STUDY OF DIGITAL MODULATION TECHNIQUES

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Introduction:

Modulation is the process of facilitating the transfer of information over a medium. Typically the objective of a digital communication system is to transport digital data between two or more nodes. In radio communications this is usually achieved by adjusting a physical characteristic of a sinusoidal carrier, either the frequency, phase, amplitude or a combination thereof . This is performed in real systems with a modulator at the transmitting end to impose the physical change to the carrier and a demodulator at the receiving end to detect the resultant modulation on reception. Hence, modulation can be objectively defined as the process of converting information so that it can be successfully sent through a medium.

Most communications systems fall into one of three categories: bandwidth efficient, power efficient, or cost efficient. Bandwidth efficiency describes the ability of a modulation scheme to accommodate data within a limited bandwidth. Power efficiency describes the ability of the system to reliably send information at the lowest practical power level. In most systems, there is a high priority on bandwidth efficiency. The parameter to be optimized depends on the demands of the particular system.

For designers of digital terrestrial microwave radios, their highest priority is good bandwidth efficiency with low bit-error-rate. They have plenty of power available and are not concerned with power efficiency. They are not especially concerned with receiver cost or complexity because they do not have to build large numbers of them. On the other hand, designers of hand-held cellular phones put a high priority on power efficiency because these phones need to run on a battery. Cost is also a high priority because cellular phones must be low-cost to encourage more users. Accordingly, these systems sacrifice some bandwidth efficiency to get power and cost efficiency.

Every time one of these efficiency parameters (bandwidth, power or cost) is increased, another one decreases, or becomes more complex or does not perform well in a poor environment. For example, in the case of radios, cost is a dominant system priority. Low-cost radios will always be in demand. In the past, it was possible to make a radio low-cost by sacrificing power and bandwidth efficiency. This is no longer possible. The radio spectrum is very valuable and operators who do not use the spectrum efficiently could lose their existing licenses or lose out in the competition for new ones. These are the tradeoffs that must be considered in digital RF communications design.

1.1 Why Digital Modulation?

The move to digital modulation provides more information capacity, compatibility with digital data services, higher data security, better quality communications, and quicker system availability. Developers of communications systems face these constraints:

- Available bandwidth
- Permissible power
- Inherent noise level of the system

The RF spectrum must be shared, yet every day there are more users for that spectrum as demand for communications services increases. Digital modulation schemes have greater capacity to convey large amounts of information than analog modulation schemes.

Anything that is wireless is analog-always. Wired signals can be analog or digital. Communications inside a computer are examples of purely digital communication, digital data over digital medium. LAN communications are digital data over analog medium. The AM and FM radios are examples of analog data over analog medium.

The ever increasing demand for digital transmission channels, in the radio frequency (RF) band presents a potentially serious problem of spectral congestion and is likely to cause severe adjacent and cochannel interference problems. This has, in recent years, led to the investigation of a wide variety of techniques for solving the problem of spectral congestion. Some solutions to this problem include: 1) new allocations at high frequencies; 2) better management of existing allocations; 3) the use of frequency-reuse techniques such as the use of narrow beam antennas and dual polarizing systems; 4) the use of efficient source encoding techniques; and5) the use of spectrally efficient modulation techniques.

1.2 Types of Modulation Techniques Used

We begin our discussion on Digital Modulation by starting with the three basic types of modulation techniques employed. These are:

- Amplitude Shift Keying (ASK)
- Frequency Shift Keying (FSK)
- Phase Shift Keying (PSK)

All of these techniques vary a parameter of a sinusoid to represent the information which we wish to send. A sinusoid has three different parts can that can be varied. These are amplitude, phase and frequency.

1.3 Hierarchy of Digital Modulation Schemes

Digital modulation techniques may be classified into *coherent* and *non-coherent* techniques, depending upon whether the receiver is equipped with a phase-recovery circuit or not. The phase-recovery circuit ensures that the oscillator supplyingthe locally generated carrier wave in the receiver is synchronized (in both frequency and phase) to the oscillator supplying the carrier wave used to originally modulate the incoming data stream in the transmitter. **(*Simon haykin*)**

The terms coherent and incoherent are frequently used when discussing the generation and reception of digital modulation. When linked to the process of modulation the term coherence relates to the ability of the modulator to control the phase of the signal, not just the frequency. For example Frequency Shift Keying (FSK) can be generated both coherently with an IQ modulator and incoherently with simply a Voltage Controlled Oscillator (VCO) and a digital voltage source, as shown in figure below.

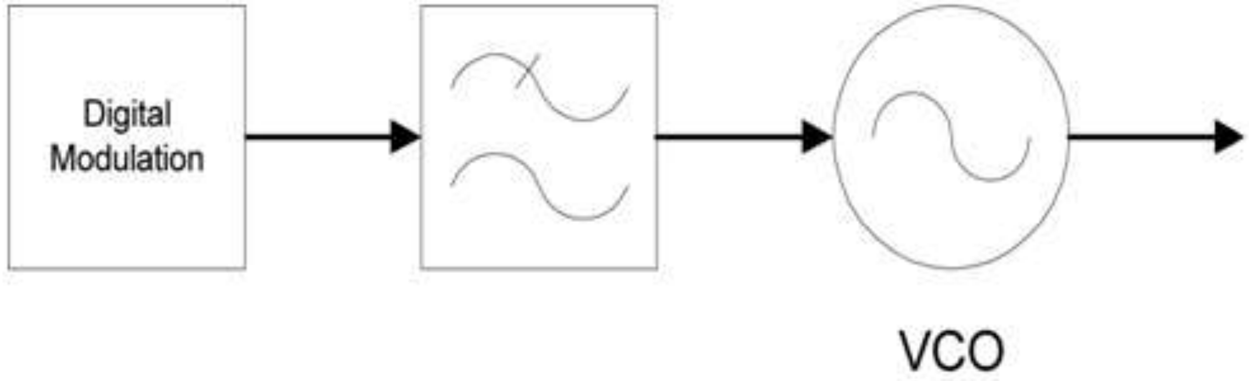

Fig 1.1 In-coherent generation of FSK

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With the system in figure 1(a) the instantaneous frequency of the output waveform is determined by the modulator (within a tolerance set by the VCO and data amplitude etc) but the instantaneous phase of the signal is not controlled and can have any value. Alternatively coherent generation of modulation is achieved as shown in figure 1(b). Here the phase of the signal is controlled, rather than the frequency

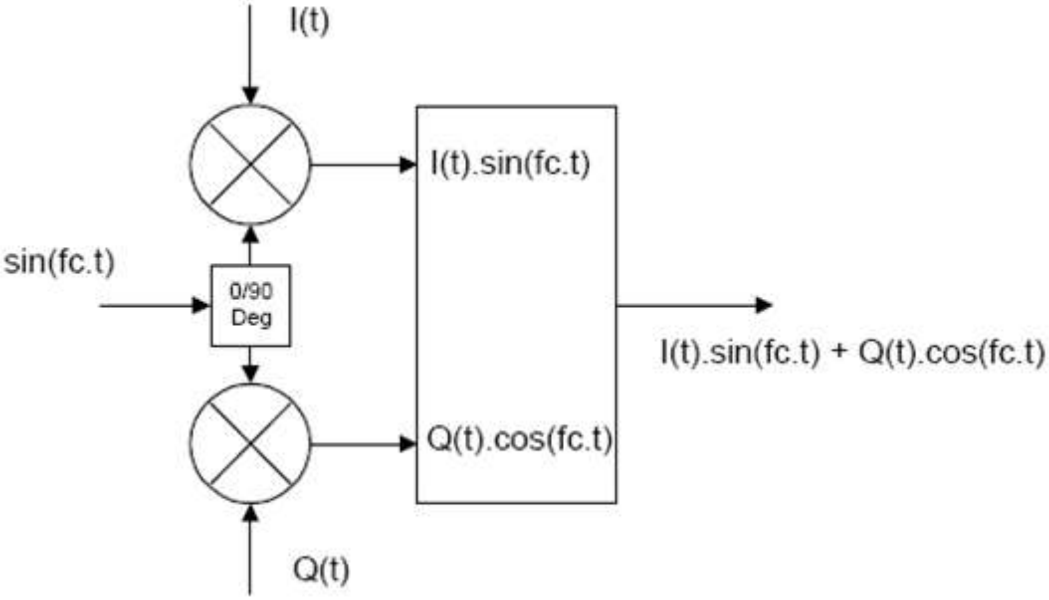


Fig 1.2: Coherent generation of FSK

Use of the term coherent with respect to the act of demodulation refers to a system that makes a demodulation decision based on the received signal phase, not frequency. The additional ‘information’ available results in an improved BER performance. The high level of digital integration now possible in semiconductor devices has made digitally based coherent demodulators common in mobile communications systems.

1.3.1 Amplitude Shift Keying (ASK)

In ASK, the amplitude of the carrier is changed in response to information and all else is kept fixed. Bit 1 is transmitted by a carrier of one particular amplitude. To transmit 0, we change the amplitude keeping the frequency constant. On-Off

Keying (OOK) is special form of ASK, where one of the amplitudes is zero as shown below.

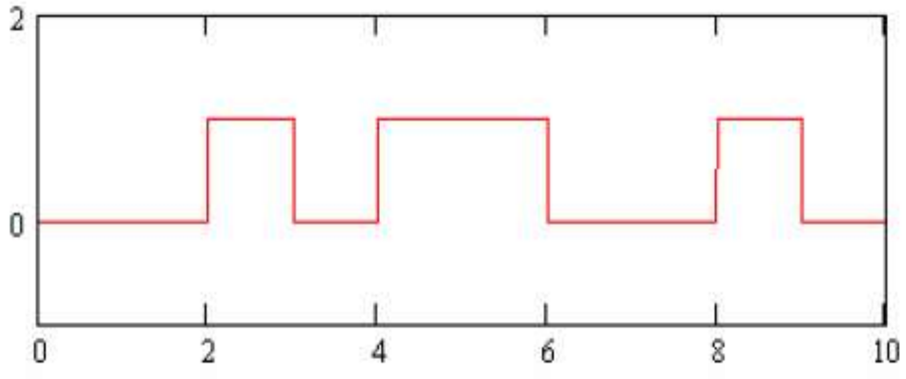


Fig 1.3 : Baseband information sequence – 0010110010

$ASK(t) = s(t) \sin(2\pi ft)$

1.3.2 Frequency Shift keying (FSK)

In FSK, we change the frequency in response to nformation, one particular frequency for a 1 and another frequency for 0 as shown below for the same bit sequence as above. In the example below, frequency f1 for bit 1 is higher than f2 used for the 0 bit.

FSK(t) = $\sin(2\pi f_1 t)$ for bit 1
$\text{Sin}(2\pi f_2 t)$ for bit 0

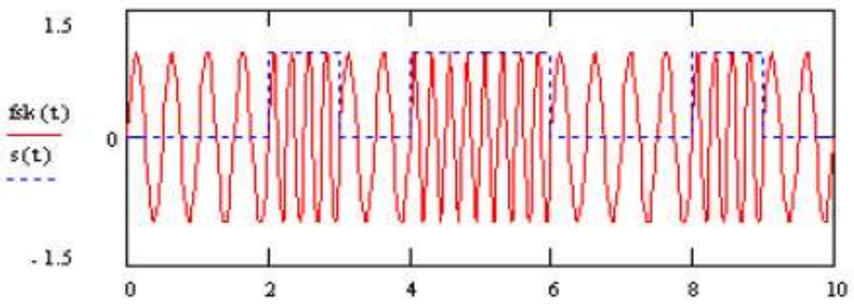


Fig 1.4 Binary FSK singnal

1.3.3 Phase Shift Keying(PSK)

In PSK, we change the phase of the sinusoidal carrier to indicate information. Phase in this context is the starting angle at which the sinusoid starts. To transmit 0, we shift the phase of sinusoid by 180 degrees. Phase shift represents the change in the state of the information in this case.

PSK(t) - Sin(2πft) for bit 1
Sin(2πft + π) for bit 0

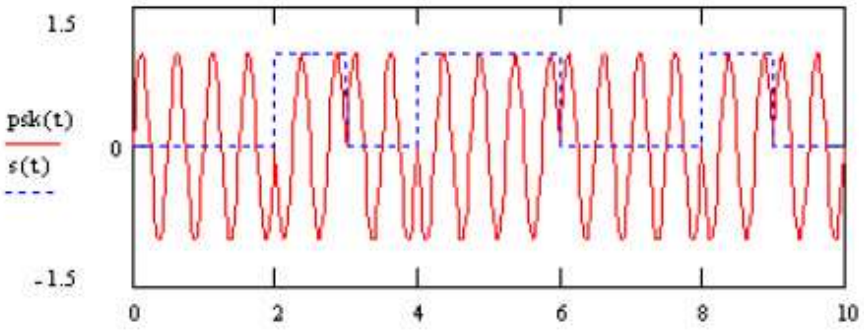


Fig 1.4 Binary PSK Carrier (Note the 180° phase shifts at bit edges)

ASK techniques are most susceptible to the effects of non-linear devices which compress and distort signal amplitude. To avoid such distortion, the system must be operated in the linear range, away from the point of maximum power where most of the non-linear behavior occurs. Despite this problem in high frequency carrier systems, Amplitude Shift Keying is often used in wire-based radio signaling, either with or without carrier.

1.4 Signal, Spaces and Basis Function

The study of signal spaces provides us with a geometric way of conceptualizing the modulation process. In a physical space when we describe a vector by its coordinates (x,y); the vector is being described by a linear combination of two functions (1,0) and (0,1). Any vector can be written as a linear combination of these two functions. These functions are called *basis functions* and are orthogonal to each other.

Another example of such a family of functions are the unit width pulses separated in time shown below. Each of these is independent of others and can clearly we can use these functions to create any random data sequence consisting of square pulses. Each one of these single pulses is a basis function. However, this is not a very efficient set of basis functions as it takes a large number of these functions to create a random signal.
Ideally we want as few basis functions as possible which when combined can create a large number of independent signals, both digital and analog. In general, basis functions should:

- Have unit energy, such as (1, 0) and the (0, 1) vectors and the above unit pulses.
- They should be orthogonal to every other function in the set, represented mathematically by

$$\int_{-\infty}^{+\infty} \phi_i(t)\phi_j(t) = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$$

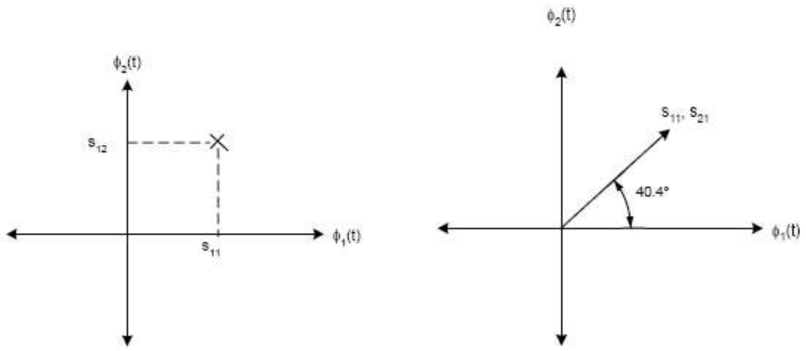
An important example of terrific basis functions is the pair of sine and cosine waves of unit amplitude. This special **basis set** is used as carriers in all real communications systems.

1.5 The concept of I and Q Channels

Without worrying what a signal is, let’s just define it as a vector. Below you see two views of a signal space. One shows a signal in rectangular and other in its polar form. We can describe the signal it in polar form by its magnitude and it phase (angle) or by its rectangular projections, such a s $_{11}$ and $_{s12}$.

In Figure (a) the x and y axis are called the In-Phase and Quadrature projections of the signal. Quantity s_{11} is I projection and s_{12} is the Q projection of the signal. Figure (b) shows the same signal in polar form, with its length equal to its amplitude and the angle is equal to its phase. These are two canonical ways of representing signals.

The co-efficients s_{11} represent the amplitude of 1 signal and s_{12} the amplitude of the Q signal. These amplitudes when plotted on the x and y axis respectively, give the signal vector. The angle the signal vector makes with the x-axis is the phase of the signal.



(a) I and Q projections **(b) Polar form**

Signal vector plotted on signal space

Fig 1.5: Signal showing Q and Q projections and the Polar form

Magnitude of signal S = $\sqrt{I^2 + Q^2}$

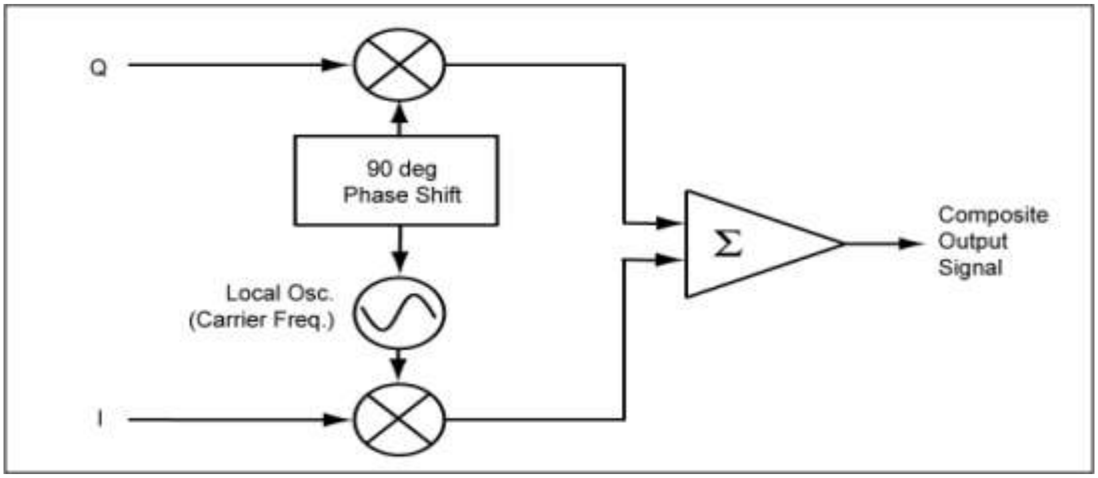
Phase of the signal = $\tan^{-1}$ (I/Q)

1.6 Why use I and Q?

Digital modulation is easy to accomplish with *I/Q* modulators. Most digital modulation maps the data to a number of discrete points on the *I/Q* plane. These are known as constellation points. As the signal moves from one point to another, simultaneous amplitude and phase modulation usually results. To accomplish this with an amplitude modulator and a phase modulator is difficult and complex. It is also impossible with a conventional phase modulator. The signal may, in principal, circle the origin in one direction forever, necessitating infinite phase shifting capability. Alternatively, simultaneous AM and Phase Modulation is easy with an *I/Q* modulator. The I and *Q* control signals are bounded, but infinite phase wrap is possible by properly phasing the *I* and *Q* signals.

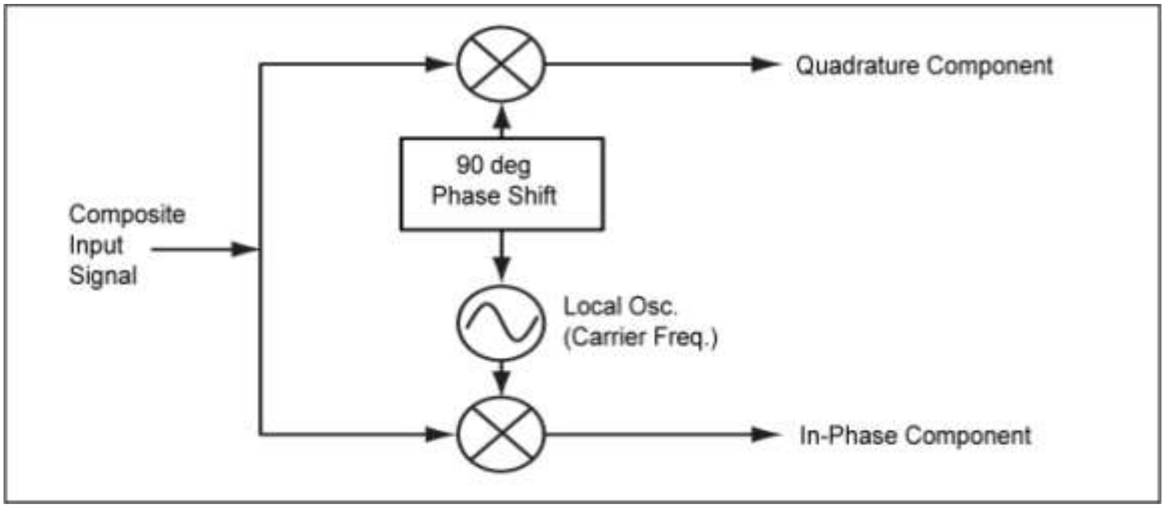
1.7.1 I and Q in a radio transmitter

I/Q diagrams are particularly useful because they mirror the way most digital communications signals are created using an *I/Q* modulator. In the transmitter, *I* and *Q* signals are mixed with the same local oscillator (LO). A 90 degree phase shifter is placed in one of the LO paths. Signals that are separated by 90 degrees are also known as being orthogonal to each other or in quadrature. Signals that are in quadrature do not interfere with each other. They are two independent components of the signal. When recombined, they are summed to a composite output signal. There are two independent signals in *I* and *Q* that can be sent and received with simple circuits. This simplifies the design of digital radios. The main advantage of *I/Q* modulation is the symmetric ease of combining independent signal components into a single composite signal and later splitting such a composite signal into its independent component parts.



1.7.2 I and Q in a radio receiver

The composite signal with magnitude and phase (or *I* and *Q*) information arrives at the receiver input. The input signal is mixed with the local oscillator signal at the carrier frequency in two forms. One is at an arbitrary zero phase. The other has a 90 degree phase shift. The composite input signal (in terms of magnitude and phase) is thus broken into an in-phase, *I*, and a quadrature, *Q*, component. These two components of the signal are independent and orthogonal. One can be changed without affecting the other. Normally, information cannot be plotted in a polar format and reinterpreted as rectangular values without doing a polar-to-rectangular conversion. This conversion is exactly what is done by the in-phase and quadrature mixing processes in a digital radio. A local oscillator, phase shifter, and two mixers can perform the conversion accurately and efficiently.



1.8 Symbols, bits and bauds

A symbol is quite apart from a bit in concept although both can be represented by sinusoidal or wave functions. Where bit is the unit of information, the symbol is a unit of transmission energy. It is the representation of the bit that the medium transmits to convey the information. Bits can be imagined as widgets, and symbols as boxes in which the widgets travel on a truck. We can have one widget per box or we can have more.

In communications, the analog signal shape, by pre-agreed convention, stands for a certain number of bits and is called a symbol.

A symbol is just a symbol. It can stand for any number of bits, no just one bit. The bits that it stands for are not being transmitted,what is transmitted is the symbol or actually the little signal packet shown below. The frequency of this packet is usually very high.

To understand and compare different modulation format efficiencies, it is important to first understand the difference between bit rate and symbol rate. The signal bandwidth for the communications channel needed depends on the symbol rate, not on the bit rate.

$$\textit{Symbol rate} = \frac{\textit{bit rate}}{\textit{the number of bits transmitted with each symbol}}$$

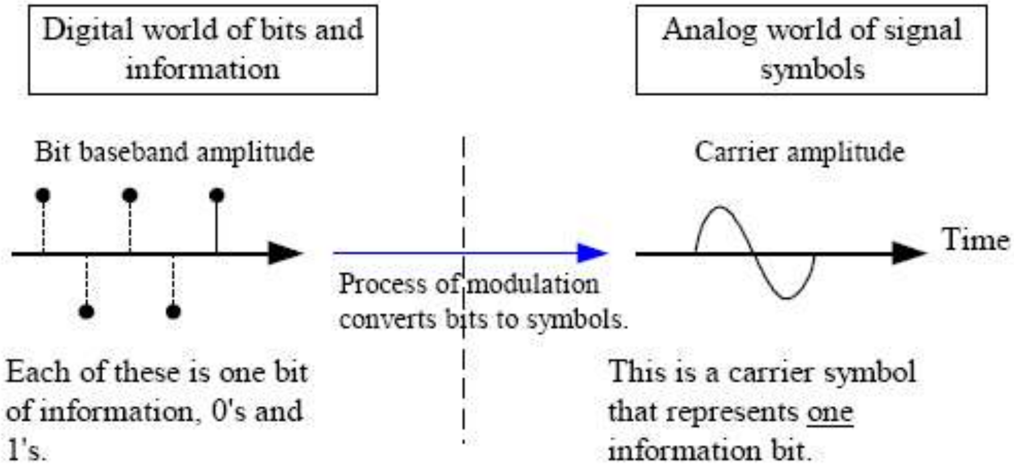


Fig 1.6 **Digital information travels on analog carrier**

CHAPTER 2

2.1 Constellation Diagrams

As discussed, the rectangular *I/Q* diagram is a polar diagram of magnitude and phase. A two-dimensional diagram of the carrier magnitude and phase (a standard polar plot) can be represented differently by superimposing rectangular axes on the same data and interpreting the carrier in terms of in-phase (*I*) and quadrature-phase (*Q*) components. It would be possible to perform AM and PM on a carrier at the same time and send data this way; it is easier for circuit design and signal processing to generate and detect a rectangular, linear set of values (one set for *I* and an independent set for *Q*).

The polar diagram shows several symbols at a time. That is, it shows the instantaneous value of the carrier at any point on the continuous line between and including symbol times, represented as *I/Q* or magnitude/phase values.

The constellation diagram shows a repetitive “snapshot” of that same burst, with values shown only at the decision points. The constellation diagram displays phase errors, as well as amplitude errors, at the decision points. The transitions between the decision points affects transmitted bandwidth. This display shows the path the carrier is taking but does not explicitly show errors at the decision points. Constellation diagrams provide insight into varying power levels,the effects of filtering, and phenomena such as Inter-Symbol Interference.

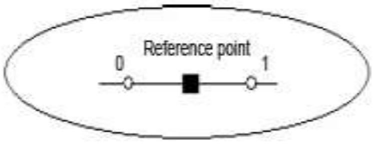
The relationship between constellation points and bits per symbol is

$M=2n$ *where* M *= number of constellation points*
n *= bits/symbol*
or $n= \log2 (M)$

This holds when transitions are allowed from any constellation point to
any other

2.2 BPSK

One of the simplest forms of digital modulation is binary or Bi-Phase Shift Keying (BPSK). One application where this is used is for deep space telemetry. The phase of a constant amplitude carrier signal moves between zero and 180 degrees. On an *I* and *Q* diagram, the *I* state has two different values. There are two possible locations in the state diagram, so a binary one or zero can be sent. The symbol rate is one bit per symbol.

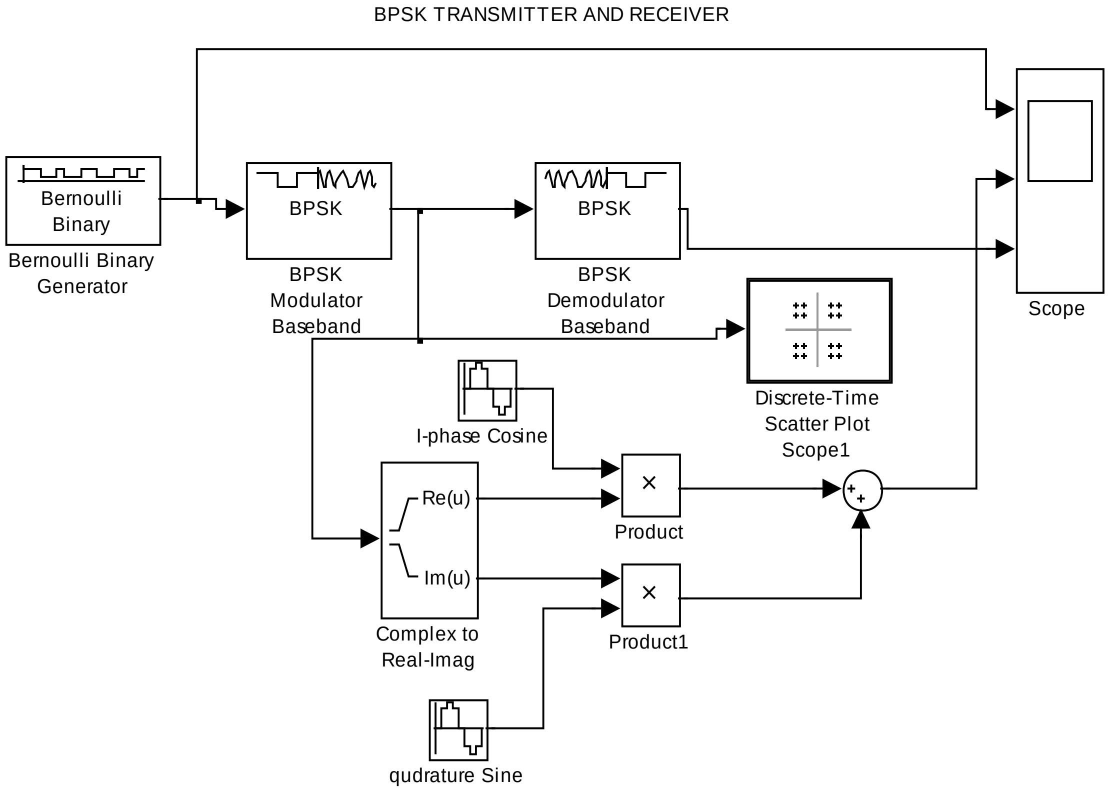


Two signaling spots, a simple modulation system

The diagram depicts two positions, which represent two symbols. Let’s give these symbols names s_1 and s_2. Simplest thing is to have one position stand for just a bit. This method of transmitting information, i.e., the bits, is called BPSK modulation. We utilize just one sinusoid as the basis function. We vary the phase of this signal to transmit information which is identical in phase. In BPSK we define two little packets of the cosine wav, one with zero phase and second one with a 180 degree different phase.

To further illustrate the BPSK model of modulation, a Simulink model was prepared and the transmitted data, received data and the constellation diagram were acquired.

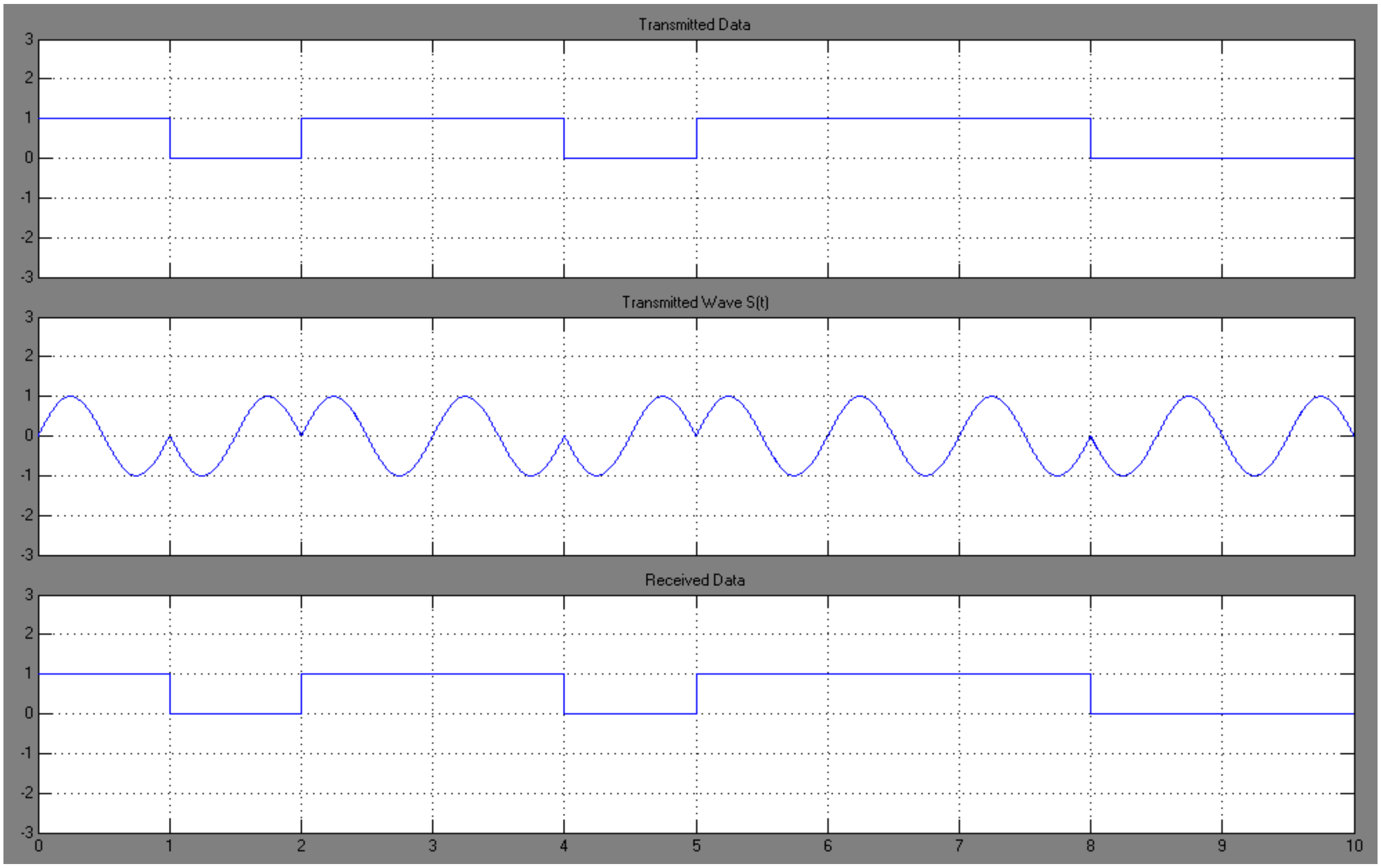
Model used to represent BPSK Transmitter and Receiver



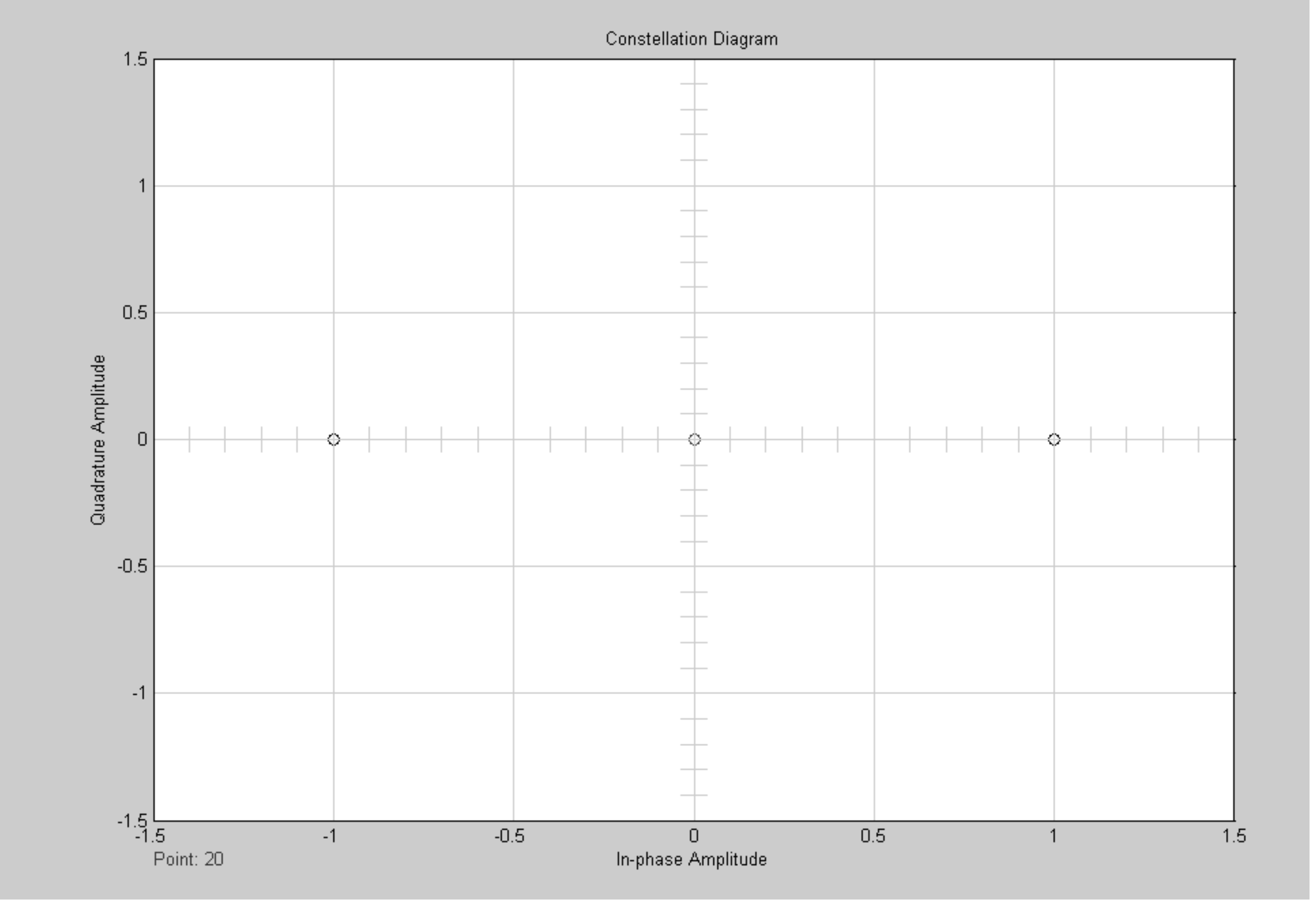
Model depicting BPSK transmitter and receiver

2.2.1 Output representing

- **Transmitted data**
- **Transmitted wave**
- **Received data**



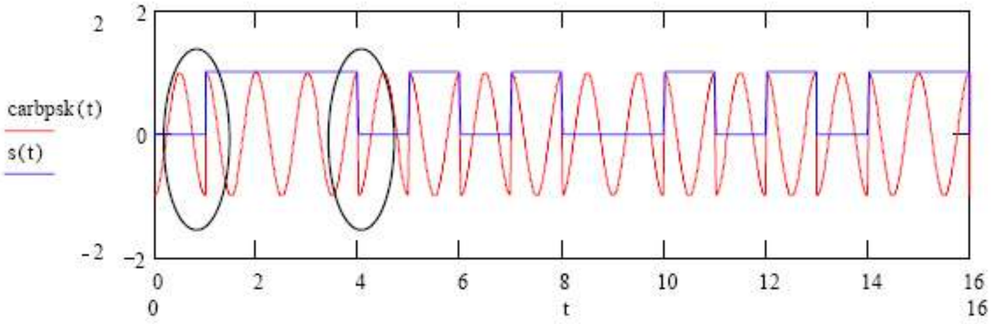
Constellation Diagram for the above BPSK Transmitter and Receiver model was obtained



2.2.2 Creating a BPSK Carrier

A bit sequence, in the case of a BPSK carrier is represented by a set of two symbols. That is, for eg., consider a sequence such as 0111 010100101011. To transmit this sequence, we need 16 symbols since each BPSK symbol stands for one bit.
These are :

S1s2s2s2 s1s2s1s2 s1s1s2s1 s2s1s2s2



- A BPSK signal for bit sequence 0111 0101 0010 1011

Although the sequence considered here is illustrative, however the figure shown differs from a real sequence in many respects.
In real systems, the carrier frequency is very high and we would be able to see a signal that covers a lot of cycles between each transition.

In a coherent BPSK system, the pair of signals, s1 and s2 used to represent binary symbols 1 and 0, respectively, is defined by

$$s1(t) = \sqrt{\frac{2Eb}{Tb}}\ \cos(2\pi fct)$$

$$s2(t) = \sqrt{\frac{2Eb}{Tb}}\ \cos(2\pi fct + \pi)$$

where $0 \le t \le Tb$ and Eb is the *transmitted energy per bit.*

2.3 Additive White Gaussian Noise

Additive white Gaussian noise (AWGN) is the most common noise model in communication systems. White means that the frequency spectrum is continuous and uniform for all frequency band of interest. The term, white, originated from the fact that white light contains equal energy over the visible frequency band. The thermal noise at the receiver amplifier shows uniform noise power per unit bandwidth at all frequencies. In communication systems, there are many different noise sources even though we represent them as one noise source in the noise model. Noises from different sources adds up and the summation of them looks like a Gaussian distribution. So the use of Gaussian noise is justified. For the convenience's sake, white refers to signal whose power spectral density is flat for the entire frequencies. The autocorrelation of the random signal is a delta function in time domain. The sufficient condition for a random process to have a delta function as the autocorrelation is that the random variables at different times are independent and have zero means[**http://cobweb.ecn.purdue.edu/~ee495w/mat-bin/sim_noise/awgn.html]**

2.4 Probability of Error (P_e)

A major goal of the passband data transmission systemsis the optimum design of the design of the receiver so as to minimize the average probability of symbol error in the presence of AWGN.

The average probability of symbol error or, equivalently, the bit error rate for coherent binary PSK is found to be:

$$Pe = ½ \operatorname{erfc}(\sqrt{Eb/N0}\ )$$

Where,

erfc() is the complementary error function

Eb the transmitted signal energy per bit

N0 is the specified noise spectral density.

2.5 What is a transition?

A transition is the time at which we switch from one symbol to the next.In case of BPSK, at every bit transition the signal does a 180 degree phase shift.

2.5.1 Why is transition important?

We worry about what the signal does at transition because of amplifier non-linearities. Amplifiers used in communication have a very hard time with sudden changes in signal amplitudes and introduce distortions. Since this makes it harder to decode the symbol, we try to control these transitions.

2. 6 Quadriphase Shift Keying

The provision of reliable performance, exemplified by a very low probability of error, is one important goal in the design of a digital communication system. Another important goal is the efficient utilization of channel bandwidth.

In QPSK, as with BPSK, information carried by the transmitted signal is contained in the phase. In particular, the phase of the carrier takes on one of four equally spaced values, such as π/4, 3π/4, 5π/4 and 7π/4. For this set of values we may define the transmitted signal as

$$S_i(t) = \begin{cases} \sqrt{\frac{2E}{T}} \cos[2\pi f c t + (2i-1)\pi/4], & 0 \leq t \leq T \\ 0 & , \text{elsewhere} \end{cases}$$

Where i = 1,2,3,4; E is the transmitted signal energy per symbol, and T is the symbol duration. The carrier frequency fc equals nc/T for some fixed integer nc.

It is used extensively in applications including CDMA (CodeDivision Multiple Access) cellular service, wireless local loop, Iridium(a voice/data satellite system) and DVB-S (Digital Video Broadcasting -Satellite). Quadrature means that the signal shifts between phase states which are separated by 90 degrees. The signal shifts in increments of 90 degrees from 45 to 135, –45, or –135 degrees. These points are chosen as they can be easily implemented using an *I/Q* modulator. Only two *I* values and two *Q* values are needed and this gives two bits per symbol. There are four states because 22 = 4. It is therefore a more bandwidth-efficient type of modulation than BPSK, potentially twice as efficient.

2.7 Probability of Error (P_e)

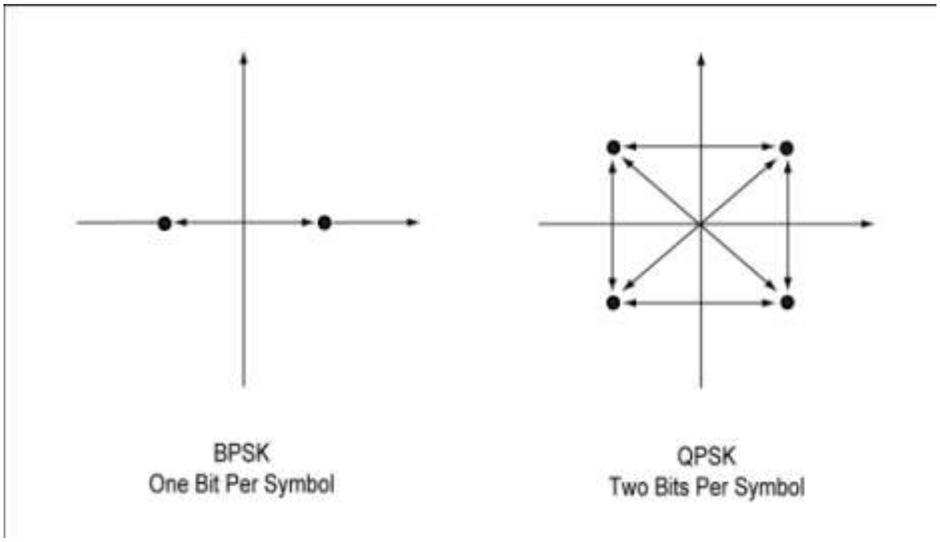
The Pe is found out in terms of ratio Eb/N0,

$$Pe \cong \operatorname{erfc}(\sqrt{Eb/N0})$$

Since Gray encoding is used for the incoming symbols, we find that the bit error rate, BER of QPSK is found to be

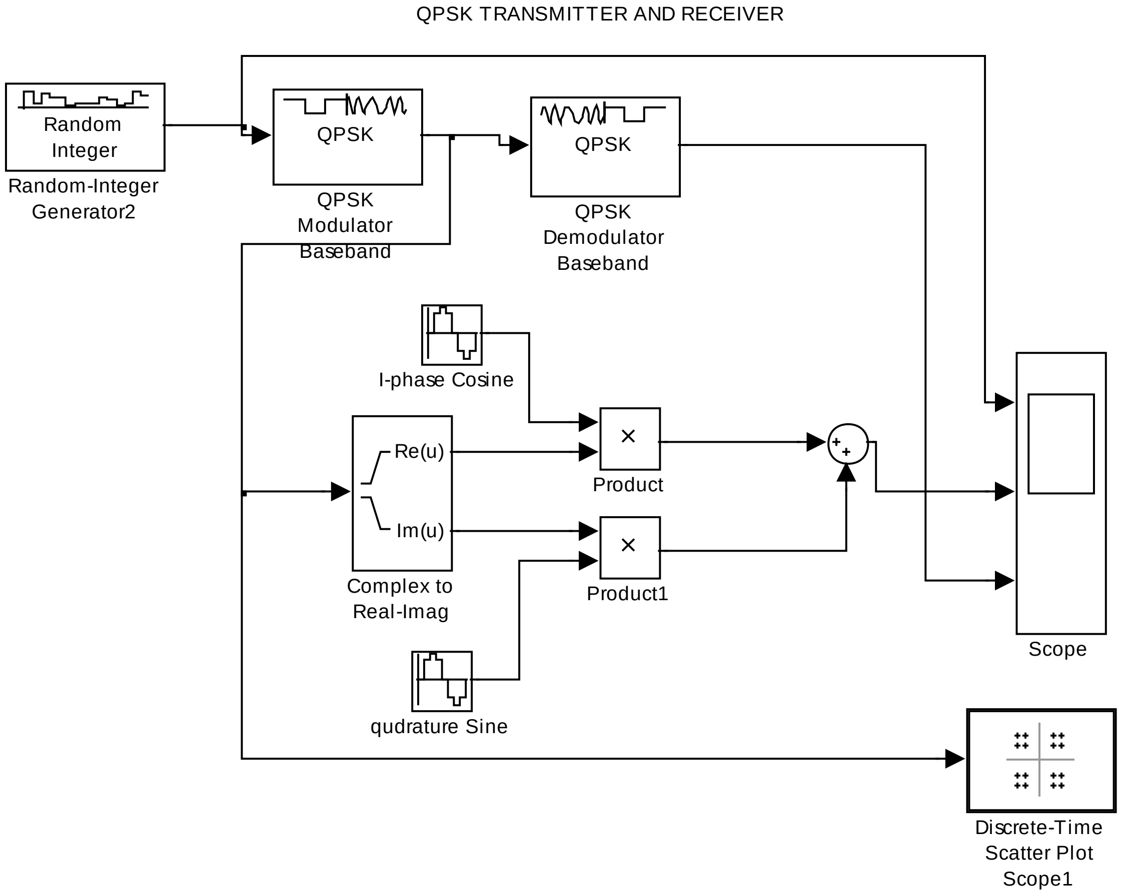
$$BER = \tfrac{1}{2} \operatorname{erfc}(\sqrt{Eb/N0})$$

Comparison between BPSK and QPSK



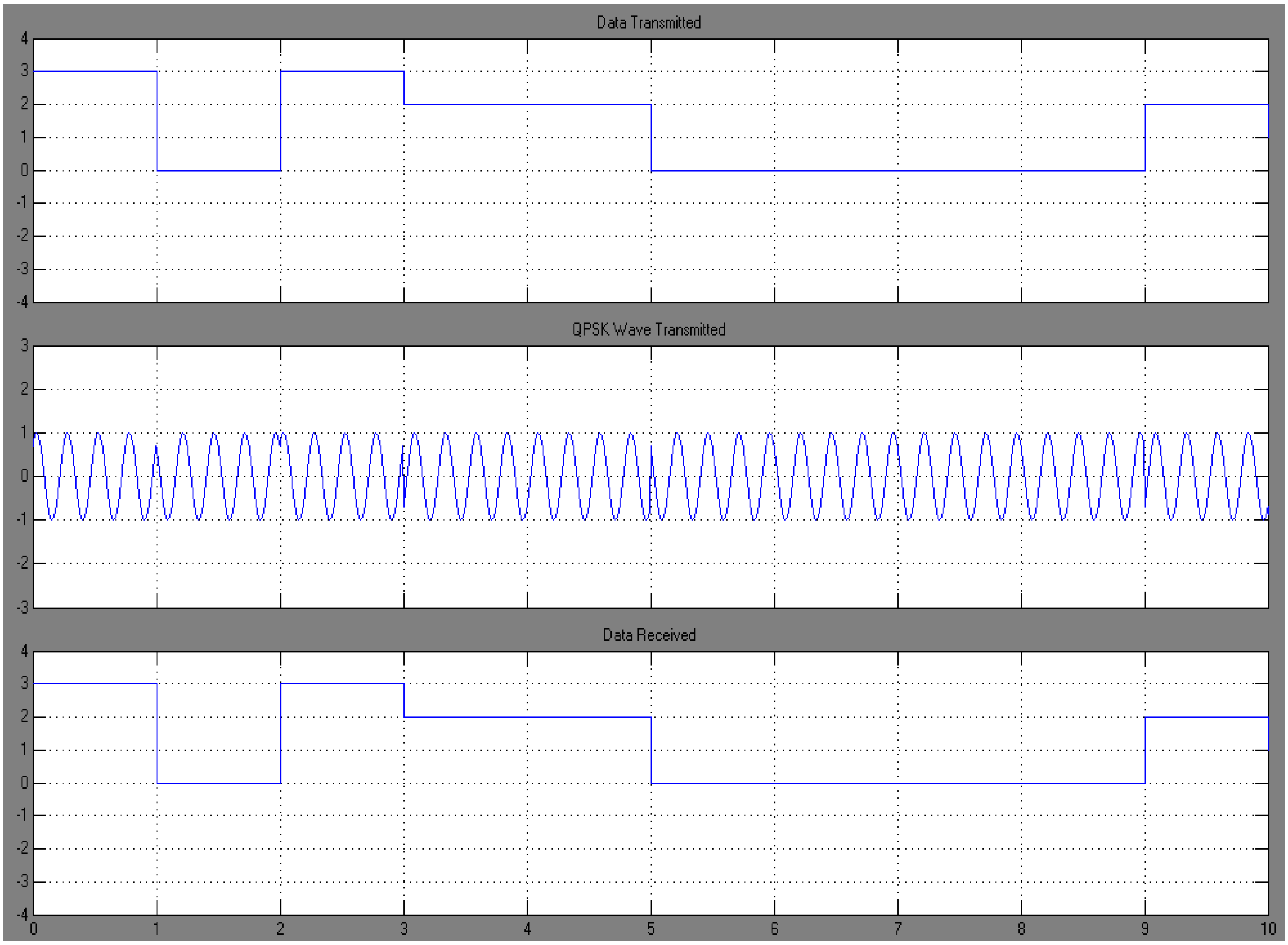
To further the idea of QPSK, a SIMULINK model was constructed and the output was generated to check the data transmitted and data received. The model was generated from the communications toolbox available as a part of MATLAB and SIMULINK software package.

The QPSK transmitter and receiver model used

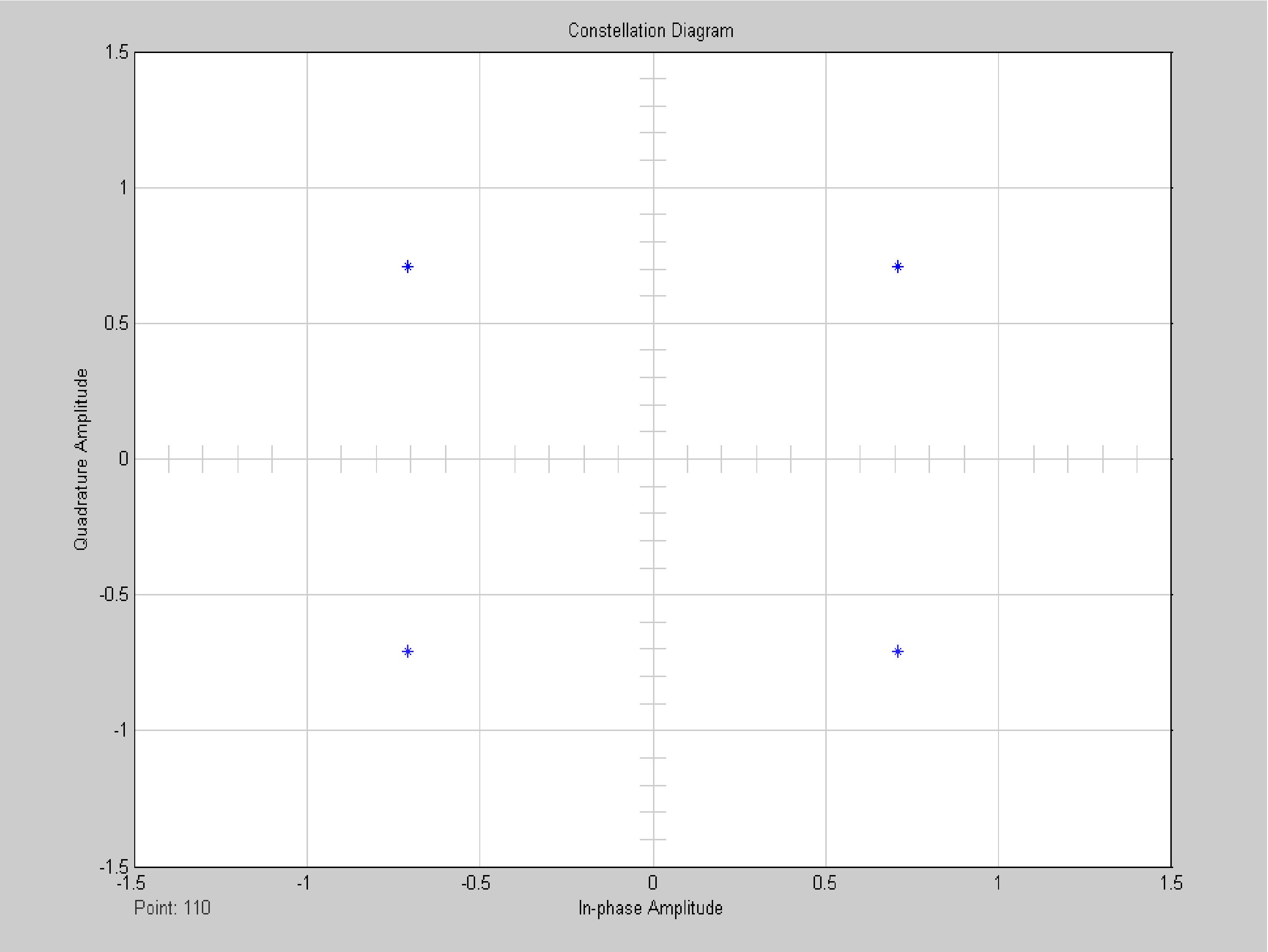


The output data generated was

- **Data transmitted**
- **QPSK wave transmitted**
- **Data received**



And the following constellation diagram was developed



2.8 Frequency Shift Keying (FSK)

FSK is a nonlinear method of passband data transmission. Frequency modulation and phase modulation are closely related. A staticfrequency shift of +1 Hz means that the phase is constantly advancing at the rate of 360 degrees per second (2 ≠ rad/sec), relative to the phase of the unshifted signal.
FSK (Frequency Shift Keying) is used in many applications including cordless and paging systems. Some of the cordless systems include DECT (Digital Enhanced Cordless Telephone) and CT2 (Cordless Telephone 2). In FSK, the frequency of the carrier is changed as a function of the modulating signal (data) being transmitted. Amplitude remains unchanged. In binary FSK (BFSK or 2FSK), a “1” is represented by one frequency and a “0” is represented by another frequency.

2.8.1 Binary FSK (BFSK)

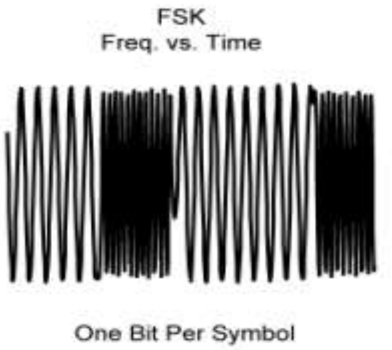
In a binary FSK system, 1 and 0 are distinguished from each other by transmitting one of two sinusoidal waves that differ in frequency by a fixed amount. A typical pair of sinusoidal waves is described by

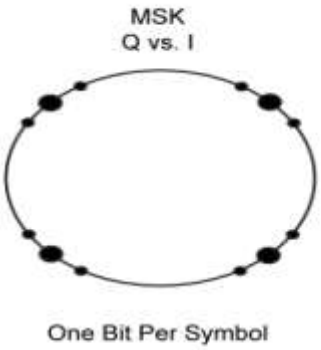
$$Si(t) = \begin{cases} \sqrt{\frac{2Eb}{Tb}}\ \cos(2\pi f_i t), & 0 \le t \le Tb \\ 0 & \text{, elsewhere} \end{cases}$$

Where i = 1,2, and Eb is the transmitted signal energy per bit; the transmitted frequency is

$f_i = (nc + i)/Tb$ for some fixed integer nc and i =1,2

Thus symbol S1(t) represents 1 and S2(t) represents 0.





2.8.2 Error probability for BFSK

The average probability of bit erroror,equivalently,the biterror rate, BER forBFSK is

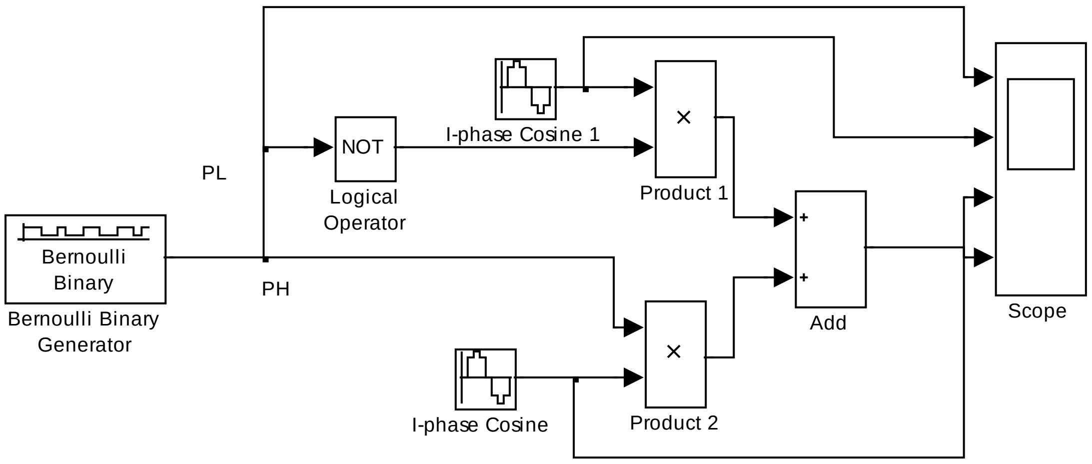
$$Pe = ½\ \mathrm{erfc}(\sqrt{Eb/2N0}\ )$$

Where, Eb and N0 stand for their usual meanings.

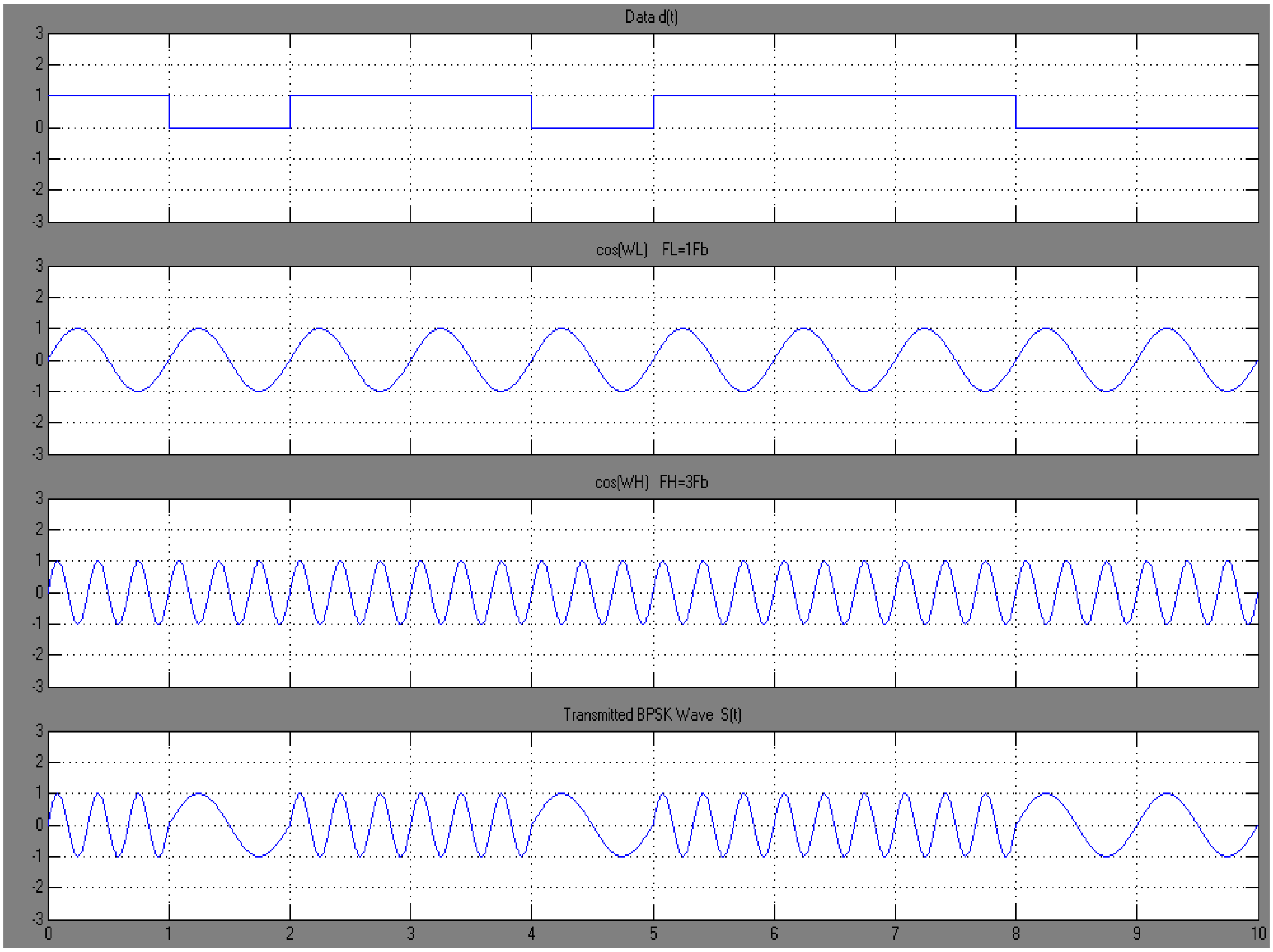
2.8.3 Simulation

To further the idea of BFSK, a SIMULINK model has been built and the required output has been generated. The model used was:

BFSK TRANSMITTER MODEL



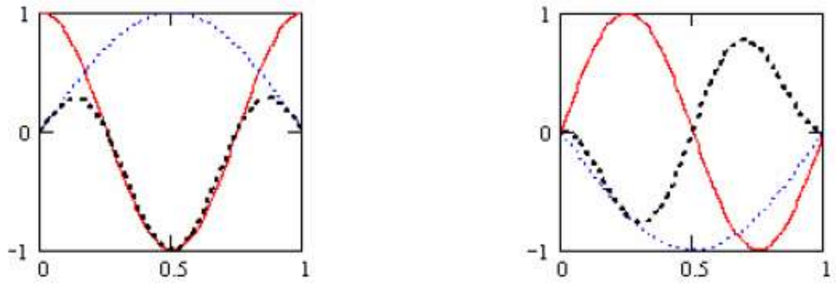
The following output was generated from the above model



2.9 Minimum Shift Keying (MSK)

Although MSK is often classified as FM modulation, t is also related to offset QPSK owing to the dual nature of FSK and PSK modulations. OQPSK is created from QPSK by delaying Q channel by half a symbol from I channel. This delay reduces the phase shifts the signal goes through at any one time and results in a an amplifier-friendly signal.

MSK can be derived from OQPSK by making one further change- OQPSK I and Q channels use square root raised cosine pulse. For MSK, change the pulse shape to a half cycle sinusoid. The figure below shows a MSK pulse signal and then multiplication by the carrier. The red curve is the carrier signal, and the blue in the MSK pulse shape and the black the multiplication of the pulse shape and the carrier giving the modulated carrier.



(a) MSK pulse and carrier for a 1 bit

(b) MSK pulse and carrier for a 0 bit

MSK pulse shaping is a half-sine wave shown in blue, positive for a 1 and negative for a 0.

The carrier signal expression for MSK is

$$c(t) = \underline{a(t)\sin\left(\frac{\pi}{2T}t\right)}\cos\left(\frac{\pi}{T}t\right) + \underline{a(t)\sin\left(\frac{\pi}{2T}t\right)}\sin\left(\frac{\pi}{T}t\right)$$

With the underlined portion, the half-sinusoid pulse shape. Since a frequency shift produces an advancing or retarding phase, frequency shifts can be detected by sampling phase at each symbol period. Phase shifts of (2N + 1) ≠/2 radians are easily detected with an *I/Q* demodulator. At even numbered symbols, the polarity of the *I* channel conveys the transmitted data, while at odd numbered symbols the polarity of the *Q* channel conveys the data. This orthogonality between *I* and *Q* simplifies detection algorithms and hence reduces power consumption in a mobile receiver. The minimum frequency shift which yields orthogonality of *I* and *Q* is that which results in a phase shift of ± ≠/2 radians per symbol (90 degrees per symbol). FSK with this deviation is called MSK (Minimum Shift Keying). The deviation must be accurate in order to generate repeatable 90 degree phase shifts. MSK is used in the GSM (Global System for Mobile Communications) cellular standard. A phase shift of +90 degreesrepresents a data bit equal to “1”, while –90 degrees represents a “0”. The peak-to-peak frequency shift of an MSK signal is equal to one-half of the bit rate.FSK and MSK produce constant envelope carrier signals, which have no amplitude variations. This is a desirable characteristic for improving the power efficiency of transmitters. Amplitude variations can exercise nonlinearities in an amplifier’s amplitude-transfer function, generating spectral regrowth, a component of adjacent channel power. Therefore, more efficient amplifiers (which tend to be less linear) can be used with constant-envelope signals, reducing power consumption.

MSK has a narrower spectrum than wider deviation forms of FSK. The width of the spectrum is also influenced by the waveforms causing the frequency shift. If those waveforms have fast transitions or a high slew rate, then the spectrum of the transmitter will be broad. In practice, the waveforms are filtered with a Gaussian filter, resulting in a narrow spectrum. In addition, the Gaussian filter has no time-domain overshoot, which would broaden the spectrum by increasing the peak deviation. MSK with a Gaussian filter is termed GMSK (Gaussian MSK).

2.10 Modulating a Random Signal

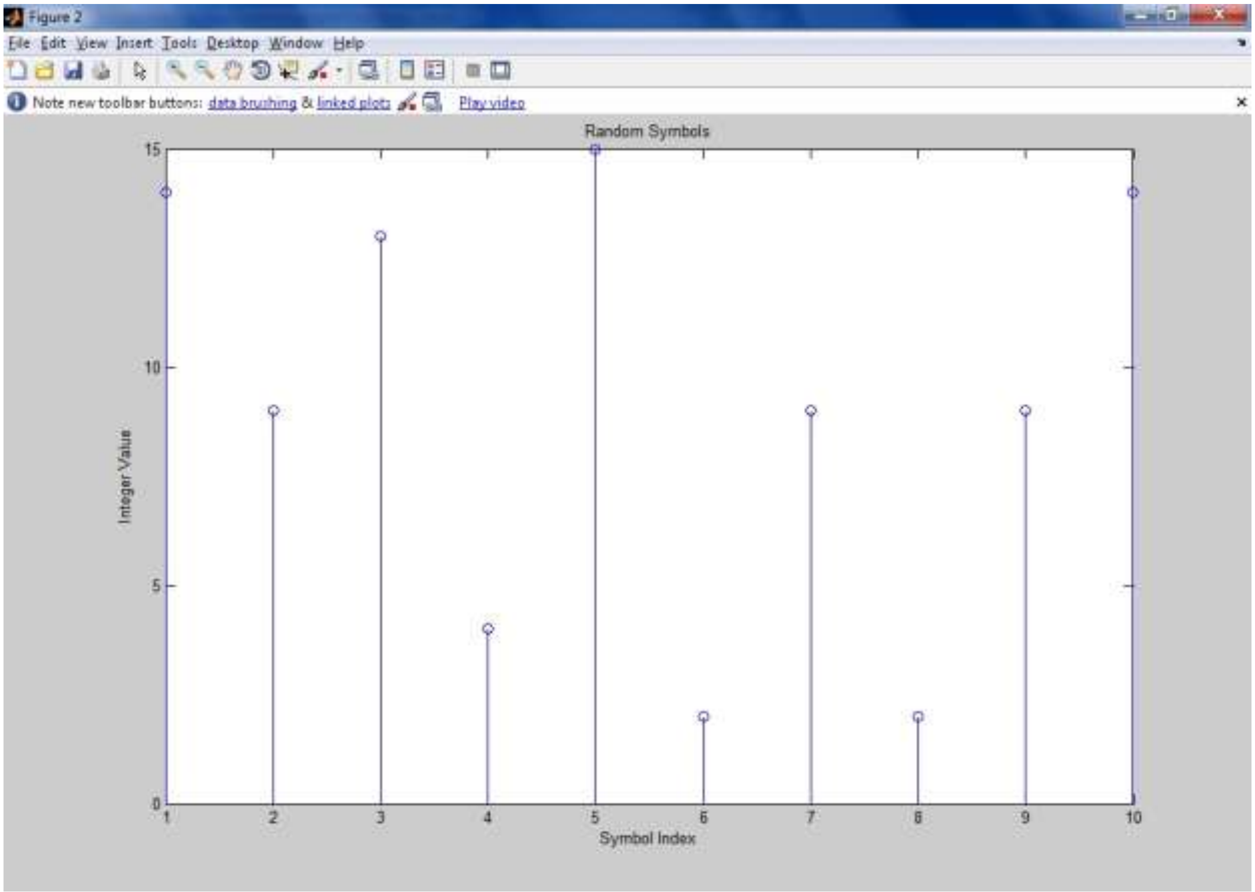
To give the reader thorough idea of modulation techniques and the know-how associated with it, we’ve tried to modulate and demodulate a random signal and obtained the following output diagrams. The scheme of modulation used is 16-QAM and was done using MATLAB.

```
%% Modulating a Random Signal


%% Setup
% Define parameters.
M = 16; % Size of signal constellation
k = log2(M); % Number of bits per symbol
n = 3e4; % Number of bits to process
nsamp = 1; % Oversampling rate

%% Signal Source
% Create a binary data stream as a column vector.
x = randint(n,1); % Random binary data stream

% Plot first 40 bits in a stem plot.
stem(x(1:40),'filled');
title('Random Bits');
xlabel('Bit Index'); ylabel('Binary Value');

%% Bit-to-Symbol Mapping
% Convert the bits in x into k-bit symbols.
xsym = bi2de(reshape(x,k,length(x)/k).','left-msb');

%% Stem Plot of Symbols
% Plot first 10 symbols in a stem plot.
figure; % Create new figure window.
stem(xsym(1:10));
title('Random Symbols');
xlabel('Symbol Index'); ylabel('Integer Value');

%% Modulation
% Modulate using 16-QAM.
y = modulate(modem.qammod(M),xsym);

%% Transmitted Signal
ytx = y;

%% Channel
% Send signal over an AWGN channel.
EbNo = 10; % In dB
snr = EbNo + 10*log10(k) - 10*log10(nsamp);
```

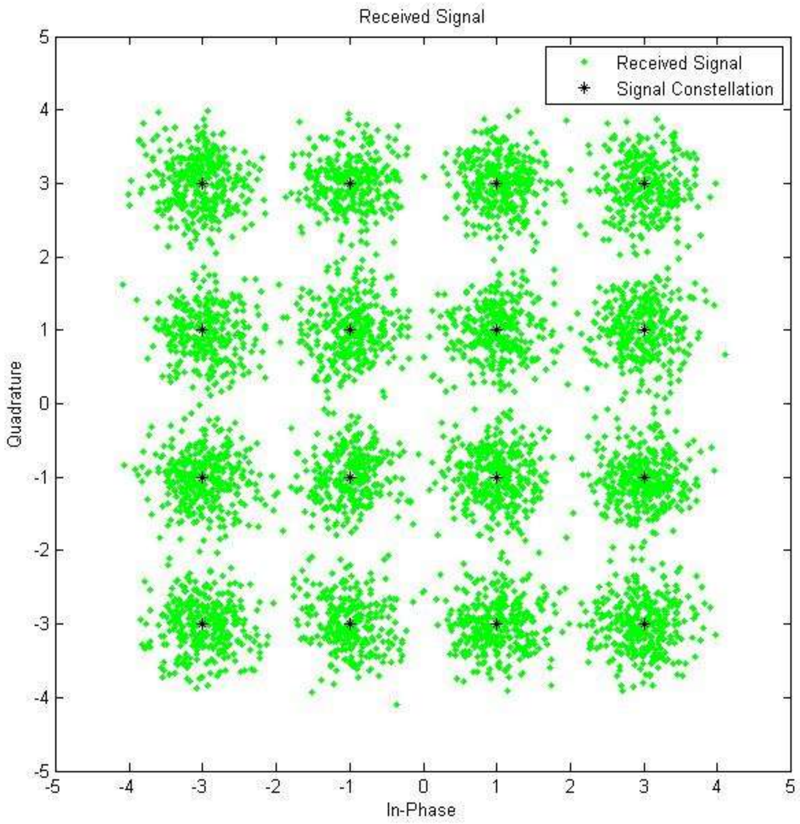
```
ynoisy = awgn(ytx,snr,'measured');

%% Received Signal
yrx = ynoisy;

%% Scatter Plot
% Create scatter plot of noisy signal and transmitted
% signal on the same axes.
h = scatterplot(yrx(1:nsamp*5e3),nsamp,0,'g.');
hold on;
scatterplot(ytx(1:5e3),1,0,'k*',h);
title('Received Signal');
legend('Received Signal','Signal Constellation');
axis([-5 5 -5 5]); % Set axis ranges.
hold off;

%% Demodulation
% Demodulate signal using 16-QAM.
zsym = demodulate(modem.qamdemod(M),yrx);

%% Symbol-to-Bit Mapping
% Undo the bit-to-symbol mapping performed earlier.
z = de2bi(zsym,'left-msb'); % Convert integers to bits.
% Convert z from a matrix to a vector.
z = reshape(z.',prod(size(z)),1);

%% BER Computation
% Compare x and z to obtain the number of errors and
% the bit error rate.
```

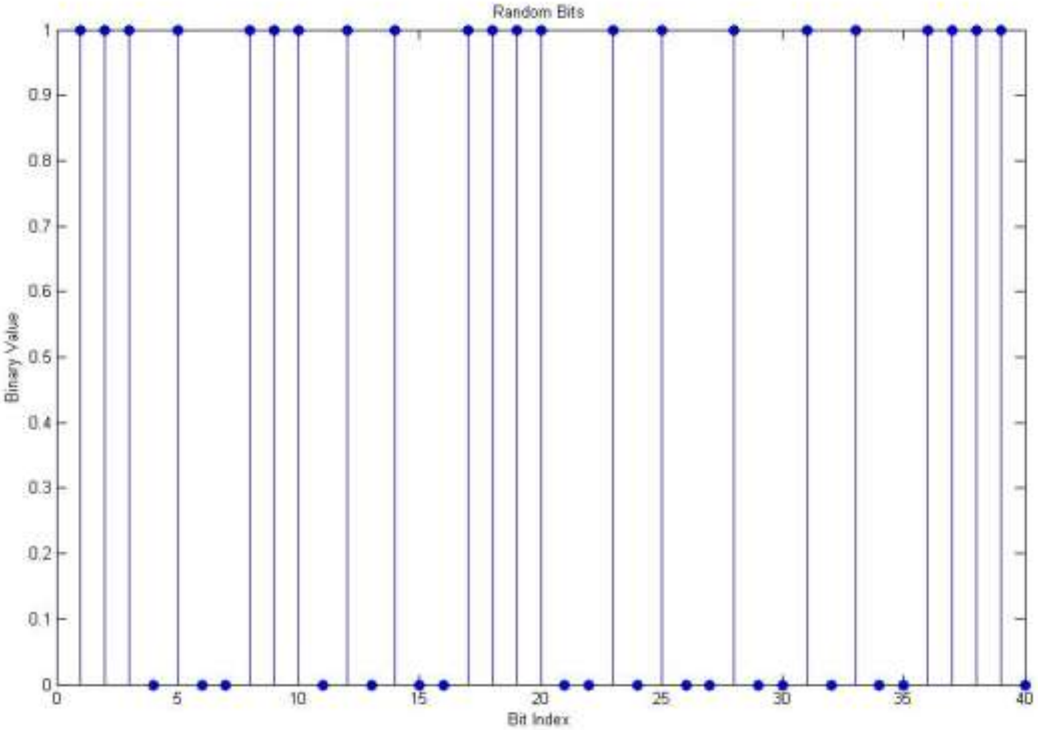
OUTPUT:

```
[number_of_errors,bit_error_rate] = biterr(x,z)


number_of_errors =


   68




bit_error_rate =


   0.0023


>>
```



Note new toolbar buttons: data brushing & linked plots Play video

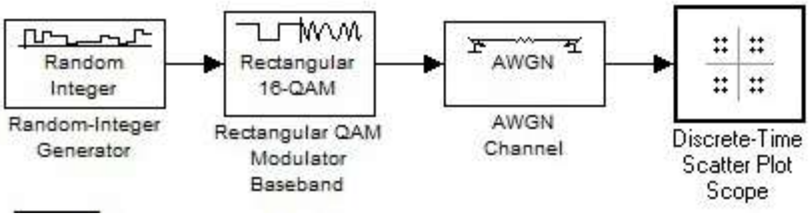

Received Signal
Received Signal
Signal Constellation
Quadrature
In-Phase
5
4
3
2
1
0
-1
-2
-3
-4
-5
-5
-4
-3
-2
-1
0
1
2
3
4
5

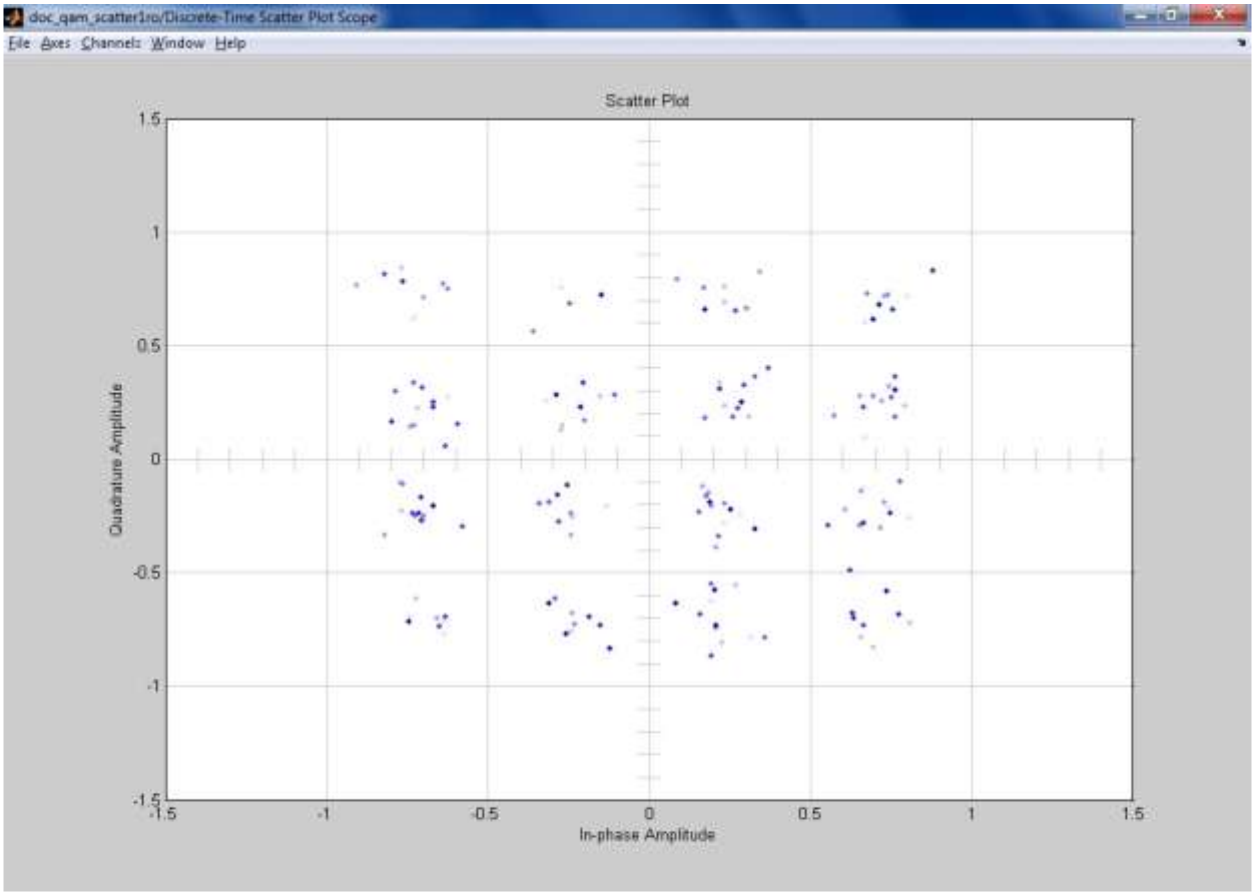

Random Bits
Binary Value
Bit Index
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40

QAM

ASK is also combined with PSK to create hybrid systems such as Quadrature Amplitude Modulation (QAM) where both the amplitude and the phase are changed at same time.

Below is an example of the QAM modulation scheme utilized to obtain the scatter diagram (also shown below).



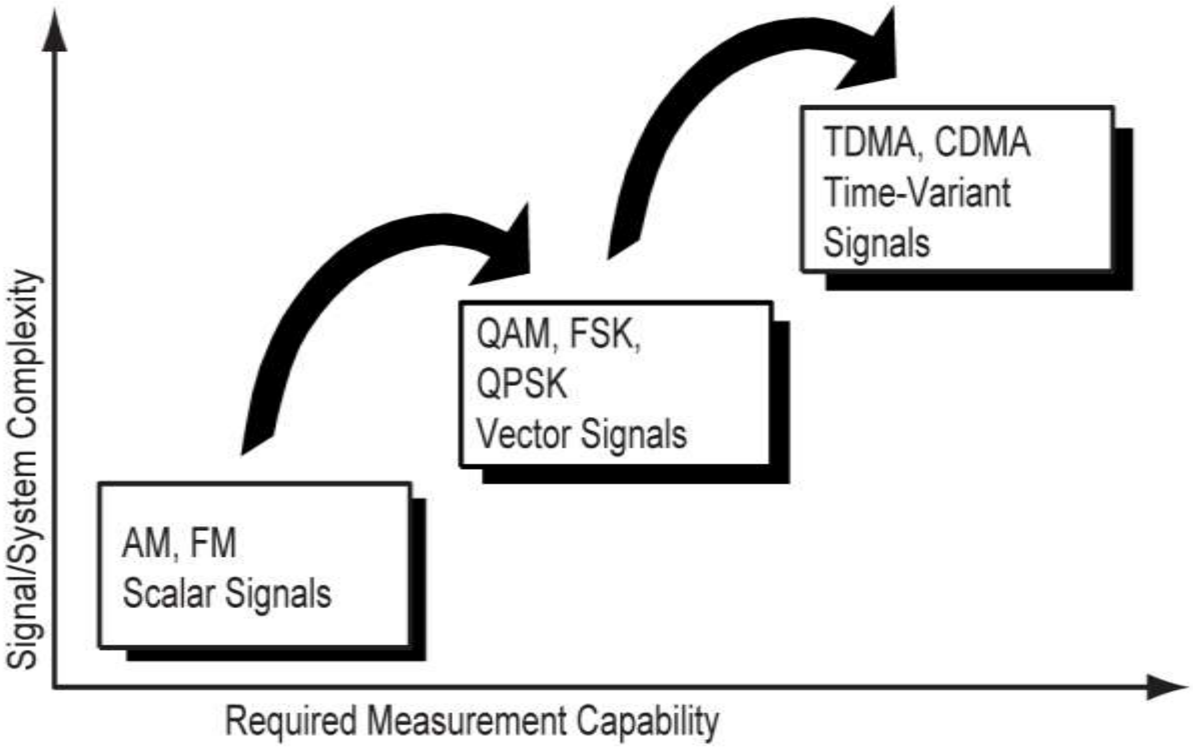


CHAPTER 3

3.1 Industry trends

Over the past few years a major transition has occurred from simple analog Amplitude Modulation (AM) and Frequency/Phase Modulation (FM/PM) to new digital modulation techniques. Examples of digital modulation include

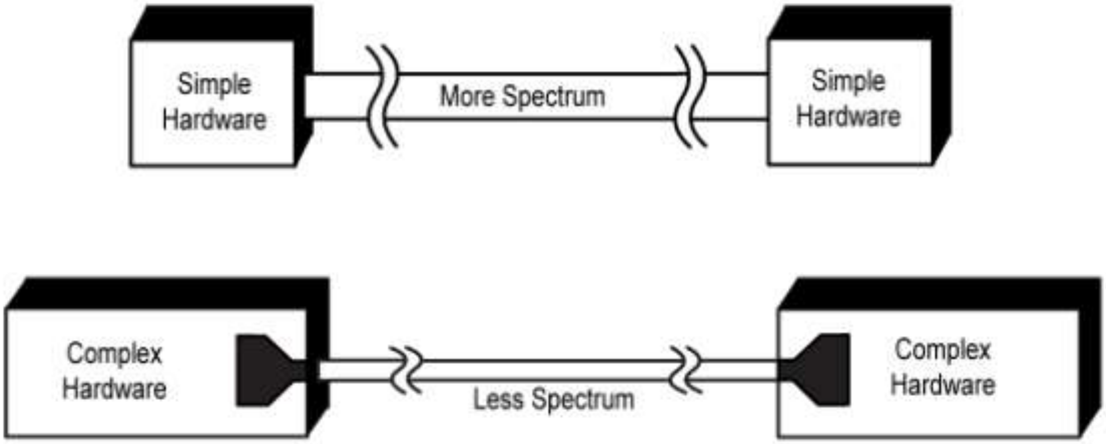
- QPSK (Quadrature Phase Shift Keying)
- FSK (Frequency Shift Keying)
- MSK (Minimum Shift Keying)
- QAM (Quadrature Amplitude Modulation)



Another layer of complexity in many new systems is multiplexing. Two principal types of multiplexing (or “multiple access”) are TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access). These are two different ways to add diversity to signals allowing different signals to be separated from one another.

3.2 Trading off simplicity and bandwidth

There is a fundamental tradeoff in communication systems. Simple hardware can be used in transmitters and receivers to communicate information. However, this uses a lot of spectrum which limits the number of users. Alternatively, more complex transmitters and receivers can be used to transmit the same information over less bandwidth. The transition to more and more spectrally efficient transmission techniques requires more and more complex hardware. Complex hardware is difficult to design, test, and build. This tradeoff exists whether communication is over air or wire, analog or digital.



3.3 Modern Modulation Systems used in Radios

The basic modem communication system comprises a large array of mobile equipments into a wireless network. The communication between all these equipment is regulated by various IEEE standards, depending on the type of wireless network in which they are connected. In order to simplify the communication, the latest developments in standardization point to a software reconfigurable hardware solution for the radio front-end. The best example is the latest wireless standard, IEEE 802.16 - WiMAX. This standard requires almost all digital modulation schemes (QPSK, QAM-16 and QAM-64) on OFDMA carrier support. Also, the radio channel bandwidth is variable starting with 1.75 MHz up to 20 MHz. Moreover, the center frequency varies from country to country, depending on local regulations.

The hardware system that allows such a high degree of software re-configurability bears the name of Software Defined Radio (SDR)

Hence, it is of utmost importance that digital modulation techniques are properly understood with respect to the SDR concept. This implies defining a figure of merit that characterizes the performance of the modulation technique. As it becomes more complex the bit-rates increase, but it becomes more difficult to properly demodulate the signal. This phenomenon can be quantified by analyzing the Bit Error Rate versus Signal-to-Noise Ratio. The modem wireless applications require more and more information to be transmitted over the medium in a shorter time interval. Therefore, higher bit-rates are needed. The bit-rate Br is given by

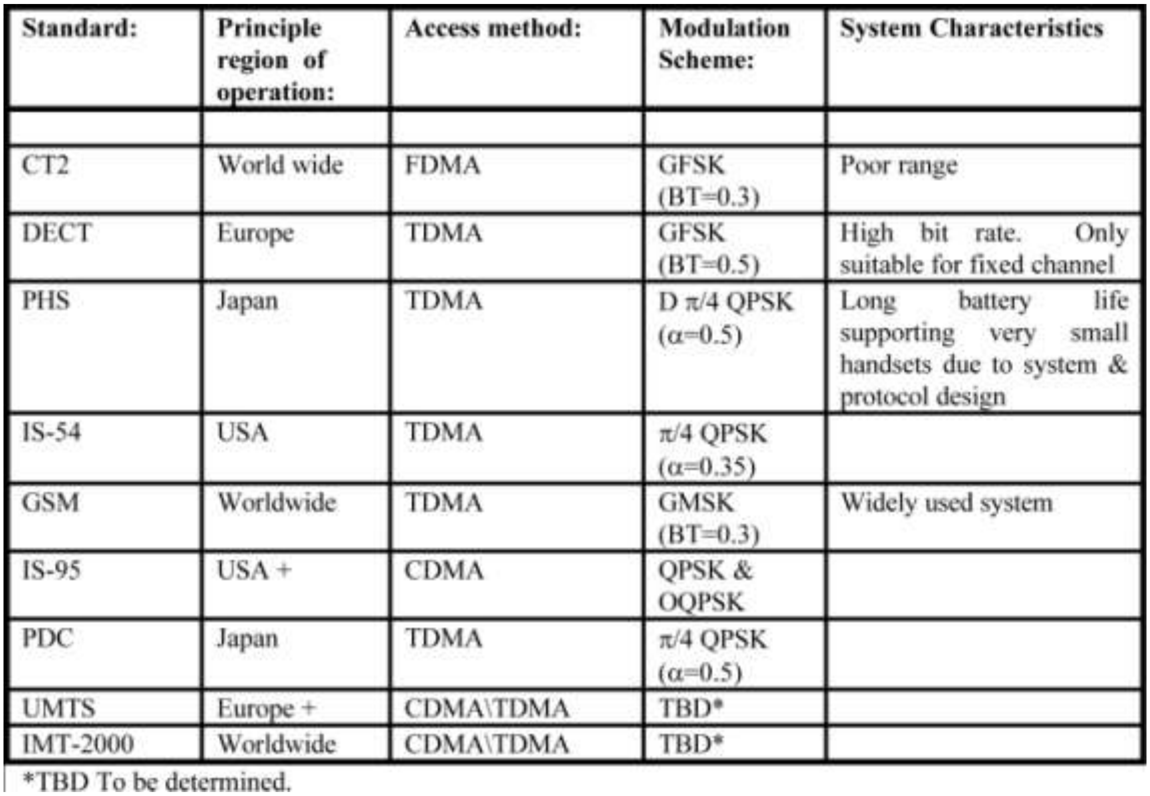
$B_r = S_r \text{ X } bps$,

where S_r is the symbol rate and bps represents the number of bits per symbol.

3.4 Spectral efficiency example in practical radios

An example is a microwave digital radio using 16QAM. This kind of signal is more susceptible to noise and distortion than something simpler such as QPSK. This type of signal is usually sent over a direct line-of-sight microwave link or over a wire where there is very little noise and interference. In this microwave-digital-radio example the bit rate is 140 Mbits per second over a very wide bandwidth of 52.5 MHz. The spectral efficiency is 2.7 bits per second per Hz. To implement this, it takes a very clear line-of-sight transmission path and a precise and optimized high-power transceiver

Summary of Current and Proposed Digital Mobile and Cellular Systems



Standard:	**Principle region of operation:**	**Access method:**	**Modulation Scheme:**	**System Characteristics**
CT2	World wide	FDMA	GFSK (BT=0.3)	Poor range
DECT	Europe	TDMA	GFSK (BT=0.5)	High bit rate. Only suitable for fixed channel
PHS	Japan	TDMA	D π/4 QPSK (α=0.5)	Long battery life supporting very small handsets due to system & protocol design
IS-54	USA	TDMA	π/4 QPSK (α=0.35)	
GSM	Worldwide	TDMA	GMSK (BT=0.3)	Widely used system
IS-95	USA +	CDMA	QPSK & OQPSK	
PDC	Japan	TDMA	π/4 QPSK (α=0.5)	
UMTS	Europe +	CDMA\TDMA	TBD*	
IMT-2000	Worldwide	CDMA\TDMA	TBD*	

*TBD To be determined.

References

[1] *J. G. Smith***,** “Spectrally efficient modulation,” in Proc. IEEE Int. Conf. Commun. (ICC ’77), June 1977, pp. 3.1-37-3.1-41.

[2] Feher; Applications of Digital Wireless Technologies to Global Wireless Communications; Prentice Hill1997; ISBN 0-13-214272-4.

[3] Lawrence E Larson; RF and Microwave Circuit Design for Wireless Communications; Artech House; 1996; ISBN 0-89006-818-6.

[5] *de Buda,R., ‘A Comparison of Two Digital Modulation Techniques’,* IEEE Trans. on Communications, CO1.1-20, pp 429-335.

[6] Langton, C., “All About Modulation”, Pearson Publications, ‘99