MOBILE SYSTEM-HT25 LECTURE 8: ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM)

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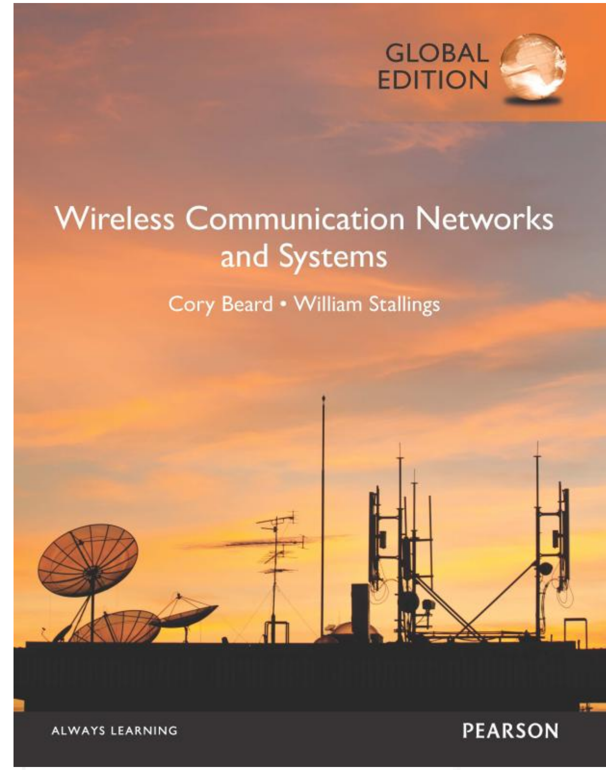
Most slides are primarily adapted from Beard & Stallings (2016), Wireless Communication Networks and Systems (Chapter 8)



Wireless Communication Networks and Systems
1st edition, Global edition
Cory Beard, William Stallings

WHERE WE ARE IN THE COURSE

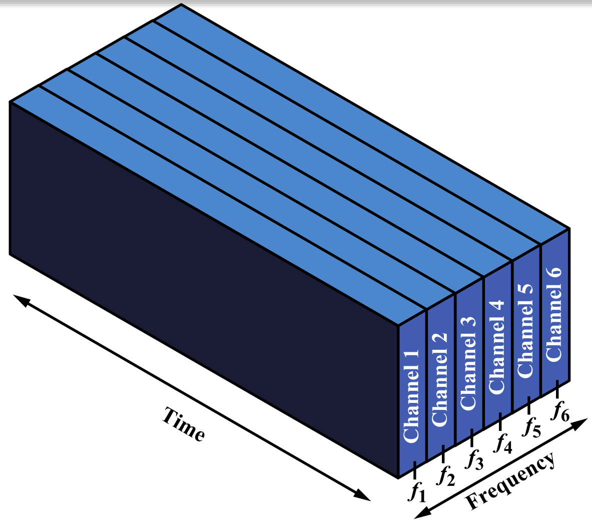
- Evolution of Wireless Communication, Transmission fundamentals, Analog and Digital Modulations (Lectures 2-4)
- The Wireless Channel (Lectures 5 and 6)
- Transmission Fundamentals (CTFT, DTFT) (Lecture 7)
- Orthogonal Frequency Division Multiplexing- OFDM (Lecture 8)
- Spread Spectrum (Lecture 10)
- Coding and Error Control (Lecture 11)
- Cellular Wireless Networks (Lecture 12)
- Short-Range Wireless Technologies & Applications of Wireless Technologies in IoT (Lecture 13)

OUTLINE

- Introduction
- Multiplexing, FDM
- How OFDM Works (DT I)
- How to Implement OFDM Efficiently?, IFFT/FFT
- Cyclic Prefix (DT II)
- Difficulties of OFDM
- OFDMA

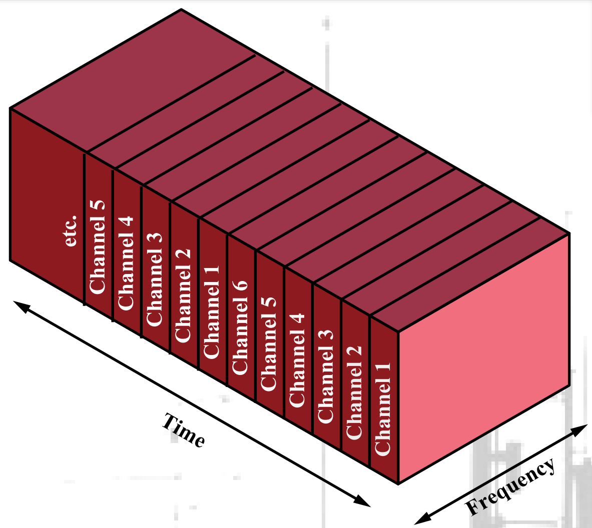
INTRODUCTION

- OFDM created great expansion in wireless networks
  - Greater spectral efficiency in bps/Hz
  - Reduced intersymbol interference (low ISI)
  - Improved error performance
- Main air interface in the change from 3G to 4G
  - Also expanded 802.11 rates
- Critical technology for broadband wireless access
  - WiMAX



(a) Frequency division multiplexing

REMINDER



(b) Time division multiplexing

2.12 FDM AND TDM

MULTIPLEXING

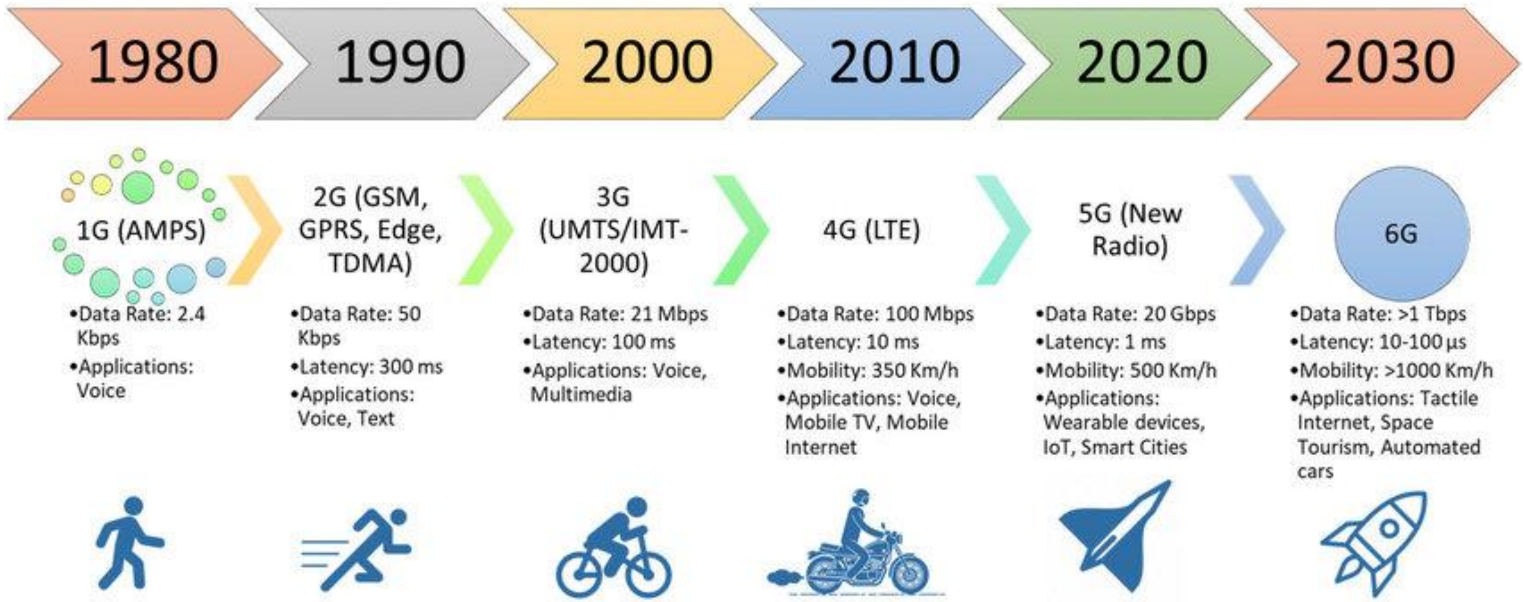
Multiplexing is a technique used in communication systems to allow multiple signals to share one communication channel by dividing the channel in frequency, time, or code.

- In FDM → signals share the channel at the same time but on different frequencies.
- In TDM → signals share the channel at different times, not simultaneously.
- In CDM (CDMA) → signals share the channel at the same time and same frequency, but with different codes

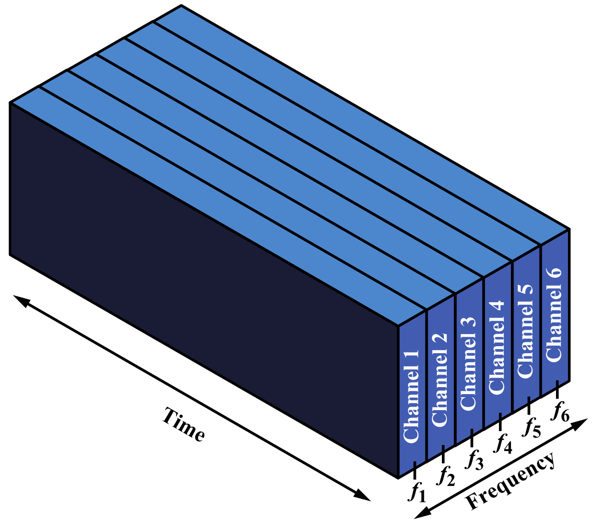
Lecture 10

EVOLUTION OF CELLULAR MOBILE COMMUNICATION SYSTEMS

https://www.researchgate.net/figure/Wireless-Communication-Evolution_fig1_353039842



- **FDMA (Frequency Division Multiple Access):**
  Based on **FDM**, where each user is assigned a unique frequency band.
  Common in **analog systems** such as **1G cellular networks**.
- **TDMA (Time Division Multiple Access):**
  Based on **TDM**, where each user transmits in an assigned **time slot** on the same frequency.
  Used in **GSM (2G)**, which combines **FDMA + TDMA**.



(a) Frequency division multiplexing

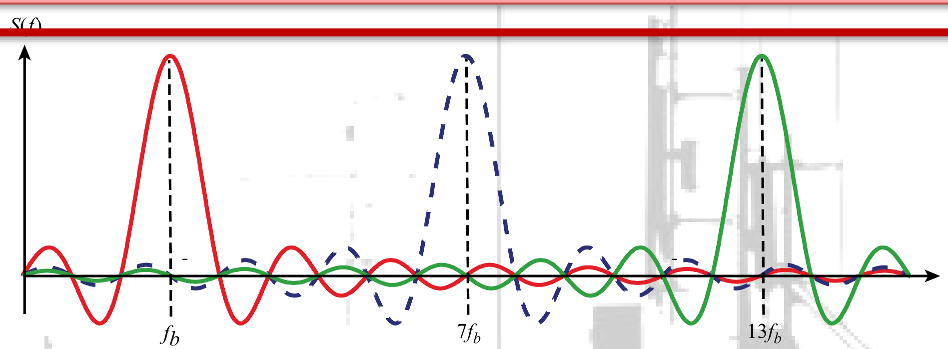
In FDM, multiple users (or signals) are each assigned their own carrier frequency (or subband) and transmitted simultaneously.

So if you have 6 bands, you literally have 6 carriers → multiple carriers

FDM

FDM subcarriers do not overlap
They are separated by guard bands to prevent inter-channel interference.
A guard band (often just called a guard) is a small unused frequency range placed between two adjacent bands
to prevent interference.

OFDM is similar to FDM in that it uses multiple carriers, but in OFDM the subcarriers can overlap without causing interference due to their orthogonality.



(c) Three carriers using traditional FDM

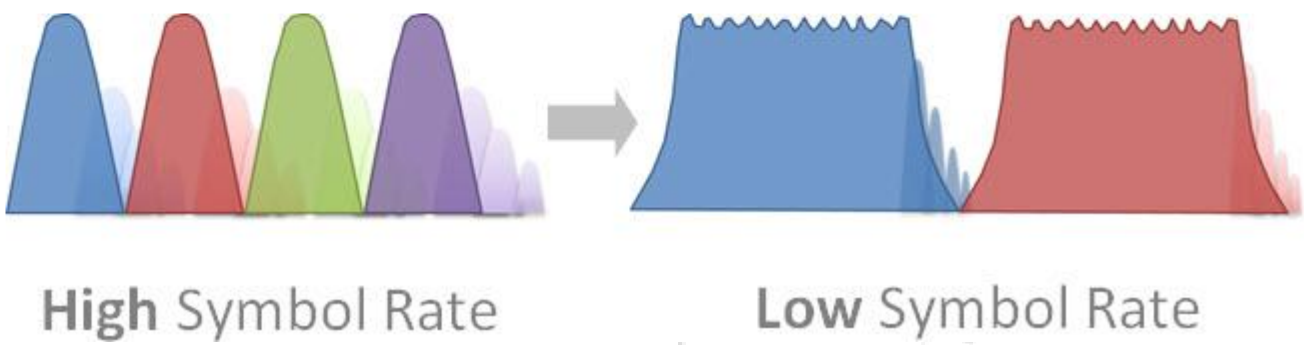
HOW OFDM WORKS

- Also called multicarrier modulation
- In Single-carrier modulation with a data stream of R bps
  - With bit duration $1/R$
  - Could be sent with bandwidth Nf_b
- OFDM splits into N parallel data streams
  - Called *subcarriers*
  - And data rate R/N for each *subcarriers* (bit time N/R)
  - Each with an effective bandwidth of f_b; the **total occupied bandwidth** is approximately $N f_b$**, but the subcarriers overlap spectrally** and are **orthogonal**, not separated.

Symbol duration per subcarrier

OFDM CAN ACHIEVE HIGHER DATA RATE (SAME SIGNAL DURATION)

OFDM splits the signal into N **slow subcarriers**
→ long symbol time → low ISI



https://www.telecomhall.net/t/what-is-isi-inter-symbol-interference-in-lte/6370#google_vignette

→ can use **higher-order modulation per subcarrier**

Higher spectral efficiency and higher data rate for the same signal length

ORTHOGONALITY

- f_b is the effective **bandwidth per subcarrier and also subcarrier spacing and**

$$f_b = \frac{1}{T}$$

  Where T is the useful OFDM symbol duration, the signals are *orthogonal.*

- Average over bit 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

ORTHOGONALITY

- **Take the received signal** (sum of many subcarriers):

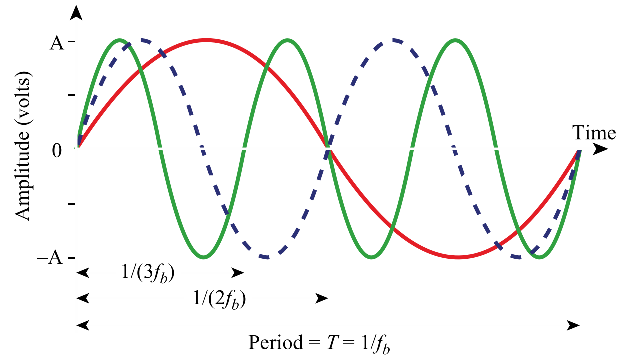
$$r(t) = \sum_{k=0}^{N-1} s_k\,(t)$$

- **Multiply** by a reference subcarrier (say $s_2(t)$)
- **Integrate over one symbol period** (matched filter or FFT equivalent)

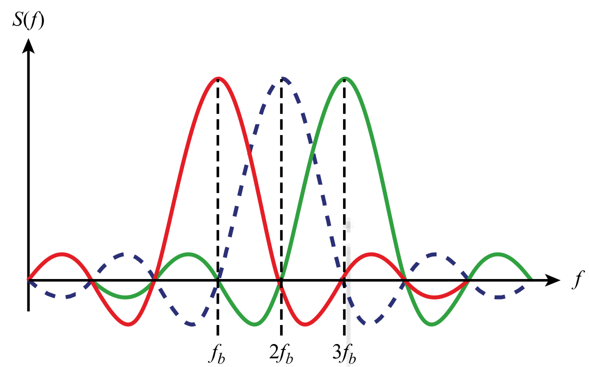
$$\int_0^T r\,(t) \cdot s_2(t)\,dt = \int_0^T \left(s_2(t) + \sum_{k \neq 2} s_k\,(t) \right) s_2(t)\,dt$$

Because of orthogonality:

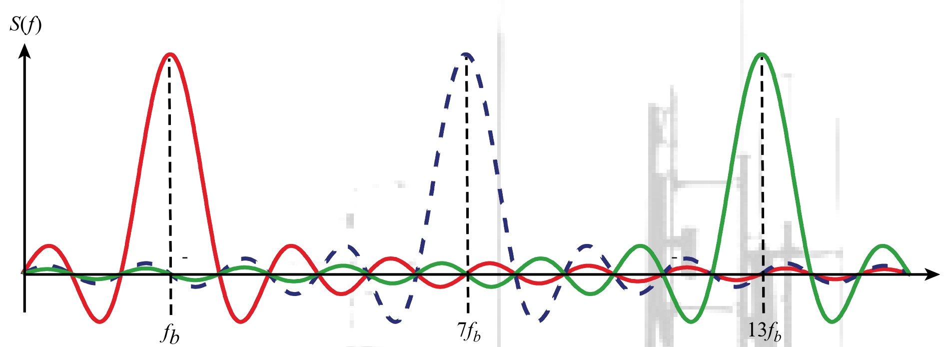
$$= \int_0^T s_2\,(t)^2\,dt \;\textit{(desired signal)}$$



(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

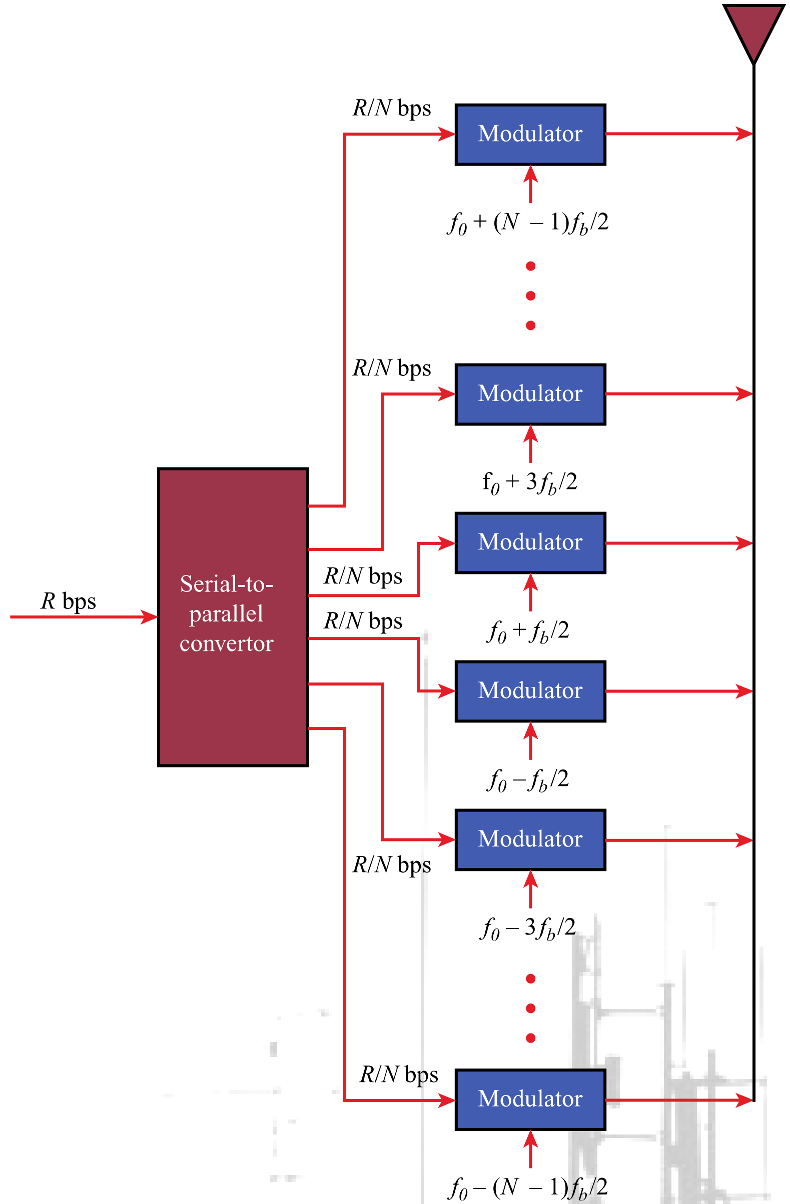
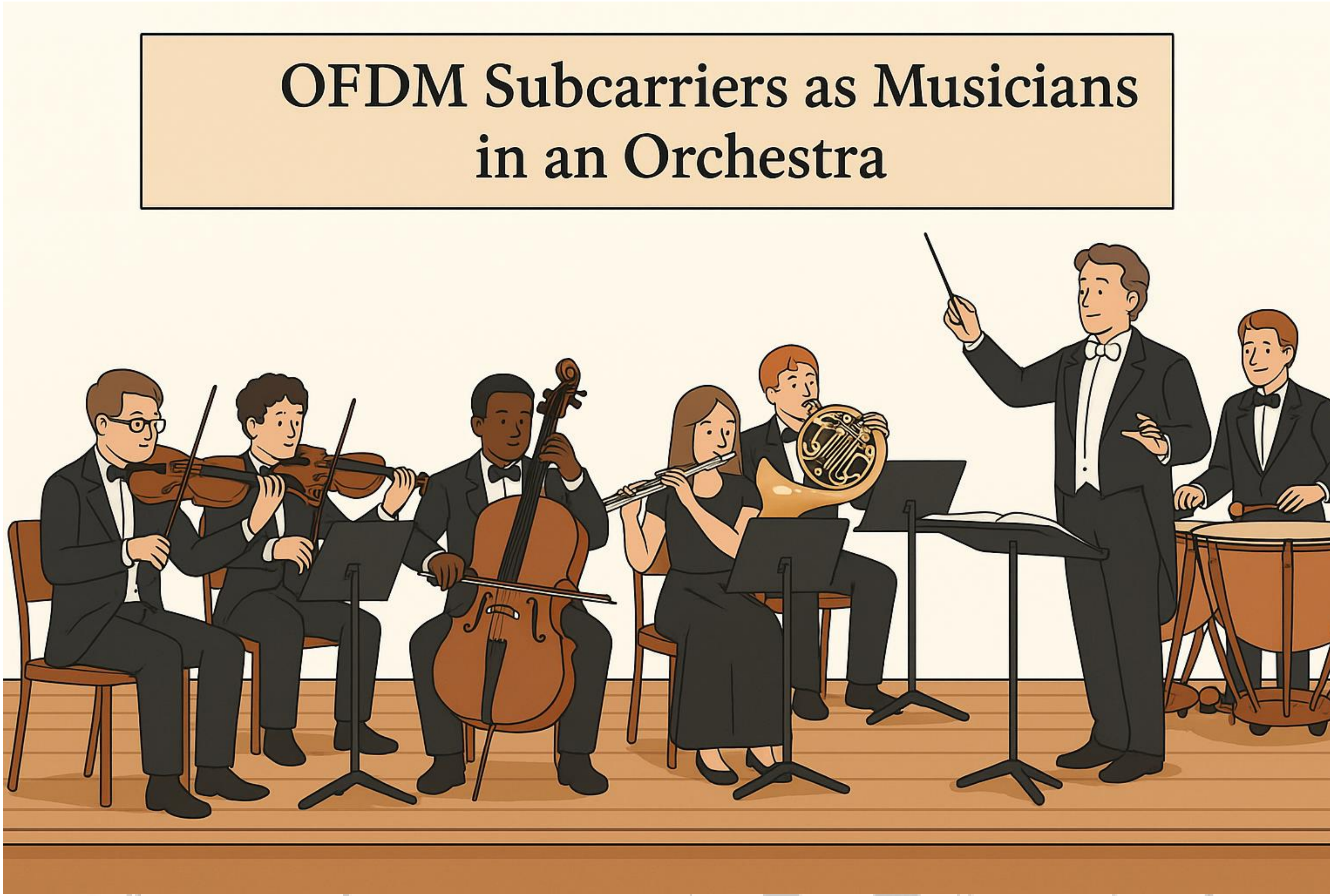


FIGURE 8.1 CONCEPTUAL UNDERSTANDING OF ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING


OFDM Subcarriers as Musicians
in an Orchestra

DISCUSSION TIME I

You've learned that OFDM and FDM both use multiple carriers to send data.

Now discuss in your group:

- **How are OFDM and FDM similar?**
- **How are they different?**
  - Think about **bandwidth usage and spectral efficiency**, **orthogonality**, **guard bands, ISI, complexity, etc.**

GROUP DISCUSSION – OFDM VS FDM:

1. Similarities

- Both **divide the available spectrum** into multiple frequency channels (subcarriers).
- Both allow **parallel transmission** of data streams across different frequencies.
- Aim: **Efficient bandwidth utilization** and **support for multiple users or data streams**.

GROUP DISCUSSION – OFDM VS FDM:

- FDM separates signals in frequency to avoid interference.
  OFDM makes them **overlap intentionally** but keeps them **mathematically orthogonal**, so they don’t interfere.
  → That’s why OFDM achieves **much higher efficiency** and **robustness** in modern wireless systems.

GROUP DISCUSSION – OFDM VS FDM:

Feature	**FDM**	**OFDM**
Subcarrier spacing	Non-overlapping; separated by guard bands	**Overlapping but orthogonal**
Guard bands	Required (to avoid interference)	Not required (orthogonality ensures no interference)
Bandwidth efficiency	Lower (wastes guard bands)	**Higher** (subcarriers overlap)
Complexity	Simpler analog implementation	But can be implemented efficiently by digital FFT/IFFT processing
ISI (Inter-symbol interference)	To keep the rate high → **shorter symbols** →higher ISI**,** Not handled inherently	**longer symbols** →low ISI**,** **Cyclic prefix** used to mitigate ISI

HOW TO IMPLEMENT OFDM EFFICIENTLY?

- By using FFT and IFFT.
- What are FFT and IFFT?

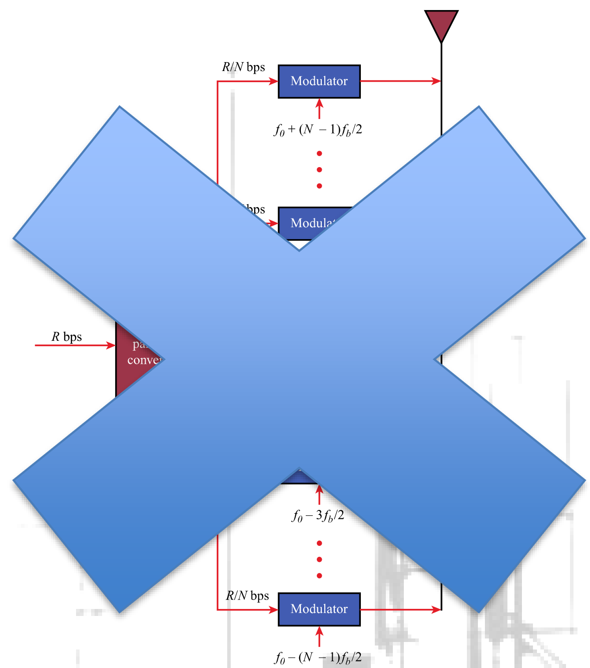


FIGURE 8.1 CONCEPTUAL UNDERSTANDING OF ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

DISCRETE FOURIER TRANSFORM (DFT)

For a sequence s$[n]$with Nsamples:

$$S[k] = \sum_{n=0}^{N-1} s\,[n]\, e^{-j2\pi kn/N} \qquad \text{for } k = 0,1,2,\ldots,N-1$$

a **sampled version** of the DTFT

$$s[n] = \frac{1}{N}\sum_{k=0}^{N-1} S\,[k]\, e^{j2\pi kn/N} \quad \text{for n} = 0,1,2,\ldots,N-1$$

DiscreteTime *domain* $\leftrightarrow$ Discrete *Frequency domain*

$$s[n] \xleftrightarrow{\text{DFT}} S[k]$$

FFT/ IFFT

- **FFT (Fast Fourier Transform)** is just a **fast algorithm** to compute the DFT.
  - If N is a power of two, the computational speed dramatically improves by using the fast version of the DFT (FFT).
- **IFFT** computes the **Inverse DFT** efficiently.

In MATLAB: $\boldsymbol{S}$ = fft($\boldsymbol{s}$,N) , $\boldsymbol{s}$ =ifft($\boldsymbol{S}$,N)

OFDM IMPLEMENTATION

- The OFDM concept (Figure 8.1) would use *N* oscillators for *N* different subcarrier frequencies
  - Expensive for transmitter and receiver

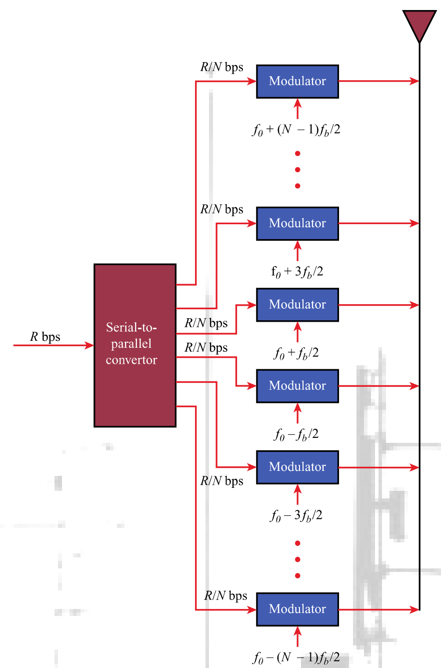
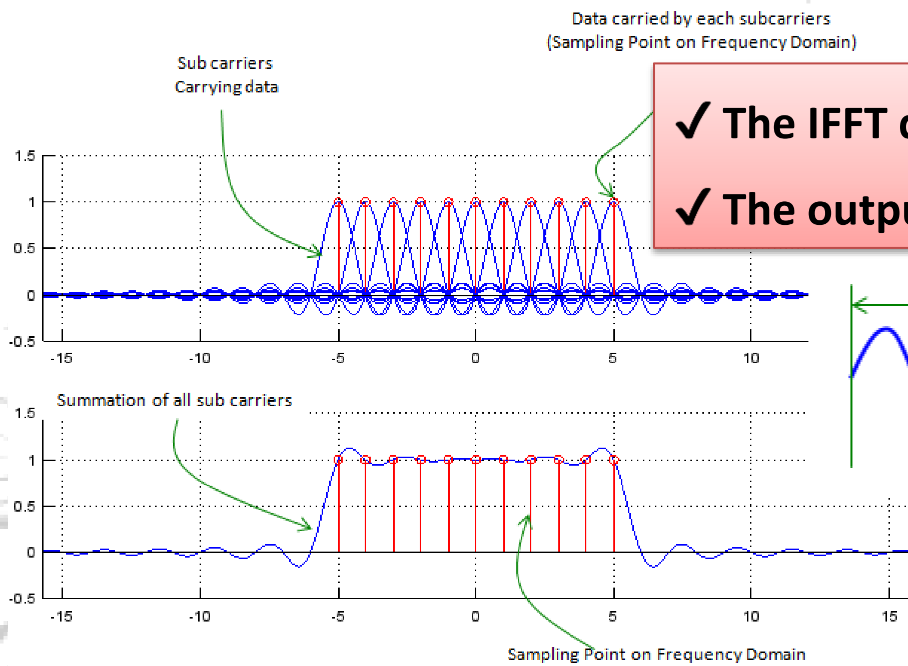


FIGURE 8.1 CONCEPTUAL UNDERSTANDING OF ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

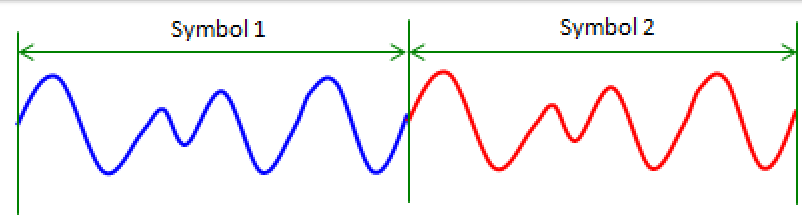
OFDM IMPLEMENTATION

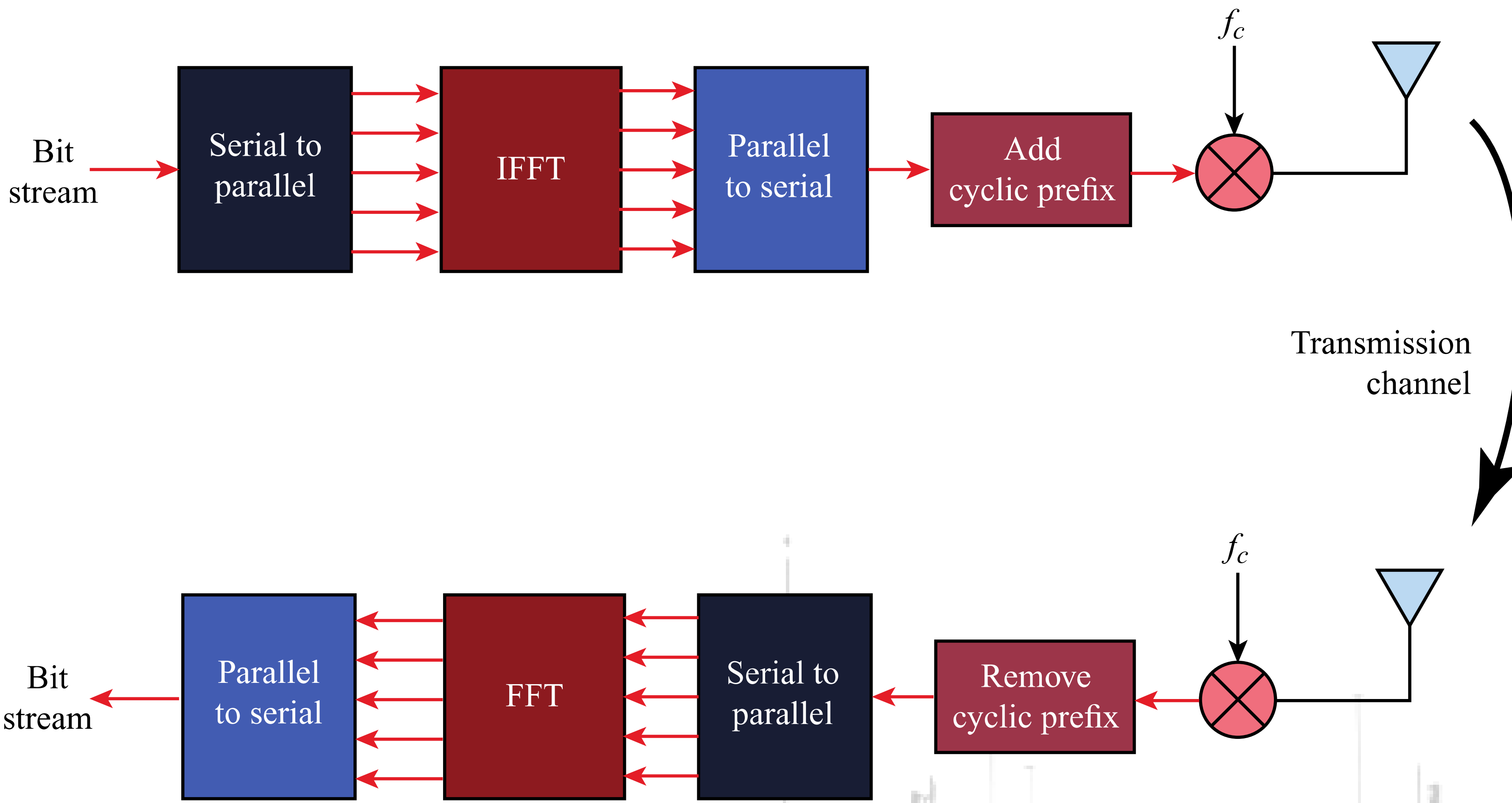
- Transmitter takes a symbol from each subcarrier
  - Makes an *OFDM symbol*
  - Uses the Inverse FFT to compute the data stream to be transmitted
  - Then it is sent on the carrier using *only one oscillator*



✓ The IFFT digitally creates all subcarriers at once

✓ The output is already a single time-domain signal





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

Like adding a buffer in a conversation – a pause before the real message

  - 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

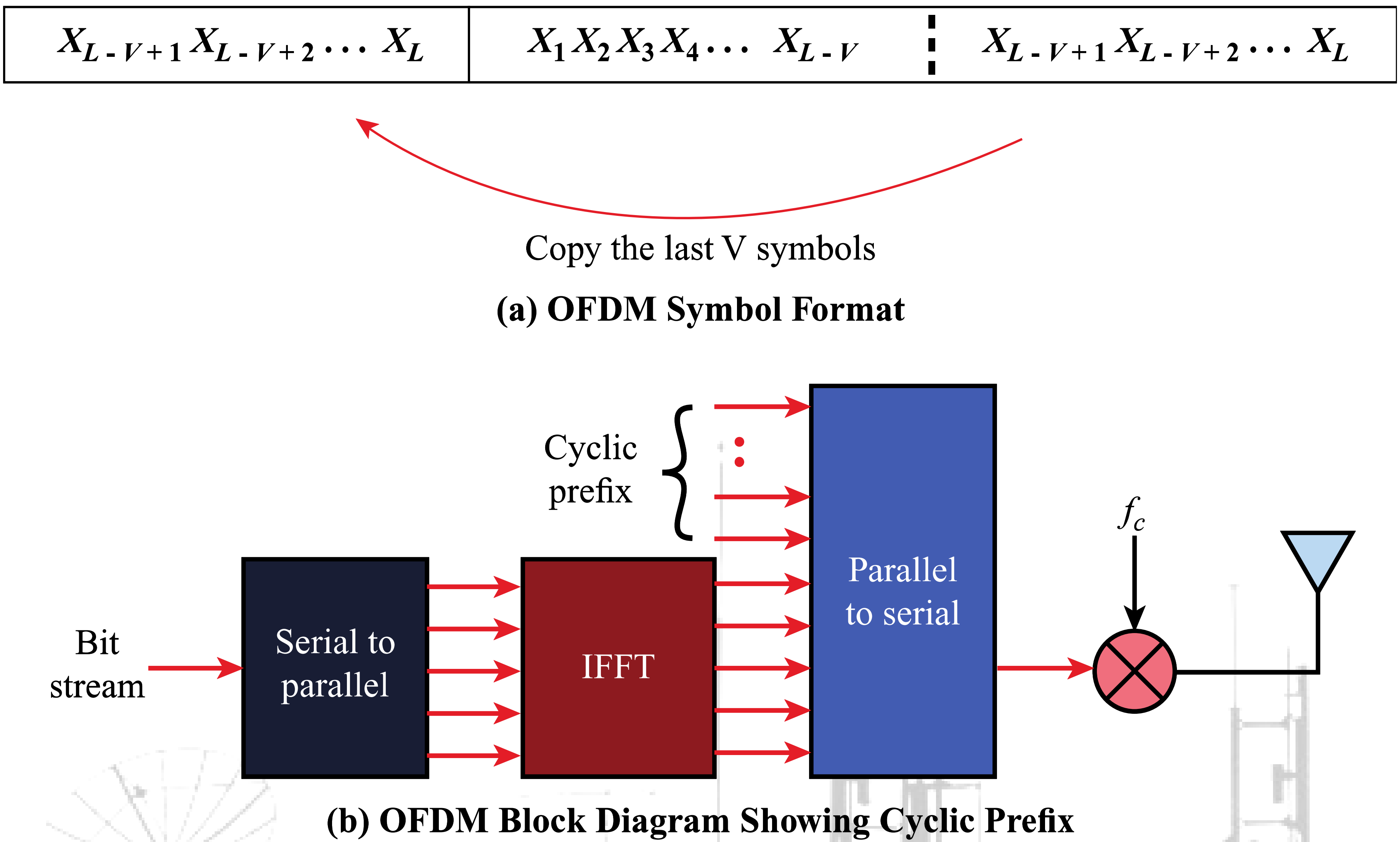


FIGURE 8.4 CYCLIC PREFIX

DISCUSSION III – THE CYCLIC PREFIX TRADE-OFF

The cyclic prefix (CP) helps OFDM fight multipath interference — like adding a short "pause" before each message.

Work in groups: What happens if we make the CP longer or shorter? When would engineers prefer a long CP, and when would they shorten it? Consider environments: indoor Wi-Fi vs. outdoor 4G, fast cars vs. slow users.

CLASS DISCUSSION

Long CP → better ISI protection but lower data rate.
Short CP → higher efficiency but risk of distortion.
It’s a balance between **robustness and spectral efficiency:**

- Use a **long CP** when multipath delays are large — usually in **wide, outdoor, or fast-moving environments**
- Use a **short CP** when multipath is small — usually in **indoor, short-range, slow-moving systems**

DIFFICULTIES OF OFDM

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

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

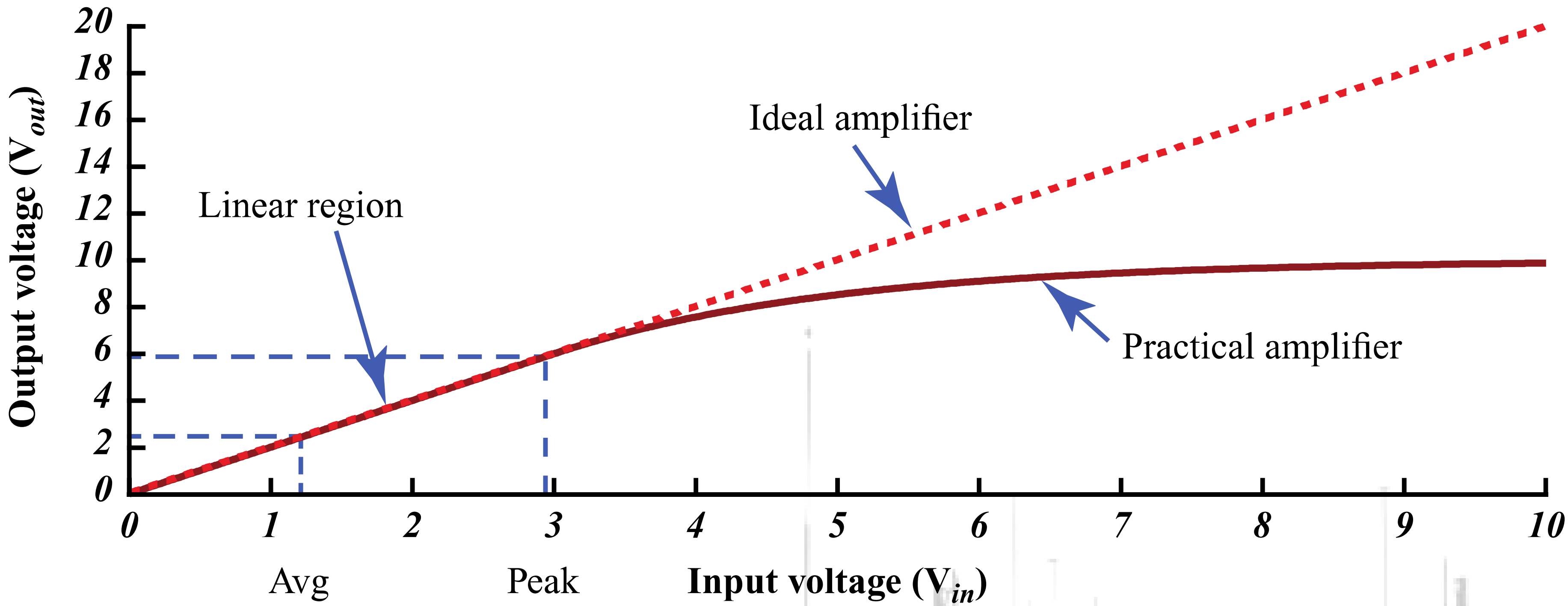
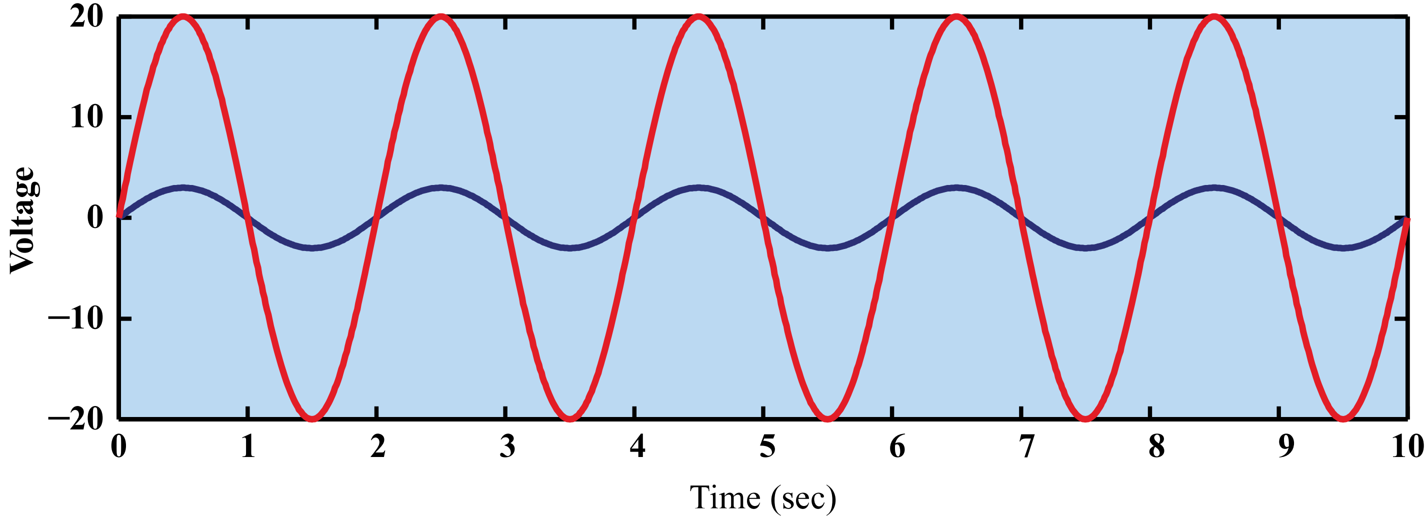
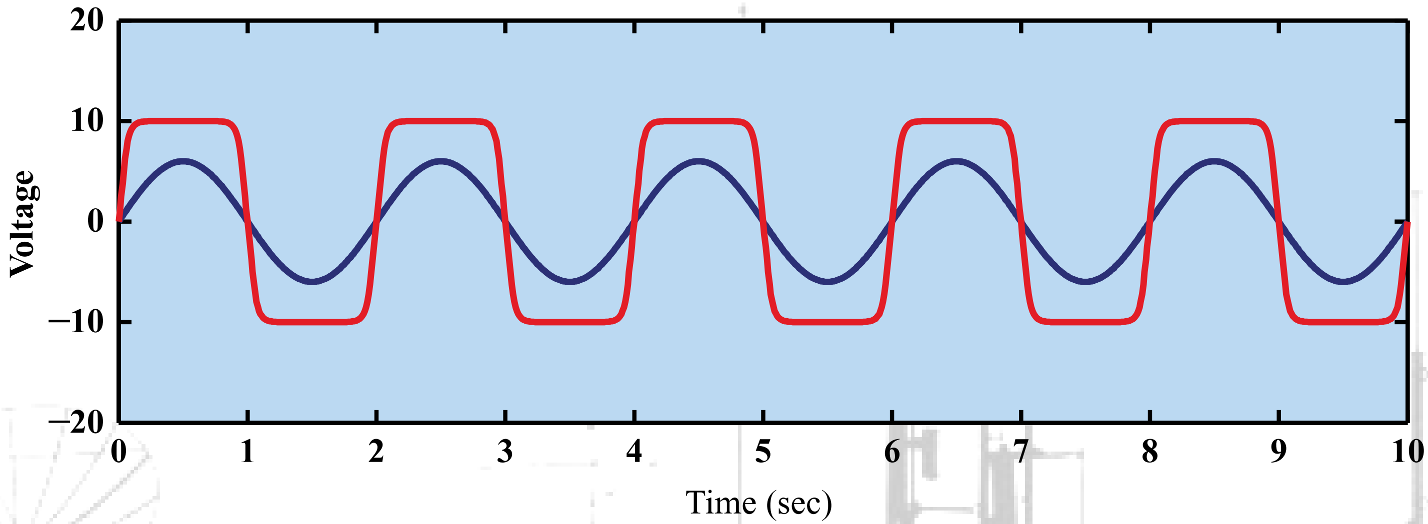


FIGURE 8.5 IDEAL AND PRACTICAL AMPLIFIER CHARACTERISTICS



(a) Input to amplifier

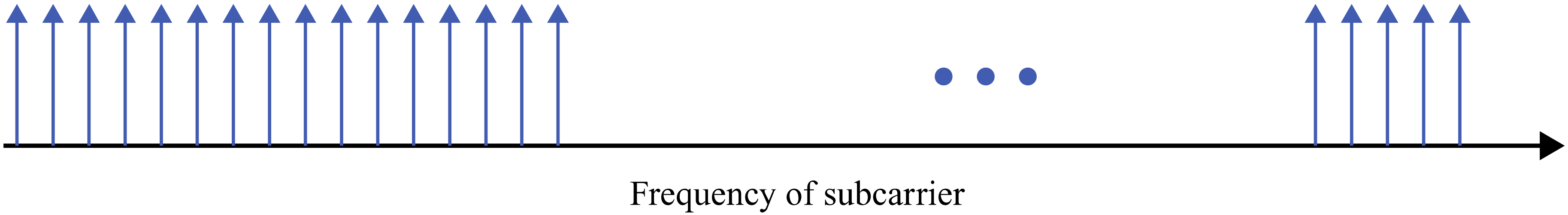


(b) Output from amplifier

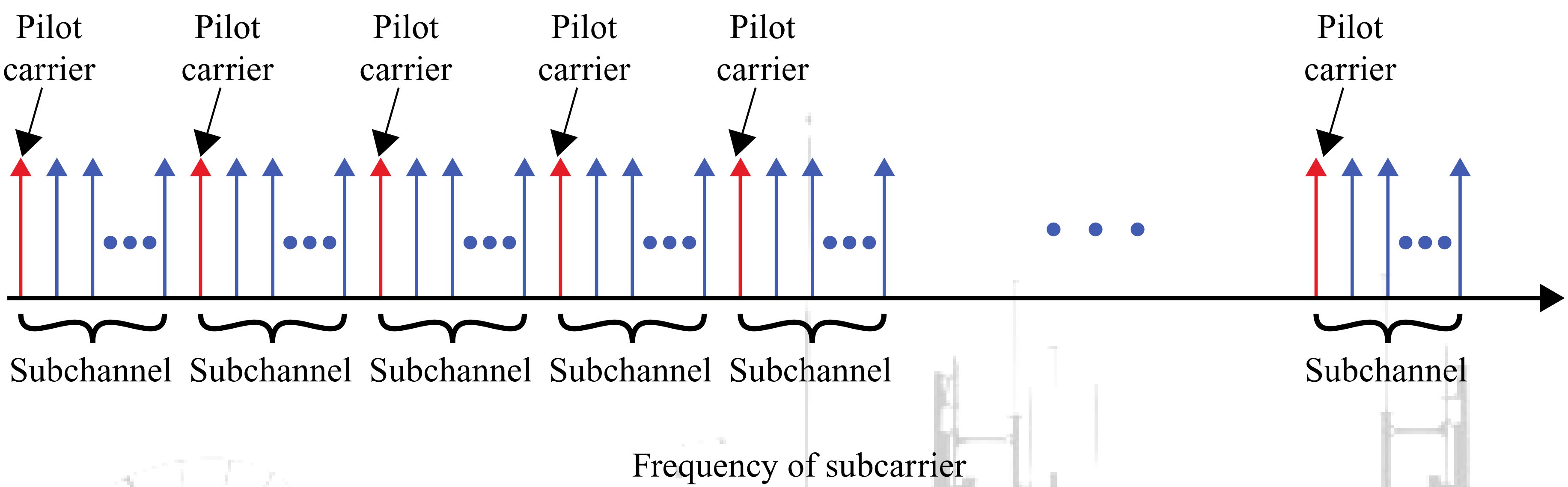
FIGURE 8.6 EXAMPLES OF LINEAR AND NONLINEAR AMPLIFIER OUTPUT

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



(a) OFDM



(b) OFDMA (adjacent subcarriers)

FIGURE 8.7 OFDM AND OFDMA

QUESTIONS?