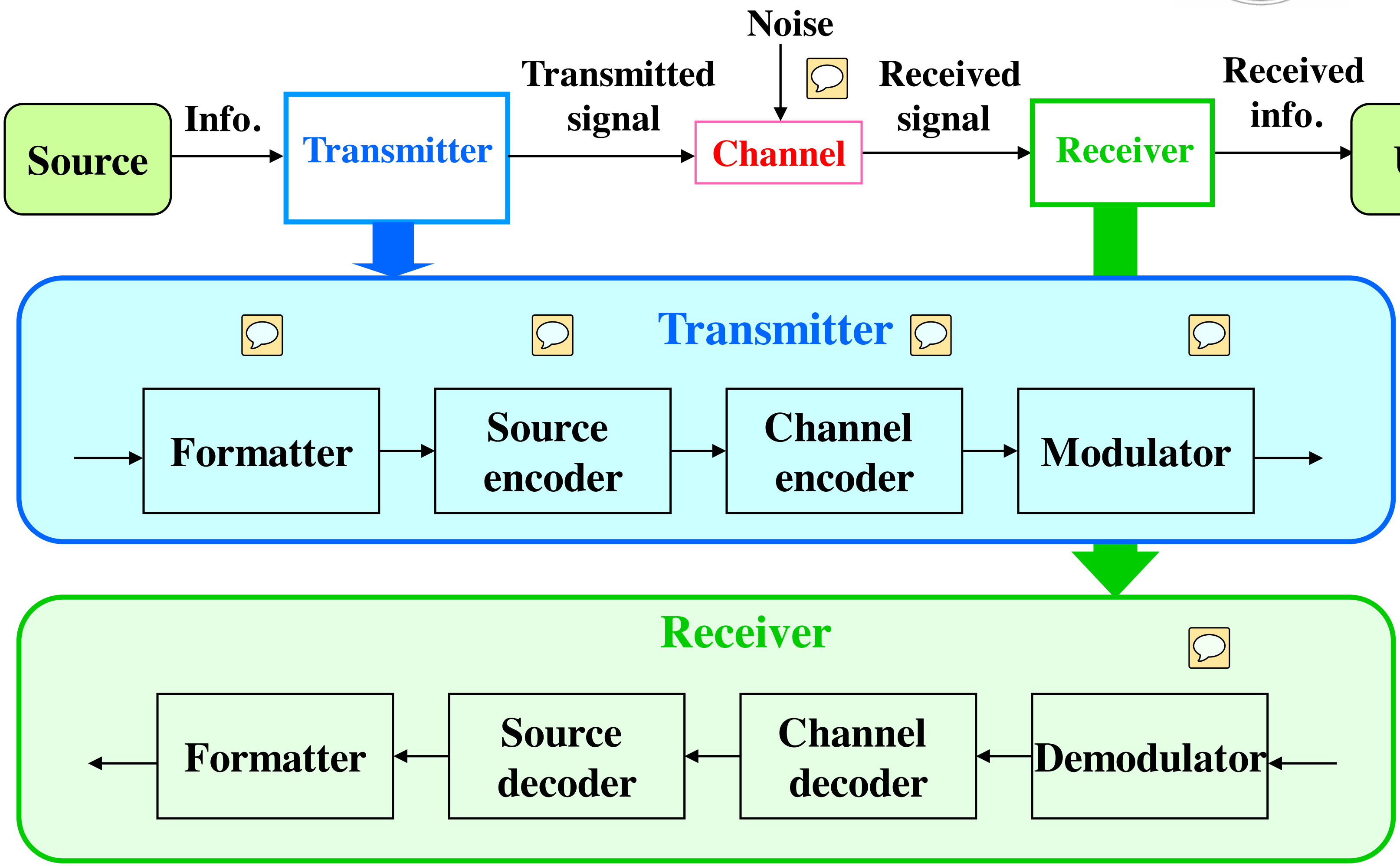
Outline

- A preliminary overview
- Propagation characteristics
- ISO-OSI Model
- **Physical layer: modulation**
- MAC layer:
  - Fixed resource assignment
  - Random access
    - Ethernet (CSMA/CD)
    - WiFi (CSMA/CA)
- Personal Area Networks
  - Bluetooth
  - Zigbee
- Cellular network dimensioning
- Cellular networks
  - From GSM (2G) to UMTS (3G)
  - LTE (4G)

General Structure of a Communication System



Channel Capacity

- Channel Capacity (C)
  - the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions
- Data rate (bps)
  - rate at which data can be communicated , impairments, such as noise, limit data rate that can be achieved
- Bandwidth (B)
  - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise (N)
  - impairments on the communications path
- Error rate - rate at which errors occur (BER)
  - Error = transmit 1 and receive 0; transmit 0 and receive 1

Reasons for choosing encoding techniques

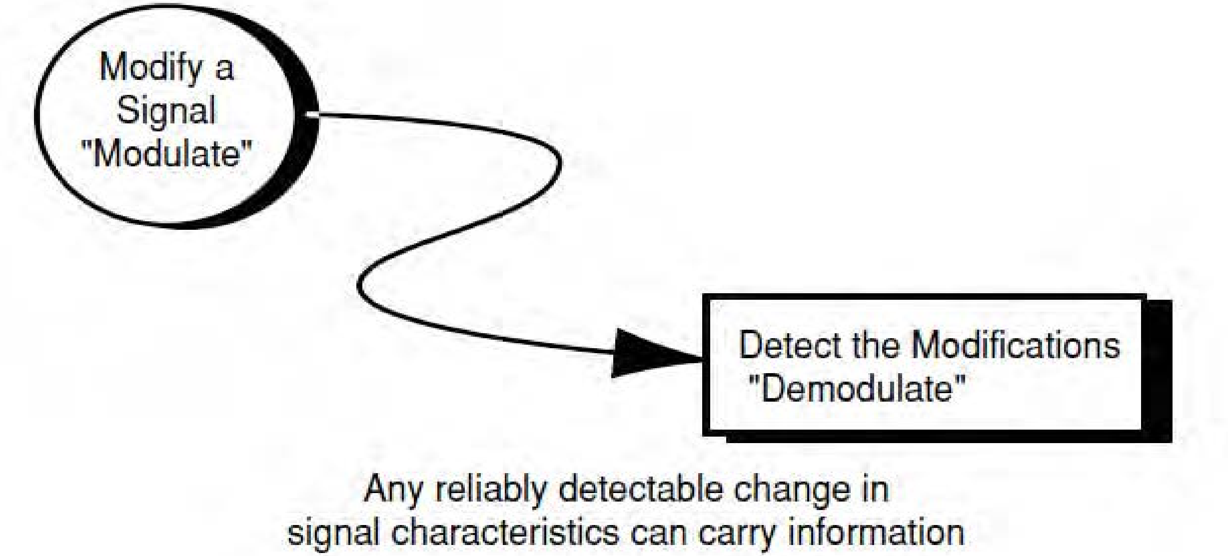
- Digital data, digital signal
  - Equipment less complex and expensive than digital-to-analog modulation equipment
- Analog data, digital signal
  - Permits use of modern digital transmission and switching equipment
- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - E.g., unguided media (air)
- Analog data, analog signal
  - Analog data in electrical form can be transmitted easily and cheaply
  - E.g., AM Radio

What is modulation ?

- Modulation = Adding information to a carrier signal

$$x(t) = A\cos(2\pi ft + \Phi)$$

  - A – amplitude
  - f – frequency
  - Φ – phase (initial angle of the sinusoidal function at its origin
- The sine wave on which the characteristics of the information signal are modulated is called a carrier signal

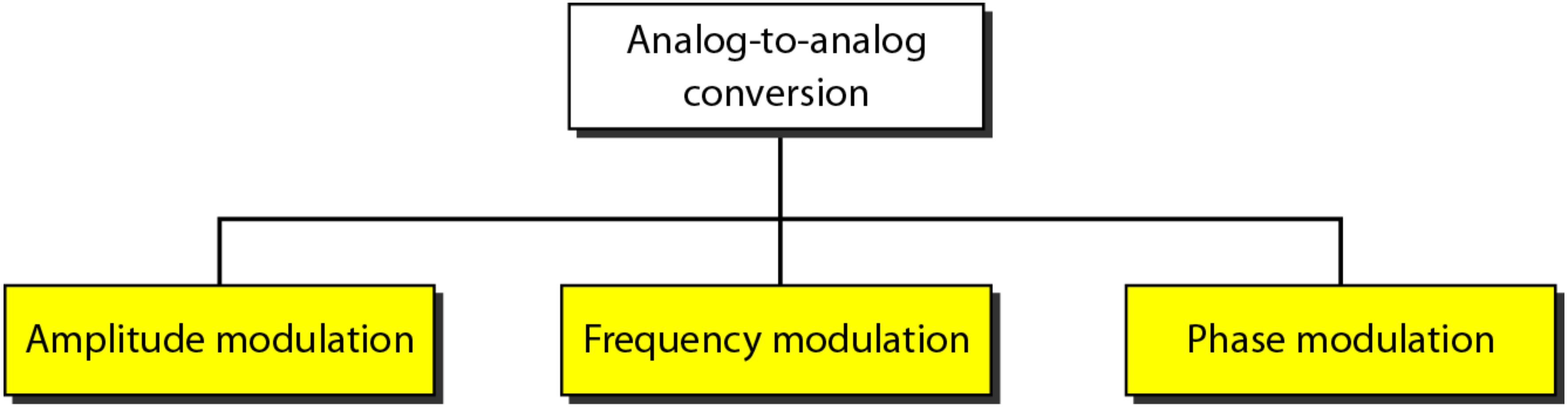


Analog(-to-analog) modulation

Analog-to-analog conversion is the representation of analog information by an analog signal. One may ask why we need to modulate an analog signal; it is already analog. Modulation is needed if the medium is bandpass in nature or if only a bandpass channel is available to us.

- Amplitude Modulation
- Frequency Modulation
- Phase Modulation

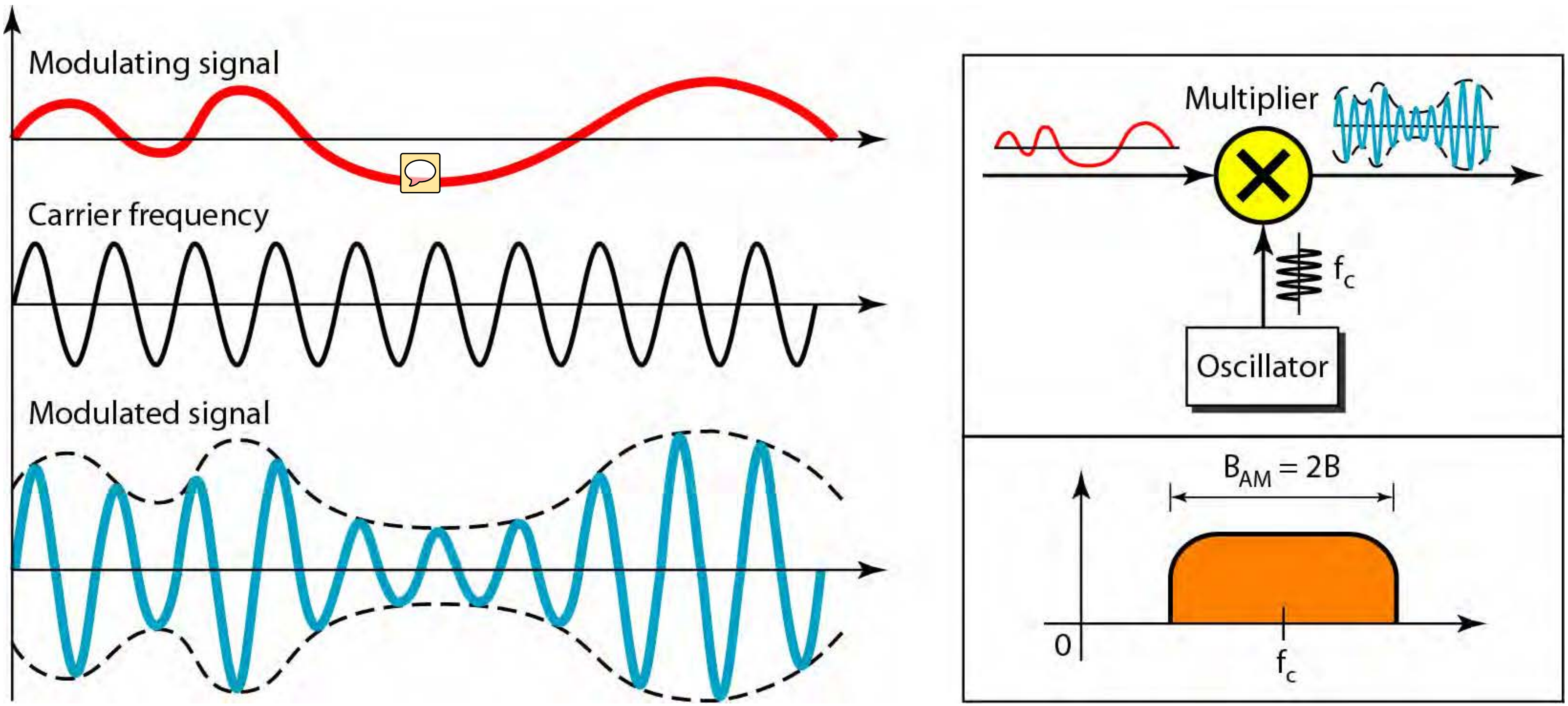
Types of analog-to-analog modulation



Amplitude Modulation (AM)

- A carrier signal is modulated only in amplitude value
- The modulating signal is the envelope of the carrier
- The required bandwidth is 2B, where B is the bandwidth of the modulating signal
- Since on both sides of the carrier freq. f_c, the spectrum is identical, we can discard one half, thus requiring a smaller bandwidth for transmission.

Amplitude Modulation (AM) - ctd



Amplitude Modulation (AM) - ctd

- The total bandwidth required for AM can be determined from the bandwidth of the audio signal: $B_{AM} = 2B$.

$$m(t) \quad \rightarrow \quad \text{information signal}$$

$$A_c \cos[2\pi f_c t] \quad \rightarrow \quad \text{carrier}$$

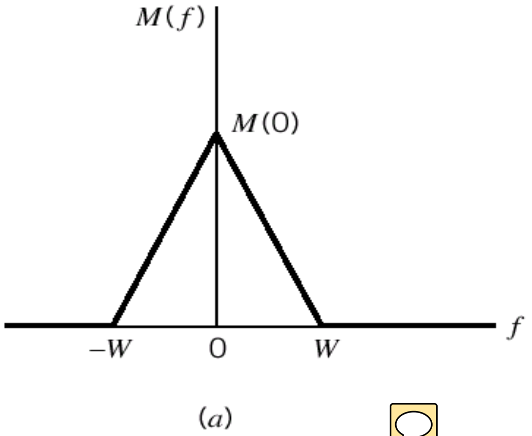
$$f_c \quad \rightarrow \quad \text{carrier frequency}$$

$$S_{AM}(t) = A_c\left[1 + m(t)\right]\cos[2\pi f_c t] \quad \rightarrow \quad \text{transmitted signal}$$

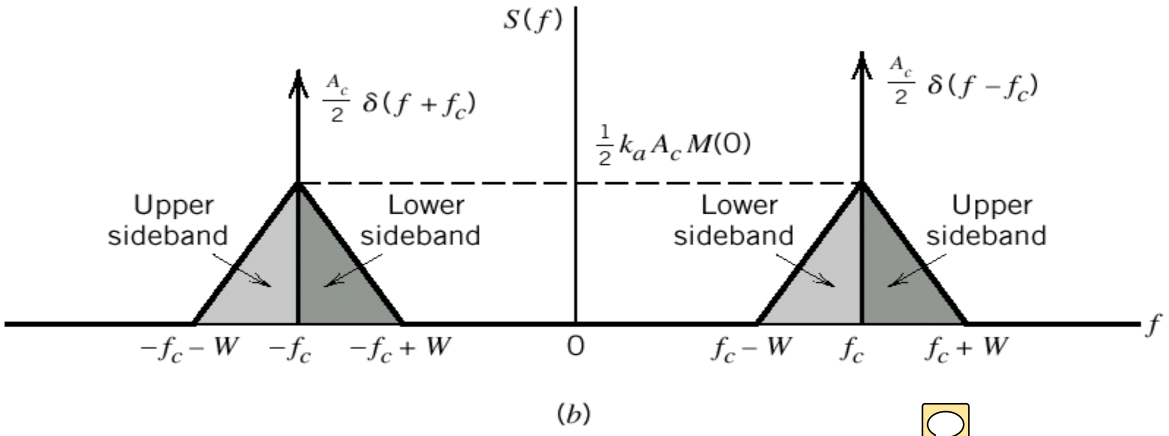
k_a

Spectrum of AM signal

$$S(f)=\frac{A_c}{2}[\delta(f-f_c)+\delta(f+f_c)]+\frac{k_a A_c}{2}[M(f-f_c)+M(f+f_c)]$$

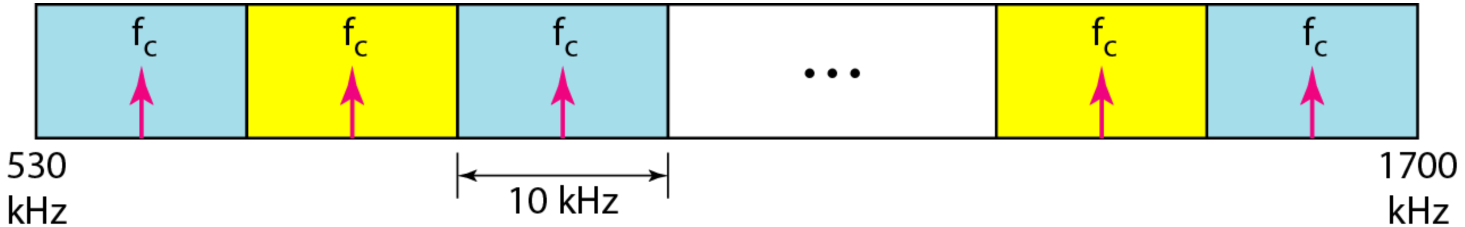


Spectrum of baseband signal.



Spectrum of AM signal.

Band allocation



Frequency Modulation

- Unlike AM, the amplitude of the FM carrier is kept constant (constant envelope) & the *carrier* frequency is varied proportional to the modulating signal $m(t)$:

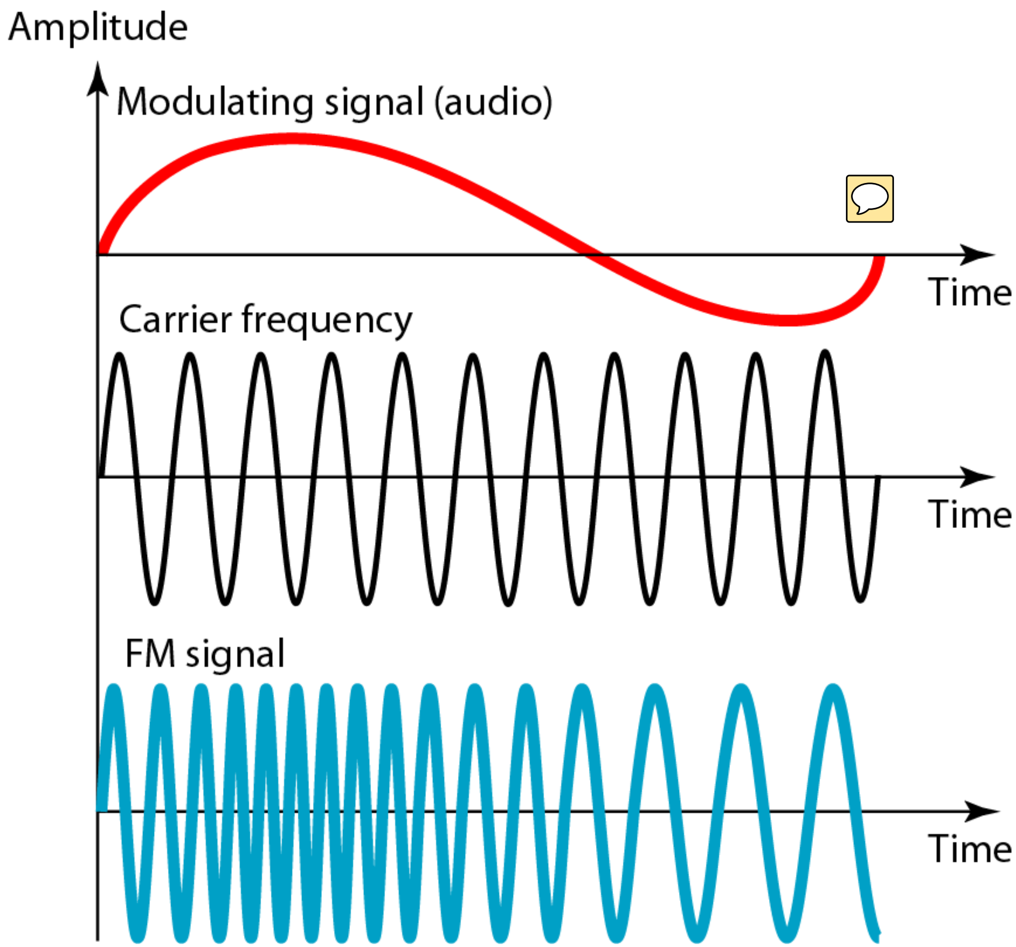
$$S_{FM}(t) = A_c \cos[\theta(t)]$$

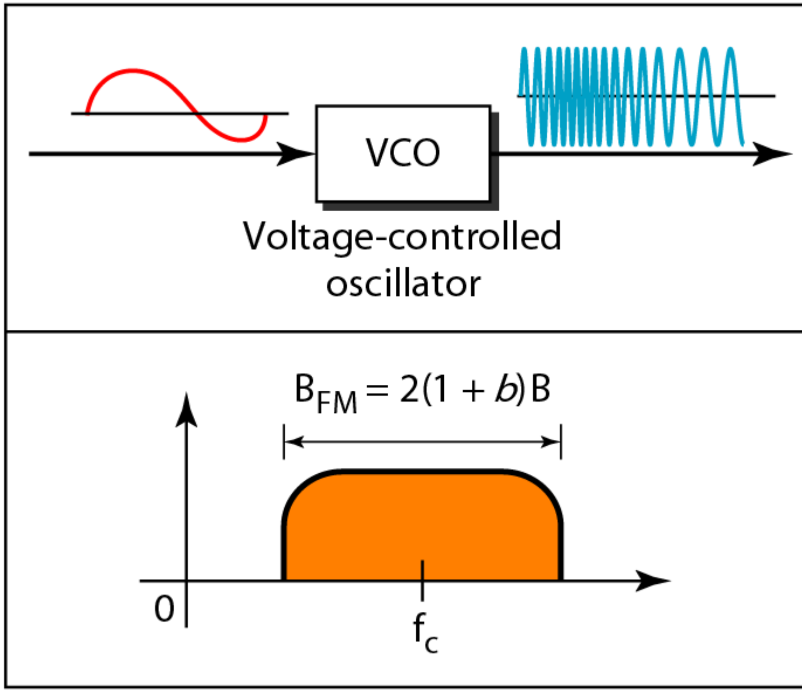
$$\begin{aligned}\omega(t) &= \text{instatantaneous angular frequency} \\ &= \frac{d\theta}{dt} = 2\pi f_c + 2\pi k_f\, m(t) \quad \leftarrow \quad \text{desired}\end{aligned}$$

  - f_c plus a deviation of $k_f m(t)$
  - k_f : frequency deviation constant (in Hz/V) - defines amount magnitude of allowable frequency change

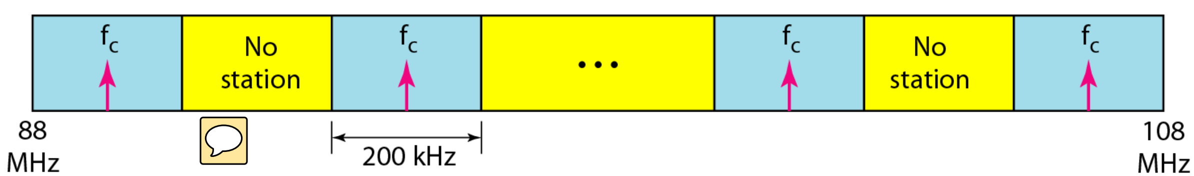
- The total bandwidth required for FM can be determined from the bandwidth of the audio signal: $B_{FM} = 2(1 + \beta)B$, where β is usually 4 ($B_{FM} = 10\ B$).

Frequency Modulation (ctd)





Band allocation



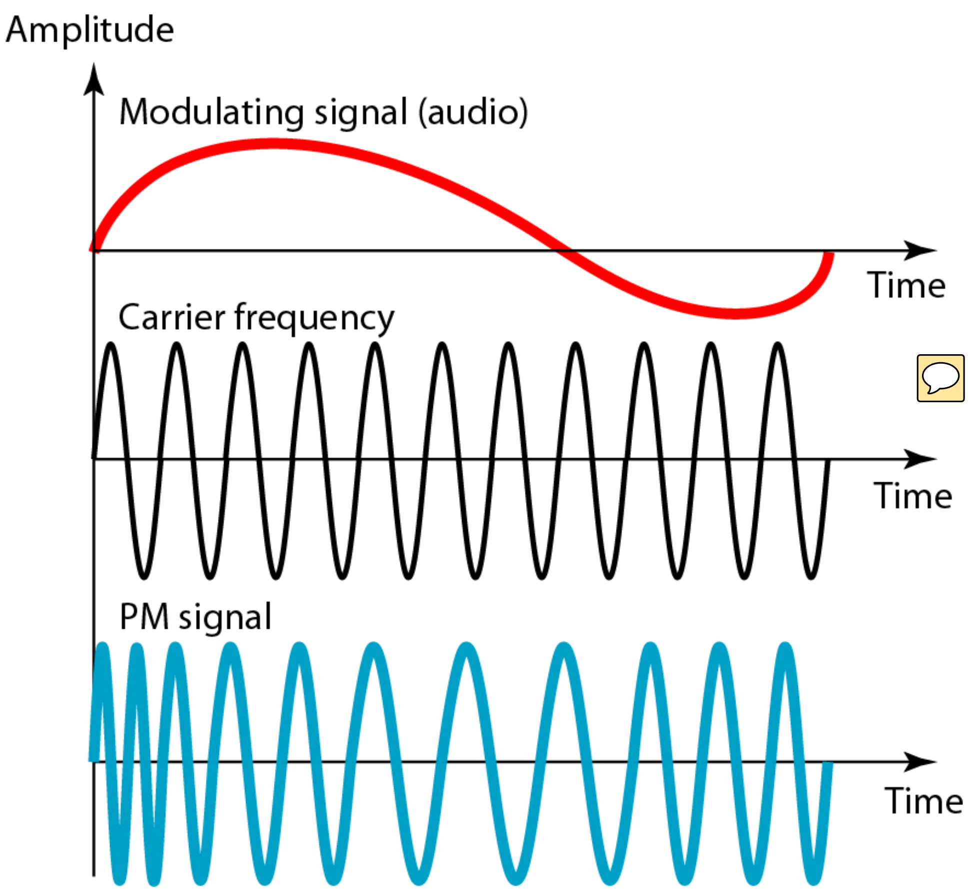
Phase Modulation (PM)

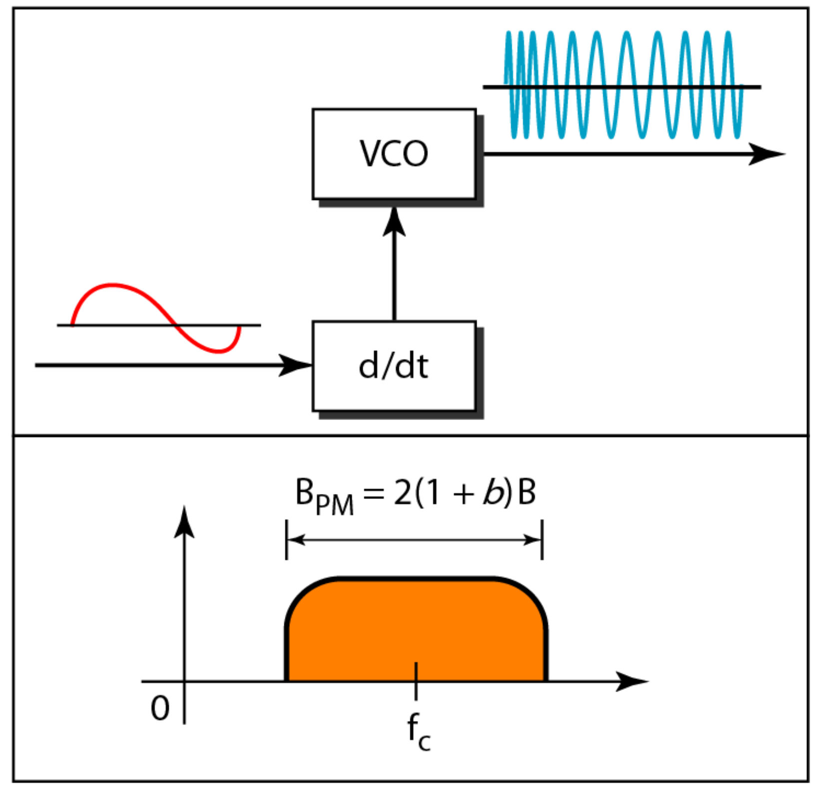
- The modulating signal only changes the phase of the carrier signal.

$$S_{PM}(t) = A_c \cos[2\pi f_c t + k_P m(t)]$$

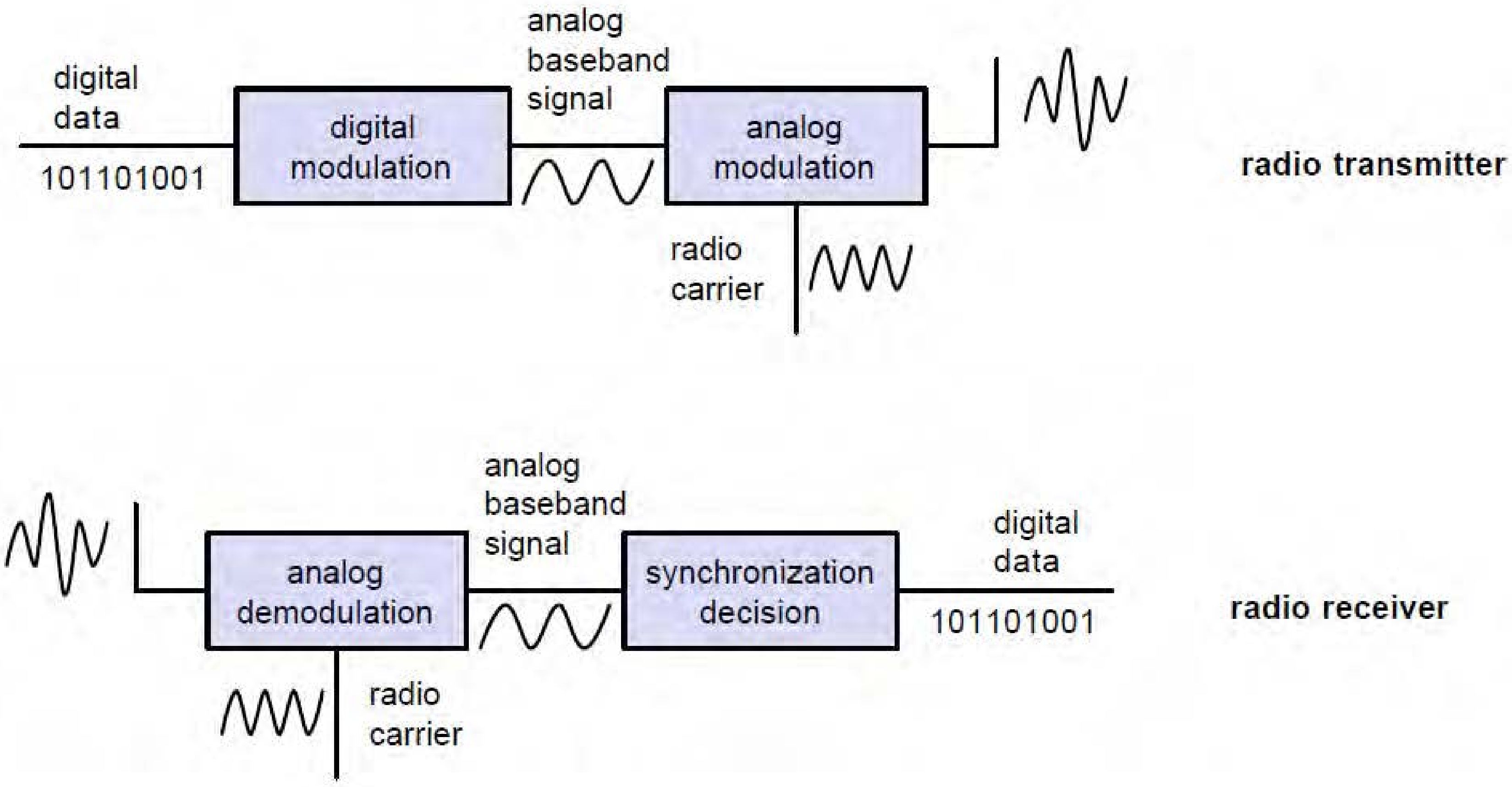
- The phase change manifests itself as a frequency change but the instantaneous frequency change is proportional to the derivative of the amplitude.
- The bandwidth is higher than for AM.
- The total bandwidth required for PM can be determined from the bandwidth and maximum amplitude of the modulating signal: $B_{PM} = 2(1 + \beta)B$, where β is usually 2 ($B_{PM} = 6\ B$).

Phase Modulation (ctd)





Digital modulation and demodulation



If the information is digital, changing parameters is called "keying"

Digital modulation: classification

Digital modulation can be broadly classified as:

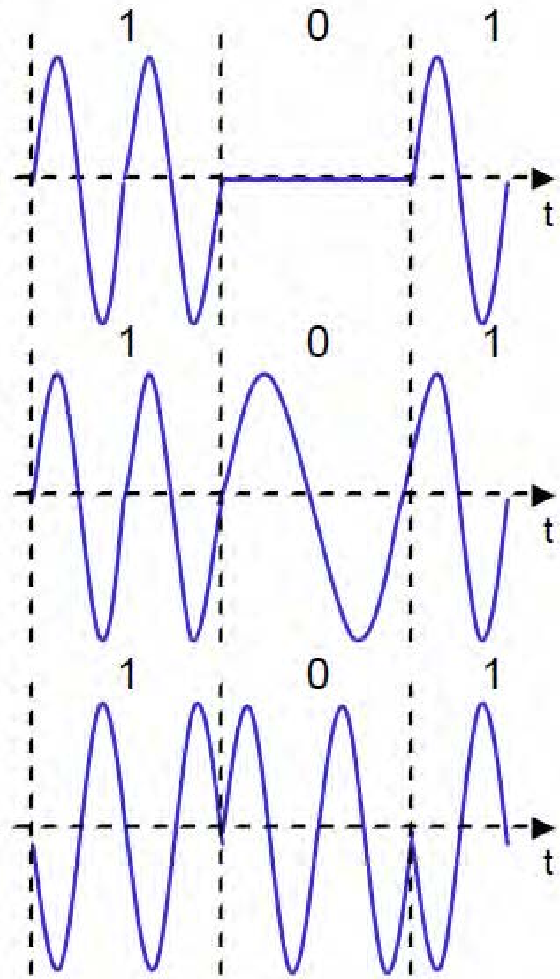
1. Linear (change Amplitude or phase)
2. Non linear modulation techniques (change frequency).

Linear Modulation Techniques:

- The amplitude/phase of the transmitted signal *s(t)* varies linearly with the modulating digital signal *m(t)*.
- They are bandwidth efficient (because the frequency does not change) and, hence, are very attractive for use in wireless communication systems where there is an increasing demand to accommodate more and more users within a limited spectrum.

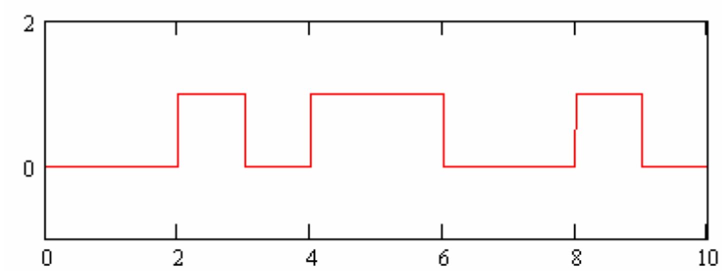
Digital modulation techniques

- Amplitude Shift Keying (ASK):
  - change amplitude with each symbol – frequency constant
  - low bandwidth requirements
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - change frequency with each symbol
  - needs larger bandwidth
- Phase Shift Keying (PSK):
  - Change phase with each symbol
  - More complex
  - robust against interference

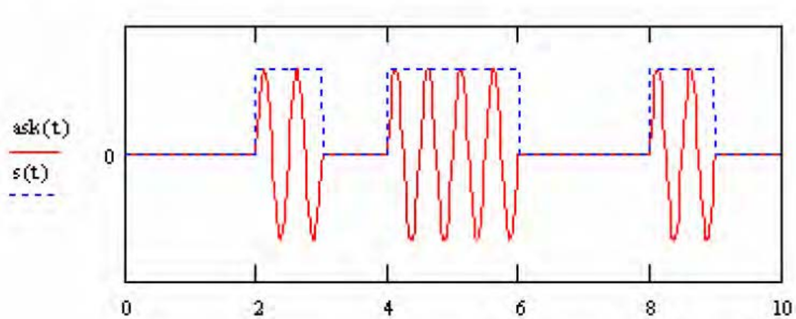


Amplitude Shift Keying (ASK)

- ASK On-off keying (OOK) – frequency is kept constant, amplitude has 2 levels (for bit 1 and for bit 0)



$$ASK(t) = s(t)\sin(2\pi f t)$$

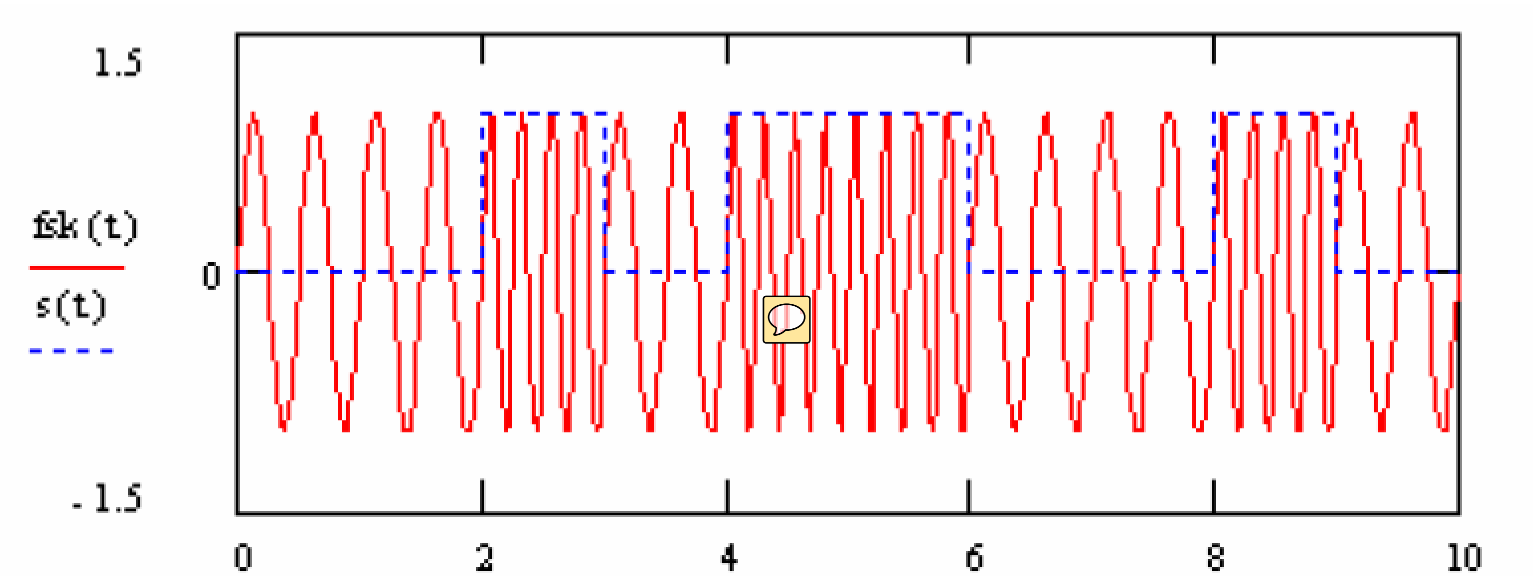


The binary sequence 0010110010

Frequency shift keying (FSK)

$$FSK(t) = \begin{cases} \sin(2\pi f_1 t) & \textit{for bit } 1 \\ \sin(2\pi f_2 t) & \textit{for bit } 0 \end{cases}$$

The carrier frequency can assume two values (f_1 and f_2)

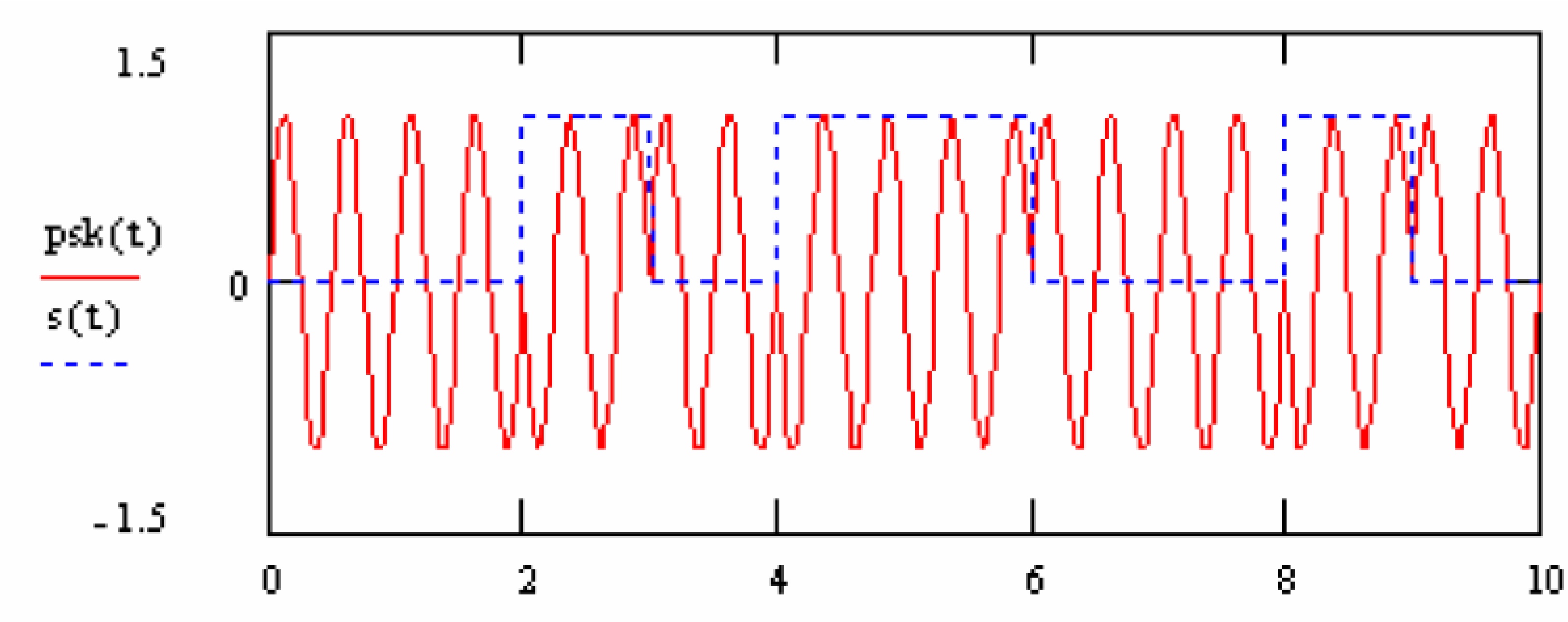


The binary sequence 0010110010 (as before)

Phase shift keying (PSK)

$$PSK(t) = \begin{cases} \sin(2\pi f t) & for\, bit\, 1 \\ \sin(2\pi f t + \pi) & for\, bit\, 0 \end{cases}$$

The phase offset can assume two values (*0* and π) - **BINARY**



The binary sequence 0010110010 (as before)

Binary phase shift keying (BPSK)

If the sinusoidal carrier has energy per bit E_b and bit duration T_b, then the transmitted BPSK signal is either:

$$S_{\mathrm{BPSK}}(t) = \sqrt{\frac{2E_b}{T_b}} \cos\left(2\pi f_c t + \theta_c\right) \qquad 0 \le t \le T_b \quad \text{(binary 1)}$$

$$S_{\mathrm{BPSK}}(t) = \sqrt{\frac{2E_b}{T_b}} \cos\left(2\pi f_c t + \pi + \theta_c\right)$$

$$= -\sqrt{\frac{2E_b}{T_b}} \cos\left(2\pi f_c t + \theta_c\right) \quad 0 \le t \le T_b \quad \text{(binary 0)}$$

Quadrature phase shift keying (QPSK)

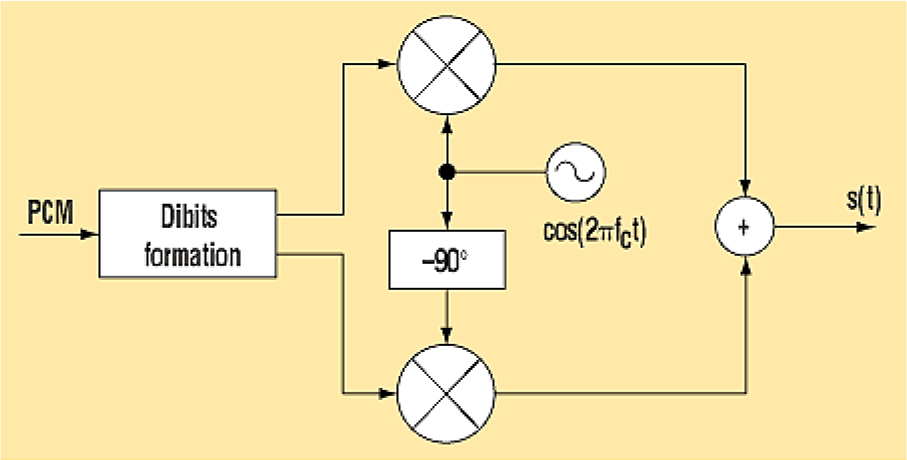
- A linear modulation scheme
- The phase of the carrier takes on 1 of 4 equally spaced values, such as $0, \pi/2, \pi$, and $3\pi/2$, where each value of phase corresponds to a unique pair of message bits.
- The QPSK signal for this set of symbol states may be defined as:

$$S_{\text{QPSK}}(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left[2\pi f_c t + (i-1)\frac{\pi}{2}\right] \qquad 0 \le t \le T_s \qquad i = 1, 2, 3, 4.$$

- QPSK has twice the bandwidth efficiency of BPSK, since 2 bits are transmitted in a single modulation symbol.

QPSK as two BPSKs

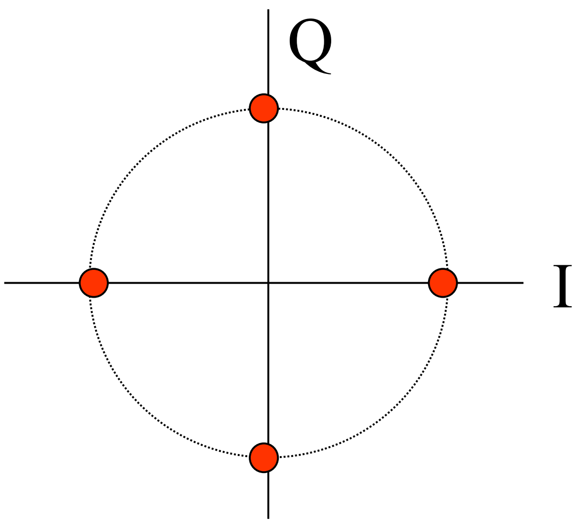
$$S_{QPSK} = \{ \sqrt{E_s}\cos\left[(i-1)\frac{\pi}{2}\right]\phi_1(t) - \sqrt{E_s}\sin\left[(i-1)\frac{\pi}{2}\right]\phi_2(t) \} \quad i = 1,2,3,4$$



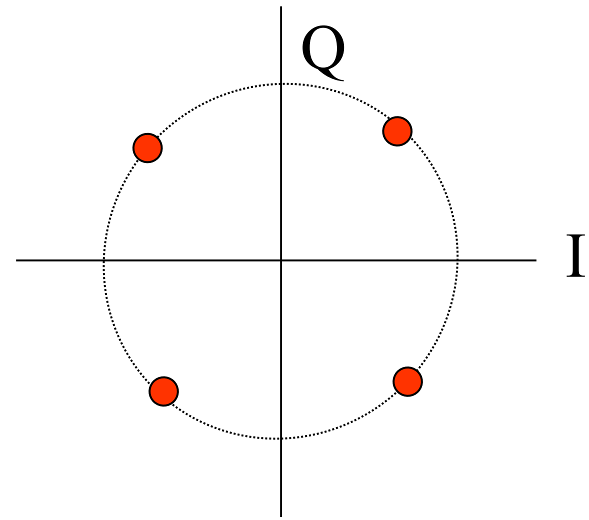
1. The classical method of implementing s(t) for a QPSK modulator is shown by this block diagram.

- QPSK can be interpreted as two independent BPSK systems (one on the I-channel and one on Q-channel) → same performance (bit error rate) but twice the bandwidth (spectrum) efficiency.

QPSK Constellation Diagram



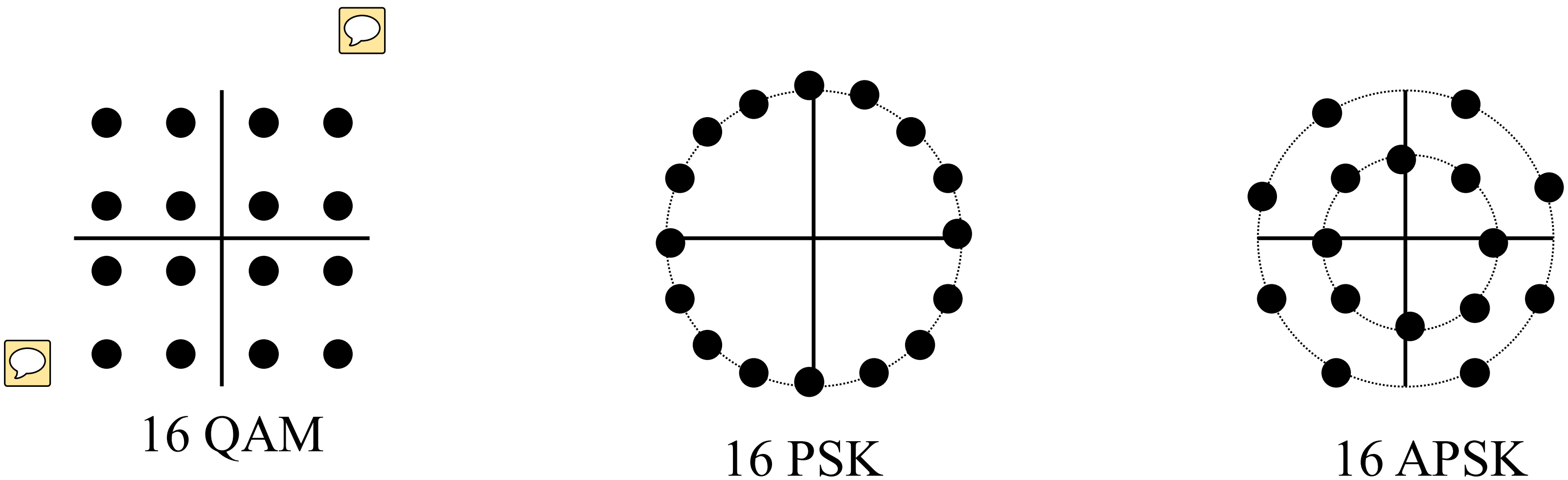
Carrier phases
$\{0, \pi/2, \pi, 3\pi/2\}$



Carrier phases
$\{\pi/4, 3\pi/4, 5\pi/4, 7\pi/4\}$

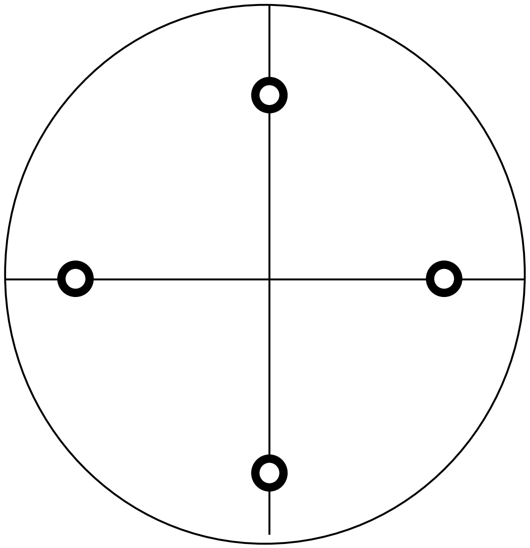
- Quadrature Phase Shift Keying has twice the bandwidth efficiency of BPSK since 2 bits are transmitted in a single modulation symbol

Multi-level (M-ary) Phase and Amplitude Modulation

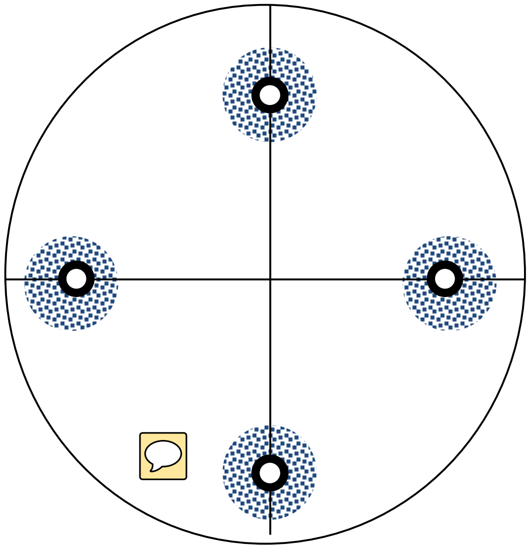


- Amplitude and phase shift keying can be combined to transmit several bits per symbol.
  - Often referred to as *linear* as they require linear amplification.
  - More bandwidth-efficient, but more susceptible to noise.
- For *M=4*, 16QAM has the largest distance between points, but requires very linear amplification. 16PSK has less stringent linearity requirements, but has less spacing between constellation points, and is therefore more affected by noise.

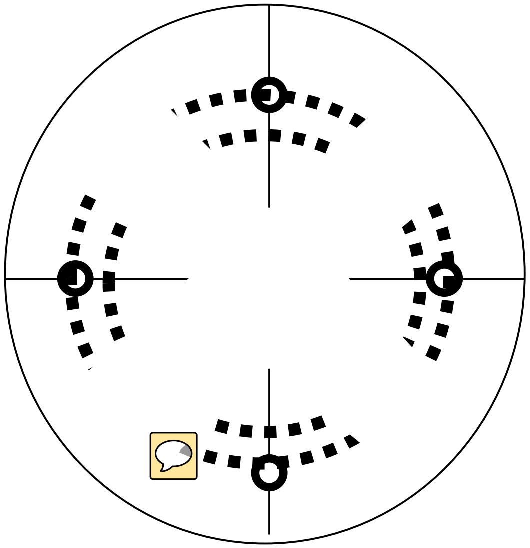
Distortions



Perfect channel



White noise



Phase jitter

Bandwidth Efficiency

$$\boxed{\frac{f_b}{W} < \log_2\left(1+\frac{E_b f_b}{\eta W}\right)}$$

$f_b =$ capacity (bits per second)

$W =$ bandwidth of the modulating baseband signal (Hz)

$E_b =$ energy per bit

$\eta =$ noise power density (watts/Hz)

Thus

$E_b f_b =$ total signal power

$\eta W =$ total noise power

$\frac{f_b}{W} =$ bandwidth use efficiency

$=$ bits per second per Hz

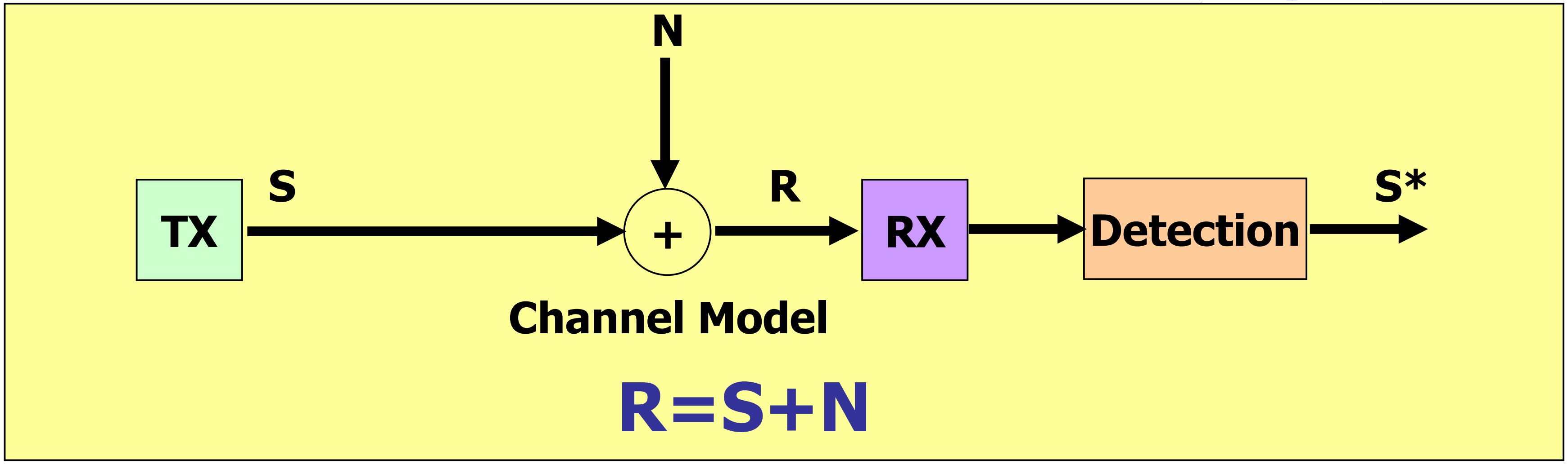
Comparison of Modulation Types

Modulation Format	Bandwidth efficiency C/B	Log2(C/B)	Error-free Eb/N0
16 PSK	4	2	18dB
16 QAM	4	2	15dB
8 PSK	3	1.6	14.5dB
4 PSK	2	1	10dB
4 QAM	2	1	10dB
BFSK	1	0	13dB
BPSK	1	0	10.5dB

Spectral Efficiencies - Examples

- GSM Europe Digital Cellular
  – Data Rate = 270kb/s; Bandwidth = 200kHz
  – Bandwidth efficiency = 270/200 = 1.35bits/sec/Hz
- IS-95 North American Digital Cellular
  – Data Rate = 48kb/s; Bandwidth = 30kHz
  – Bandwidth efficiency = 48/30 = 1.6bits/sec/Hz

Basic Communication Model in AWGN



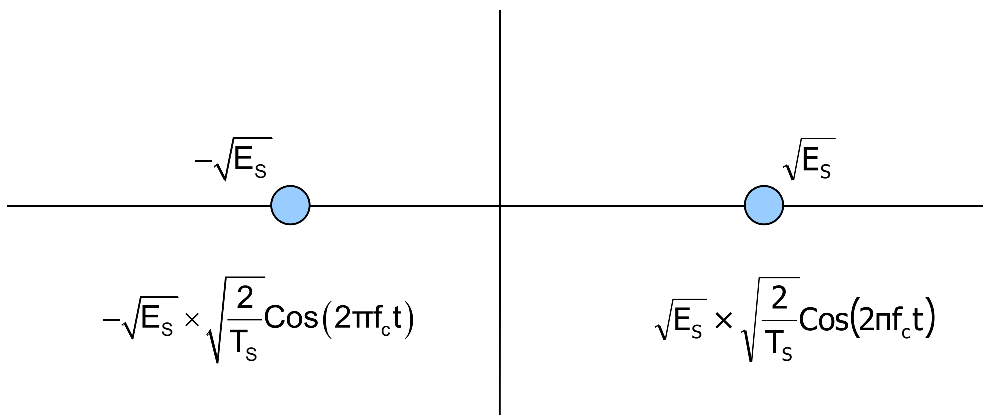
Detection Performance:

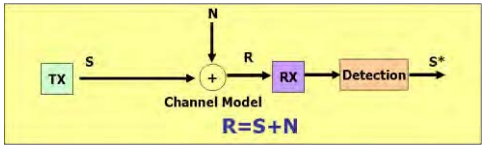
- Correct Detection
  - S = S*
- Erroneous Detection
  - S ≠ S*

BPSK Modulation over AWGN Channels

$S \in \left\{ -\sqrt{E_S}, \sqrt{E_S} \right\}$

E_S ➔ Energy per Symbol



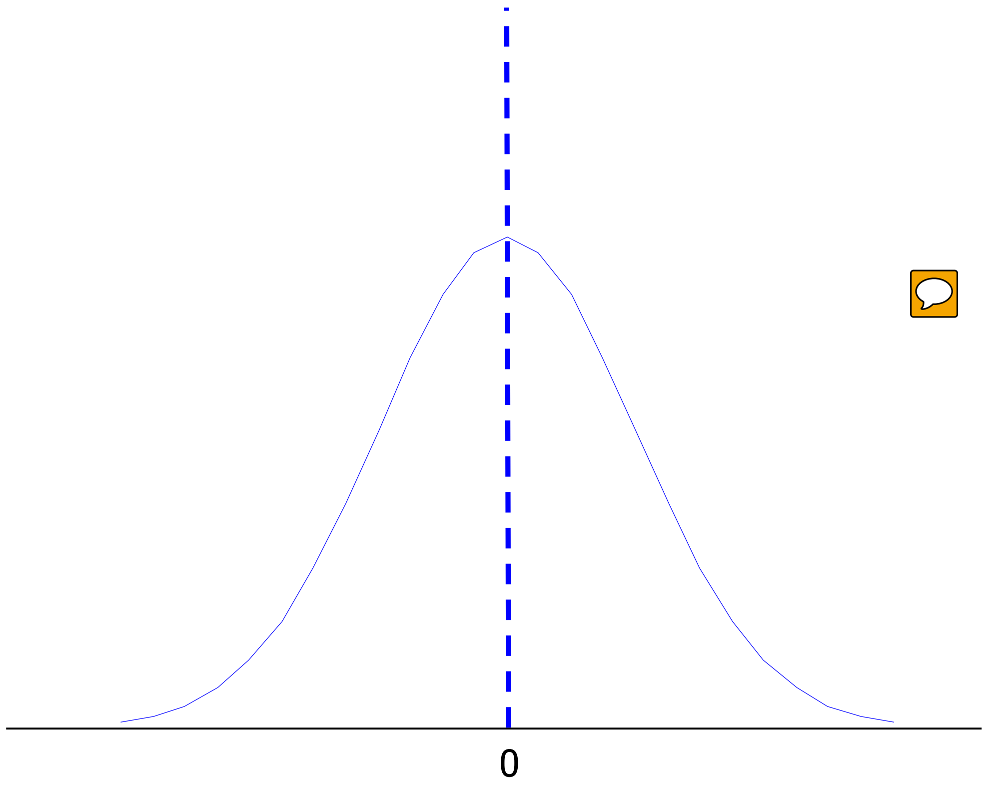


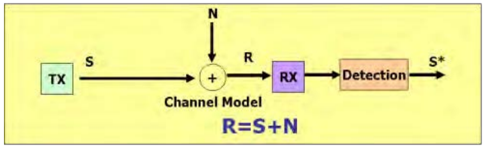
BPSK Modulation over AWGN Channels

$N \in]-\infty, \infty[$

Gaussian Noise

$$f_N(n) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}}$$



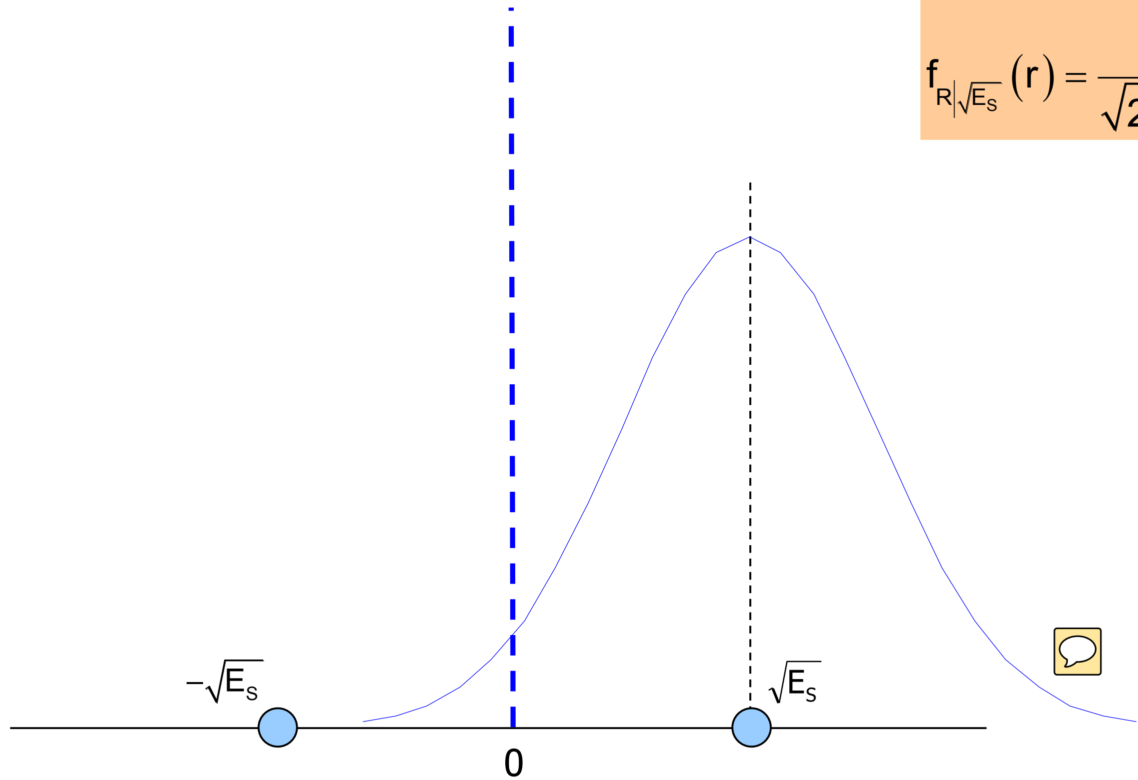


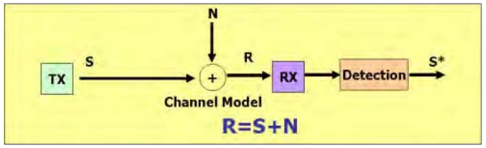
BPSK Modulation over AWGN Channels

$R \in \left]-\infty, \infty\right[$

Received signal distribution given $\sqrt{E_S}$ transmitted

$$f_{R|\sqrt{E_S}}(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\left(r-\sqrt{E_S}\right)^2}{2\sigma^2}}$$





BPSK Modulation over AWGN Channels

$R \in]-\infty, \infty[$

Error Calculation given $\sqrt{E_S}$ transmitted

$$f_{R|\sqrt{E_S}}(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\left(r-\sqrt{E_S}\right)^2}{2\sigma^2}}$$

$$P_{e|\sqrt{E_S}} = \Pr[r<0] = \Pr\left[n < -\sqrt{E_S}\right]$$

$$P_{e|\sqrt{E_S}} = \int_{-\infty}^{-\sqrt{E_S}} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}} dn$$

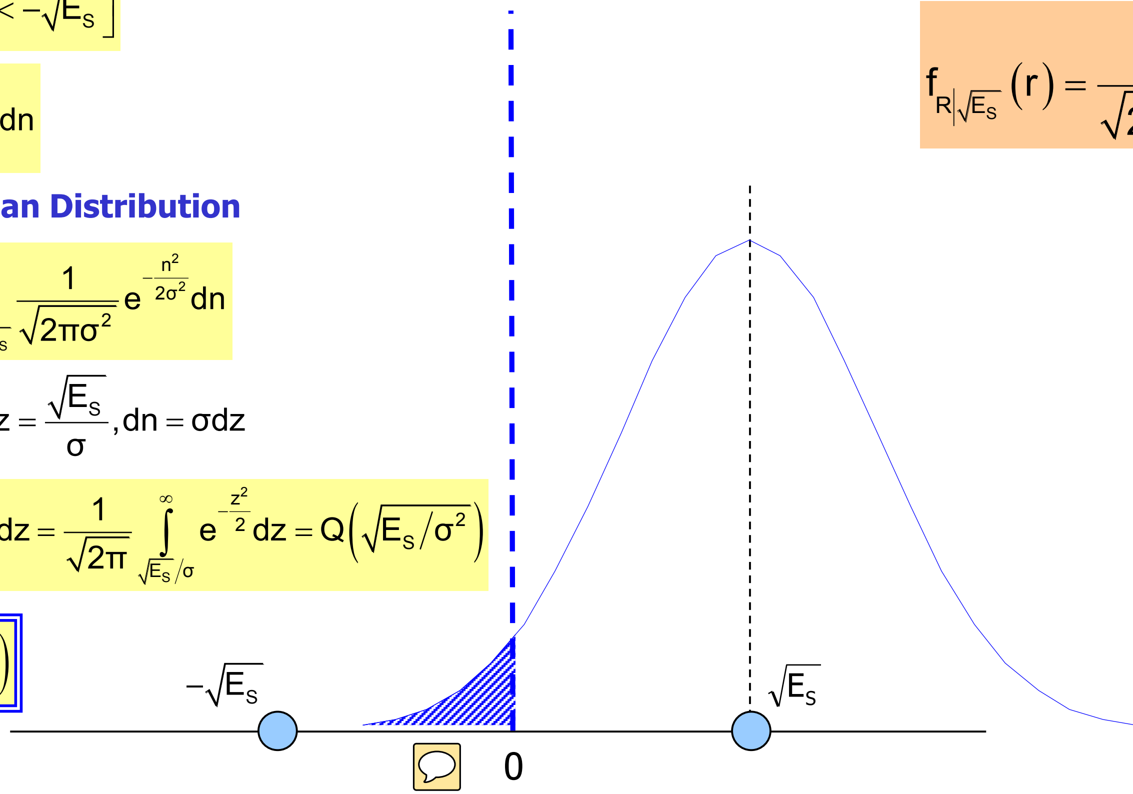
Symmetry of Gaussian Distribution

$$\int_{-\infty}^{-\sqrt{E_S}} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}} dn = \int_{\sqrt{E_S}}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}} dn$$

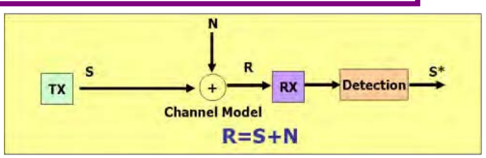
Let $z = \frac{n}{\sigma}, n = \sqrt{E_S} \Rightarrow z = \frac{\sqrt{E_S}}{\sigma}, dn = \sigma dz$

$$P_{e|\sqrt{E_S}} = \int_{\sqrt{E_S}/\sigma}^{\infty} \frac{\sigma}{\sqrt{2\pi\sigma^2}} e^{-\frac{z^2}{2}} dz = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{E_S}/\sigma}^{\infty} e^{-\frac{z^2}{2}} dz = Q\left(\sqrt{E_S/\sigma^2}\right)$$

$$\boxed{P_{e|\sqrt{E_S}} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right)}$$



$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{z^2}{2}} dz \qquad Q(x) = \frac{1}{2}\operatorname{erfc}\left(x/\sqrt{2}\right)$$

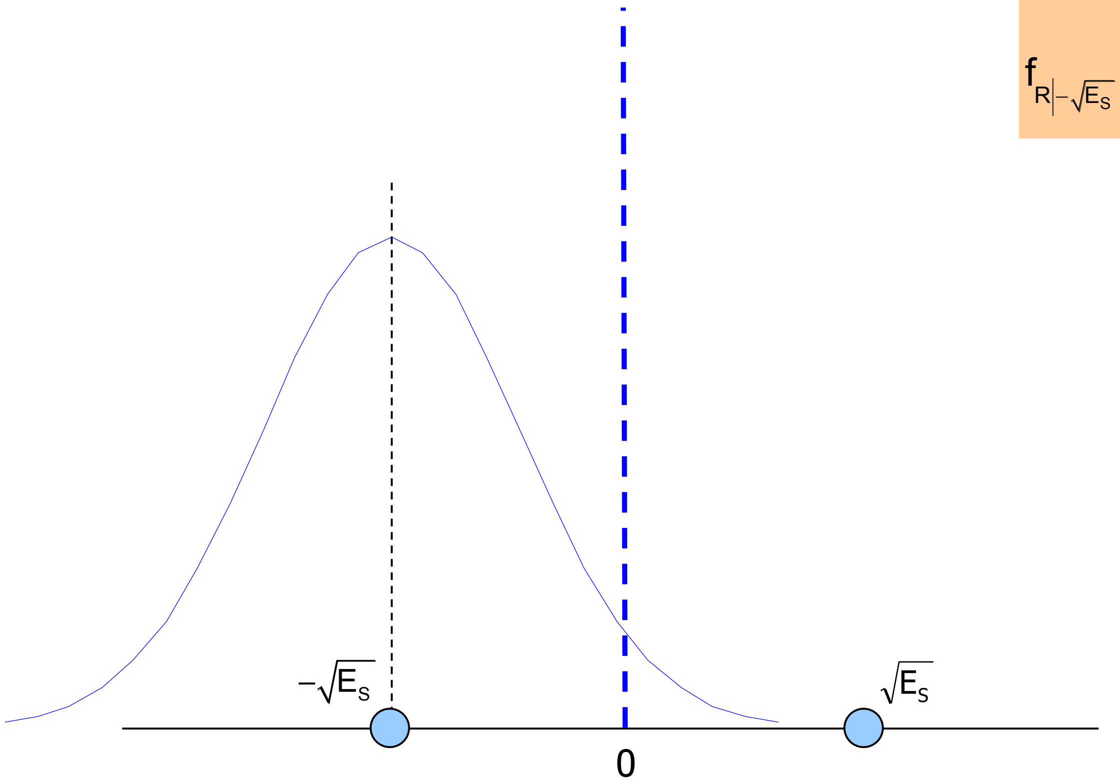


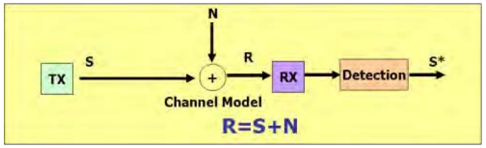
BPSK Modulation over AWGN Channels

$R \in \left]-\infty, \infty\right[$

Received signal distribution given $-\sqrt{E_S}$ transmitted

$$f_{R|-\sqrt{E_S}}(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\left(r+\sqrt{E_S}\right)^2}{2\sigma^2}}$$





BPSK Modulation over AWGN Channels

$R \in \left]-\infty, \infty\right[$

$$f_{R|-\sqrt{E_S}}(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\left(r+\sqrt{E_S}\right)^2}{2\sigma^2}}$$

Error Calculation given $-\sqrt{E_S}$ transmitted

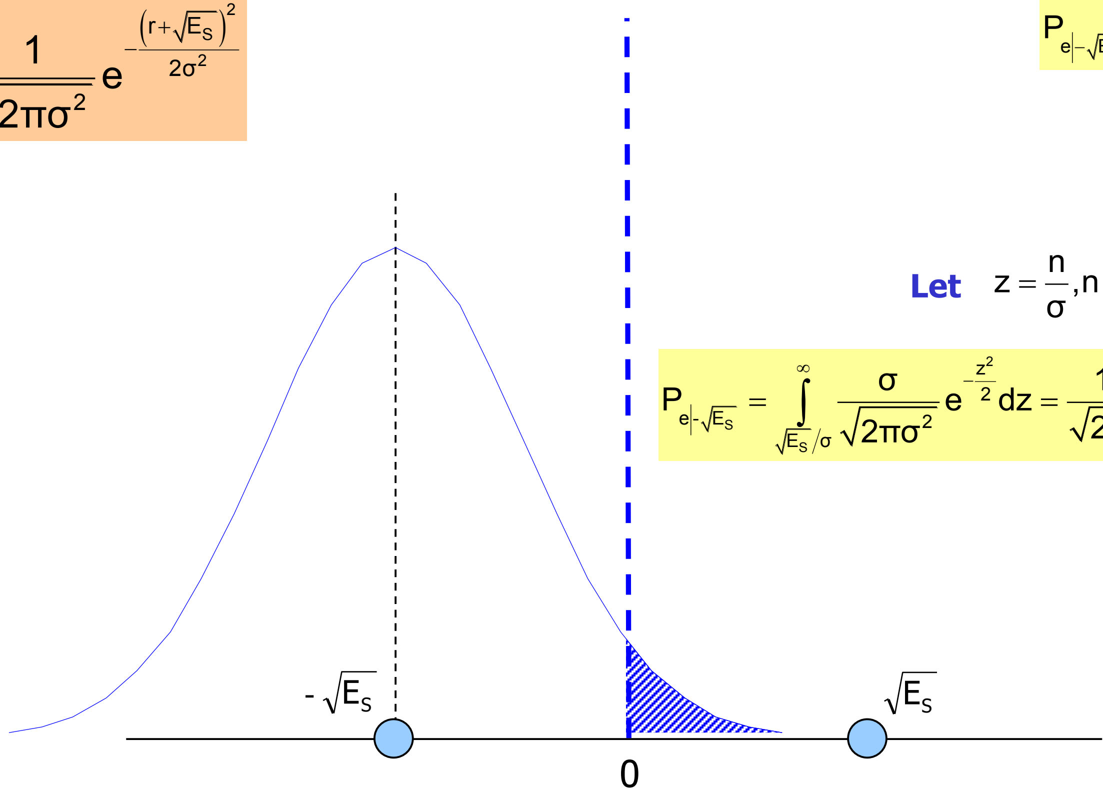
$$P_{e|-\sqrt{E_S}} = \Pr\left[r > 0\right] = \Pr\left[n > \sqrt{E_S}\right]$$

$$P_{e|-\sqrt{E_S}} = \int_{\sqrt{E_S}}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{n^2}{2\sigma^2}} dn$$

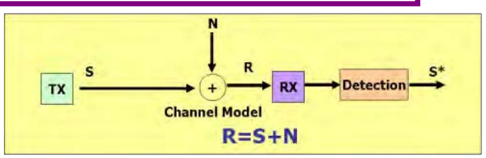
Let $z = \frac{n}{\sigma}, n = \sqrt{E_S} \Rightarrow z = \frac{\sqrt{E_S}}{\sigma}, dn = \sigma dz$

$$P_{e|-\sqrt{E_S}} = \int_{\sqrt{E_S}/\sigma}^{\infty} \frac{\sigma}{\sqrt{2\pi\sigma^2}} e^{-\frac{z^2}{2}} dz = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{E_S}/\sigma}^{\infty} e^{-\frac{z^2}{2}} dz = Q\left(\sqrt{E_S/\sigma^2}\right)$$

$$\boxed{P_{e|-\sqrt{E_S}} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right)}$$



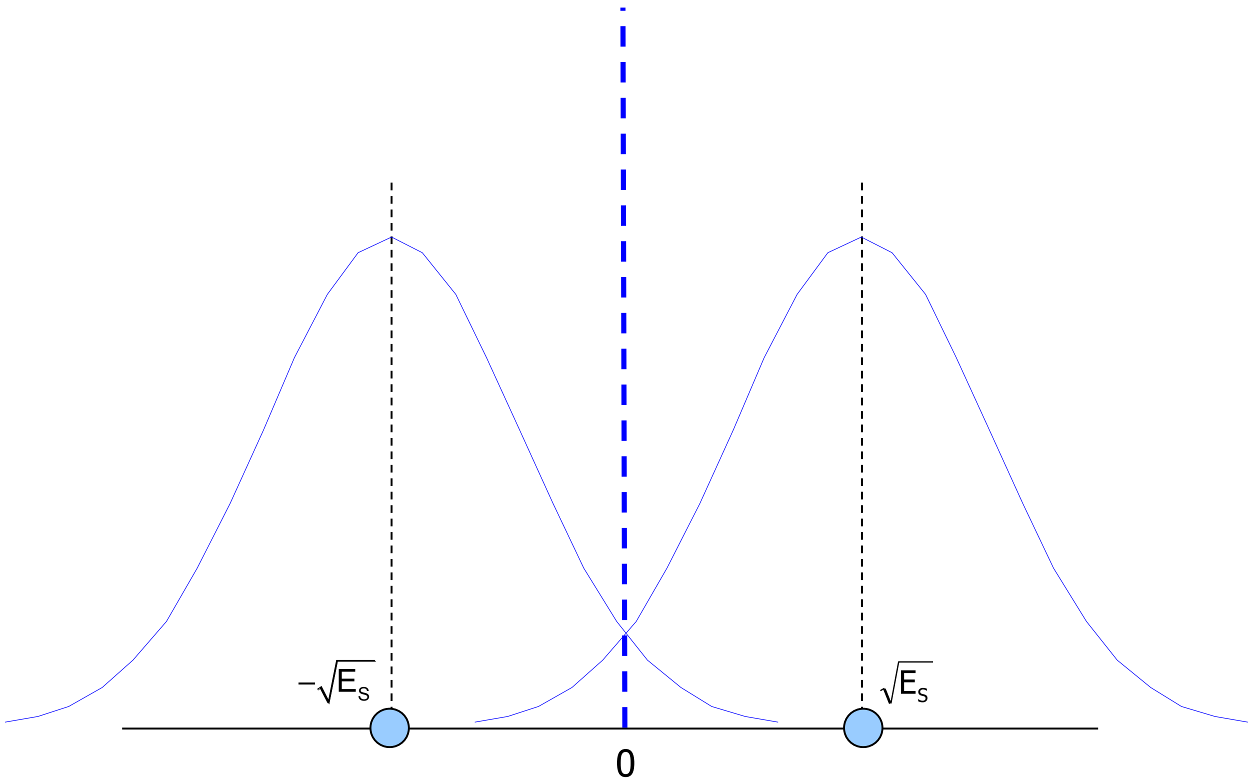
$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-\frac{z^2}{2}} dz \qquad Q(x) = \frac{1}{2}\operatorname{erfc}\left(x/\sqrt{2}\right)$$

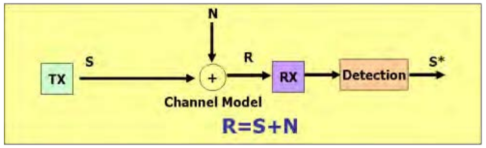


BPSK Modulation over AWGN Channels

$E_S \uparrow \Rightarrow P_e \downarrow$

Signal Power & Symbol Error Performance

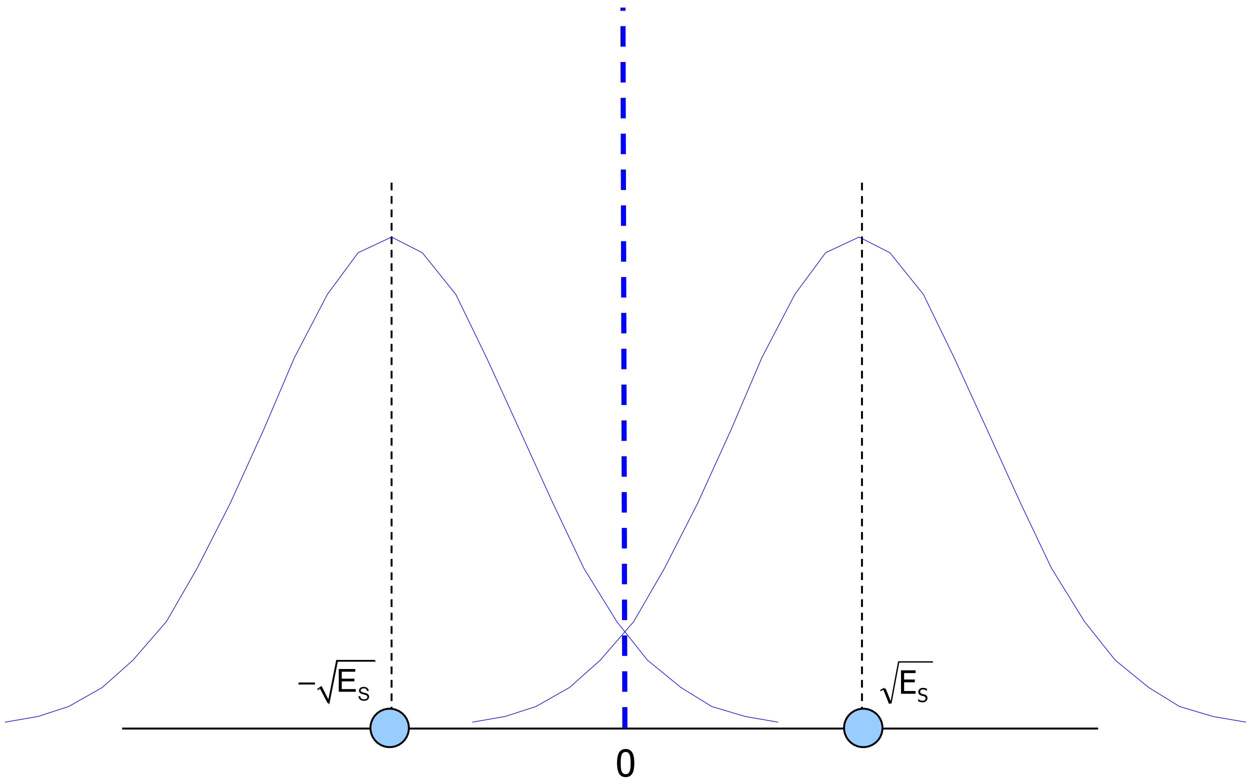


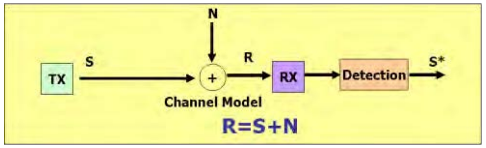


BPSK Modulation over AWGN Channels

$\sigma^2 \downarrow \Rightarrow P_e \downarrow$

Signal Power & Symbol Error Performance





BER of BPSK over AWGN Channels

$$P_e = \Pr\left\lfloor -\sqrt{E_S} \right\rfloor \times P_{e|-\sqrt{E_S}} + \Pr\left\lfloor \sqrt{E_S} \right\rfloor \times P_{e|\sqrt{E_S}}$$

$$P_e = \frac{1}{2} \times \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right) + \frac{1}{2} \times \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right) = \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_S/2\sigma^2}\right)$$

Notes:

- Define N_0 Total Noise Power
  - $N_0/2$ ➔ Noise Power over Cosine axis, i.e., $\sigma^2 = N_0/2$
- Each symbol corresponds to a single bit
  - $E_b = E_S$
  - $P_b = P_e$

$$P_b = \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_b/N_0}\right)$$