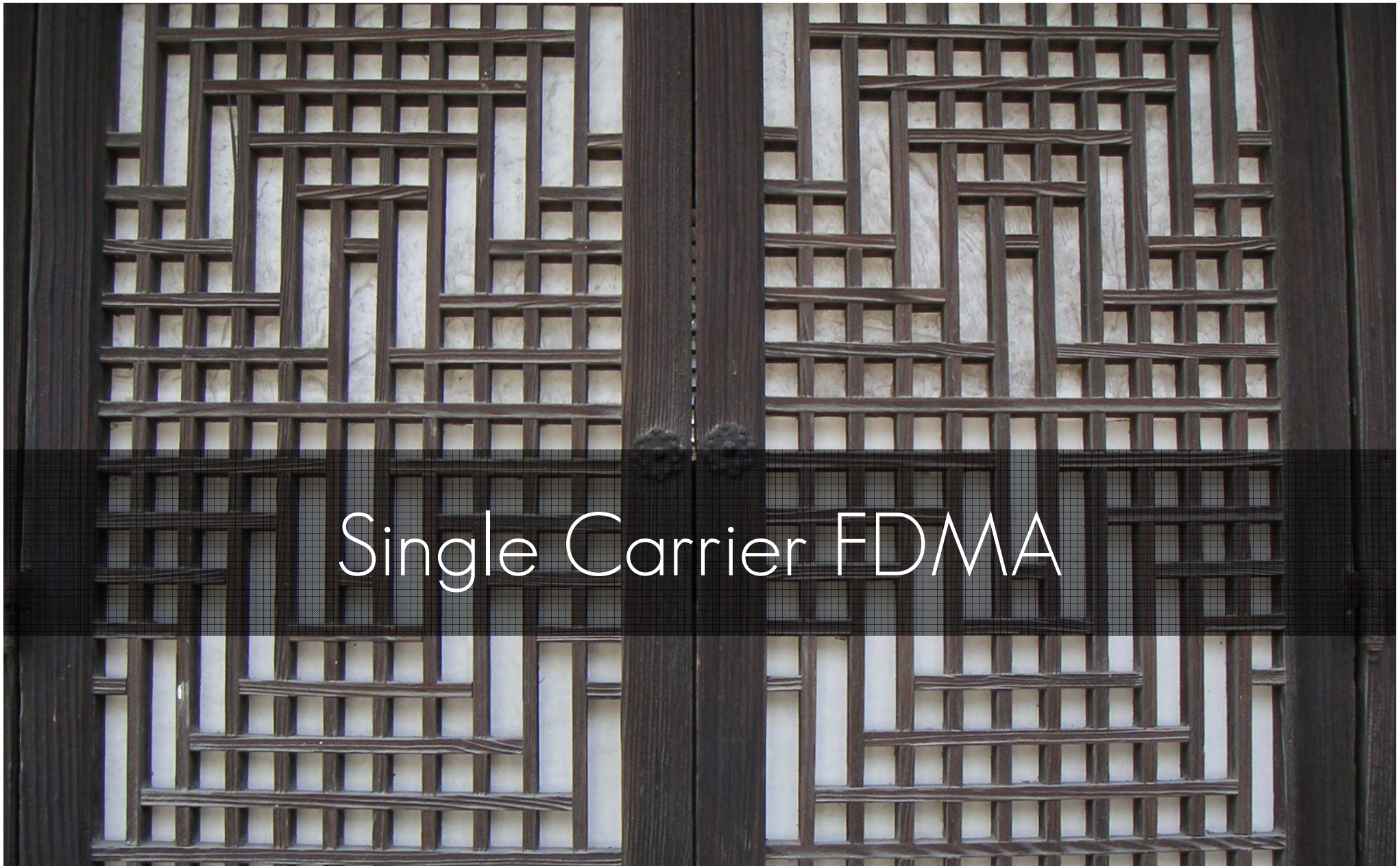


Single Carrier FDMA

May 18, 2008

Hyung G. Myung (hgmyung@ieee.org)

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.

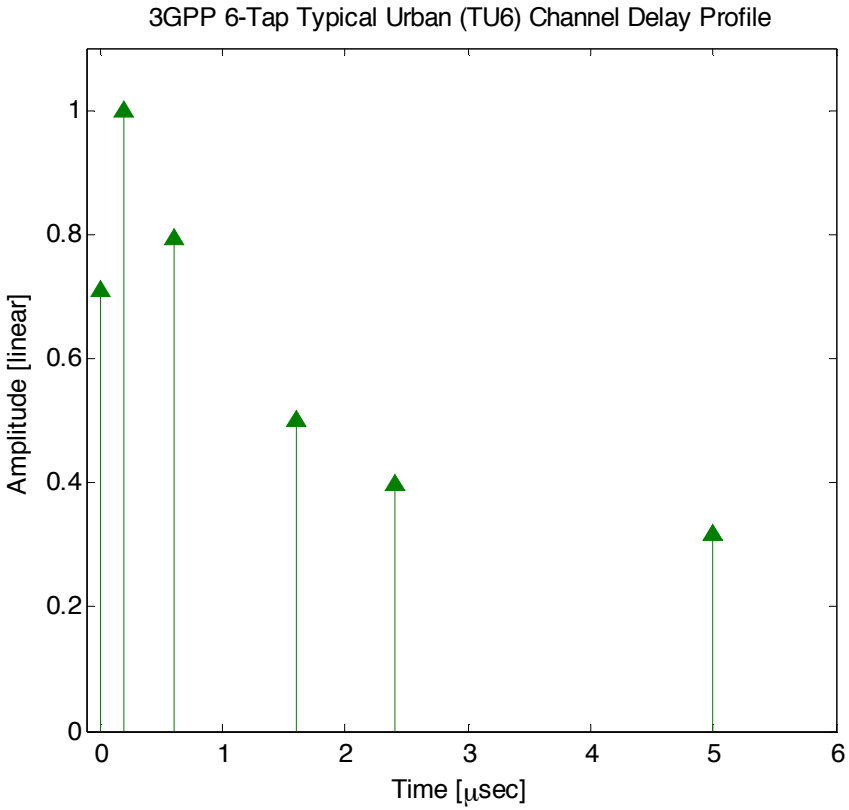
Broadband Multipath Channel

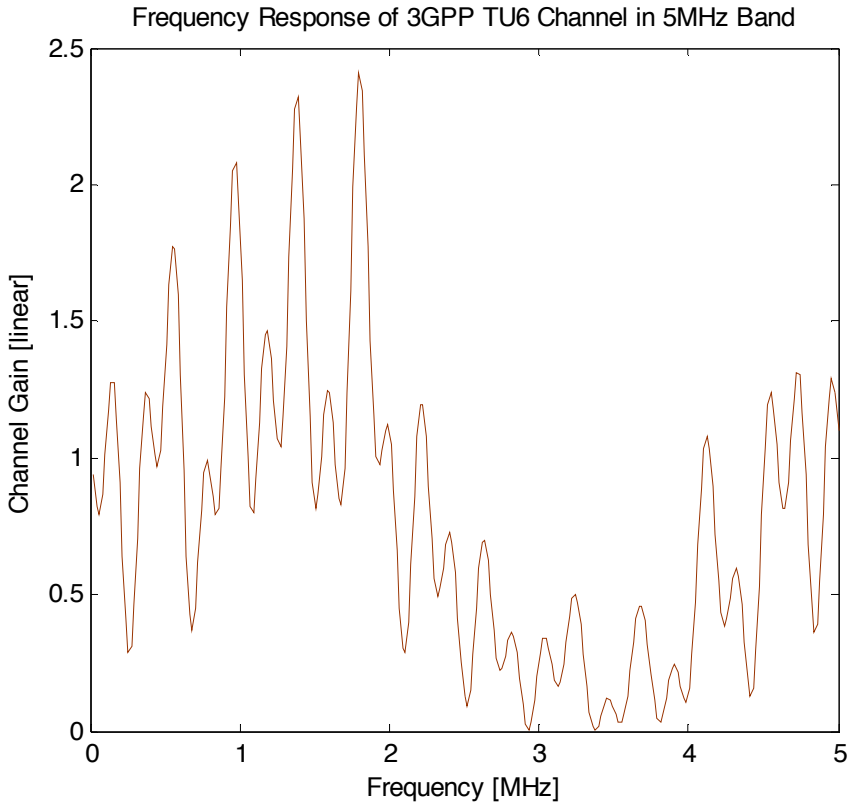
- Demand for higher data rate is leading to utilization of wider transmission bandwidth.

	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.



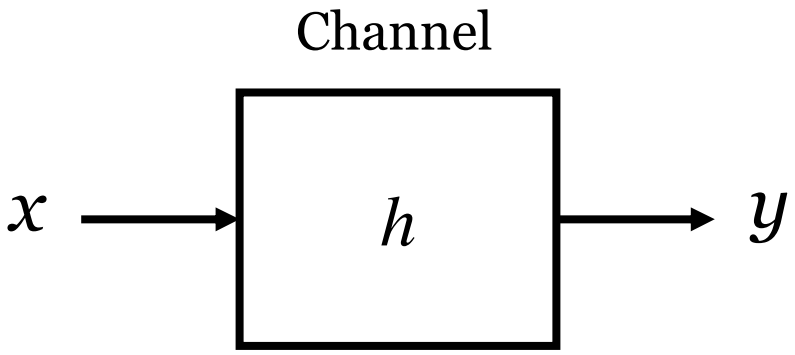


Frequency Domain Equalization

- 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

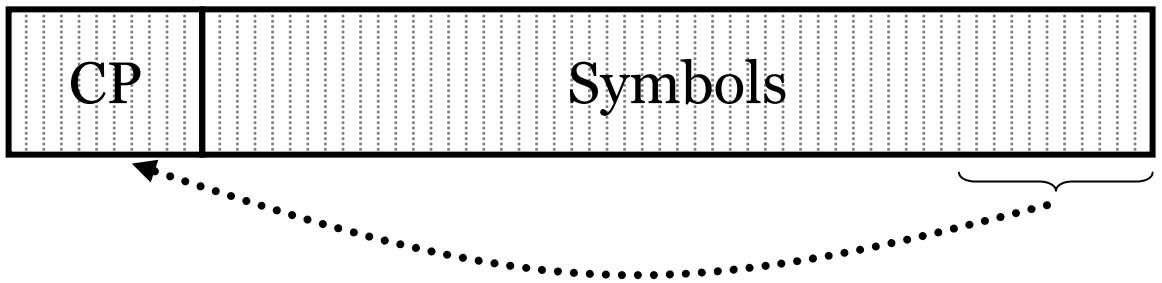
$Y = H \cdot X$

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.

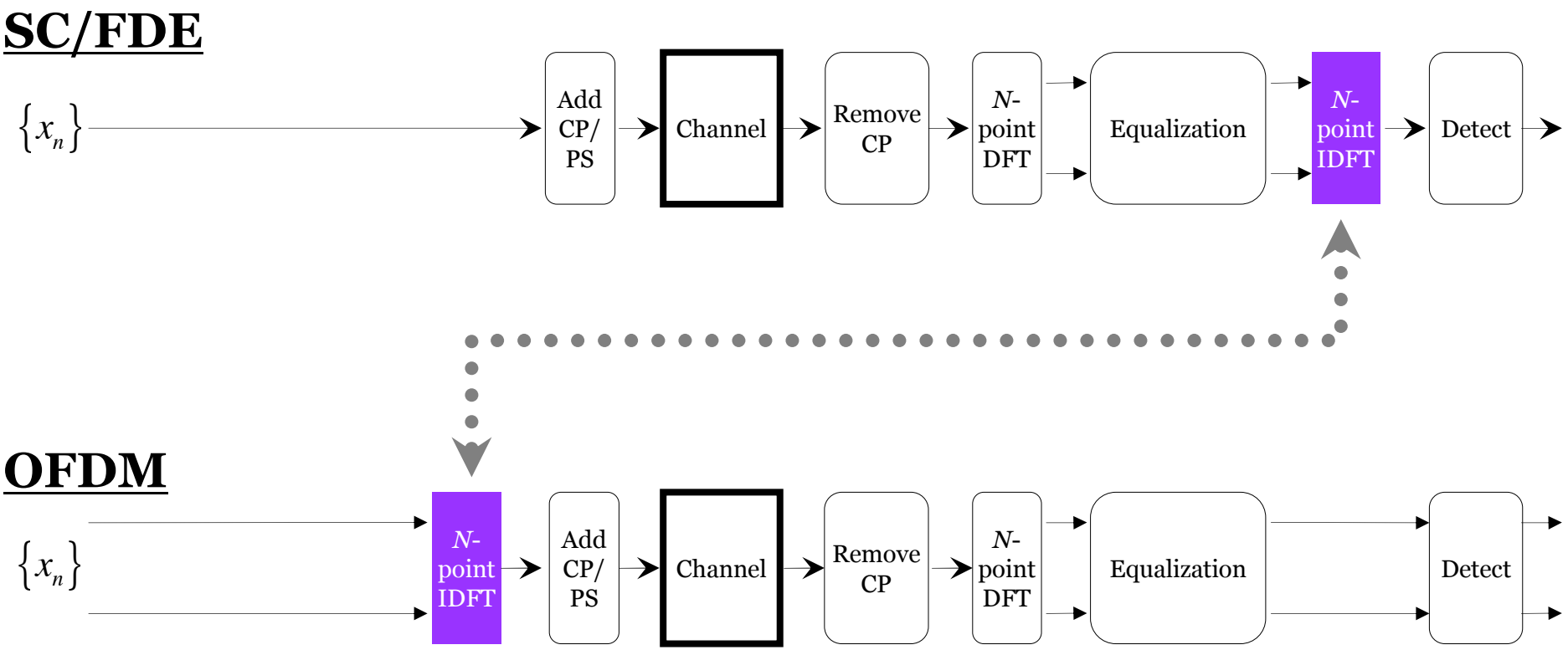


FDE

– 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

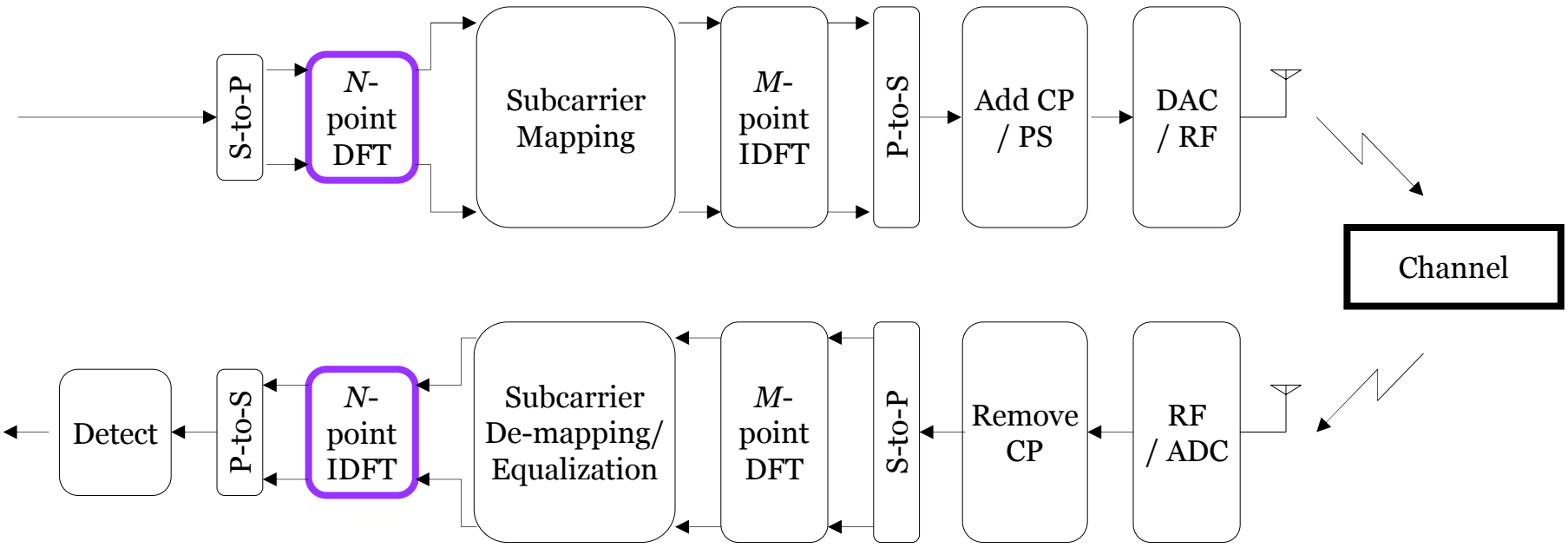
– cont.

- 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.

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



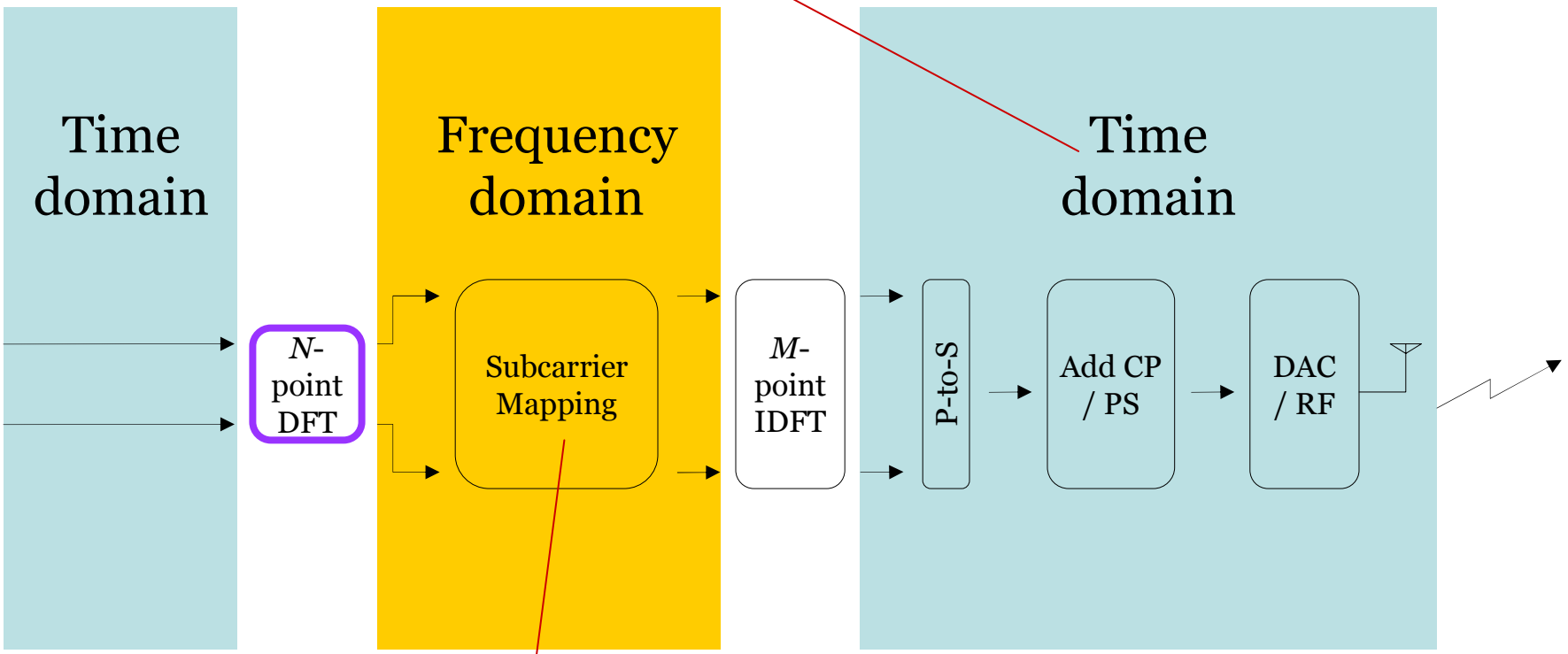
SC-FDMA: □ + □

OFDMA: □

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

Why "Single Carrier" "FDMA"?

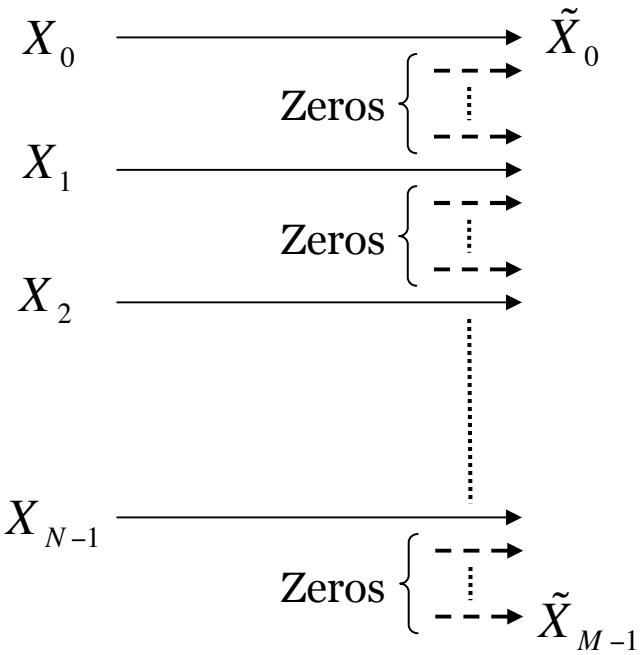
"Single Carrier" : Sequential transmission of the symbols over a single frequency carrier.



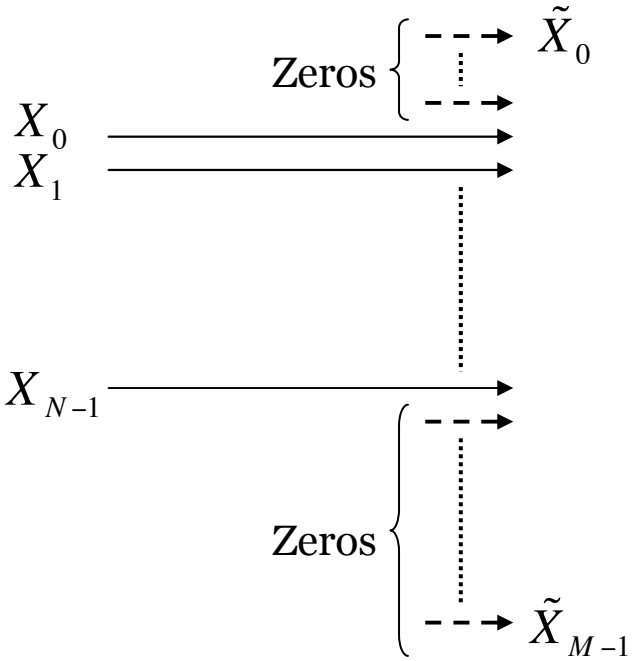
"FDMA" : User multiplexing in the frequency domain.

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

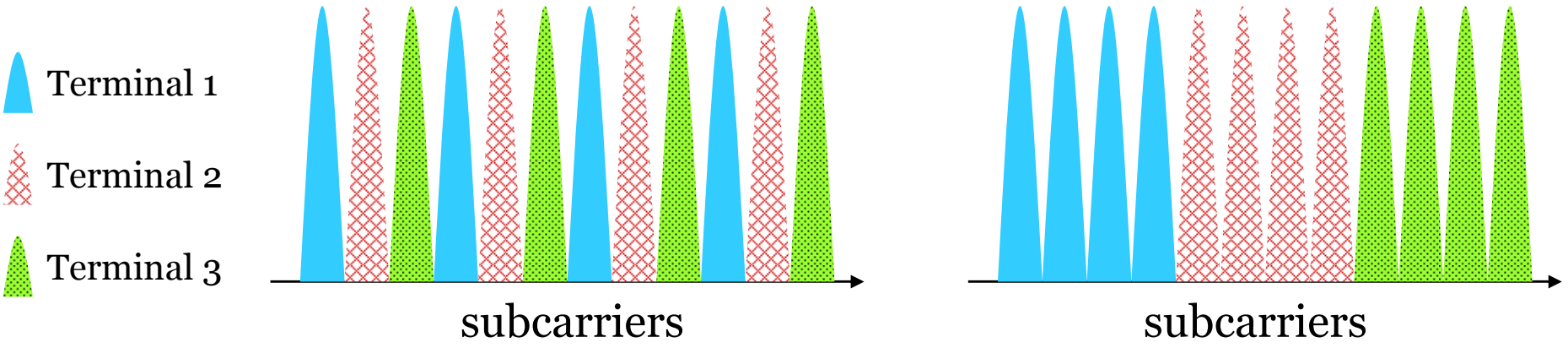


Localized

Subcarrier Mapping

- cont.

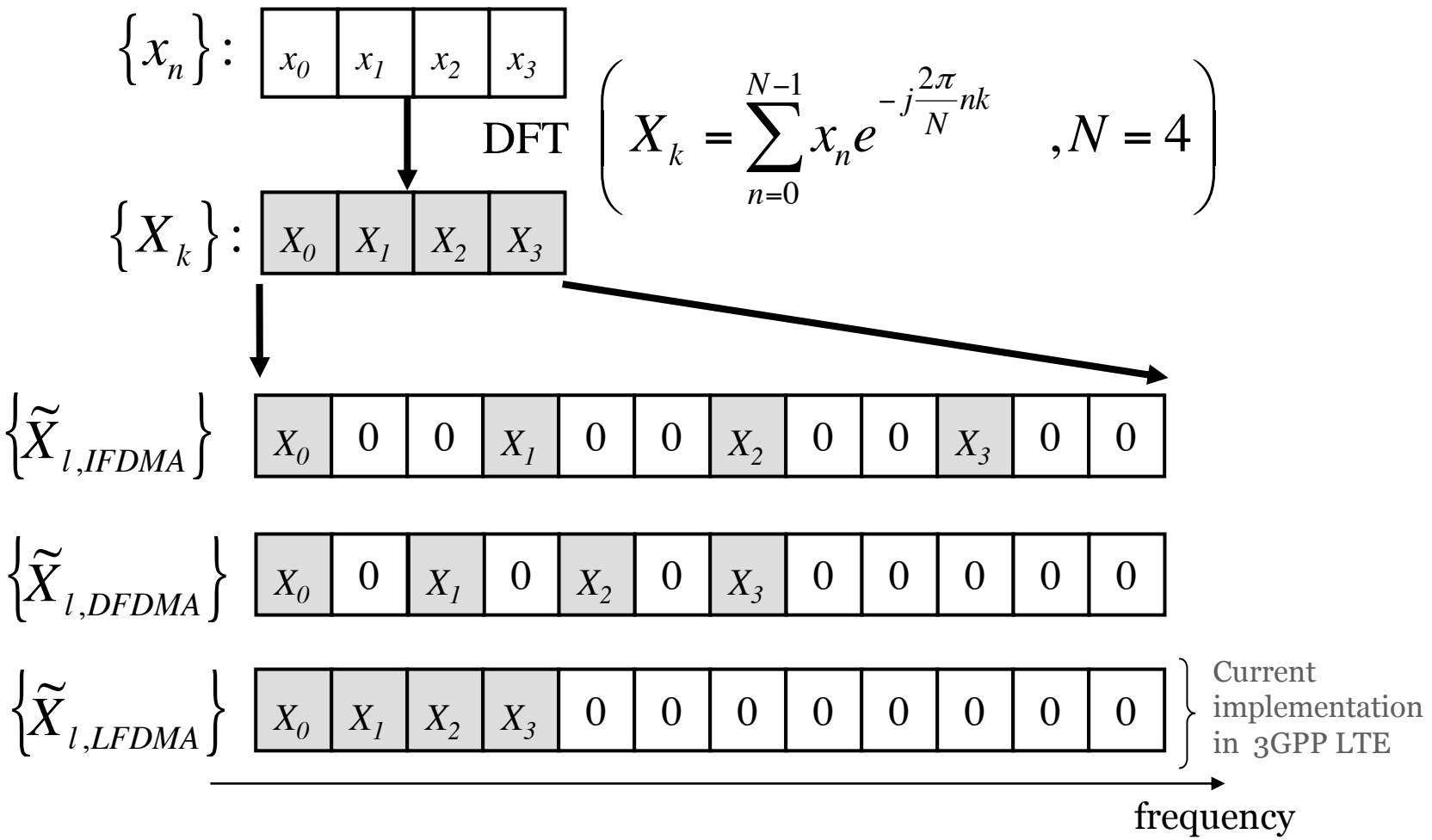
- Data block size (N) = 4, Number of users (Q) = 3, Number of subcarriers (M) = 12.



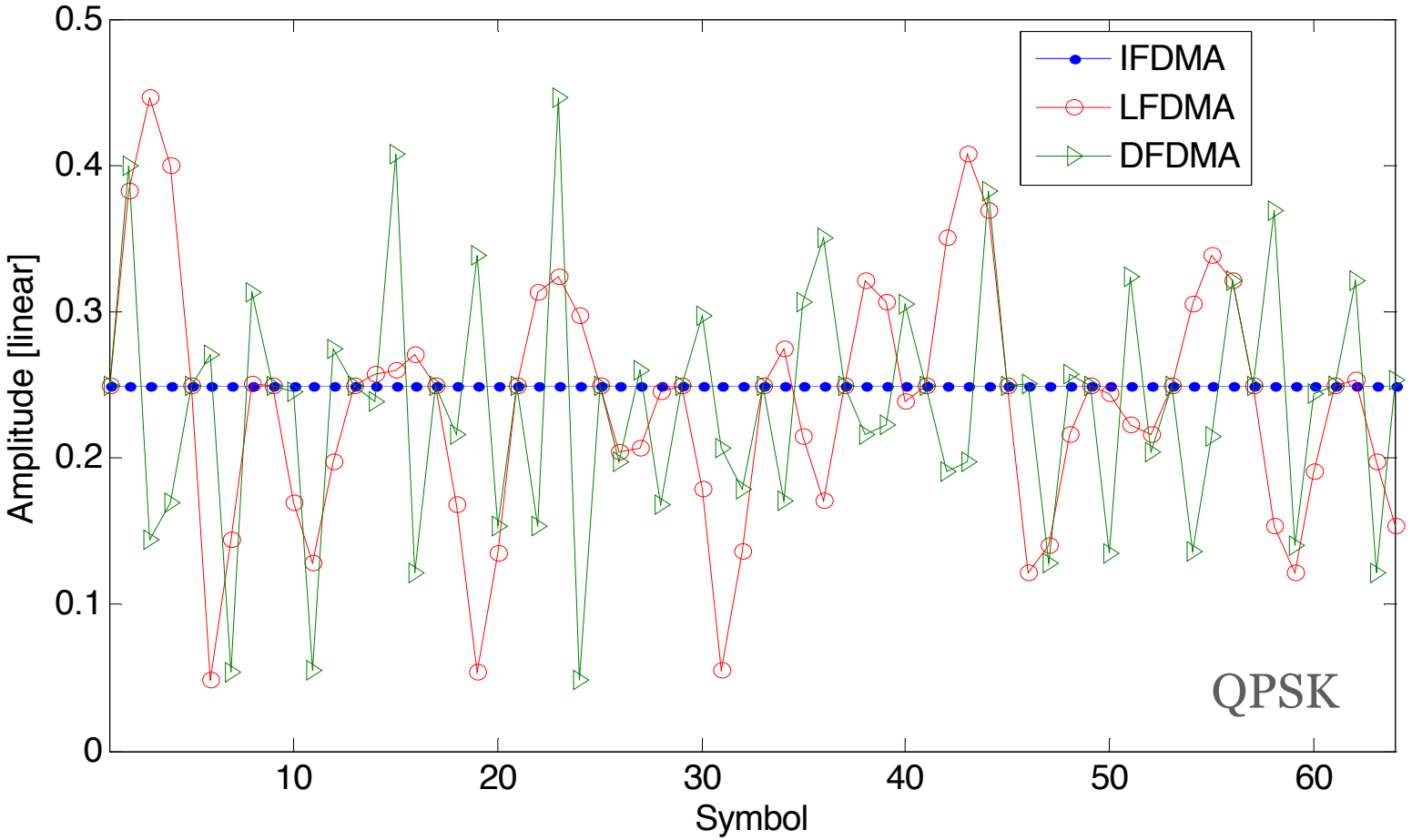
Distributed Mode **Localized Mode**

Subcarrier Mapping

- cont.



Amplitude of SC-FDMA Symbols

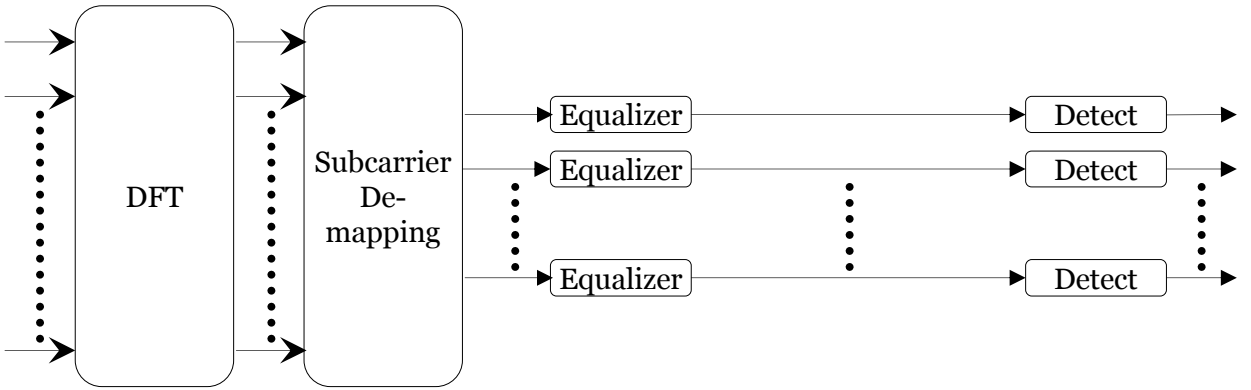


SC-FDMA and OFDMA

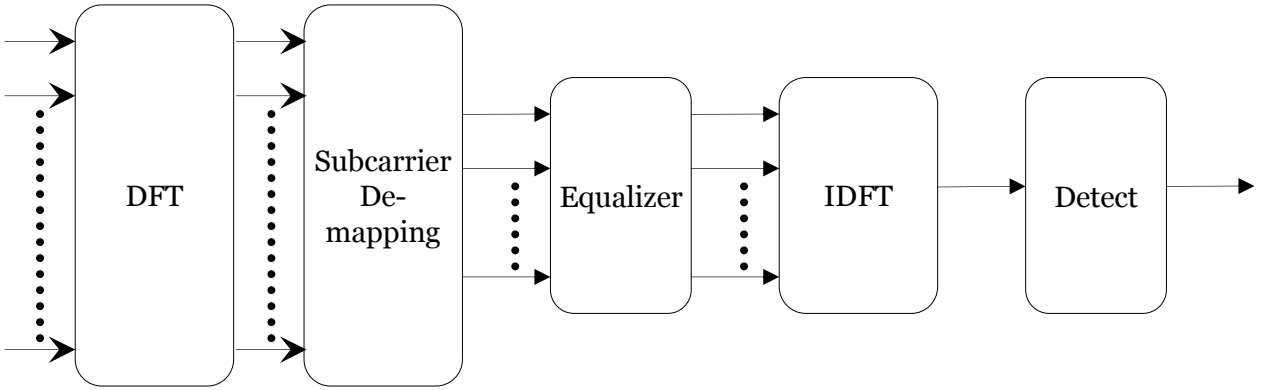
- cont.

- Different equalization/detection aspects

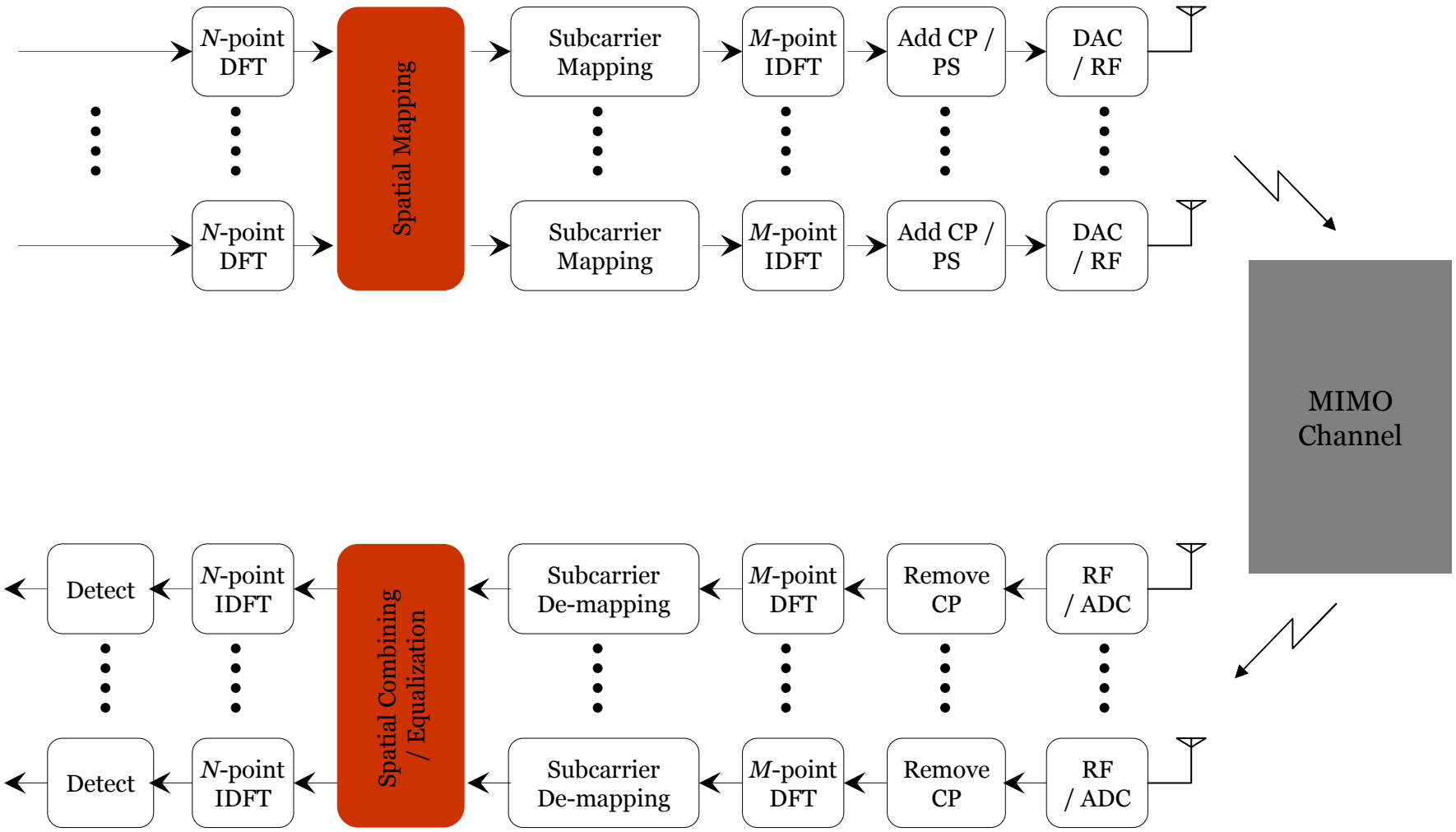
OFDMA



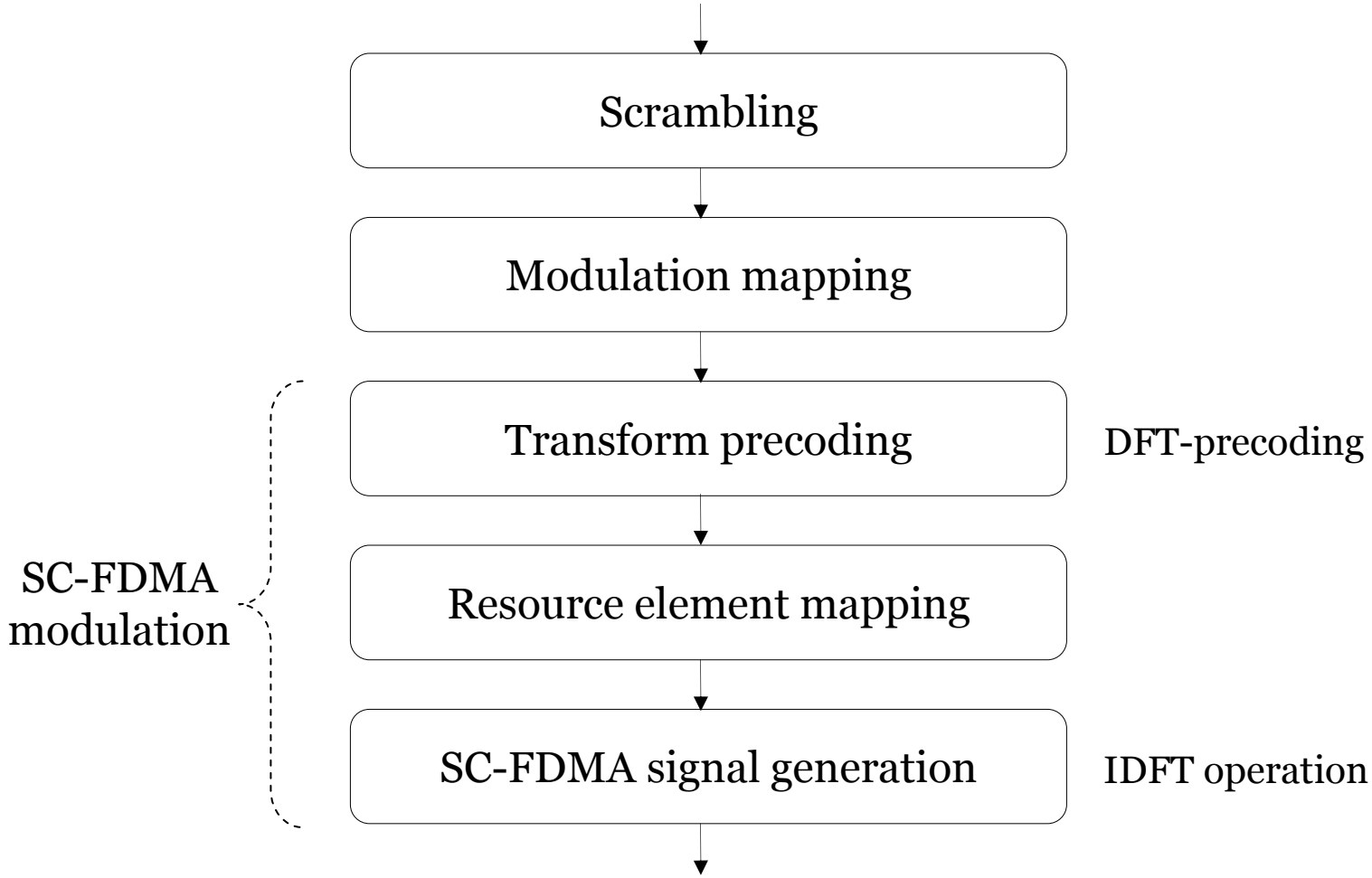
SC-FDMA



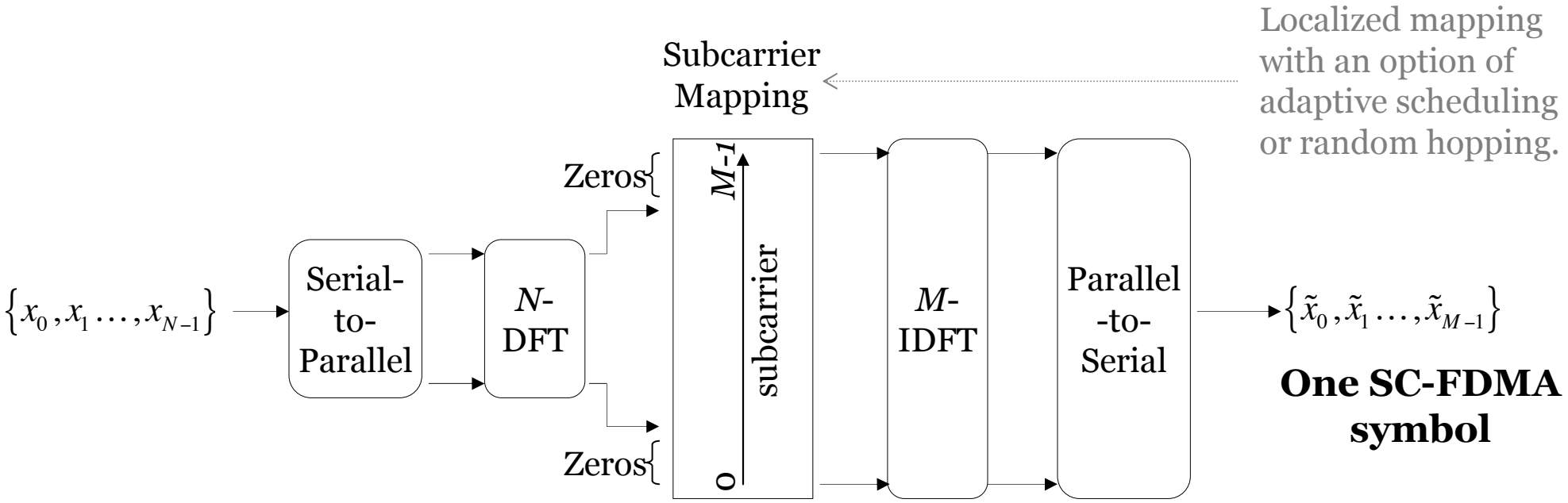
SC-FDMA MIMO


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

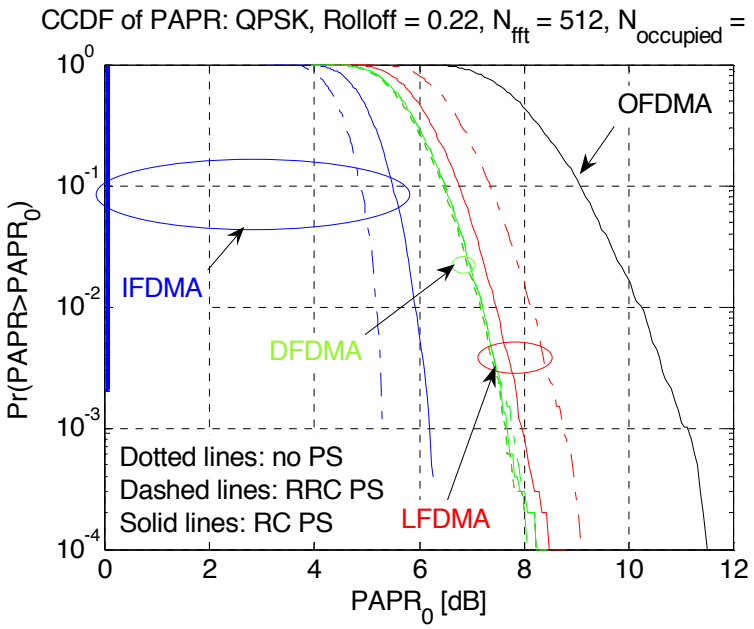
UL Physical Channel Processing



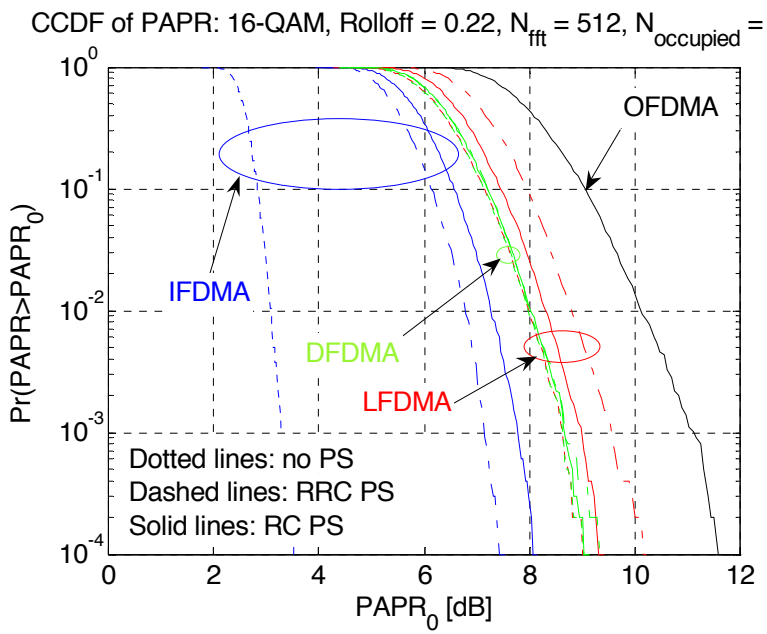
SC-FDMA Modulation in LTE UL



PAPR Characteristics



(a) QPSK



(b) 16-QAM

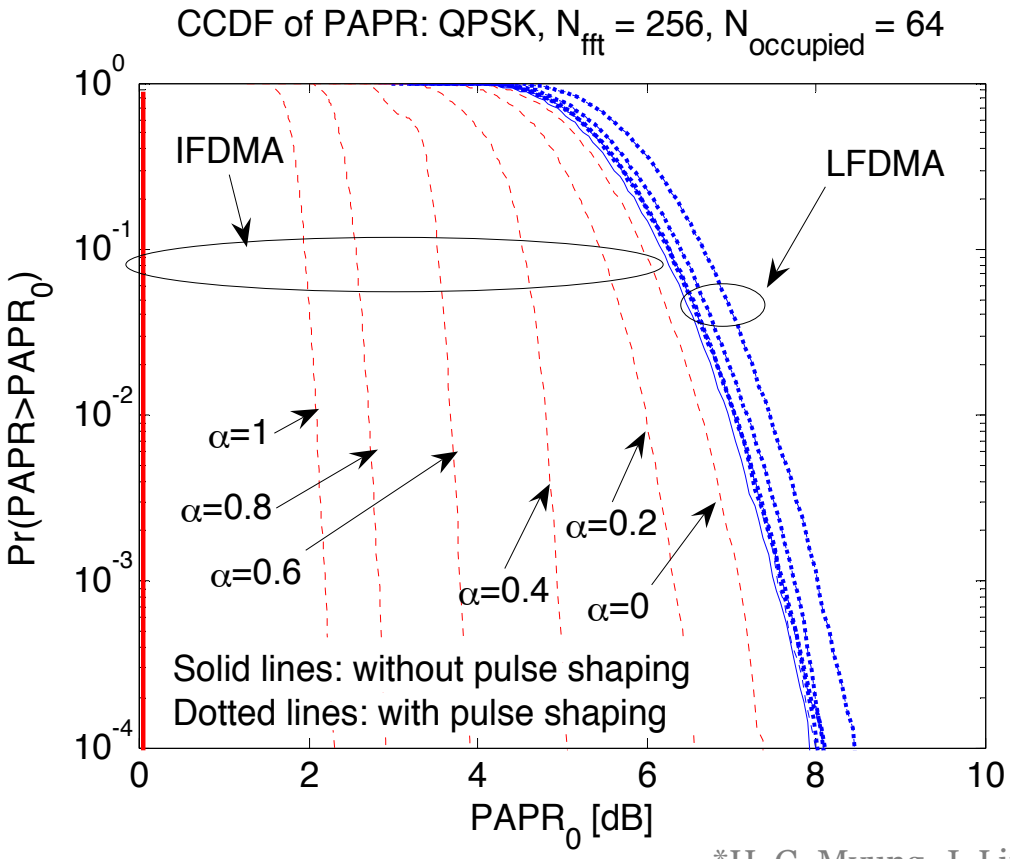
* Monte Carlo simulations (Number of iterations: > 10^4)
* Time domain pulse shaping with 8-times oversampling
* N_{fft}: number of total subcarriers = FFT size
* $N_{occupied}$: number of occupied subcarriers = data block size
* RC: raised-cosine, RRC: root raised-cosine
* Rolloff factor of 0.22

*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.

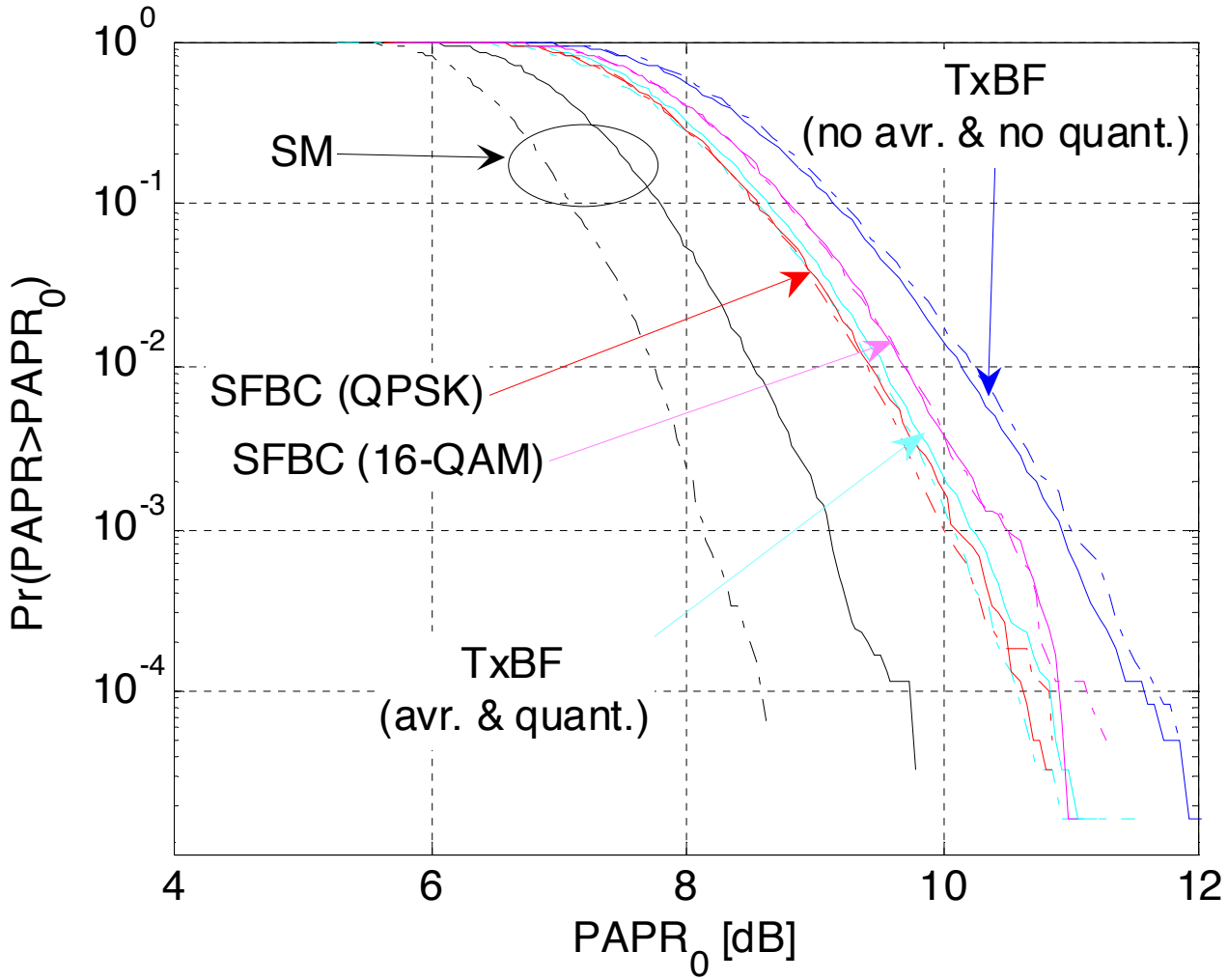
- PAPR and different rolloff factors



*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

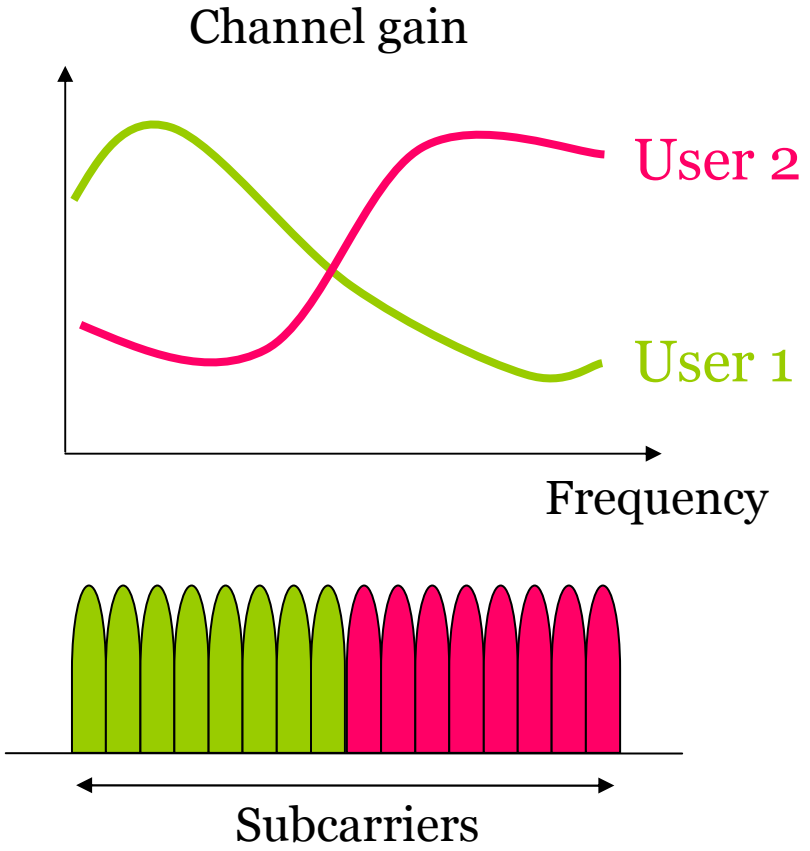
PAPR of SC-FDMA MIMO



*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

Channel-Dependent Scheduling (CDS)

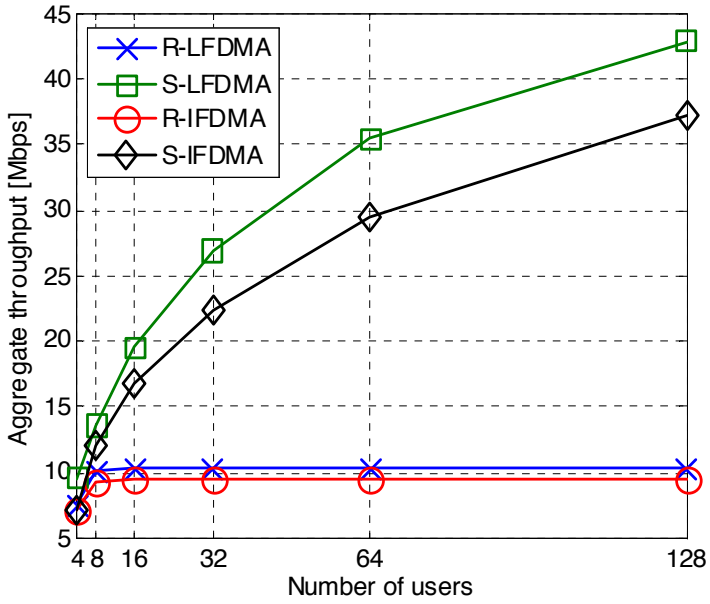
- Channel-dependent scheduling
  - Assign subcarriers to a user in excellent channel condition.
- Two subcarrier mapping schemes have advantages over each other.
  - Distributed: Frequency diversity.
  - Localized: Frequency selective gain with CDS.



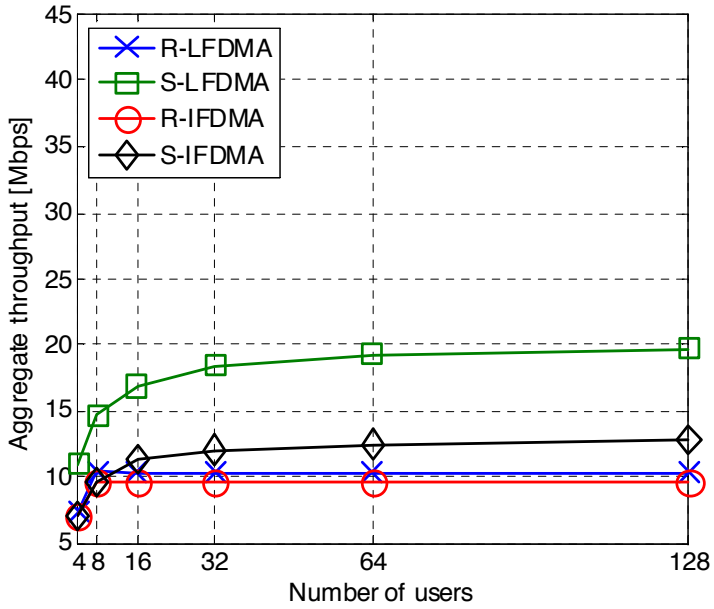
CDS

- cont.

Utility: sum of user throughput



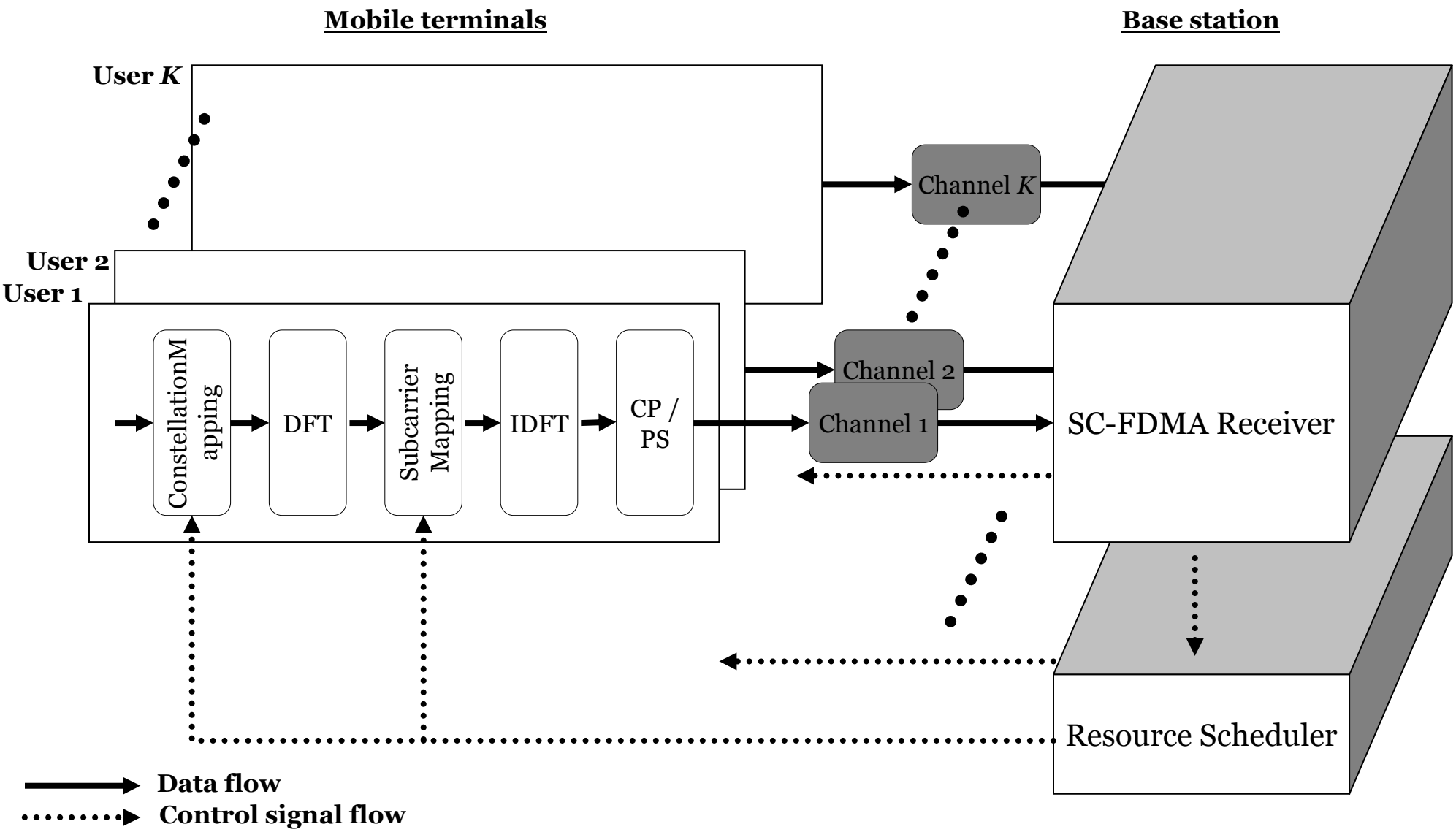
Utility: sum of logarithm of user throughput



*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

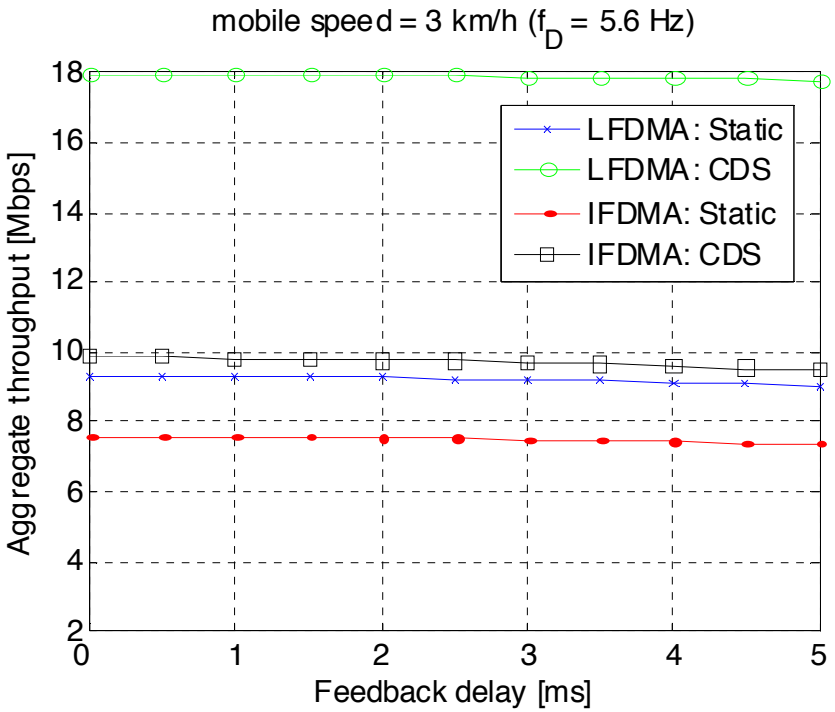
* Capacity based on Shannon's upper bound.
* Time synchronized uplink data transmission.
* Perfect channel knowledge.
* No feedback delay or error.

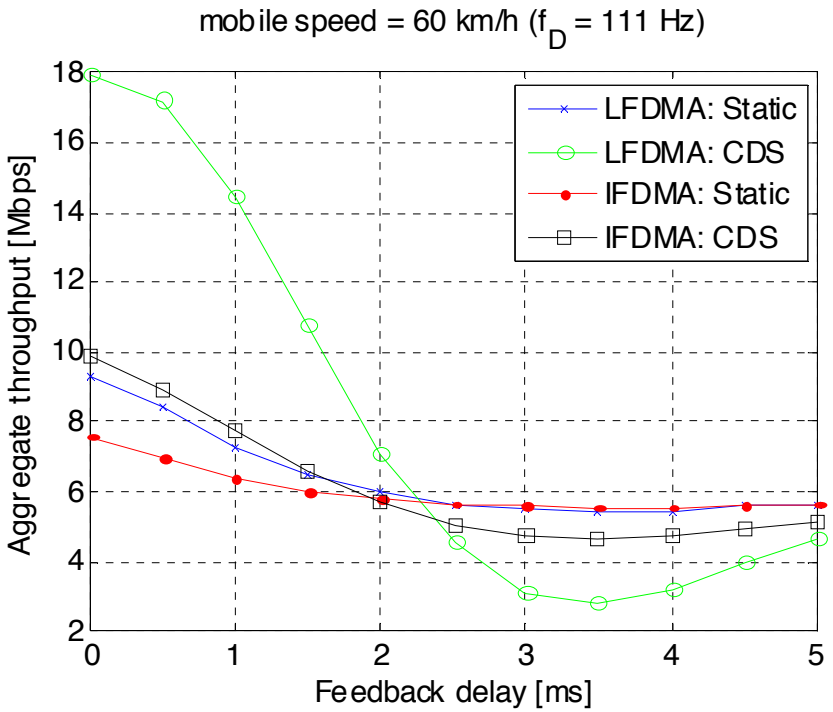
Uplink SC-FDMA with Adaptive Modulation and CDS



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

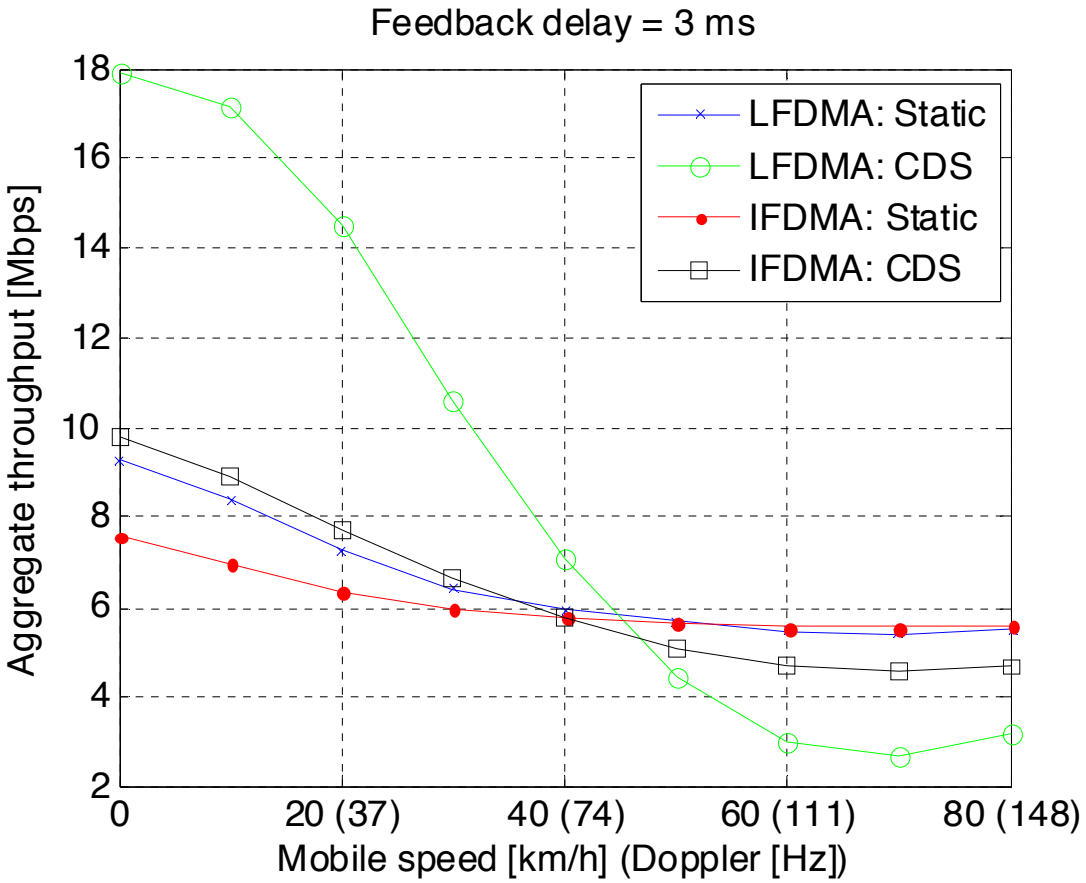
* Utility: sum of user throughput

*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.

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