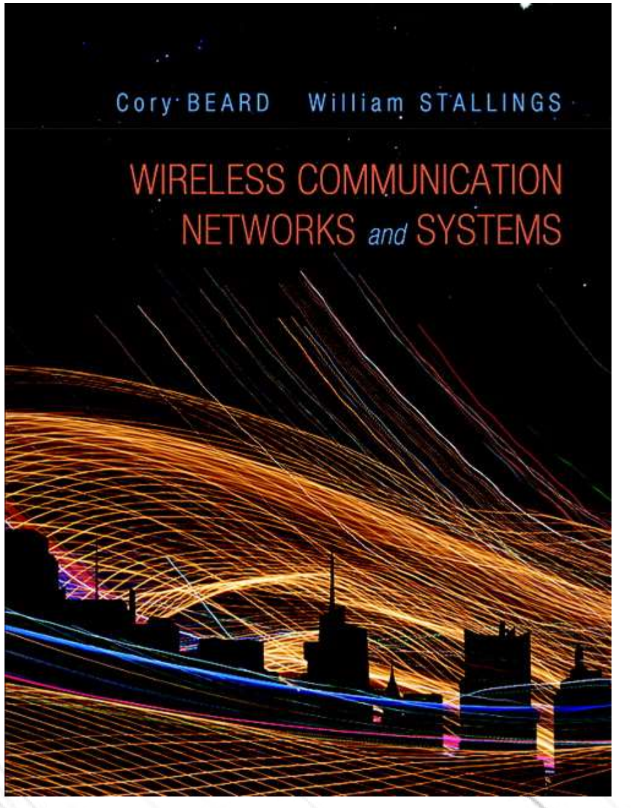
CHAPTER 8
ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM)



Wireless Communication Networks and Systems

1st edition

Cory Beard, William Stallings

INTRODUCTION

- OFDM created great expansion in wireless networks
  - Greater efficiency in bps/Hz
- Main air interface in the change from 3G to 4G
  - Also expanded 802.11 rates
- Critical technology for broadband wireless access
  - WiMAX

HOW OFDM WORKS

- Also called multicarrier modulation
- Start with a data stream of R bps
  - Could be sent with bandwidth Nf_b
  - With bit duration $1/R$
- OFDM splits into N parallel data streams
  - Called *subcarriers*
  - Each with bandwidth f_b
  - And data rate R/N (bit time N/R)

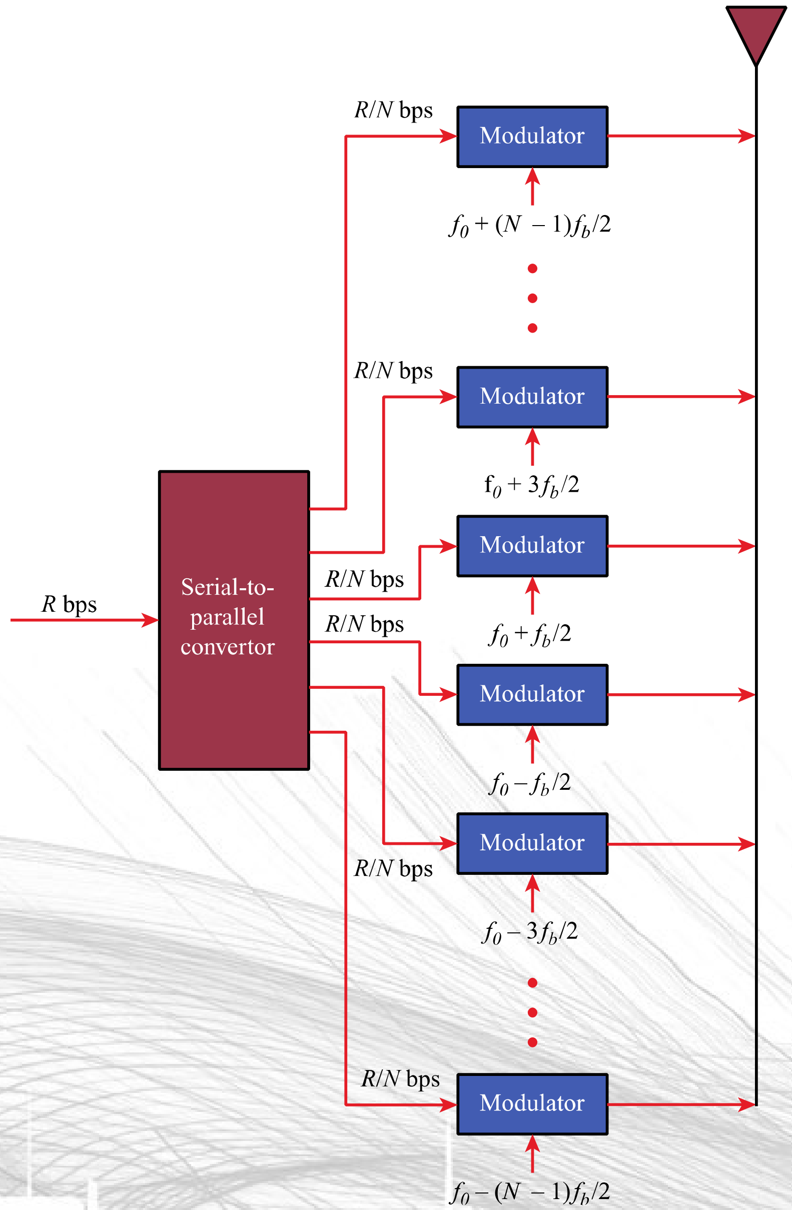
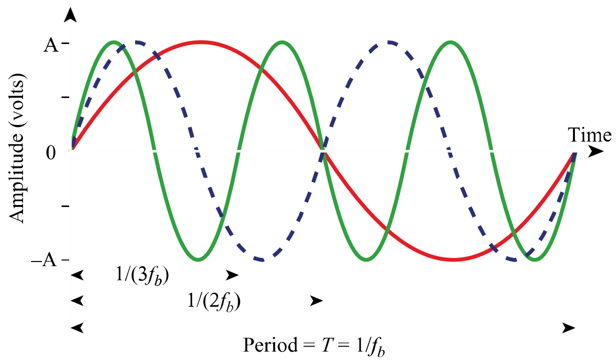


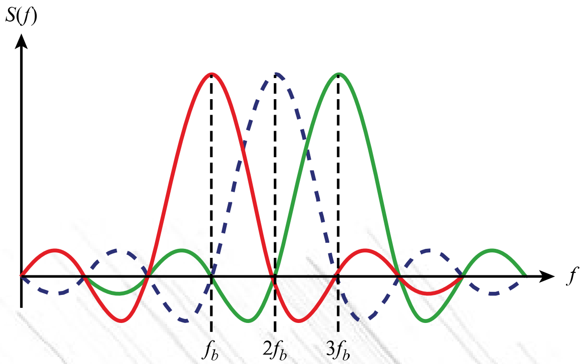
FIGURE 8.1 CONCEPTUAL UNDERSTANDING OF ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

ORTHOGONALITY

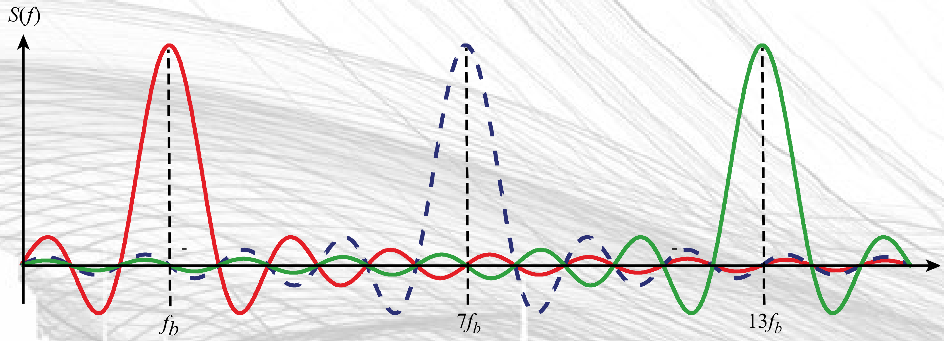
- The spacing of the f_b frequencies allows tight packing of signals
  - Actually with overlap between the signals
  - Signals at spacing of f_b ,$2f_b$, $3f_b$,etc.
- The choice of f_b is related to the modulation symbol rate to make the signals *orthogonal*
  - Average over symbol time of $s_1(t) \times s_2(t) = 0$
  - Receiver is able to extract only the $s_1(t)$ signal
    - If there is no corruption in the frequency spacing
- Traditional FDM makes signals completely avoid frequency overlap
  - OFDM allows overlap which greatly increases capacity



(a) Three subcarriers in time domain



(b) Three orthogonal subcarriers in frequency domain



(c) Three carriers using traditional FDM

FIGURE 8.2 ILLUSTRATION OF ORTHOGONALITY OF OFDM

ORTHOGONALITY

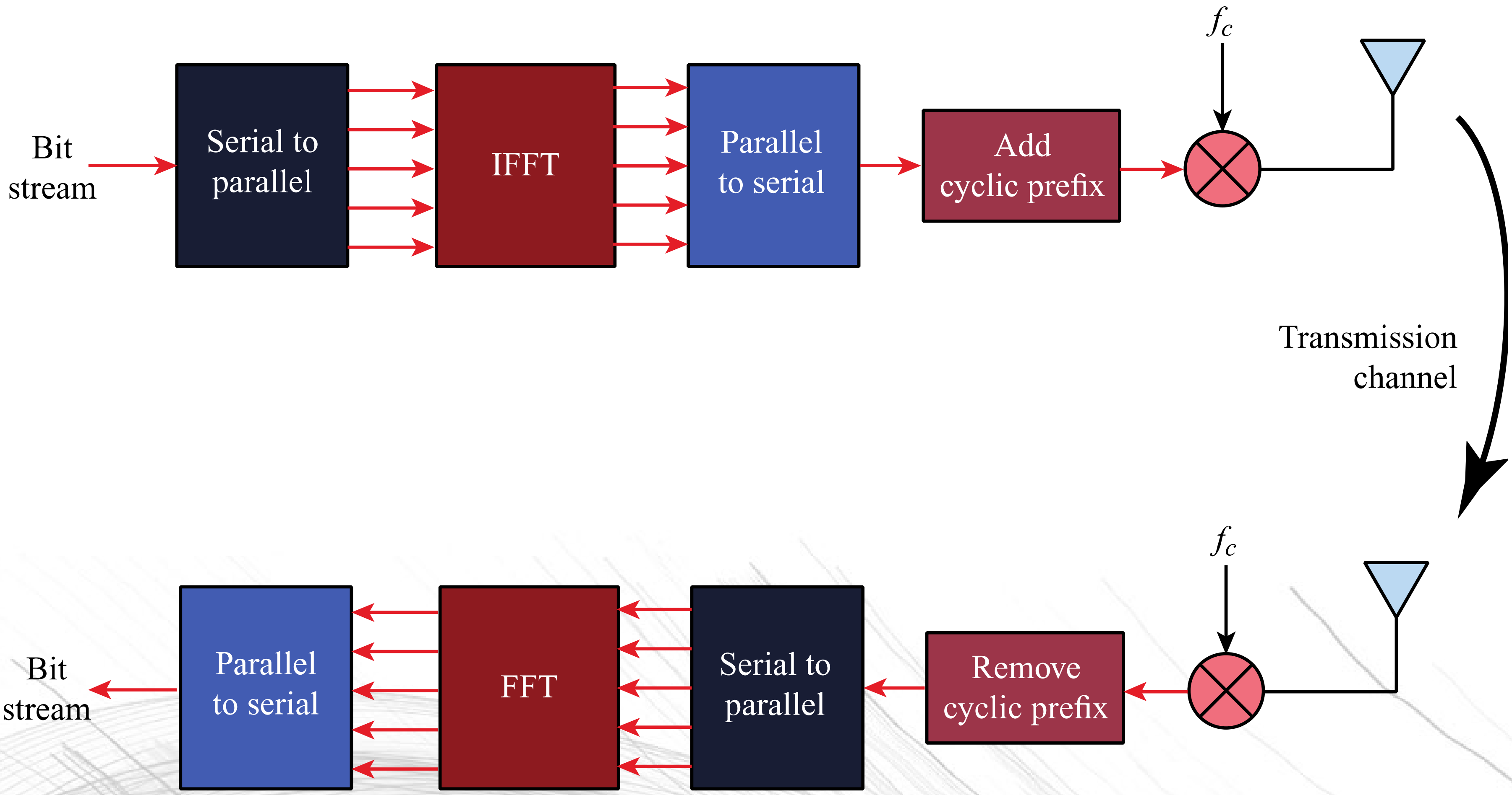
- Given an OFDM subcarrier symbol time of T
  - f_b must be a multiple of $1/T$
- Example: IEEE 802.11n wireless LAN
  - 20 MHz total bandwidth
    - Only 15 MHz can be used
  - 48 subcarriers
  - $f_b = 0.3125$ MHz
  - Signal is translated to 2.4 GHz or 5 GHz bands

BENEFITS OF OFDM

- Frequency selective fading only affects some subcarriers
  - Can easily be handled with a forward error-correcting code
- More importantly, OFDM overcomes intersymbol interference (ISI)
  - ISI is a caused by multipath signals arriving in later bits
  - OFDM bit times are much, much longer (by a factor of *N*)
    - ISI is dramatically reduced
  - *N* is chosen so the root-mean-square delay spread is significantly smaller than the OFDM bit time
  - It may not be necessary to deploy equalizers to overcome ISI
    - Eliminates the use of these complex and expensive devices.

OFDM IMPLEMENTATION

- Inverse Fast Fourier Transform (IFFT)
  - The OFDM concept (Figure 8.1) would use *N* oscillators for *N* different subcarrier frequencies
    - Expensive for transmitter and receiver
  - Discrete Fourier Transform (DFT) processes digital signals
    - If *N* is a power of two, the computational speed dramatically improves by using the fast version of the DFT (FFT).
  - Transmitter takes a symbol from each subcarrier
    - Makes an *OFDM symbol*
    - Uses the Inverse FFT to compute the data stream to be transmitted
    - OFDM symbol provides the weights for each subcarrier
    - Then it is sent on the carrier using *only one oscillator*

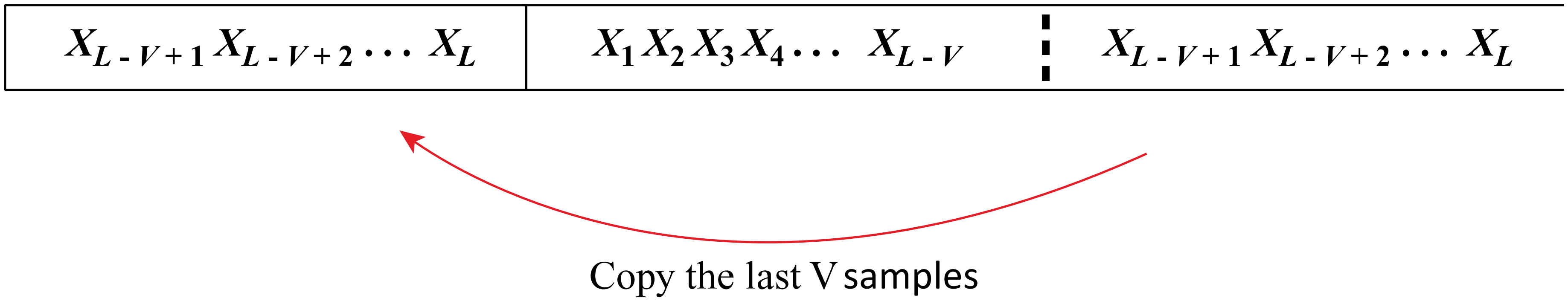


FFT = fast Fourier transform
IFFT = inverse fast Fourier transform

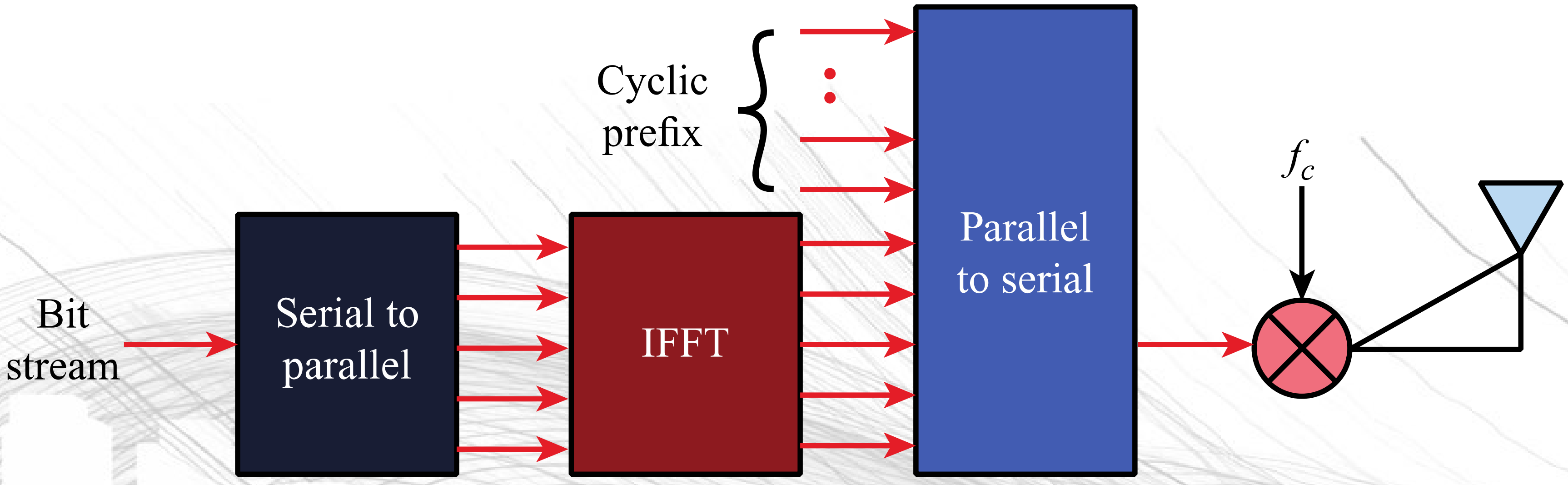
FIGURE 8.3 IFFT IMPLEMENTATION OF OFDM

CYCLIC PREFIX

- OFDM's long bit times eliminate most of the ISI
- OFDM also uses a *cyclic prefix* (CP) to overcome the residual ISI
  - Adds additional time to the OFDM symbol before the real data is sent
    - Called the *guard interval*
    - ISI diminishes before the data starts
  - Data from the end of the OFDM symbol is used as the CP
    - Simplifies the computations



(a) OFDM Symbol Format



(b) OFDM Block Diagram Showing Cyclic Prefix

FIGURE 8.4 CYCLIC PREFIX

DIFFICULTIES OF OFDM

- Peak-to-average power ratio (PAPR)
  - For OFDM signals, this ratio is much higher than for single-carrier signals
  - OFDM signal is a sum of many subcarrier signals
    - Total can be very high or very low
- Power amplifiers need to amplify all amplitudes equally

$$V_{out} = KV_{in}$$

  - Should have a linear characteristic with slope K on a V_{out} vs. V_{in} curve
  - Yet practical amplifiers have limited linear ranges
    - Causing distortion if outside the linear range

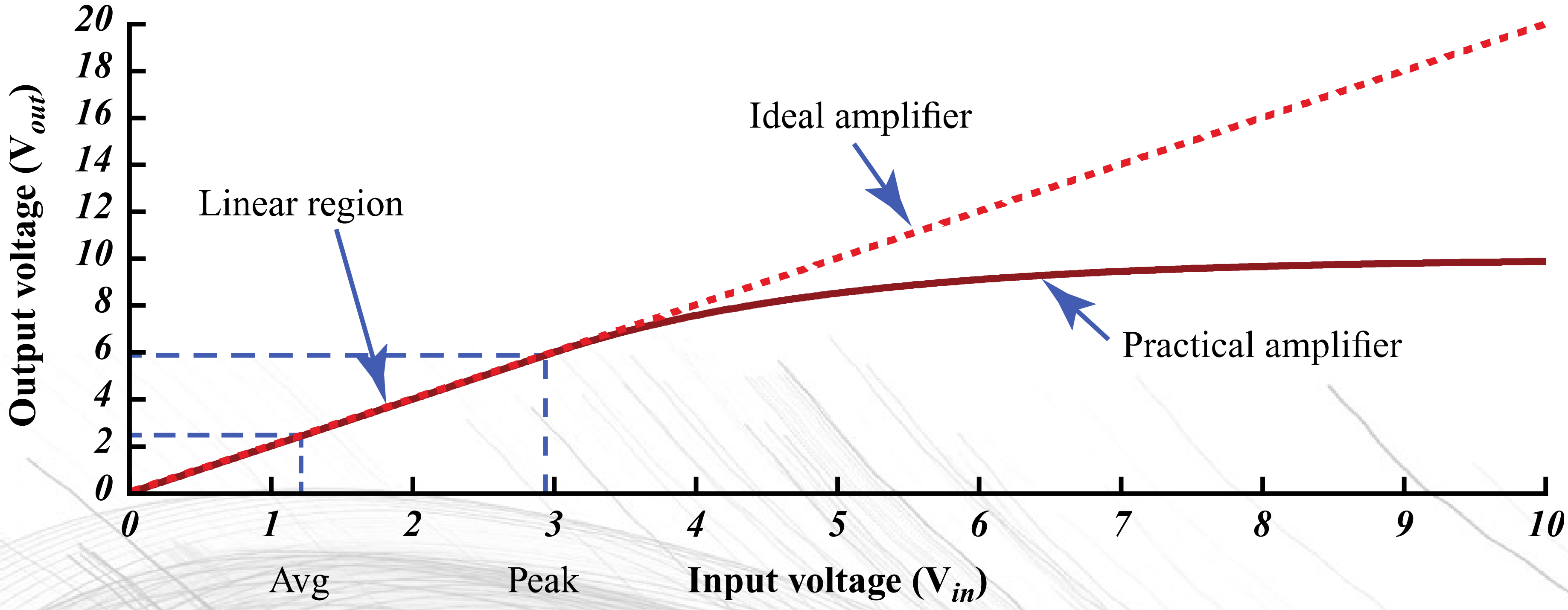


FIGURE 8.5 IDEAL AND PRACTICAL AMPLIFIER CHARACTERISTICS

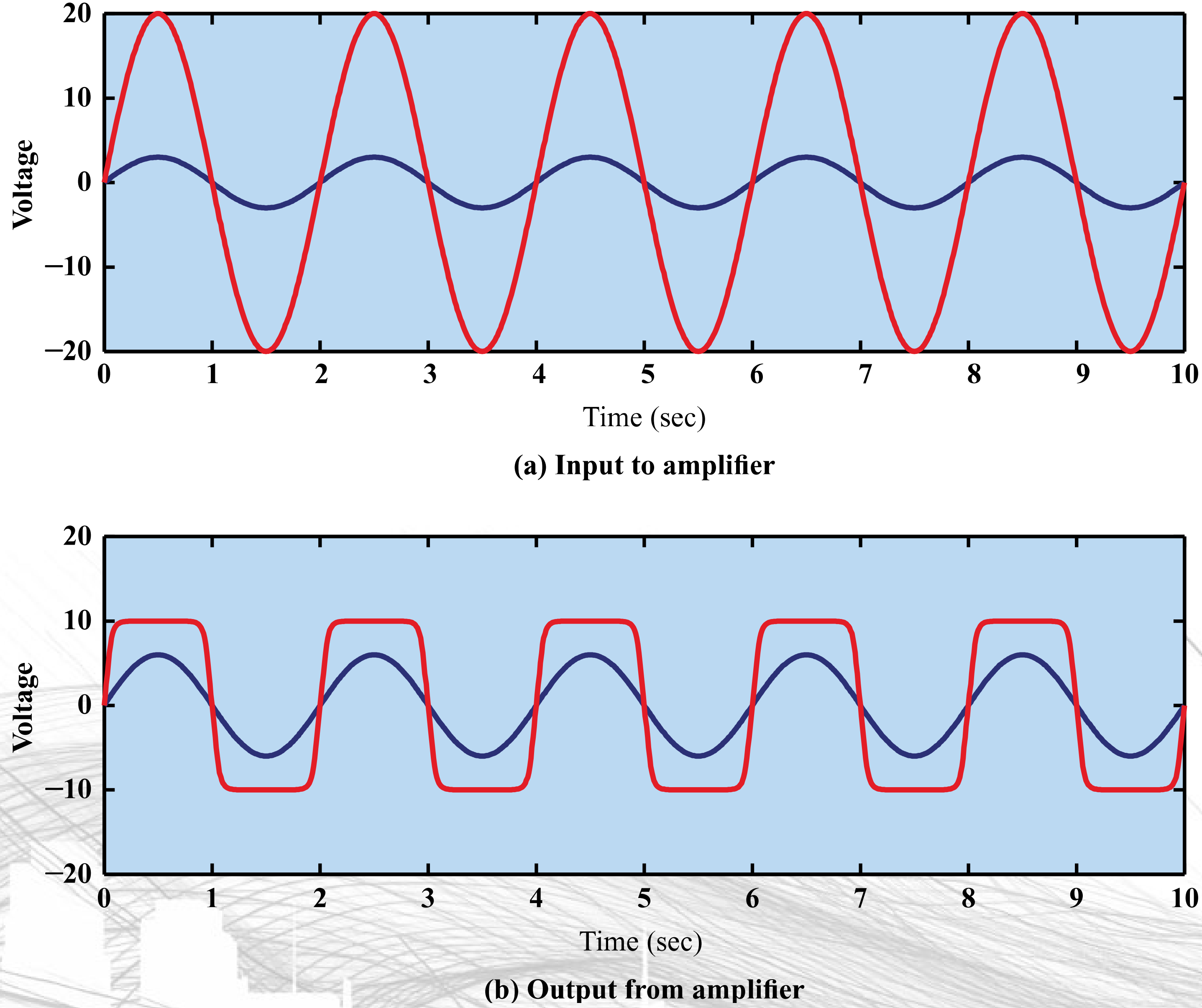


FIGURE 8.6 EXAMPLES OF LINEAR AND NONLINEAR AMPLIFIER OUTPUT

DIFFICULTIES OF OFDM

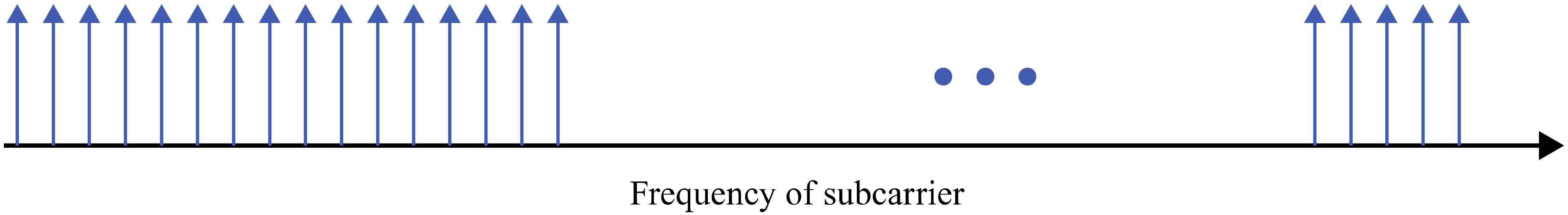
- PAPR problem (continued)
  - Expensive amplifiers have wide linear range
- Solutions
  - Could reduce the peak amplitude
    - Called *input backoff*
    - But this would increase the signal to interference plus noise ratio (SINR)
      - Noise and interference would be relatively stronger because signal is weaker
  - Specific PAPR reduction techniques can be used
    - Specialized coding, phase adjustments, clipping, etc.
    - Single-carrier FDMA (SC-FDMA)

DIFFICULTIES OF OFDM

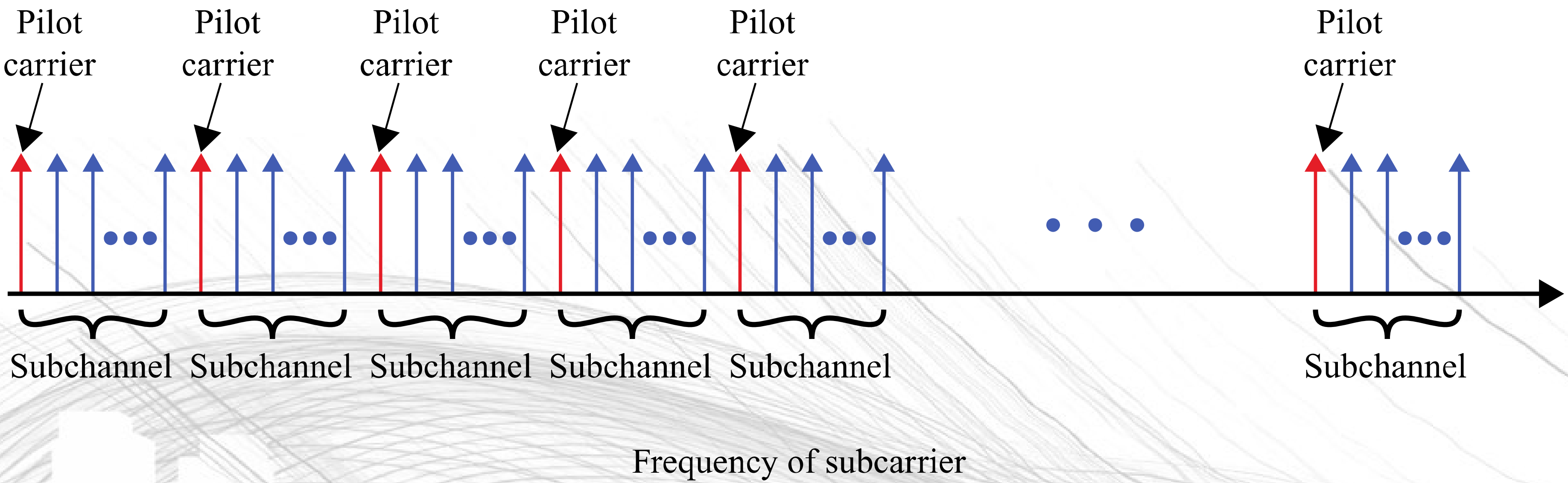
- Intercarrier Interference (ICI)
  - OFDM frequencies are spaced very precisely
  - Channel impairments can corrupt this
  - Cyclic prefix helps reduce ICI
    - Larger CP allows broader subcarrier bandwidth
    - But CP time should be limited so as to improve spectral efficiency
    - A certain level of ICI may be tolerated to have smaller CPs
  - Doppler spread, mismatched oscillators, or even one subcarrier can cause ICI
    - Spacing between subcarriers may need to be increased
    - Could also use different pulse shapes, self-interference cancellation, or frequency domain equalizers.

OFDMA

- Orthogonal Frequency Division Multiple Access (OFDMA) uses OFDM to share the wireless channel
  - Different users can have different slices of time and different groups of subcarriers
  - Subcarriers are allocated in groups
    - Called subchannels or resource blocks
    - Too much computation to allocate every subcarrier separately
- Subchannel allocation
  - Adjacent subcarriers – similar SINR
    - Must measure to find the best subchannel
  - Regularly spaced subcarriers – diverse SINR
  - Randomly space subcarriers – diverse SINR and reduced adjacent-cell interference



(a) OFDM



(b) OFDMA (adjacent subcarriers)

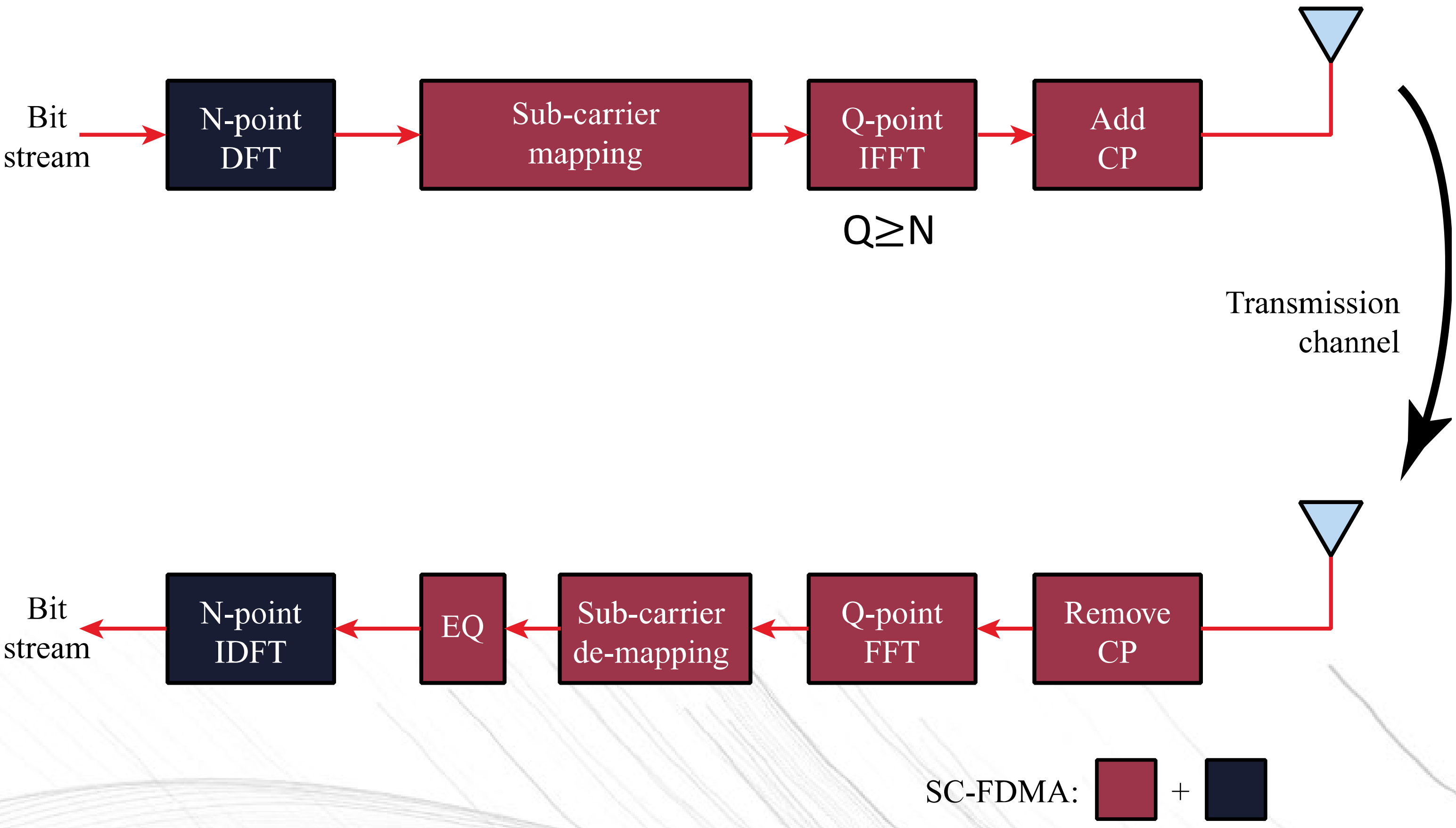
FIGURE 8.7 OFDM AND OFDMA

OPPORTUNISTIC SCHEDULING

- Schedule subchannels and power levels based on
  - Channel conditions
  - Data requirements
- Adjust in a dynamic fashion
  - Use channel variations as an opportunity to schedule the best choice in users
    - Hence the term *opportunistic scheduling*
  - Criteria (maybe more than one used simultaneously)
    - System efficiency – pick users with best throughput
    - Fairness – proportional fairness considers the ratio of users' current rates to the users' average rates to know when a channel is best *for them*
    - Requirements – audio, video
    - Priority – public safety, emergency, or priority customers

SINGLE-CARRIER FDMA

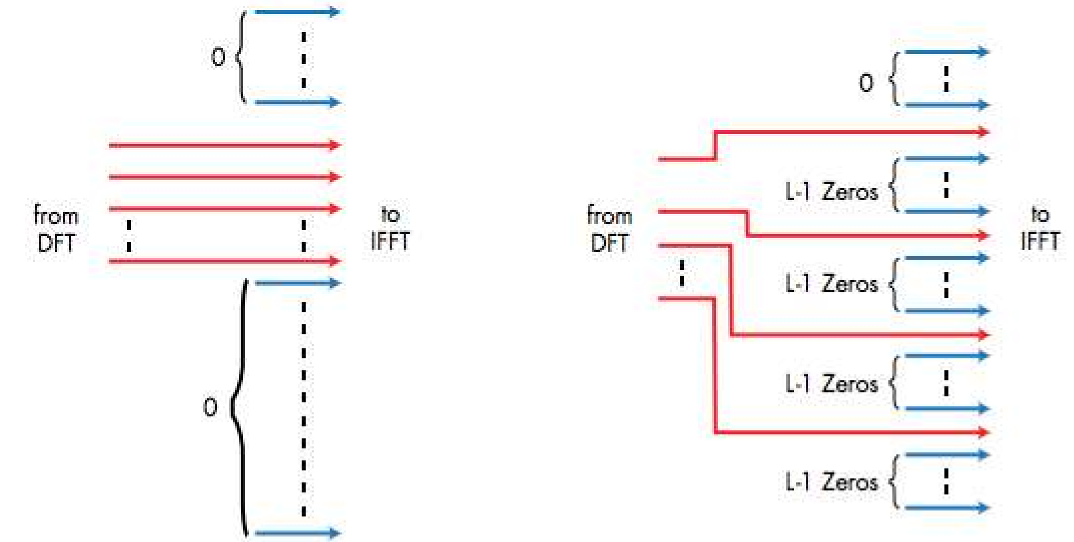
- SC-FDMA has similar structure and performance to OFDMA
  - But lower PAPR
  - Mobile user benefits – battery life, power efficiency, lower cost
  - Good for uplinks
- Uses extra DFT operation and frequency equalization compared to OFDM
  - DFT prior to IFFT
  - Spreads data symbols over all subcarriers
  - Every data symbol is carried by every subcarrier
- Multiple access is possible
  - Subcarrier groups assigned to different users.
  - User transmits in assigned subcarriers treating other users´s subcarriers as nulls.



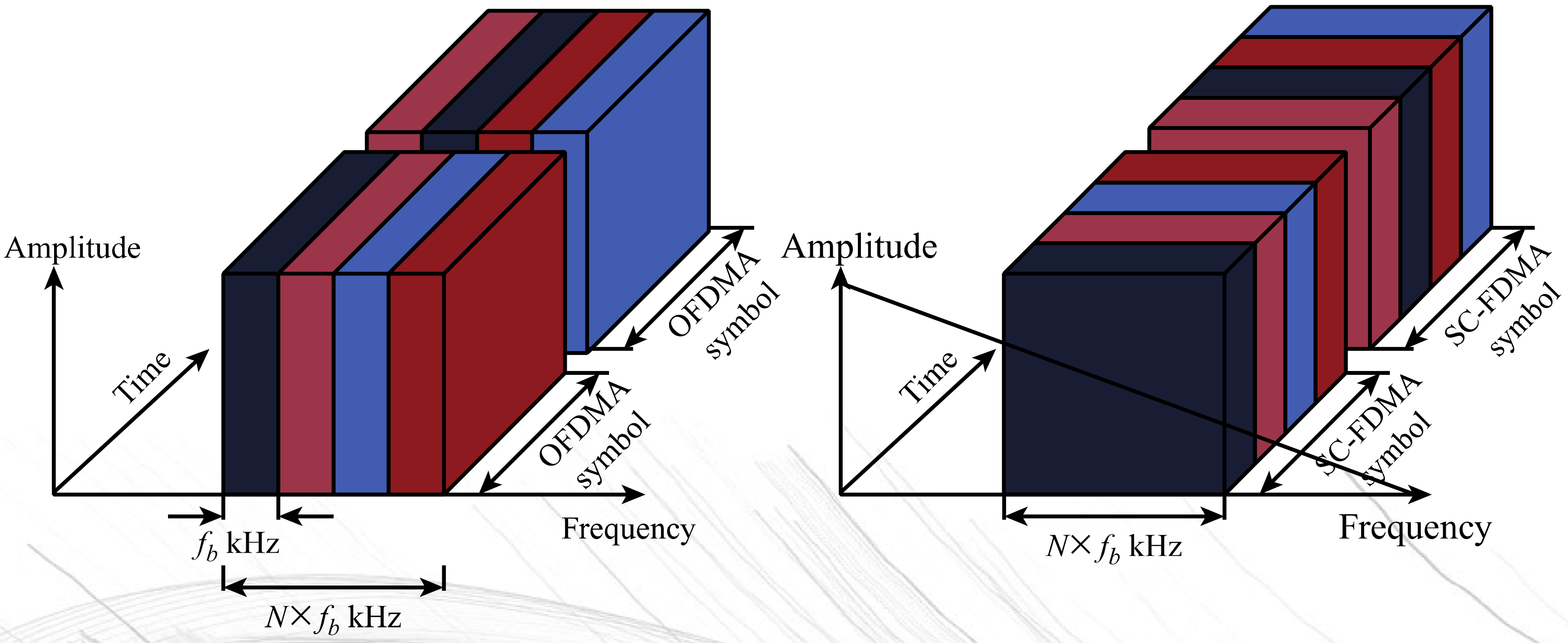
DFT = discrete Fourier transform
IDFT = inverse discrete Fourier transform
FFT = fast Fourier transform
IFFT = inverse fast Fourier transform
EQ = subcarrier equalization
CP = cyclic prefix

FIGURE 8.8 SIMPLIFIED BLOCK DIAGRAM OF OFDMA AND SC-FDMA

SUBCARRIER MAPPING



Subcarriers assigned to one user correspont to nulls in the subcarrier mapping of other users.



(a) OFDMA: Data symbols occupy f_b kHz for one OFDMA symbol period

(b) SC-FDMA: Data symbols occupy $N\times f_b$ kHz for 1/N SC-FDMA symbol period

FIGURE 8.9 EXAMPLE OF OFDMA AND SC-FDMA