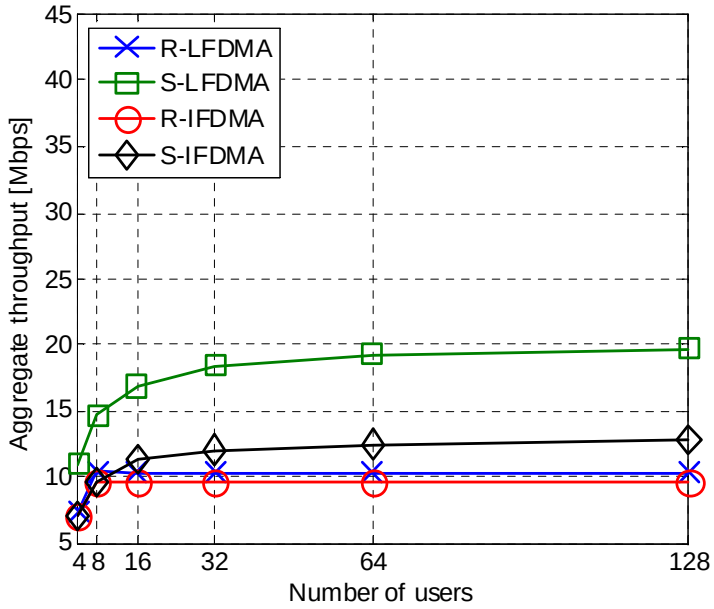
CDS

– cont.

Utility: sum of user throughput



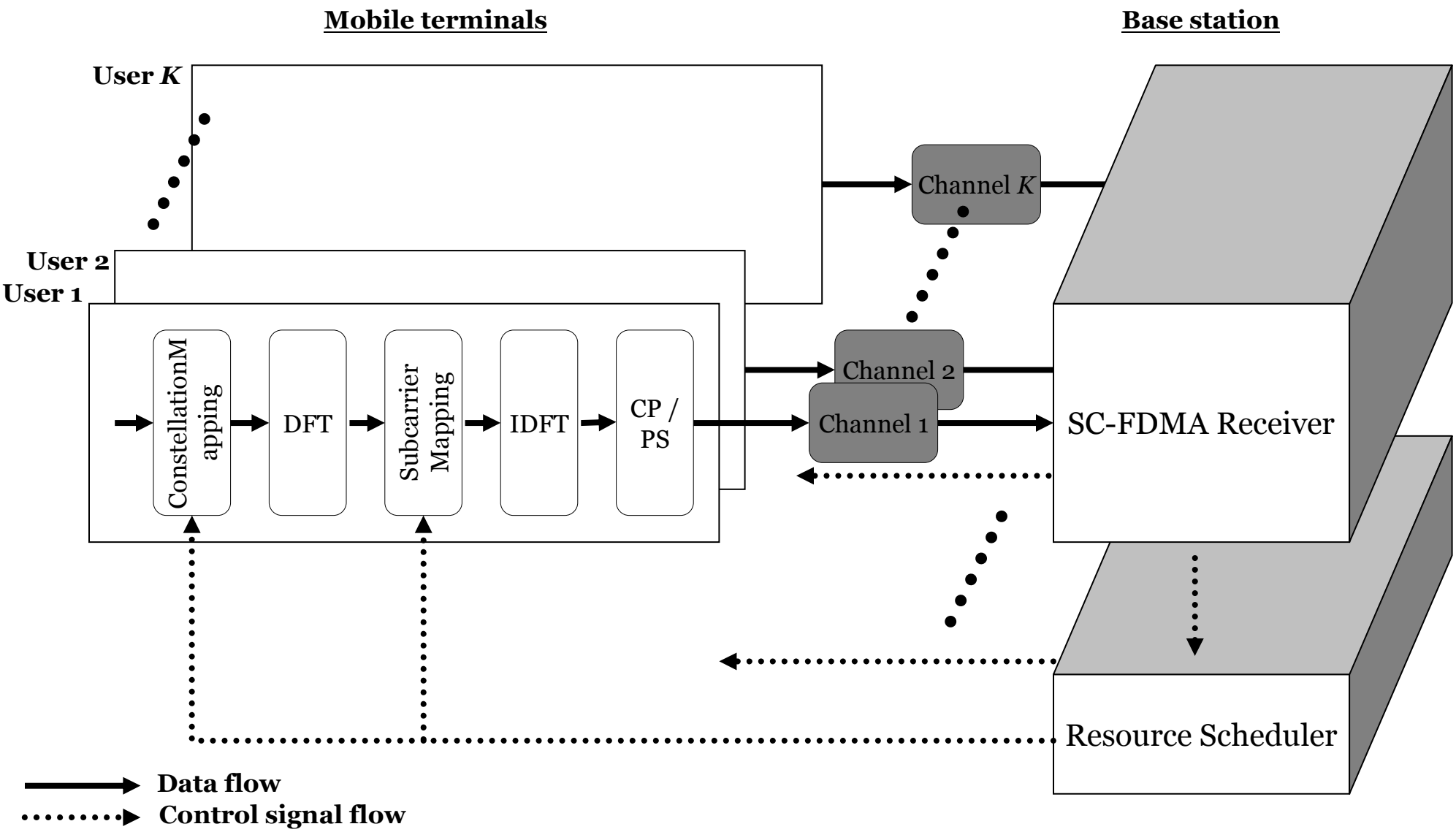
Utility: sum of logarithm of user throughput



*J. Lim, H. G. Myung, K. Oh, and D. J. Goodman, "Proportional Fair Scheduling of Uplink Single-Carrier FDMA Systems", *IEEE PIMRC 2006*, Helsinki, Finland, Sep. 2006

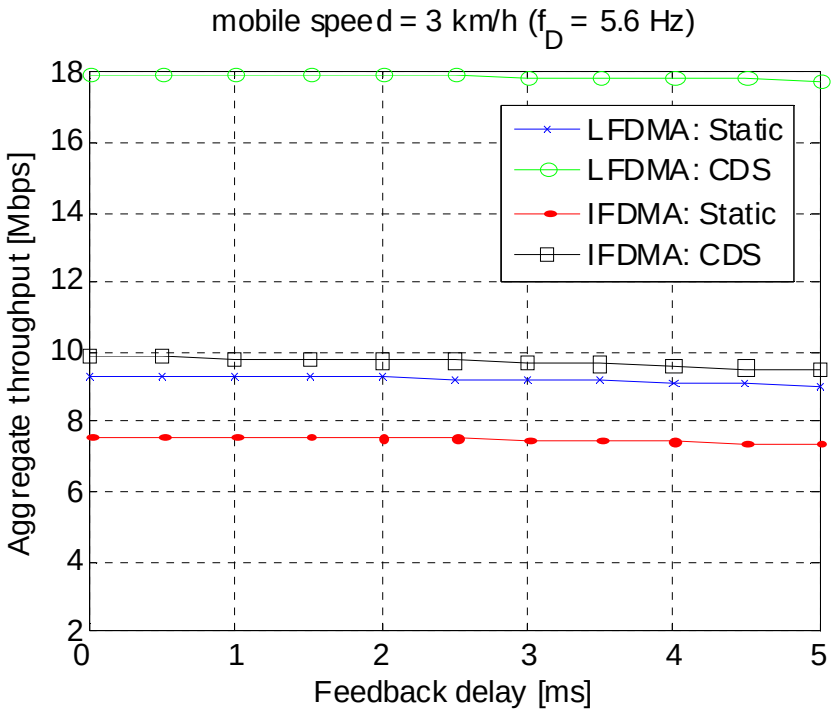
* Capacity based on Shannon's upper bound.
* Time synchronized uplink data transmission.
* Perfect channel knowledge.
* No feedback delay or error.

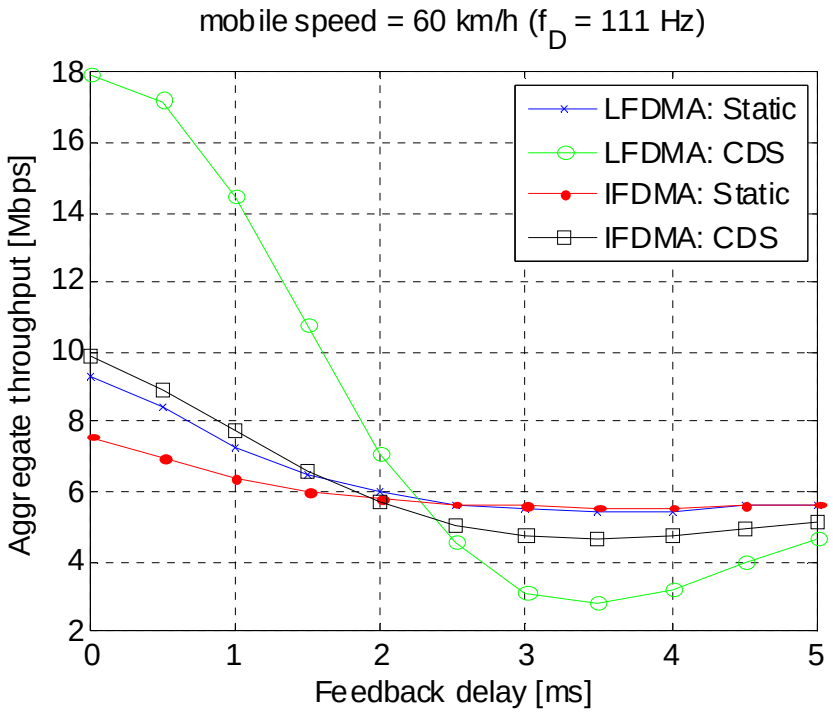
Uplink SC-FDMA with Adaptive Modulation and CDS



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

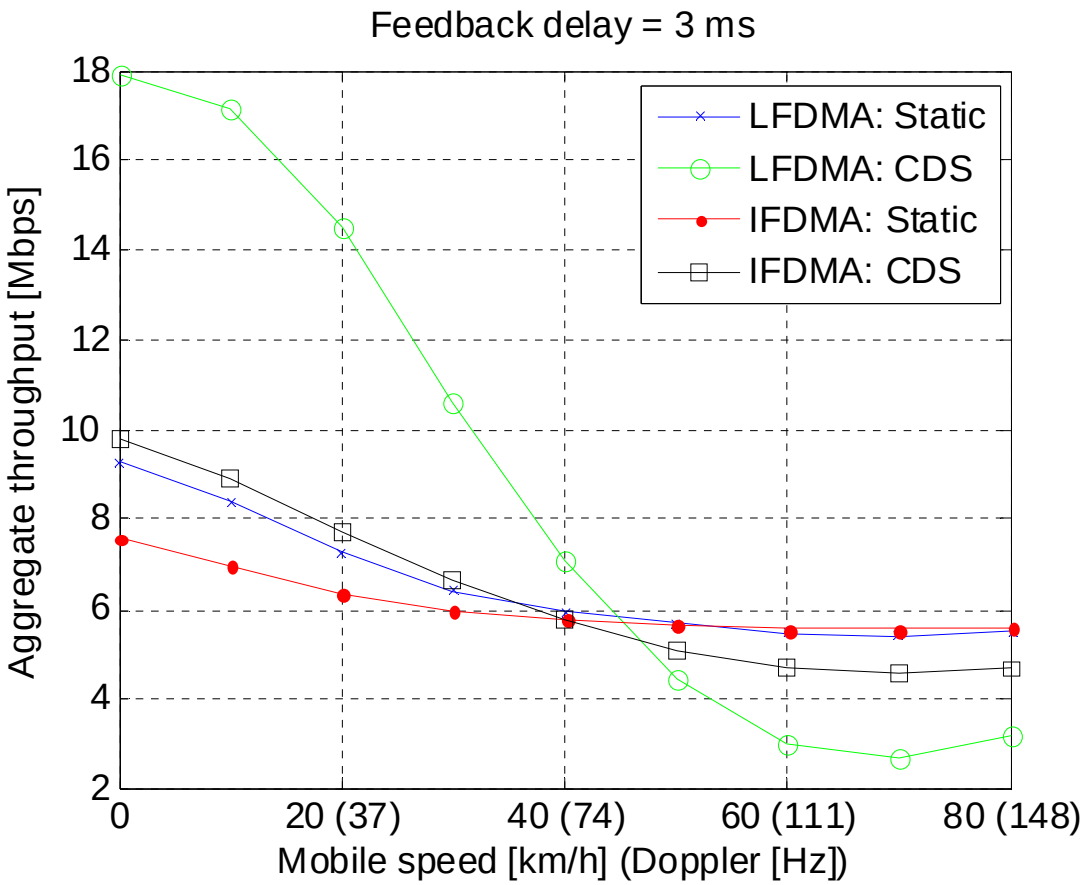
* Utility: sum of user throughput

*H. G. Myung, K. Oh, J. Lim, and D. J. Goodman, "Channel-Dependent Scheduling of an Uplink SC-FDMA System with Imperfect Channel Information," *IEEE WCNC 2008*, Las Vegas, USA, Mar. 2008

Simulation Results

– cont.

- Aggregate throughput vs. mobile speed



*H. G. Myung, K. Oh, J. Lim, and D. J. Goodman, "Channel-Dependent Scheduling of an Uplink SC-FDMA System with Imperfect Channel Information," *IEEE WCNC 2008*, Las Vegas, USA, Mar. 2008.

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Summary and Conclusions

Summary and Conclusions

- 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

References and Resources

– cont.

- LTE Spec
  - http://www.3gpp.org/ftp/Specs/html-info/36-series.htm
- SC-FDMA resource page
  - http://hgmyung.googlepages.com/scfdma
- Comprehensive list of SC-FDMA papers
  - http://hgmyung.googlepages.com/scfdma2

Final Word

SC-FDMA ⏩ Low PAPR

May 18, 2008

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