**BSc in Computer Engineering**
**CMP4204**
**Wireless Technologies**

# Lecture 3

# Digital Modulation

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# 1. Introduction

Radio Modulation techniques involve the addition of information to an electronic carrier Radio Frequency (RF) signal. A carrier signal is one with a steady waveform constant height (amplitude) and frequency.

Information can be added to the RF carrier by varying its amplitude, frequency, phase or polarisation and this information can be recovered by a process of de-modulation at the receiving end.

# 2. Modulation

Modulation describes a range of techniques for encoding information on a carrier signal, typically a sine-wave signal. A device that performs modulation is known as a modulator. We have already seem Amplitude Modulation (AM) and Frequency Modulation (FM) and Single SideBand Modulation (SSB) in lecture 1 so this lecture will focus on digital modulation techniques.

Modulation techniques include:

- Amplitude Modulation (AM)
- Frequency Modulation (FM)
- Single SideBand Modulation (SSB)
- **Pulse Code Modulation (PCM)**
- **Amplitude Shift Keying (ASK)**
- **Frequency Shift Keying (FSK)**
- **Phase Modulation (PM)**
- **Phase Shift Keying (PSK)**
- **Quadrature Amplitude Modulation (QAM)**

# 3. Pulse Code Modulation (PCM)

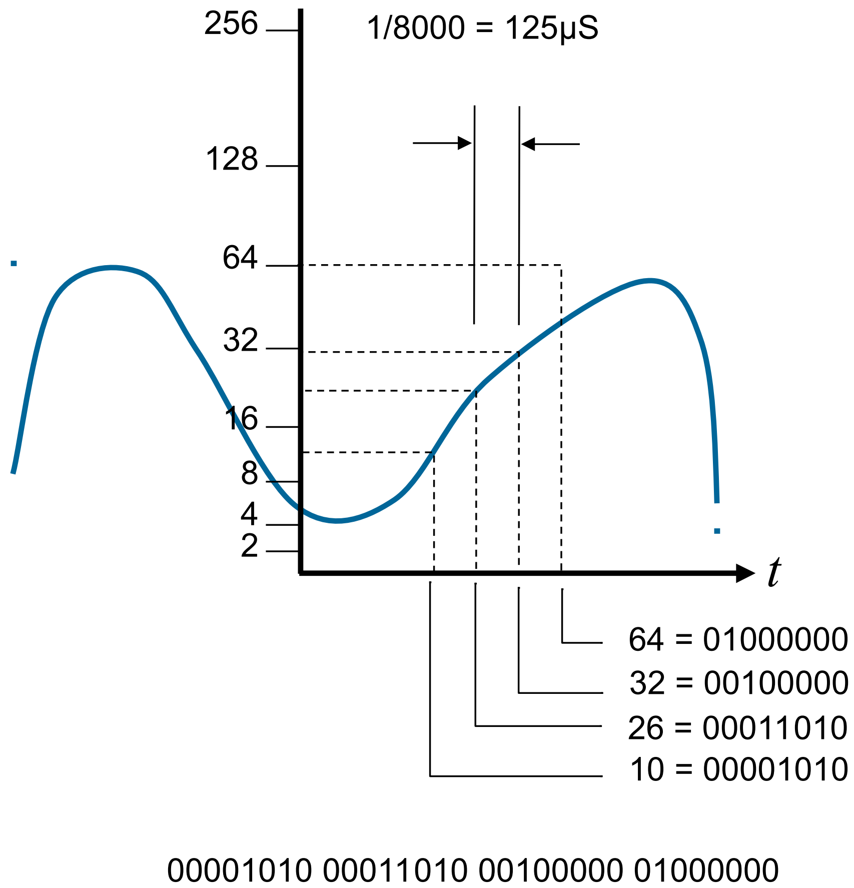


**Illustration 1: Pulse Code Modulation (PCM)**

Pulse Code Modulation (PCM) is a digital representation of an analogue signal. It is not a modulation of the same type as those we have just looked at as they carried an analogue signal on an analogue carrier. In this case we carry an analogue signal in digital form.

The signal is sampled at a sampling frequency ($f_s$). This means the value of the signal, a sample, is captured at uniform distances ($T = 1/f_s$). Every sample is quantised to a series of symbols in a code in which there are a discrete number of possible symbol values. Where the number of possible values is two, the code is said to be a binary code. The sampling rate is governed by Nyquist Theorem which states that

> "*Converting from an analogue signal to digital, the sampling frequency must be greater than twice the highest frequency of the input signal in order to be able reconstruct the original perfectly from the sampled version*".

If the sampling frequency is less than this limit, then frequencies in the original signal that are above half the sampling rate will be *aliased* and will appear in the resulting signal as lower frequencies. Therefore, an analogue low-pass filter is typically applied before sampling to ensure that no components with frequencies greater than half the sample frequency remain. This is called an "anti-aliasing filter".

The theorem also applies when reducing the sampling frequency of an existing digital signal.

PCM is used in digital telephone systems or for digital audio recording on Compact Disc (CD).

## 4. Digital Modulation in radio

Developers of communications systems face constraints like the limited available bandwidth. The RF spectrum must be shared between all users, the limited permissible power in the desired frequency range and of course the inherent noise level of the system.

Digital modulation schemes have greater capacity to provide large amounts of information than analogue modulation schemes ensuring more information capacity, compatibility with digital data services, higher security, better quality communications, more rapid system availability.

Analogue systems use a lot of spectrum to transmit/receive information, limiting the number of users but by more complex hardware could be used to transmit/receive the same information over less bandwidth in digital systems. The disadvantage traditionally has been that complex hardware is difficult to design, test, and build. This is the so called “simplicity/ bandwidth trade off”.

The only difference between analogue modulation and digital modulation is that digital modulation restricts the modulating baseband signal to discrete states rather than allowing the modulating signal to take on any value between a maximum and a minimum value.

When AM, FM or PM are used in a digital modulation scheme the names become Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK) and Phase Shift Keying (PSK). The shift keying term derived from the telegraph key. The modern use implies shifting between discrete states.

## 4.1 Amplitude Shift Keying (ASK)

Amplitude-shift keying (ASK) is a form of modulation that represents digital data as variations in the amplitude of a carrier wave.

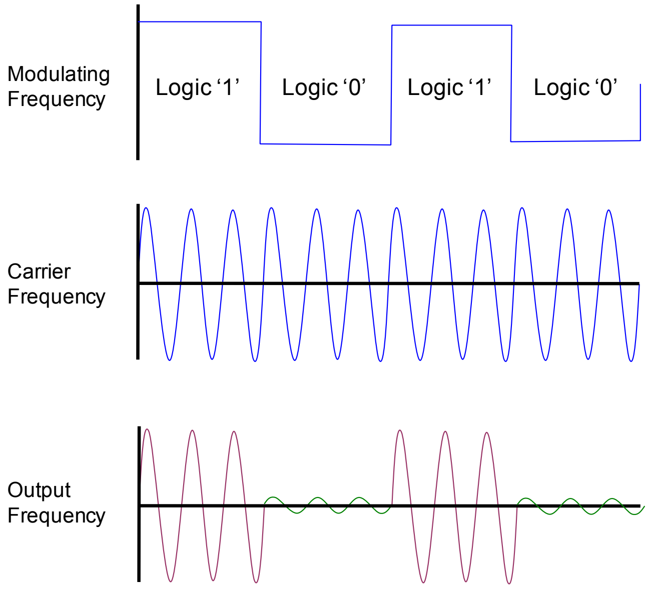


**Illustration 2: Amplitude Shift Keying**

The amplitude of an analogue carrier signal varies in accordance with the bit stream (modulating signal), keeping frequency and phase constant. The level of amplitude can be used to represent binary logic '0's and '1's. We can think of a carrier signal as an ON or OFF switch. In the modulated signal, logic '0' is represented by the absence of a carrier, thus giving OFF/ON keying operation and hence the name given.

Like AM, ASK is also linear and sensitive to atmospheric noise, distortions, propagation conditions on different paths. Both ASK modulation and demodulation processes are relatively inexpensive. The ASK technique is also commonly used to transmit digital data over optical fibre. For Light Emitting Diode (LED) transmitters, binary '1' is represented by a short pulse of light and binary '0' by the absence of light. Laser transmitters normally have a fixed "bias" current that causes the device to emit a low light level. This low level represents binary '0', while a higher-amplitude light wave represents binary '1'.

In Illustration 3 we see the Binary ASK (BASK) modulator. It is supplied with a carrier type signal $A_c cos(\omega_c t)$ [1] and the modulating signal is $x_{BB}$ which is varying between 'High' or 'Low', '1' or '0'. The modulator basically turns on or off the carrier at the rate of the modulating signal such that the output $x_{BASK}\ (t)$ equals $A_c[m x_{BB}] cos(\omega_c t)$. The '*m*' is the modulation index or modulation depth and it describes by how much the modulated variable of the carrier signal varies around its unmodulated level, in this case it is '1'.

[1] $\omega = 2\pi f$ = Angular Velocity

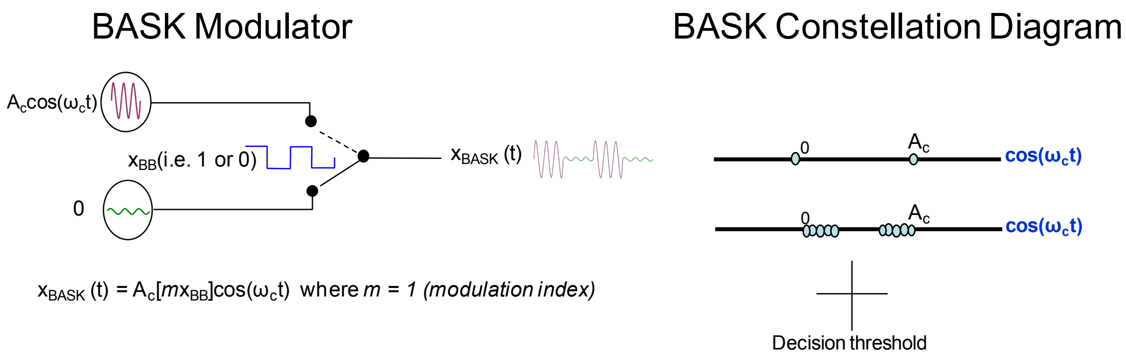


**Illustration 3: BASK Modulator**

The BASK constellation diagram is thus quite simple. With ‘Low’ being represented by ‘0’ and ‘High’ by $A_c cos(\omega_c t)$.

The distance between the points in a constellation is an indication of robustness of the modulated signal to noise.

The decision threshold should be at $A_c/2$ in order to reduce the Bit Error Rate (BER).

## 4.2 Frequency Shift Keying (FSK)

Frequency Shift Key (FSK) is a method of transmitting digital signals. The two binary states, logic ‘0’ (low) and ‘1’ (high), are each represented by an analogue waveform. Logic ‘0’ is represented by a wave at a specific frequency, and logic ‘1’ is represented by a wave at a different frequency. A modem converts the binary data from a computer to FSK for transmission over telephone lines, cables, optical fibre, or wireless media. The modem also converts incoming FSK signals to digital low and high states for the receiving computer.

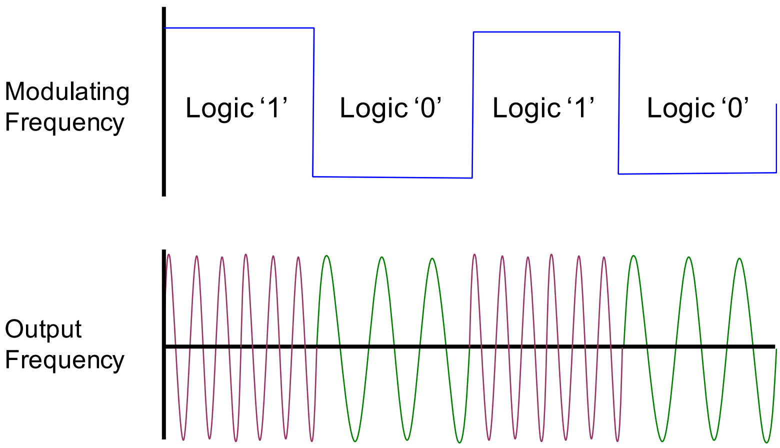


**Illustration 4: Frequency Shift Keying (FSK)**

FSK was introduced for use with mechanical teleprinters in the mid-1900s. The standard speed of those machines was 45 baud, equivalent to about 45 bits per second. When personal computers became common and networks came into being, this signalling speed was too low. During the 1970s, modems were developed that ran at faster speeds and the quest for ever greater bandwidth has continued ever since.

Today, a standard telephone modem operates at thousands of bits per second. Cable, Digital Subscriber Line (DSL) and wireless modems work at megabit speeds and optical fibre modems function at many Mbps. But the basic principle of FSK has not changed over time.

Here we can see the Binary FSK (BFSK) modulator. It is supplied with two signals at different frequencies $A_c cos(\omega_{c1}t)$ and $A_c cos(\omega_{c2}t)$. The modulating signal is $x_{BB}$ which is varying between 'High' or 'Low', '1' or '0'. The modulator basically turns on whichever frequency that maps to the bit such that the output $x_{BFSK}$ $(t)$ equals either $A_c$ $cos(\omega_{c1}t)$ or $A_c$ $cos(\omega_{c2}t)$. As we now have two separate frequencies the BFSK constellation diagram shows these as separate vectors as shown in Illustration 5.

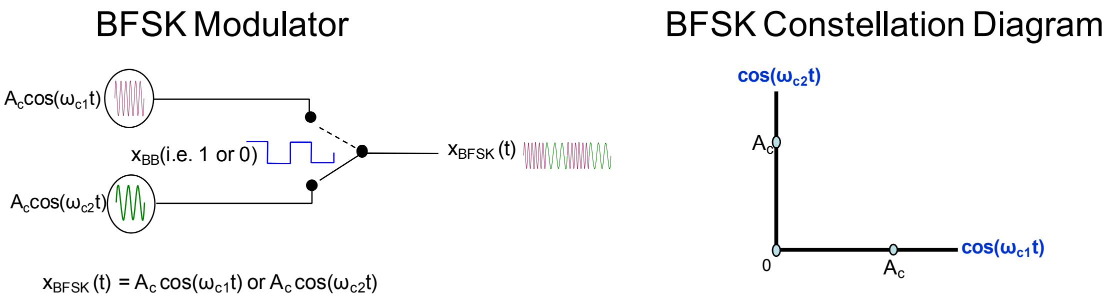


**Illustration 5: Frequency Shift Keying (FSK)**

## 4.3 Phase Modulation

In lecture 1 AM was described as the modulation of the carrier ($f_c$) amplitude by the modulating signal ($f_s$) while in FM the frequency of $f_c$ was modulated by $f_s$. Another characteristic of the $f_c$ that can be modulated is *phase*. If the instaneous phase of $f_c$ is altered by $f_s$ it is possible to recover the modulating signal at a receiver much the same as for AM and FM.

## 4.4 Phase Shift Keying (PSK)

Phase Shift Key (PSK) is a digital modulation scheme that conveys data by changing, or modulating, the phase of a reference signal (the carrier wave).

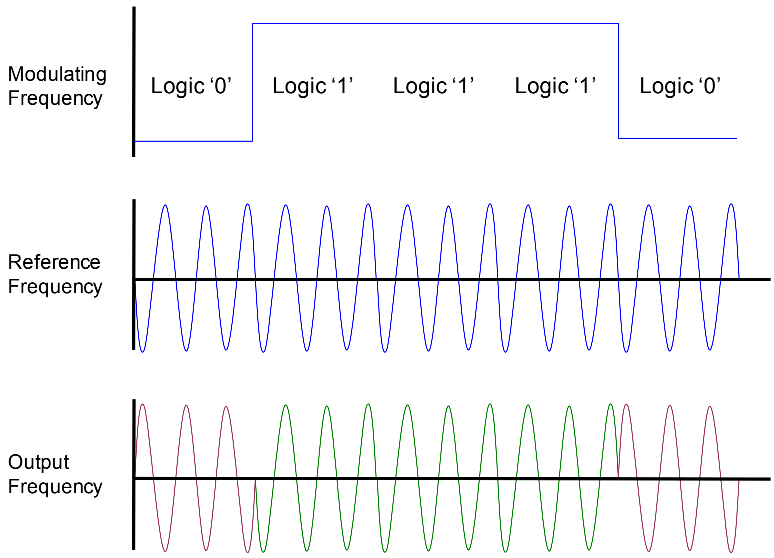


**Illustration 6: Phase Shift Keying (PSK)**

Any digital modulation scheme uses a finite number of distinct signals to represent digital data. PSK uses a finite number of phases, each assigned a unique pattern of binary bits. Usually, each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase. The demodulator, which is designed specifically for the symbol-set used by the modulator, determines the phase of the received signal and maps it back to the symbol it represents, thus recovering the original data. This requires the receiver to be able to compare the phase of the received signal to a reference signal. Such a system is termed coherent.

### 4.4.1 Differential Phase Shift Keying (DPSK)

DPSK can be significantly simpler to implement than ordinary PSK since there is no need for the demodulator to have a copy of the reference signal to determine the exact phase of the received signal (it is a non-coherent scheme). In exchange, it produces more erroneous demodulations. The exact requirements of the particular scenario under consideration determine which scheme is used.

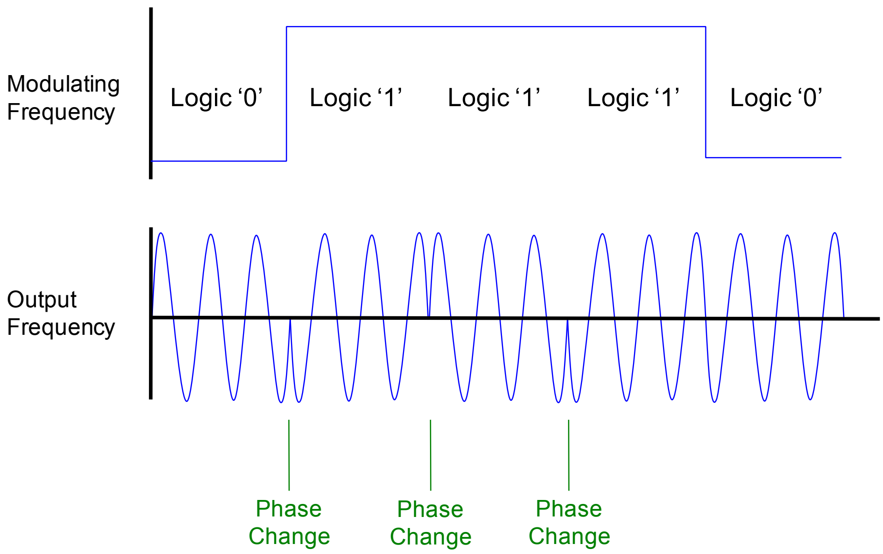


**Illustration 7: Differential Phase Shift Keying (DPSK)**

Alternatively, instead of using the bit patterns to set the phase of the wave, it can instead be used to change it by a specified amount. The demodulator then determines the changes in the phase of the received signal rather than the phase itself. Since this scheme depends on the difference between successive phases. DPSK can be significantly simpler to implement than ordinary PSK since there is no need for the demodulator to have a copy of the reference signal.

Basically the receiver compares the phase of the current digit to that of the previous digit, if they are the same then the digit is considered to be a '0' but if the phase changes the digit is considered to be a '1'.

In the diagram below we see the Binary PSK (BPSK) modulator. It is supplied with a carrier type signal $A_c cos(\omega_c t)$ in two phases 180° apart. The modulating signal is $x_{BB}$ which is varying between 'High' or 'Low', '1' or '0'. The modulator selects the required phase at the rate of the modulating signal such that the output $x_{BPSK}\ (t)$ equals $A_c\, cos[\omega_c t + \Phi]$ where $\Phi = 0 \text{ or } 180°$.

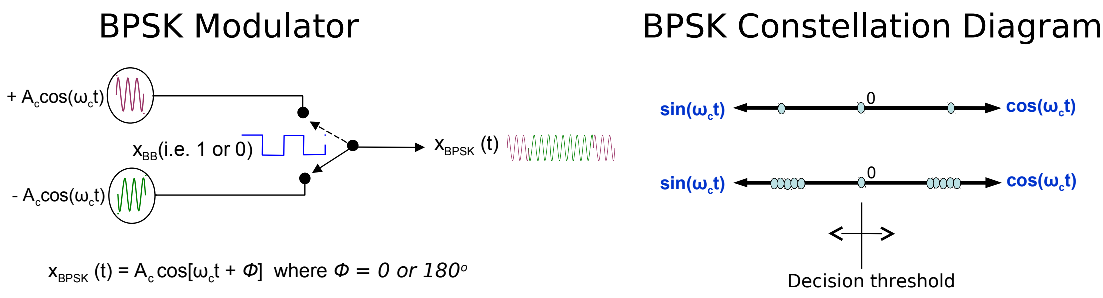


**Illustration 8: BPSK Modulator**

The BPSK constellation diagram is also quite simple, 'Low' being represented by $-A_c cos(\omega_c t)$ and 'High' by $+A_c cos(\omega_c t)$.

The decision threshold is chosen such that the distance between "high" and "low" states in the constellation diagram is the largest, determining a minimum Bit Error Rate (BER).

### 4.4.2 Quadrature Phase Shift Keying (QPSK)

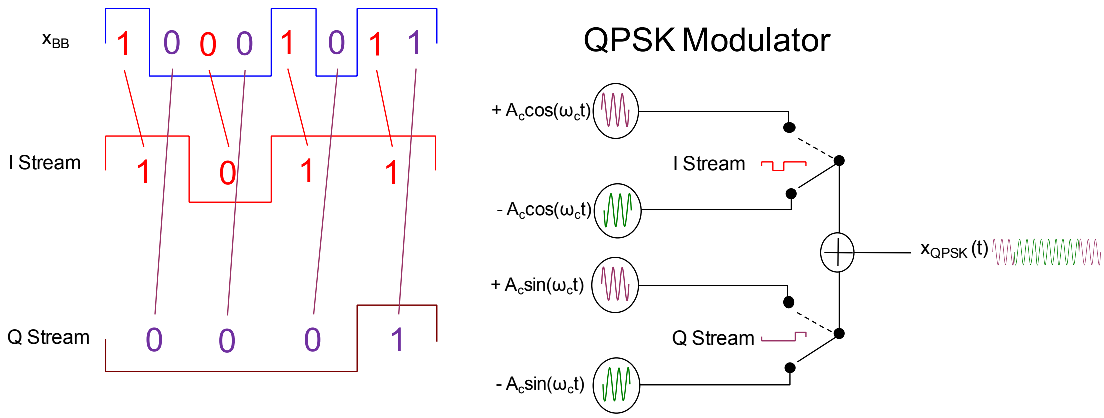


**Illustration 9: Quadrature PSL (QPSK) Modulator**

Quadrature PSK or 4-PSK, QPSK uses four points on the constellation diagram. With four phases, QPSK can encode two bits per symbol, shown in the diagram below to minimise the Bit Error Rate (BER) or twice the rate of BPSK. Analysis shows that this may be used either to double the data rate compared to a BPSK system while maintaining the bandwidth of the signal or to maintain the data-rate of BPSK but halve the bandwidth needed.

Although QPSK can be viewed as a quaternary modulation, it is easier to see it as two independently modulated quadrature carriers. With this interpretation $x_{BB}$ is split into two streams, I and Q with one used to modulate the in-phase component of the carrier, while the other used to modulate the quadrature-phase component of the carrier. BPSK is used on both carriers and they can be independently demodulated.

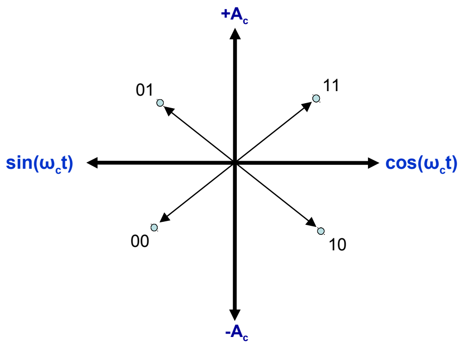


**Illustration 10: QPSK**

### 4.4.3 Quadrature Differential Phase Shift Keying (QDPSK)

Quadrature Differential Phase Shift Keying (QDPSK) sometimes coined Differential Quadrature Phase Shift Keying (DQPSK) is similar to QPSK except that for each of the streams I and Q DPSK is implemented instead of PSK.

In QDPSK, the phase-shifts are 0°, 90°, 180°, -90° corresponding to data '00', '01', '11', '10'. This kind of encoding may be demodulated in the same way as for non-differential PSK but the phase ambiguities can be ignored. Thus, each received symbol is demodulated to one of the M points in the constellation and a comparator then computes the difference in phase between this received signal and the preceding one. The difference encodes the data as described above.

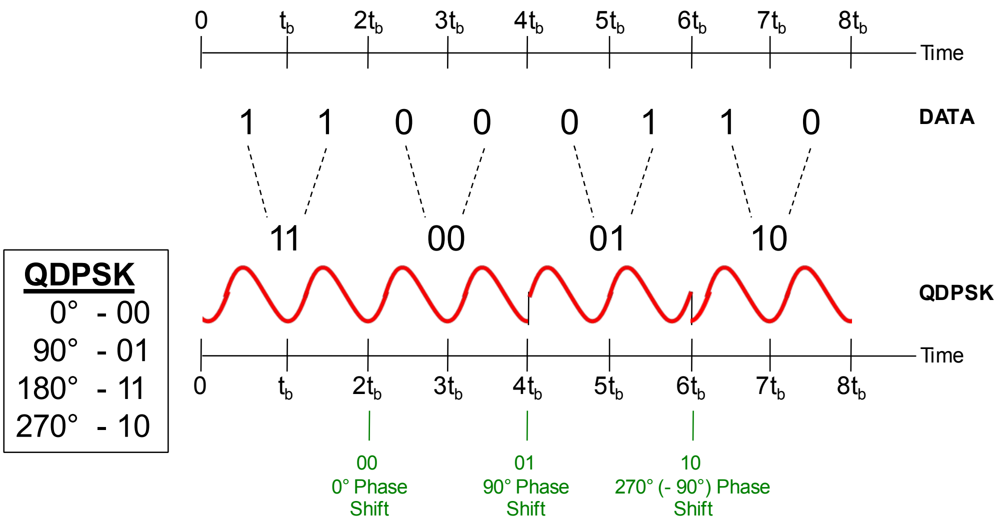


**Illustration 11: Quadrature Differential PSK (QDPSK)**

The modulated signal is shown in Illustration 11 for QDPSK as described above. It is assumed that the signal starts with zero phase, and so there is a phase shift in the signal at $t = 0$.

## 4.5 Quadrate Amplitude Modulation (QAM)

| Bit value | Amplitude | Phase shift |
|---|---|---|
| 0000 | 2 | 0° (360°) |
| 0001 | 1 | 0° (360°) |
| 0010 | -2 | 0° (360°) |
| 0011 | -1 | 0° (360°) |
| 1100 | 2 | 90° |
| 1101 | 1 | 90° |
| 1110 | -2 | 90° |
| 1111 | -1 | 90° |
| 1000 | 2 | 180° |
| 1001 | 1 | 180° |
| 1010 | -2 | 180° |
| 1011 | -1 | 180° |
| 0100 | 2 | 270° (-90°) |
| 0101 | 1 | 270° (-90°) |
| 0110 | -2 | 270° (-90°) |
| 0111 | -1 | 270° (-90°) |

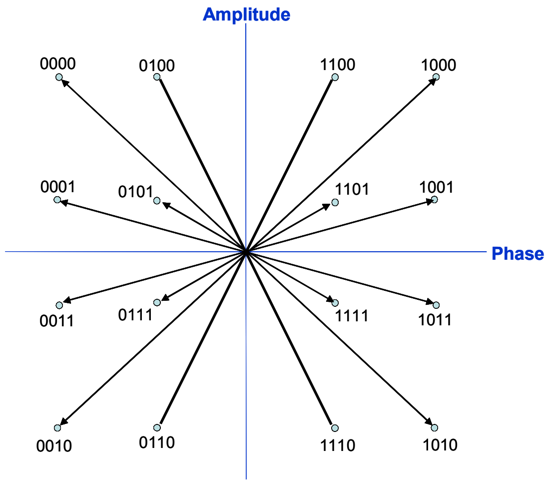


**Illustration 12: Quadrature Amplitude Modulation (QAM)**

QAM conveys data by changing both the amplitude and the phase of the signal to give a number of unique signals. In the example above 16QAM using 4 phase shifts and 4 amplitudes we have 16 unique signal types, each of which can represent 4 bits per line ($2^4=16$).

There are four I values and four Q values and therefore 16 possible states for the signal. It can transition from any state to any other state at every symbol time. Since 16 = $2^4$, four bits per symbol can be sent; this consists of two bits for I and two bits for Q. The symbol rate is one fourth of the bit rate and it is more efficient than BPSK and QPSK.

Note that QPSK is the same as 4QAM.

QAM also operates at 32QAM, 64QAM, 128QAM and 256QAM. These can be seen compared in Illustration 13 where the increasing levels of complexitity are there to see.

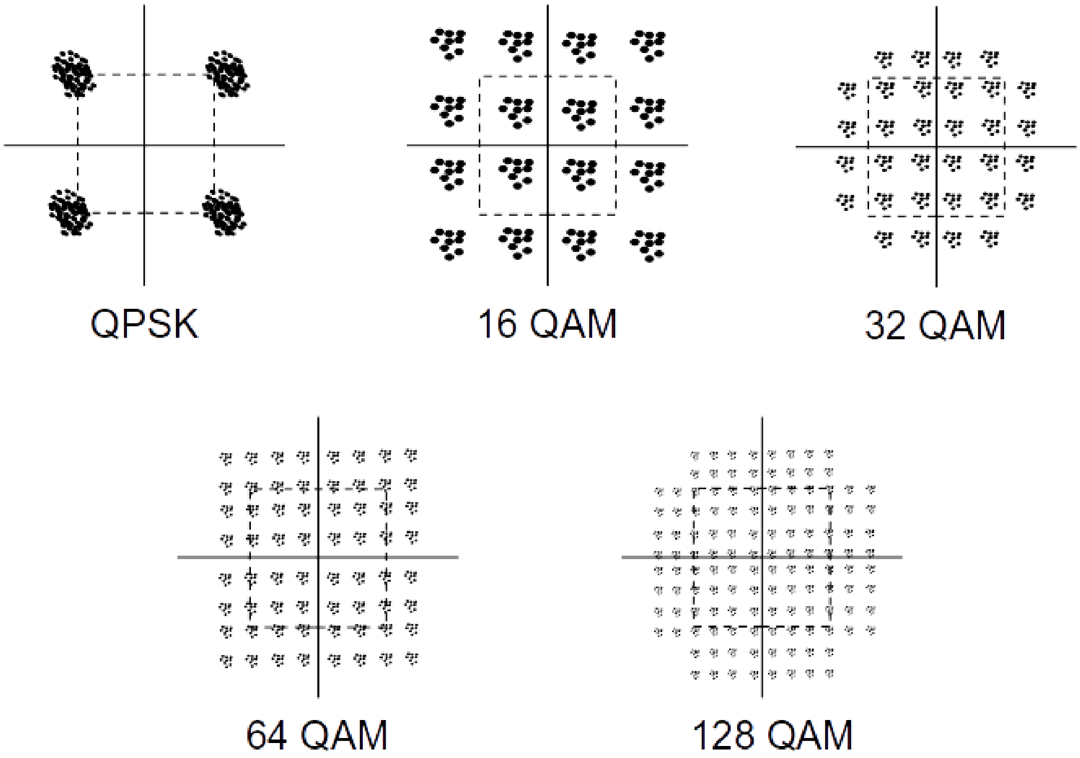


**Illustration 13: Constellation patterns**

# 5. Information/Bit Rate

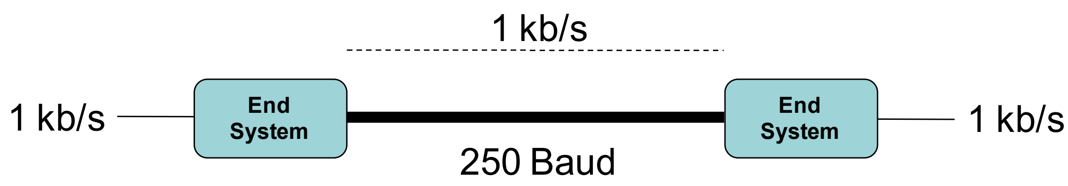


**Illustration 14: Information Bit Rate**

The average number of end user bits transferred per second, in one direction. It is the frequency of a system bit stream. In the diagram above the Information rate is 1kb/s.

## 5.1 Signalling/Symbol Rate

The number of times per second the amplitude, frequency or phase of the signal transmitted down a communications channel changes each second.

The symbol rate is the gross bit rate, inclusive of channel coding overhead, divided by the number of bits transmitted in each symbol. Symbol rate is measured in symbols per second, hertz (Hz), or baud (Bd).

$$\textit{Symbol rate} = \frac{\textit{Bit rate}}{\textit{Number of bits transmitted with each symbol}}$$

**Illustration 15: Symbol rate**

The term baud is synonymous with symbol rate, but is less frequently used today as it has in the past been commonly misused to mean bit rate or data rate.

BPSK Symbol rate == Bit rate

QPSK Symbol rate == (Bit rate)/2 QPSK is twice as bandwidth efficient as BPSK

16QAM Symbol rate == (Bit rate)/4 16QAM is four times as bandwidth efficient as BPSK

Example:

- If one bit is transmitted per symbol, (BPSK), then the symbol rate would be the same as the bit rate ⇒ 80 kbits per second.
- If two bits are transmitted per symbol, (QPSK), then the symbol rate would be half of the bit rate ⇒ 40 kbits per second.

### 5.1.1 Bandwidth efficiency

Bandwidth efficiency describes how efficiently the allocated bandwidth is utilised or the ability of a modulation scheme to accommodate data, within a limited bandwidth.

- BPSK 1 bit/second/Hz
- QPSK 2 bits/second/Hz
- 8PSK 3 bits/second/Hz
- 16 QAM 4 bits/second/Hz
- 32 QAM 5 bits/second/Hz
- 64 QAM 6 bits/second/Hz
- 128 QAM 7 bits/second/Hz
- 256 QAM 8 bits/second/Hz

# 6. Self-test Quiz

1. Define signalling rate and information rate.
2. Describe the following Shift Keying methods:
   c. ASK
   d. FSK
   e. PSK.
6. Contrast the difference between QPSK and QDPSK.
7. With the aid of a diagram describe QAM.
8. Sketch the constellation diagram of QPSK and briefly explain.
9. With the aid of a diagram describe the operation of QDPSK.
10. Calculate the information rate for a modem operating at 10kBd using 256QAM.

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