ECS455: Chapter 6

Applications

6.2 WiMAX

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Advanced Mobile Wirless Systems

	Mobile WiMAX (IEEE)	3GPP LTE	3GPP2 UMB (Ultra Mobile Broadband)
Channel bandwidth	5, 7, 8.75, and 10 MHz	1.4, 3, 5, 10, 15, and 20 MHz	1.25, 2.5, 5, 10, and 20 MHz
DL multiplex	OFDM	OFDM	OFDM
UL multiple access	OFDMA	SC-FDMA	OFDMA and CDMA
Duplexing	TDD	FDD and TDD	FDD and TDD
Subcarrier mapping	Localized and distributed	Localized	Localized and distributed
Subcarrier hopping	Yes	Yes	Yes
Data modulation	QPSK, 16-QAM, and 64-QAM	QPSK, 16-QAM, and 64-QAM	QPSK, 8-PSK, 16-QAM, and 64-QAM
Subcarrier spacing	10.94 kHz	15 kHz	9.6 kHz
FFT size (5 MHz bandwidth)	512	512	512

[Myung and Goodman, 2008]

802.16 (WiMAX)

- **WirelessMAN**
- Provide wireless data over long distances.
- TG proceedings can be found at http://ieee802.org/16/tge/index.html.
- **Certification** is done by the WiMAX Forum
- Oct 2007: ITU officially approved WiMAX as part of the **3G** standard. It is the first non-cellular tech to get approval as 3G.

WiMAX (Forum)

- WiMAX = **Worldwide Interoperability for Microwave Access**
- www.wimaxforum.org
- Non-profit organization
- Formed to promote and **certify** conformance, compatibility, and interoperability of products based on IEEE 802.16 standards
- Same role that **Wi-Fi alliance** is playing for **IEEE 802.11** family of standards.
- It is worthwhile noting that IEEE802.16 is not the same as WiMAX.
  - IEEE802.16 develops the technology specification.
  - WiMAX ensures conformance and interoperability of 802.16 products, and develops the network architecture for IEEE802.16 compliant equipments.

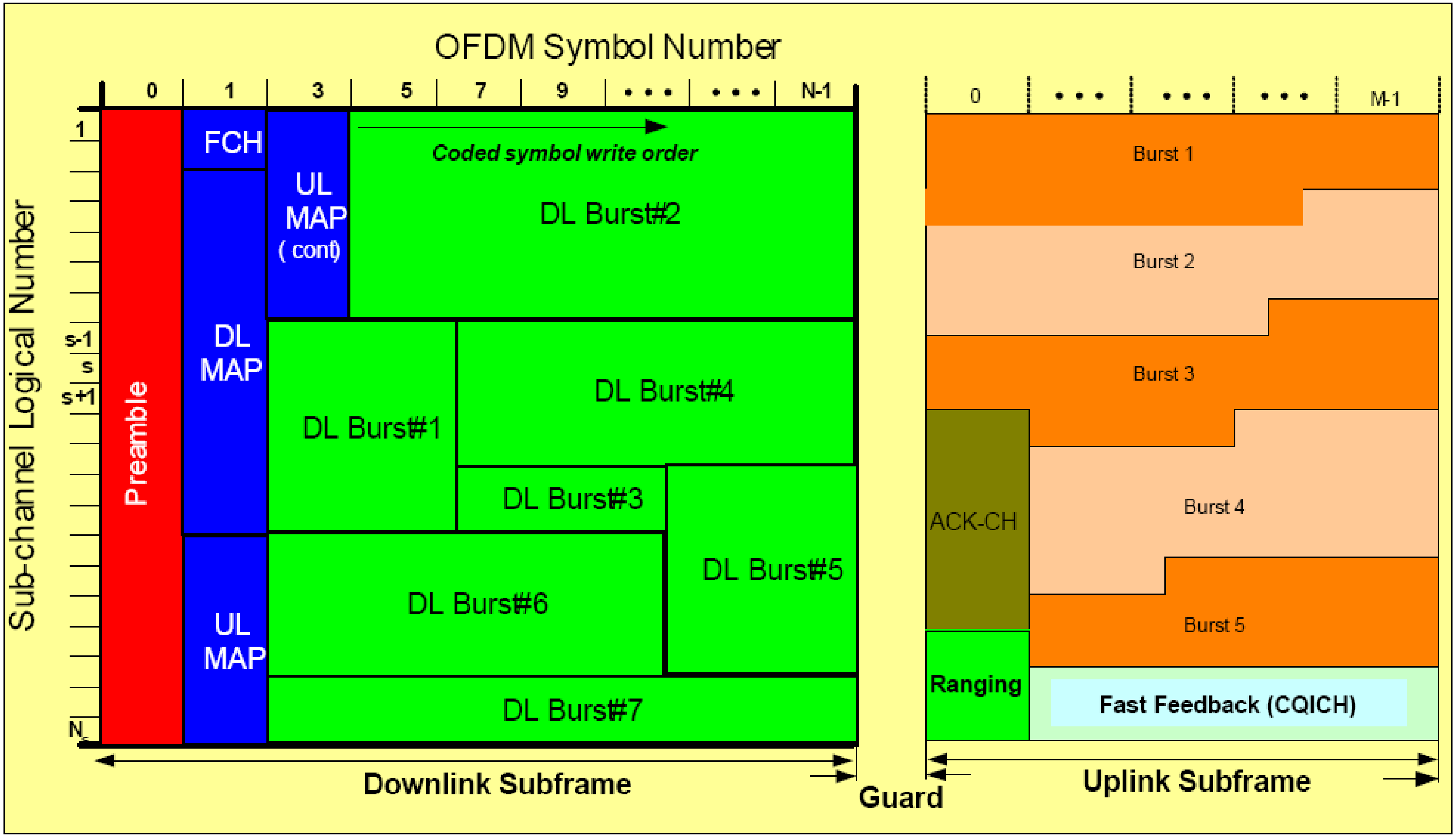
Original 802.16

- Completed in **2001**
- Intended primarily for telecom **backhaul** applications in **point-to-point line-of-sight** configurations using spectrum above 10 GHz.
- Use a radio interface based on a ***single-carrier waveform***.
- Ex. RF signal provided the communication between the two hubs located on top of big buildings that could see each other, and each hub was connected through wires to other nodes inside the building.

“Fixed” WiMAX

- **802.16-2004** based systems
- Fixed broadband wireless MAN
- Added multiple radio interfaces, including one based on OFDM-256 and one based on **OFDMA**.
- Support **point-to-multipoint** communications, sub-10 GHz operation, and **non-line-of-sight** communications.
- Potential applications include wireless Internet Service Provider (ISP) service, local telephony bypass, as an alternative to cable modem or DSL service, and for cellular backhaul for connections from cellular base stations to operator infrastructure networks.

WiMAX OFDMA Frame Structure (TDD)



Resource Allocation

- Dynamically assign subset of subcarriers to individual users for intervals of time.
- Active (data and pilots) sub-carriers are grouped into subsets of subcarriers called **subchannels**.
- Subchannels are further grouped into **bursts** which can be allocated to wireless users.
- Each burst allocation can be changed from frame to frame.
- This allows the BS to dynamically adjust the bandwidth usage according to the current system requirements.
- Based on feedback about the channel conditions, the system can implement **adaptive user-to-subcarrier assignment**.
  - As long as these subcarrier assignments are executed quickly, fast fading and narrow-band co-channel interference performance is improved compared to OFDM.
  - This, in turn, improves system spectral efficiency.

“Mobile” WiMAX

- Used to describe **802.16e-2005** based systems.
- 802.16e-2005 = 802.16-2004 standard + 802.16e amendment
- Specify **scalable** OFDM for the physical layer and makes further modifications to the MAC layer to accommodate high-speed mobility
- Adds **mobility** capabilities including support for radio operation while mobile, handovers across base stations, and handovers across operators.
- Not backward-compatible with IEEE 802.16-2004 networks
- Employ many of the same mechanisms as HSPA to maximize throughput and spectral efficiency, including high-order modulation, efficient coding, adaptive modulation and coding, and Hybrid Automatic Repeat Request (HARQ).
- The principal difference from HSDPA is the use of **OFDMA**.
  - OFDM systems exhibit greater orthogonality on the uplink, so IEEE 802.16e-2005 may have slightly greater uplink spectral efficiency than even HSUPA.

Scalable OFDMA (S-OFDMA)

- A multiple-access/multiplexing scheme
- Provide
  - multiplexing operation of data streams from multiple users onto the downlink sub-channels and
  - uplink multiple access by means of uplink sub-channels.
- Support scalable channel BWs from 1.25 to 20 MHz (to comply with varied worldwide requirements).
- The FFT size is scalable from 128 to 2,048 (2^{11}).
  - When the available bandwidth increases, the FFT size is also increased such that the **subcarrier spacing is always 10.94kHz**.
  - This keeps the OFDM symbol duration, which is the basic resource unit, fixed and therefore makes scaling have minimal impact on higher layers.
- Allow for the data rate to scale easily with available channel bandwidth.

Trends

- WiMAX has emerged as a potential alternative to cellular technology for wide-area wireless networks.
- WiMAX is trying to challenge existing wireless technologies—promising greater capabilities and greater efficiencies than alternative approaches such as HSPA.
- But as WiMAX, particularly mobile WiMAX, has come closer to reality, vendors have continued to enhance HSPA, and actual WiMAX advantages are no longer apparent.
- Any potential advantages certainly do not justify replacing 3G systems with WiMAX.
- Instead, WiMAX has gained the greatest traction in developing countries as an alternative to wireline deployment.

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6.3 LTE

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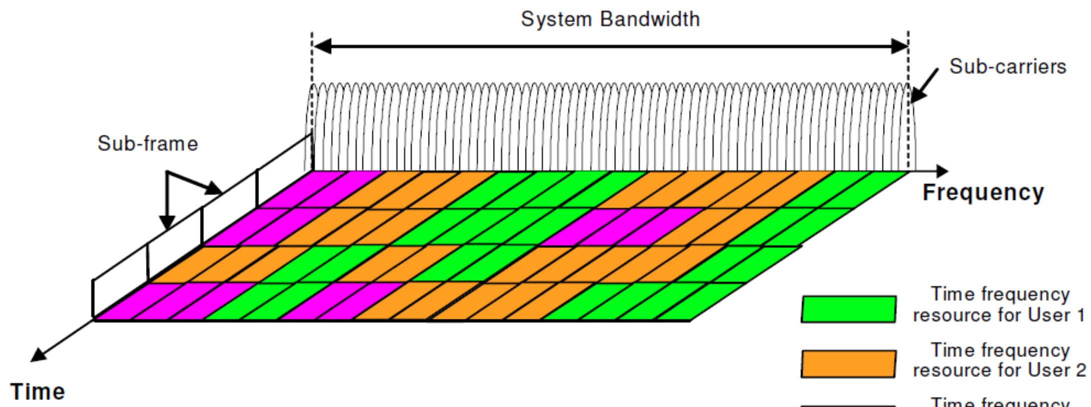
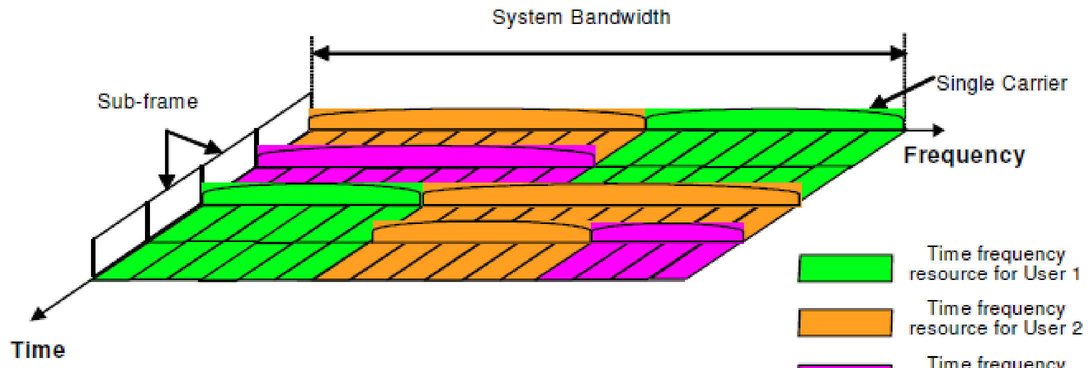
LTE: Multiple Access

- Downlink: **OFDMA**



- Uplink: **SC-FDMA**



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6.3.1 OFDMA in LTE

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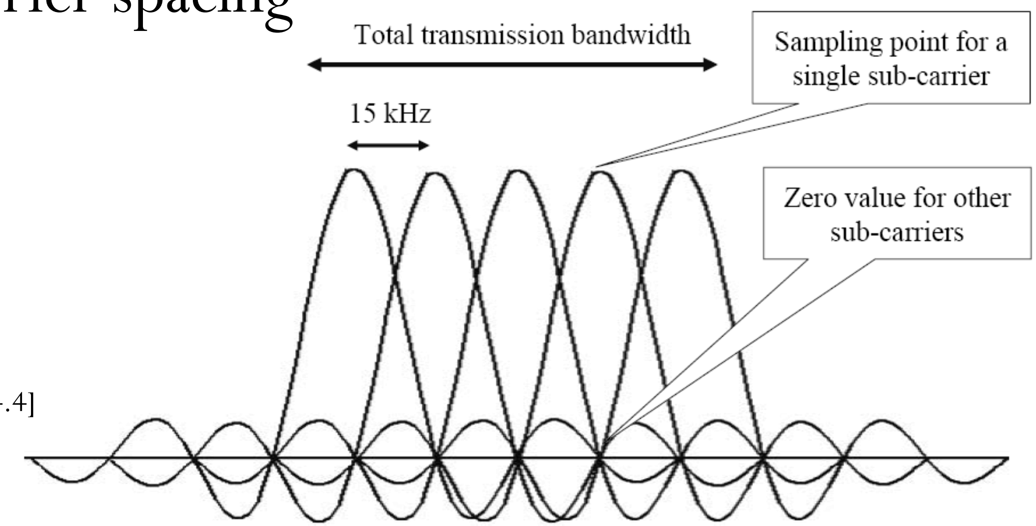
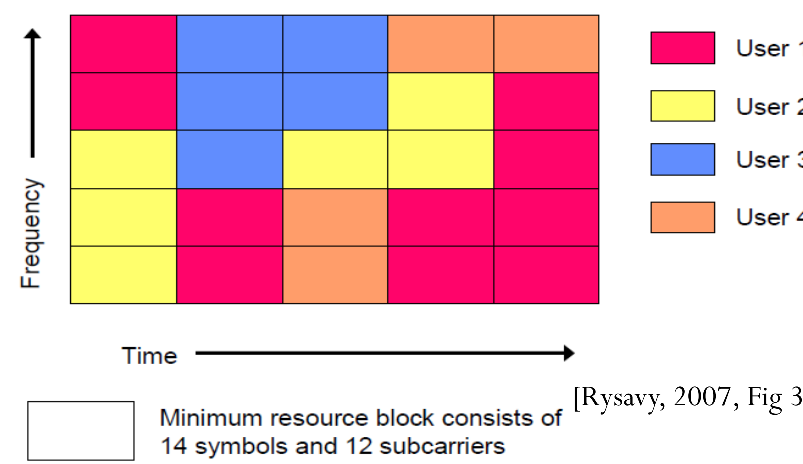
LTE: OFDMA

- 15 kHz subcarrier spacing



[Holma and Toskala, 2009, Fig 4.4]

- Downlink Resource Assignment in Time and Frequency



[Rysavy, 2007, Fig 37]

OFDM use in Cellular

- Although OFDM has been used for many years in communication systems, its use in mobile devices is more recent.
- The European Telecommunications Standards Institute (ETSI) first looked at OFDM for GSM back in the late 1980s
  - However, the processing power required to perform the many **FFT operations** was **at that time too expensive** and demanding
- In 1998, 3GPP seriously considered OFDM for UMTS
  - Chose an alternative technology based on CDMA.
- Today the cost of digital signal processing has been greatly reduced.

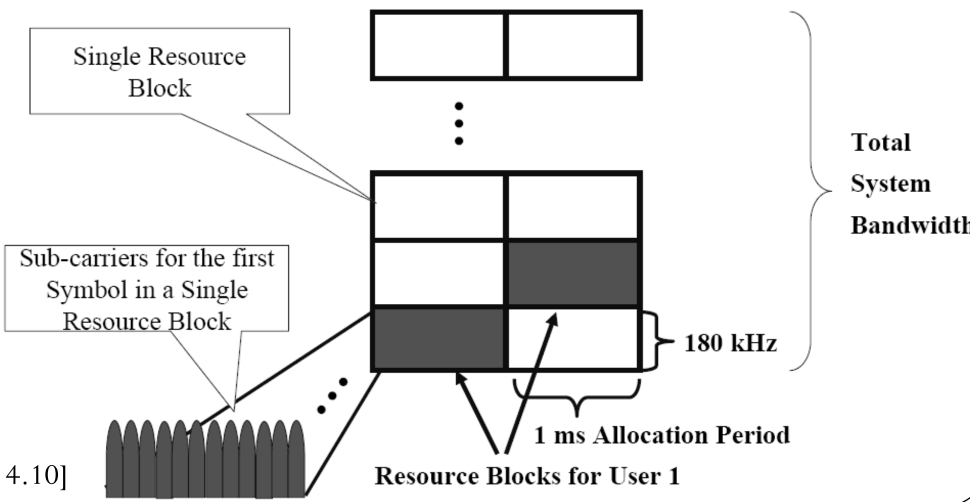
OFDMA: Resource Allocation (1)

- HSDPA
  - Allocations were only in the time domain and code domain but always occupied the full bandwidth.
- OFDMA
  - The possibility of having different sub-carriers to allocated users enables the scheduler to benefit from the diversity in the frequency domain.
  - This element of allocating resources dynamically in the frequency domain is often referred to as **frequency domain scheduling** or **frequency domain diversity**.

OFDMA: Resource Allocation (2)

- Allocation is not done on an individual sub-carrier basis but is based on **resource blocks**.
  - It would be far too inefficient to try either to obtain feedback with 15 kHz sub-carrier resolution or to signal the modulation applied on a individual sub-carrier basis.
- Each resource block consisting of 12 sub-carriers, thus resulting in the minimum bandwidth allocation being 180 kHz.
- When the respective allocation resolution in the time domain is 1 ms, the downlink transmission resource allocation thus means filling the resource pool with 180 kHz blocks at 1 ms resolution.

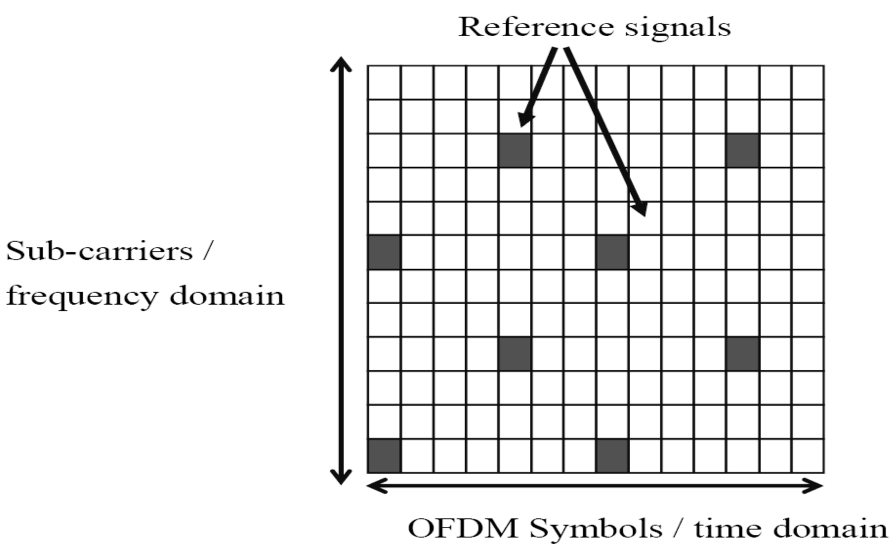
Note that the resource block in the specifications refers to the 0.5 ms slot, but the resource allocation is done anyway with the 1 ms resolution in the time domain.



[Holma and Toskala, 2009, Fig 4.10]

OFDMA: Channel Estimation

- Have reference or pilot symbols.
- With the proper placement of these symbols in both the time and frequency domains, the receiver can interpolate the effect of the channel to the different sub-carriers from this time and frequency domain reference symbol 'grid'.



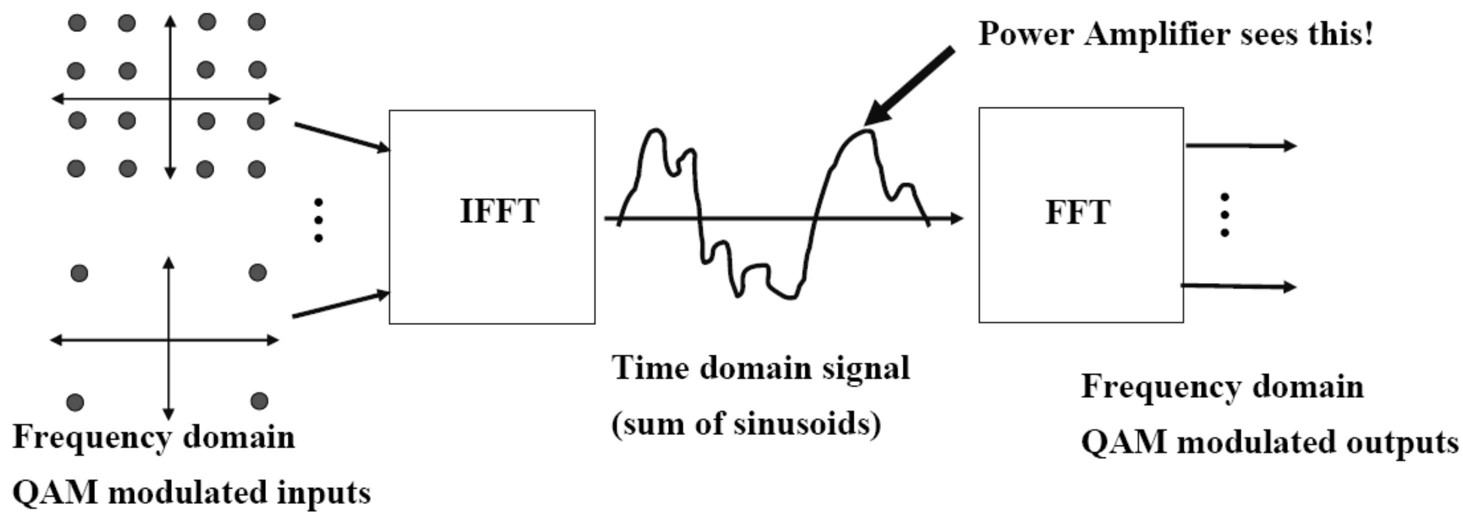
[Holma and Toskala, 2009, Fig 4.8]

OFDMA: Equalizer

- Frequency domain equalizer basically reverts the channel impact for each sub-carrier.
- The frequency domain equalizer in OFDMA simply multiplies each sub-carrier (with the complex-valued multiplication) based on the estimated channel frequency response (the phase and amplitude adjustment each sub-carrier has experienced) of the channel.
- This is clearly a **simpler** operation compared with WCDMA and is not dependent on channel length (length of multipath in chips) as is the WCDMA equalizer.

OFDMA Problem: PAPR

- The OFDMA signal envelope varies strongly, compared to a normal QAM modulator, which is only sending one symbol at a time (in the time domain).



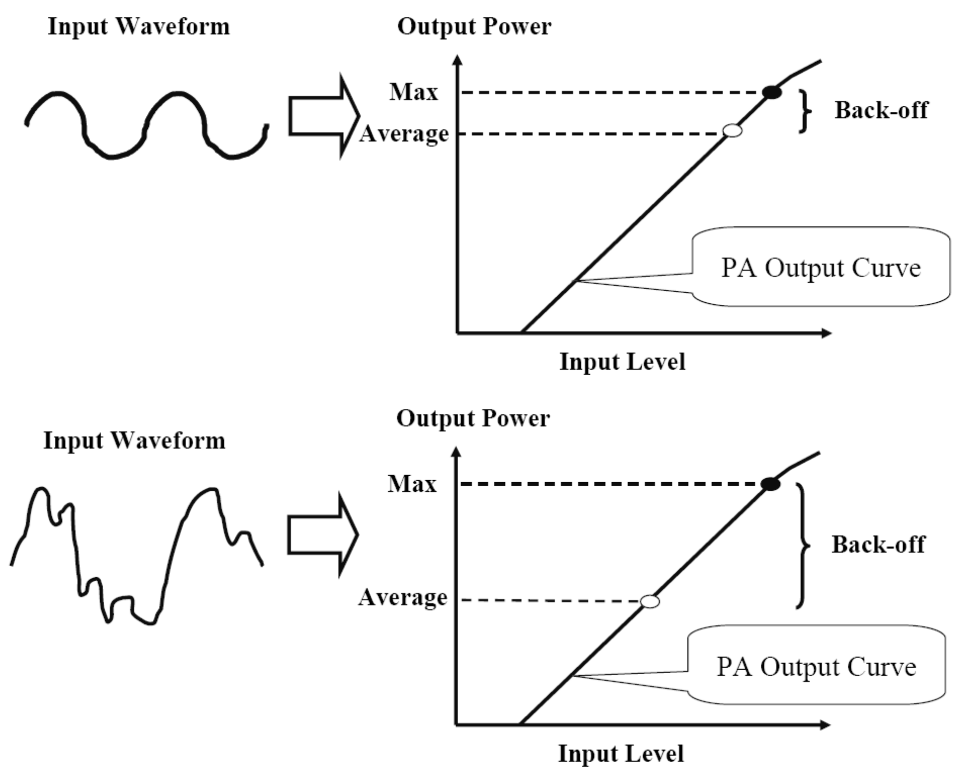
[Holma and Toskala, 2009, Fig 4.11]

OFDMA Problem: PAPR (2)

- This causes some challenges to the amplifier design as, in a cellular system, one should aim for maximum power amplifier efficiency to achieve minimum power consumption.
- A signal with a higher envelope variation (such as the OFDMA signal in the time domain) requires the amplifier to use **additional back-off.**
  - The amplifier must stay in the linear area with the use of extra power back-off.
  - The use of additional back-off leads to a **reduced amplifier power efficiency** or a smaller output power.
  - This either causes the uplink range to be shorter or, when the same average output power level is maintained, the battery energy is consumed faster due to higher amplifier power consumption.
    - The latter is not considered a problem in fixed applications where the device has a large volume and is connected to the mains, but for small mobile devices running on their own batteries it creates more challenges.
- This was the key reason why 3GPP decided to use OFDMA in the downlink direction but to use the power efficient SC-FDMA in the uplink direction.

Power amplifier back-off requirements

- Power amplifier back-off requirements for different input waveforms



[Holma and Toskala, 2009, Fig 4.12]

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6.3.2 SC-FDMA in LTE

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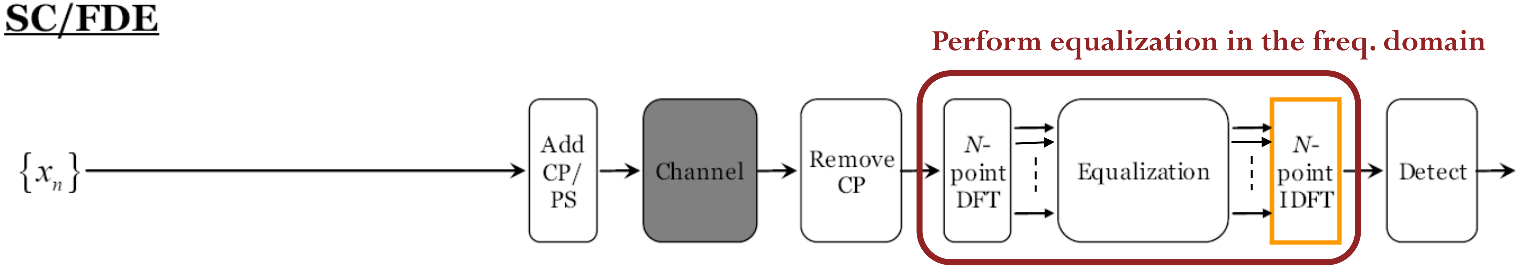
SC/FDE

- Broadband multipath channels.
- **Conventional time domain equalizers are impractical** because of the complexity (very long channel impulse response in the time domain).
- Frequency domain equalization (FDE) is more practical.
- **Single Carrier with Frequency Domain Equalization** (SC/FDE)
  - Another way to fight the frequency-selective fading channel.
  - Deliver performance similar to OFDM with essentially the same overall complexity, even for long channel delay

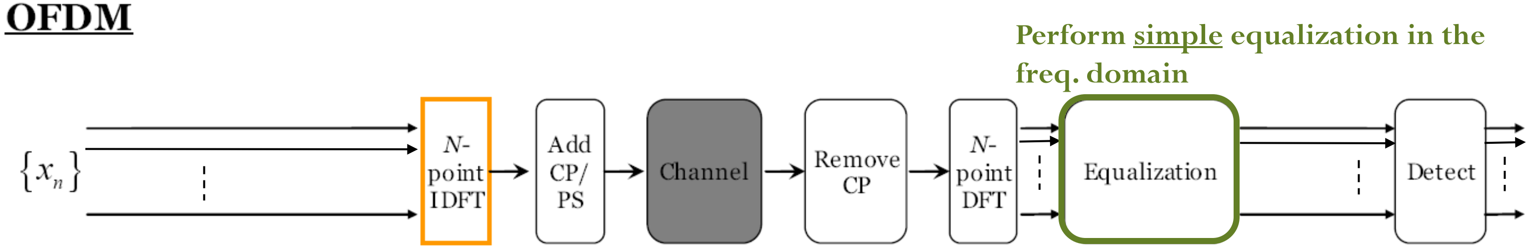
SC/FDE (2)

- SC/FDE receiver transforms the received signal to the frequency domain by applying DFT and does the equalization process in the frequency domain.
- Most of the well-known time domain equalization techniques, such as minimum mean-square error (MMSE) equalization, decision feedback equalization, and turbo equalization, can be applied to the FDE

SC/FDE



OFDM



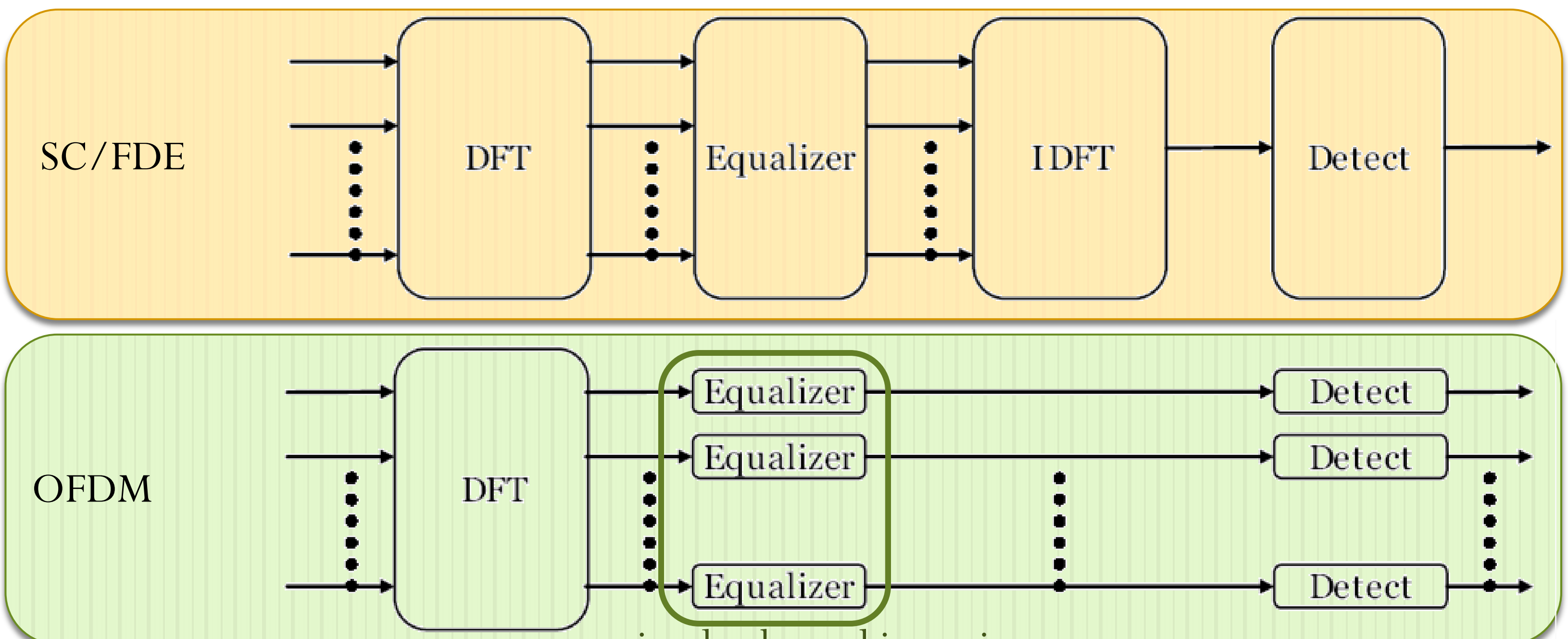
[Myung, 2007, Fig. 2.3]

SC/FDE vs. OFDM: Receiver

- OFDM performs data detection on a per-subcarrier basis in the frequency domain whereas SC/FDE does it in the time domain after the additional IDFT operation.

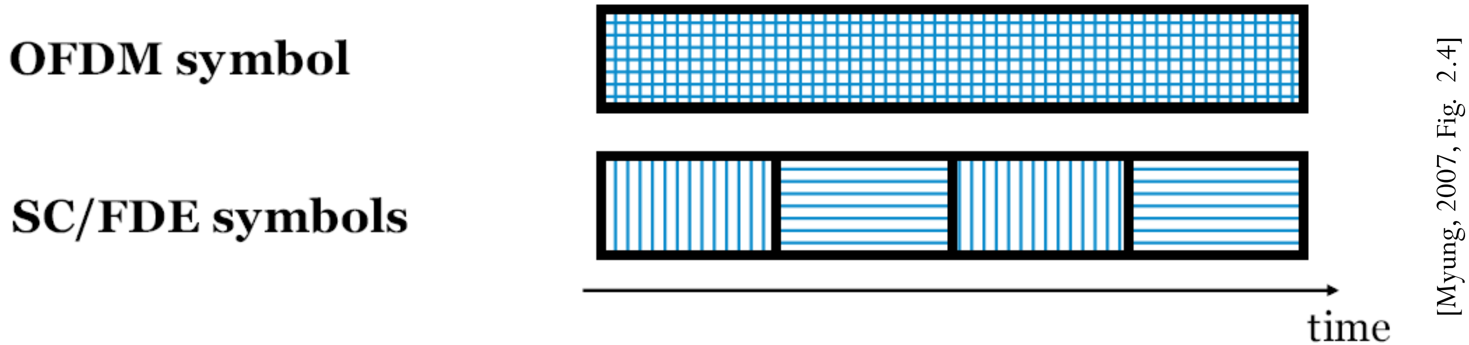
OFDM is more sensitive to a null in the channel spectrum and it requires channel coding or power/rate control to overcome this deficiency.

[Myung, 2007, Fig. 2.4]



SC/FDE vs. OFDM

- The duration of the modulated time symbols are expanded in the case of OFDM with parallel transmission of the data block during the elongated time period.



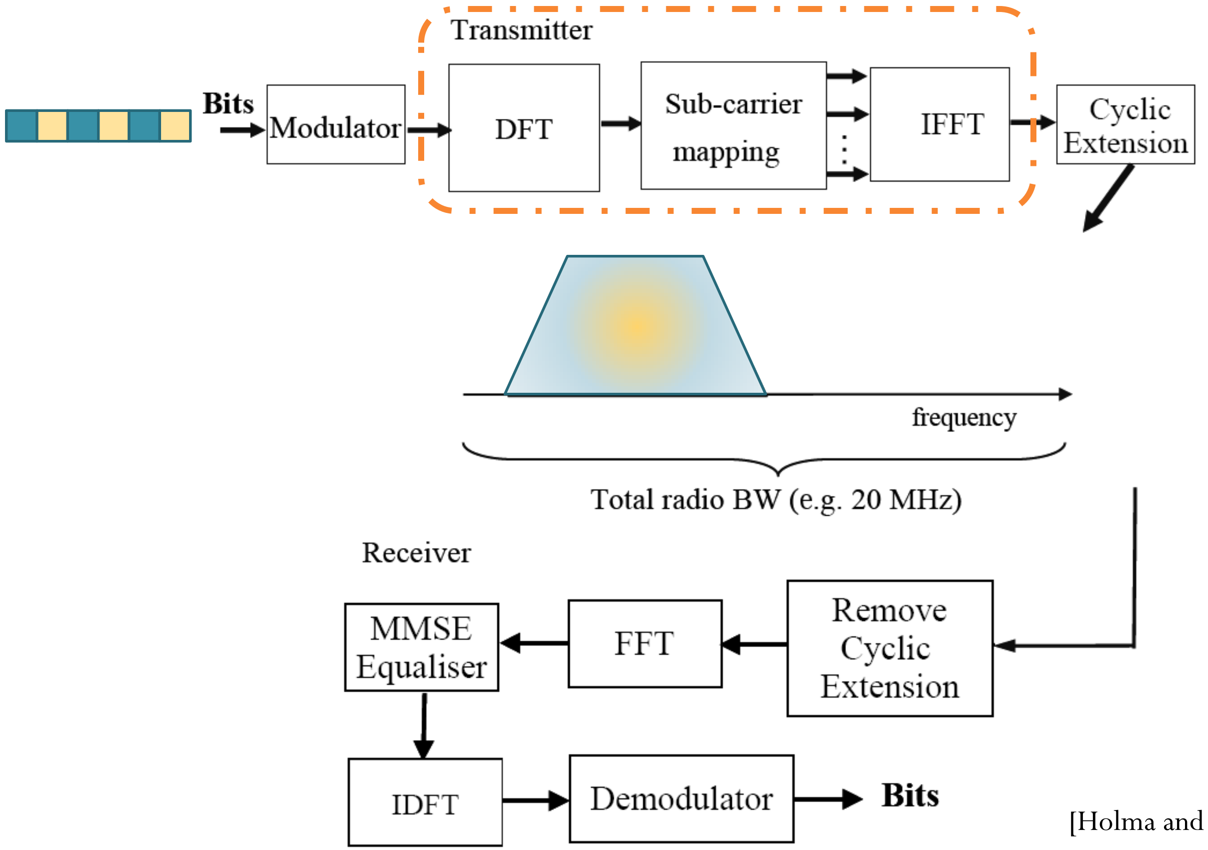
- Channel equalization and receiver decision
  - In OFDM systems, both are performed in the frequency domain
  - In SCFDE systems the receiver decisions are made in the time domain, although channel equalization is performed in the frequency domain.

SC/FDE Advantages (over OFDM)

- Low PAPR due to single carrier modulation at the transmitter.
  - Allow the use of less costly power amplifiers
- Robustness to spectral null.
- Lower sensitivity to carrier frequency offset.
- Lower complexity at the transmitter
  - The transmitter's IFFT block is moved to the receiver.
  - Benefit the mobile terminal in cellular **uplink** communications.

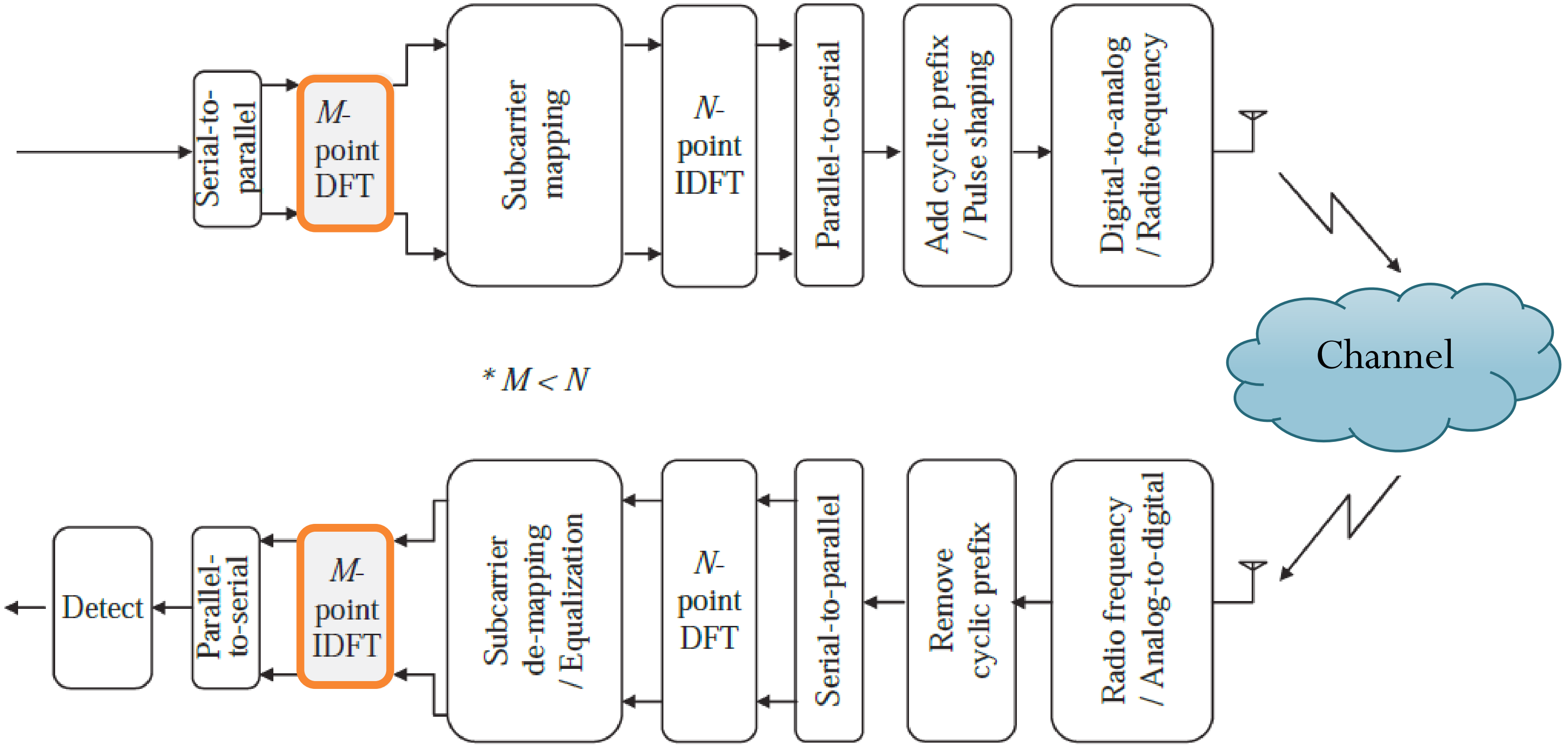
SC-FDMA

- Single carrier FDMA (SC-FDMA) is an extension of SC/FDE to accommodate multi-user access.



[Holma and Toskala, 2009, Fig 4.13]

Structure: SC-FDMA vs. OFDMA



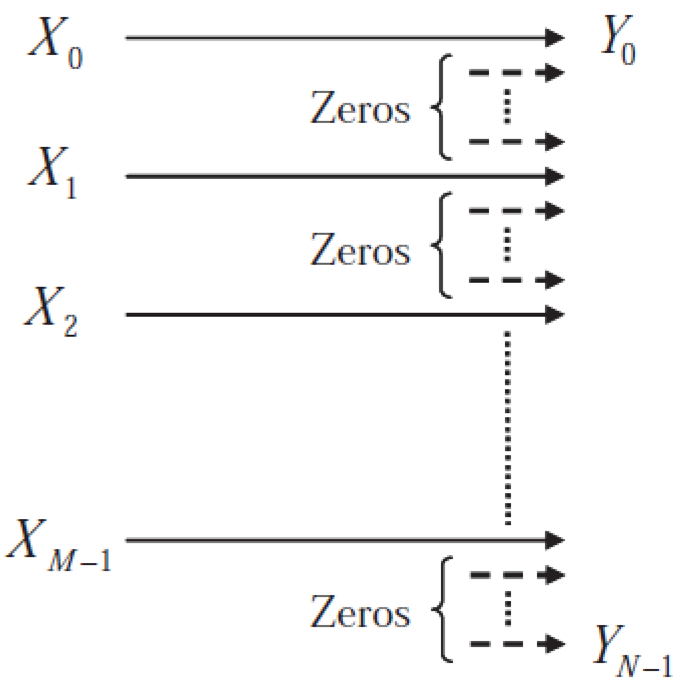
SC-FDMA: ☐ + ☐

OFDMA: ☐

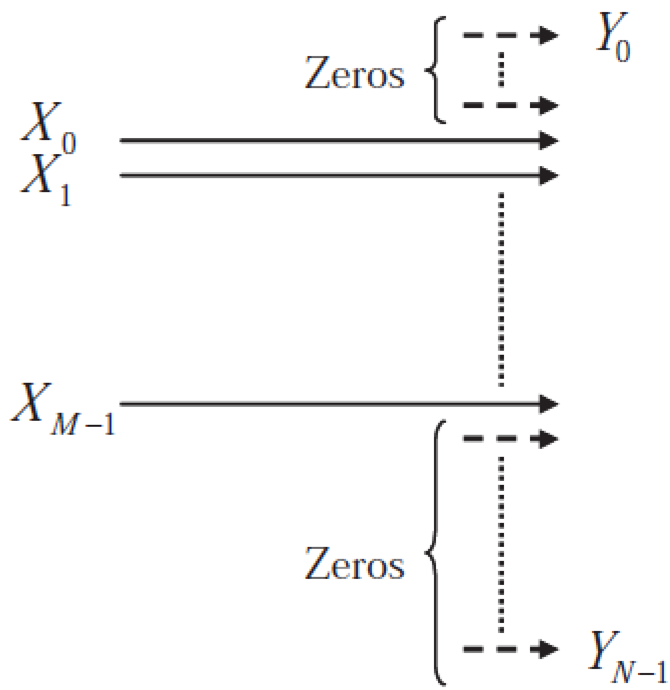
SC-FDMA (2)

- Can be regarded as "DFT-spread" OFDMA (DFT-SOFDM) or "DFT-precoded" OFDMA
  - Time domain data symbols are transformed to frequency domain by DFT before going through OFDMA modulation.
- Lower peak-to-average power ratio (PAPR) (than OFDM) because of its inherent single carrier structure.
  - 2 to 6 dB PAR advantage over the OFDMA method used by other technologies such as IEEE 802.16e.
- QAM modulation, where each symbol is sent one at a time as in TDMA.
- Users are orthogonal because they occupy different subcarriers in the frequency domain
  - Similar to OFDMA.

SC-FDMA: Subcarrier mapping

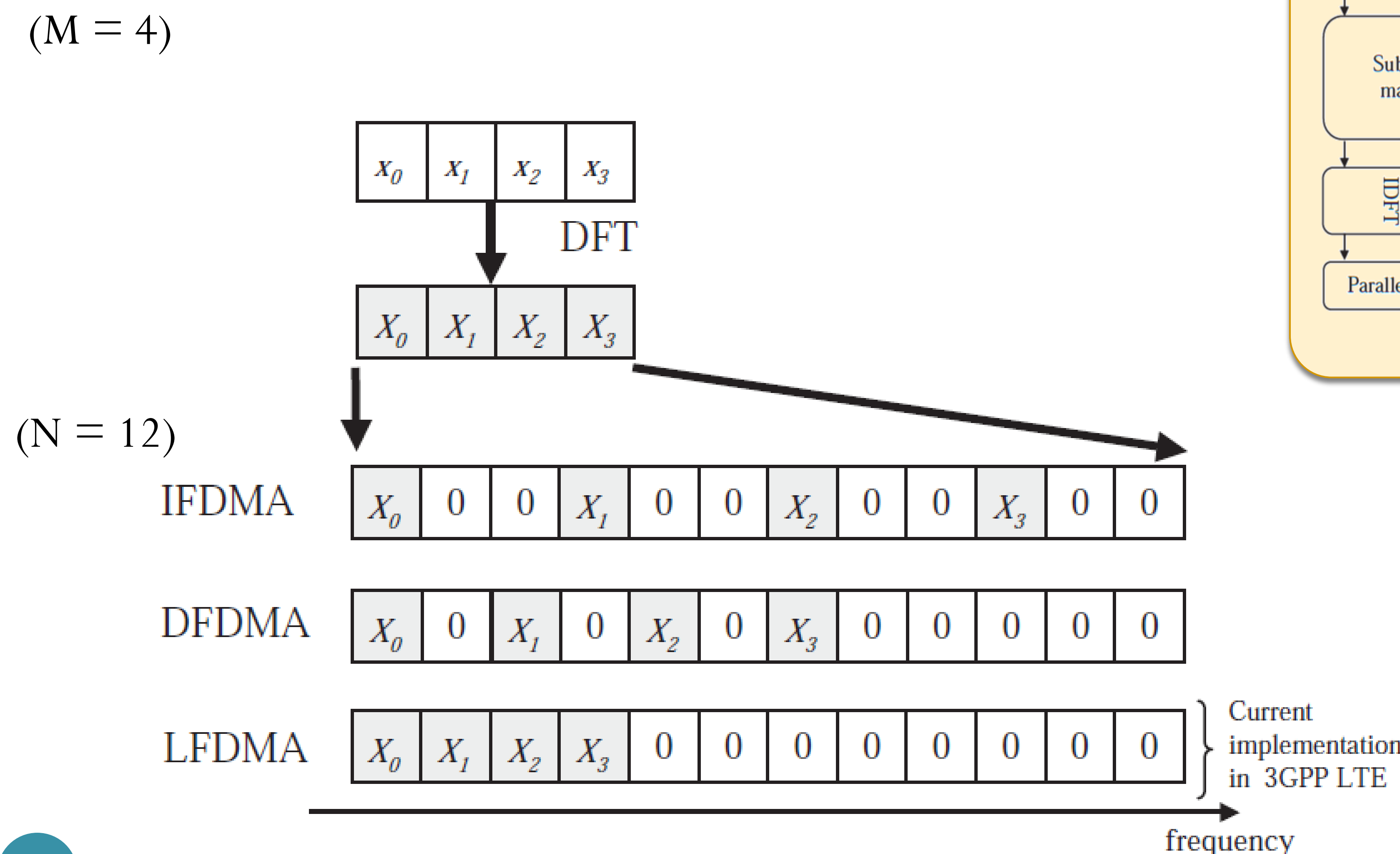


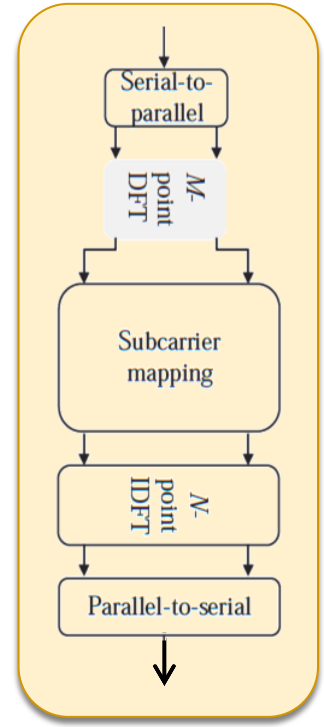
Distributed FDMA
(DFDMA)



Localized FDMA
(LFDMA)

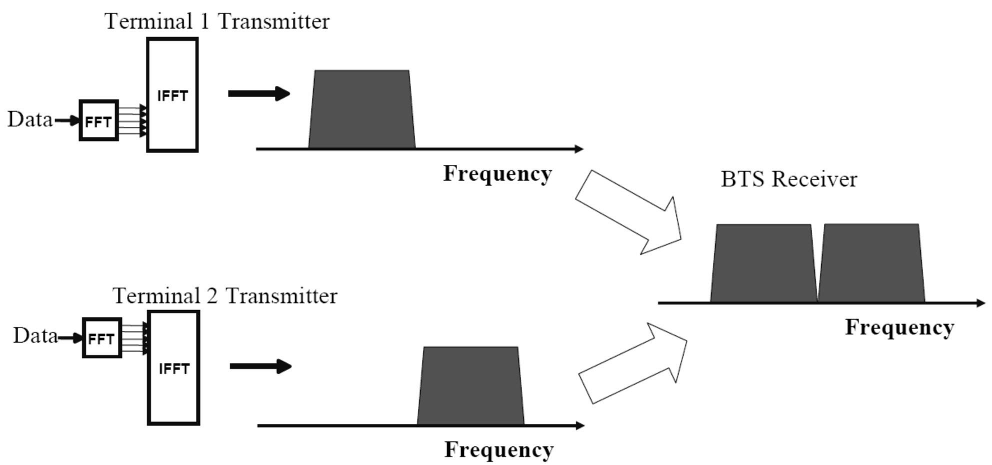
Subcarrier mapping (2)



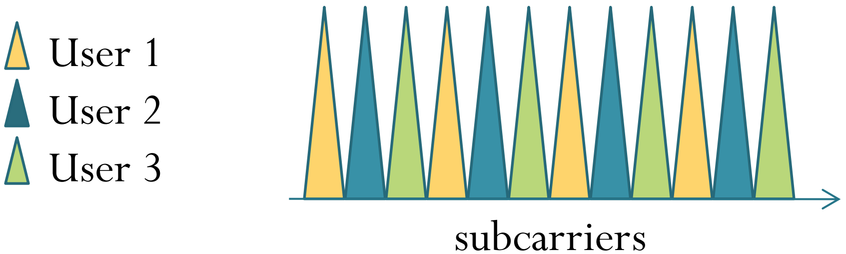


Subcarrier mapping (3)

- The signals of the three different terminals arriving at a base station occupy **mutually exclusive sets of subcarriers**.
- Localized FDMA



- Interleaved (distributed) FDMA



IFDMA: Freq-Domain

(Block of size M in time-domain) (Block of size M in freq-domain)

$$\left[s[0], s[1], s[2], s[3]\right] \xrightarrow{\text{DFT}} \left[S[0], S[1], S[2], S[3]\right]$$

[0 ,S[0], 0 , 0 ,S[1], 0 , 0 ,S[2], 0 , 0 ,S[3], 0]

(Block of size N in freq-domain)

[X[0],X[1],X[2],X[3],X[4],X[5],X[6],X[7],X[8],X[9],X[10],X[11]]

Shift amount = r

Only terms that have $k = r + \ell M$ will be non-zero.

IFDMA: Time-Domain Expression

$$x[n] = \text{IDFT}\{X[k]\} = \frac{1}{N}\sum_{k=0}^{N-1} X[k] e^{j\frac{2\pi}{N}nk}$$

Only terms that have $k = r + \ell M$ will be non-zero.

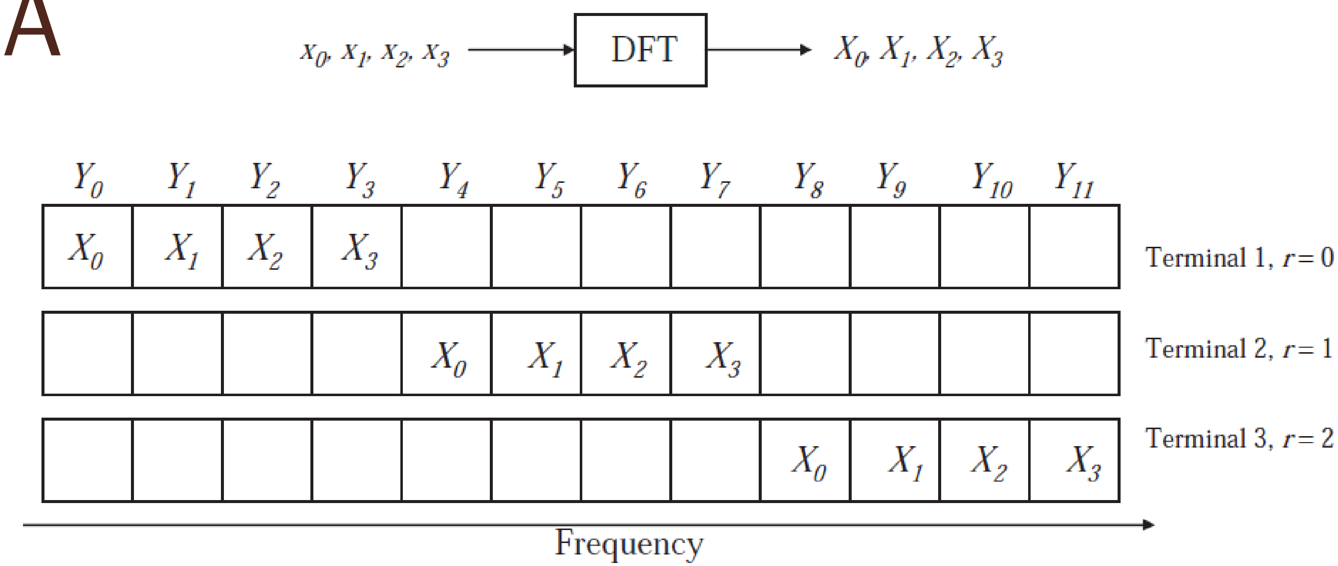
$$x[n] = \frac{1}{N}\sum_{\ell=0}^{M-1} X[r+\ell M] e^{j\frac{2\pi}{N}n(r+\ell Q)} = e^{j\frac{2\pi}{N}nr}\frac{1}{Q}\left(\frac{1}{M}\sum_{\ell=0}^{M-1} S[\ell] e^{j\frac{2\pi}{M}n\ell}\right)$$

$$= e^{j\frac{2\pi}{N}nr}\frac{1}{Q}\left(\underbrace{\frac{1}{M}\sum_{\ell=0}^{M-1} S[\ell] e^{j\frac{2\pi}{M}n\ell}}_{\text{IDFT formula}}\right) = e^{j\frac{2\pi}{N}nr}\frac{1}{Q}s[n \bmod M]$$

[Myung and Goodman, 2008, Appendix A.1]

LFDMA

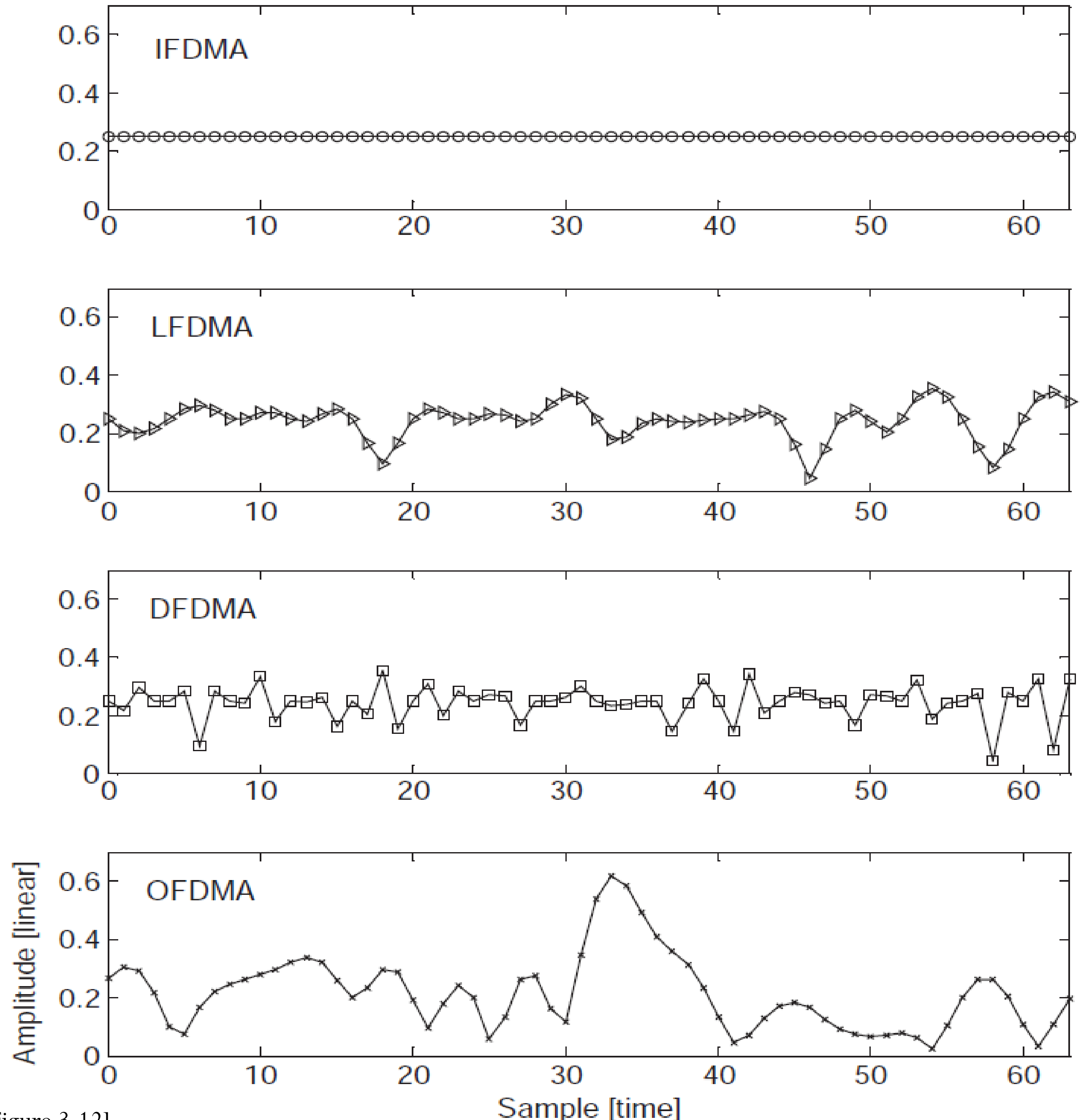
(Assume $r = 0$.)



$$y_n = y_{Q\cdot m+q} = \begin{cases} \frac{1}{Q} x_{(n) \bmod M}, & q = 0 \\ \frac{1}{Q}\cdot\left(1 - e^{j2\pi\frac{q}{Q}}\right)\cdot\frac{1}{M}\sum_{p=0}^{M-1}\frac{x_p}{1 - e^{j2\pi\left\{\frac{(m-p)}{M}+\frac{q}{QM}\right\}}}, & q \neq 0 \end{cases}$$

- Has exact copies of input time symbols with a scaling factor of 1/Q at sample positions that are integer multiples of Q.
- Intermediate values are weighted sums of all the time symbols in the input block.

PAPR



[Myung and Goodman, 2008, Figure 3.12]

OFDMA and SC-FDMA: Similarity

- Work in blocks of data
  - Each block consists of M modulation symbols;
- Divide the transmission bandwidth into sub-bands with information carried on discrete subcarriers
- Frequency domain channel equalization
- Use cyclic prefix to
  - Prevent inter-block interference (IBI)
    - Act as a guard time between successive blocks
  - Convert a discrete time linear convolution into a discrete time circular convolution.
    - Point-wise multiplication of the DFT frequency samples in the frequency domain
- When there are M symbols per block and N subcarriers, both can transmit signals from $Q = N/M$ terminals simultaneously.

OFDMA and SC-FDMA: Differences

- Suppose the original symbol duration is T seconds.
- OFDMA symbol duration is expanded to $M \times T$ seconds.
  - This time **<u>expansion</u>** reduces ISI

- The SC-FDMA symbol duration is T/Q seconds
  - **<u>Compressed</u>** by #users
  - Same as in a TDMA system.

Shifts of burden

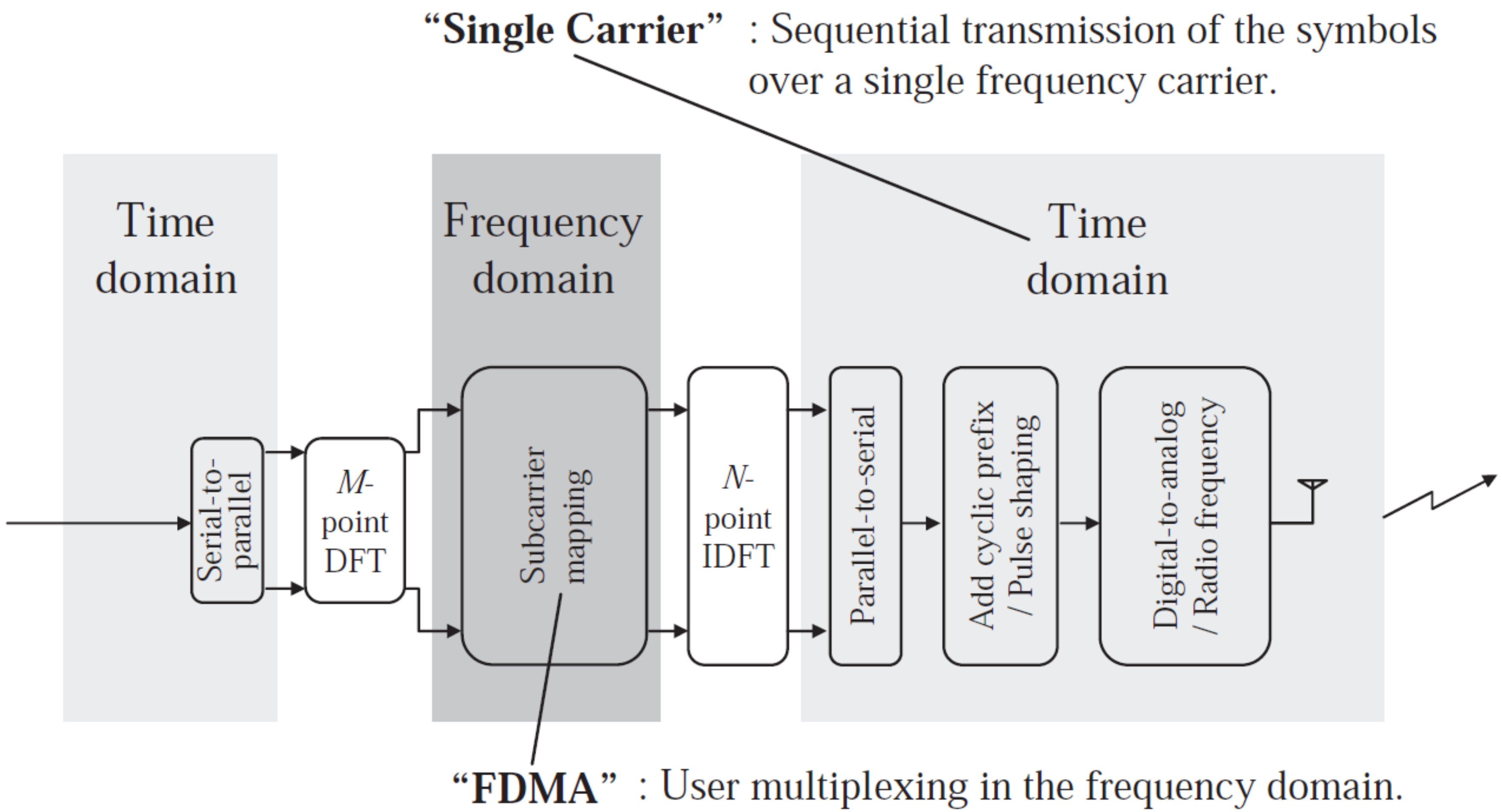
Advantage of SC-FDMA:

SC-FDMA for uplink transmission places both

- the main transmitter burden (power amplifier) and
- the main receiver burden (compensation for ISI)

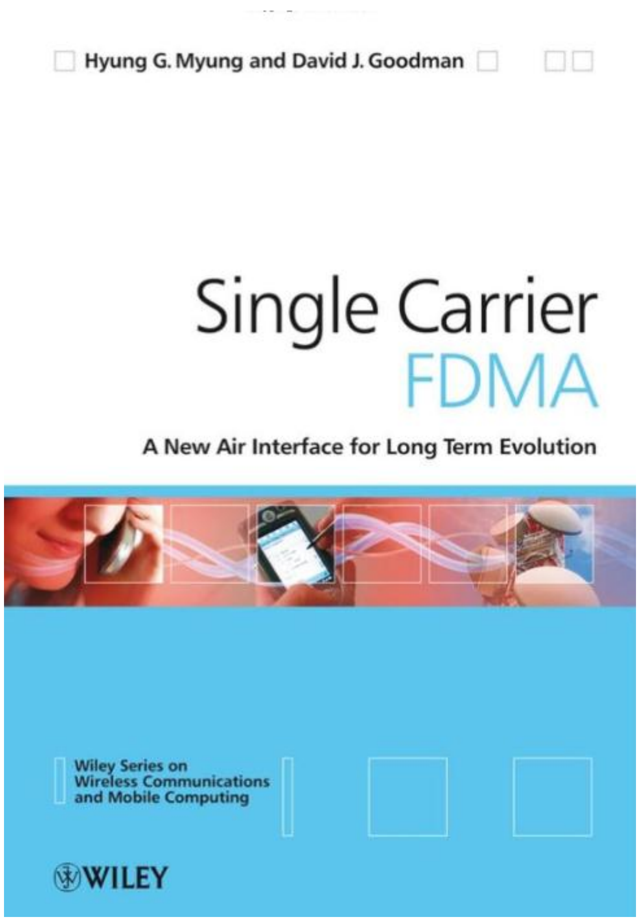
at base stations rather than at portable terminals.

Summary: SC-FDMA



[Myung and Goodman, 2008, Figure 3.22]

Reference for SC-FDMA



H.G. Myung and D.J. Goodman, *Single Carrier FDMA: A New Air Interface for Long Term Evolution*, Wiley, 2008.