Chapter 5: Analogue Transmission

Table of Contents

Although in an ideal world, we would always be using digital signals, in real life we still have to use analogue signals at times, mostly due to a scarcity of resources. Most of the transmission media we use are bandpass, which makes it difficult to handle digital data.

There are two scenarios. Either we have to convert digital data to analogue signals, or we have to convert analogue signals to analogue signals.

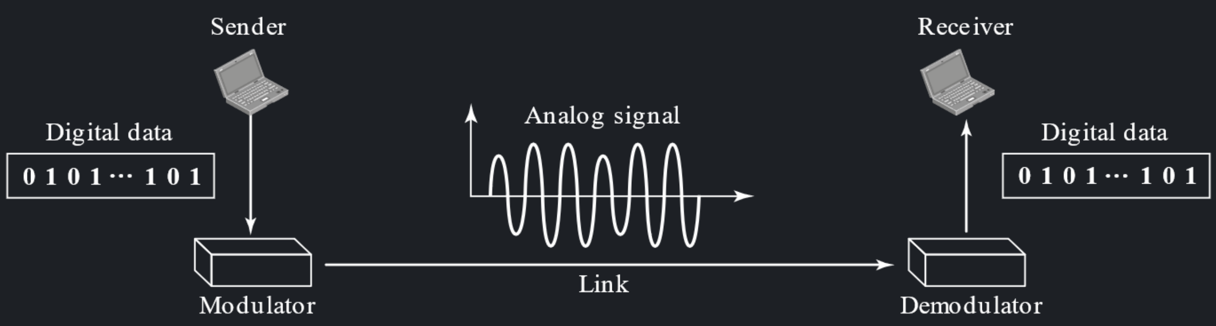
In this chapter, we will only be studying the basics of the different modulation techniques, without going into the details of their implementation.

5.1 Digital-to-Analogue Conversion

In digital-to-analogue conversion, we change one characteristic of an analogue signal based on the digital data. This gives us three fundamental conversion techniques, amplitude shift key (ASK), frequency shift key (FSK) and phase shift key (PSK). From the names, we can easily tell which characteristic of the analogue signal is being changed based on the digital data. In each of the shifting techniques, we take a basic analogue signal, called the carrier frequency, and alter it based on the data.

Sometimes, it is useful to shift both amplitude and phase in the analogue signal. This gives us the quadrature amplitude modulation (QAM) technique. This is a bit more complex, but much more common nowadays.

Similarly, we will be seeing three modulation techniques in the next section which takes a base analogue signal and modulates the amplitude, frequency or phase based on the input analogue signal.



When we change the carrier frequency, although it may seem like it is a simple sine curve, it is actually a complex composite signal. This means the bandwidth requirement is high and is a concern. For analogue signals, the signal rate is given by:

$$S = N \times \frac{1}{r}$$

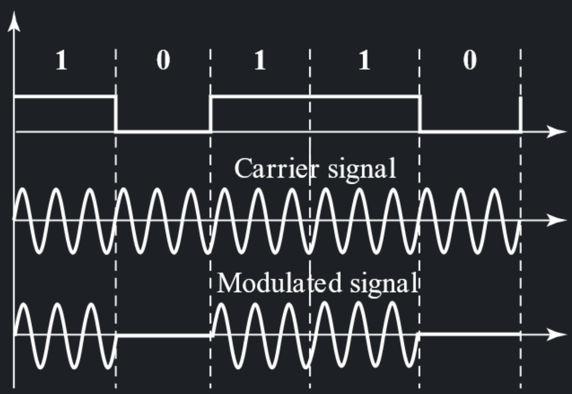
where N is the data rate in bits per second, and r is the number of data elements carried by each signal element, i.e. $r = \log_2 L$.

In analogue transmission of digital data, the signal rate is always less than or equal to the data rate.

Amplitude Shift Key (ASK)

In amplitude shift key, we change the amplitude of the carrier frequency based on the digital data. Both frequency and phase remain constant.

A very basic amplitude shift key technique is called binary amplitude shift (BAS) key, or On-Off Keying (OOK). The amplitude of the carrier frequency is a non-zero value for 1s in the digital data and a zero value for 0s in the digital data. This is done with the help of an oscillator and a multiplier.



Since $\mathrm{r} = 1$, $S = \mathrm{N}$ for BAS key. The bandwidth is given by $\mathrm{B} = (1 + \mathrm{d})S$, where d is a value between 0 to 1, depending on the modulation technique we choose. Although the carrier signal is a simple sine wave, the process of modulation we choose will produce a non-periodic compositive signal.

The carrier frequency we choose for ASK must be in the middle of the bandwidth so that it can cover both sides of the carrier frequency, thus better utilizing the bandwidth. For full-duplex communication, which is normally used in data communication, the complete bandwidth is divided into two parts, one for data transmission in each direction, and two carrier frequencies are needed, each of which are in the middle of one of the parts.

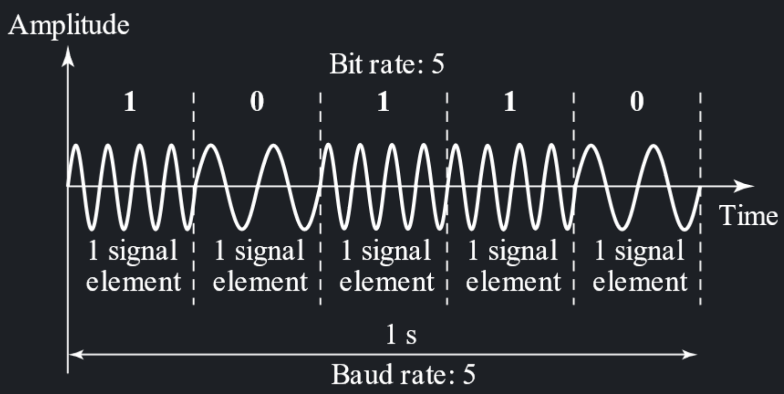
Note that it is also possible to have a single signal element that corresponds on multiple data elements. This would cause multiple levels of amplitude. However, this is not normally done, as preference is given to QAM. We shall discuss this in more detail when discussing QAM.

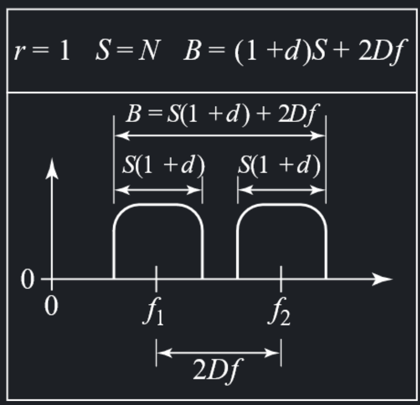
Amplitude shift key is highly susceptible to noise. This is because any noise can cause the amplitude of the signal to increase, thus causing incorrect readings.

Frequency Shift Key (FSK)

In frequency shift key, the frequency of the carrier signal varies depending on the digital data. The amplitude and phase remain the same.

In FSK, we use two frequencies. For 1 bits, we use a frequency f_1 and for 0 bits we use a frequency f_2. This is done with the help of a voltage controller oscillator. Of course, this is the case for when a single signal element represents a single data element, i.e. $r = 1$. If instead a single signal element was representing multiple data elements, we would need more frequencies, e.g. 4 different frequencies are required if a signal element represented 2 data elements.





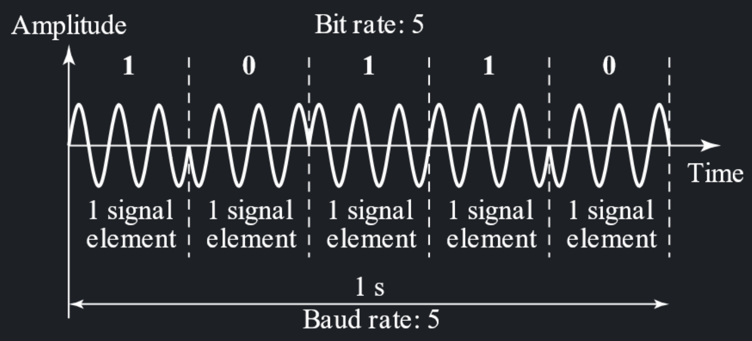
We need to ensure that the carrier frequencies are not so close that they begin to interfere with each other. Thus, even though $r = 1$ and $S = N$, the bandwidth requirement is higher. For just two frequencies, which is used for $r = 1$, $B = (1 + d)S + 2\Delta f$, where $2\Delta f$ is the difference between f_1 and f_2. A thumb rule is that $2\Delta f$ should be equal to half of the total bandwidth. This larger bandwidth is one of the drawbacks of FSK compared to ASK. If we use multilevel FSK, we will need $(L - 1)2\Delta f$ gaps for L levels.

Note that, just like with ASK, f_1 and f_2 are the mid points of their corresponding bandwidths. The main carrier frequency is at the centre of the overall bandwidth. Again, the carrier frequencies are simple sine waves, but modulation creates non-periodic composite signals with continuous frequencies.

A small problem is that when moving from one frequency to another, the phase may change. If it does not, then it is called coherent frequency shifting, but if it does, it is called non-coherent frequency shifting. The example shown above is coherent.

Phase Shift Key (PSK)

In phase shift key, the phase of the carrier signal varies to represent different signal elements. Amplitude and frequency remain the same. The simplest form of this is binary phase shifting.

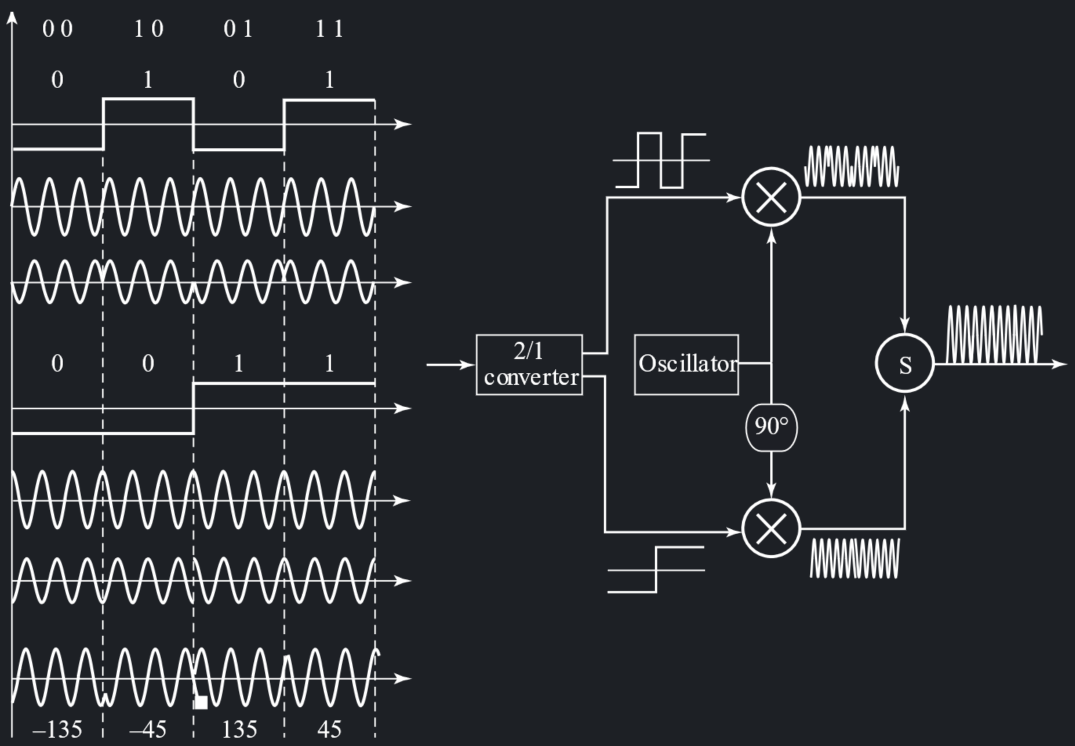


The advantage of PSK is that it is less susceptible to noise. Just like with ASK, $r = 1$, $S = N$ and $B = (1 + d)S$.

Quadrature PSK (QPSK)

Multilevel PSK can also exist, with different phases being used to represent different signal elements. This is the method used in Quadrature PSK (QPSK) or 4-PSK, where there are four variants of phase shifting, each representing 2 bits, i.e. $r = 2$. Of course, an additional cost is that the receiver needs to be sensitive enough to distinguish between the four phases.

The way this is actually implemented is, every pair of bits is divided into two parts and sent in two directions. The second part is shifted by $90°$. After that, both parts are shifted as in binary PSK, and the results are combined.



The overall effect is to give us four different phases.

Constellation Diagrams

In a constellation diagram, a signal element is represented by a point. The projection of the point on the x-axis represents its amplitude on the in-phase component, the projection of the point on the y-axis represents its amplitude on the quadrature component and the angle with the x-axis determines the phase.

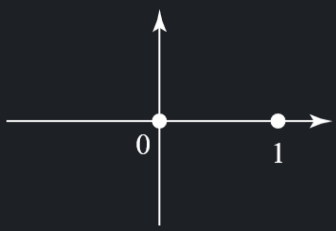
Thus, for QPSK, the diagram will look like this:

Q PSK

Each point has a component on the in-phase and the quadrature components, which is why we end up with $45°$ angles.

Constellation diagrams can also be made for ASK and BPSK.

The diagram for ASK has a point at the centre and one on the positive x-axis, since ASK involves just one amplitude and there is no phase shifting.

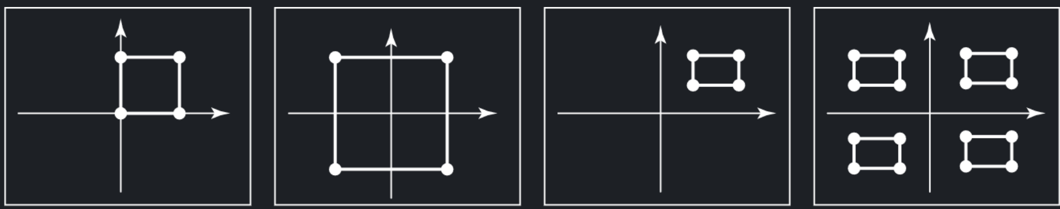


The diagram for BPSK has two points, one on either side of the x-axis. The point on the negative x-axis tells us that it has a $180°$ shift.

Constellation diagrams cannot represent frequencies. As such, they are not used with FSK.

Quadrature Amplitude Modulation (QAM)

Quadrature amplitude modulation essentially involves changes in both phase and amplitude. Constellation diagrams can help us quickly gather a lot of information about these, so we will be using them.



a. 4-Q AM b. 4-Q AM c. 4-Q AM d. 16-Q AM

The first diagram tells us that there are four signal elements with just one amplitude (since all non-zero elements are the same length from the centre). Two of the signal elements have $0°$ phase shift, one has a $45°$ phase shift and another has a $90°$ phase shift.

The second diagram is similar, except that the phase shifts are different and the amplitudes are all non-zero.

The next two diagrams are more complicated, but follow the same thinking.

5.2 Analogue-to-Analogue Conversion

The reason we need to 'convert' an analogue signal to an analogue signal is because we frequently have to deal with bandpass transmission mediums. All the transmission mediums we use have the same bandwidth, but not all sources follow that bandwidth. As such, we need to shift the analogue signal to fit the transmission medium. Thus, this is not so much conversion as it is shifting.

Three techniques are used, amplitude modulation (AM), frequency modulation (FM) and phase modulation (PM). In each case, the named attribute of the carrier signal is changed based on the amplitude of the input signal.

For amplitude modulation, the bandwidth required is twice the bandwidth of the original signal, $\mathrm{B_{AM}} = 2\mathrm{B}$. AM radio channels are generally given $10\mathrm{kHz}$ spans of bandwidth, since human voice and music is covered by $5\mathrm{kHz}$.

For frequency modulation, this is $\mathrm{B_{FM}} = 2(1+\beta)\mathrm{B}$, where β depends on the modulation technique and normally has a value of 4. As such, FM requires a much greater bandwidth than AM, and are given $200\mathrm{kHz}$ spans of bandwidth between $88\mathrm{MHz}$ and $108\mathrm{MHz}$. Stereo signals are covered within $15\mathrm{kHz}$, making the required bandwidth at least $150\mathrm{kHz}$, which explains the allocated bandwidth span. We could theoretically pack 100 stations like this, but that would increase the chances of overlaps between signals. Thus, every other spot is left blank.

Phase modulation is conceptually the same thing as frequency modulation. This can be proven mathematically, but we won't go there. PM has the same bandwidth requirements, at $\mathrm{B_{PM}} = 2(1+\beta)\mathrm{B}$. However, the value of β could be 1 or 3 for PM.

For all the techniques, the carrier frequency is in the middle of the allocated bandwidth.