Modulation - Introduction

Introduction

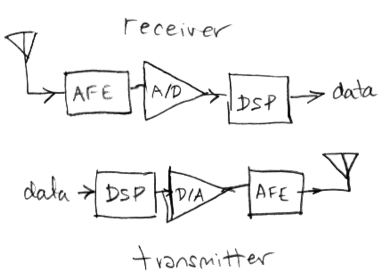
The purpose of modulation is to shift an information-bearing signal that is centered around a frequency of zero (the "baseband signal") to a signal that is centered about a "carrier frequency".

This is necessary because many channels, both wired and wireless, can only pass a range of frequencies. Examples include CATV (cable TV) systems, voice-band modems, ADSL, and all wireless channels including cellular and cordless phones, and broadcasting.

Modern communications systems, with the exception of audio broadcasting (the "AM" and "FM" bands), use digital modulation. The advantages of digital modulation include:

- energy efficiency: better audio or video quality with the same or lower power consumption
- bandwidth efficiency: more users can be supported in the same bandwidth
- flexibility: digital modulation can transmit both data and digitized waveforms of any type (audio or video)
- security: data can be effectively encrypted

Modern communications equipment is implemented using digital signal processing. An analog "front end" (AFE) is used to convert the signal to baseband. Then the baseband signal is sampled and digitized. This digital signal is processed by a digital signal processor (DSP) to recover the data. The reverse process is used at the transmitter:



This type of implementation allows most of the signal processing to be performed digitally. In most cases a DSP implementation is preferred because:

- it is less expensive because it requires less IC die area and
- it provides better performance (lower implementation loss) because it is easier to control noise and distortion when the signal is processed digitally.

Information

The term "bit" means a "binary digit" which is a digit that can be 0 or 1.

A bit is also a measure of information. Consider an information source that generates discrete statistically-independent random messages. A bit of information is defined as the negative of the log (base 2) of the probability of a particular message. For example, if there are only two equally-likely messages each one contains $-\log_2(0.5) = 1$ bit of information.

Exercise 1: A data source generates letters at random. The probability of the letter 'e' being generated is 0.125. How many bits of information are being transmitted by the letter 'e'?

Modulation Efficiency

Two criteria that are used to compare modulation techniques are spectral efficiency and power efficiency. Each of these has to be specified under given conditions. These conditions could include the error rate, type of channel, amount and type of noise, etc.

Spectral efficiency is the amount of data that can be transmitted per unit bandwidth:

$$\eta = \frac{R}{B}$$

where R is the data rate and B is the bandwidth.

Signal to noise ratio (SNR) is defined as the ratio of the signal power to the noise power:

$$\text{SNR} = \frac{S}{N}$$

where S is the signal power and N is the noise power.

Power efficiency is defined as:

$$\frac{E_b}{N_0} = \frac{S}{N}\frac{B}{R}$$

where E_b is the energy per bit (S/R) and N_0 is the average power spectral density of the noise (N/B).

Exercise 2: A GSM cellular system transmit at a rate of 384 kb/s over 200kHz channels. What is the spectral efficiency in b/s/Hz?

Exercise 3: The 802.11 standard requires that receivers achieve a packet error rate (PER) of 10% at a data rate of 24 Mb/s for an input level of -74dBm and a noise level 10dB higher than the thermal noise power spectral density of -173dBm/Hz. What is the power efficiency (unitless)?

Power Limited vs Bandwidth Limited Channels

There is usually a trade-off between power efficiency and spectral efficiency.

When power efficiency is more important than spectral efficiency this is called a power-limited channel. A typical example is a satellite link which must get its power from solar cells but where highly directional antennas can be used to limit interference to other users of the same spectrum.

On the other hand, cellular phone systems are typically considered to be bandwidth-limited because electrical power is much less expensive and there is a high demand for the available spectrum.

Bandwidth

The frequency response of a channel or the spectrum of a signal is a function of frequency. The "bandwidth" of a signal or channel is an attempt to summarize that function with a single number. There are many definitions of bandwidth

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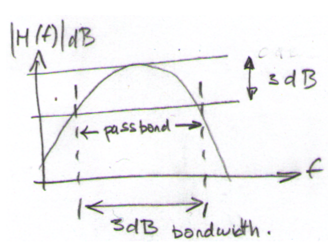
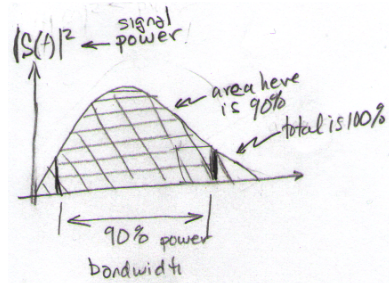
A common definition is the *3dB bandwidth*. This refers to the frequency range where the amplitude response is less than 3dB down from the maximum. Thus a signal component transmitted at the edge of the passband would have half of the power it would have if transmitted at the frequency with the lowest loss. Other bandwidth definitions can use values other than 3dB.



A definition of bandwidth that is often applied to signals rather than channels is the *90% power bandwidth*. This is the frequency range that contains 90% of the signal power. Other values than 90% can be used.



Other definitions of bandwidth are used for specialized purposes.

AWGN Channel

The Additive White Gaussian Noise (AWGN) channel is a channel often used for comparing modulation techniques. This is a frequency-flat channel that only adds white, normally-distributed noise to the signal.

Capacity

The Shannon capacity of a channel is the information rate above which it is not possible to transmit data without an arbitrarily low error rate. For the simple AWGN channel is given by:

$$C = B\log_2\left(1 + \frac{S}{N}\right)$$

Exercise 4: What is the capacity of a 3 kHz channel with an SNR of 20dB?

To implement systems that operate at close to channel capacity requires coding. Some systems using modern codes, such as "Turbo codes" can operate within a fraction of a dB of capacity.