ECE 5325/6325: Wireless Communication Systems
Lecture Notes, Spring 2013

Lecture 13

Today: (1) PAM, QAM, and PSK, (2) Questions

- Reading: Today: Molish 12.1; Tue after break: Goldsmith handout (on Blackboard).
- Exam 2 is on Tuesday Feb 26 at 9:10am - 10:10am.
- Homework 5 due at start of class today.

1 PAM, QAM, and PSK Modulation

Last lecture we talked about how a digital transmitter sends one of M symbols, that is, linear combinations, of a small number N of orthogonal waveforms. The TX's choice from the M possible linear combinations lets it send one of $\log_2 M$ bits per symbol. This section talks specifically about options for linear combinations when we set our the first waveform to a cosine, and the second to a sinusoid.

1.1 PAM

Three "types" of modulations only use one (orthogonal) waveform, $\phi_0(t) = \cos(2\pi f_c t)p(t)$, where $p(t)$ is the pulse shape. (It has nothing to be orthogonal to, except for waveforms sent during other symbol periods.) A linear combination, then, is just $a_{i,0}p(t)$, for some constant $a_{i,0}$. A few different modulations are so named by their choice of M different choices of $a_{i,0}$, for $i = 0, \ldots, M-1$.

- On-off-keying (OOK): $M = 2$, and we choose $a_{0,0} = 0$, and $a_{1,0} = 1$. When sending a "0" bit, the transmitter doesn't send anything. It only actually transmits energy when sending a "1" bit.
- Binary PAM, a.k.a. binary phase-shift-keying (BPSK): $M = 2$, and we choose $a_{0,0} = -1$, and $a_{1,0} = 1$. Now, the amplitude of the sinusoid being transmitted is switched from a $+1$ to a -1, or vice versa, when the bit switches. This is also a phase shift of 180^o, which is why it can be called "phase shift" keying.
- M-ary PAM: Binary PAM is extended in M-ary PAM to include M (for M equal to some power of 2) equally spaced amplitudes, centered on zero. So, for example, $M = 4$ PAM would have $a_{0,0} = -3$, $a_{1,0} = -1$, $a_{2,0} = +1$, $a_{3,0} = +3$. In general, for M-ary PAM, $a_{i,0} = 2i - M + 1$.

Note that *differential phase shift keying* (DPSK) is an implementation variant of BPSK, which we will discuss next lecture.

1.2 M-ary QAM and PSK

Many types of modulations use the following two orthogonal waveforms:

$$\begin{aligned}\phi_0(t) &= \cos(2\pi f_c t)p(t) \\ \phi_1(t) &= \sin(2\pi f_c t)p(t)\end{aligned}$$

where $p(t)$, again, is the pulse shape. These symbols $\mathbf{a}_i = [a_{i,0}, a_{i,1}]^T$ can then be plotted on a 2-D graph, typically with the $\phi_0(t)$ amplitude plotted on the horizontal axis, and the $\phi_1(t)$ amplitude plotted on the vertical axis.

There are two main "types" of modulations which use these two orthogonal waveforms:

- Phase-shift keying (PSK): PSK places all $\mathbf{a}_i$ uniformly on the unit circle. That is, $\|\mathbf{a}_i\| = 1$ for all i. For $M = 2$, this is the same as BPSK. For $M = 4$, the symbols are spaced every 90 degrees and thus the constellation looks like the four corners of a square, and is also called quadrature phase shift keying (QPSK). For $M = 8$, symbols are every 45 degrees apart.

- QAM: Generally, any modulation that uses $\phi_0(t)$ and $\phi_1(t)$ above can be considered as QAM. So PSK is a sometimes a subtype of QAM. But QAM is not limited to $\|\mathbf{a}_i\| = 1$. For example, square QAM has $M = 2^{2k}$ for some integer $k \geq 4$, where symbols are arranged in a square grid, centered at zero. Note $M = 4$ square QAM is the same as QPSK. But $M = 16$ and $M = 64$ are also common values of M for square QAM.

We drew in the previous lecture notes five different constellation diagrams of PSK and QAM modulations.

Note that for QPSK or square M-QAM, you send $\log_2 M$ bits total per symbol. We can also look at the modulation as sending two independent signals, one on the in-phase (horizontal axis) and one on the quadrature (vertical axis), each sending $\frac{1}{2}\log_2 M$ bits per symbol.

Note that OQPSK and $\pi/4$ QPSK are variations on QPSK, that have equivalent fidelity performance and identical bandwidth as QPSK, but they are "constant envelope" modulations, which we will discuss later.

Bandwidth: Note that for PAM, PSK, and QAM, assuming SRRC pulse shaping with rolloff factor α, the null-to-null bandwidth of the signal is $B = (1 + \alpha)/T_s$, where $1/T_s$ is the symbol rate.