Wireless Communications background*

farrukh inam
Thomas Almholt

This work is produced by OpenStax-CNX and licensed under the
Creative Commons Attribution License 3.0†

Abstract

This module looks at the basic concepts of wireless communications. It is part of a collection created for College Seniors to select the best components for their Senior Projects.

Basics of Digital Communications [3]

Communication theory aims to explore and develop methods that suppress as far as possible the effect of noise and to transmit, simultaneously, as many discrete signals as possible through a channel. Spectral analysis is a tool that connects time domain signals to frequency domain allowing insight into the characteristics of broadband and narrowband signals in a communication bandwidth.

Spectral Analysis

Frequency has a ubiquitous role in the process of communication. It is used as a carrier and bandwidths are specified in terms of it. It is therefore important to have tools with which frequency content in a signal can be easily determined. This can be achieved using the Fourier transform and its discrete counterpart the DFT. The Fourier transform of a signal $\mathrm{w}(\mathrm{t})$ is defined as

$\mathrm{W}(\mathrm{f}) = \int_{-\infty} \mathrm{w}(\mathrm{t}) \exp(-\mathrm{j}2\pi\mathrm{ft})\,\mathrm{dt}$ Eqn. (1)

And it's inverse if as follows

$\mathrm{w}(\mathrm{t}) = \int_{-\infty} \mathrm{W}(\mathrm{f}) \exp(\mathrm{j}2\pi\mathrm{ft})\,\mathrm{df}$ Eqn. (2)

The above equation shows that $\mathrm{w}(\mathrm{t})$ is a weighted sum of sinusoids in the interval $-\infty$ to $+\infty$. The weights are complex numbers $\mathrm{W}(\mathrm{f})$. If at any particular frequency the magnitude spectrum is strictly positive then that frequency is said to be present in $\mathrm{w}(\mathrm{t})$. The set of all frequencies present in a signal is its frequency content and if this content consists of frequencies in a certain range then $\mathrm{w}(\mathrm{t})$ is said to be bandlimited with a certain bandwidth.

Digital Modulation

It is the process of converting digital symbols into waveforms that are compatible with the characteristics of the transmission medium. In the case of baseband modulation, these waveforms take the shape of pulses designed to reduce inter symbol interference (ISI). In the case of bandpass modulation, these shaped pulses modulate a sinusoidal carrier wave that is converted to electromagnetic (EM) field for propagation over distances. In free space, antennas radiate and receive EM signals. Antennas operate effectively only when their dimensions are of the order of magnitude of quarter wavelength $\left(\frac{\Lambda}{4}\right)$ of the transmitted signal. If the signal frequency is very high, antenna dimension become practical, however, high frequencies get attenuated by the atmosphere and therefore cannot travel great distances.

*Version 1.1: Aug 27, 2012 11:00 am -0500

†http://creativecommons.org/licenses/by/3.0/

Basic Modulation Techniques

Any message can be converted to binary digits called bits. For transmission, these bits are grouped together and encoded into sequences whose elements are the symbols of an alphabet set. In order to utilize bandwidth more efficiently, these alphabets are once again encoded in waveforms called pulses which are then combined to form a baseband signal. E.g. a bit stream 010010010100101110101 01 can be paired as 01 00 10 01 01 11 and so on. Then the pairs can be encoded as -1, -3, 1, -1, +3 and so on, to produce the symbol sequence. There are many ways in which mapping from bits to symbols can be made. Bit stream can be mapped to 8-level 16-level 256-level etc. After the original message is grouped into alphabets, it must be turned into analog waveforms by choosing a pulse shape $\mathrm{p}(\mathrm{t})$ and then transmitting $--\mathrm{p}(\mathrm{t}-\mathrm{kT})$, $-3\mathrm{p}(\mathrm{t}--\mathrm{kT})$, $\mathrm{p}(\mathrm{t}--\mathrm{kT})$, $-\mathrm{p}(\mathrm{t}--\mathrm{kT})$, $3\mathrm{p}(\mathrm{t}--\mathrm{kT})$. In general this 4-level signal takes the form as follows:

$\mathrm{d}(\mathrm{t})=\sum_k I_k \mathrm{p}(\mathrm{t}-\mathrm{kT}); I_k\{\pm 1, \pm 3\}; \mathrm{k}=1, 2, \ldots$ *Eqn.* (3)

Where $\mathrm{d}(\mathrm{t})$ is an analog waveform consisting of pulses at symbol time kT and amplitude of the pulse is proportional to the associated symbol value. Ideally the pulse would be chosen so that the value of message at k does not interfere with message at any other time (no ISI) and that the pulse makes efficient use of bandwidth.

ISI can manifest itself in two ways. When the pulse shape $\mathrm{p}(\mathrm{t})$ is wider in time than a single symbol time interval T and when the pulses experience channel distortions and multipath fading effects.

Let us consider a two level system in which $s_0(\mathrm{t})$ and $s_1(\mathrm{t})$ are finite energy signals representing logical 0 and 1 respectively. These signals can be of any shape but must have finite energy in the signaling interval. Then a frame work of representing basic modulation schemes can be constructed. Below are some fundamental digital modulation schemes.

Amplitude Shift Keying

In ASK, the information is conveyed by varying the amplitude of a carrier wave in accordance with the symbol stream. An expression for ASK is as follows:

$s_k(t)=I_k \mathrm{p}(\mathrm{t}) \cos(\mathrm{w}_0 \mathrm{t}+); \mathrm{I}_\mathrm{k}\{0,1\}; 0 \leq \mathrm{t} \leq \mathrm{T};$ Eqn. (4)

where the phase term is an arbitrary constant. Binary ASK signaling also called on-off keying was one of the earliest forms of digital modulation used in radio telegraphy. ASK has a high peak to average ratio and is no longer widely used however, TI's low power wireless RFICs support this modulation schemes for various data rate for sensor applications.

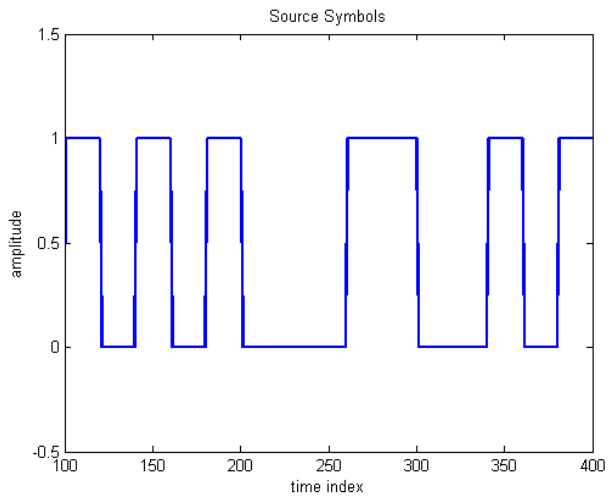

Figure 1

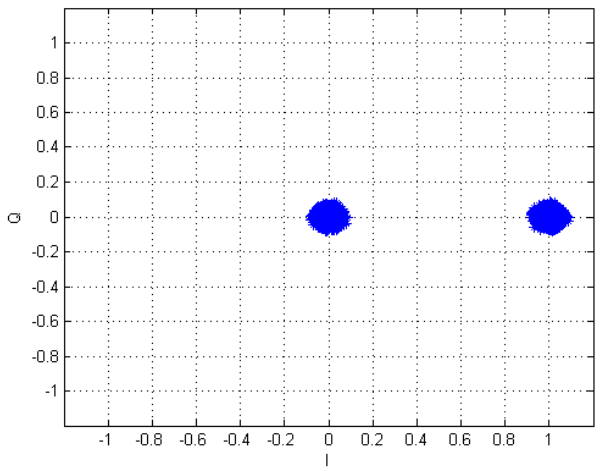

Figure 3

continued on next page

Table 1: ASK modulation

Frequency Shift Keying

The general analytical expression for FSK is given below

$s_k(t) = A\cos(\mathrm{w_0 t} + 2\pi \mathrm{I_k} \Delta \mathrm{ft} +)\,;\mathrm{k} = 1, ...\mathrm{M}; 0 \leq \mathrm{t} \leq \mathrm{T}$ *Eqn.* (5)

Where the frequency Δf is the amount of shift in the carrier frequency corresponding to the alphabet I_k $\varepsilon\{\pm 1, \pm 3. \ . \ .,\pm \mathrm{M}\}$ and phase term is an arbitrary constant. The FSK waveform sketch in figure shows typical frequency changes at the symbol interval. The change from one frequency to another can be rather abrupt and this gives rise to spikes in the spectrum of FSK. The minimum required bandwidth for orthogonal FSK signal for coherent detection is 1/2T where as for non-coherent detection the bandwidth is 1/T. FSK does not have constellation plots because of constant rotation of the signal vector in the IQ plane.

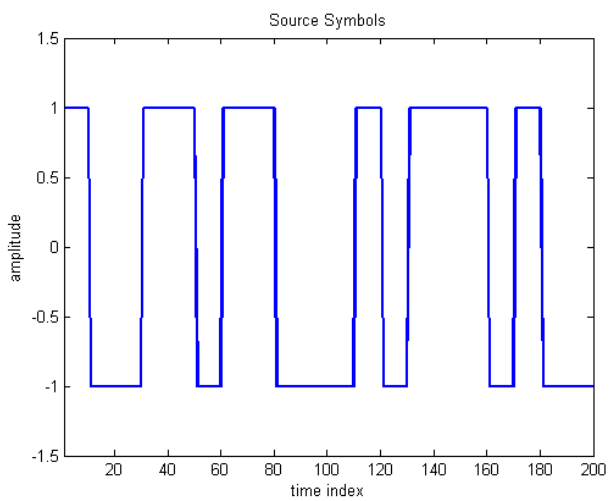

Figure 5

continued on next page

	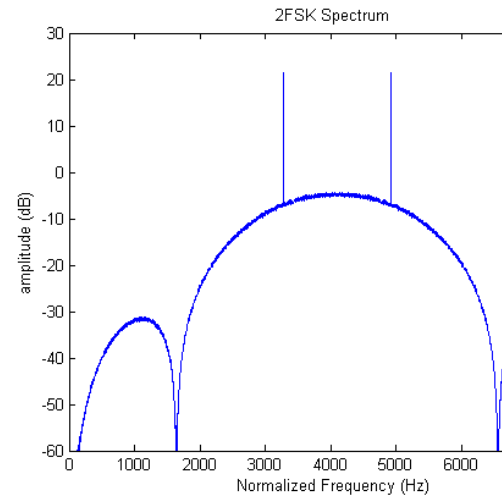 **Figure 7**

Table 2: FSK modulation

Phase Shift Keying

PSK was developed during early days of deep space program and is widely used in commercial satellite links. The general expression for PSK is

$s_k(t) = \mathrm{p}(\mathrm{t})\cos(\mathrm{w}_0\mathrm{t} + {}_\mathrm{k})\,;\mathrm{k} = 1, ..., \mathrm{M}0 \leq \mathrm{t} \leq \mathrm{T}$ Eqn. (6)

Where the phase term, $_i$ will have M discrete values typically give by

${}_k(\mathrm{t}) = \frac{2\pi \mathrm{k}}{M}\mathrm{k} = 1, ...\mathrm{M}$ *Eqn.* (7)

In the basic case of binary PSK, the modulating data signal shifts the phase of the waveforms to one of two states, either zero or π. The waveform sketch in the figure shows abrupt phase changes in the signaling interval.

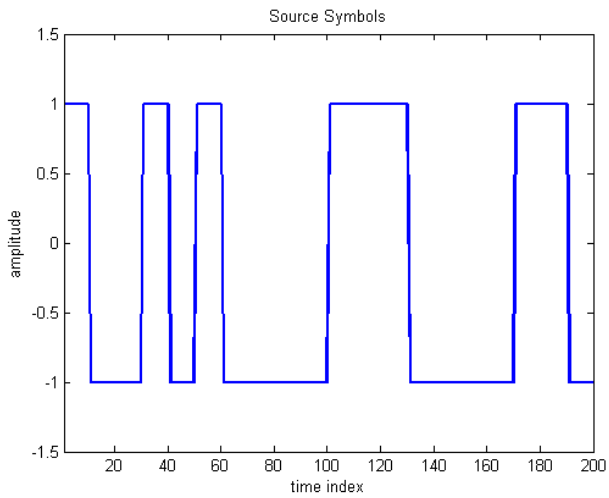

Figure 8

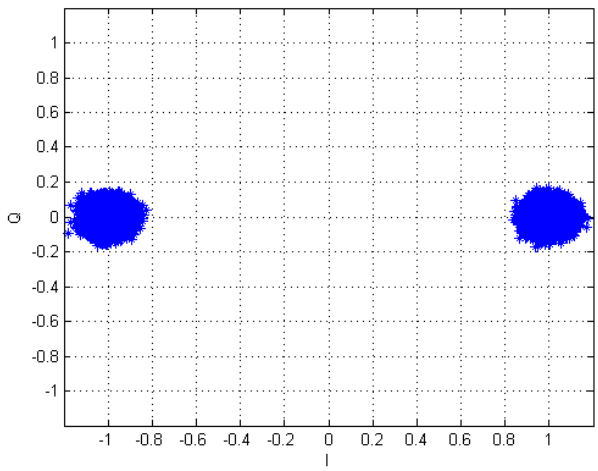

Figure 10

Table 3: PSK modulation

Comparison metric for digital communication and BER curves

One of the most important metrics of performance in digital communication is the plot of bit error probability P_b versus energy per bit over noise power spectral density ($\frac{E_b}{N_0}$). This dimension less ratio is a standard quality measure for digital communication system performance. The smaller the $\frac{E_b}{N_0}$ required the more efficient is the detection process for a given probability of error. In digital communication system one discrete symbol is transmitted which may be one bit or more in a fixed signaling interval. In analog where the information source is continuous, this discrete structure does not exist. In digital system therefore a figure of merit should allow us to compare one system with another at a bit or symbol level and hence $\frac{E_b}{N_0}$ renders itself naturally for that purpose. A relationship between the signal to noise ratio (SNR), data rate and bandwidth is expressed below:

$\frac{E_b}{N_0} = \frac{S}{N}\left(\frac{B}{R}\right)$ *Eqn.* (8)

M = 2M = 32

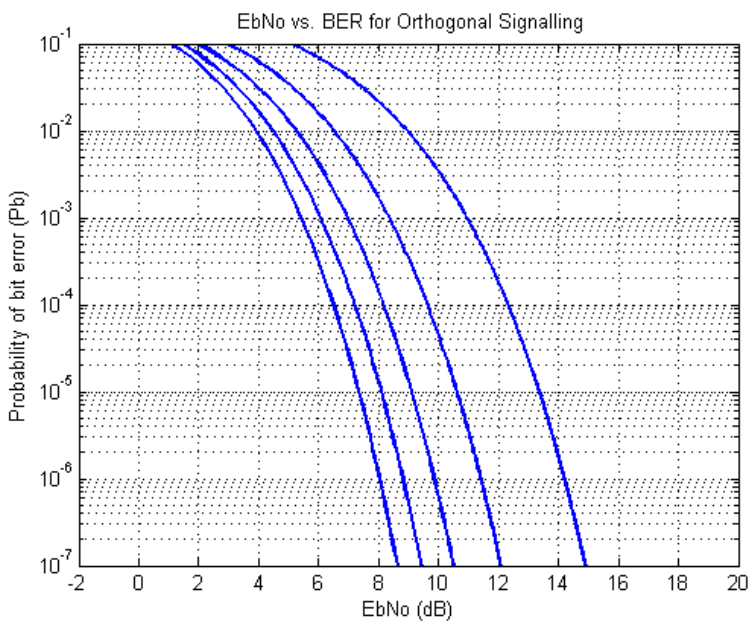

Figure 12

M = 32M

continued on next page

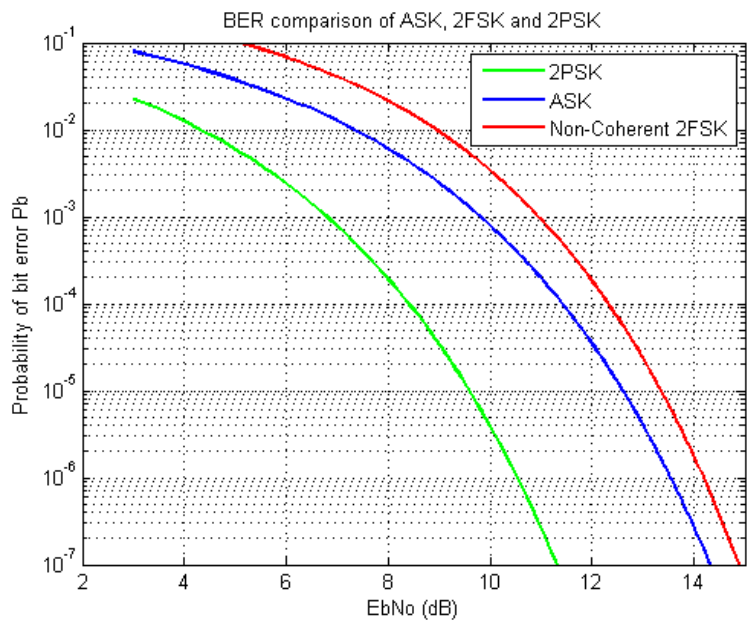

Figure 14

Table 4: Typical P_b vs. $\frac{E_b}{N_0}$ curves for orthogonal and multiphase signaling.

Digital modulation methods can be classified in two ways with opposite behavioral characteristics. The first class is orthogonal signaling and its error performance follows the curves in figure 4a. The second class constitutes non-orthogonal signaling shown in figure 4b. Error performance improvement or degradation depends on signaling category.

Channel Capacity

A fundamental theorem due to Claude Shannon states that it is possible in principle using some coding scheme to transmit information with an arbitrarily small probability of error provided that the data rate R is less than or equal to the channel capacity C. Shannon's work showed that the SNR, and bandwidth set a limit on transmission rate but not on probability of error. The channel capacity of a white bandlimted Gaussian noise channel is:

$$C = \text{Blog}_2\left(1 + \frac{E_b}{N_0}\frac{B}{R}\right) bits/sec/Hz \quad \textbf{Eqn. (9)}$$

Where B is the channel bandwidth, $\frac{E_b}{N_0}$ is the energy/bit. E.g. with an SNR of 30dB, using Eqn (8) and Eqn (9), the capacity of a circuit with 2.4kHz bandwidth is approximately 24kbps where as at 10dB SNR the capacity drops to about 8.3kbps. Thus the above theorem allows a designer to apply tradeoffs in bandwidth, signal power and various modulation methods to establish a communication link with desired probability of error.

Similarly the required $\frac{E_b}{N_0}$ for a modem operating at channel capacity of 28.8kbps in AWGN bandwidth of 3.4kHz will be approximately 16.3dB.

Bandwidth and Power Constraints [1]

The design of a digital communication system begins with the channel description, received power, available bandwidth, noise statistics and definition of system requirements e.g. data rates and error performance.

Two primary communication criteria are the received power and available bandwidth. In bandwidth limited systems, spectrally efficient schemes are used to save bandwidth at expense of power and in power limited systems power efficient schemes can be used at expense of bandwidth.

For any digital communication system the relationship between received power to noise-power spectral density $\frac{P_r}{N_0}$ and received $\frac{E_b}{N_0}$ is given by

$\frac{P_r}{N_0} = \frac{E_b}{N_0} R$ **Eqn 10**

Where $N_0 = \frac{N}{B}$. This relationship is frequently used in designing and evaluating digital communication systems.

Bandwidth Limited System [1]

Bandwidth efficiency increases as BT_b product decreases. Therefore signals with small BT_b products are employed in bandwidth limited systems. In uncoded systems the objective is to maximize the information rate within allowable bandwidth at expense of $\frac{E_b}{N_0}$ while maintaining a required P_b. MPSK and MQAM are examples of bandwidth efficient modulation schemes with bandwidth efficiency:

$\frac{R}{B} = \log_2(M)\, bits/sec/Hz$ **Eqn. (11)**

Suppose we have to choose between MFSK and MPSK for the following parameters: bandwidth = 4kHz, data rate = 10kbps and $\frac{P_r}{N_0}$= 60dB-Hz. First we find that the received $\frac{E_b}{N_0}$ = 55 – 10*log10(10000) = 15dB. Since required data rate exceeds the bandwidth required, we choose MPSK. Next we decide on the value of M that will give a symbol rate that is closest to the bandwidth of 4kHz. We see that fro M = 8, symbol rate is 3.2 kHz. Next we find that for P_b of less than 10e-5, the required is around 13 (from BER curves) which is less than the received so we choose 8PSK.

Power Limited Systems [1]

For this type of system where power is limited but bandwidth is plenty the following tradeoff are possible: 1. Improved P_b at expense of bandwidth for fixed $\frac{E_b}{N_0}$. 2. Reduction in $\frac{E_b}{N_0}$ at expense of bandwidth for fixed P_b . MFSK which is an orthogonal signaling technique used in power limited systems, has a bandwidth efficiency of noncoherent MFSK given by:

$\frac{R}{B} = \frac{\log_2(\mathrm{M})}{M} bits/sec/Hz$ **Eqn. (12)**

Suppose now we have available bandwidth of 45 kHz and $\frac{P_r}{N_0}$= 50dB-Hz again the goal is to choose modulation scheme to meet same BER performance. We find that the received $\frac{E_b}{N_0}$ = 50 – 10log(10000) = 10dB. Since we have plenty of bandwidth compared to the data rate, we choose MFSK as our modulation scheme. In an effort to conserve power, we look for the largest M such that minimum bandwidth for MFSK doesn't exceed 45 kHz. We see that for M = 16, the required $\frac{E_b}{N_0}$ to keep P_b less than 10e-5 is around 8dB (from BER curves) which is below 8.2dB.

References:

[1] Digital Communications fundamentals and applications by Bernard Sklar.

[2] Wireless Communications by Andrea F. Molisch

[3] Telecommunication Breakdown: Concepts of communication transmitted via Software-Defined Radio. By C. Richard Johnson and William A. Sethares

[4] RF System Design of Transceivers for Wireless Communications by Qizheng Gu