

Part 2:

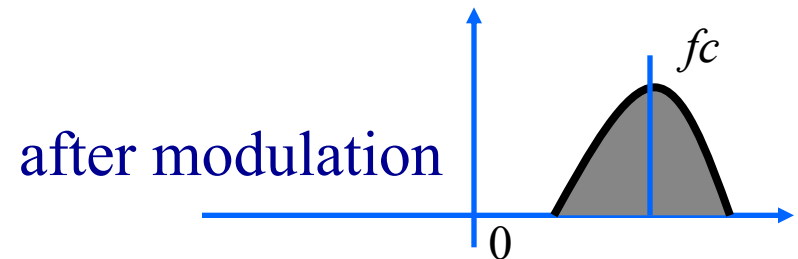
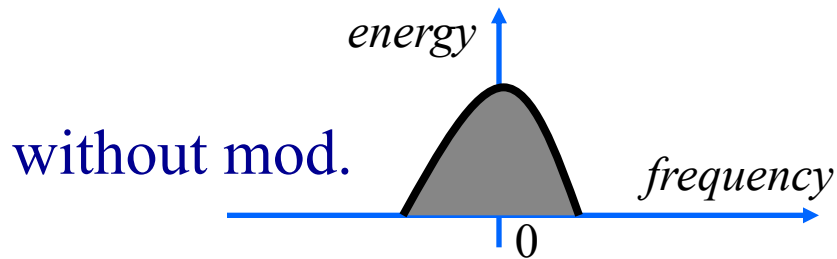
Wireless Communication

- Section 1: Wireless Transmission
- *Section 2: Digital modulation*
- Section 3: Multiplexing/Medium Access Control

Digital Modulation

Why Modulate?

- Modulation is the process of encoding information from a message source in a manner suitable for transmission
- In general it involves translating a **baseband** signal (source signal) to a **modulated signal** at a higher frequency (carrier frequency, f_c)



- Motivations:
 - **Reduce antenna size**: by increasing the carrier frequency, the wavelength λ decreases, as well as the antenna size (proportional to λ)
 - **Allow to share the spectrum** by choosing different f_c

Digital vs Analog Modulation

- Analog modulation uses mainly AM (Amplitude) and FM (Frequency Modulation)
 - characterized by a continuous variation of the parameter being modulated
- Modern mobile communication systems use **digital modulation techniques**
 - characterized by a discrete variation of the parameter(s) being modulated
- Offers key advantages:
 - greater noise immunity and **robustness** to channel impairments
 - more **flexibility**

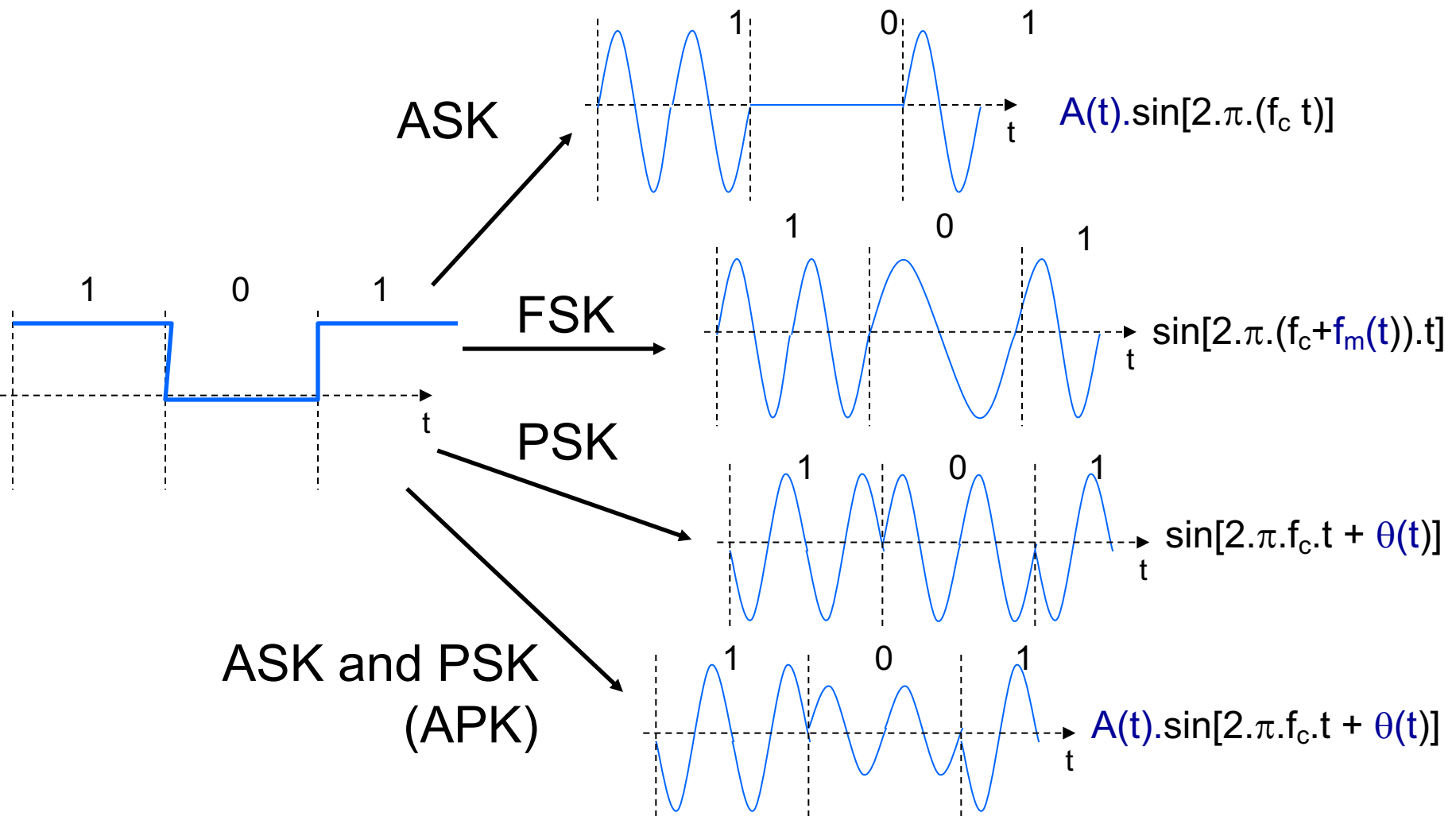
Digital Modulation techniques

- Process by which a sequence of pulses (message) of duration T is transformed into a sequence of sinusoidal waveforms, $s(t)$ of duration T .
- The general form of the modulated signal is:

$$s(t) = A(t) \cdot \sin[2\pi \cdot (f_c + f_m(t)) \cdot t + \theta(t)]$$

- Digital modulation can then be defined as the process whereby the **amplitude, frequency, phase or a combination of them** is varied in accordance with the information to be transmitted
- A scheme that uses:
 - amplitude is called **ASK** (Amplitude Shift Keying)
 - frequency is called **FSK** (Frequency Shift Keying)
 - phase is called **PSK** (Phase Shift Keying)

Digital Modulation techniques (2)



Factors that influence the choice of Digital Modulation

The performance of a modulation scheme is often measured in terms of its **power and bandwidth efficiencies**.

- **Power efficiency:**

- Problem: in order to increase noise immunity (i.e. maintain a certain BER, or Bit Error Rate), it is necessary to increase the signal power

Power efficiency describes the **ability to preserve the fidelity of a digital message at low power levels**

- The power efficiency expresses the "signal energy over the noise energy" ratio required at the receiver to guaranty a certain BER
- $\text{BER}=10^{-6}$ means at most one bit is in error every 10^6 bits transmitted

Factors that influence the choice of Digital Modulation (2)

- **Bandwidth efficiency:**

- Problem: increasing the data rate implies decreasing the pulse width of the digital symbol, which increases the bandwidth of the signal.
- Bandwidth efficiency describes **how efficiently the allocated bandwidth is used**
- Defined as the ratio of the throughput per Hertz (bps/Hz)
- Shannon theorem gives the fundamental upper bound:

$$C / B_w = \log_2(1+S/N)$$

where C is the channel capacity (bps), B_w the bandwidth (Hz) and S/N the signal-to-noise ratio.

Factors that influence the choice of Digital Modulation (3)

- Very often there is a **tradeoff**
 - adding **error correction coding** reduces the bandwidth efficiency (redundant information is transmitted) but increases the power efficiency (fewer remaining errors at lower S/N)
 - **M-ary schemes** increase the bandwidth efficiency but require higher transmission power to keep the same BER
- Other factors are important
 - cost and complexity of the receiver
 - for wireless networks, the robustness under various types of channel impairments such as Rayleigh fading and multipath dispersion

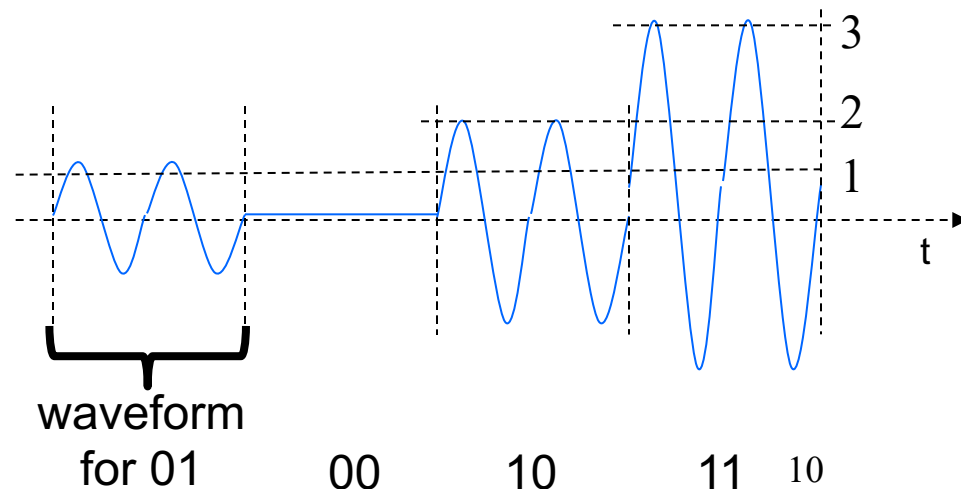
Amplitude Shift Keying (ASK)

$$S_i(t) = A_i(t) \sin[2\pi f_c t + \theta] \quad 0 \leq t \leq T, i = 1..M$$

– where the amplitude has M discrete values

- If $M = 2$, the amplitude is either 0 or 1. The scheme is called **Binary ASK**.
- If $M > 2$, each waveform carry $\log_2(M)$ bits. This scheme is therefore more bandwidth efficient. It is called **M-ary ASK**.
 - $M = 4$; $\log_2(4) = 2$ bits/waveform

- » $A_1 = 0$ corresponds to 00
- » $A_2 = 1$ corresponds to 01
- » $A_3 = 2$ corresponds to 10
- » $A_4 = 3$ corresponds to 11



Frequency Shift Keying (FSK)

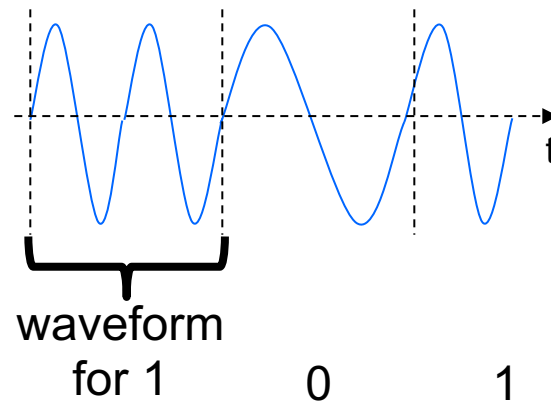
$$S_i(t) = (2E/T)^{1/2} \sin[2\pi(f_c + f_i)t + \theta] \quad 0 \leq t \leq T, i = 1..M$$

– where f_i has M discrete values, E is the symbol energy and T the symbol time duration.

- If $M = 2$, the scheme is called **Binary FSK** and the carrier frequency switches between 2 values

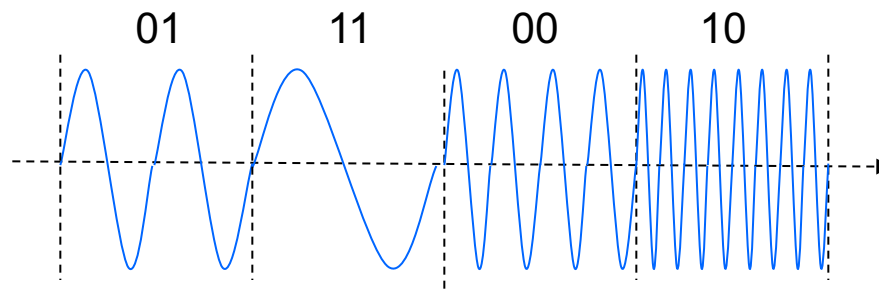
» $f_1 = f_c + f_m$ corresponds to bit 1

» $f_0 = f_c - f_m$ corresponds to bit 0



Frequency Shift Keying (FSK) (2)

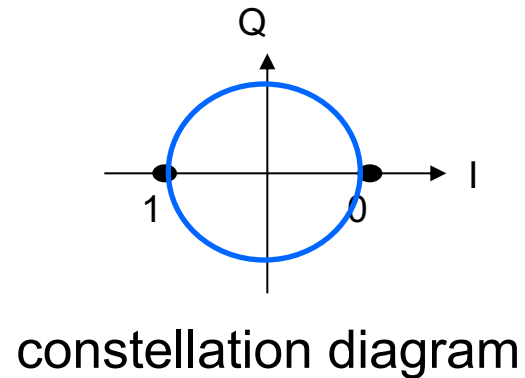
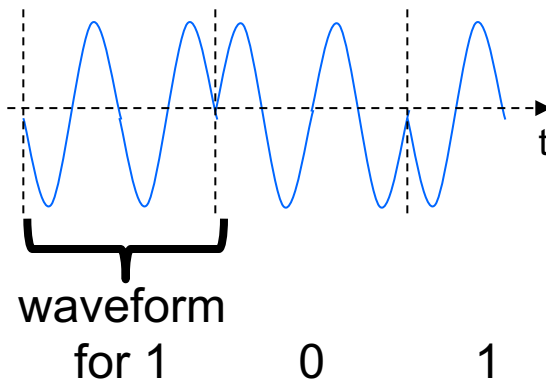
- If $M > 2$, each waveform carries $\log_2(M)$ bits. This scheme is therefore more bandwidth efficient. It is called **M-ary FSK**.
 - $M = 4$; $\log_2(4) = 2$ bits/waveform
 - » $f_1 = f_c + f_m$ corresponds to 00
 - » $f_2 = f_c - f_m$ corresponds to 01
 - » $f_3 = f_c + 2 f_m$ corresponds to 10
 - » $f_4 = f_c - 2 f_m$ corresponds to 11



Phase Shift Keying (PSK)

$$S_i(t) = (2E/T)^{1/2} \sin[2\pi f_c t + \theta_i(t)] \quad 0 \leq t \leq T, i = 1..M$$

- where the phase $\theta_i(t)$ has M discrete values given by: $\theta_i(t) = 2\pi i/M$
 - M -ary PSK can be displayed as **constellation** diagrams
- If $M = 2$, the scheme is called **Binary PSK** and the phase switches between 2 values, 0 and π .
 - $\theta_i(t) = 0$ corresponds to 0
 - $\theta_i(t) = \pi$ corresponds to 1

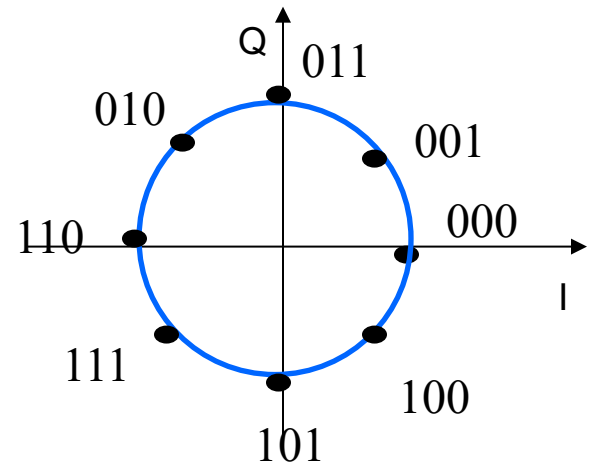


Phase Shift Keying (PSK) (2)

- If $M > 2$, the scheme is called **M-ary PSK** and carries $\log_2(M)$ bits/waveform

– If $M=8$, 3 bits/waveform

- » $s_0(t) = (2E/T)^{1/2} \sin[2.\pi.f_c.t]$
- » $s_1(t) = (2E/T)^{1/2} \sin[2.\pi.f_c.t + \pi/4]$
- » $s_2(t) = (2E/T)^{1/2} \sin[2.\pi.f_c.t + \pi/2]$
- » ...
- » $s_7(t) = (2E/T)^{1/2} \sin[2.\pi.f_c.t + 7.\pi/4]$



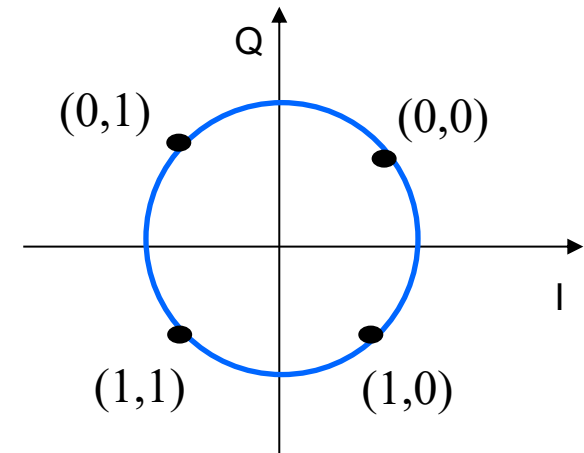
constellation diagram

- Question : how to assign bits to waveforms? Are all solutions equivalent? In practice Gray Codes are used to limit bit errors for adjacent waveforms...

A particular case: Quadrature PSK (QPSK)

- If $M=4$ then the scheme is called Quadrature PSK

$$S_i(t) = (2E/T)^{1/2} \cos[2\pi f_c t + i\pi/2] \quad i=1,\dots,4$$



constellation diagram

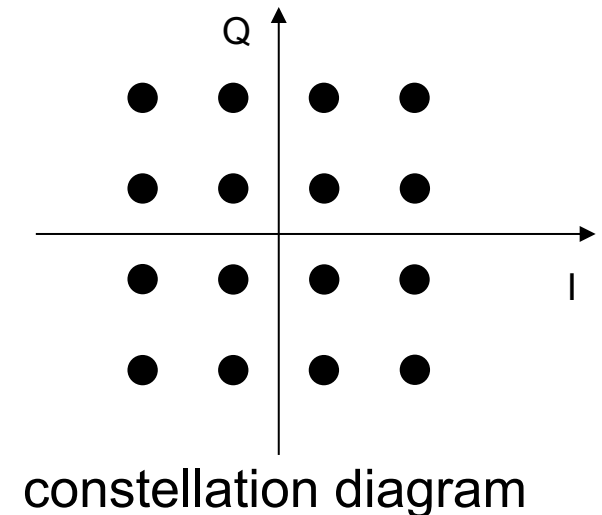
Phase Shift Keying (PSK) (3)

- the bandwidth efficiency of an M-ary PSK scheme increases as M increases (more bits per waveform)
- ...however the distance between 2 points in the constellation is reduced, so the error rate increases too
- As M increases, the transmission power must be increased to keep the BER (Bit Error Rate) at a target (e.g., 10^{-6}) and the power efficiency decreases

| M | 2 | 4 | 8 | 16 | 32 | 64 |
|---|------|------|-----|------|------|------|
| R/B_w in bits/Hz (bandwidth efficiency) | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 |
| required S/N (power efficiency) | 10.5 | 10.5 | 14 | 18.5 | 23.4 | 28.5 |

Amplitude and Phase modulation

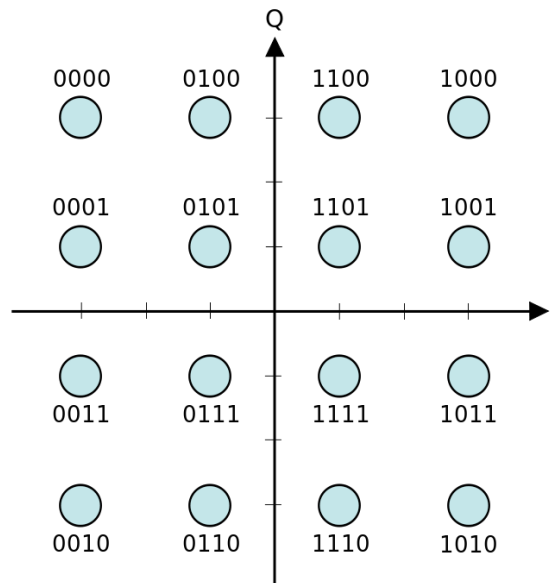
- **M-ary QAM** modulates both the amplitude and phase of the carrier
 - called Quadrature Amplitude Modulation (QAM) because waveforms can be produced as the sum of two carriers that are out of phase by 90° , each of them being subject to an ASK
- If $M=16$, it is called 16-QAM
 - $M = 16$; $\log_2(16) = 4$ bits/waveform
 - NB: energy per waveform isn't constant
 \Rightarrow some waveforms are more prone to errors than others



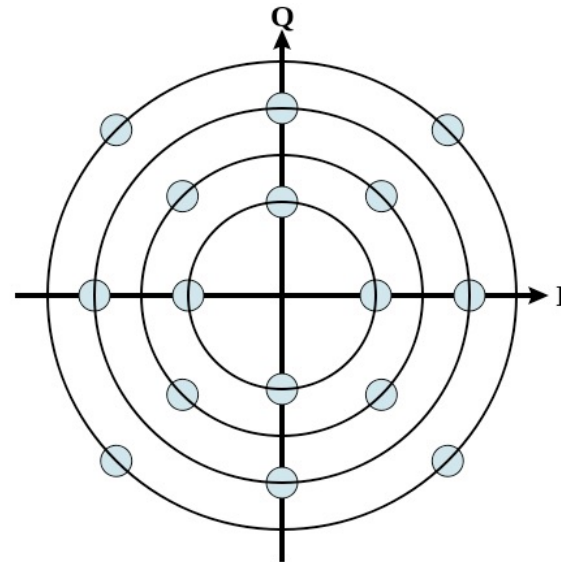
see https://en.wikipedia.org/wiki/Quadrature_amplitude_modulation

Amplitude and Phase modulation

- 16-QAM, 64-QAM and 256-QAM are common
 - no M-ary ASK, FSK or PSK can reach such a high bandwidth efficiency with a good power efficiency
- for a given M value, several constellations are possible
 - differ by the easiness to produce the waveforms
 - differ by their noise immunity (distance between contiguous waveforms)



constellation diagram for
rectangular 16-QAM



constellation diagram for
circular 16-QAM

multi-carrier modulation with OFDM

- idea: it is more efficient to split the available bandwidth into sub-carriers than modulating a single carrier
 - more **flexible**
 - **adaptable to varying noise conditions** at certain frequencies
- Orthogonal Frequency Division Multiplexing (OFDM) uses
 - multiple narrow-band sub-carriers
 - sub-carriers are orthogonal, i.e., do not overlap with one another
 - use the most appropriate QAM modulation on each sub-carrier
 - spread information on the sub-carriers
 - » e.g., those with higher M-ary QAM transmit more bits
- now used almost everywhere
 - » ADSL
 - » Wifi (IEEE 802.11g and above)
 - » DVB-T (French TNT)
 - » 4G/LTE (variant of OFDM)

multi-carrier modulation with OFDM (2)

- Example: ADSL (i.e., a **wired** technology!)
 - 256 channels, each of bandwidth 4.4 KHz
 - channel 1: analogic voice
 - channel 2 to 6: signaling
 - 250 remaining channels [25 kHz, 1.1 MHz]: upstream/downstream data
 - measure S/N of each channel and adjust the M-ary QAM accordingly

