COMP 3721
Introduction to Data Communications

05b - Week 5 - Part 2

Learning Outcomes

- By the end of this lecture, you will be able to
  - Explain three digital-to-analog conversion techniques.
  - Describe the constellation diagrams.
  - Explain analog-to-analog conversion techniques.

Introduction

- Why do we need D2A and A2A?
- **D2A**:
  - E.g., when you play music on your smartphone and listen through wired headphones, the digital music file is converted into **analog audio signals** by the smartphone's **DAC** before reaching your ears.
- **A2A**:
  - Radio stations broadcast **analog signals** in the form of **continuous electromagnetic waves** that carry audio information, so you can listen to the radio.

Review and Definition of Some Terms

- **Data element** vs **Signal element**
- **Data rate** (**bit rate**) vs **Signal rate** (**baud rate**)
- In analog transmission of digital data, $r = \log_2 L$ (L is the number of different signal elements/levels) and **baud rate** <= **bit rate** ($S = N/r$).

Review and Definition of Some Terms

- **Data element** vs **Signal element**
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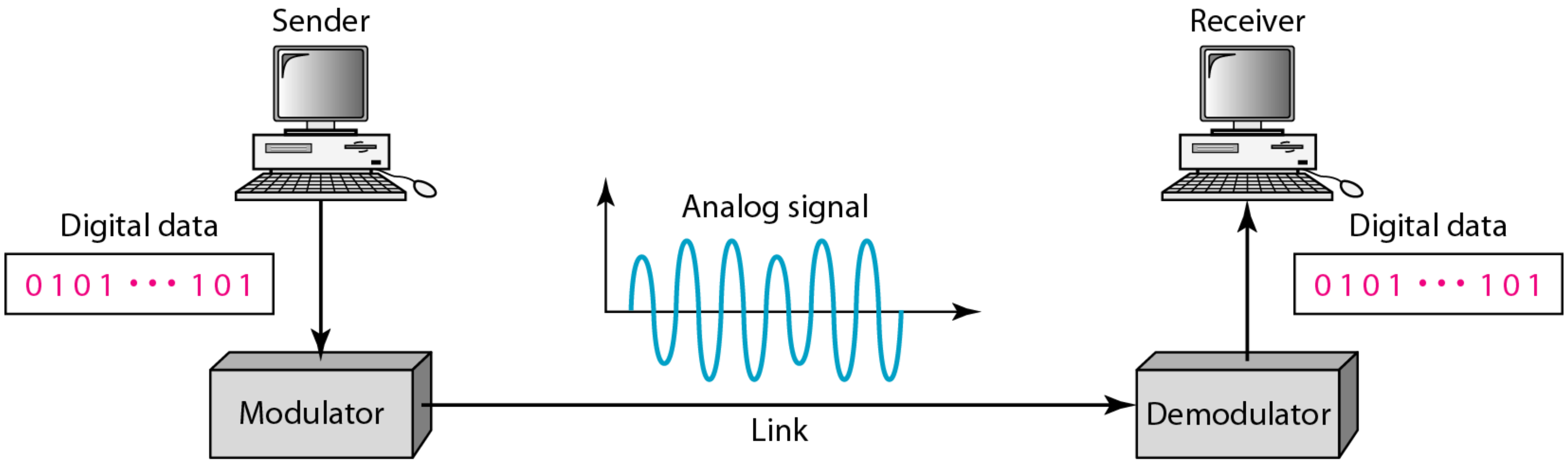
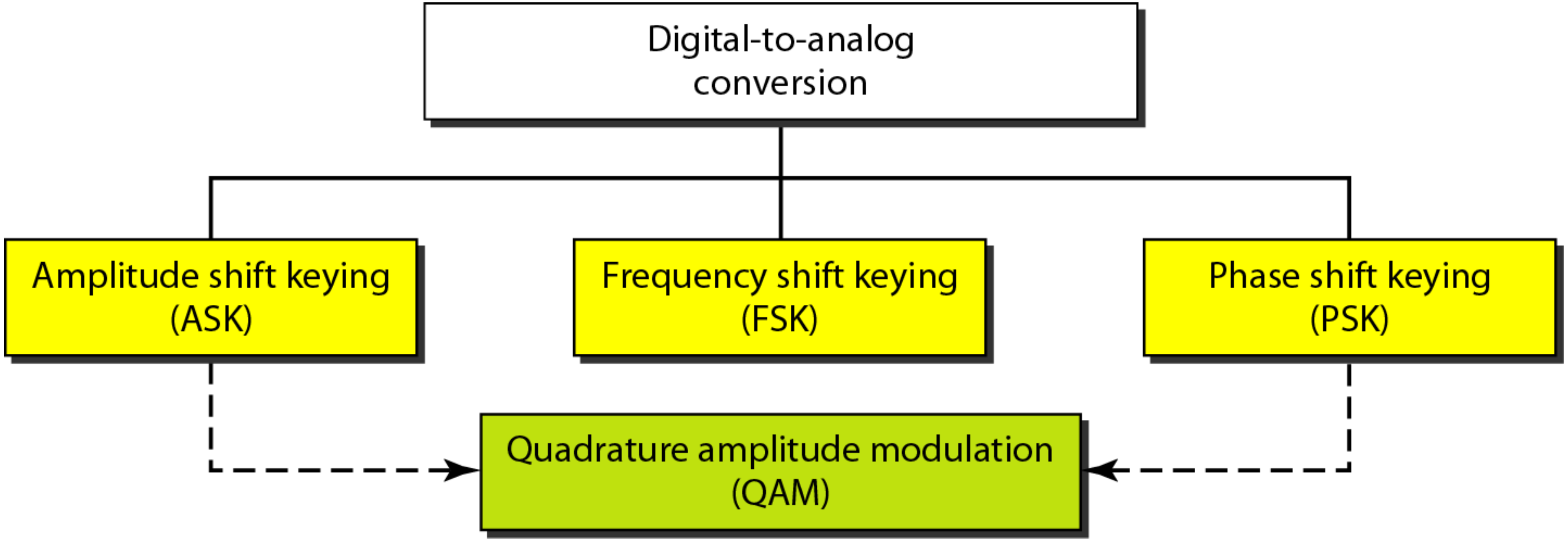
- In analog transmission of digital data, $r = \log_2 L$ (L is the number of different signal elements/levels) and **baud rate** <= **bit rate** ($S = N/r$).
- **Carrier signal** (**carrier frequency**)
  - A **high-frequency signal** produced by the sending device and acts as a base for the information signal.
  - The carrier signal is **a simple sine wave**.
  - The receiver is tuned to the frequency of the carrier signal.

Digital-To-Analog Conversion

- Converting digital data to a **bandpass** analog signal.
  - Modifying **any of the three characteristics** (**amplitude**, **frequency**, and **phase**) of a sine wave (i.e., carrier signal) based on the information in the digital data.
  - The process is called **modulation** or **shift keying**.



Types of Digital-To-Analog Conversion

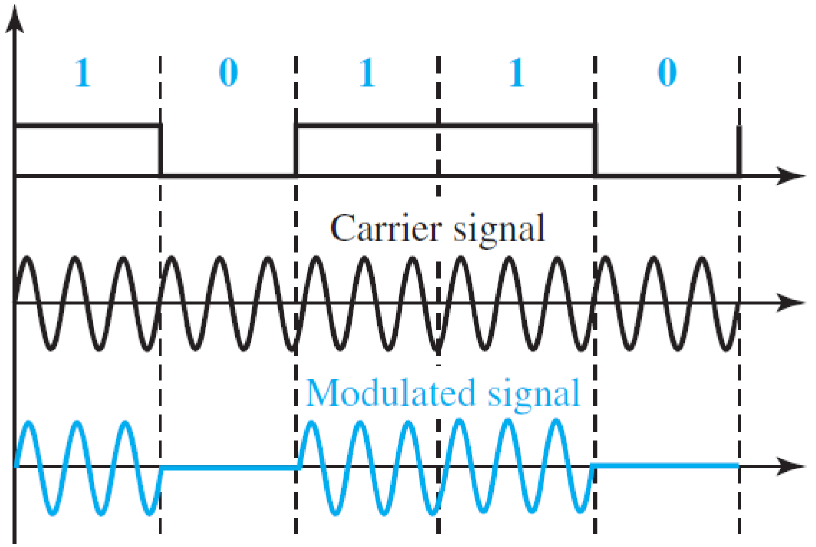


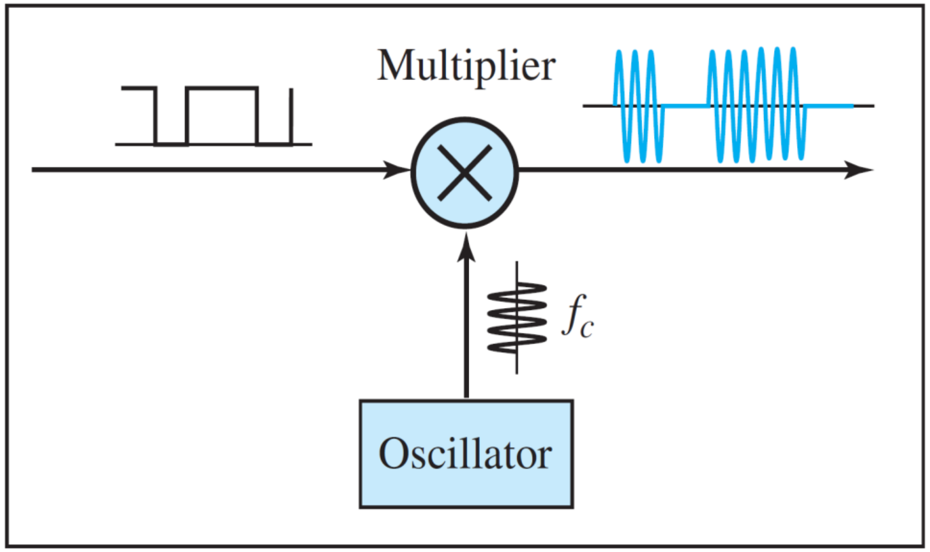
Amplitude Shift Keying (ASK)

- The **amplitude of the carrier signal** is **varied** to create signal elements.
- Both **frequency** and **phase** remain constant.

Binary ASK (BASK)

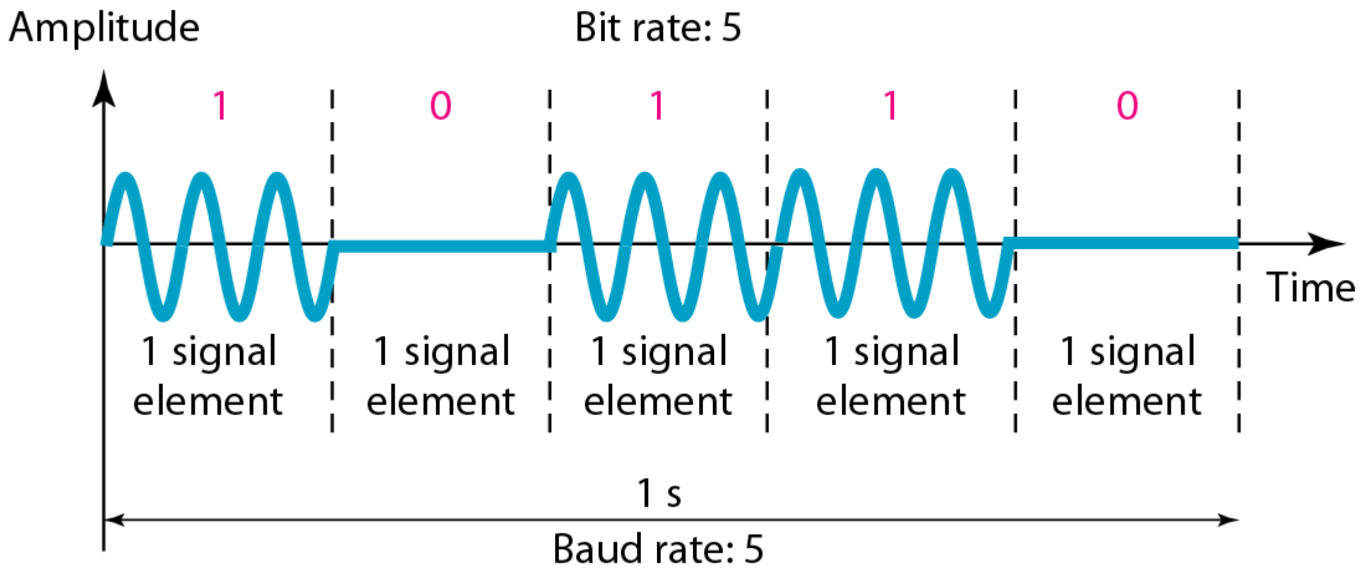
- Implemented using only **two levels** of signal elements.
- Also called **OOK** (**On-Off Keying**).
- Peak amplitude→ for one signal level is 0, for the other one is equal to the peak amplitude of the carrier signal.

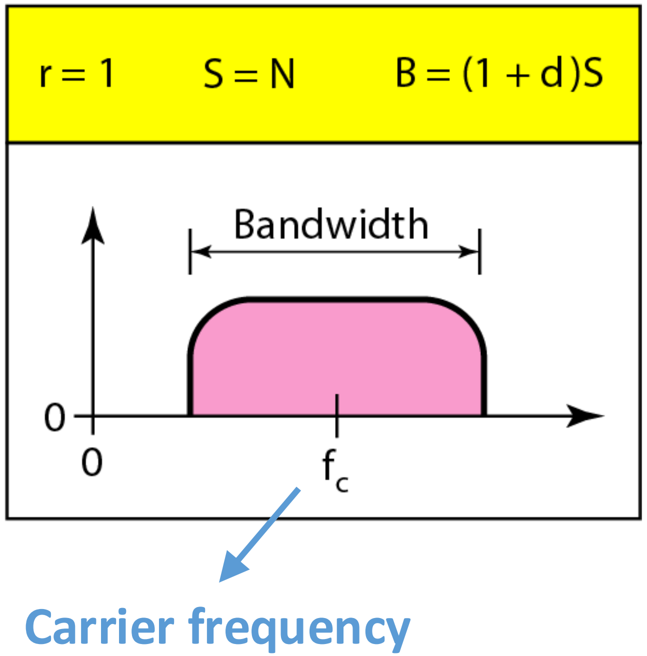




Bandwidth for ASK

- The process of modulation produces a **nonperiodic composite signal**.
- Bandwidth is **proportional** to the **signal rate**.





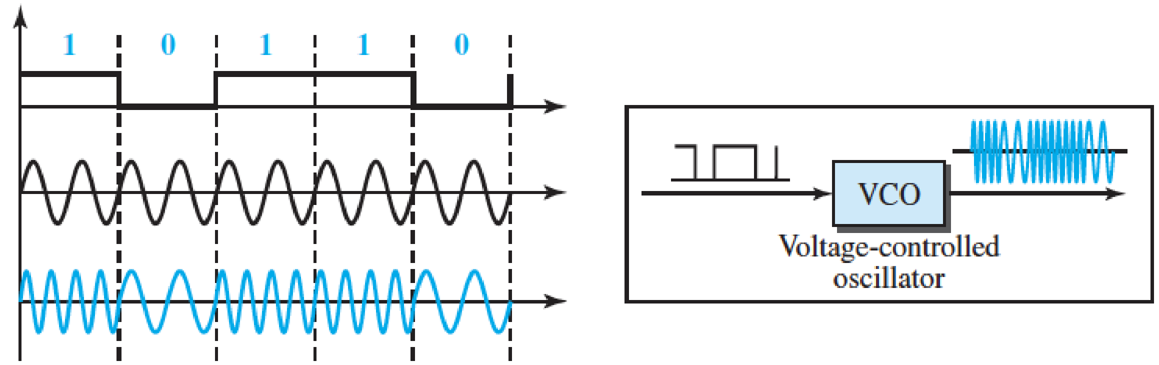
Multi-Level ASK

- More than two voltage levels is used → but it is not common
- More than 1 bit can be sent in a signal element.
- Example:
  - **4 different amplitudes** (voltage levels) → **2 bits per signal element** (r = 2)
  - 8 different amplitudes (voltage levels) → 3 bits per signal element (r = 3)
  - …

Frequency Shift Keying (FSK)

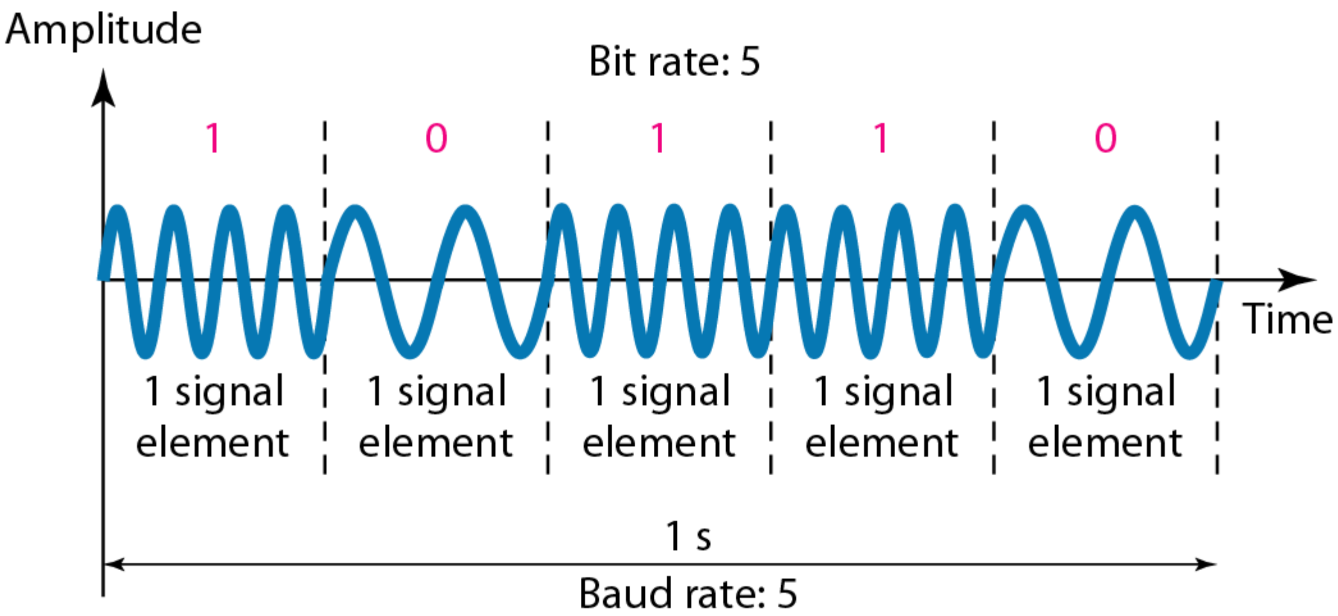
- The **frequency** of the **carrier signal** is **changed** to represent data.
- The frequency of the modulated signal is
  - Constant for the duration of one signal element.
  - Changes for the next signal element if the data element changes.
- **Peak amplitude** and **phase** are **constant** for all signal elements.

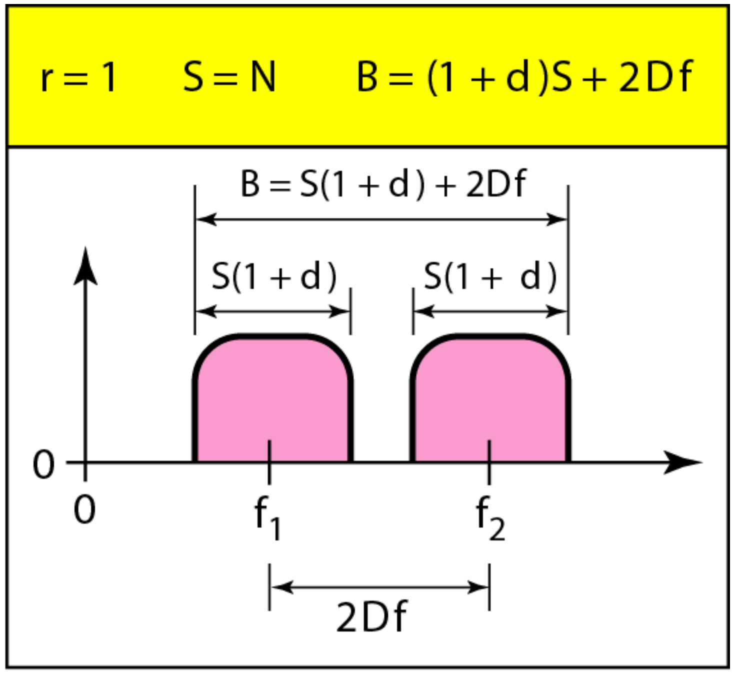
Figure 5.7 *Implementation of BFSK*



Binary FSK (BFSK)

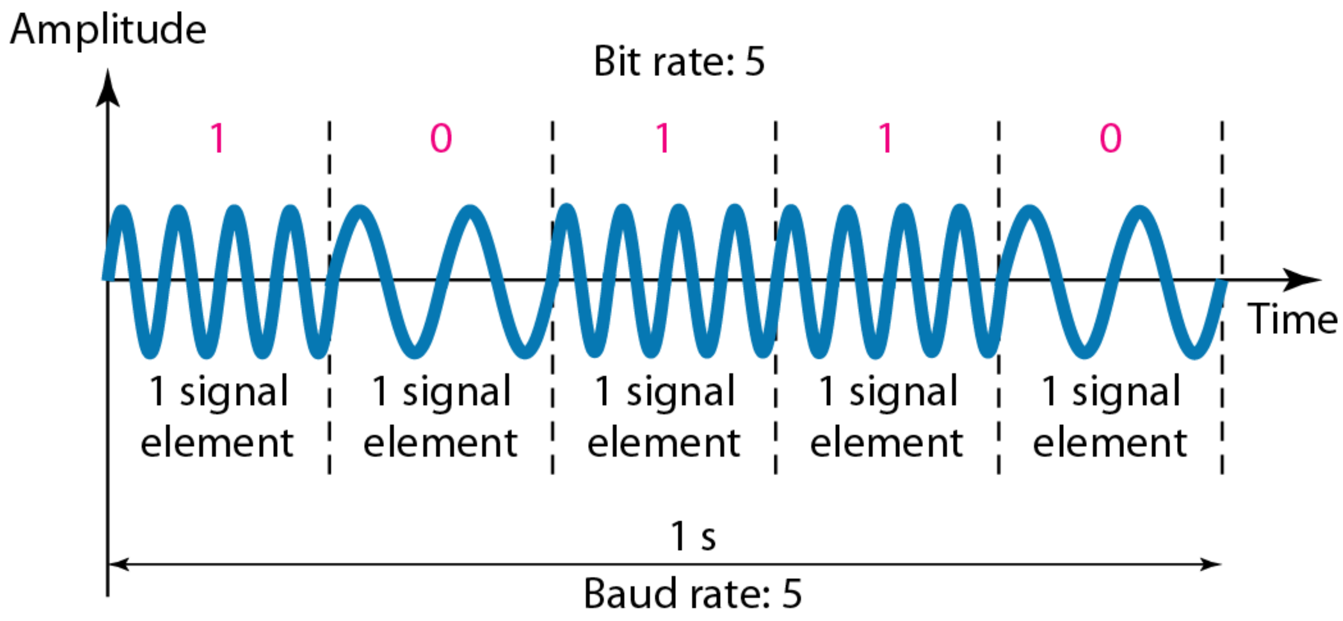
- **Two carrier frequencies**, f_1 and f_2 are used.
  - If the data element is 0, f_1 is used.
  - If the data element is 1, f_2 is used.

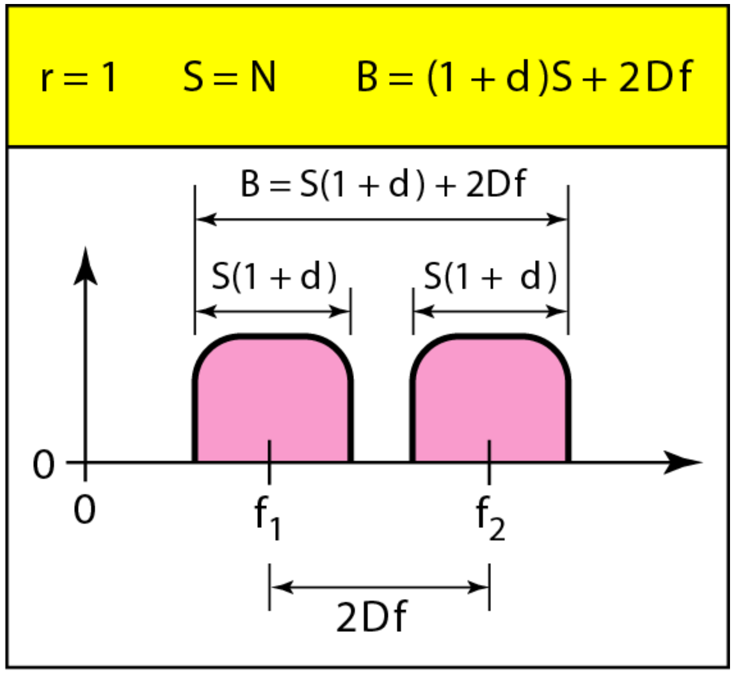




Binary FSK (BFSK)

- (Δ_f is shown as **Df** in the figure.)
- Both f_1 and f_2 are Δ_f apart from the midpoint between the two bands. The difference between the two frequencies is $2\Delta_f$.





Multilevel FSK (MFSK)

- More than two frequencies are used
- Examples:
  - **4 frequencies** to send 2 bits at a time (**2 bits per signal element**)
  - 8 frequencies to send 3 bits at a time (3 bits per signal element)
  - …

Phase Shift Keying (PSK)

- The **phase of the carrier** is changed to represent **two or more different signal elements**.
- Both **peak amplitude** and **frequency** remain **constant** as the phase changes.
- More common than ASK or FSK.
- Less susceptible to **noise** than ASK, why?

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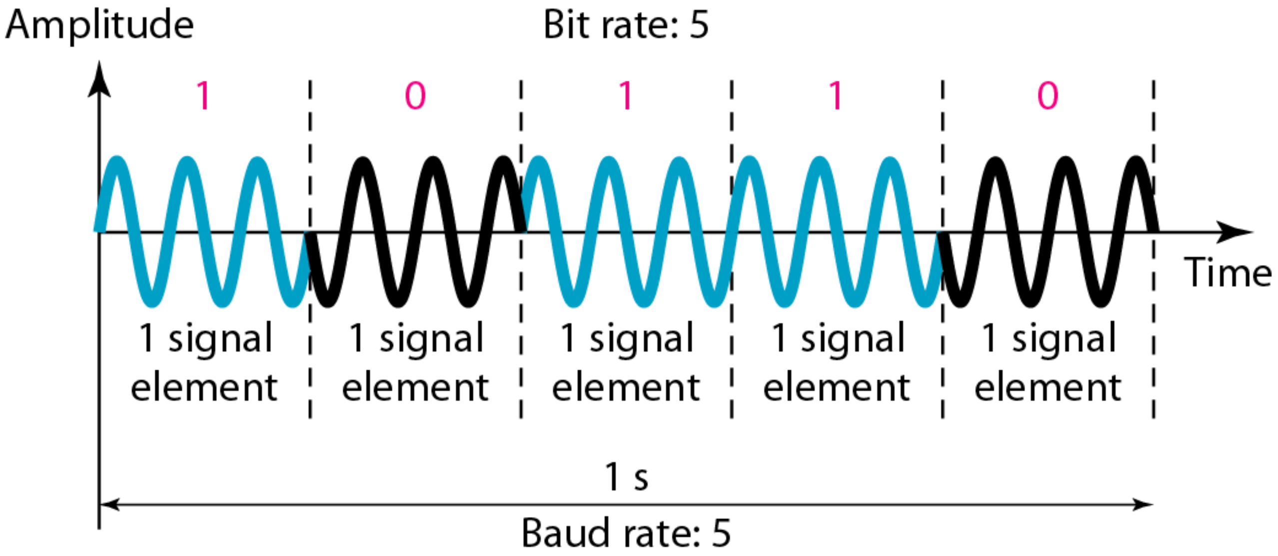
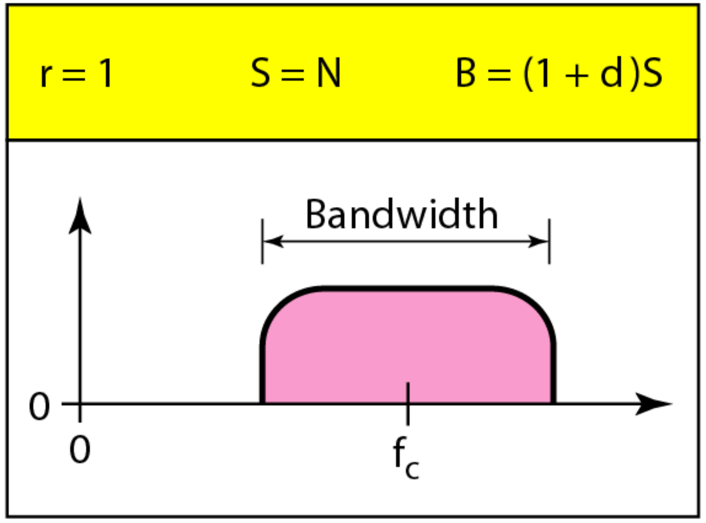
- More common than ASK or FSK.
- Less susceptible to **noise** than ASK, why?
  - Because noise can change the **amplitude** easier than it can change the phase.
- PSK **needs more sophisticated hardware** to be able to distinguish between phases.

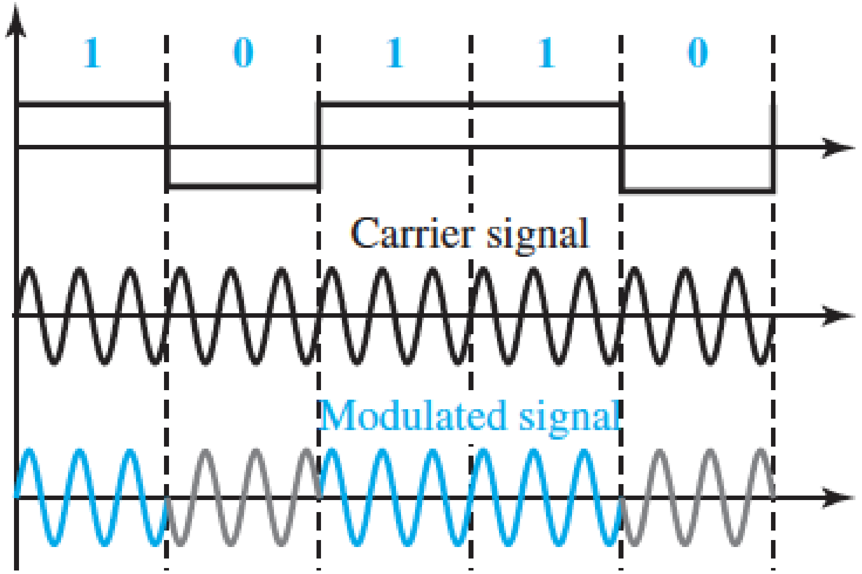
Binary PSK (BPSK)

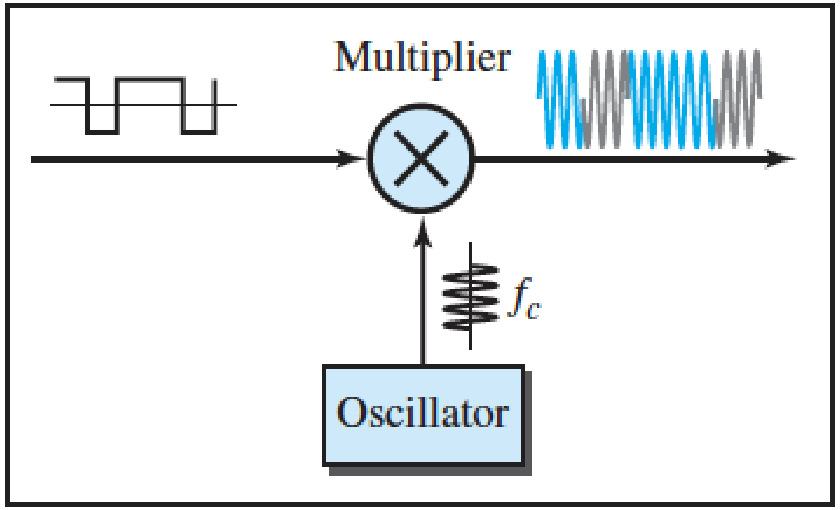
- **Two signal elements** are used (one with a phase of 0°, and the other with a phase of 180°)
- **Same bandwidth** as BASK but less than BFSK.





Binary PSK Implementation

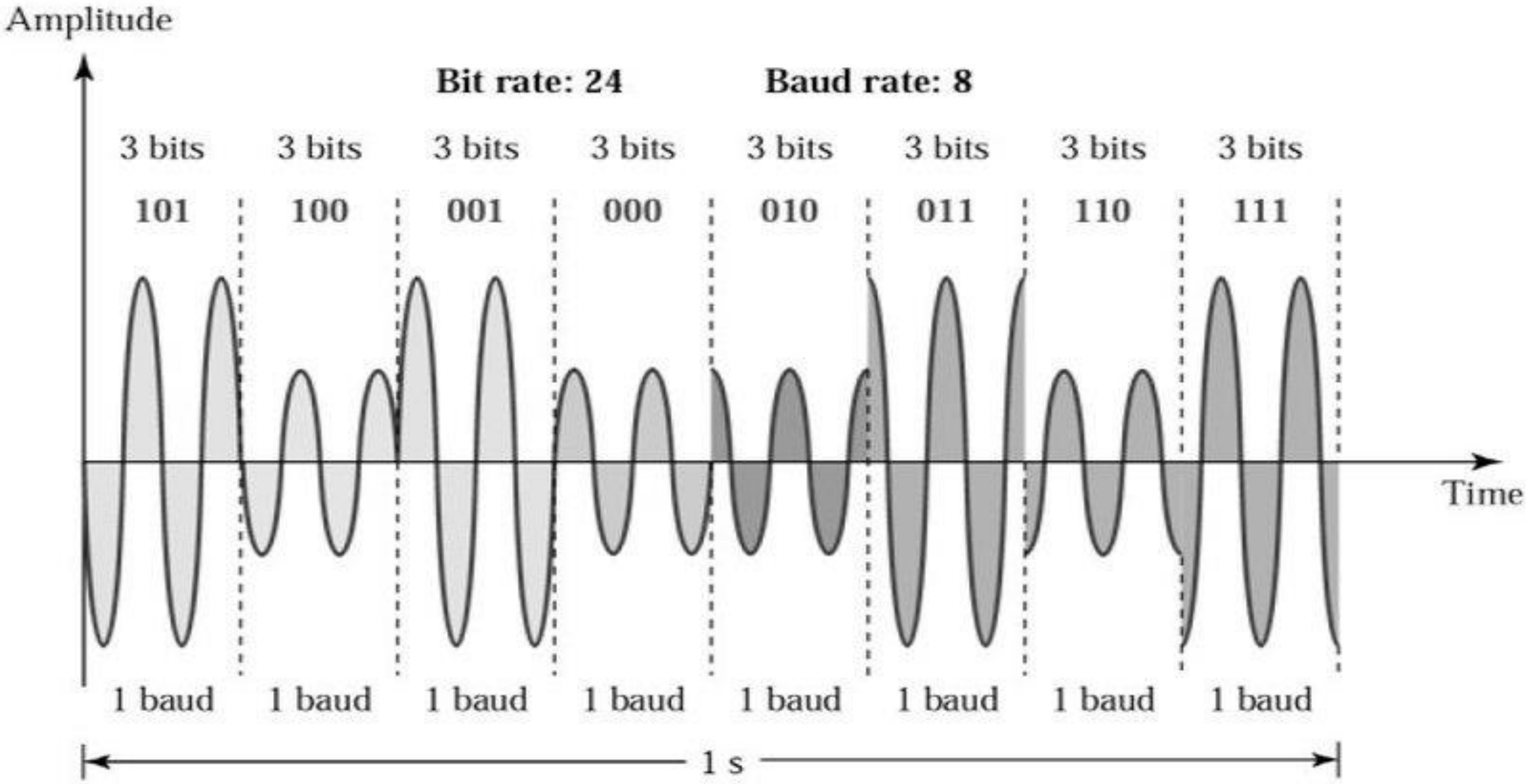




Quadrature Amplitude Modulation (QAM)

- Combines **ASK** and **PSK**.
- The **dominant method** of **digital-to-analog modulation**.
- Using **two carriers**, one **in-phase** and the other **quadrature** (i.e., the two carrier signals are out-of-phase with each other by 90°), with **different peak amplitude** levels for each carrier.
- The same advantages as PSK over ASK.
- The same **minimum required bandwidth** as ASK and PSK.
- Widely used as as a modulation scheme for digital telecommunication systems, such as in 802.11 Wi-Fi standards.

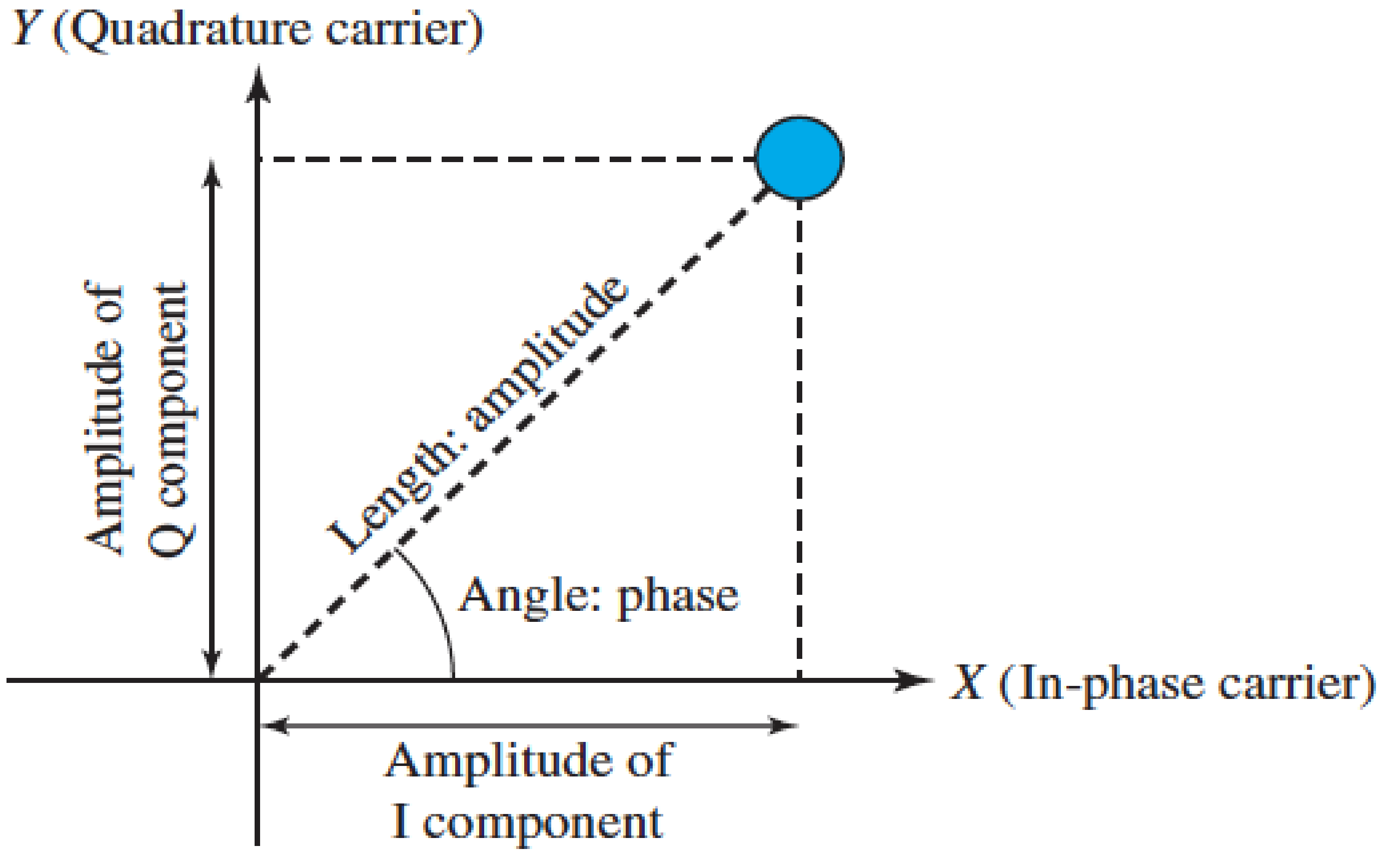
Typical Modulated 8-QAM Waveform



Constellation Diagram

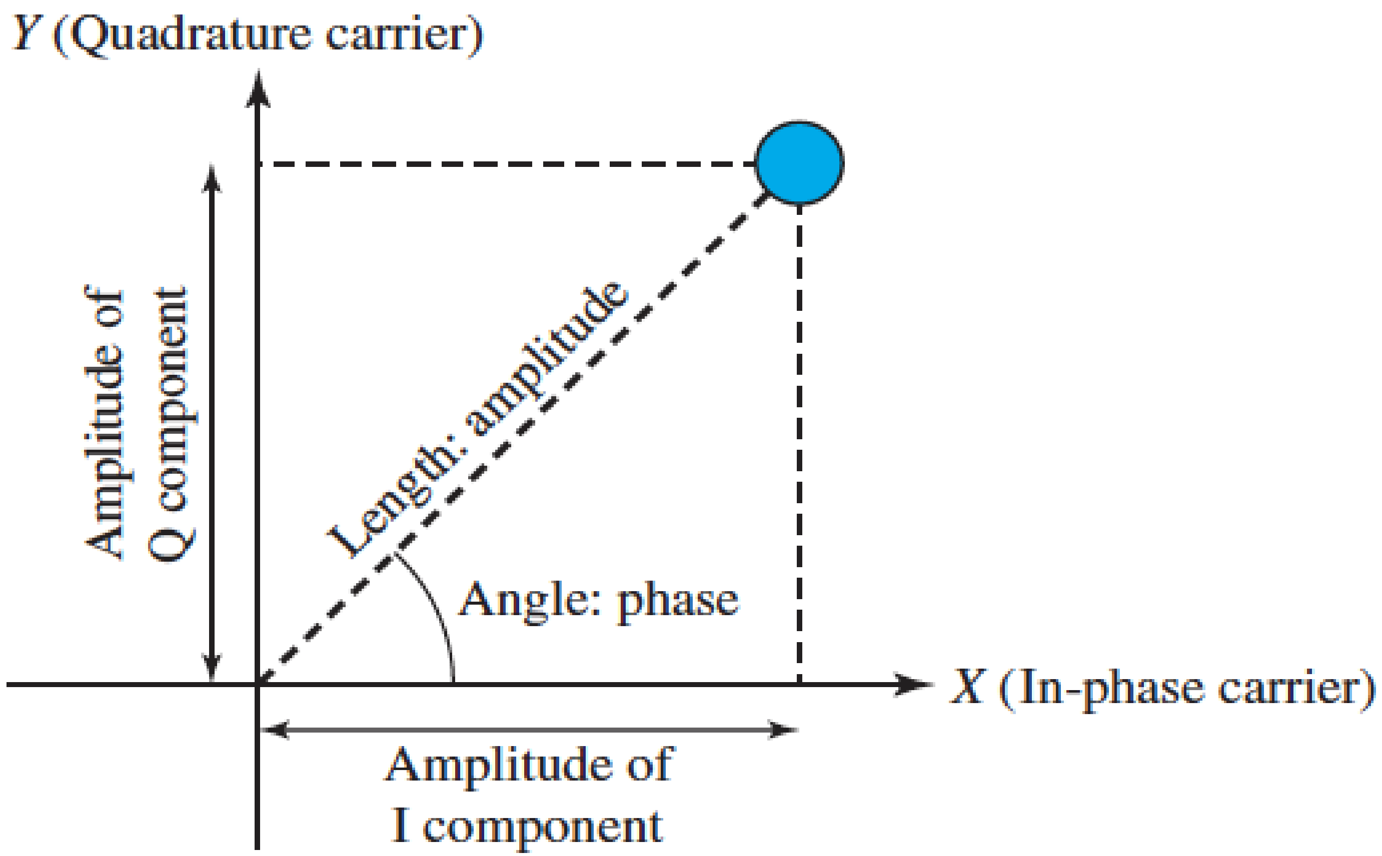
- A representation of a signal modulated by a digital modulation scheme.
- Assists us in defining the **amplitude** and **phase** of a signal element, particularly when we are using two carriers (one in-phase, one quadrature).
- Useful when dealing with multilevel ASK, PSK and **QAM**.
- A **signal element type** is represented as a **dot** (a bit or combination of bits it can carry is often written next to it).

Constellation Diagram

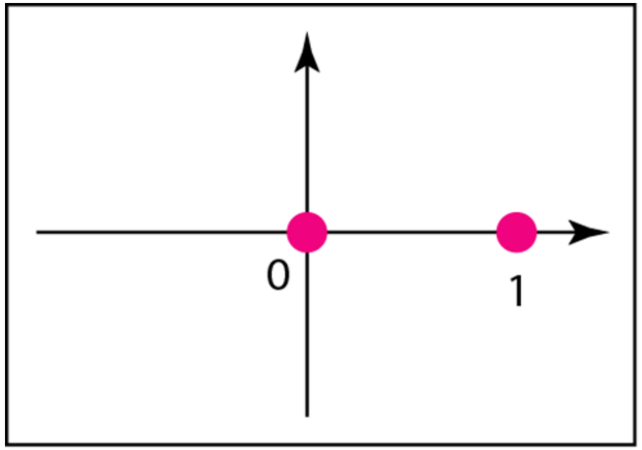


Constellation Diagram

- A modulation with ***n* constellation points** transmits **$\log_2 n$ bits per signal element**.

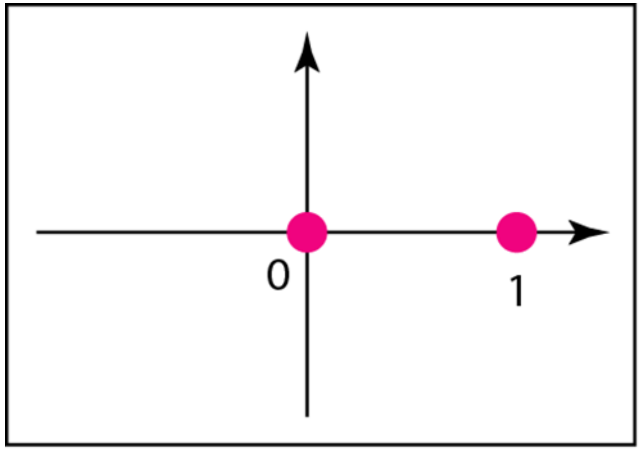


Constellation Diagram – Example 1



a. ASK (OOK)

Constellation Diagram – Example 1



a. ASK (OOK)

- **Binary ASK**:
  - Only an in-phase carrier → the two points should be on the X axis.
  - Binary 0 has an amplitude of 0 V. Binary 1 has an amplitude more than zero.

Constellation Diagram – Example 2

- Draw the constellation diagram for binary ASK, with peak amplitude values of 1 V and 3 V.

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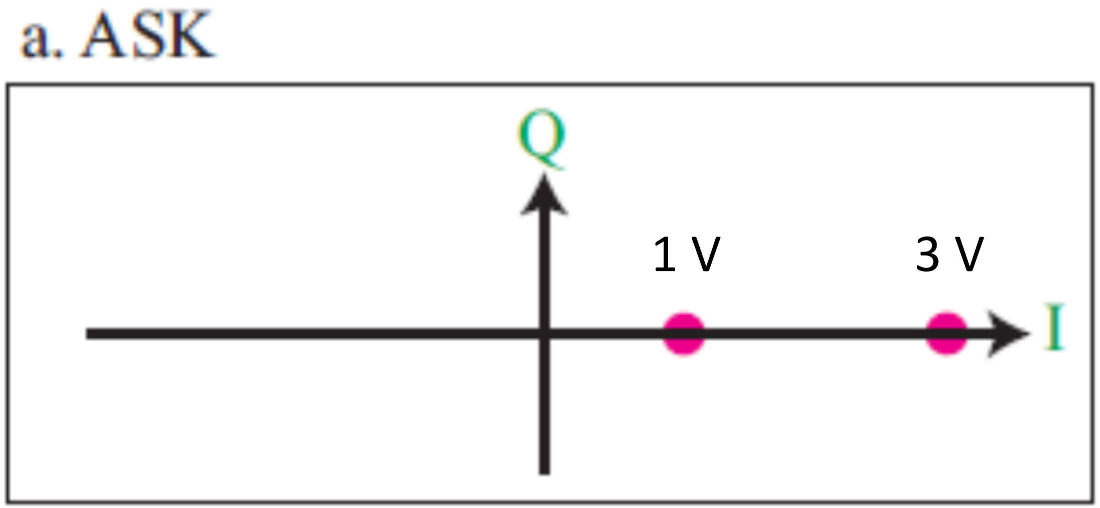
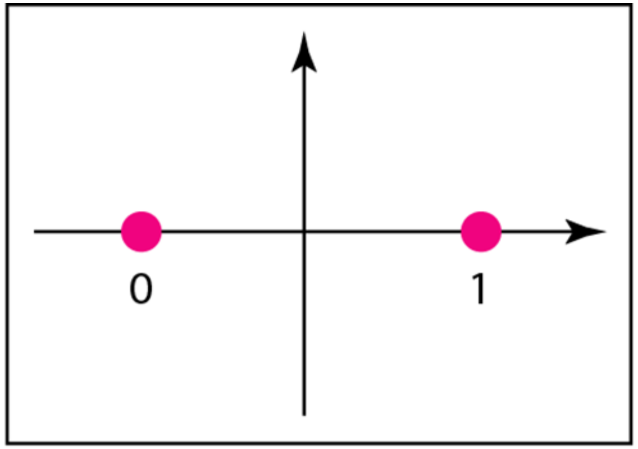
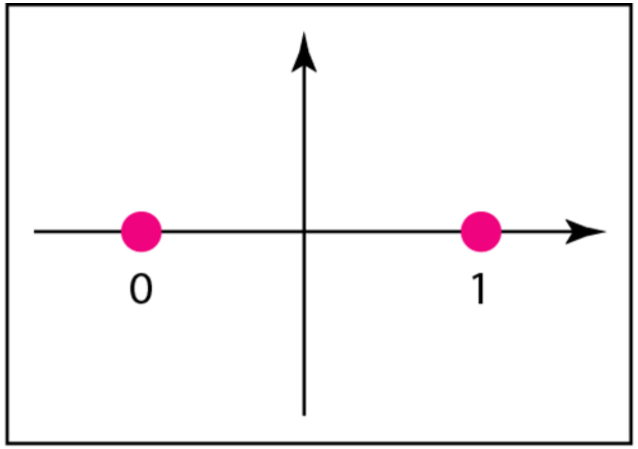


Constellation Diagram – Example 3



Constellation Diagram – Example 3



b. BPSK

- **BPSK** also uses only an in-phase carrier.
- It creates two different signal elements, one with amplitude 1 V and in phase and the other with amplitude 1 V and 180° out of phase.

Constellation Diagram – Example 4

- Draw the constellation diagram for BPSK, with a peak amplitude value of 2 V.

Constellation Diagram – Example 4

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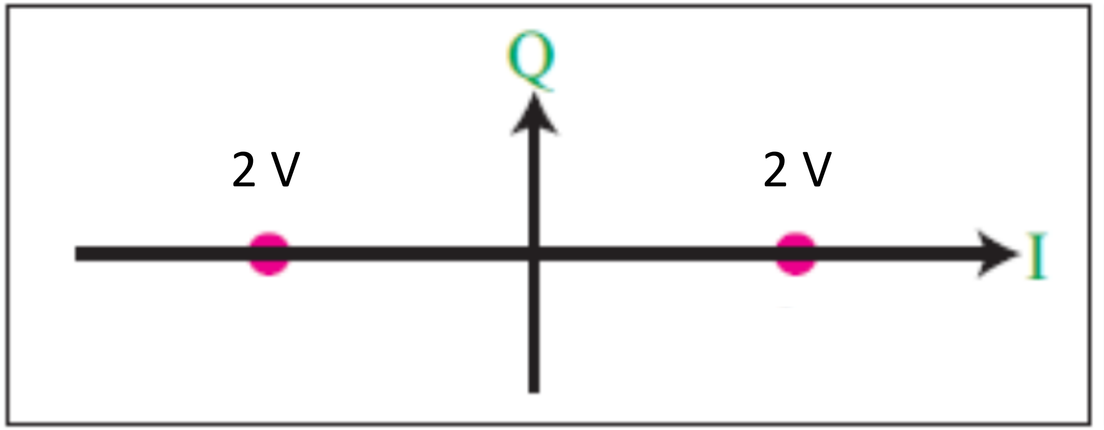

Constellation Diagram – Example 5

- Draw the constellation diagram for 8-QAM with two different peak amplitude values, 1 V and 3 V, and four different phases.

Constellation Diagram – Example 5

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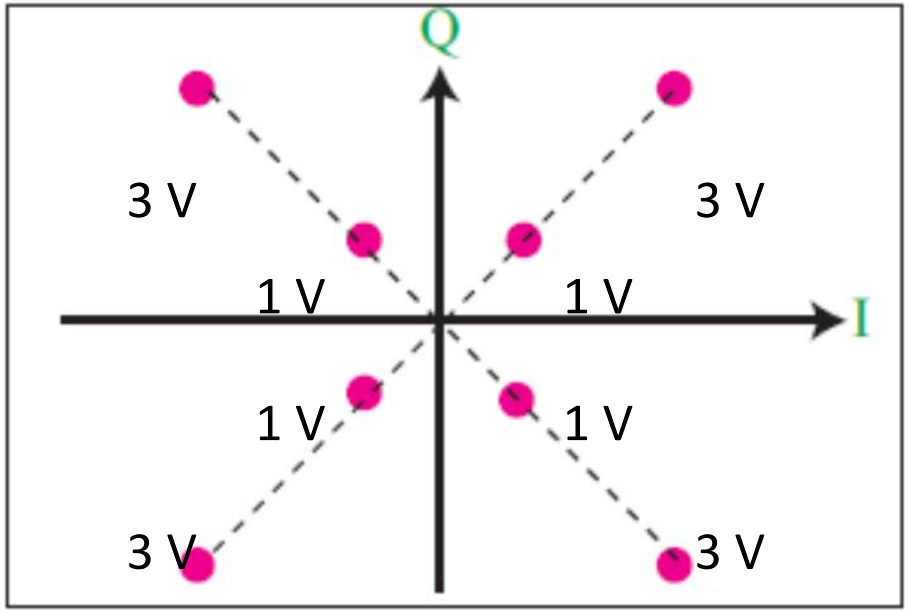
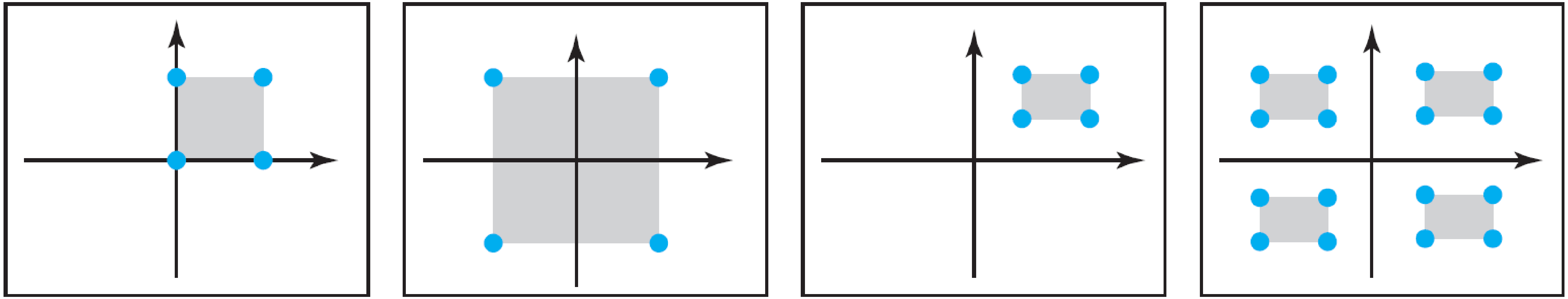


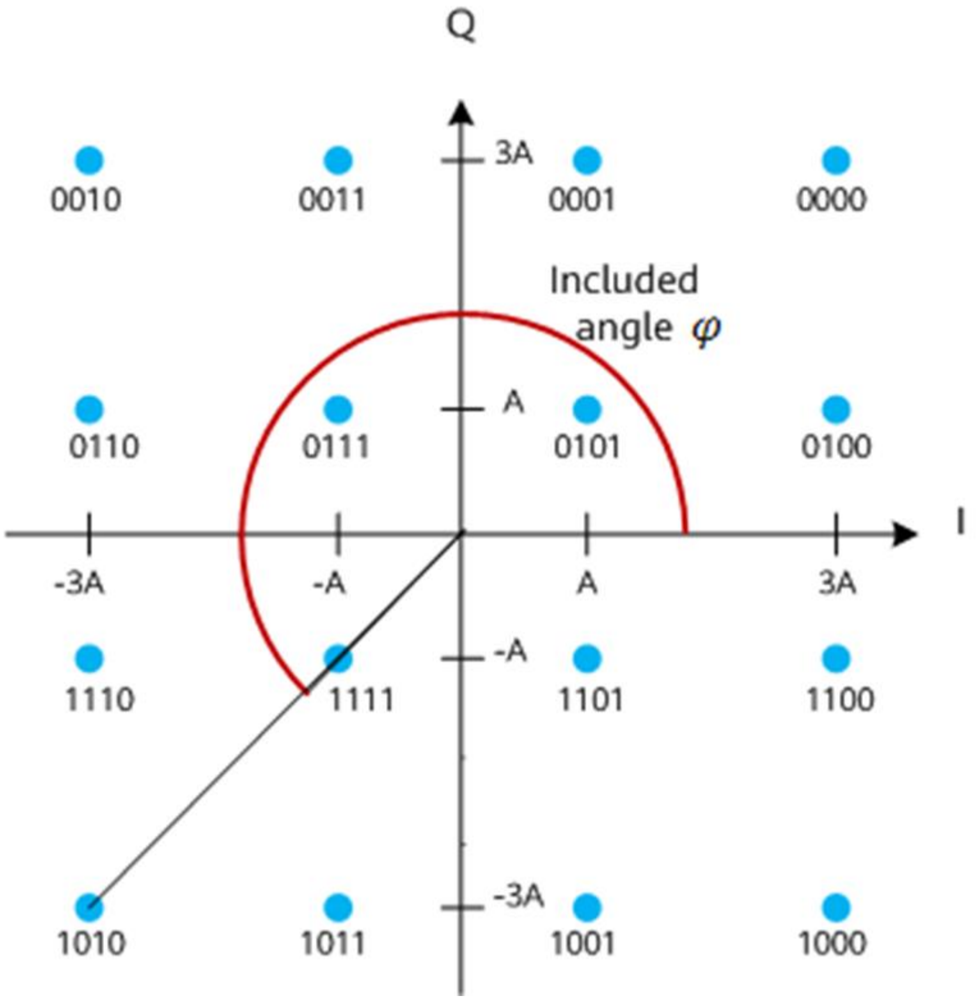
Constellation Diagrams for Some QAMs



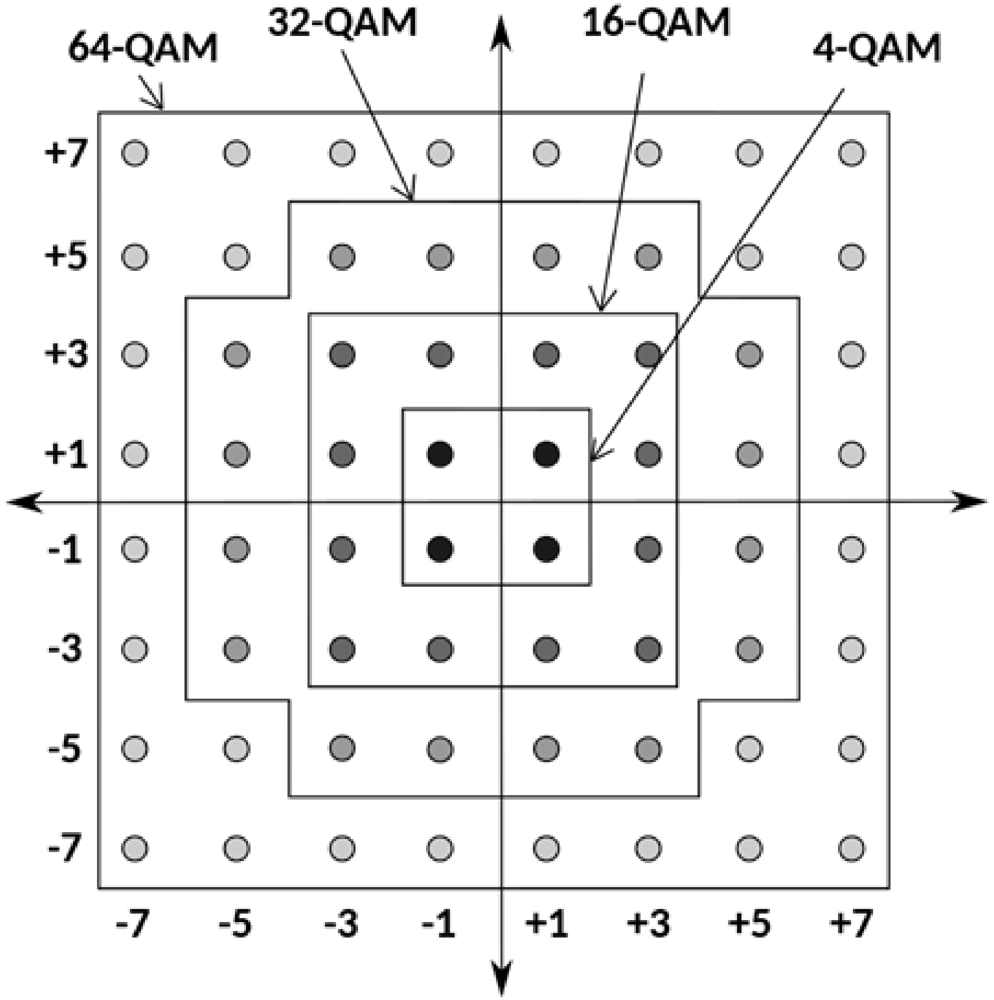
a. 4-QAM b. 4-QAM c. 4-QAM d. 16-QAM

Constellation Diagram – Example 6

- **16-QAM**:
- The distance ***A*** from the point to the origin (0,0) represents the amplitude after modulation.
- The angle ***φ*** of the point represents the phase after modulation.

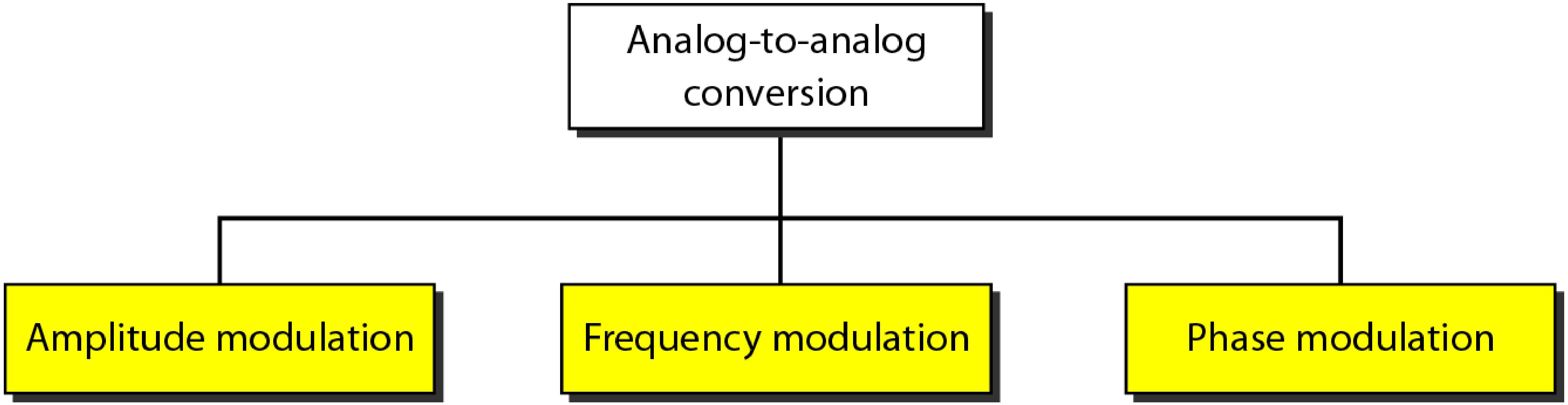


Constellation Diagram – Different n-QAM



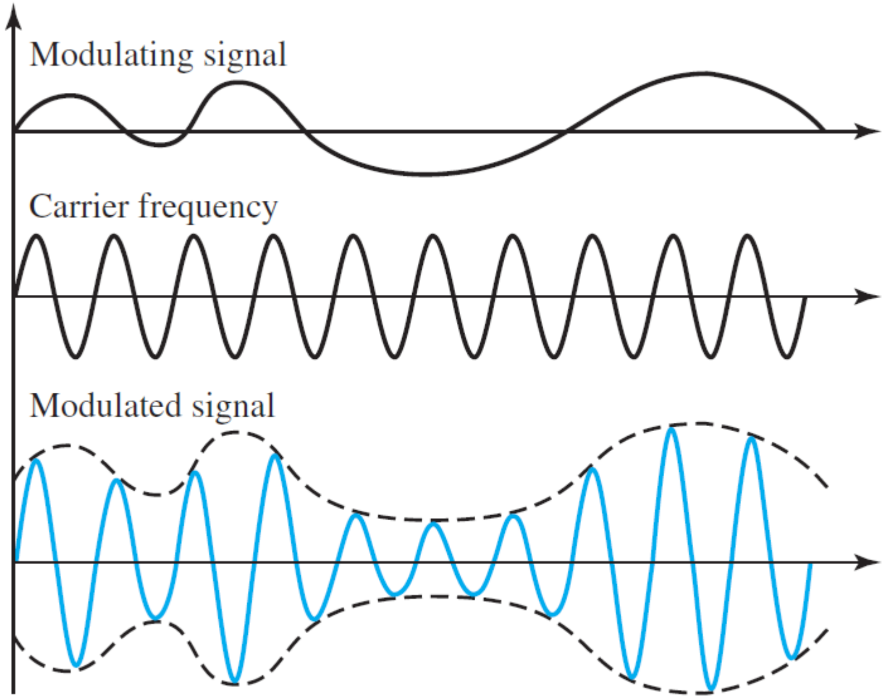
Bits per Symbol	Number of Symbols	QAM Modulation
4	$2^4 = 16$	16-QAM
6	$2^6 = 64$	64-QAM
8	$2^8 = 256$	256-QAM
10	$2^{10} = 1024$	1024-QAM
12	$2^{12} = 4096$	4K-QAM
…		

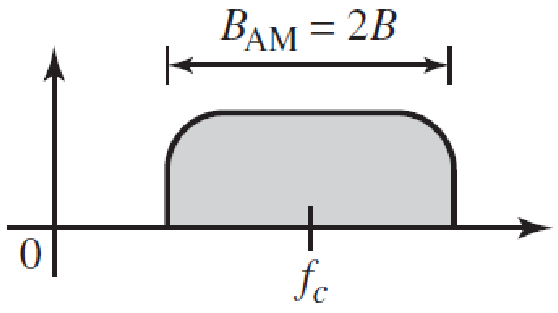
Types of Analog-To-Analog Modulation



Amplitude Modulation (AM)

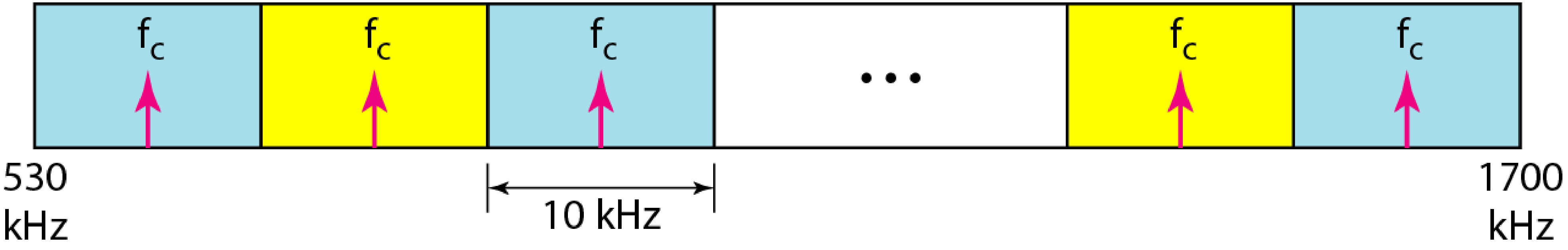
- The carrier signal is modulated so that its amplitude varies with the changing amplitudes of the modulating signal.
  - The frequency and phase of the carrier remain the same.
- The **bandwidth** of the **modulated signal** is **twice** the **bandwidth** of the **modulating signal** and covers a range centered on the **carrier frequency**.





Bandwidth Allocation for AM Radio

- The bandwidth of an audio signal (speech and music) is usually 5 kHz → **AM radio** station needs a **bandwidth** of **10 kHz**.
- The Federal Communications Commission (FCC) allows 10 kHz for each AM station.
- To avoid **interference**, each **station's carrier frequency** must be **separated** from those on either side of it by **at least 10 kHz**.



UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL AIDS
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/ NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE

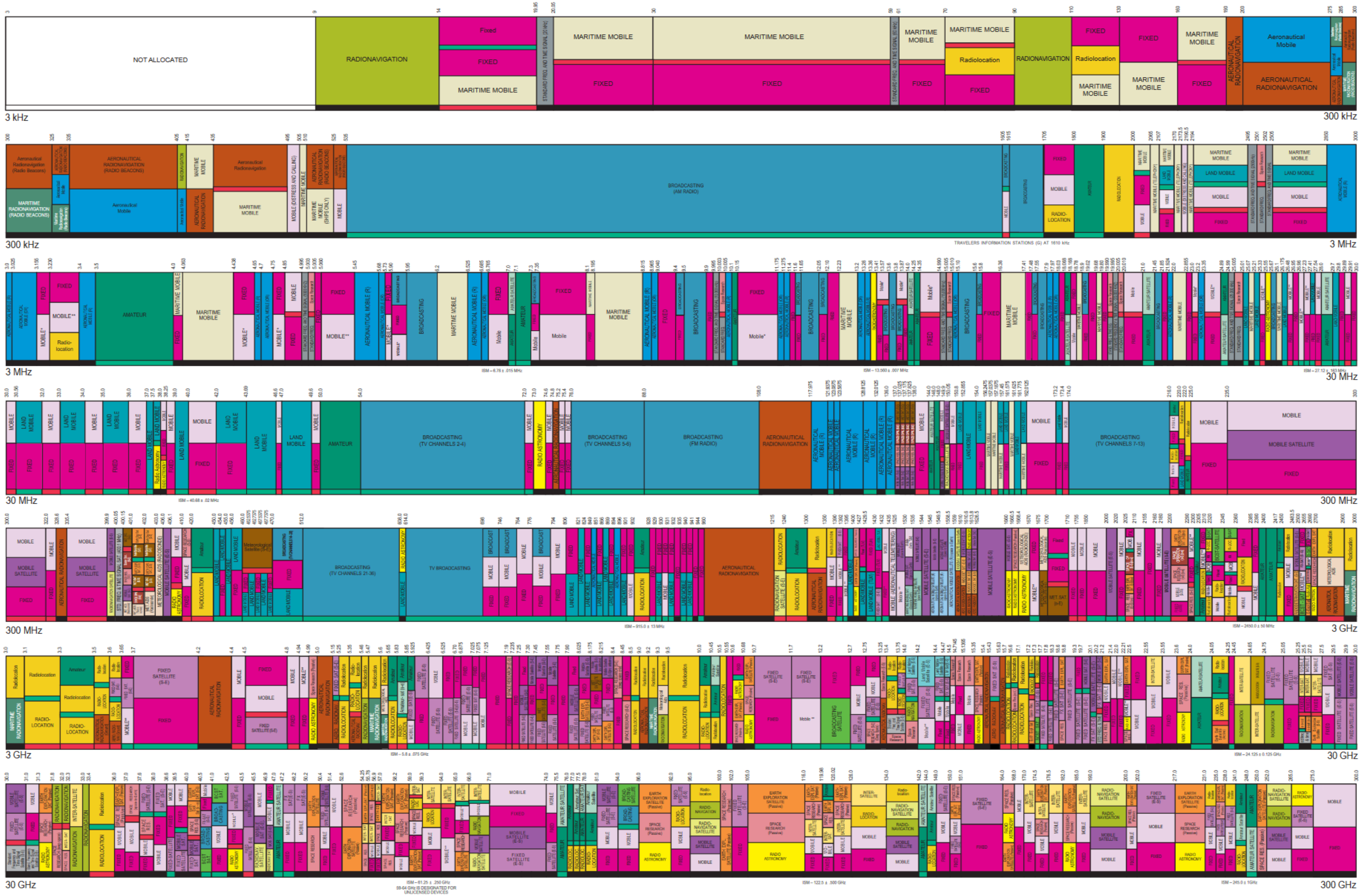
ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

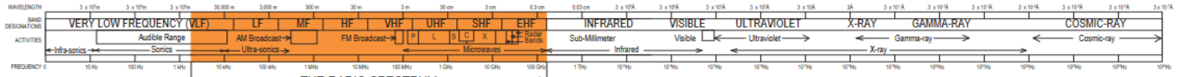
This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it does not completely reflect all aspects, i.e., footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

October 2003



* EXCEPT AERO MOBILE (R)
** EXCEPT AERO MOBILE

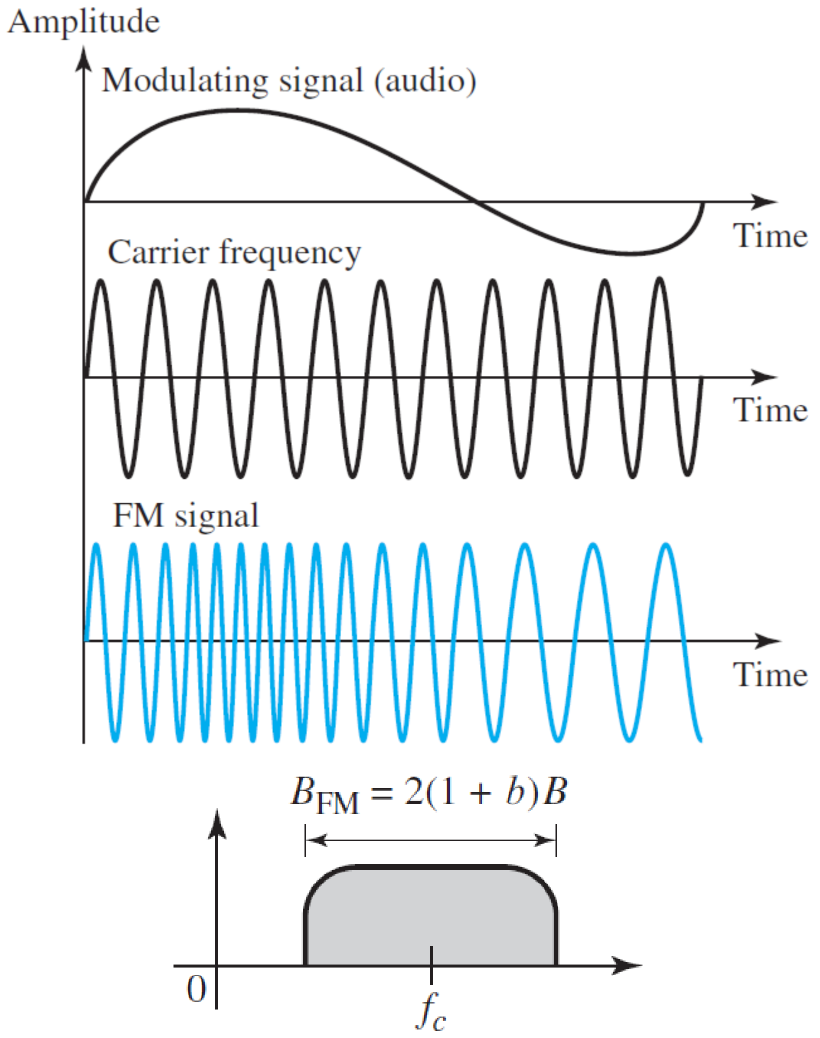


THE RADIO SPECTRUM
MAGNIFIED ABOVE

PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

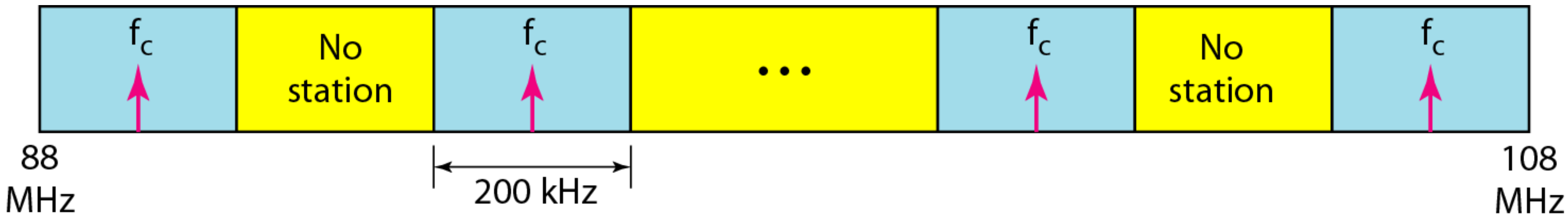
Frequency Modulation (FM)

- The frequency of the carrier signal is modulated to follow the changing voltage level (amplitude) of the modulating signal.
  - The **peak amplitude** and **phase** of the carrier signal remain constant.
- The total bandwidth required for FM can be determined from the bandwidth of the analog (modulating) signal.



Bandwidth Allocation for FM Radio

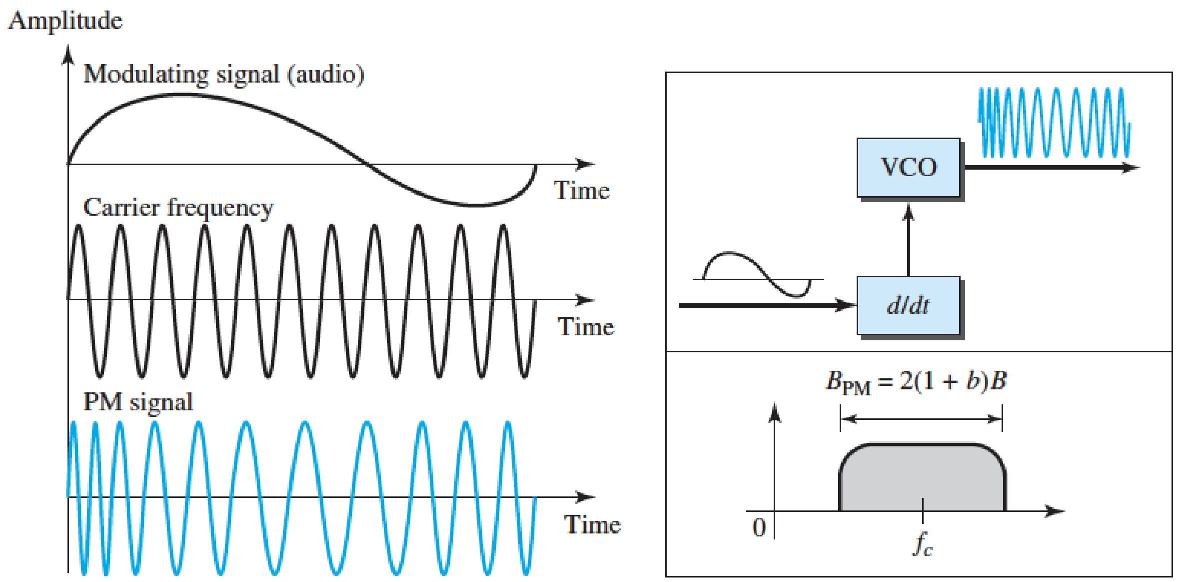
- The bandwidth of an audio signal (speech and music) in **stereo** is almost **15 kHz**.
- The FCC allows **200 kHz** for each FM station (i.e., $\beta = 4$ with extra 50 kHz guard band).
- **Stations** must be separated by **at least 200 kHz** to keep their bandwidths from overlapping.



Phase Modulation (PM)

- The phase of the carrier signal is modulated to follow the changing voltage level (amplitude) of the modulating signal.
  - The **peak amplitude** and **frequency** of the carrier signal remain fixed.

Figure 5.20 *Phase modulation*



Summary

- When we have a **bandpass channel**, we require **analog transmission**.
  - Digital-to-analog conversion (**ASK**, **FSK**, **PSK**, **QAM**)
  - Analog-to-analog conversion (**AM**, **FM**, **PM**)

References

[1] Behrouz A. Forouzan, Data Communications & Networking with TCP/IP Protocol Suite, 6th Ed, 2022, McGraw-Hill companies.

[2] Jong-Wan Kim, Chang-Hee Lee, Modulation format identification of square and non-square M-QAM signals based on amplitude variance and OSNR, *Optics Communications*, Volume 474, 2020. https://doi.org/10.1016/j.optcom.2020.126084.

Reading

- Chapter 2 of the textbook, section 2.4.
- Chapter 2 of the textbook, section 2.8 (Practice Test)