114-1 電工實驗（通信專題）

IQ Components & Frequency Conversion

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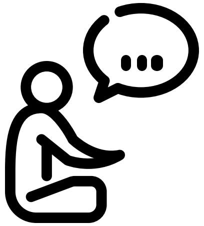
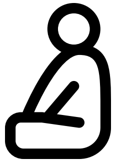
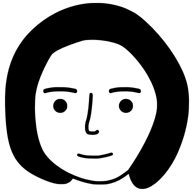
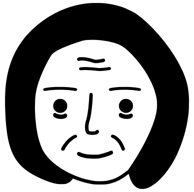
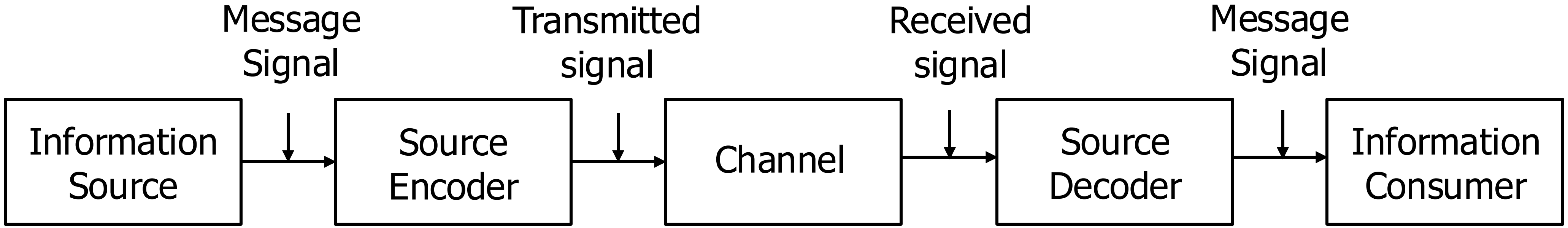
What is communications?

- Information transfer across space or time

Transmitter	Channel	Receiver
	(air)	
		

Analog vs Digital Communications - Analog

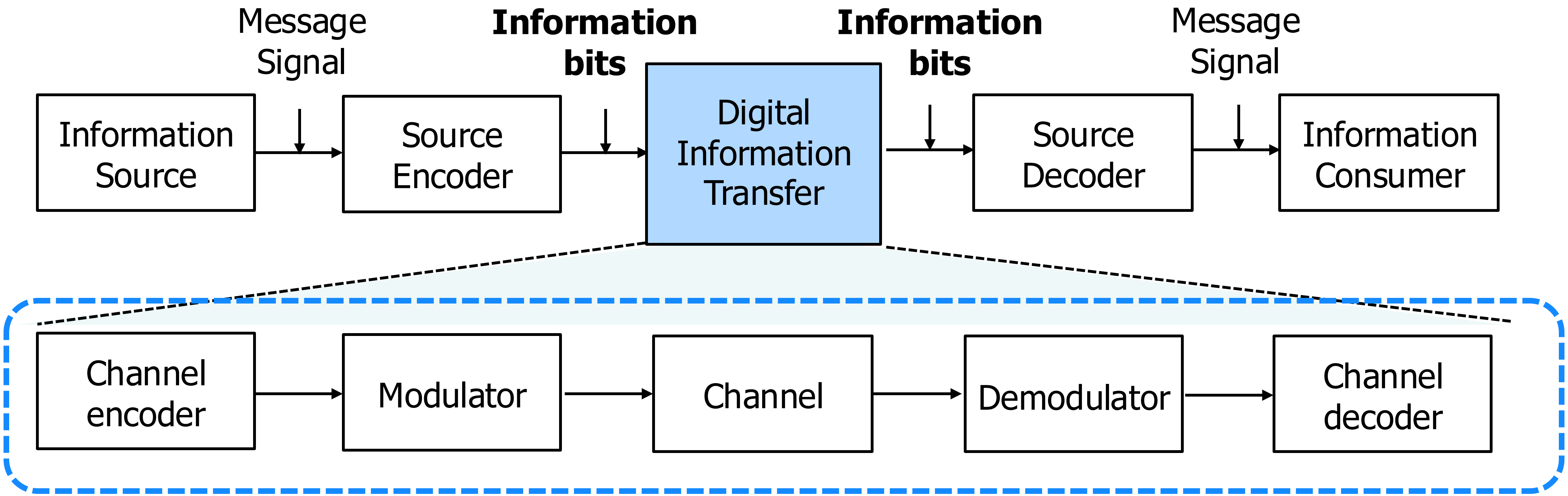


- AM (amplitude modulation) radio, vinyl records, …

Analog vs Digital Communications - Digital

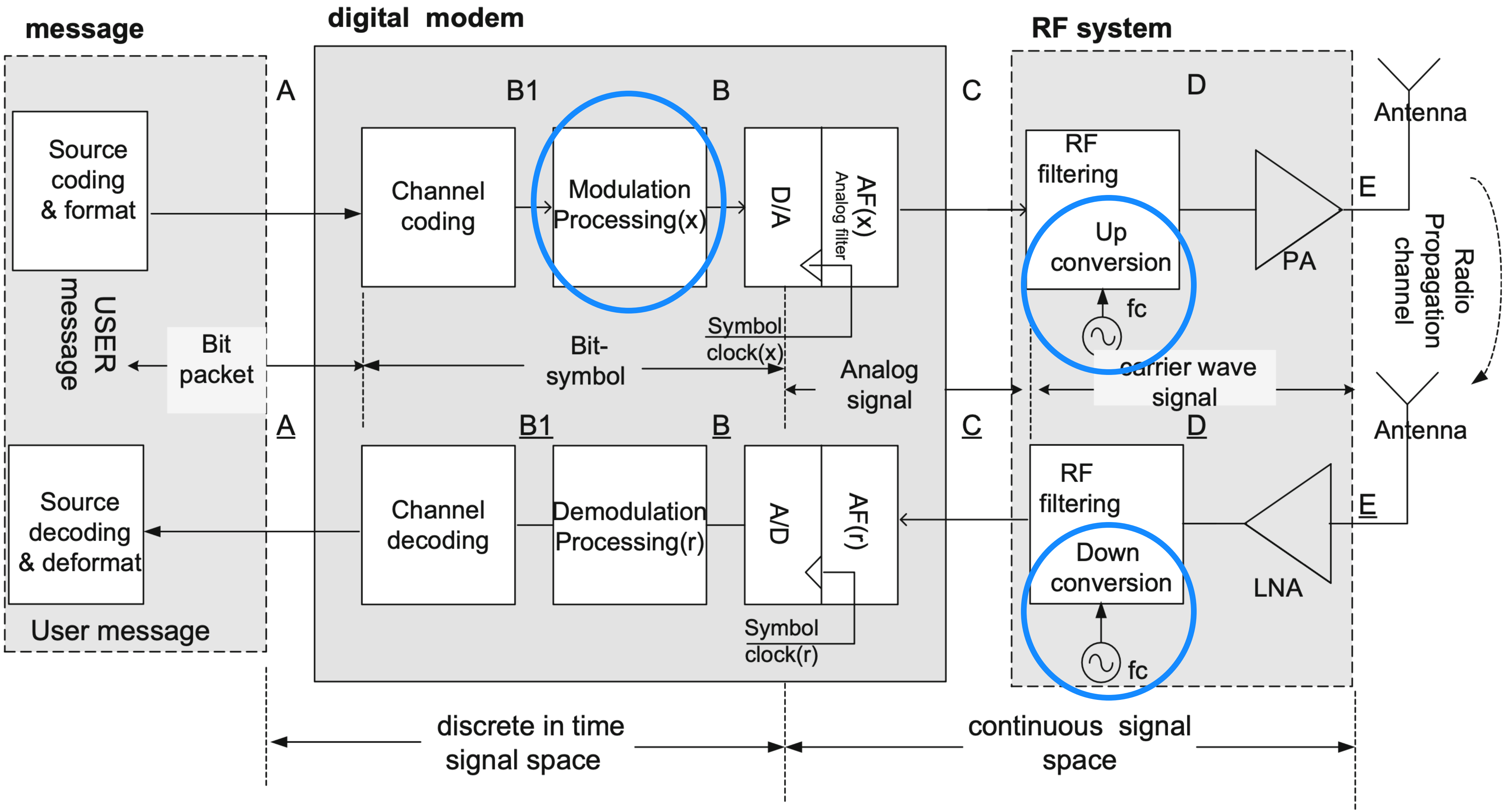
1. Source coding and compression
2. Digital information transfer

Achieve reliable communications over unreliable channels



The focus of this class

Digital Radio Communication System Block Diagram



Modulation with IQ Components

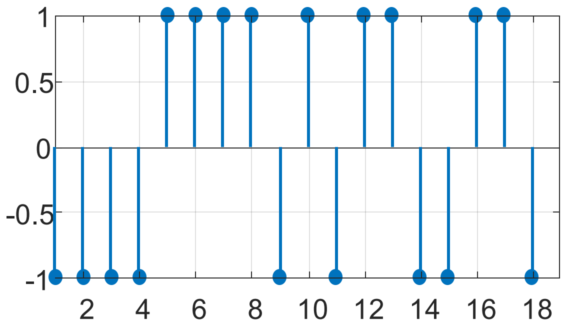
Modulation & Demodulation

- Modulation: information to signal
- Demodulation: Signal to information

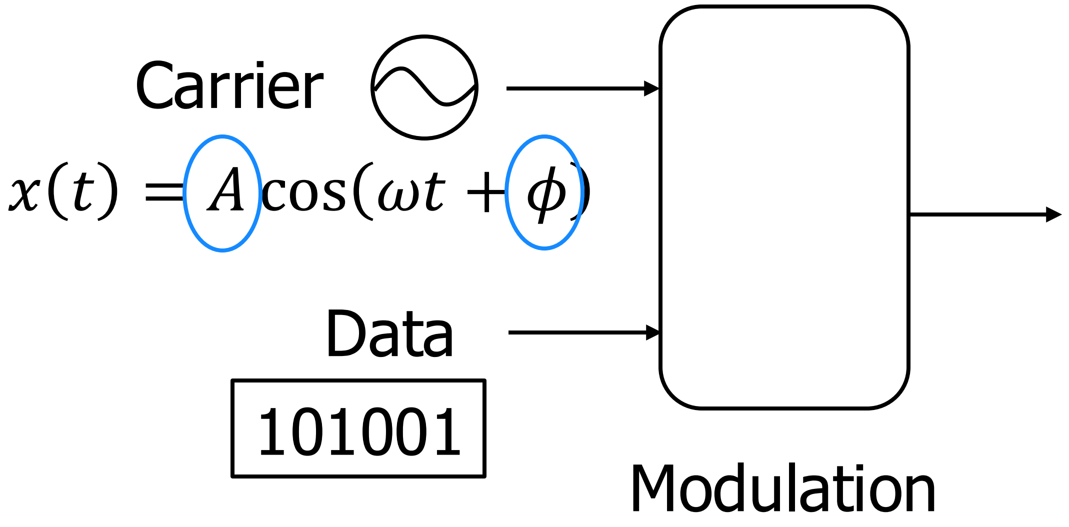
Bits: [1, 1, 1, 1, 0, 0, 0, 0, 1, 0, 1, 0, 0, 1, 1, 0, 0, 1]

Modulation

Demodulation



Modulation in Radio Systems

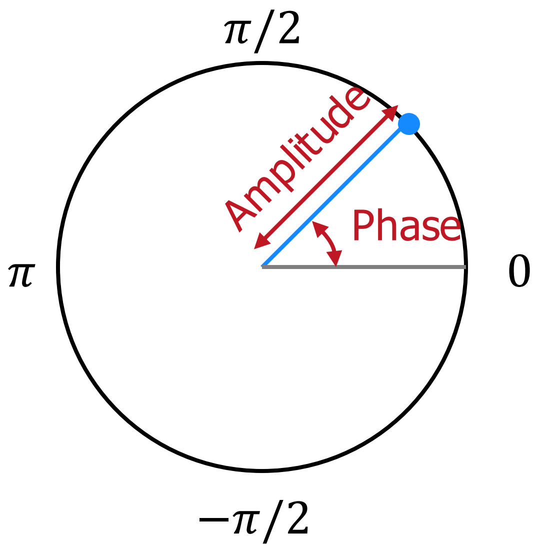


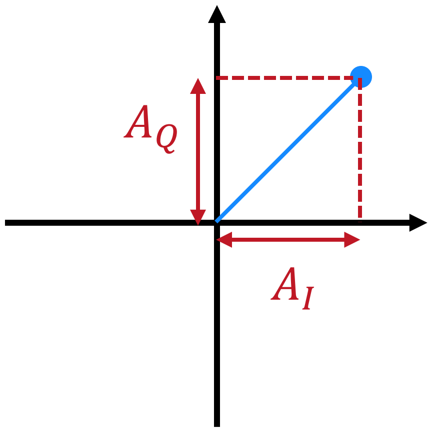
- Overlay data onto carrier signal (sinusoid)
- How? Sinusoids have two very accessible parameters
- Amplitude and Phase

Signal Representation: Phasor

Polar: Amplitude & Phase

Rectangular: In-phase (I) & Quadrature (Q)





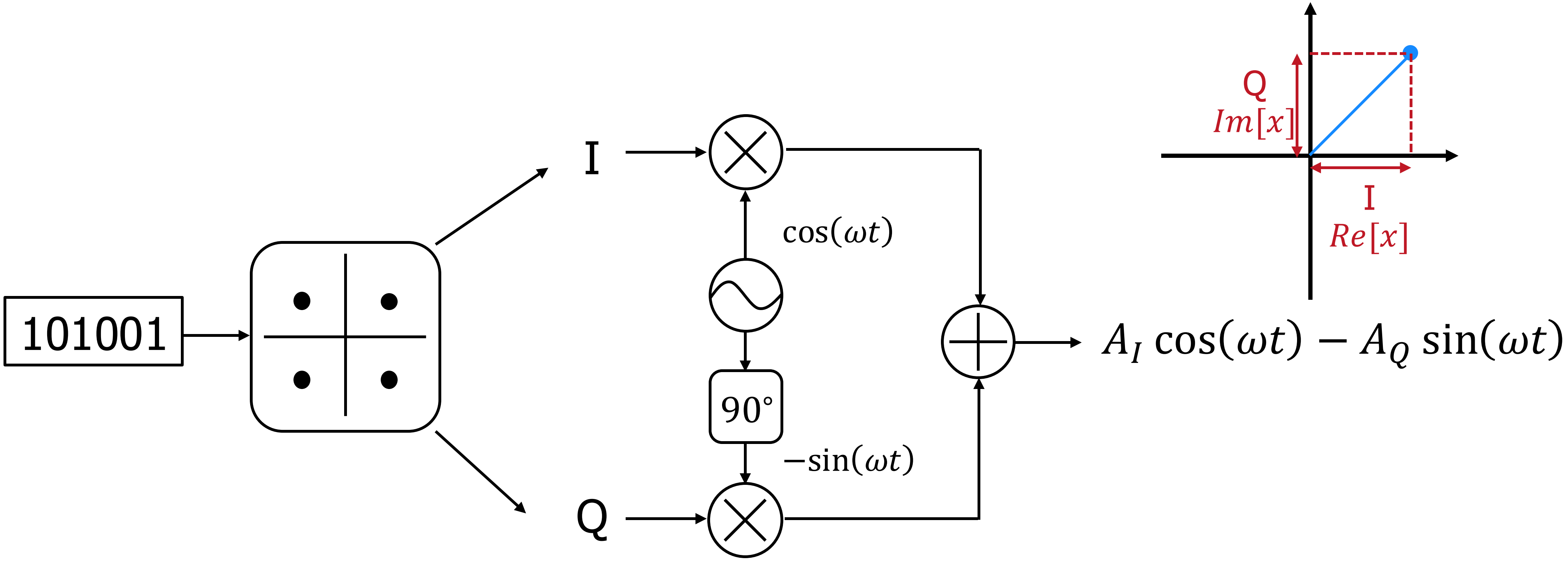
$$x(t) = A\cos(\omega t + \phi)$$

$$x(t) = A_I \cos(\omega t) - A_Q \sin(\omega t)$$

$$A_I = A\cos(\phi)\,, A_Q = A\sin(\phi)$$

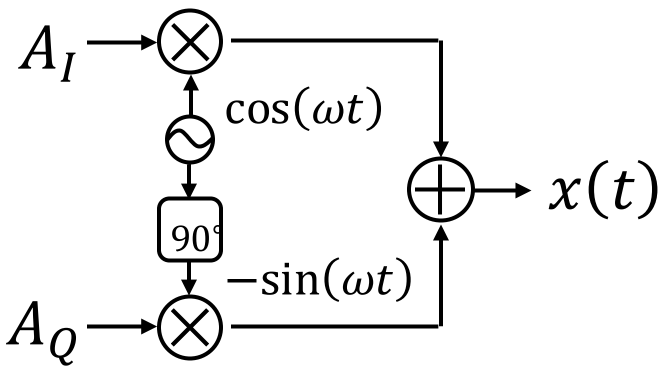
Signal Representation

Rectangular (I,Q) form enables practical implementation

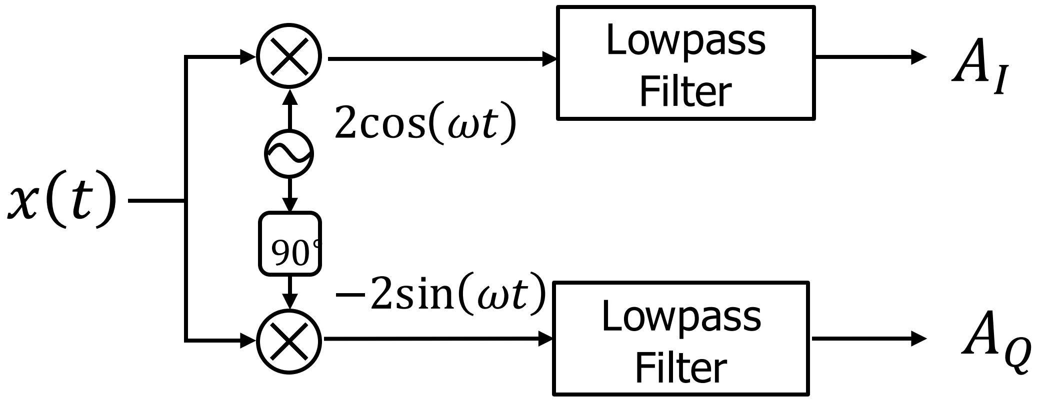


Modulation = mapping data bits to (I,Q) values

Note: Get Back A_I, A_Q with Downconversion



Upconversion



Downconversion

Digital Modulation

Symbols

Complex modulated values

Constellation (or Alphabet)

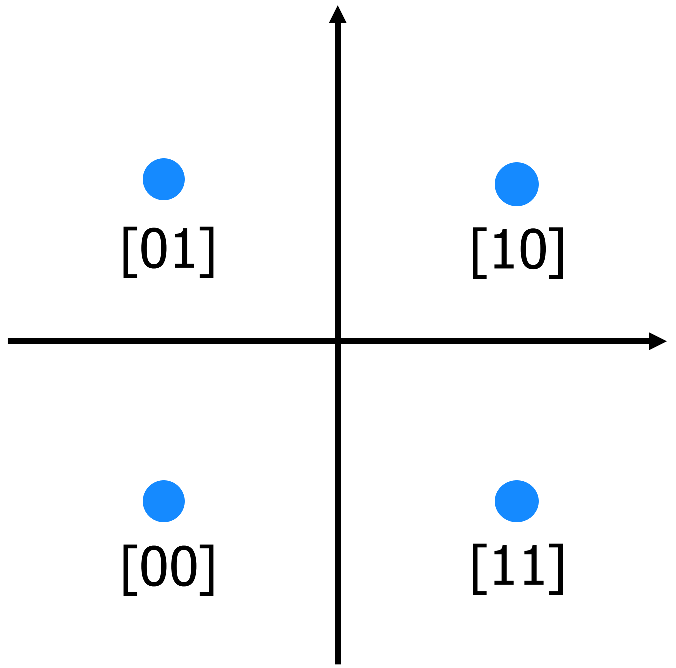
Set of symbols

Modulation Order

Number of symbols in the constellation, M

Bits to Constellation

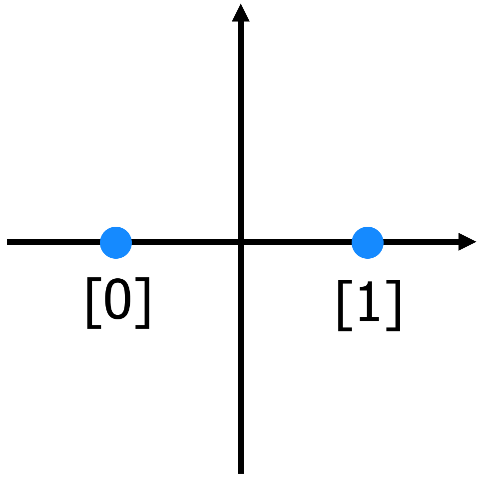
M-order constellation can encode $\log_2(M)$ bits per symbol



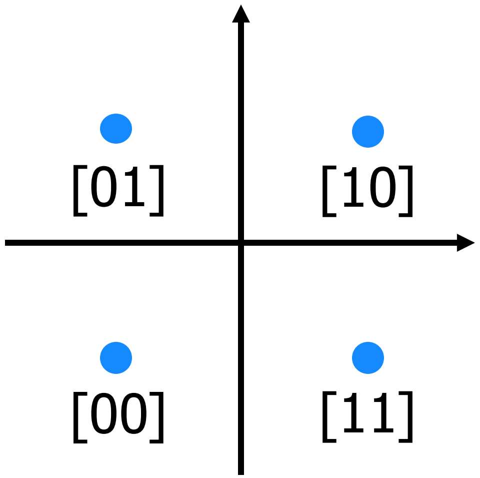
Phase Shift Keying (PSK)

Encodes information only in phase

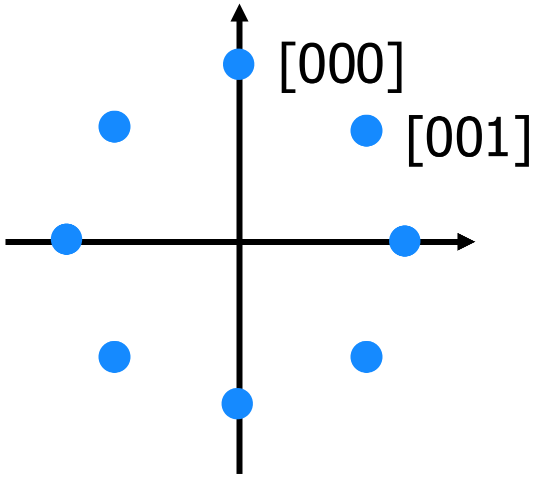
BPSK (M=2)



QPSK (M=4)



8-PSK (M=8)



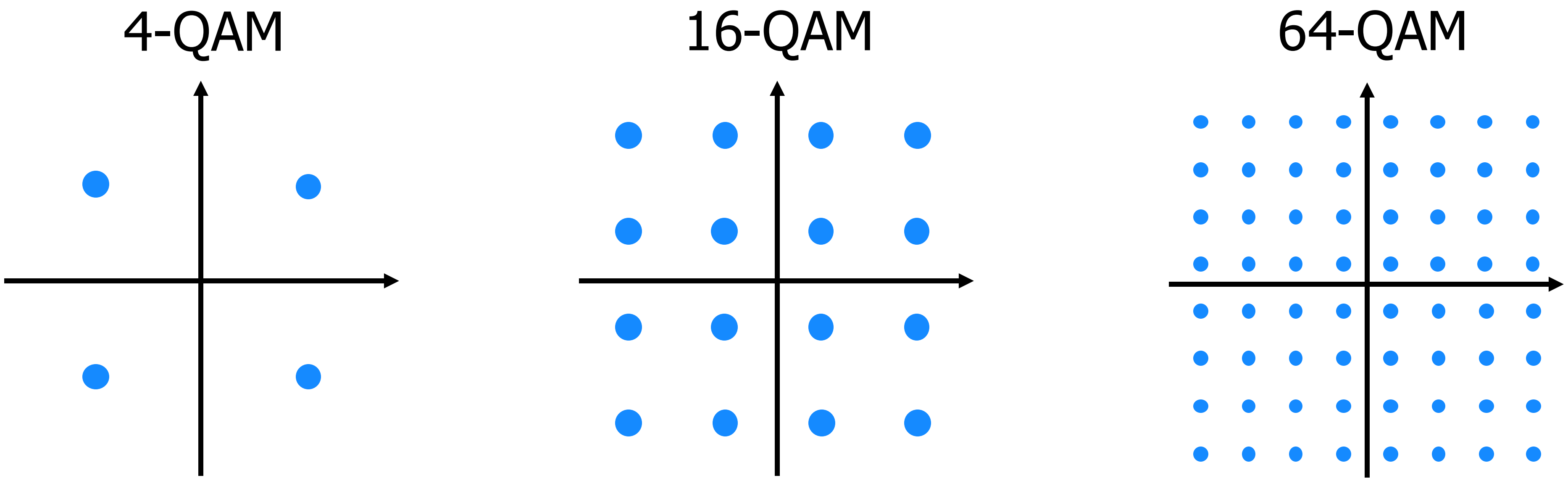
Constant Power envelope

Pros: no need to recover amplitude, no need for linear amplifier

Con: wastes amplitude dimension

Quadrature Amplitude Modulation (QAM)

Encodes information in both amplitude and phase



Common in wideband systems

802.11b	802.11g/n	802.11ac
16-QAM	64-QAM	256-QAM

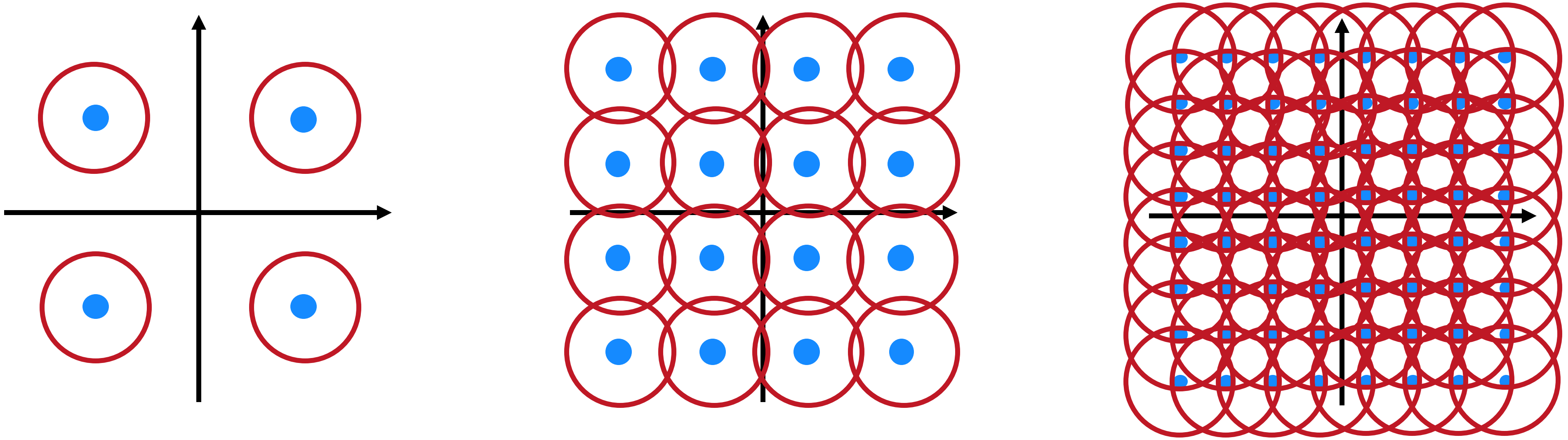
Tradeoff: Rate vs. Error Probability

By increasing modulation order, M, we get:

More data in the same bandwidth

Lower noise tolerance (i.e., higher error probability)

4-QAM (2 bits/symbol) | 16-QAM (4 bits/symbol) | 64-QAM (6 bits/symbol)



SNR dictates feasible constellation size

Signal-to-Noise Ratio (SNR)

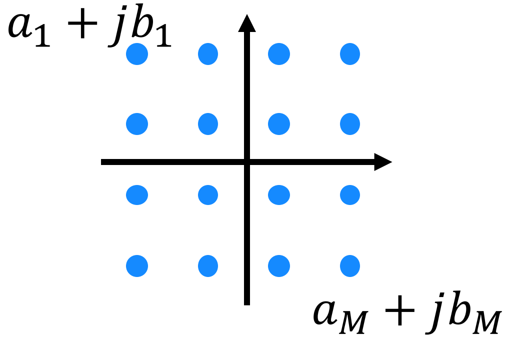
Energy per symbol

For M-ary signaling with equal priors

$$E_s = \frac{1}{M}\sum_{m=1}^{M} \|a_m + jb_m\|^2$$

Energy per bit

$$E_b = \frac{E_S}{\log_2 M}$$



Signal-to-Noise Ratio (SNR)

$$SNR = \frac{E[S^2]}{E[N^2]} = \frac{P_{signal}}{P_{noise}}$$

Usually in dB

$$SNR_{dB} = 10\log_{10} SNR$$

Eb/N0:
SNR normalized by bit (amount of information transferred)

$$\frac{E_b}{N_0} = \frac{SNR}{\log_2 M}$$

Bit-to-Symbol Mapping

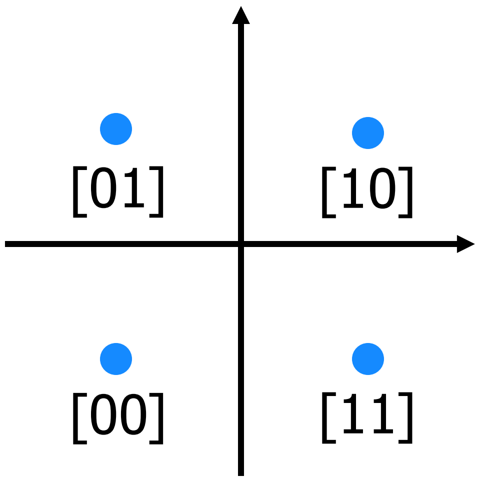
Confusing with neighbors is the most likely error

➔ Best to minimize bit-difference between neighbors

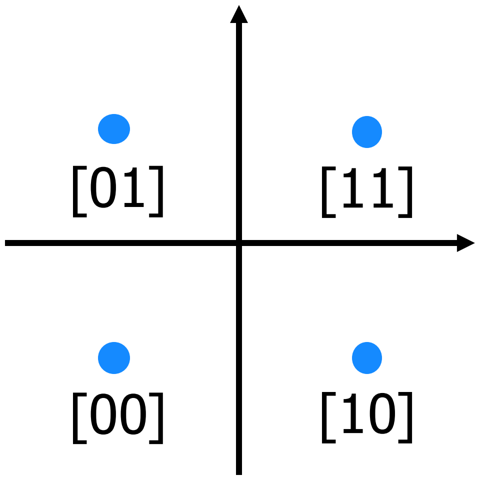
Gray Coding

Neighboring symbols differ by only one bit

Extra performance at zero cost (this is rare!)



Natural-coded QPSK



Gray-coded QPSK

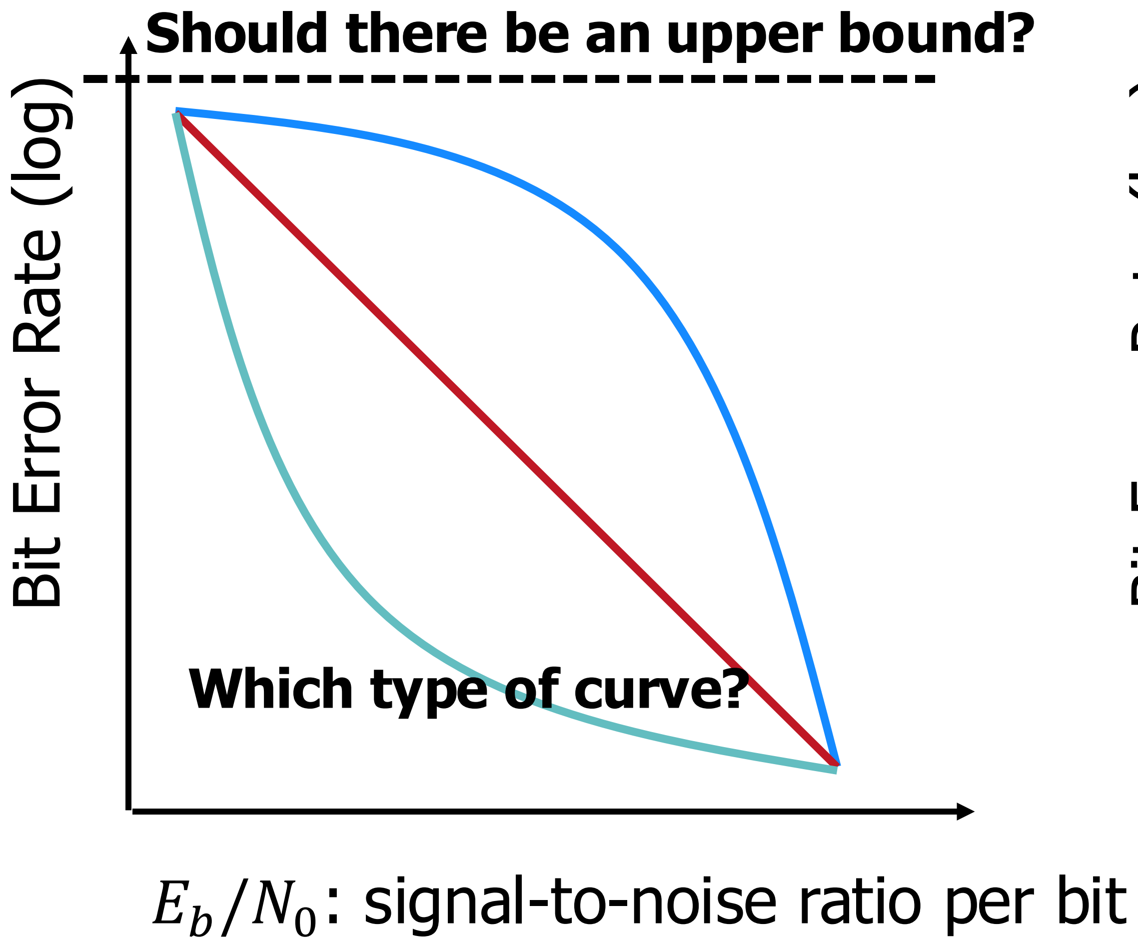
BER vs SNR

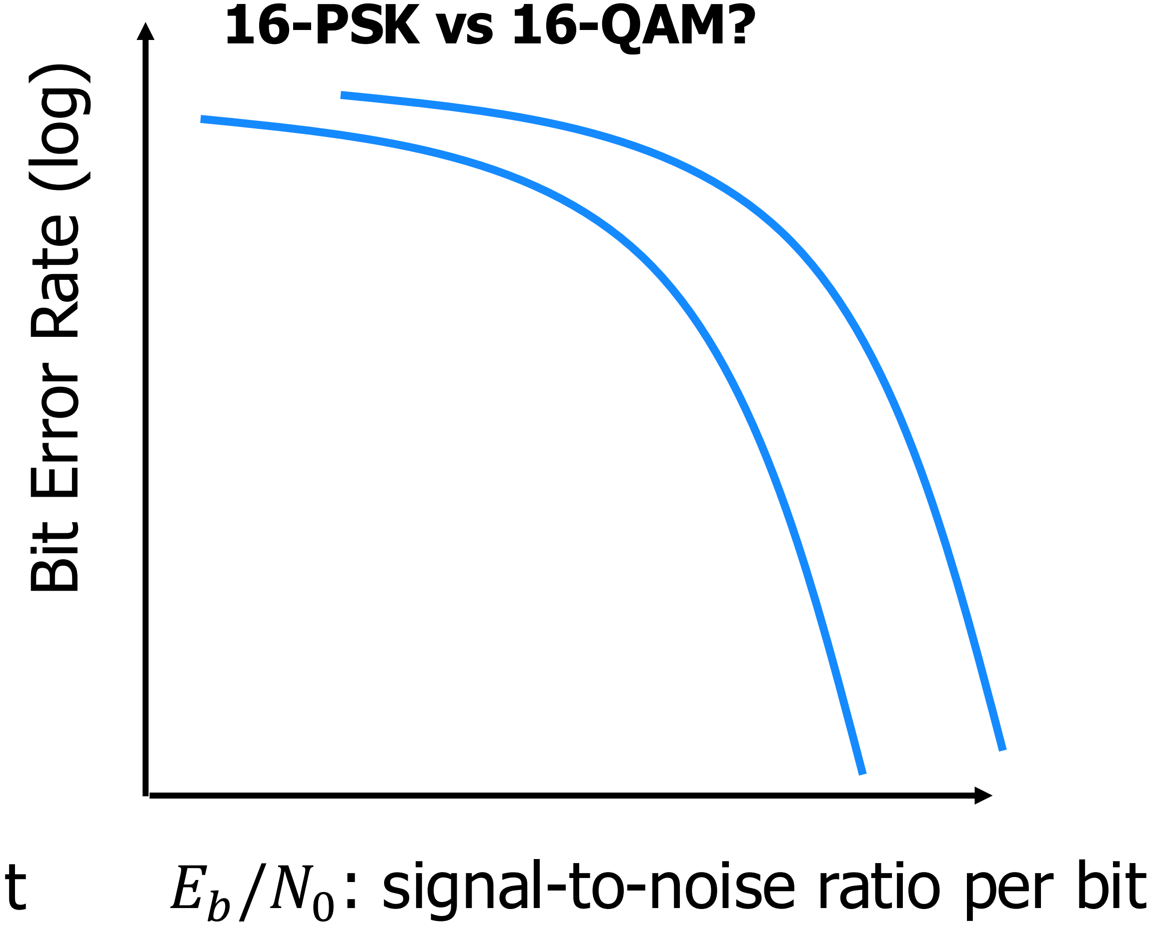
Let's have some thought experiments

Natural code vs Gray code?

4-PSK vs 8-PSK?

16-PSK vs 16-QAM?





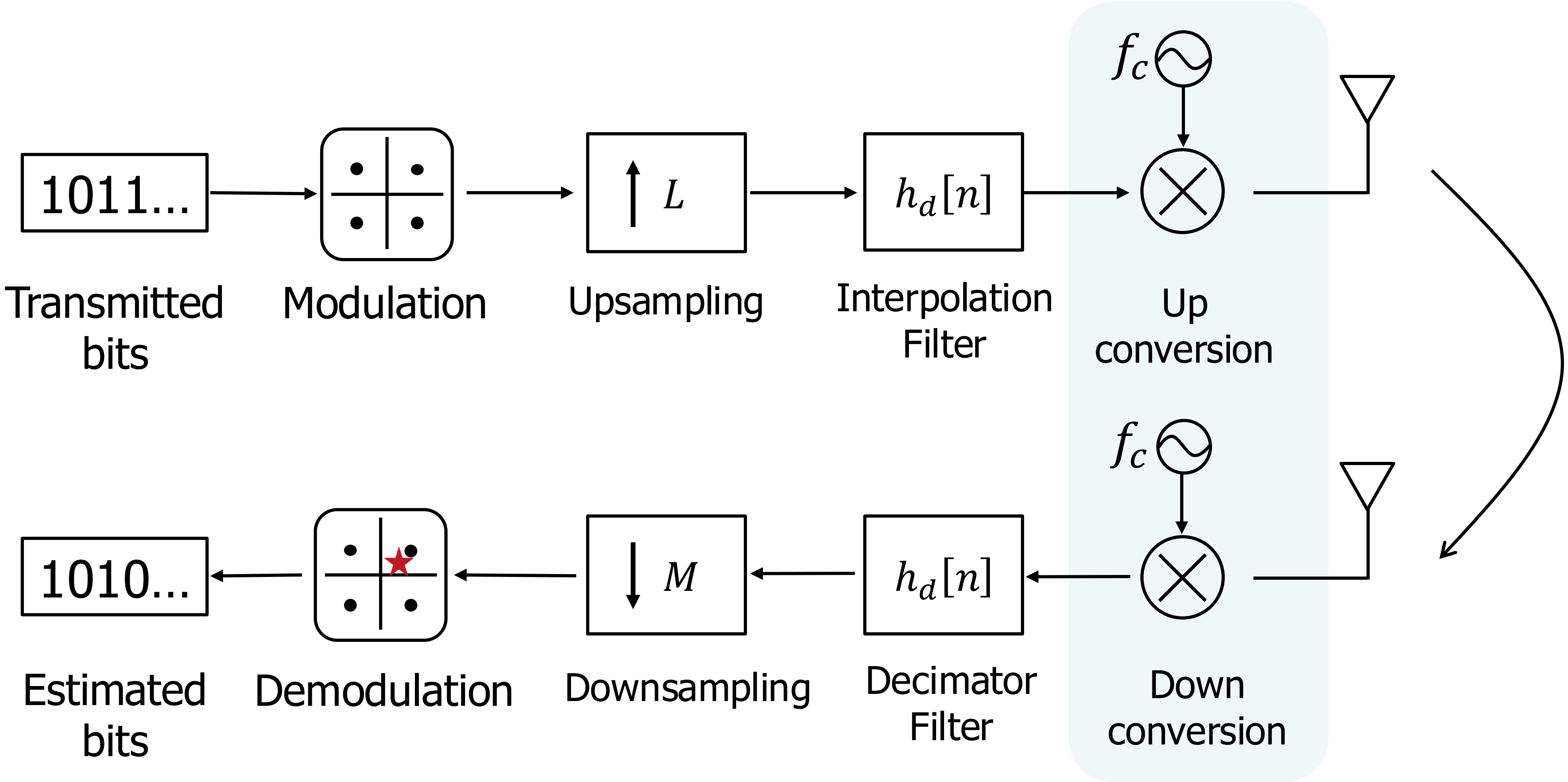
Acknowledgment

Dr. Clayton Shepard

Prof. Rahman Doost-Mohammady

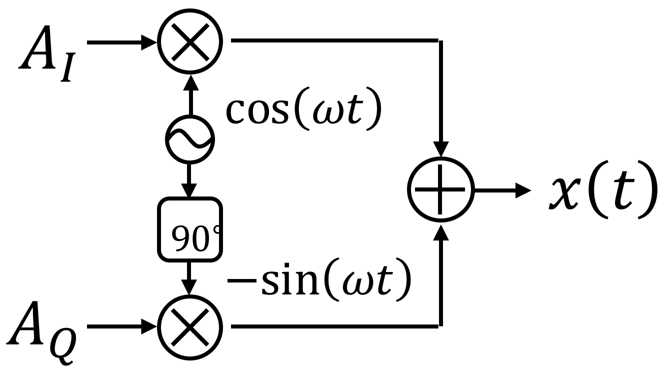
Up/Down conversion

Upconversion & Downconversion

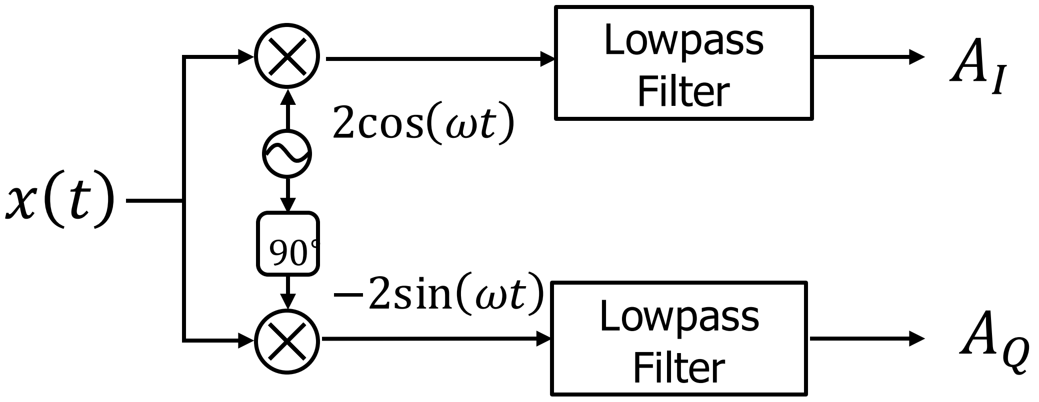


Baseband ⟶ Radio Frequency (RF)

Upconversion & Downconversion



Upconversion



Downconversion

Upconversion: Three Representations

$$x(t) = A\cos(2\pi f_c t + \theta) \qquad (1)$$

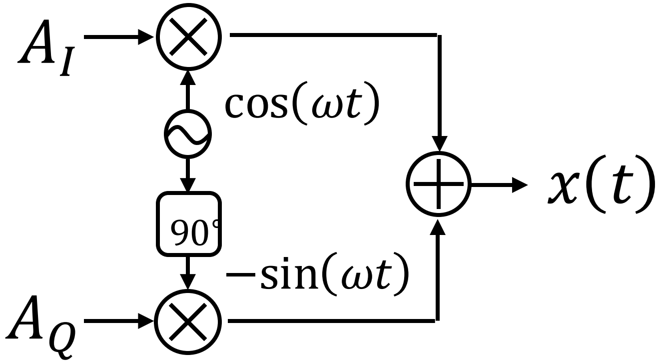
Polar Cosine wave modulated by a baseband signal with amplitude (A) and phase (θ)

$$= A_I \cos(2\pi f_c t) - A_Q \sin(2\pi f_c t) \qquad (2)$$

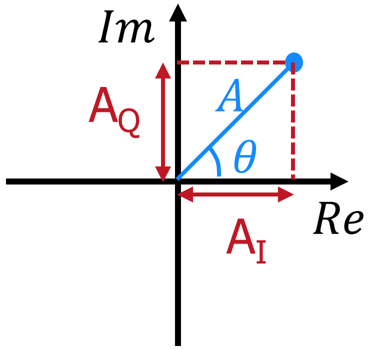
Rectangular $A_I = A\cos(\phi)\,, A_Q = A\sin(\phi)$

$$= Re\{[A_I + jA_Q]\, e^{j2\pi f_c t}\} \qquad (3)$$

Complex envelope $u = A_I + jA_Q$



Hardware implementation

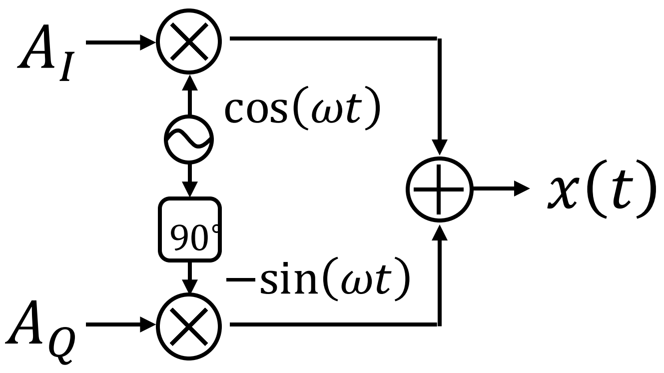


$A_I + jA_Q$: Complex envelope

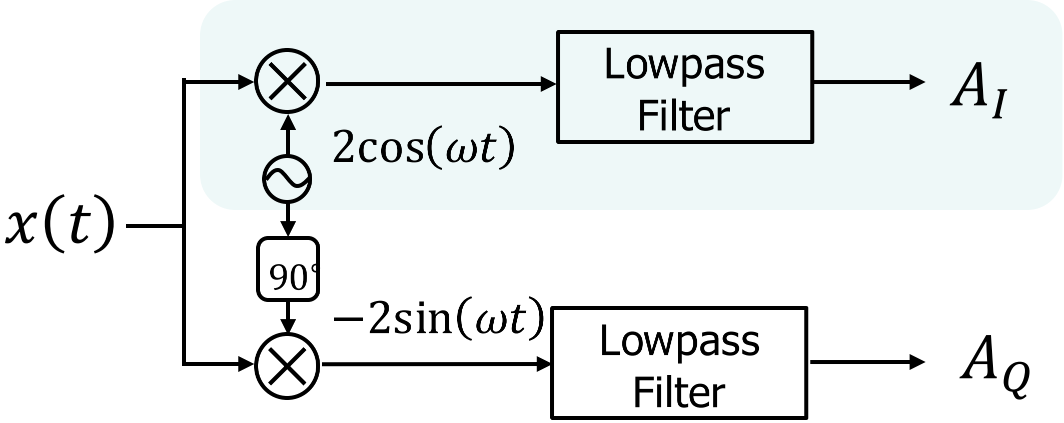
Question

- How to transmit complex signals/constellations over-the-air?
- Is the signal transmitted over-the-air real or complex?

Downconversion: Getting Back A_I, A_Q



Upconversion

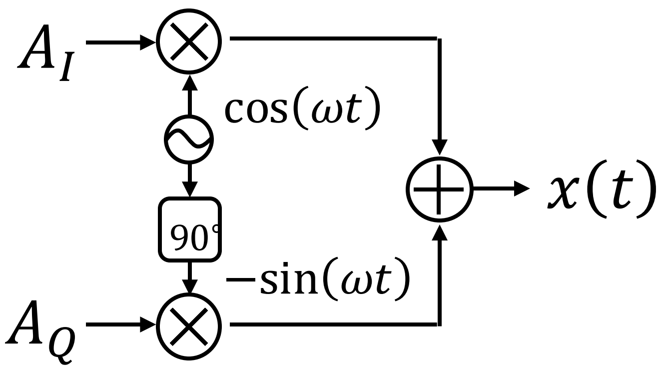


Downconversion

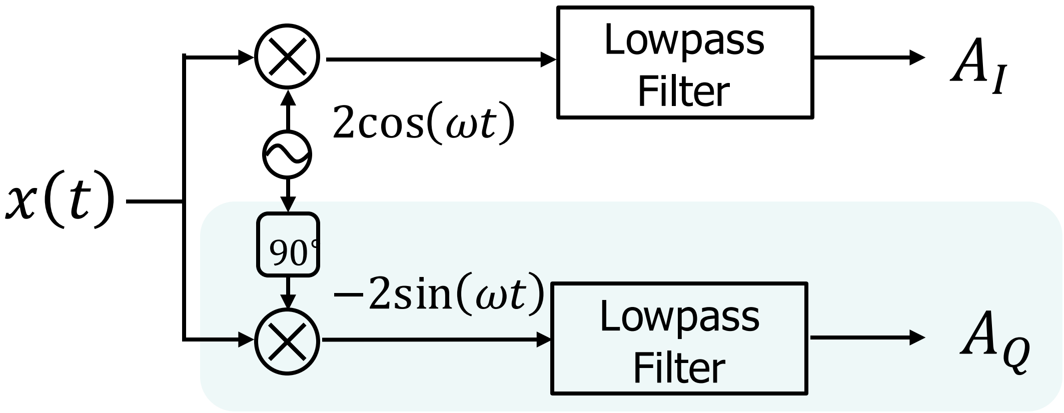
$$
\begin{aligned}
& x(t) \cdot 2\cos(2\pi f_c t) \\
& \quad = 2A_I \cos^2(2\pi f_c t) - 2A_Q \sin(2\pi f_c t)\cos(2\pi f_c t) \\
& \quad = A_I + \boxed{A_I \cos(4\pi f_c t) - A_Q \sin(4\pi f_c t)}
\end{aligned}
$$

Get rid of them by lowpass filtering

Downconversion: Getting Back A_I, A_Q



Upconversion



Downconversion

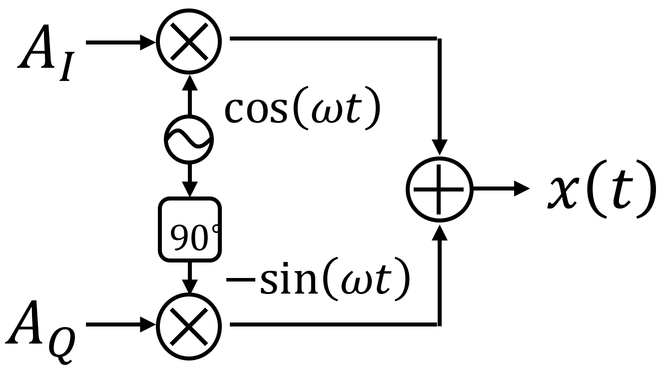
$$x(t) \cdot [-2\sin(2\pi f_c t)]$$

$$= -2A_I \cos(2\pi f_c t)\sin(2\pi f_c t) + 2A_Q \sin^2(2\pi f_c t)$$

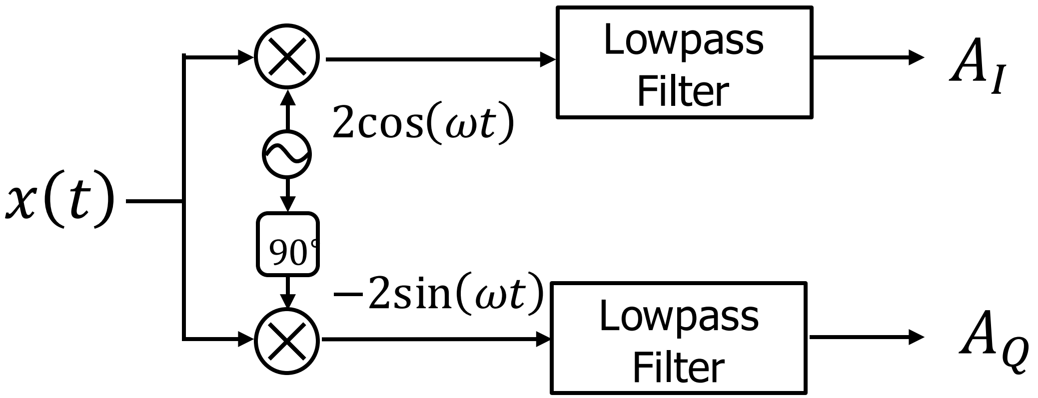
$$= A_Q - \boxed{A_I \sin(4\pi f_c t) - A_Q \cos(4\pi f_c t)}$$

Get rid of them by lowpass filtering

Downconversion: Back to Complex Envelope



Upconversion



Downconversion

$$
\begin{aligned}
&x(t)\cdot 2e^{-j2\pi f_c t}\\
&\quad = 2\big[A_I\cos(2\pi f_c t) - A_Q\sin(2\pi f_c t)\big]\big[\cos(2\pi f_c t) - j\sin(2\pi f_c t)\big]\\
&\quad = \boxed{A_I + jA_Q} + \boxed{C_1\sin(4\pi f_c t) + C_2\cos(4\pi f_c t)}
\end{aligned}
$$

Complex envelope Get rid of them by lowpass filtering

Upconversion: Frequency Domain

$$x(t) = Re\{[A_I + jA_Q]\, e^{j2\pi f_c t}\}$$

Let $u(t) = A_I + jA_Q$

$$= Re\{u(t)\, e^{j2\pi f_c t}\}$$

Let $c(t) = u(t)\, e^{j2\pi f_c t}$

$$= Re\{c(t)\}$$

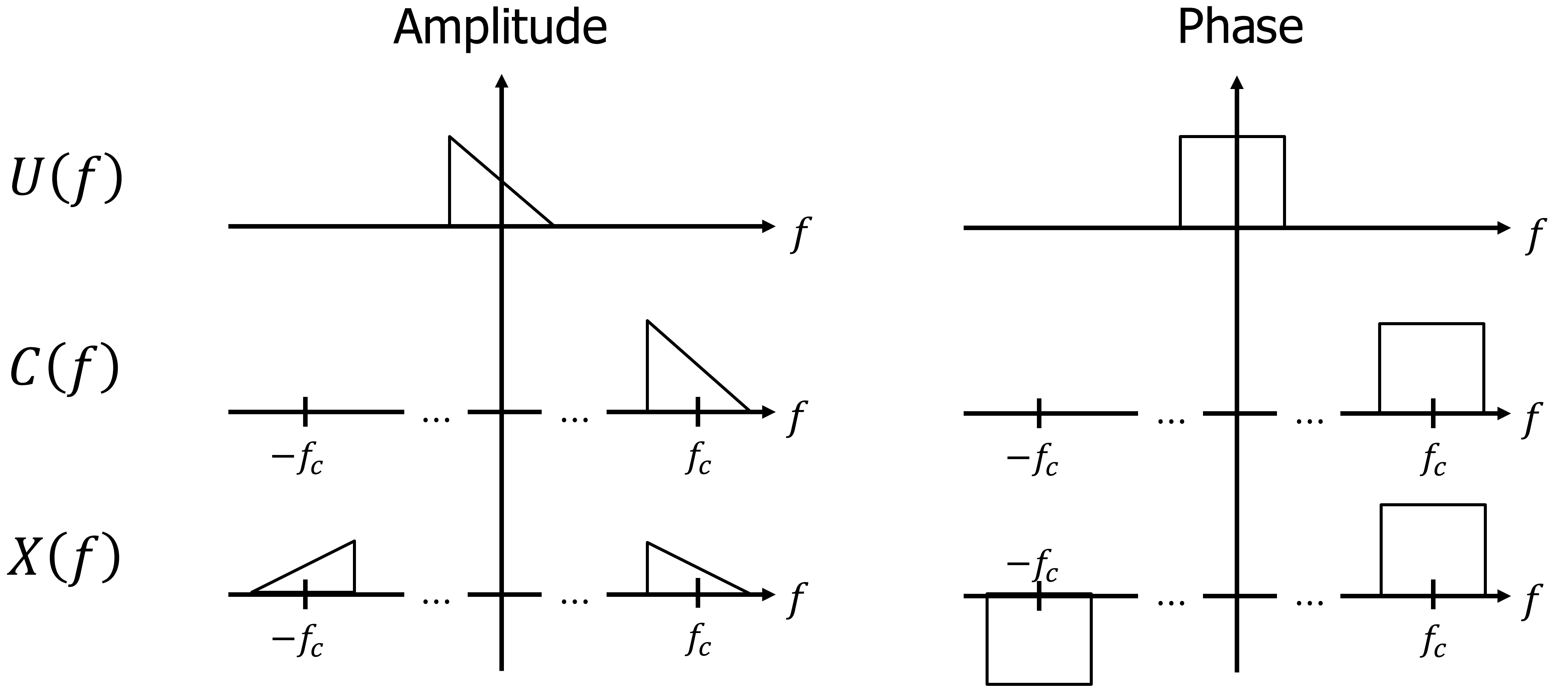
$$\Longleftrightarrow$$

$$X(f) = \frac{1}{2}(\, C(f) + C^*(-f)\,)$$

where $C(f) = U(f - f_c)$

$$X(f) = \frac{1}{2}\left(\, C(f) + C^*(-f) \,\right)$$

where $C(f) = U(f - f_c)$



Downconversion: Frequency Domain

$y(t) = x(t) \cdot 2e^{-j2\pi f_c t}$

Let $d(t) = x(t)\, e^{-j2\pi f_c t}$

$\downarrow$ Lowpass filtering

$u(t)$

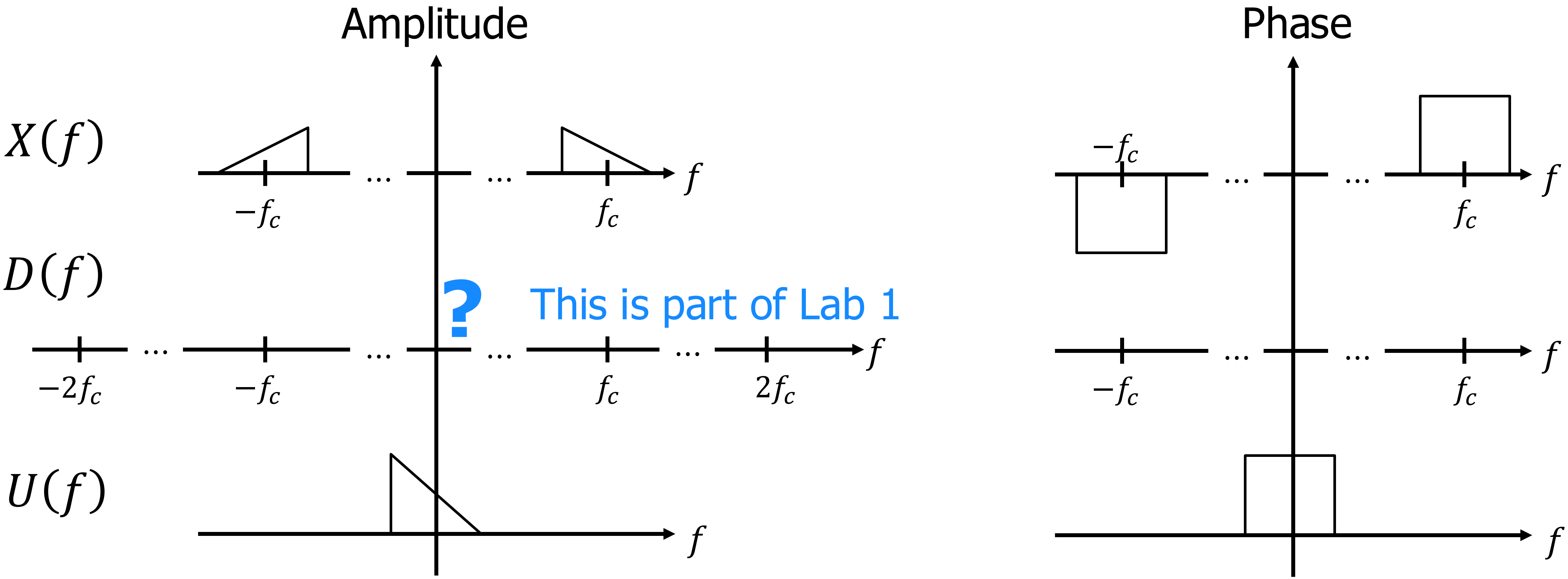
$\Longleftrightarrow$

$$U(f) = lowpass\{\, 2 \cdot D(f) \,\}$$

where $D(f) = X(f + f_c)$

$$U(f) = lowpass\{\, 2 \cdot D(f) \,\}$$

where $D(f) = X(f + f_c)$



References

- Modern Digital Radio Communication Signals and Systems by Sung-Moon Michael Yang [NTU Library Link]
  - Chap 1.2
- Introduction to Communication Systems 1st Edition by Upamanyu Madhow [Unofficial version on UC Santa Barbara Website]
  - Chap 2 & 3

Lab 1 is released.
Due Sep. 16 (2 weeks from now)