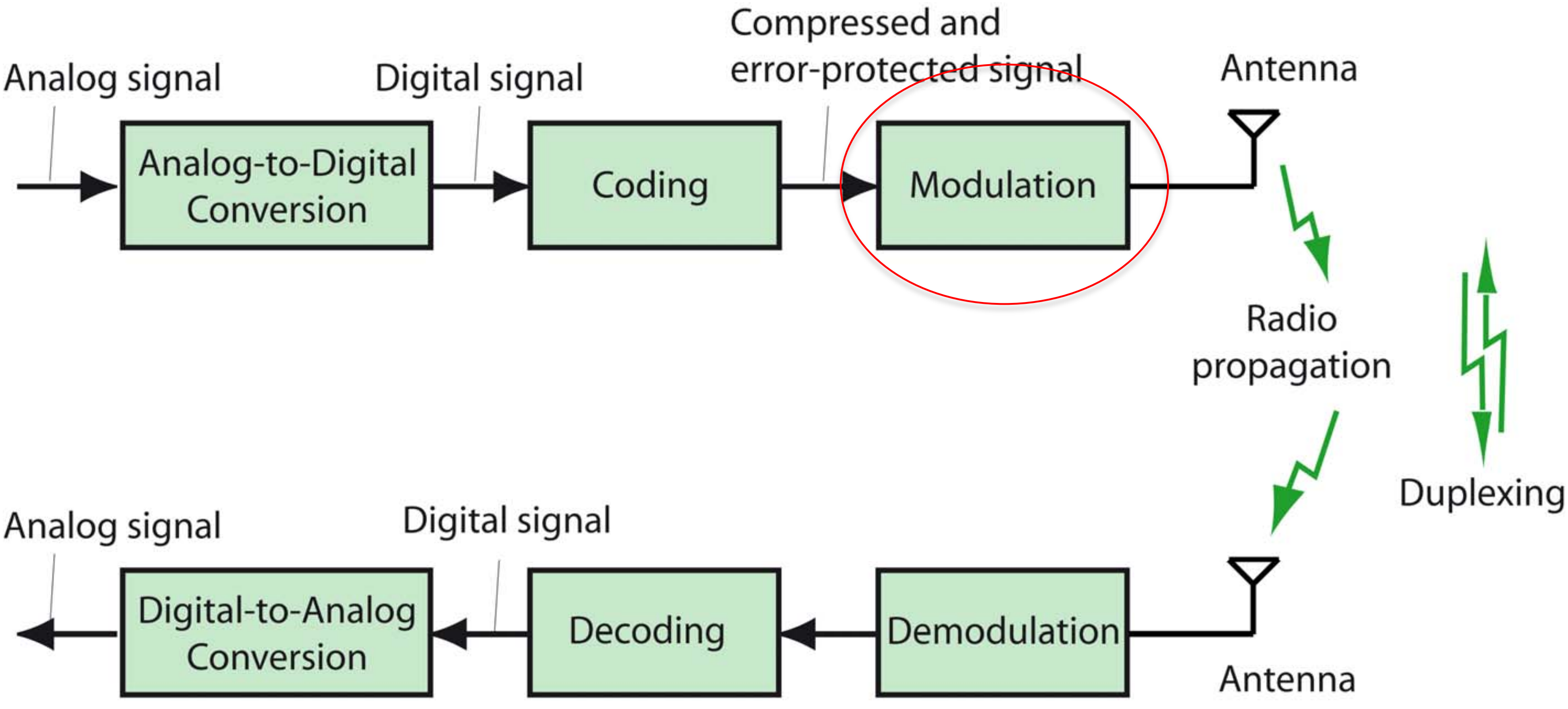
V

Mobile Communication Networks

Modulation

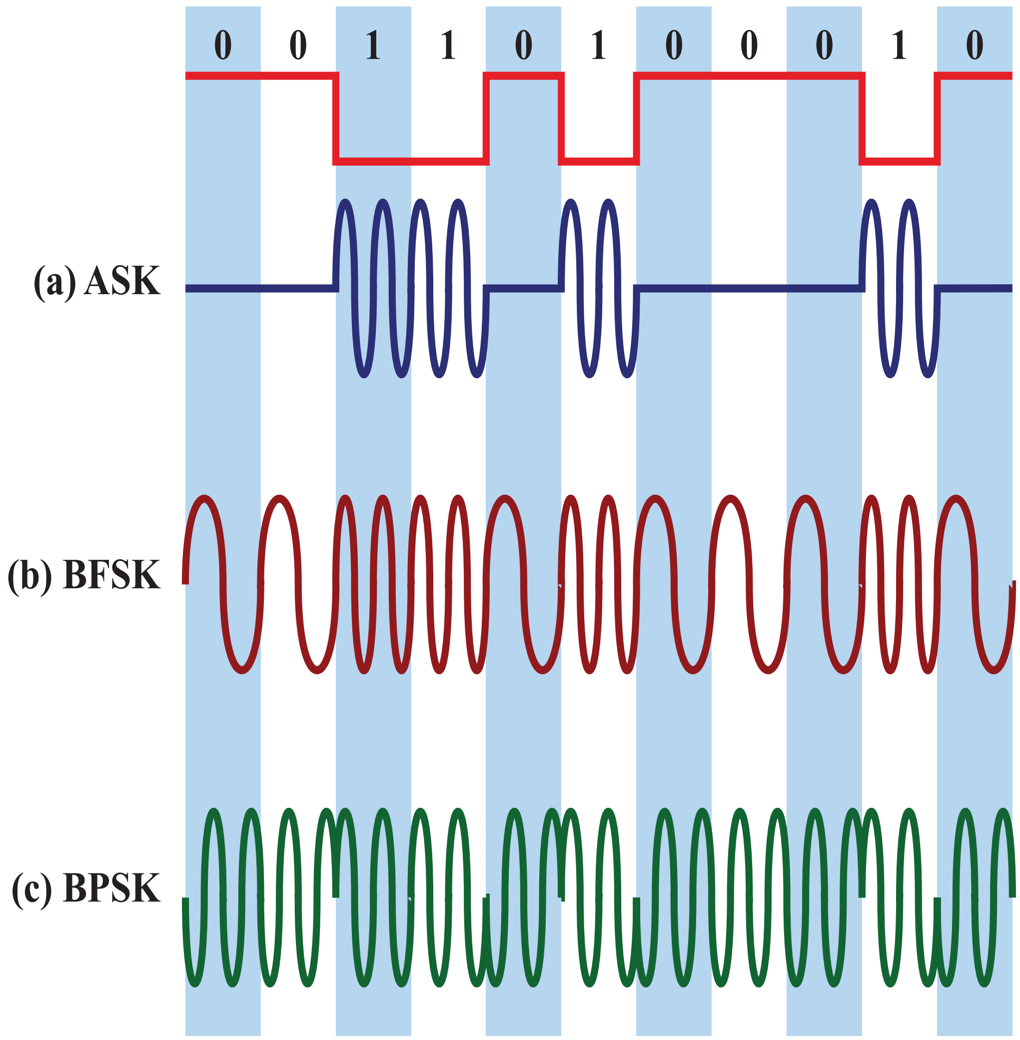

Analog signal
Digital signal
Compressed and
error-protected signal
Antenna
Analog-to-Digital
Conversion
Coding
Modulation
Radio
propagation
Duplexing
Analog signal
Digital signal
Digital-to-Analog
Conversion
Decoding
Demodulation
Antenna

Signals *(revision)*

- physical representation of data
- function of time and location
- signal parameters: parameters representing the value of data
- signal parameters of periodic signals:
  period T, frequency $f=1/T$, amplitude A, phase shift φ
  - sine wave as special periodic signal for a carrier:

$$s(t) = A(t) \sin(2 \pi f(t) t + \varphi(t))$$

Modulation of Analog Signals for Digital Data



How to choose the Digital Modulation Method?

- **Criteria** to take into account when choosing the digital modulation method
  - **Power efficiency**, i.e., the E_b/N_0 ratio for a specific error probability
  - **Bandwidth efficiency**, i.e., the data rate per unit bandwidth
  - Performance on **multipath fading channels** and under non-linear distortion
  - Implementation **cost** and **complexity**

- Conflicting requirements that cannot be satisfied simultaneously

Amplitude-Shift Keying

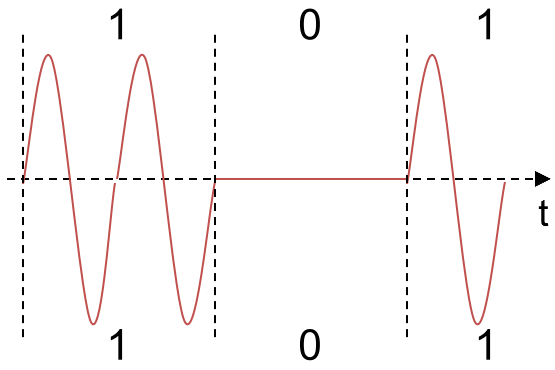
- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ 0 & \text{binary } 0 \end{cases}$$

- where the carrier signal is $A\cos(2\pi f_c t)$

Amplitude-Shift Keying

- Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference



Binary **Frequency-Shift Keying** (BFSK)

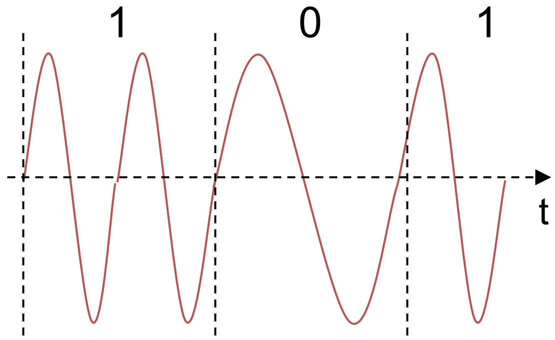
- Two binary digits represented by two different frequencies near the carrier frequency

$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary } 1 \\ A\cos(2\pi f_2 t) & \text{binary } 0 \end{cases}$$

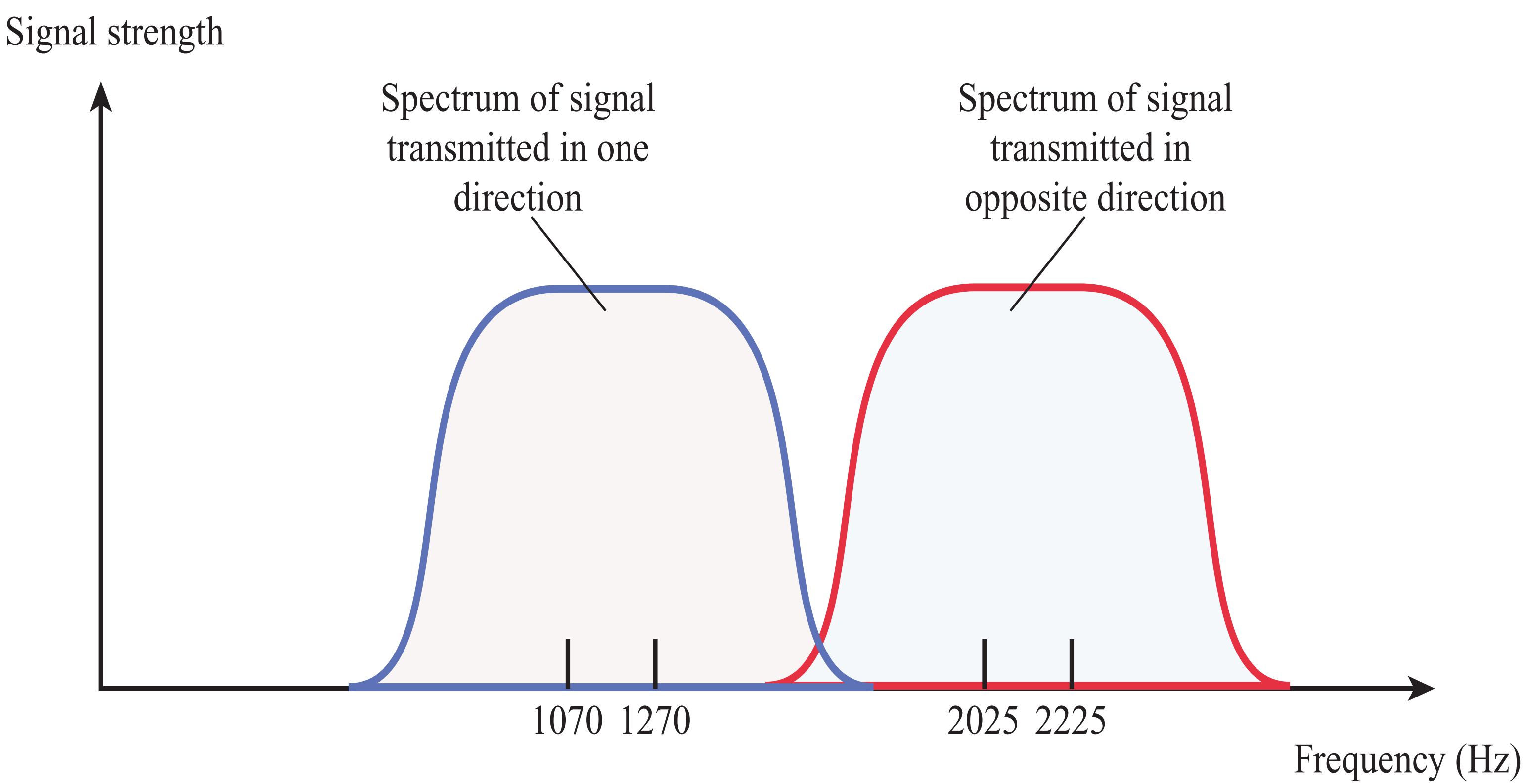
  - where f_1 and f_2 are offset from carrier frequency f_c by equal but opposite amounts f_d

Binary Frequency-Shift Keying (BFSK)

- Frequency Shift Keying (FSK):
  - needs larger bandwidth



Full-Duplex FSK Transmission on a Voice Grade Channel



Multiple Frequency-Shift Keying (MFSK)

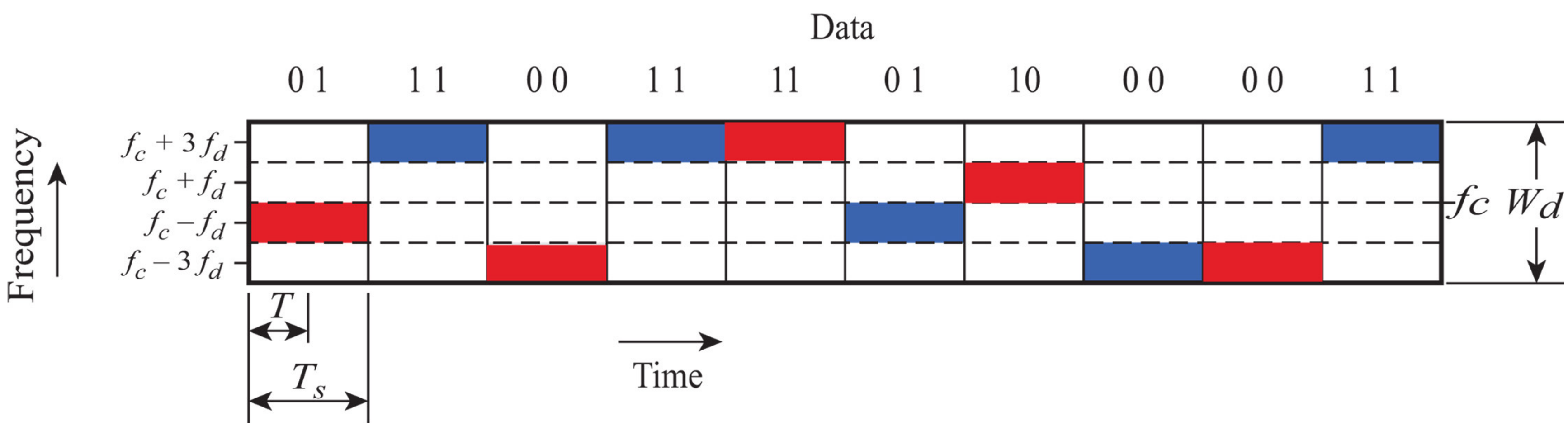
- More than two frequencies are used
- More bandwidth efficient but more susceptible to error

$$s_i(t) = A\cos 2\pi f_i t \quad 1 \le i \le M$$

- $f_i = f_c + (2i - 1 - M)f_d$
- f_c = the carrier frequency
- f_d = the difference frequency
- M = number of different signal elements = 2^L
- L = number of bits per signal element

Multiple Frequency-Shift Keying (MFSK)

MFSK Frequency Use (M = 4)



Phase-Shift Keying (PSK)

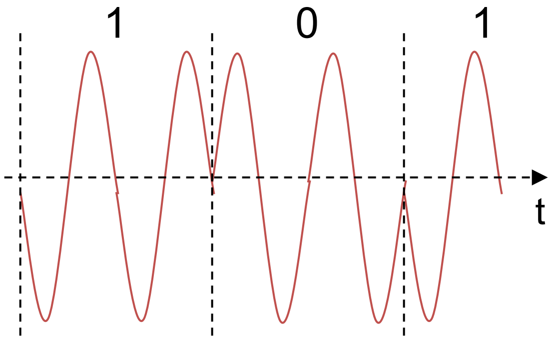
- Two-level PSK (BPSK)
  - Uses two phases to represent binary digits

$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary 1} \\ A\cos(2\pi f_c t + \pi) & \text{binary 0} \end{cases}$$

$$= \begin{cases} A\cos(2\pi f_c t) & \text{binary 1} \\ -A\cos(2\pi f_c t) & \text{binary 0} \end{cases}$$

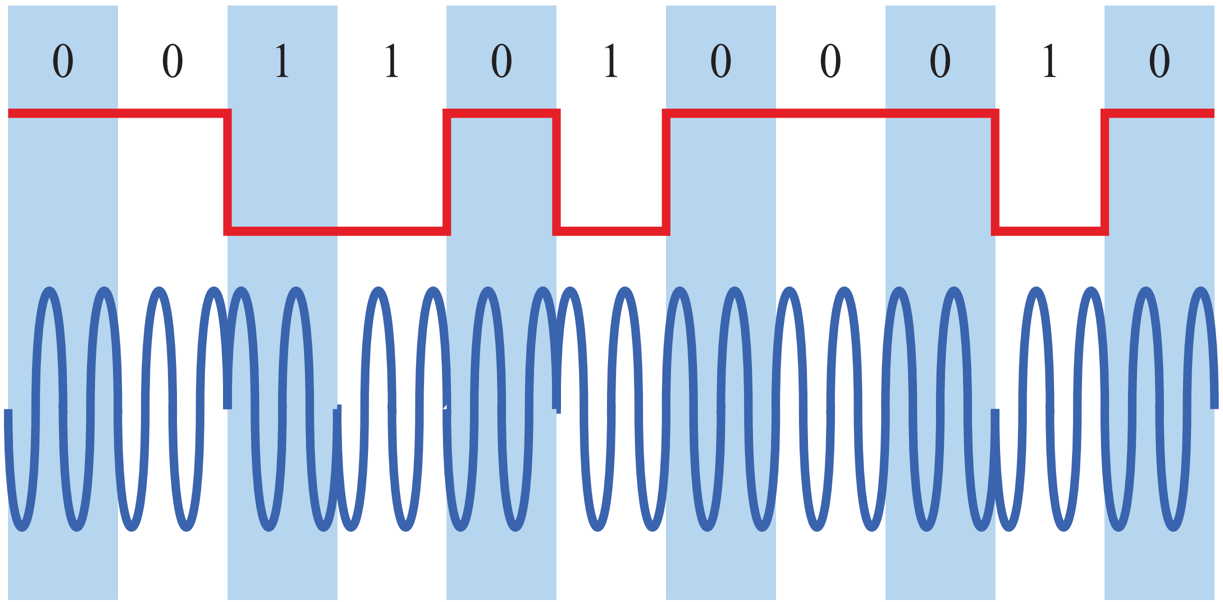
Phase-Shift Keying (PSK)

- Phase Shift Keying (PSK):
  - more complex
  - robust against interference



Differential Phase-Shift Keying (DPSK)

- Phase shift with reference to previous bit
  - Binary 0 – signal burst of same phase as previous signal burst
  - Binary 1 – signal burst of opposite phase to previous signal burst

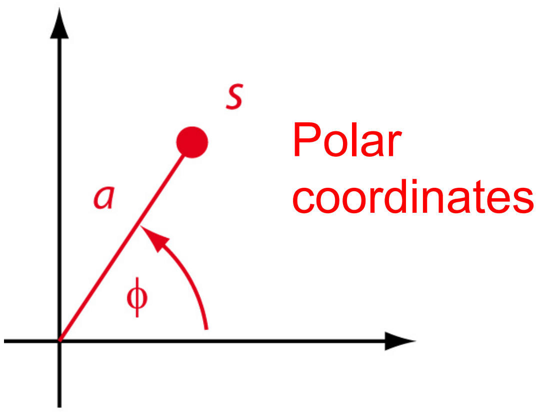


Signal Representation and Basic Concept

Amplitude-Phase-Notation:

$$s(t) = a(t)\ \cos\left(2\pi f_0 t + \phi(t)\right)$$

Signal space:



Basic concept of linear digital modulation:

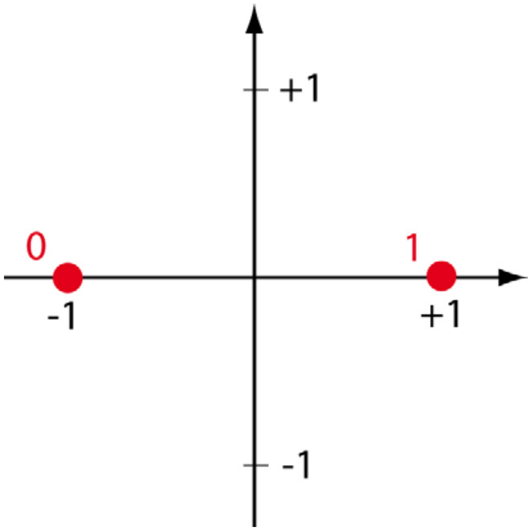
- Each *m* subsequent bits of the bit sequence are combined to one symbol:

- Each of the 2^m symbols has a different point (a, ϕ) in the signal space.
- The signal $s(t)$ is transmitted according to the above equation.

Binary Phase Shift Keying (BPSK)

Each single bit is mapped to a symbol (*m* = 1):

$$v = \underbrace{1}_{s_1} \quad \underbrace{0}_{s_2} \quad \underbrace{0}_{s_3} \quad \ldots$$



How many symbols are needed?

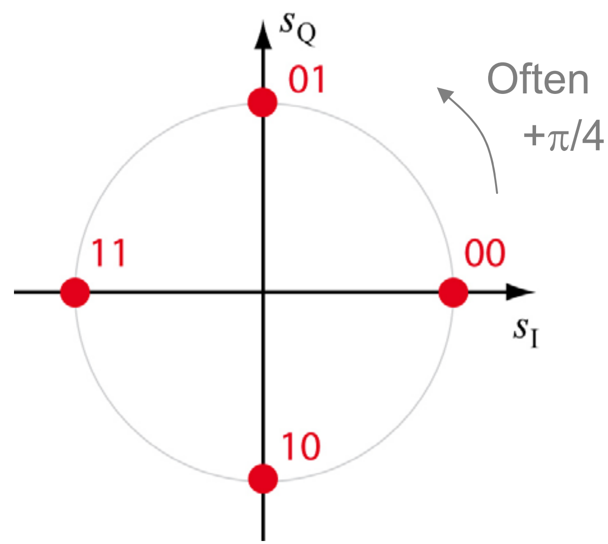
Since two symbols are required, the scheme is a “binary modulation”.

Quadrature Phase Shift Keying (QPSK)

Each *m* = 2 subsequent bits are mapped to a symbol:

$$v = \underbrace{1 \quad 0}_{s_1} \quad \underbrace{0 \quad 1}_{s_2} \quad \underbrace{0 \quad 1}_{s_3} \quad \ldots$$

- How many symbols are needed?



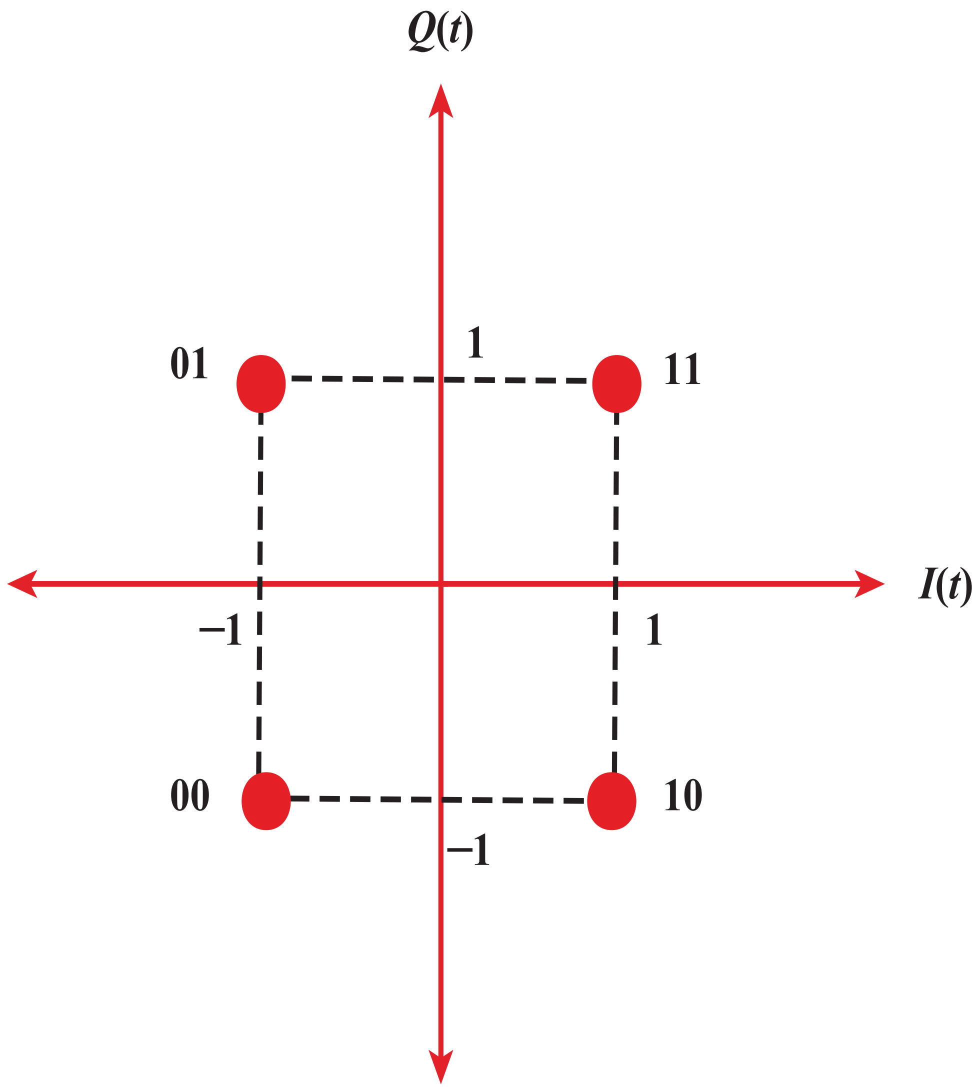
- The data rate is twice the data rate of BPSK.
- Used in UMTS, Bluetooth 2
- It should now be clear, how higher order modulation schemes, such as 8PSK, work.

Quadrature Phase-Shift Keying (QPSK)

- Four-level PSK (QPSK)
  - Each element represents more than one bit

$$s(t)=\begin{cases} A\cos\left(2\pi f_c t+\dfrac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t+\dfrac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t-\dfrac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t-\dfrac{\pi}{4}\right) & 10 \end{cases}$$

QPSK Constellation Diagram



Modulation Rate (or Signal rate)

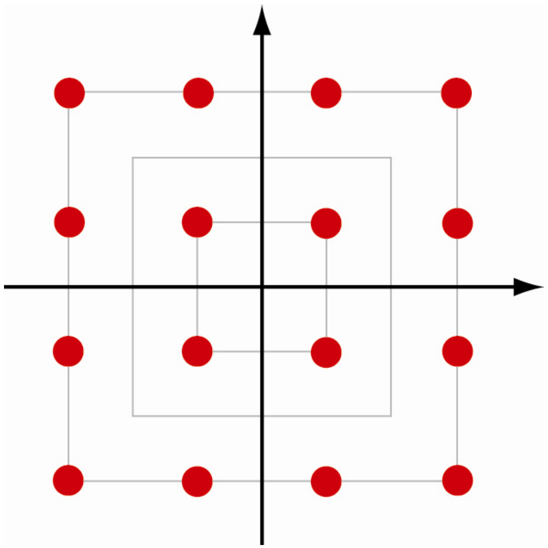
- Multilevel modulation (MPSK, MQAM)
  - Modulation Rate D (or symbol rate):

$$D = \frac{R}{L} = \frac{R}{\log_2 M}$$

- D = modulation rate, in baud, signals/sec, or symbols/sec.
- R = data rate, bps
- M = number of different signal elements = 2^L
- L = number of bits per signal element

Quadrature Amplitude Modulation (QAM)

QAM is a combination of ASK and PSK



16-QAM

- Combining m = 4 bits in 1 symbol
- The data rate is twice the one of QPSK
- Used in wireline modems and HSDPA (High Speed Downlink Packet Access)

General Case: *M*-ary linear modulation

- m subsequent bits are combined in one symbol
- The number of required symbols is $M = 2^m$

Bit error rate increases with m, but less errors compared to comparable PSK schemes

QAM

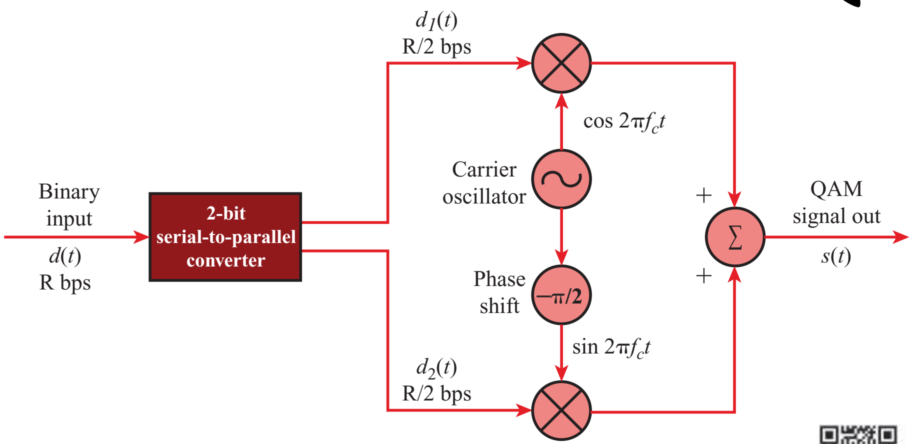


Figure 7.12 QAM Modulator

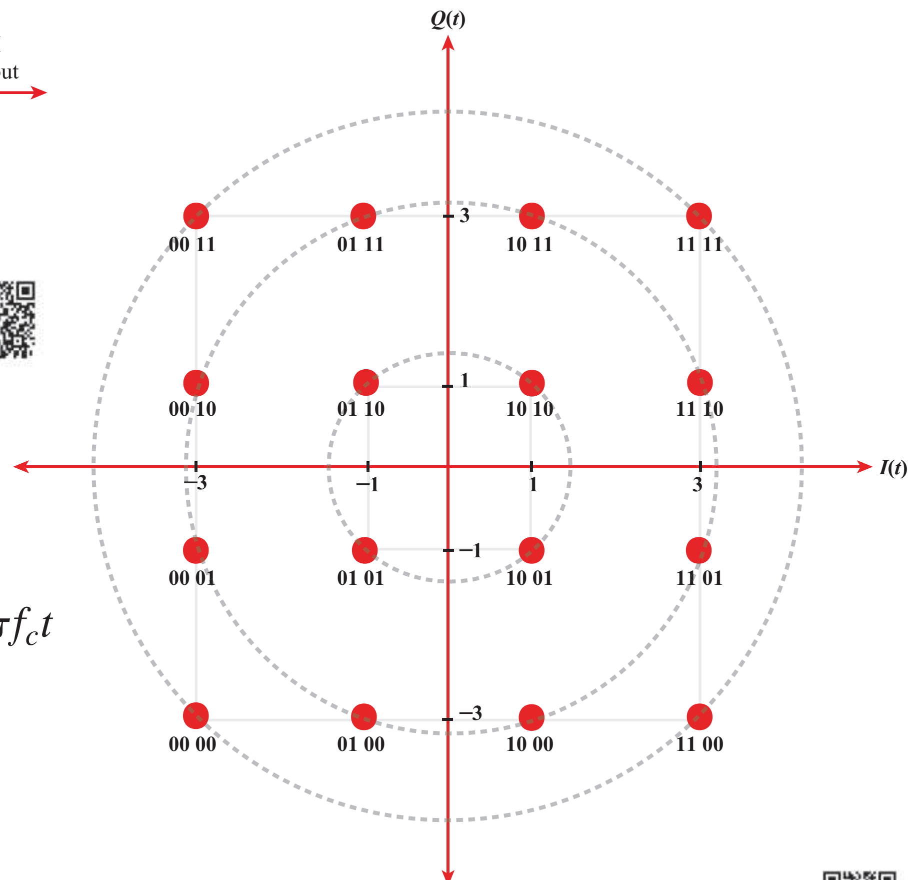


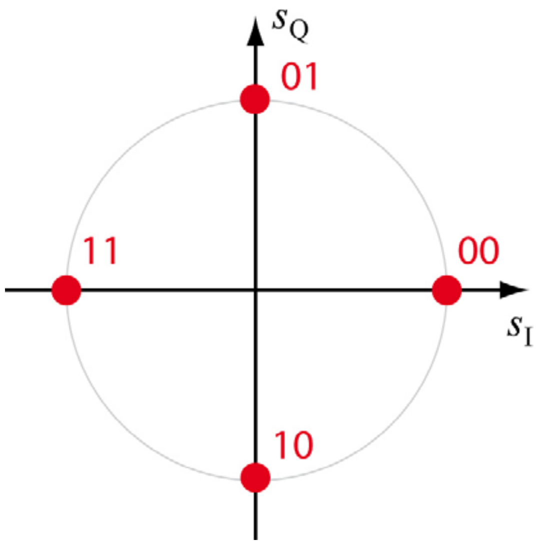
Figure 7.11 16QAM Constellation Diagram

QAM $s(t) = a_n(t)\cos 2\pi f_c t + b_n(t)\sin 2\pi f_c t$

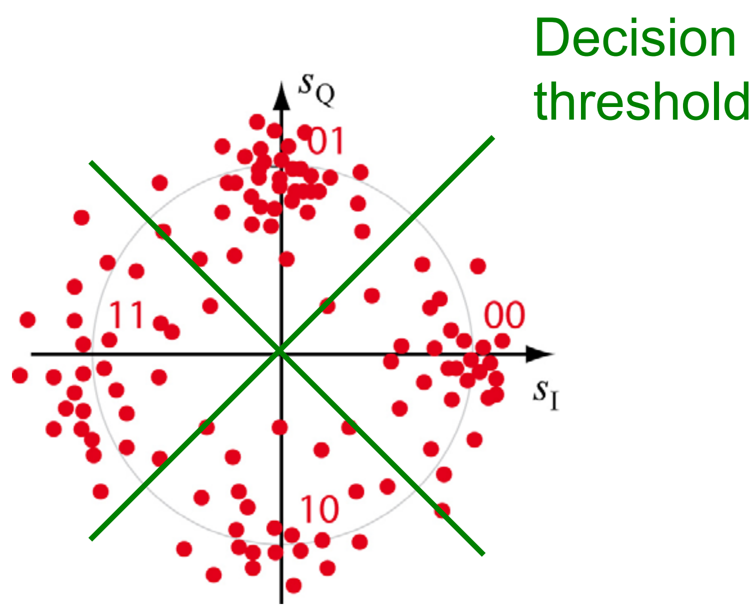
Symbol Decisions in Signal Constellation

Example:

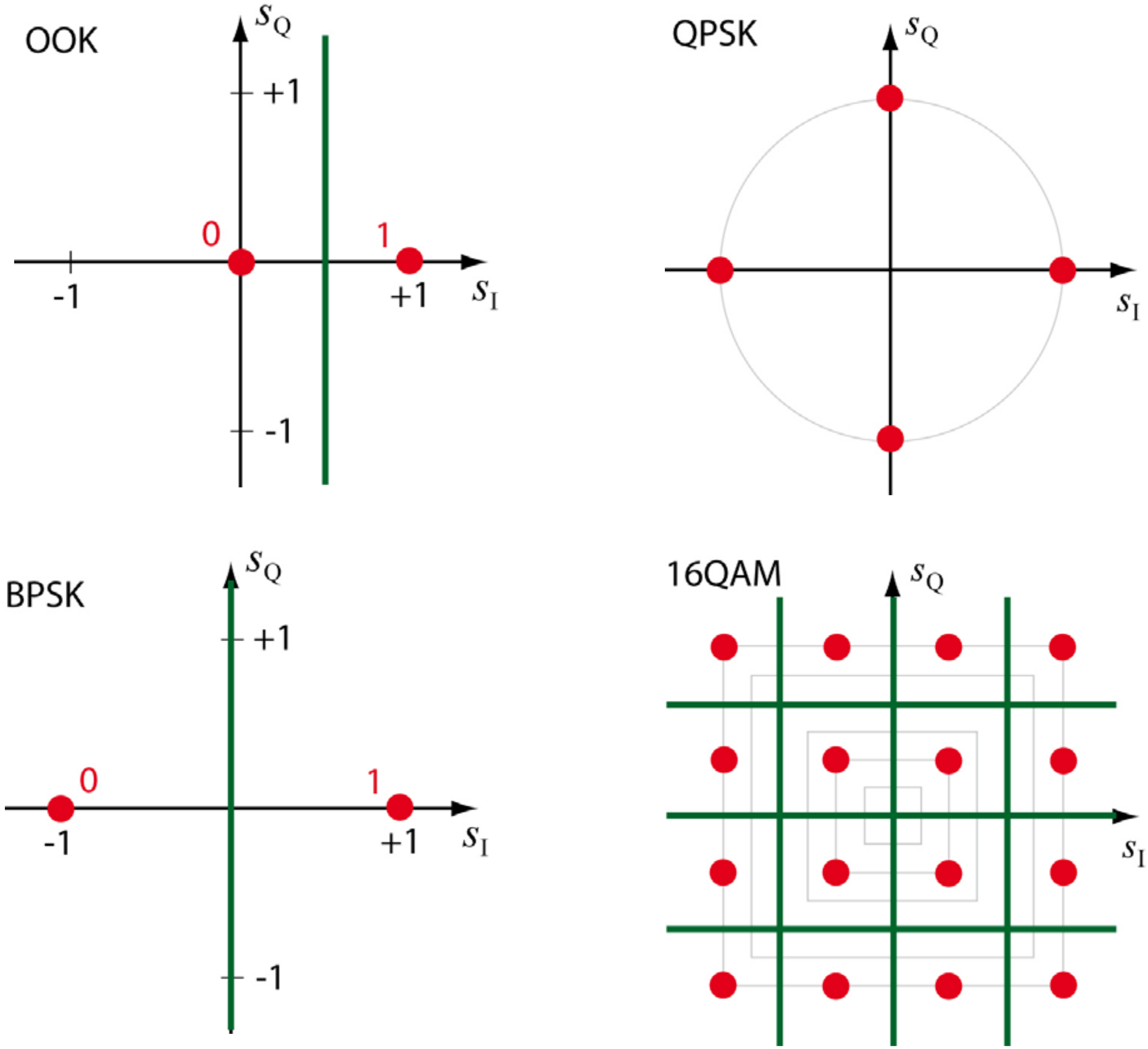
Sent signal



Received signal



Symbol Decisions in Signal Constellation



Bit rate
(#symbols)

versus

error probability
(distance btw symbols)

WiFi (IEEE 802.11n)

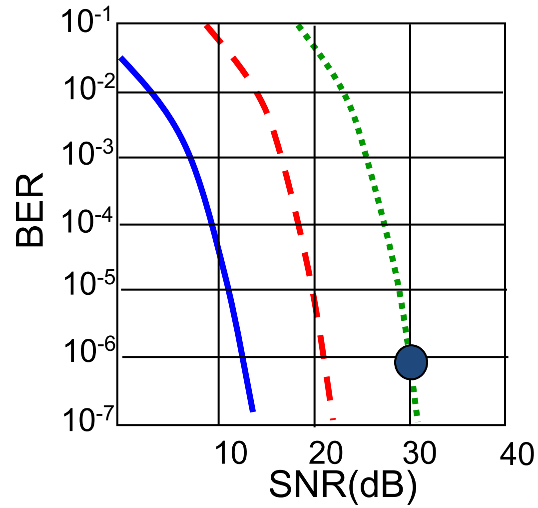
Modulation and coding schemes

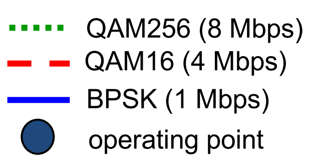
MCS index	Spatial streams	Modulation type	Coding rate	Data rate (in Mbit/s)[a]			
				20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15
1	1	QPSK	1/2	13	14.4	27	30
2	1	QPSK	3/4	19.5	21.7	40.5	45
3	1	16-QAM	1/2	26	28.9	54	60
4	1	16-QAM	3/4	39	43.3	81	90
5	1	64-QAM	2/3	52	57.8	108	120
6	1	64-QAM	3/4	58.5	65	121.5	135
7	1	64-QAM	5/6	65	72.2	135	150
8	2	BPSK	1/2	13	14.4	27	30
9	2	QPSK	1/2	26	28.9	54	60
10	2	QPSK	3/4	39	43.3	81	90
11	2	16-QAM	1/2	52	57.8	108	120
12	2	16-QAM	3/4	78	86.7	162	180
13	2	64-QAM	2/3	104	115.6	216	240
14	2	64-QAM	3/4	117	130	243	270
15	2	64-QAM	5/6	130	144.4	270	300
16	3	BPSK	1/2	19.5	21.7	40.5	45

802.11 Rate Adaptation

Rate Adaptation

- base station, mobile dynamically change transmission rate (physical layer modulation technique) as mobile moves, SNR varies





1. SNR decreases, BER increase as node moves away from base station

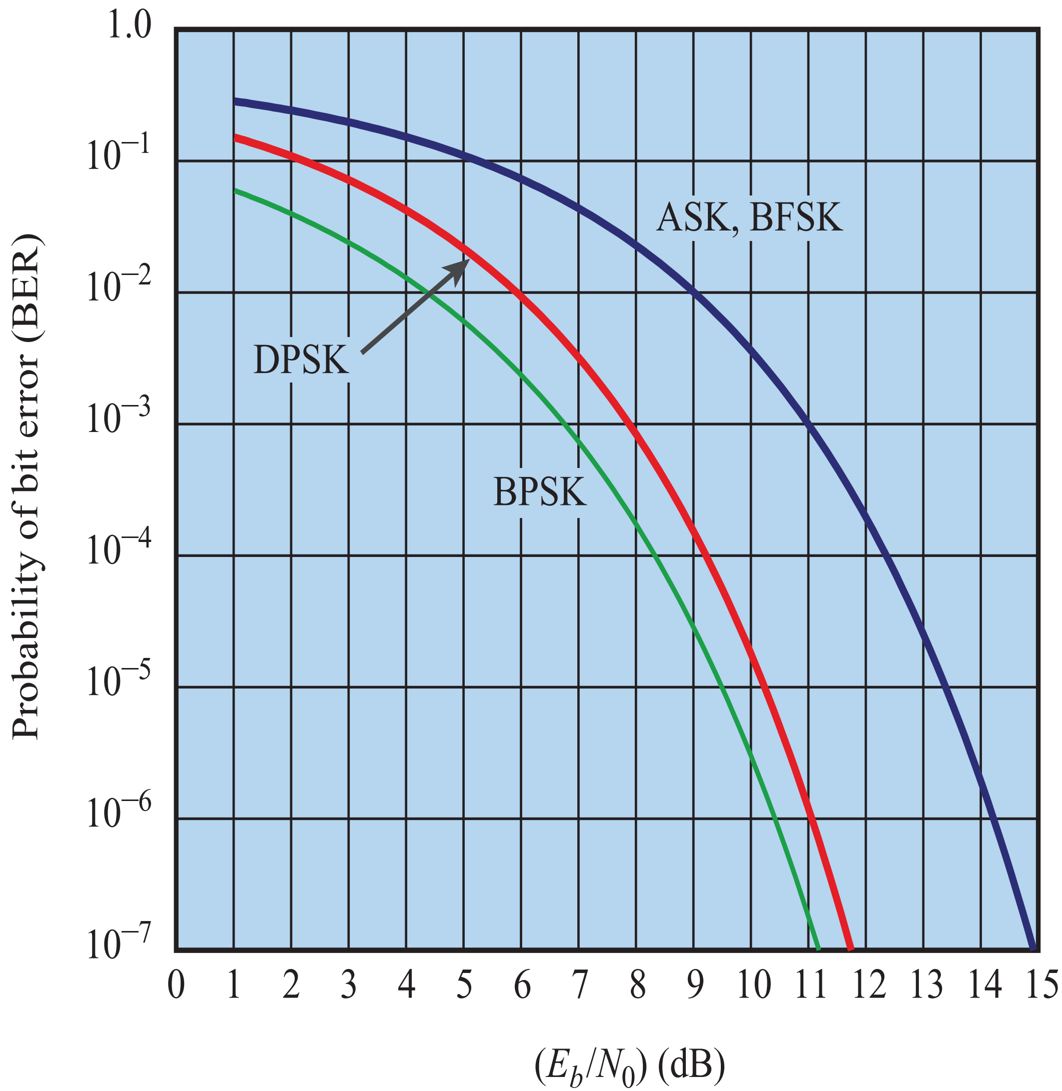
2. When BER becomes too high, switch to lower transmission rate but with lower BER

Complexity: Coherent vs. Non-Coherent Detection

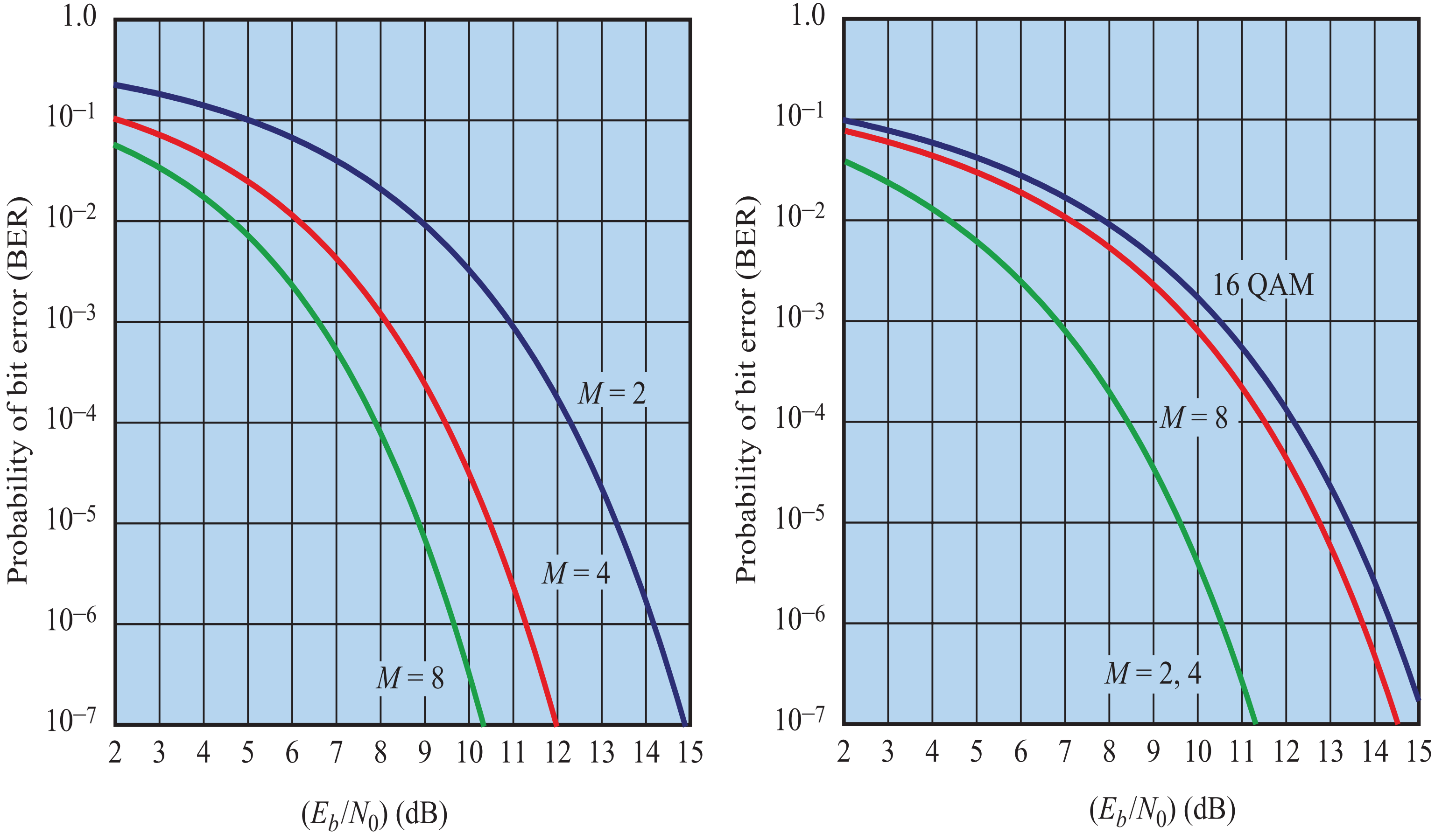
- **Coherent detection** requires exact knowledge of the phase of the signal (receiver is "phase locked"). This reference may be difficult to obtain or significantly increase receiver complexity.
  Example: PSK

- **Non-coherent detection** does not require this knowledge.
  Example: FSK, Differential PSK (DPSK)

Theoretical Bit Error Rate for Various Encoding Schemes



Theoretical Bit Error Rate for Multilevel FSK, PSK, and QAM



(a) Multilevel FSK (MFSK)

(b) Multilevel PSK (MPSK) and 16 QAM

Criteria for Choosing a Modulation Scheme

	Linear Modulation (ASK/PSK)	**Non-linear Modulation** (FSK)
Bandwidth efficiency (max bit/s / Hz)	better	Nonlinear processing leads to spectral broadening.
Power efficiency (min energy / bit to achieve certain bit error probability)	Linear amplifiers are typically less power efficient	better
Cost and complexity of implementation	Linear amplifiers are typically more expensive	better
Robustness to wireless transmission	Amplitude and phase of the transmitted signal are more susceptible to variations from fading and interference	Better, due to constant envelope

Conflicting requirements → Find best tradeoff for the particular system to be designed

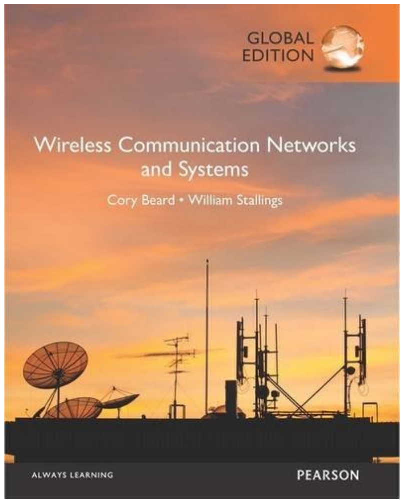
Modulation Schemes in Current Technologies (Cellular communications)

GSM	Gaussian Minimum Shift Keying (MSK), a kind of FSK
GSM / EDGE	8-PSK
UMTS	QPSK
HSDPA	QPSK, 16-QAM (adaptive modulation)
HSDPA+	QPSK, 16-QAM, 64-QAM (adaptive modulation)
LTE	QPSK, 16-QAM, 64-QAM (adaptive modulation)
LTE-A	…, 64-QAM, 256-QAM (adaptive modulation)
5G NR	…, 64-QAM, 256-QAM (adaptive modulation)

Modulation Schemes in Current Technologies (Local and Personal wireless communications)

DECT	FSK (Gaussian FSK or Gaussian MSK)
802.11b	Differential PSK (BPSK, QPSK)
802.11a, g	BPSK, QPSK, 16-QAM, 64-QAM (adaptive modulation)
802.11n	BPSK, QPSK, 16-QAM, 64-QAM (adaptive modulation)
802.11ac	…, 64-QAM, 256-QAM (adaptive modulation)
802.11ax	…, 256-QAM, 1024-QAM (adaptive modulation)
802.15.4	BPSK (at 868/915 MHz), Offset-QPSK (at 2.4 GHz)
Bluetooth	Gaussian FSK (1 Mbit/s)
Bluetooth v2	Differential $\pi/4$-QPSK (2 Mbit/s) and 8-PSK (3 Mbit/s)

Literature



Wireless Communication Networks and Systems,

C. Beard and W. Stallings, Prentice Hall

- Chap 7