Bandpass signalling

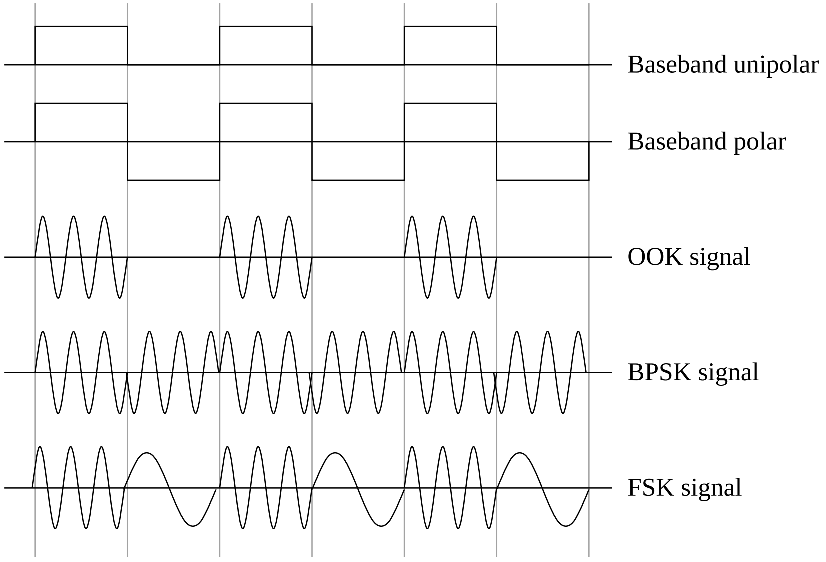
Thus far only baseband signalling has been considered: an information source is usually a baseband signal.

Some communication channels have a bandpass characteristic, and will not propagate baseband signals. In these cases, *modulation* is required to impart the source information onto a bandpass signal with a carrier frequency f_c by the introduction of amplitude and/or phase perturbations.

Bandpass digital communication systems involve modulating a baseband digital signal onto a carrier using AM, PM, FM, or some generalised technique. The most common binary bandpass signalling techniques are

- **On-off keying**, which consists of keying a sinusoidal carrier on and off with a unipolar binary signal
- **Binary phase-shift keying**, which consists of shifting the phase of a sinusoidal carrier 0° or 180° with a unipolar binary signal
- **Frequency-shift keying**, which consists of shifting the frequency of a sinusoidal carrier from a *mark* frequency (sending a 1) to a *space* frequency (sending a 0) according to the baseband digital signal.

Examples of signals generated using these techniques are shown below:



Amplitude-shift keying

Recall that amplitude modulation of the baseband signal $m(t)$ involves forming the signal

$$s(t) = \mathrm{Re}\left\{ g(t) e^{j\omega_c t} \right\},$$

where the complex envelope of the signal is either

$$g(t) = Am(t)$$

in the case of a suppressed carrier (or otherwise $g(t) = A[1 + m(t)]$). These equations reduce to the representation for the AM signal

$$s(t) = Am(t)\cos(\omega_c t).$$

An on-off keying signal is similarly represented in the form above, but in this case the modulating signal $m(t)$ is a unipolar baseband **digital** signal. If we make the assumption that the baseband signal is comprised of rectangular pulses, then we have

$$m(t) = \begin{cases} 1 & \text{symbol 1} \\ 0 & \text{symbol 0.} \end{cases}$$

Thus the modulated signal can simply be created by gating the carrier with the on-off baseband signal.

In general, amplutude-shift keying is similar except that $m(t)$ is not required to be zero for one of the symbols. For example, the modulating function $m(t)$ may be chosen to take on two different nonzero values when a 0 or a 1 are transmitted.

The PSD of the modulated signal consists of two shifted replicas of the complex envelope, one centred on f_c and the other on f_c. The bandwidth of the modulated signal is therefore twice that of the baseband signal.

In the event that the receiver has access to (or can estimate) the edges of the bit intervals, **coherent** or **synchronous** detection can be performed. The optimal decoder is then the matched filter, with impulse response

$$h(t) = A\cos(\omega_c(T - t))$$

in the case of OOK, where T is the signal interval. The output of this matched filter upon receipt of a 1 is then

$$\int_0^T A^2 \cos^2(\omega_c t) dt = A^2 T/2.$$

The output is nominally zero upon receipt of a 0, except for the effects of noise. The noise at the output of the filter is $E\eta/2$, where $\eta/2$ is the PSD of the noise at the receiver input.

Under the assumption of equal bit probabilities, the probability of a bit error in this case can be obtained in the same way as for baseband signalling as

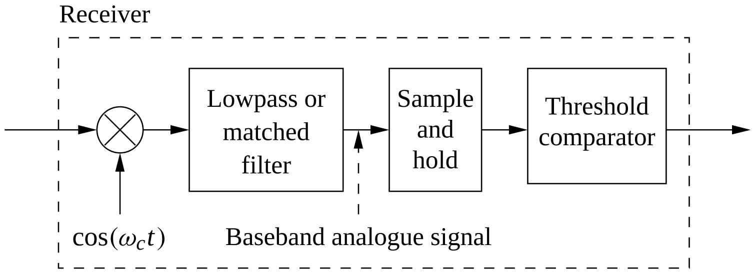
$$P_\epsilon = \mathrm{erfc}\left(\frac{E}{2\sqrt{E\eta/2}} \right) = \mathrm{erfc}\sqrt{\frac{E}{2\eta}}.$$

The average signal power is then $S = 1/2(A^2/2)$, and assuming that $T = 1/(2B)$ the noise power is $N = \eta B$. The bit error probability can therefore be written as

$$P_\epsilon = \mathrm{erfc}\sqrt{\frac{S}{2N}}.$$

Thus the performance of an ASK system is equivalent to an on-off baseband system in terms of the SNR required for a given error rate.

A coherent receiver for an OOK signal can also be developed, and involves translating the signal back to baseband (or to an intermediate frequency), and performing matched filtering on the result. Such a system is demonstrated below:



The performance of this receiver is essentially the same as for matched filtering on the modulated signal.

There is no requirement that the signal $m(t)$ be limited to taking on either the value zero or one. In fact, any baseband digital signal waveform can be used, and modulated up to the carrier frequency prior to transmission. The results here indicate that the process of modulating the signal has no effect on the performance of the bandpass system over that of the baseband system.

If bit synchronisation is not achievable, or simplicity is a criterion, then envelope detection can be used to recover the baseband signal from the modulated carrier. For equiprobable 0's and 1's the probability of error is

$$P_\epsilon = \frac{1}{2} e^{-E/4\eta} + \frac{1}{2} \operatorname{erfc} \sqrt{\frac{E}{2\eta}}.$$

For error probabilities of $P_\epsilon < 10^{-4}$ the required SNRs are such that there is only about a 1dB penalty for the use of envelope detection.

The performance of OOK is generally poorer than that of other modulation systems, and it is seldom used in practice.