Example (2)

- Example 2: Express 50 W in
  - (a) dBW
  - (b) dBm

(a) P(dBW) = 10 log (50) = 17 dBW

(b) P(dBm) = 10 log (50x1000) dBm

= 10 log (50) + 10 log (1000) dBm

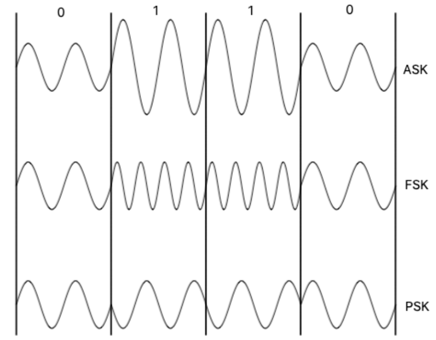
= 17 + 30 = 47 dBm

Coding Terminology

- **Symbol:** **the smallest element of a signal with a given amplitude, frequency, and phase that can be detected** 1 0
- **Modulation Rate:** = 1/symbol_duration = Baud rate (or symbol rate)
- **Data Rate:** Bits per second (bps)
- A symbol may carry multiple bits
  - A binary signal with only two different symbols would carry 1 bit per symbol (baud rate = data rate)
  - For an M-ary signal, data rate = baud rate x $\log_2(M)$

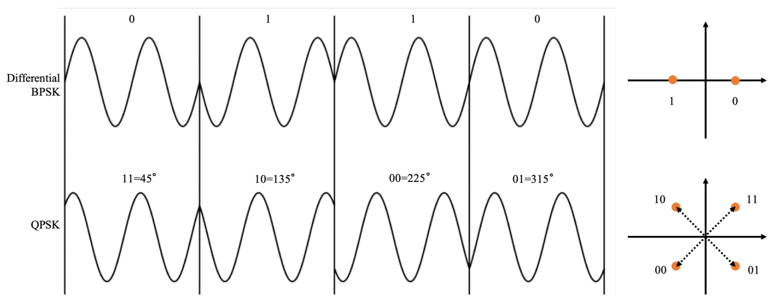
Modulation

- Digital version of modulation is called keying
  - **Amplitude Shift Keying (ASK)**
  - **Frequency Shift Keying (FSK)**
  - **Phase Shift Keying (PSK):** Binary PSK (BPSK)



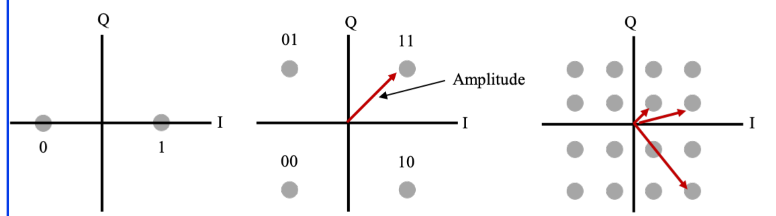
Modulation (Cont)

- **Differential BPSK:** Does not require reference signal
- **Quadrature Phase Shift Keying (QPSK)**



QAM

- Quadrature Amplitude and Phase Modulation
- 4-QAM, 16-QAM, 64-QAM, 256-QAM, …
- Used in DSL and wireless networks
- Constellation diagram (shows combinations of amplitudes and phases)



Binary (1 amplitude, 2 phases) 4-QAM (1 amplitude, 4 phases) 16-QAM (3 amplitudes, 12 phases)

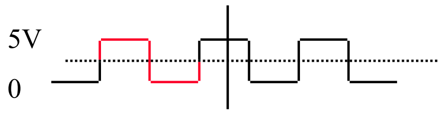
- 4-QAM ⇒ 2 bits/symbol, 16-QAM ⇒ 4 bits/symbol, …

QAM in Action

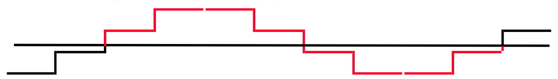
Wireless Technology	QAM Supported
4G	256 QAM
5G	1024 QAM
WiFi 802.11n	16 QAM, 64 QAM
WiFi5 802.11ac	256 QAM
WiFi6 802.11ax	1024 QAM

Channel Capacity

- Capacity = Maximum data rate (bps) for a channel
- **Nyquist Theorem (noiseless channel)**: Bandwidth = B Hz
  Baud rate ≤ 2 B
- Bi-level Encoding: Max. Data rate = 2 × Bandwidth



- Multilevel: Capacity = 2 × Bandwidth × $\log_2$ M
  M = Number of levels



Example: M=4, Capacity = 4 × Bandwidth

Example

Assume that you have discovered a novel material that has negligible electrical noise. What is the maximum data rate that this material could achieve over a phone wire having a bandwidth of 3100 Hz if data was encoded with 64-QAM?

Solution

We have B= 3100 M = 64

$\text{Data rate} = 2 \times 3100 \times \log_2 64 = 37{,}200 \text{ bps}$

Shannon's Theorem (noisy channel)

- Bandwidth = B Hz
  Signal-to-noise ratio = S/N
- Maximum number of bits/sec = B $\log_2$ (1+S/N) [error free communication]
- Example: Phone wire bandwidth = 3100 Hz

S/N = 30 dB

10 $\log_{10}$ S/N = 30

$\log_{10}$ S/N = 3

S/N = 10^3 = 1000

Capacity = 3100 $\log_2$ (1+1000) = 30,894 bps