Lecture 3: Wireless Physical Layer: Modulation Techniques

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CS 653 Spring 2014

Jan 13, Monday

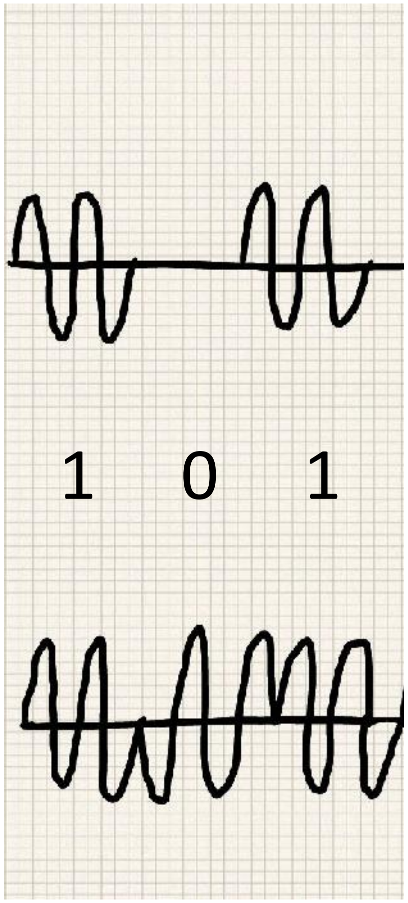
调制

Modulation

- We saw a simple example of amplitude modulation in the last lecture
- Modulation – how to transmit a stream of bits using a carrier wave of a particular frequency and a certain bandwidth
- Carrier wave $s = A \cos (2 \pi f t + \phi)$
- Can modulate one or more of the following to transmit bits
  - Amplitude A
  - Frequency f
  - Phase ϕ
- We will cover only a high level overview of modulation techniques in this lecture

Amplitude Shift Keying (ASK)

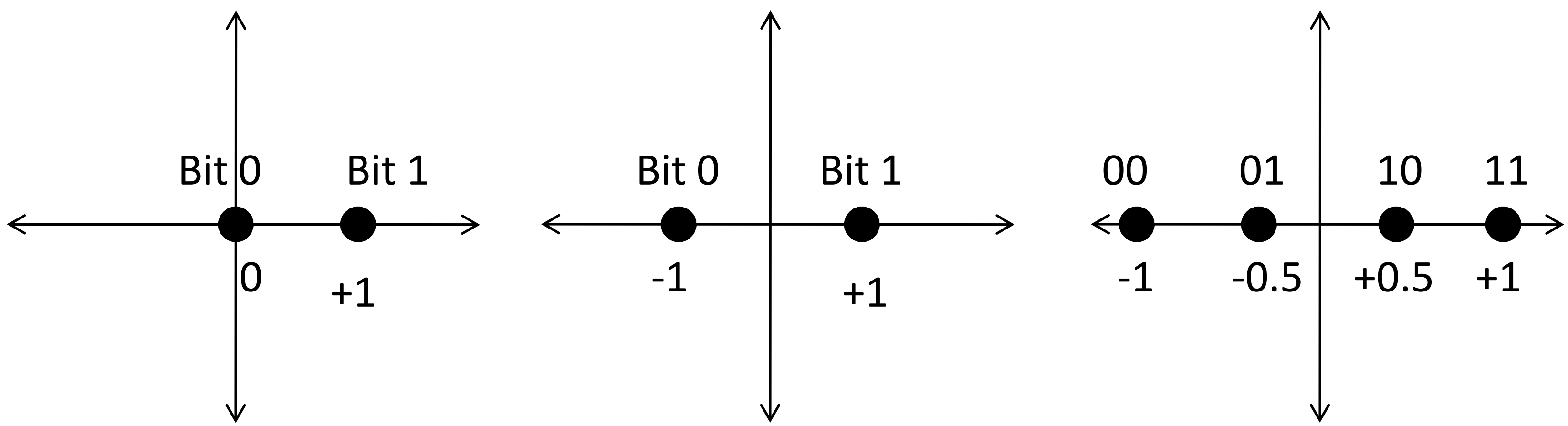
- Use amplitude of 0 for bit “0” and 1 for bit “1”. This is called 2-ASK.
- Note that the actual amplitude depends on the transmit power, we will use 1 to denote the maximum A
- Or, use -1 for bit “0” and +1 for bit “1”. Amplitude -1 means that the wave is “inverted”
- We can encode multiple bits. For example, 4 different amplitude values to convey 2 bits: 00, 01, 10, 11. (4-ASK)



星座图

Constellation diagrams

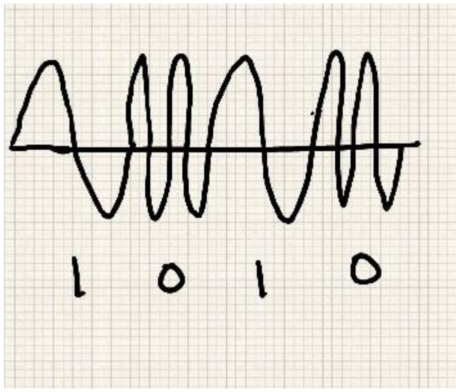
- Easy way to represent modulation schemes instead of drawing waveforms
- Value on x-axis determines the amplitude of wave used for encoding the corresponding bit(s)



- The above constellation diagrams show two different 2-ASK schemes and one 4-ASK scheme

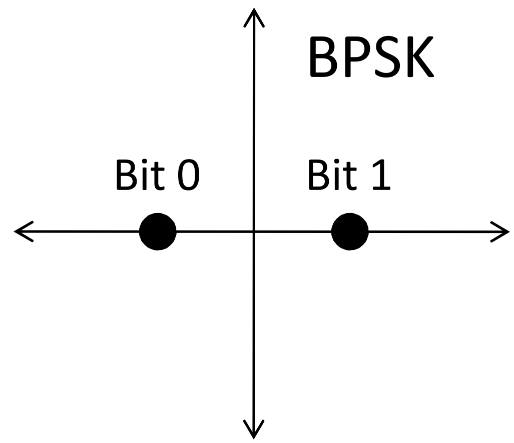
Frequency shift keying (FSK)

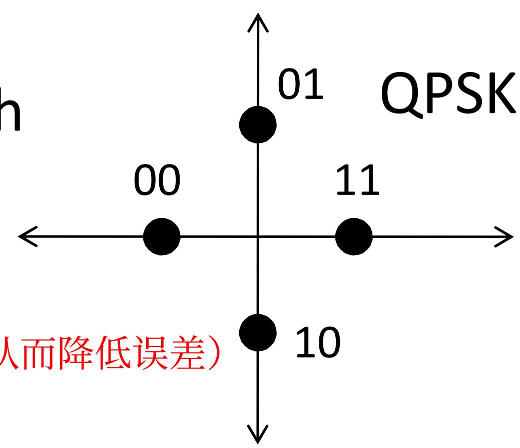
- Use two different frequencies to transmit bit 0 and bit 1 (binary FSK)
- Can also send multiple bits
- Not very widely used, as it consumes more bandwidth than other techniques



Phase Shift Keying (PSK)

- Use different phases of the wave to send bits
- Binary PSK (BPSK) – phase 0 and phase π to send bits 0 and 1. Looks like 2-ASK with amplitudes -1 and +1
- QPSK (quaternary PSK): use 4 phases to send 2 bits
- For PSK constellation diagrams, the radial angle indicates phase, distance from origin indicates amplitude (always 1 for PSK)
- Gray coding: assign bits to constellations such that adjacent constellations differ in one bit (so that errors are lower)

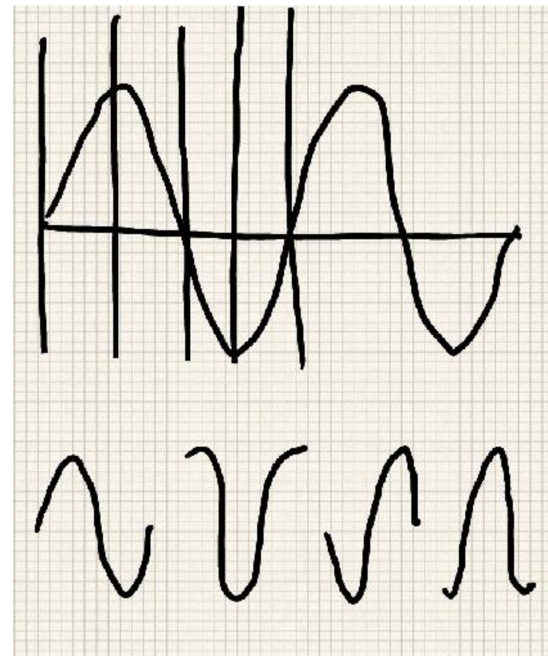




格雷编码：将比特分配给星座图，以使相邻星座图相差一个比特（从而降低误差）

PSK (2)

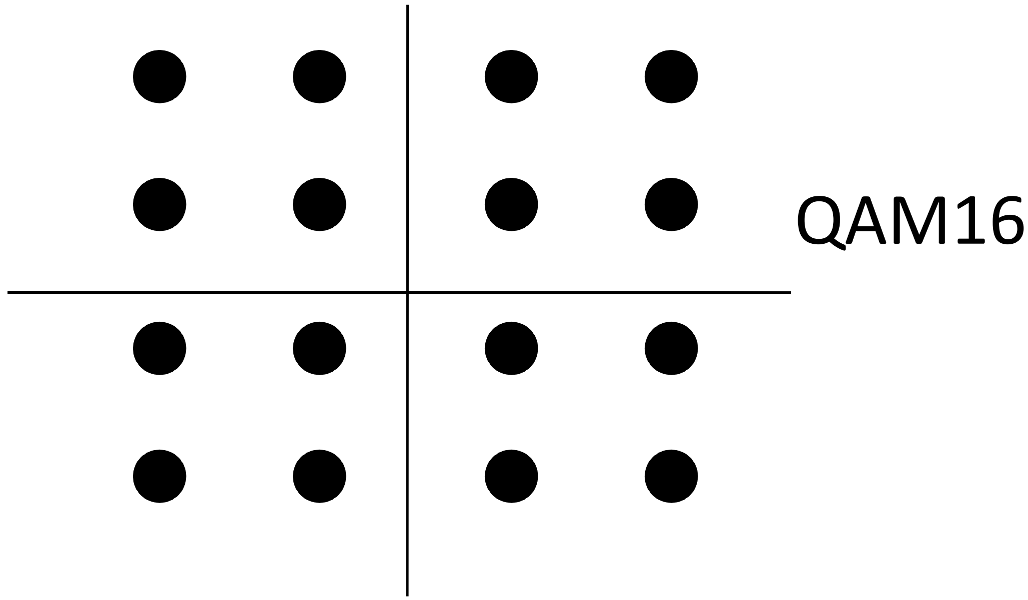
- Example of QPSK wave forms. 4 different phases to send bits 00, 01, 10, 11
- A symbol is a set of two bits that map to a wave form
- Transmitter stitches together waveforms for each symbol 变送器将波形缝合在一起
- 8-PSK is also possible, but inefficient. Not widely used
- PSK needs “phase lock” between transmitter and receiver to estimate phase at receiver
- Another idea: differential QPSK (DQPSK) – just take the difference in phase between previous and current symbol to convey information. No phase lock.



QPSK waveforms

Quadrature Amplitude Modulation (QAM)

- Use both amplitude and phase to send information
- QAM16, QAM64 etc – widely used for high speed in mobile systems
- Denser QAM constellations require higher SNR to decode correctly

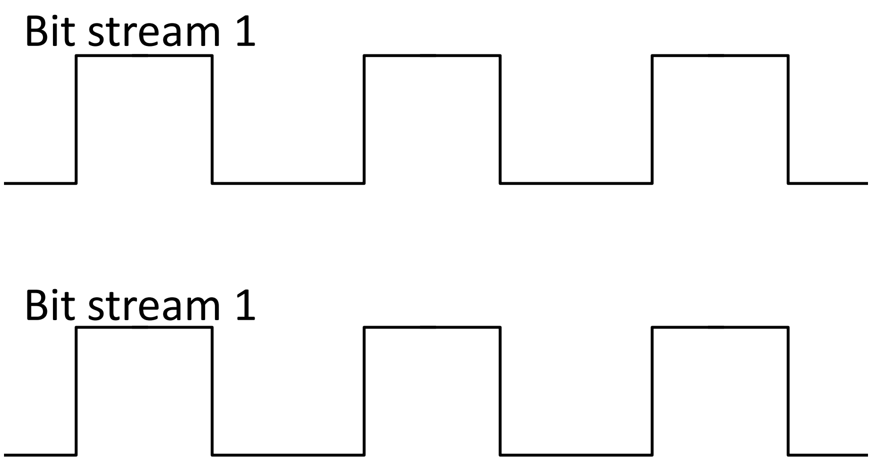


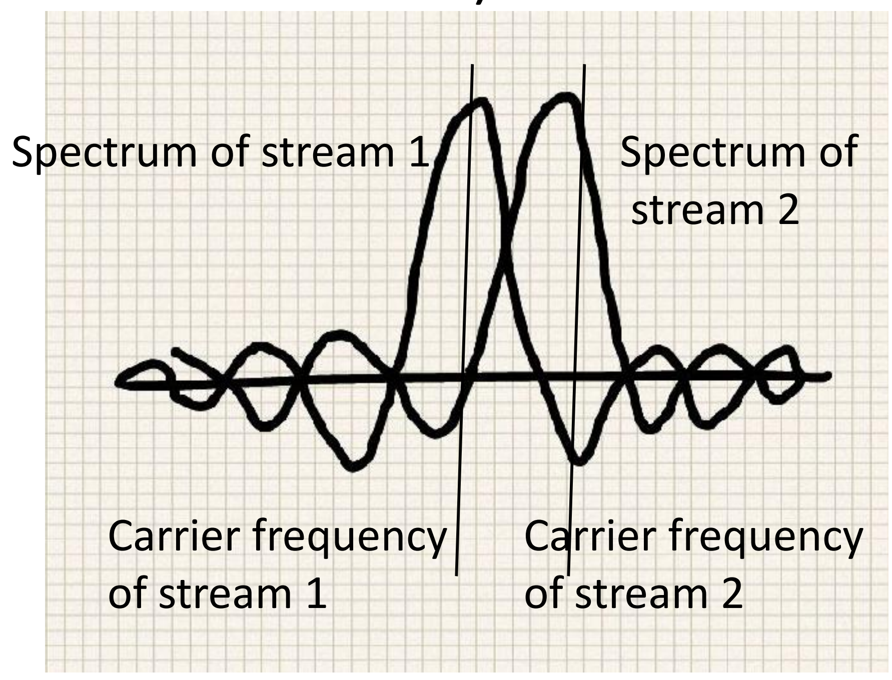
Single Carrier Modulation vs. Multi-carrier Modulation

- So far, ASK, PSK, QAM etc are all examples of single carrier modulation schemes – one stream of bits modulating one carrier signal
- How fast can we send – depends on bandwidth, sampling rate of hardware etc (last lecture)
- Note that most modulation techniques require knowing exact amplitude and phase of carrier, so we must compensate effect of channel "h" (Equalization)
- If each symbol duration is longer than multipath delay spread of channel, all copies of a symbol arrive in the same symbol duration. Easier to estimate the channel "h" and compensate for it at receiver
- If symbol duration < delay spread, copies of previous symbol interfere with current symbol – inter-symbol interference (ISI)
- When large delay spread causes ISI, we need complicated equalization techniques to cancel out effects of all previous symbols ("multi-tap equalization") at receiver
- Single carrier systems – tradeoff between how fast you can send and how complex your receiver can be. Not very suitable for high rates in compact mobile devices
- Solution – multi-carrier modulation

Multi-carrier modulation

- Split bit stream into multiple parallel streams. Modulate each stream with different carriers within the allocated band. Send each stream slowly, so that no ISI happens. Recover each stream separately at receiver.
- Will the parallel streams not interfere? It is possible to choose slightly different carrier frequencies for each stream, such that the carriers don't interfere (i.e., when each carrier is at peak, all other carriers are zero).





Orthogonal Frequency Division Multiplexing (OFDM)

- This technique is called OFDM. The standard modulation technique in almost all high speed systems today.
- Split channel into multiple subcarriers (e.g., 64 subcarriers in 802.11/WiFi)
- Send a parallel stream of data over each subcarrier "slowly" (relative to delay spread)
- At receiver, only simple equalization ("single-tap equalization) required
- Can recover multiple streams of data simultaneously at receiver

OFDM (2)

- Receiver is simple, but transmitter is very complex? Generate multiple carriers and modulate, then add up?
- There is an easier way to do it using fourier transform.
- Recall, DFT takes a time domain signal and converts it into weights (amplitudes and phases) of each of the individual frequencies. Inverse DFT reverses this process.
- At OFDM transmitter, for each symbol, take the bits from each parallel stream, map to amplitude and phase (PSK or QAM modulations). Now, take these amplitude and phase of the N subcarriers, perform inverse fourier transform to get time domain signal, then modulate this signal alone at center frequency.
- Fast Fourier Transform (FFT) algorithm is efficient implementation of DFT. FFT and invert FFT (iFFT) hardware implementations make OFDM very easy to implement.

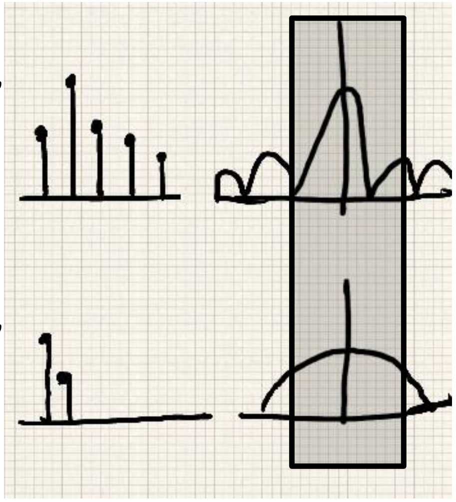
正交频分复用

Frequency domain view of OFDM

- Why does OFDM work?
- Channel impulse response “h” -> its DFT is called channel frequency response “H” (captures attenuation of each frequency in the band)
- With large delay spread, frequency response of the channel varies within the band. At receiver, we need to estimate the complex shape of the “H” curve to “invert” the channel.
  - And vice versa. For low delay spread, channel frequency response stays the same over the entire band. See figure below.
- With OFDM, each stream has its own narrow band, where H stays almost the same. So need to estimate only one value of “H” for each sub-band. Easier to do.

Channel impulse response “h” with large delay spread

Channel frequency response “H” varies a lot in the frequency band



Channel impulse response “h” with small delay spread

Channel frequency response “H” almost constant in the band

相干带宽

Coherence Bandwidth

- Larger spread of “h” in time domain means more variation in H in frequency domain
- Coherence bandwidth of a channel – the bandwidth over which channel frequency response H stays the same.
- Coherence bandwidth ~ 1/DelaySpread
- In channels with lot of multipath (large delay spread), coherence bandwidth can be lower than width of channel. Such channels are called frequency selective channels.
- For WiFi, channel bandwidth is 20 MHz. Coherence bandwidth is sometimes lower than this. Hence OFDM is preferred choice.

相干带宽是描述时延扩展的指标，是表征多径信道特性的一个重要参数。它是指某一特定的频率范围，在该频率范围内的任意两个频率分量都具有很强的幅度相关性，即在相干带宽范围内，多径信道具有恒定的增益和线性相位。通常，相干带宽近似等于最大多径时延的倒数。从频域看，如果相干带宽小于发送信道的带宽，则该信道特性会导致接收信号波形产生频率选择性衰落，即某些频率成分信号的幅值可以增强，而另外一些频率成分信号的幅值会被削弱。

Coherence Time

- Recall: movement in sender / receiver / environment causes apparent shift in frequency of carrier wave (Doppler shift). Doppler shift proportional to speed of movement.
- Recall from previous slide: larger spread of “h” in time domain means more variation in H in frequency domain
- Similarly, larger spread in frequency of received signal means more variation in signal over time. (time and frequency domain relationships have this duality usually)
- Coherence time of a channel – duration of time for which the channel response “h” stays the same
- If coherence time > packet duration, slow fading channels. Can assume channel is same for multiple packets. E.g., indoor channels.
- If coherence time < packet duration, fast fading channels. Channel changes within a packet. E.g., outdoor vehicular channels.