ECE 463: Digital Communications Lab.

Lecture 4: Modulation Part I

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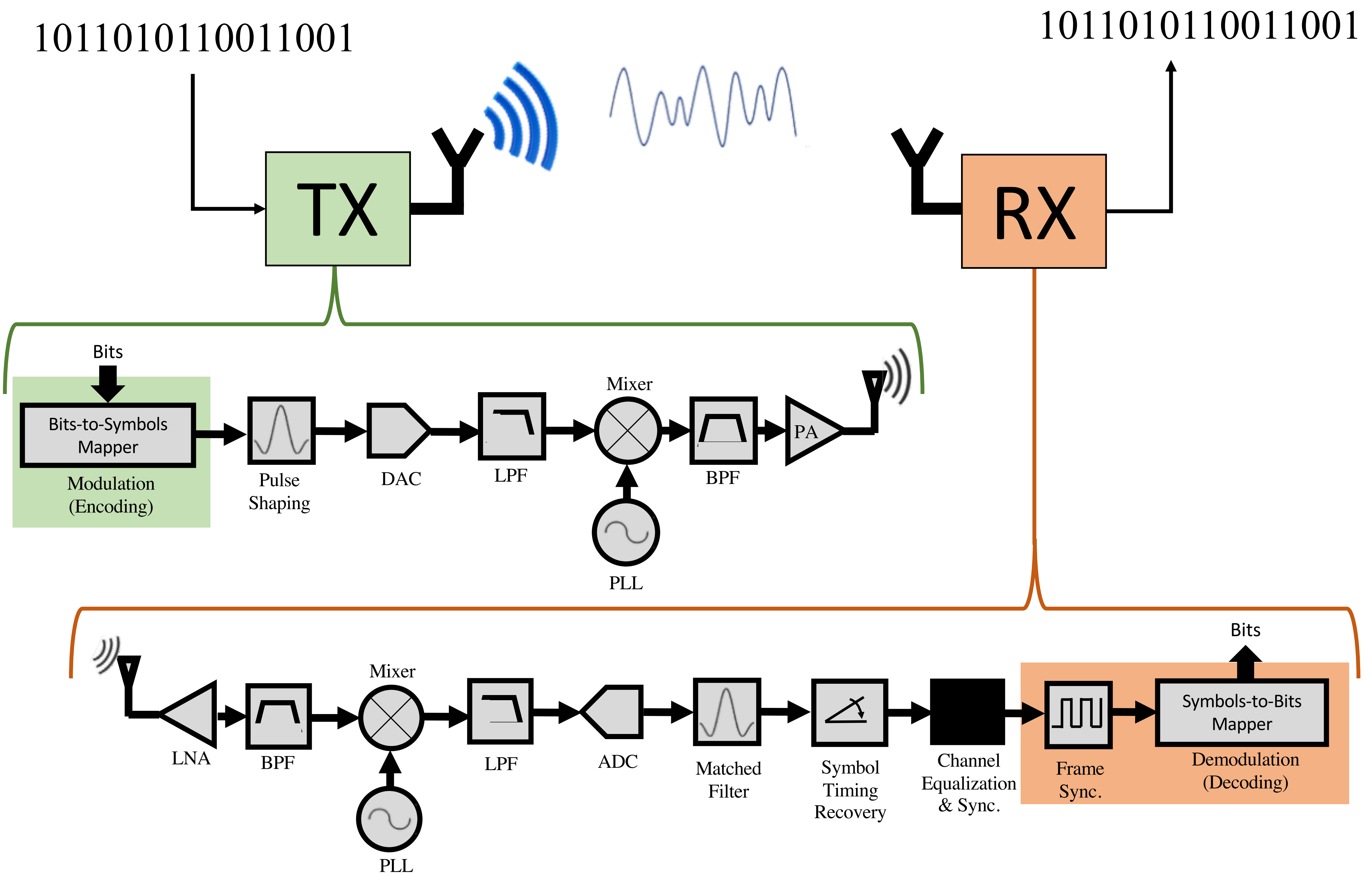
Previous Lecture:

- ✓ Pulse Shaping Filters
- ✓ Matched Filters
- ✓ Symbol Timing Recovery
- ✓ Eye Diagrams

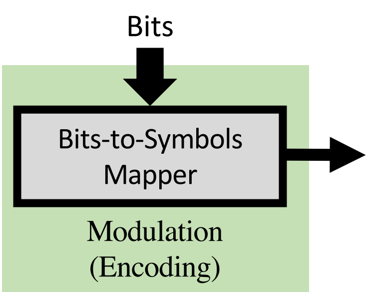
This Lecture:

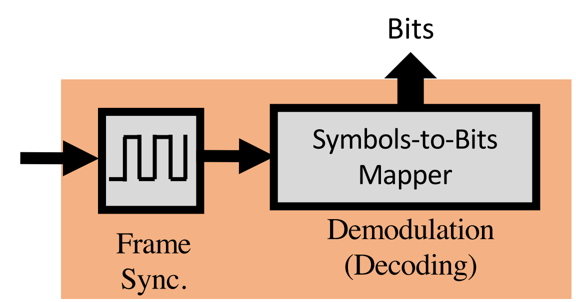
- ❑ Channel Distortion
- ❑ Non-Coherent vs. Coherent Modulation

Digital Communication System

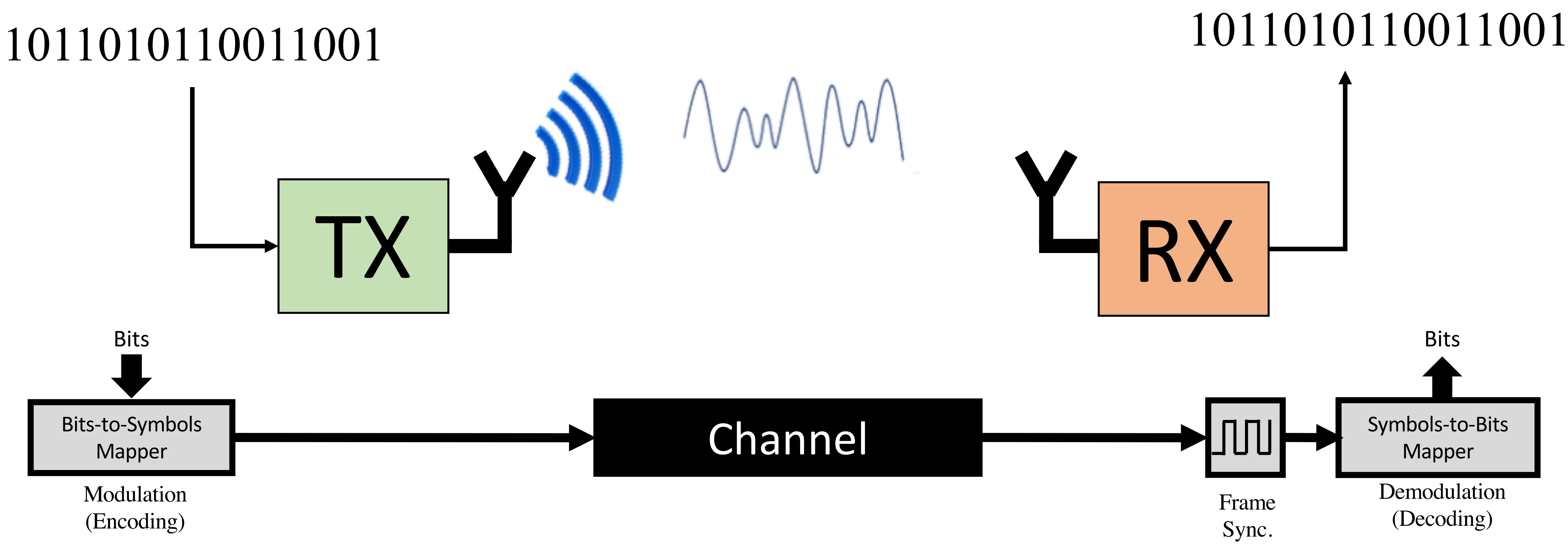


Digital Communication System





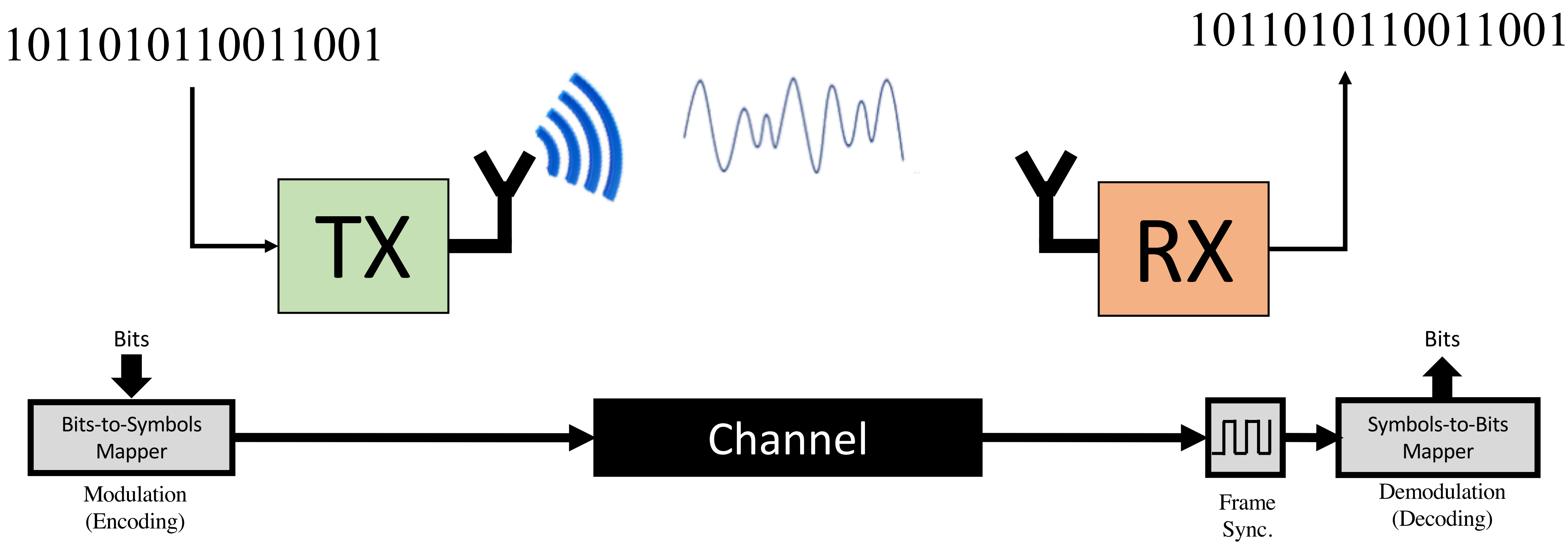
The Channel



$x(t)$ ➡ ➡ $y(t) = x(t) + v(t)$

Channel adds noise (AWGN)!

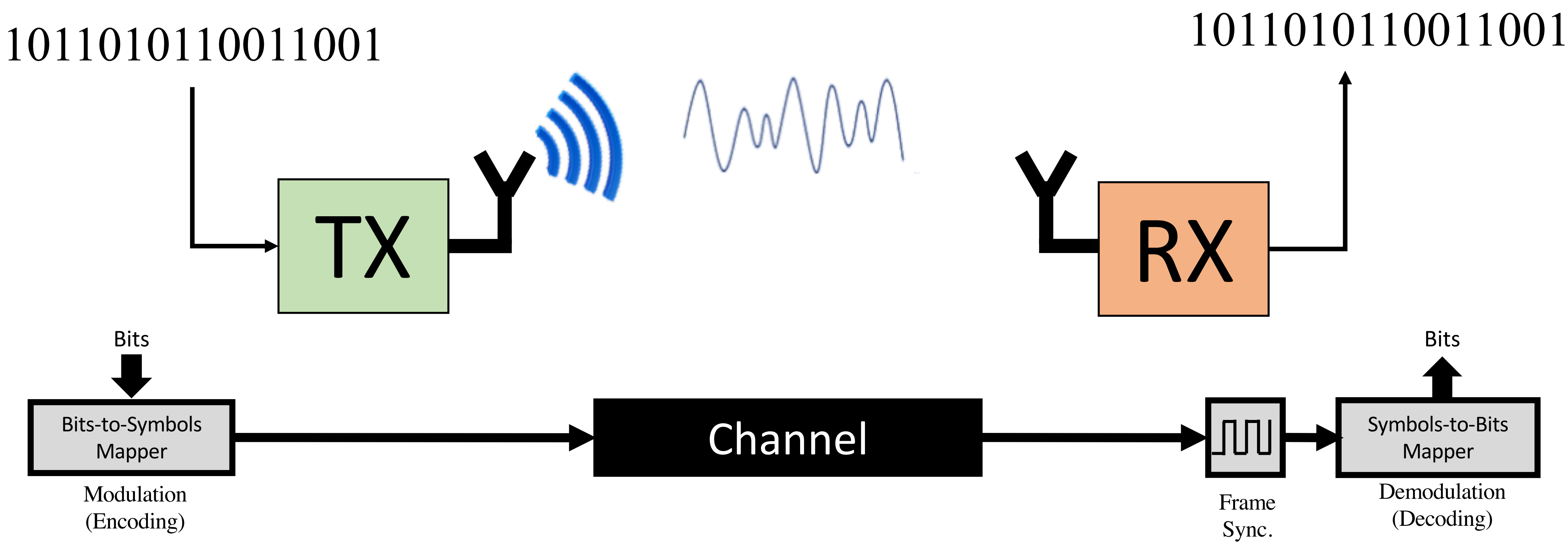
The Channel



$x(t)$ ➡ ➡ $y(t) = x(t - \tau) + v(t)$

Channel delays the signal!

The Channel

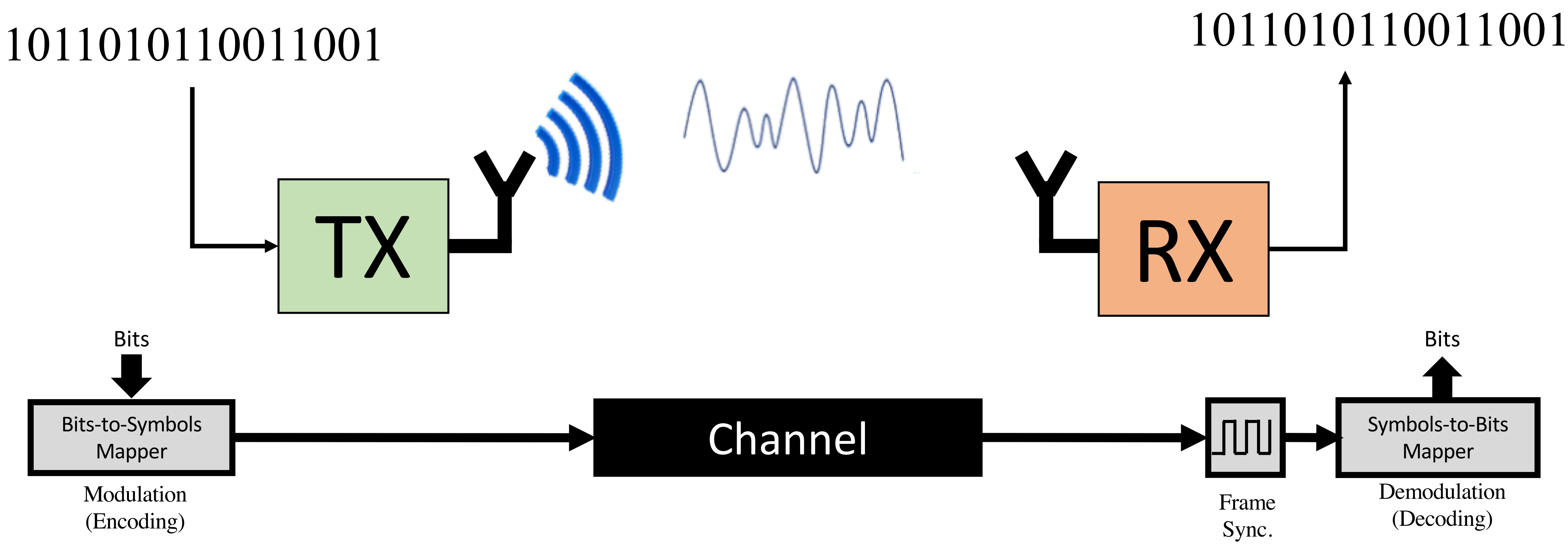


$x(t)$ ➡ ➡ $y(t) = \mathbf{h}\, x(t-\tau) + v(t)$

Channel attenuates the signal (Pathloss)

$$P_{RX} = G_{TX} G_{RX} \frac{\lambda^2}{(4\pi d)^2} P_{TX} \quad \Rightarrow \quad |h| \propto \frac{\lambda}{d}$$

The Channel

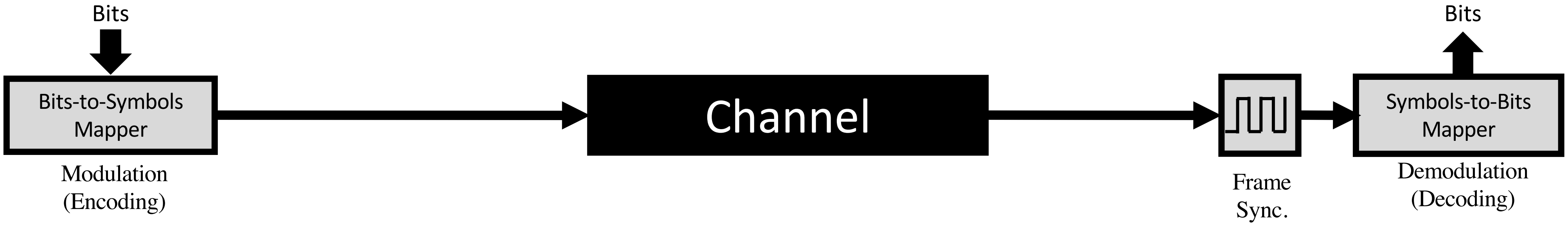


$x(t)$ ➡ ➡ $y(t) = \boldsymbol{h}\, x(t-\tau) + v(t)$

Channel rotates the signal (Adds Phase)

$$h \propto \frac{\lambda}{d} e^{j\phi}$$

The Channel



$$x(t) \;\rightarrow\; \;\rightarrow\; y(t) = \boldsymbol{h}\, x(t-\tau) + v(t)$$

$$x(t) \times e^{-j2\pi f_c t} \rightarrow |h| x(t-\tau) e^{-j2\pi f_c (t-\tau)} \rightarrow \times e^{j2\pi f_c t} \rightarrow |h| x(t-\tau) e^{j2\pi f_c \tau} \;\uparrow$$

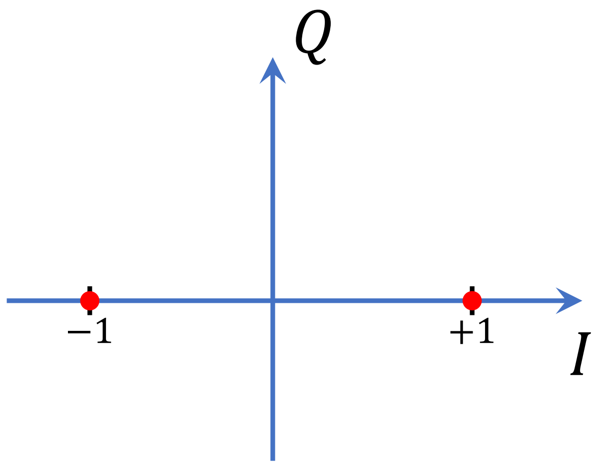
$$h \propto \frac{\lambda}{d} e^{j\phi} \;\rightarrow \phi = 2\pi f_c \tau = 2\pi \frac{c}{\lambda}\frac{d}{c} = 2\pi \frac{d}{\lambda} \;\rightarrow h \propto \frac{\lambda}{d} e^{j2\pi d/\lambda}$$

The Channel

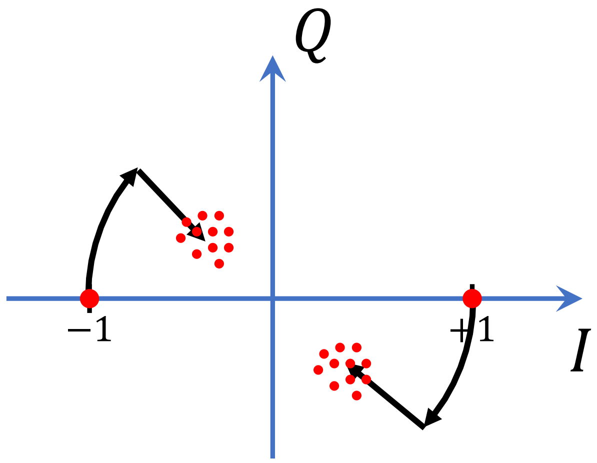
Consider BPSK Modulation.

$$0 \rightarrow -1$$

$$1 \rightarrow +1$$



$x(t)$

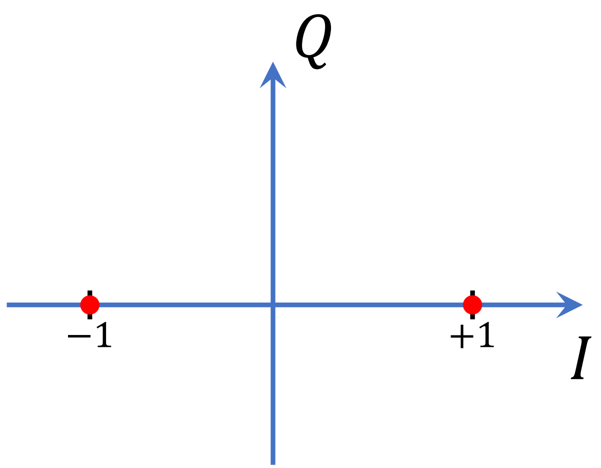


$h \times x(t) + v(t)$

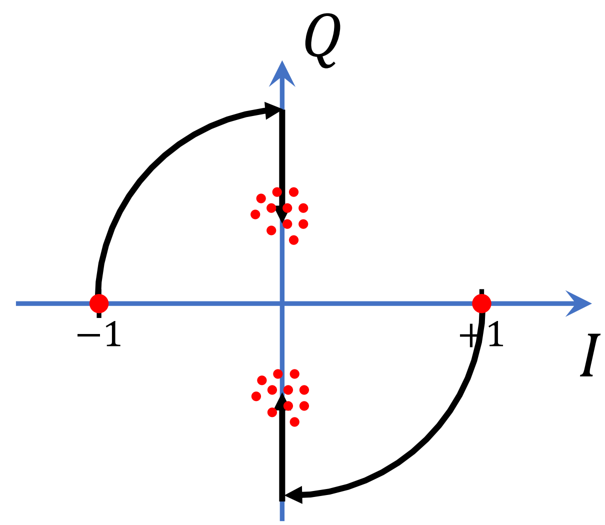
The Channel

Consider BPSK Modulation.

$$0 \rightarrow -1$$
$$1 \rightarrow +1$$



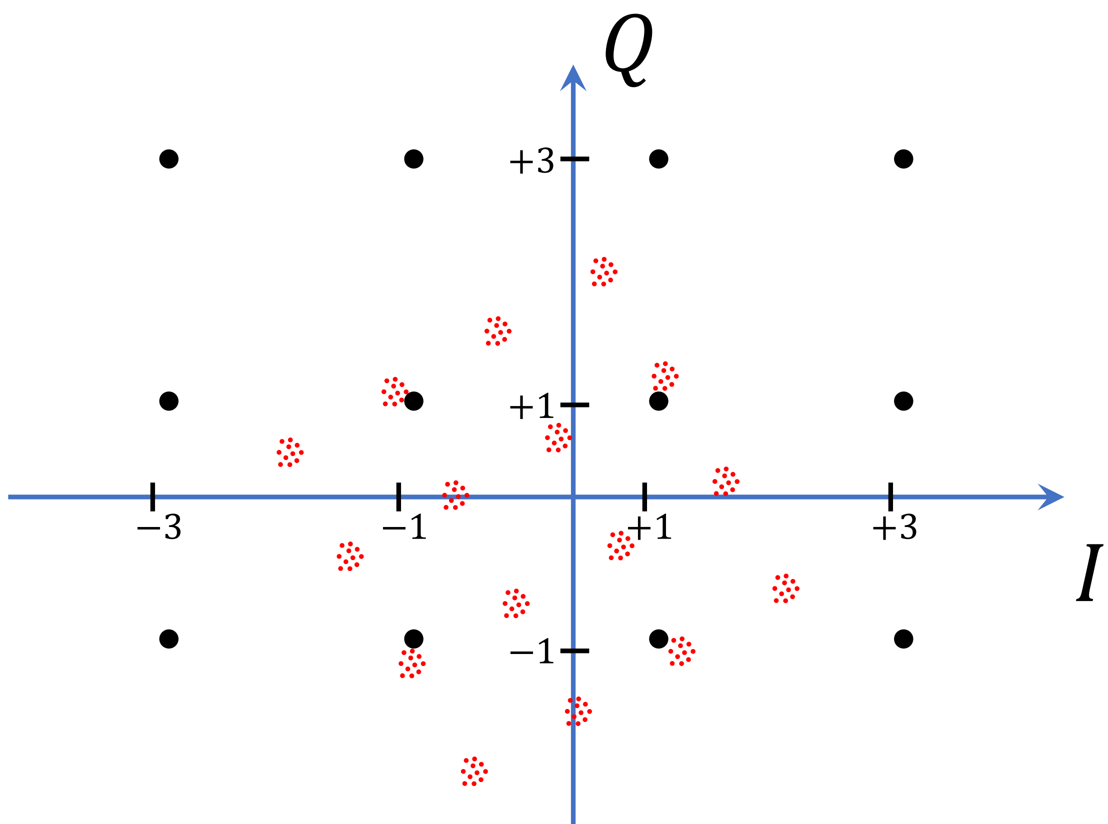
$x(t)$



$h \times x(t) + v(t)$

The Channel

Consider QAM Modulation



Next Lecture

Dem[redacted]ulating correctly requires COHERENCE!

i[redacted]eed to estimate & correct for the channel h

CHANNEL EQUALIZATION

Modulation

Based on the type of receiver

Coherent

Signal at RX must be phase coherent with TX signal to be able to decode correctly.

⇩

Need to correct for channel as well as timing and frequency offsets.

Non-Coherent

No need for phase coherence at the receiver to decode.

⇩

“No” need for channel equalization

⇩

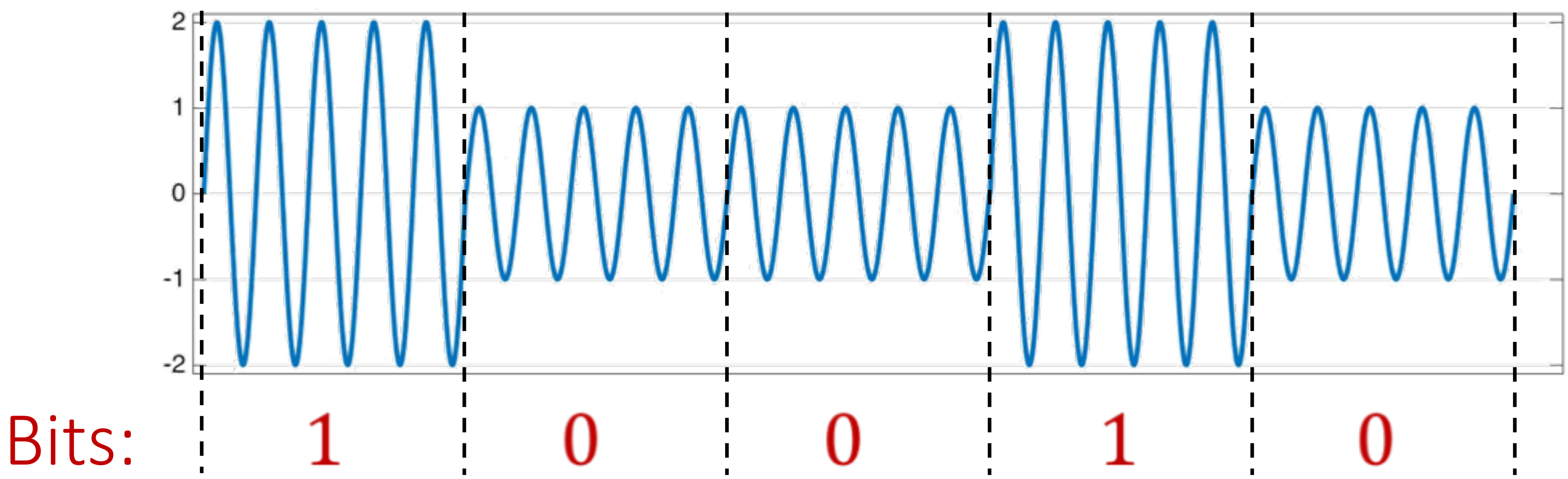
Simpler Receiver Architecture

Modulation

Based on how the bits are encoded

ASK

Amplitude Shift Keying

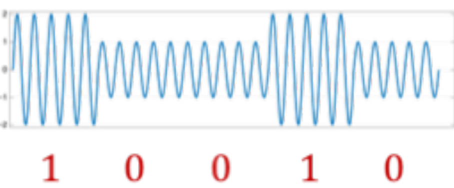


Modulation

Based on how the bits are encoded

ASK

Amplitude Shift Keying

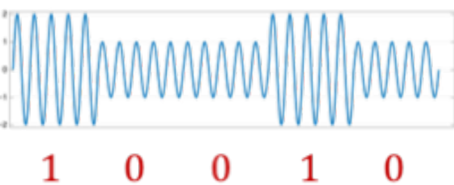


Modulation

Based on how the bits are encoded

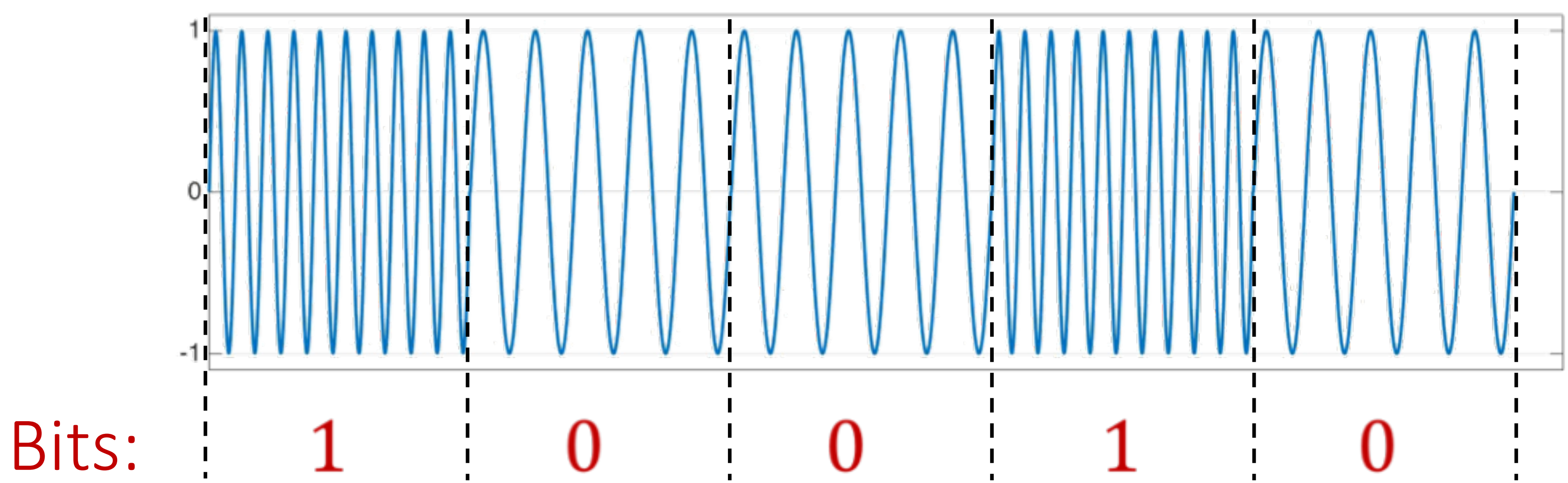
ASK

Amplitude Shift Keying



FSK

Frequency Shift Keying

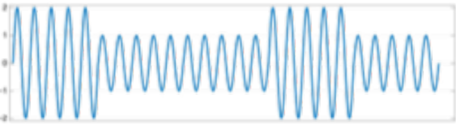


Modulation

Based on how the bits are encoded

ASK

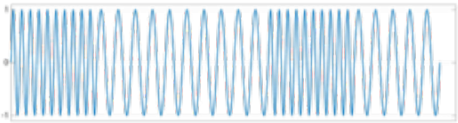
Amplitude Shift Keying



1 0 0 1 0

FSK

Frequency Shift Keying



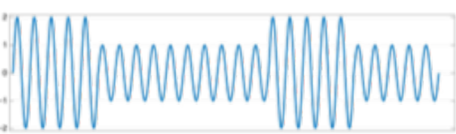
1 0 0 1 0

Modulation

Based on how the bits are encoded

ASK

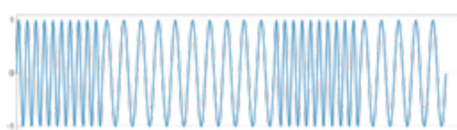
Amplitude Shift Keying



1 0 0 1 0

FSK

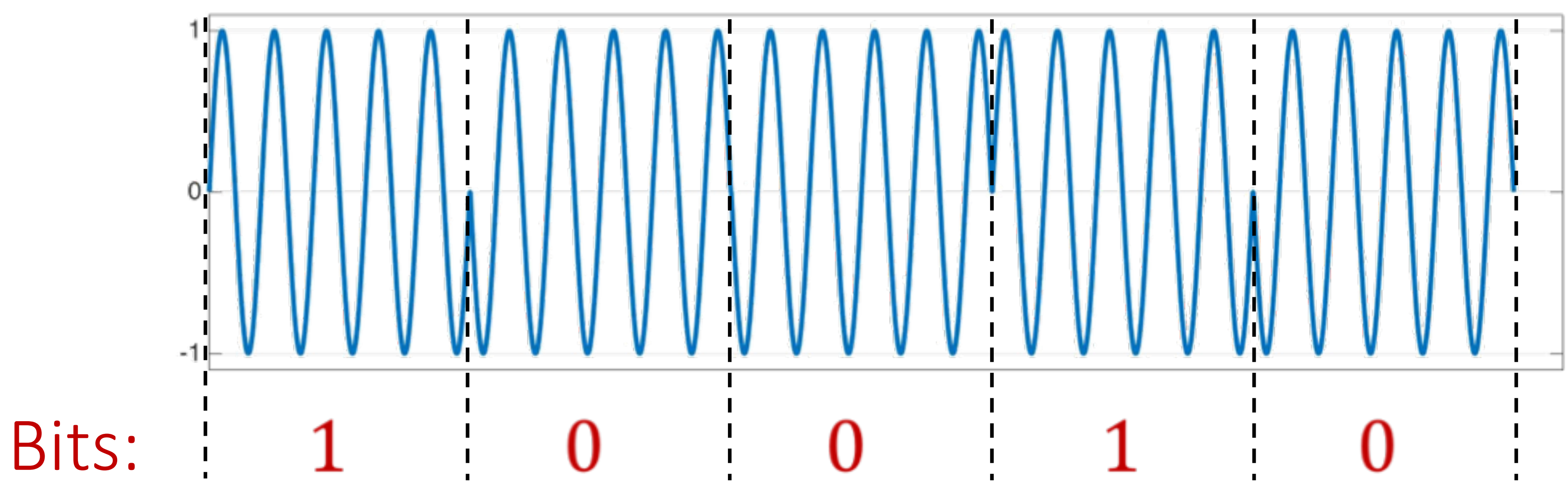
Frequency Shift Keying



1 0 0 1 0

PSK

Phase Shift Keying

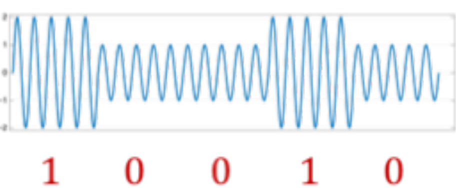


Modulation

Based on how the bits are encoded

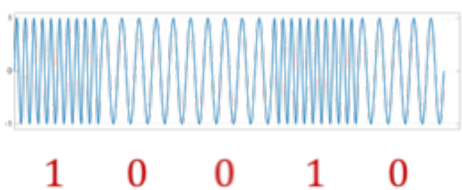
ASK

Amplitude
Shift Keying



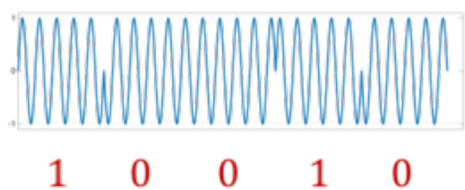
FSK

Frequency
Shift Keying

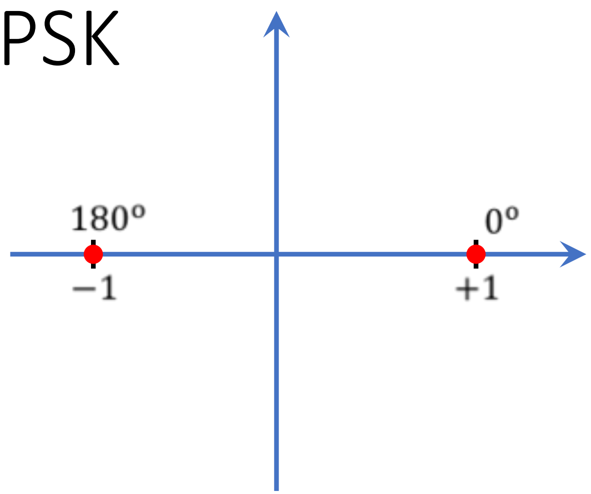


PSK

Phase
Shift Keying



BPSK

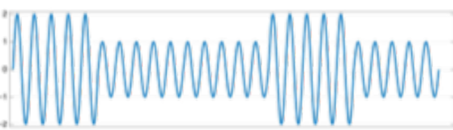


Modulation

Based on how the bits are encoded

ASK

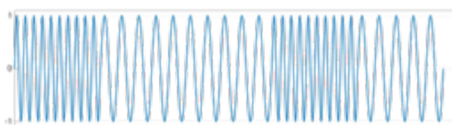
Amplitude
Shift Keying



1 0 0 1 0

FSK

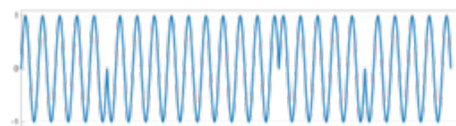
Frequency
Shift Keying



1 0 0 1 0

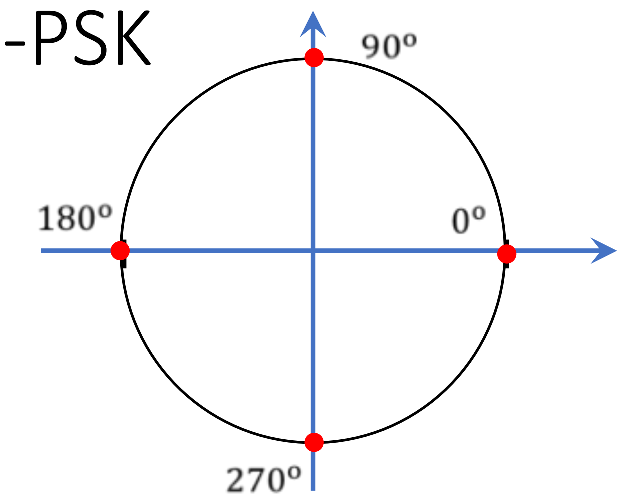
PSK

Phase
Shift Keying



1 0 0 1 0

4-PSK

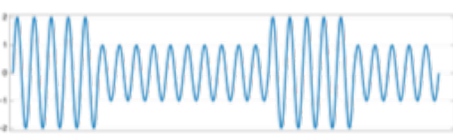


Modulation

Based on how the bits are encoded

ASK

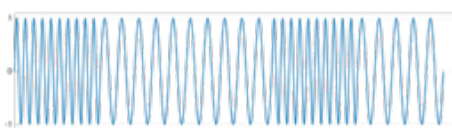
Amplitude Shift Keying



1 0 0 1 0

FSK

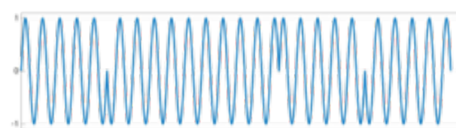
Frequency Shift Keying



1 0 0 1 0

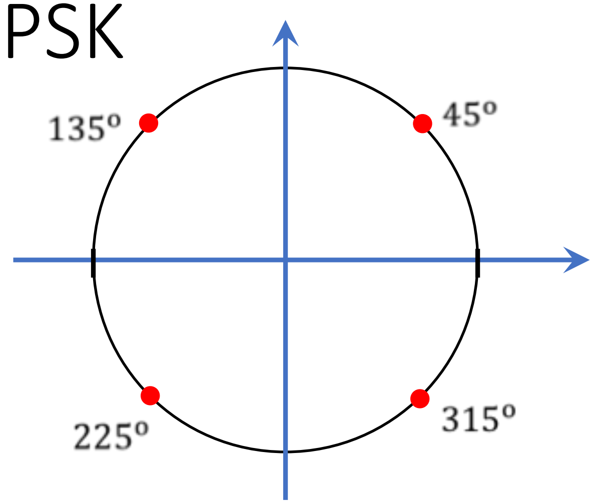
PSK

Phase Shift Keying



1 0 0 1 0

4-PSK

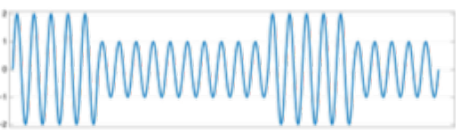


Modulation

Based on how the bits are encoded

ASK

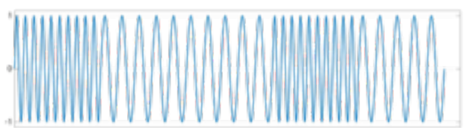
Amplitude
Shift Keying



1 0 0 1 0

FSK

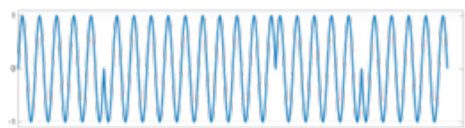
Frequency
Shift Keying



1 0 0 1 0

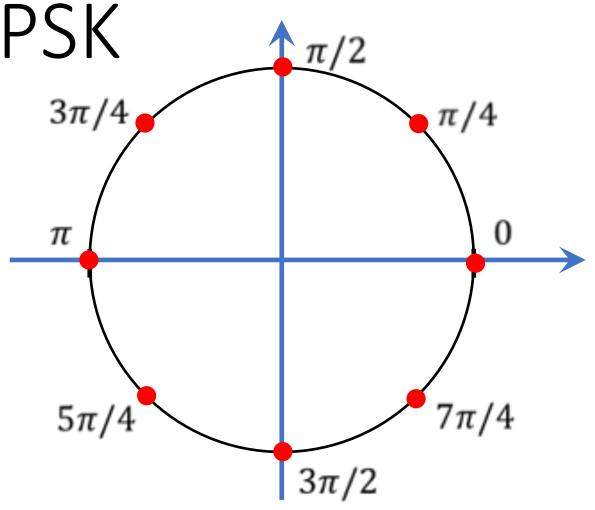
PSK

Phase
Shift Keying



1 0 0 1 0

8-PSK

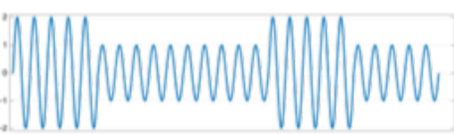


Modulation

Based on how the bits are encoded

ASK

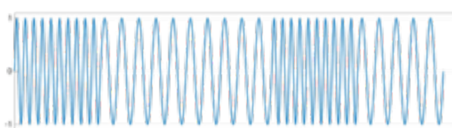
Amplitude
Shift Keying



1 0 0 1 0

FSK

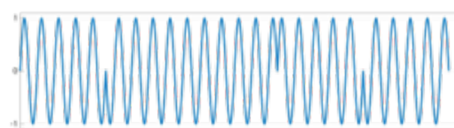
Frequency
Shift Keying



1 0 0 1 0

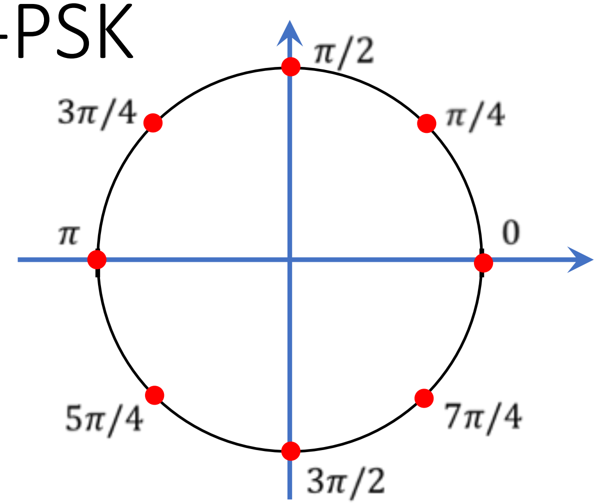
PSK

Phase
Shift Keying



1 0 0 1 0

M-PSK



Phase is integer multiple of: $\frac{2\pi}{M}$

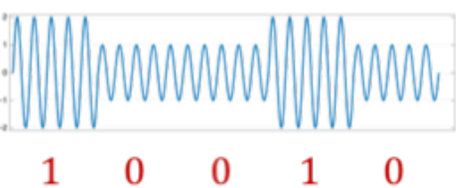
Bits per symbol: $\log_2 M$

Modulation

Based on how the bits are encoded

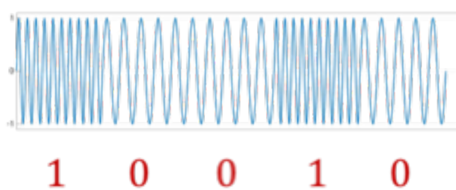
ASK

Amplitude Shift Keying



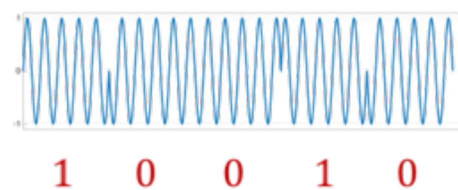
FSK

Frequency Shift Keying



PSK

Phase Shift Keying



QAM

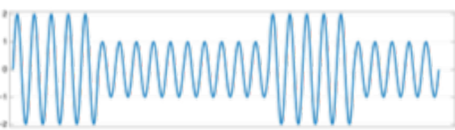
Phase & Amplitude Modulation (APSK)

Modulation

Based on how the bits are encoded

ASK

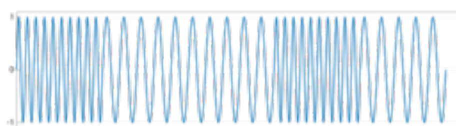
Amplitude Shift Keying



1 0 0 1 0

FSK

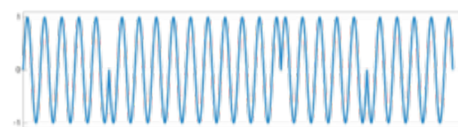
Frequency Shift Keying



1 0 0 1 0

PSK

Phase Shift Keying

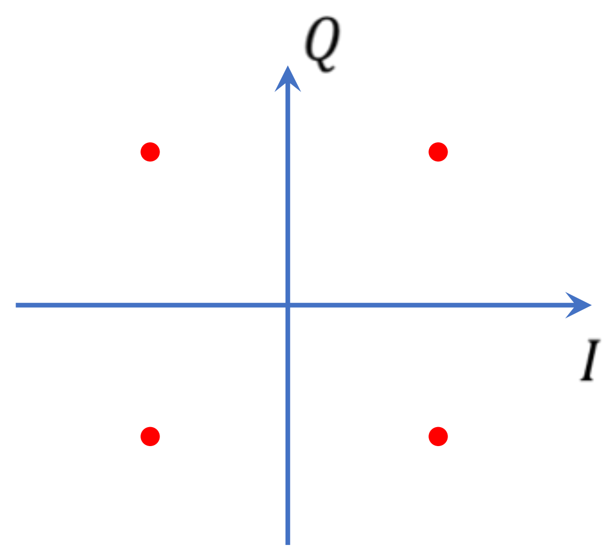


1 0 0 1 0

QAM

Phase & Amplitude Modulation (APSK)

4-QAM

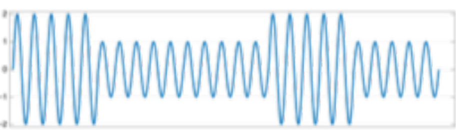


Modulation

Based on how the bits are encoded

ASK

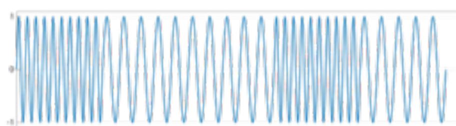
Amplitude Shift Keying



1 0 0 1 0

FSK

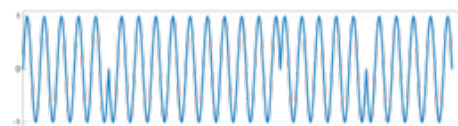
Frequency Shift Keying



1 0 0 1 0

PSK

Phase Shift Keying

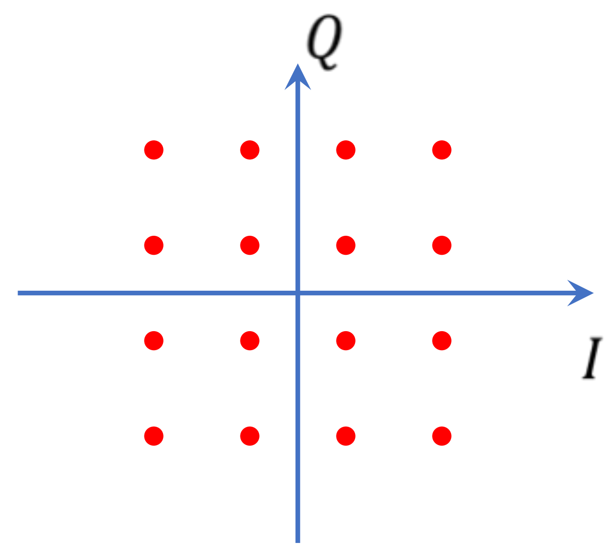


1 0 0 1 0

QAM

Phase & Amplitude Modulation (APSK)

16-QAM

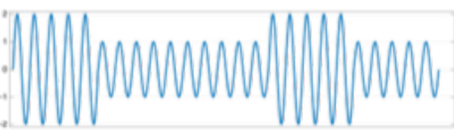


Modulation

Based on how the bits are encoded

ASK

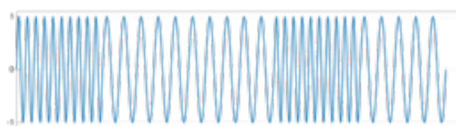
Amplitude Shift Keying



1 0 0 1 0

FSK

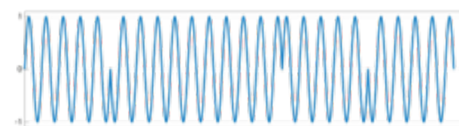
Frequency Shift Keying



1 0 0 1 0

PSK

Phase Shift Keying

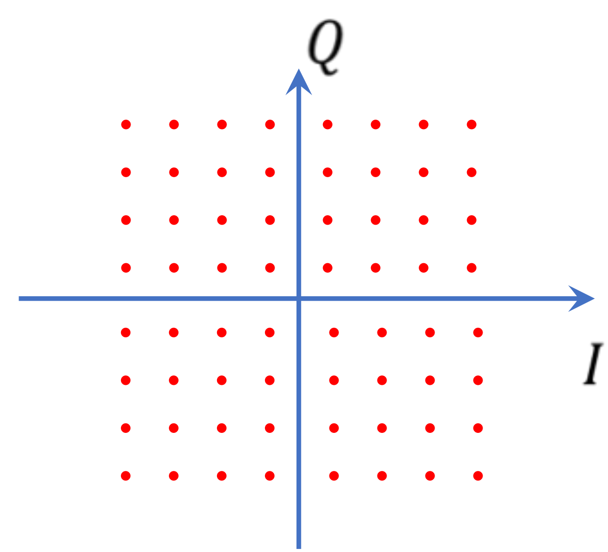


1 0 0 1 0

QAM

Phase & Amplitude Modulation (APSK)

64-QAM

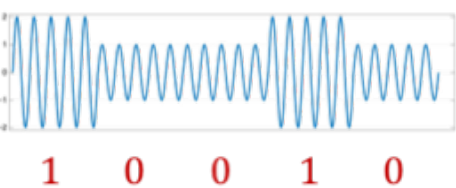


Modulation

Based on how the bits are encoded

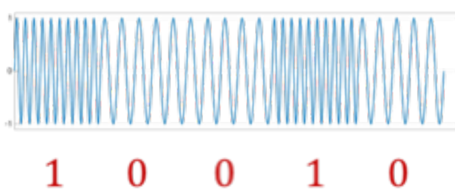
ASK

Amplitude
Shift Keying



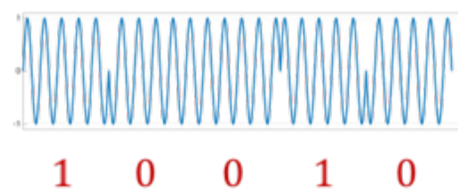
FSK

Frequency
Shift Keying



PSK

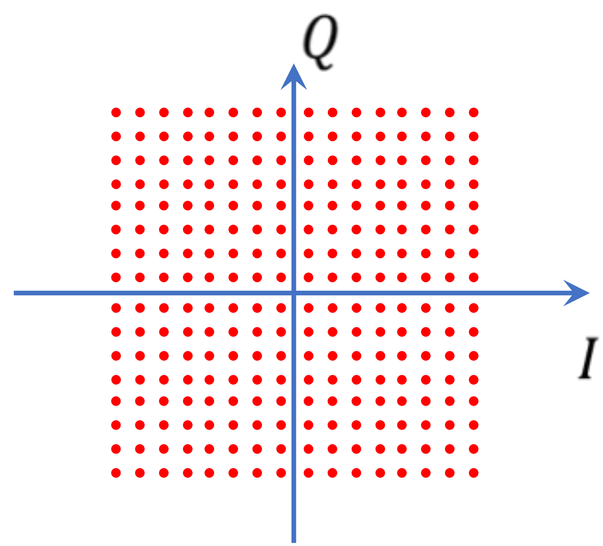
Phase
Shift Keying



QAM

Phase &
Amplitude
Modulation
(APSK)

256-QAM

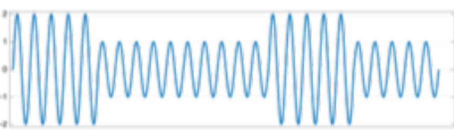


Modulation

Based on how the bits are encoded

ASK

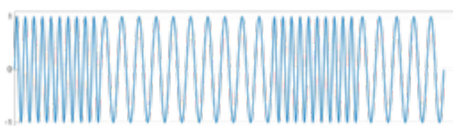
Amplitude Shift Keying



1 0 0 1 0

FSK

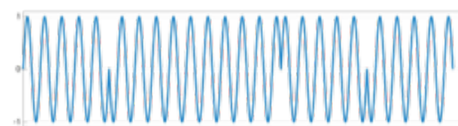
Frequency Shift Keying



1 0 0 1 0

PSK

Phase Shift Keying

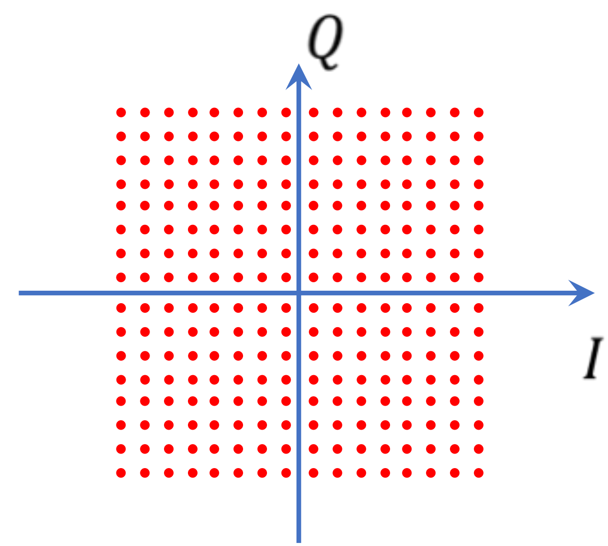


1 0 0 1 0

QAM

Phase & Amplitude Modulation (APSK)

M-QAM



IQ gird: $\sqrt{M} \times \sqrt{M}$

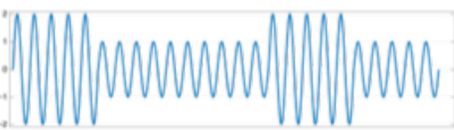
Bits per symbol: $\log_2 M$

Modulation

Based on how the bits are encoded

ASK

Amplitude Shift Keying

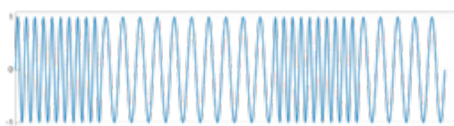


1 0 0 1 0

OOK, ASK

FSK

Frequency Shift Keying

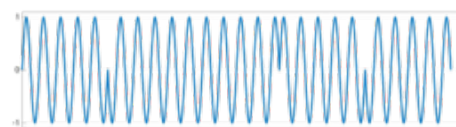


1 0 0 1 0

CFSK, MSK, GMSK

PSK

Phase Shift Keying



1 0 0 1 0

BPSK, QPSK, CPM

QAM

Phase & Amplitude Modulation (APSK)

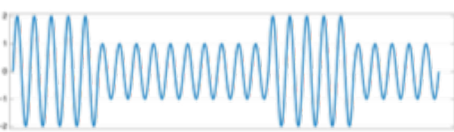
PAM, M-QAM

Modulation

Based on how the bits are encoded

ASK

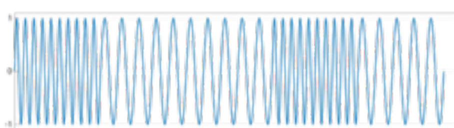
Amplitude Shift Keying



1 0 0 1 0

FSK

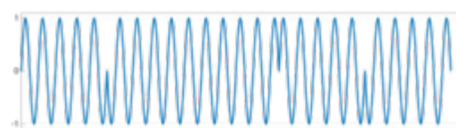
Frequency Shift Keying



1 0 0 1 0

PSK

Phase Shift Keying



1 0 0 1 0

QAM

Phase & Amplitude Modulation (APSK)

PPM

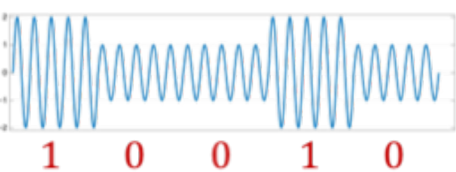
Pulse Position Modulation

Modulation

Based on how the bits are encoded

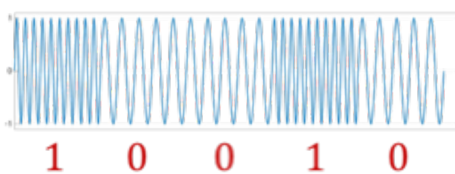
ASK

Amplitude Shift Keying



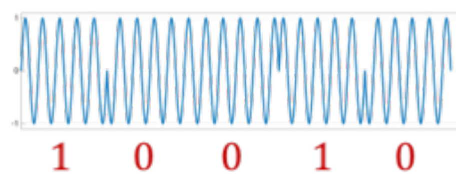
FSK

Frequency Shift Keying



PSK

Phase Shift Keying

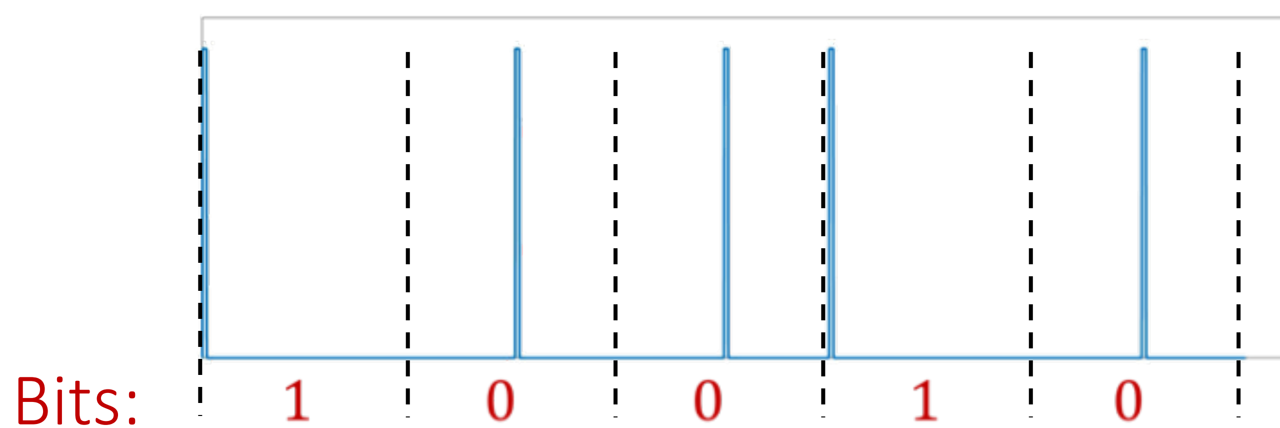


QAM

Phase & Amplitude Modulation (APSK)

PPM

Pulse Position Modulation

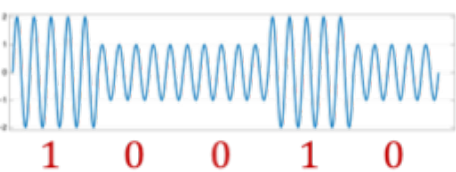


Modulation

Based on how the bits are encoded

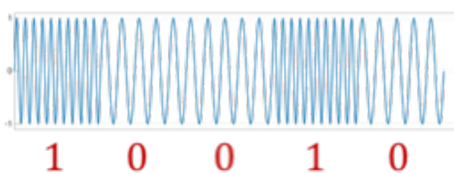
ASK

Amplitude Shift Keying



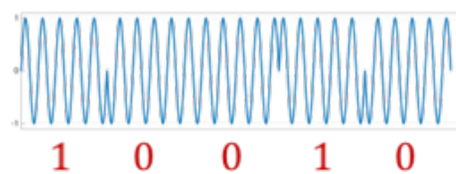
FSK

Frequency Shift Keying



PSK

Phase Shift Keying

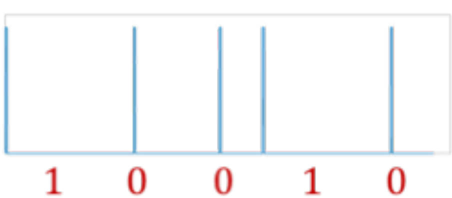


QAM

Phase & Amplitude Modulation (APSK)

PPM

Pulse Position Modulation

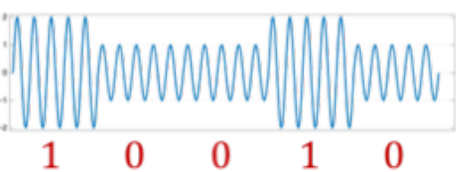


Modulation

Based on how the bits are encoded

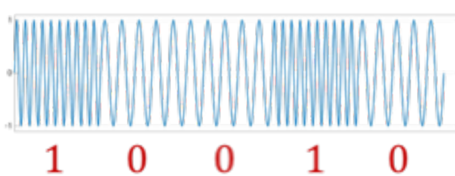
ASK

Amplitude Shift Keying



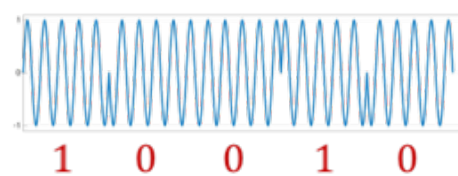
FSK

Frequency Shift Keying



PSK

Phase Shift Keying

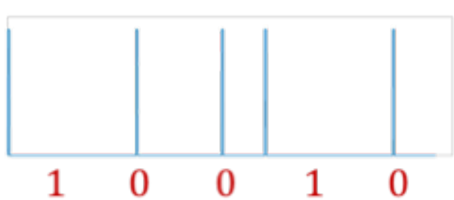


QAM

Phase & Amplitude Modulation (APSK)

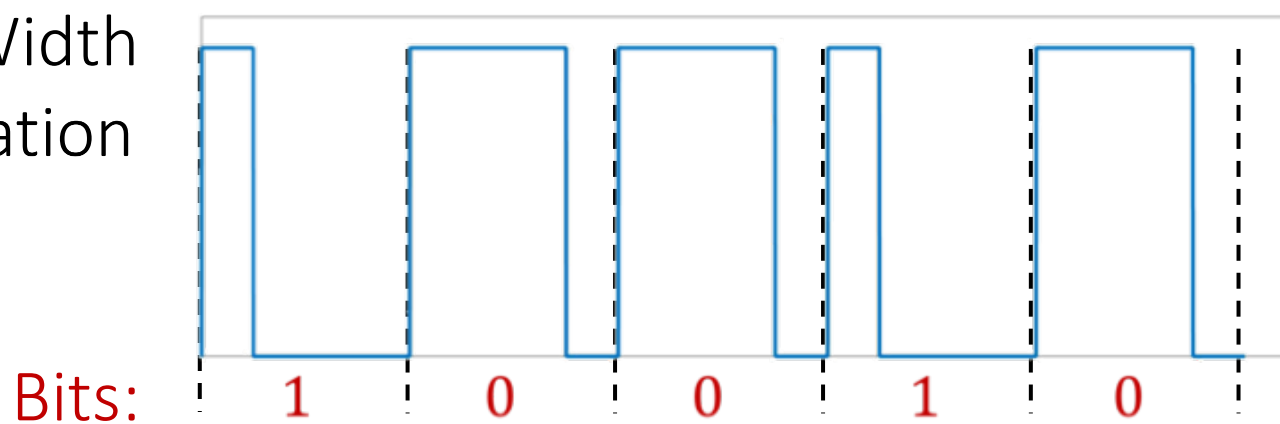
PPM

Pulse Position Modulation



PWM

Pulse Width Modulation

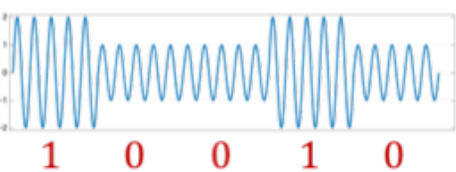


Modulation

Based on how the bits are encoded

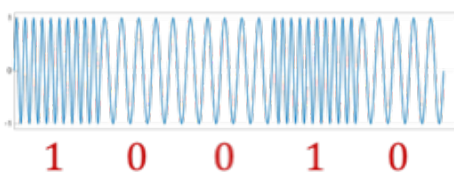
ASK

Amplitude Shift Keying



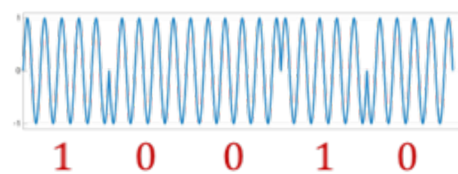
FSK

Frequency Shift Keying



PSK

Phase Shift Keying

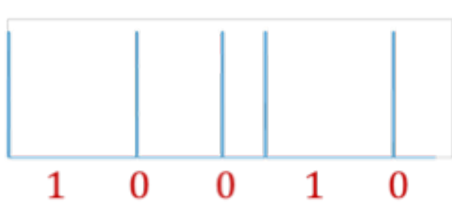


QAM

Phase & Amplitude Modulation (APSK)

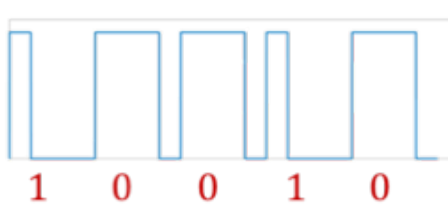
PPM

Pulse Position Modulation



PWM

Pulse Width Modulation

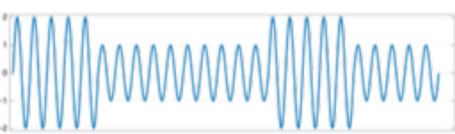


Modulation

Based on how the bits are encoded

ASK

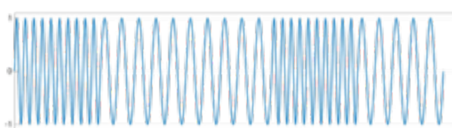
Amplitude Shift Keying



1 0 0 1 0

FSK

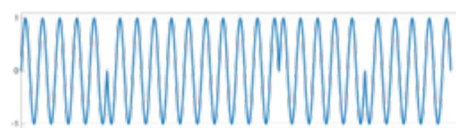
Frequency Shift Keying



1 0 0 1 0

PSK

Phase Shift Keying



1 0 0 1 0

QAM

Phase & Amplitude Modulation (APSK)

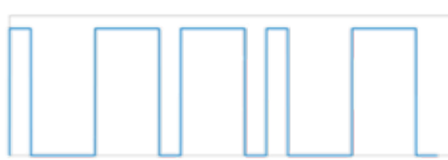
PPM

Pulse Position Modulation

1 0 0 1 0

PWM

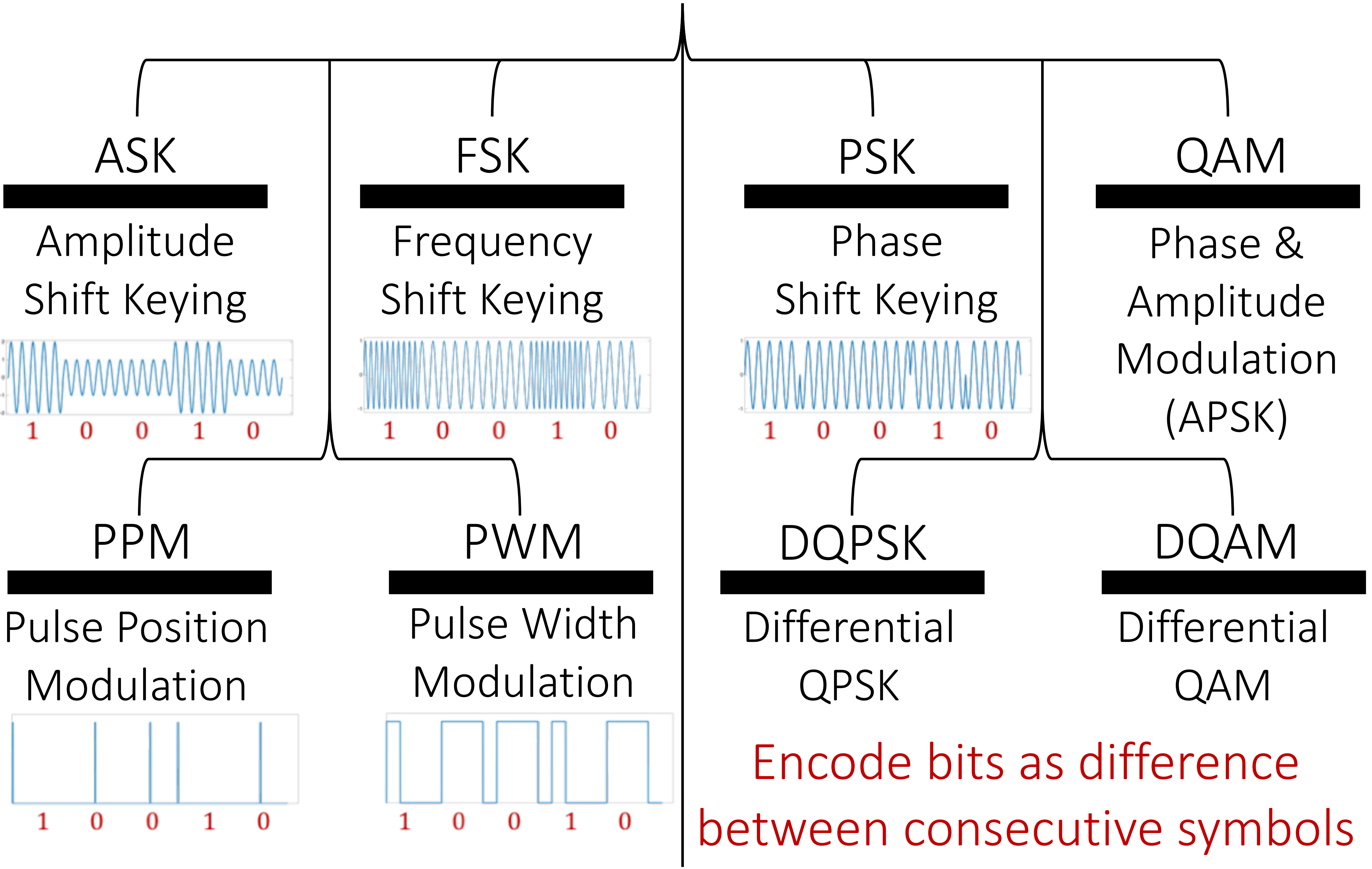
Pulse Width Modulation



1 0 0 1 0

Modulation

Based on how the bits are encoded



DBPSK: Differential Binary Phase Shit Keying

BPSK Modulation

$$0 \rightarrow -1$$
$$1 \rightarrow +1$$

$$x(t) \begin{cases} \hat{b} = 0 \; if \; x(t) < 0 \\ \hat{b} = 1 \; if \; x(t) > 0 \end{cases}$$

$$y(t) = hx(t)$$

$$\rightarrow \text{Real}\{y(t)\} = \text{Real}\{h\}x(t)$$

Without knowing h, it is not possible to decode correctly.

DBPSK Modulation

$$0 \rightarrow x(t+1) = -x(t)$$
$$1 \rightarrow x(t+1) = +x(t)$$

$$\hat{b} = 0 \; if \; x(t)x^*(t+1) < 0$$

$$\hat{b} = 1 \; if \; x(t)x^*(t+1) > 0$$

$$y(t) = hx(t)$$

$$\rightarrow y(t)y^*(t+1) = hx(t)h^*x^*(t+1)$$

DBPSK: Differential Binary Phase Shit Keying

BPSK Modulation

$$0 \rightarrow -1$$
$$1 \rightarrow +1$$

$$x(t) \begin{cases} \hat{b} = 0 \; if \; x(t) < 0 \\ \hat{b} = 1 \; if \; x(t) > 0 \end{cases}$$

$$y(t) = hx(t)$$

$$\rightarrow \text{Real}\{y(t)\} = \text{Real}\{h\}x(t)$$

Without knowing h, it is not possible to decode correctly.

DBPSK Modulation

$$0 \rightarrow x(t+1) = -x(t)$$
$$1 \rightarrow x(t+1) = +x(t)$$

$$\hat{b} = 0 \; if \; x(t)x^*(t+1) < 0$$
$$\hat{b} = 1 \; if \; x(t)x^*(t+1) > 0$$

$$y(t) = hx(t)$$

$$\rightarrow y(t)y^*(t+1)$$
$$= |h|^2 x(t)x^*(t+1)$$

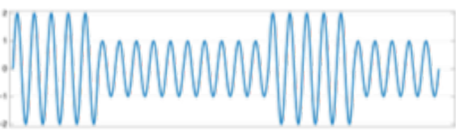
Without knowing h, it is possible to decode correctly.

Modulation

Based on how the bits are encoded

ASK

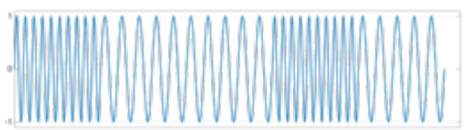
Amplitude Shift Keying



OOK, ASK

FSK

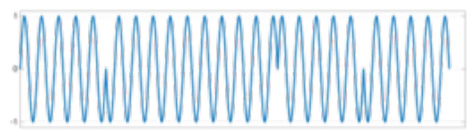
Frequency Shift Keying



CFSK, MSK, GMSK

PSK

Phase Shift Keying



BPSK, QPSK, CPM

QAM

Phase & Amplitude Modulation (APSK)

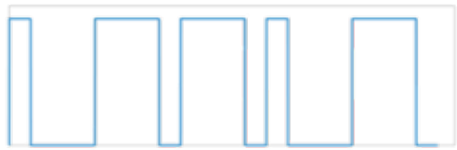
PAM, M-QAM

PPM

Pulse Position Modulation

PWM

Pulse Width Modulation



DQPSK

Differential QPSK

DBPSK, DQPSK,

DQAM

Differential QAM

DQAM

Definitions & Variables

- $x(t)$: Transmitted Baseband Signal
- $v(t)$: Additive Gaussian Noise
- $y(t)$: Received Signal
- τ: Propagation delay in the signal
- h: Channel Coefficient.
- P_{RX}: Received Power
- P_{TX}: Transmitted Power
- G_{RX}: Receiver Antenna Gain
- G_{TX}: Transmitter Antenna Gain
- λ: Wavelength
- d: Distance between transmitter and receiver
- ϕ: Channel Phase
- f_c: Carrier Frequency
- c: Speed of light
- $I = \Re\mathfrak{e}\{x(t)\}$ & $Q = \Im\mathfrak{m}\{x(t)\}$
- M: Number of constellation points in modulation
- $\hat{b}$: Decoded bit