# **Military Communications**

There is a host of technologies that are in use in the state-of-the-art communications equipment used by the Armed Forces world over. Be it the land-based systems or systems in use at sea, in air or space, military communications equipment embraces many technologies. No one technology dominates military communications systems; instead, a number of technologies are used to provide secure and reliable communications. Different generations of communications equipment have been in use by the Armed Forces for various applications over the last 100 years or so. Improvements seen in each new generation of communications equipment have been largely driven by the development of better hardware, including improved components, more sophisticated circuits and more precise manufacturing. The opening chapter begins with discussion on the fundamental topics of communication such as communication techniques and systems; antennas and propagation modes; optical communications including both free-space communication, fibreoptic communication and laser communication, particularly for underwater applications. This is followed by detailed description of emerging concepts employed in the current generation of communications equipment such as software-defined radio, net-centric warfare and  $C^4$ ISR. Some representative military communications equipment for the whole range of applications are briefly discussed towards the end.

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# 1.1 Introduction to Military Communications

Military communications technologies are complex and wide ranging. Development of new technologies and advances in existing technologies has led to different generations of communications equipment. Each generation of equipment has leveraged enhanced life and performance of components and emergence of a range of new components due to technological advances. Extended operating time of portable radios used by the Armed Forces in the battlefield due to availability of new battery technologies is one such example. Some of the major concerns faced by military planners relate to improving security and reliability of communications. Another concern relates to integration, which means achieving interoperability among a wide range of communications systems and technologies.

Features and capabilities of communications equipment both for commercial and military usage are undergoing revolutionary changes leading to availability of new generation of sophisticated communications devices and equipment enabling faster, more secure, less costly and more flexible communications. As outlined in the previous paragraph, security and interoperability are the two major concerns. While security-related issues have been resolved a large extent,

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Figure 1.1 LG's V10 smart phone. (Source: LG Electronics, https://creativecommons.org/licenses/by/2.0/deed. en.CC BY 2.0.)

integration of contrasting communications technologies (or in other words interoperability of different technologies and equipment) is one of the most important challenges facing military technology developers.

Modern radio and networking technologies such as smart phones, tablets, high-speed networks and other sophisticated technologies offer many new opportunities, though they too pose challenges vis-à-vis security and interoperability issues. Very few communication devices have seen such rapid growth and usage and consequential benefits as the smart phones and tablets. Smart phones with touch screen interfaces, internet access and an operating system capable of executing downloaded apps perform many of the functions of a computer. A tablet too is a portable PC with a form factor slightly larger than that of a smart phone. Both can fit into the cargo pocket of a soldier's uniform. Smart phone and tablet apps have given troops the ability to perform a range of tasks anytime anywhere and allowed commanders to instantly distribute essential documents directly to the troops. Network and device security concerns had earlier hindered widespread deployment of smart phones in the Armed Forces and with the availability of new generation smart phones, such as those using Google's Android 6.0 Marshmallow OS, these concerns have been addressed. This has even brought smart phones onto classified networks enabling soldiers access secret level mission command computer systems. Reportedly, the US Government has certified some smart phones, such as the LG G5 using Android OS version 6.0.1 and the V10 using Android OS version 5.1.1 (Figure 1.1), for use in environments where security is the top concern.

Keeping pace with smart phone and other commercial radio innovations, the next major military communications relevant technology evolving quite rapidly is that of *Ground Mobile Radio* (GMR). GMR of the future will focus on two main approaches, namely *Soldier Radio Waveform* (SRW) and *Wideband Networking Waveform*. SRW is an open-standard voice and data waveform used to extend wideband battlefield networks to the tactical edge. It is designed as a mobile ad-hoc waveform and it functions as a router within a wireless network. It is used to transmit vital information over long distances and elevated terrains including mountains and other natural or

#### Figure 1.2 AN/PRC-154 JTRS Rifleman Radio.



manmade obstructions, and allows communication without a fixed infrastructure such as cellular tower or satellite. The WNW is the next-generation high throughput military waveform, developed under the Joint Tactical Radio System (JTRS) Ground Mobile Radio (GMR) program. It uses the Orthogonal Frequency Division Multiplexing (OFDM) Physical Layer. With its mobile ad-hoc networking (MANET) capabilities, the waveform is designed to work well in both urban landscape as well as a terrain-constrained environment, since it can locate specific network nodes and determine the best path for transmitting information. Combination of these two technologies allows secure networked communications among platoon, squad and team level soldiers. It will also facilitate communication with combat commanders via satellite. The JTRS-HMS (Joint Tactical Radio System Handheld Manpack Small form fit) Rifleman RadioType AN/PRC-154 (Figure 1.2) developed by Thales and General Dynamics, designed to deliver networking connectivity to front line troops and capable of transmitting voice and data simultaneously via SRW (Soldier Radio Waveform), is one example of a GMR accepted for military use. JTRS also interfaces with smart phones. A vehicle-mounted software-defined radio system for ground mobile communications is the one being developed under the Mid-Tier Networking Vehicular Radio (MNVR) programme of the U.S. Army based on the Falcon family of wide band tactical radios. The Harris Corporation has developed the AN/VRC-118 (V)1 under this programme (Figure 1.3).

Another significant technological development has been in the field of wireless networking such as the *Mesh Networks* including *Mobile Ad-hoc Networks* (MANETs). These networking technologies are potentially capable of supporting both JTRS as well as smart phones. Also, these networking technologies provide high-bandwidth networking capabilities for handheld radios, ground and airborne vehicle communications, and security and tactical wireless sensors such as those used to monitor wireless security cameras positioned around critical infrastructure. MANETs can be networked to interconnect multiple mobile phones within a specified coverage area offering greater bandwidth and better connectivity. One application of the MANET is its use by convoys and other team-oriented missions to remain in constant communication with their movement spread over a large terrain. Another application of mesh networks is their use for control and coordination of unmanned ground vehicles. These remotely controlled unmanned vehicles following predefined paths may be used as targets by fighter aircraft pilots during training exercises in the same manner as Pilotless Target Aircraft (PTA) used by Air-Defence ground forces for training purposes.



Figure 1.3 AN/VRC-118 (V)1 MNVR. (Source: Courtesy of Harris Corporation.)

Satellite communication too plays an important role in military communications. Though smart phones and other cutting edge communications technologies have impacted on the utility of satellites for military communications, satellite communication continues to remain relevant with its potential of providing ubiquitous satellite coverage to terrestrial communications systems including smart phones. It would be worthwhile mentioning here that, other than the communications services, military satellites are extensively used for intelligence gathering, weather forecasting, early warning and providing navigation and timing data. Software Reprogrammable Payload (SRP), a satellite-rooted technology with its down-to-earth communication potential, is an adaptation of a small radio receiver designed for space applications into a full-fledged radio frequency system initially targeted for UAS (Unmanned Airborne System) communications. SRP is nothing but an airborne SDR (Software-Defined Radio) that facilitates beyond line-of-sight communications. The SRP development program is a joint effort between the Office of Naval Research (ONR), Naval Research Lab (NRL) and Marine Corps Aviation. SRP is a flexible, reconfigurable while-in-operation software-defined radio designed to meet current and future requirements of Unmanned Aircraft System (UAS) communications by Marine Corps. It is currently targeted at the American unmanned aerial vehicle AAI Shadow. The ability to reconfigure SRP's function in operation ensures that marines are able to share data, access capabilities and effectively command while they engage the adversary. SRP, configured around a software-defined radio platform, is designed to perform multiple functions, which include UHF communications relay with interference mitigation, UHF IP router capability, an automated identification system, single channel ground and airborne radio systems and so on. SRP has an open architecture very similar to that of JTRS and is interoperable with it.

Another communication technology that can become a potential game changer in military communications is that of *Cognitive Radio* for reasons of being inherently interoperable, having higher compatibility, reduced interference and enhanced security. The concept of cognitive radio addresses the problem of spectrum congestion that causes acute scarcity of spectrum space. It uses computer intelligence to automatically adapt to band conditions and user requirements.

Cognitive radio in fact refers to an array of technologies that allow radios self-reconfiguration in terms of operating mode selection, optimal power output and dynamic spectrum access for interference management. Cognitive radios have the ability to monitor, sense and detect the conditions of their operating environment, and dynamically reconfigure their own characteristics to best match those conditions. Due to the dynamic access feature, cognitive radio applies situation-aware access to available bands to choose the right radio band for the right purpose. Cognitive technologies including the dynamic spectrum access are being increasingly incorporated into communication devices and technologies such as smart phones, ground mobile radios, mesh networks and other emerging military communications technologies. Cognitive technology developed by XG Technology Inc. that uses six algorithms to evaluate spectrum conditions has already been tested by the US Army.

Many new communication technologies are being developed and maturing. In future, there will be a focus on adoption of more easily developed and deployable technologies due to shrinking military budgets. It will also drive them towards looking at commercial communication technologies, which will further lead to a more collaborative approach and greater focus on communication technologies with multiple users.

# 1.2 Communication Techniques

In the previous section, we briefly discussed different current and emerging military communication devices and technologies. These are discussed in detail in the latter part of the chapter. Some representative military communication equipment for a range of application scenarios is discussed towards the end of the chapter. Keeping in view the target readers, before we get down to discussing specific military communication technologies and equipment, it would be worthwhile discussing fundamental topics of communication as that would provide a better understanding of more advanced topics.

### 1.2.1 Types of Information Signals

When it comes to transmitting information over an RF communication link, be it a terrestrial link or a satellite link, it is essentially voice, data or video. A communication link therefore handles three types of signals; namely voice signals like those generated in telephony, radio broadcast and the audio portion of a TV broadcast, data signals produced in computer-to-computer communications and video signals like those generated in a TV broadcast or video conferencing. Each of these signals is called a base band signal. The base band signal is subjected to some kind of processing known as base band processing to convert the signal to a form suitable for transmission. Band limiting of speech signals to 3000 Hz in telephony and use of coding techniques in case of digital signal transmission are examples of base band processing. The transformed base band signal then modulates a high-frequency carrier so that it is suitable for propagation over the chosen transmission link. The demodulator on the receiver end recovers the base band signal from the received modulated signal. The three types of information signals are briefly described in the following paragraphs.

### 1.2.1.1 Voice Signals

Though the human ear is sensitive to a frequency range of 20 Hz–20 kHz, the frequency range of a speech signal is less than this. For the purpose of telephony, the speech signal is band limited to an upper limit of 3400 Hz during transmission. The quality of received analogue voice

signal has been specified by CCITT to give a worst-case base band signal-to-noise ratio of 50 dB. Here, the signal is considered to be a standard test tone and maximum allowable base band signal noise power is 10 nW. Other than signal bandwidth and signal-to-noise ratio, another important parameter that characterizes voice signal is its dynamic range. Speech or voice signal is characterized to have a large dynamic range of 50 dB.

In the case of digital transmission, the quality of recovered speech signal depends upon the number of bits transmitted per second and the bit error rate (BER). The BER to give good speech quality is considered to be  $10^{-4}$ ; that is, 1 bit error in 10 kB though a BER of  $10^{-5}$  or better is common.

#### 1.2.1.2 Data Signals

Data signals refer to a digitized version of a large variety of information services including voice telephony, video and computer generated information exchange. It is indeed the most commonly used vehicle for information transfer due to its ability to combine on to a single transmission support the data generated by a number of individual services, which is of great significance when it comes to transmitting multimedia traffic integrating voice, video and data.

Again, it is the system bandwidth that determines how fast the data can be sent in a given period of time expressed in bits/second. Obviously, the bigger the size of file to be transferred in a given time, the faster the required data transfer rate or greater the required bandwidth. Transmission of video signal requires a much larger data transmission rate (or bandwidth) than that required by transmission of a graphics file. A graphics file requires a much a larger data transfer rate than that required by a text file. The desired data rate may vary from a few tens of kb/s to tens of Mb/s for various information services. However, data compression techniques allow transmission signals at a rate much lower than that theoretically needed to do so.

### 1.2.1.3 Video Signals

The frequency range or bandwidth of a video signal produced as a result of television quality picture information depends upon the size of the smallest picture information, referred to as a pixel. The greater the number of pixels, the higher the signal bandwidth. As an example, in the 625-line, 50 Hz TV standard where each picture frame having 625 lines is split into two fields of 312.5 lines and the video signal is produced as a result of scanning 50 fields per second in an interlaced scanning mode, assuming a worst-case picture pattern where pixels alternate from black to white to generate one cycle of video output, the highest video frequency is given by eqn. 1.1.

$$f = \frac{\left(aN/2\right)}{t_h} \tag{1.1}$$

where N = Number of lines per frame

 $t_h$  = Time period for scanning one horizontal line

For a 625-line, 50 Hz system, it turns out to be 6.5 MHz. This calculation, however, does not take into account the lines suppressed during line and frame synchronization. For actual picture transmission, the chosen bandwidth is 5 MHz for a 625-line, 50 Hz system and 4.2 MHz for a 525-line, 60 Hz system. And it does not seem to have any detrimental effect on picture quality.

### 1.2.2 Amplitude Modulation

In *Amplitude Modulation*, the instantaneous amplitude of the carrier signal varies directly as the instantaneous amplitude of the modulating signal. The frequency of the carrier signal



remains constant. Figure 1.4 shows the modulating signal, carrier signal and modulated signal in the case of a single tone modulating signal.

If the modulating signal and the carrier signal are expressed, respectively, by  $v_m = V_m \cos \omega_m t$ and  $v_c = V_c \cos \omega_c t$ , then the modulated signal can be expressed mathematically by eqn. 1.2.

$$v(t) = V_c (1 + m\cos\omega_m t)\cos\omega_c t \tag{1.2}$$

Where m = Modulation index =  $V_m / V_c$ 

When more than one sinusoidal or cosinosoidal signals with different amplitudes amplitude modulate a carrier, the overall modulation index in that case is given by eqn. 1.3.

$$m = \sqrt{\left(m_1^2 + m_2^2 + m_3^2 + \dots\right)} \tag{1.3}$$

Where  $m_1$ ,  $m_2$ ,  $m_3$  are modulation indices corresponding to individual signals.

*Percentage of modulation* or *depth of modulation* is given by  $m \times 100$  and for depth of modulation equal to 100%, m = 1 or  $V_m = V_c$ .

### 1.2.2.1 Frequency Spectrum of the AM Signal

Expanding the expression for the modulated signal given in eqn. 1.2, we get

$$v(t) = V_c \cos \omega_c t + \left(\frac{mV_c}{2}\right) \cos(\omega_c - \omega_m) t + \left(\frac{mV_c}{2}\right) \cos(\omega_c + \omega_m) t$$
(1.4)

The frequency spectrum of an amplitude modulated signal in case of a single frequency modulating signal thus contains three frequency components; namely the carrier frequency component ( $\omega_c$ ), the sum component ( $\omega_c + \omega_m$ ) and the difference frequency component ( $\omega_c - \omega_m$ ). The sum component represents the upper side band and the difference component the lower side band. Figure 1.5 shows the frequency spectrum.

It should be mentioned here that, in actual practice, the modulating signal is not a single frequency tone. In fact, it is a complex signal. This complex signal can always be represented mathematically in terms of sinusoidal and cosinosoidal components. Thus if a given modulating signal is equivalently represented as a sum of, say, three components ( $\omega_{m1}$ ,  $\omega_{m2}$  and  $\omega_{m3}$ ),





Figure 1.5 Frequency spectrum of the AM signal.

then the frequency spectrum of the AM signal, when such a complex signal amplitude modulates a carrier, contains the frequency components ( $\omega_c$ ), ( $\omega_c + \omega_{m1}$ ), ( $\omega_c - \omega_{m1}$ ), ( $\omega_c + \omega_{m2}$ ), ( $\omega_c - \omega_{m2}$ ), ( $\omega_c + \omega_{m3}$ ) and ( $\omega_c - \omega_{m3}$ ).

#### 1.2.2.2 Power in the AM Signal

The total power  $(P_t)$  in an AM signal is related to the unmodulated carrier power  $(P_c)$  by eqn. 1.5.

$$P_t = P_c \left[ 1 + \left(\frac{m^2}{2}\right) \right] = P_c + P_c \left(\frac{m^2}{4}\right) + P_c \left(\frac{m^2}{4}\right)$$
(1.5)

Where  $(P_c m^2/4)$  is the power in either of the two side bands; that is, upper and lower side bands. For 100% depth of modulation for which m = 1, total power in an AM signal is  $(3P_c/2)$  and power in each of the two side bands is  $(P_c/4)$  with the total side band power equal to  $(P_c/2)$ . These expressions indicate that, even for 100% depth of modulation, power contained in the sidebands, which contains the actual information to be transmitted, is only one-third of the total power in the AM signal.

Power content of different parts of the AM signal can also be expressed in terms of peak amplitude of unmodulated carrier signal ( $V_c$ ) by eqn. 1.6.

Total power in AM signal, 
$$P_t = \frac{V_c^2}{2} + m \frac{V_c^2}{8} + m \frac{V_c^2}{8}$$
 (1.6)

Power in either of the two side bands =  $m \frac{V_c^2}{8}$ 

#### 1.2.2.3 Noise in the AM Signal

We shall now examine the noise performance when an AM signal is contaminated with noise. Let us assume *S*, *C* and *N* are the signal, carrier and noise power levels, respectively. Let us also assume that the receiver has a bandwidth of *B*. In the case of a conventional double side band system, it equals  $2f_m$  where  $f_m$  is the highest modulating frequency. If  $N_b$  is the noise power at the output of the demodulator, then

 $N_b = AN$ , where A is the scaling factor for the demodulator

Now, signal power in each of the side band frequencies is one-quarter of the carrier power as explained in the earlier paragraphs. That is,  $S_L = S_U = C / 4$ 

Also, 
$$S_{bL} = S_{bU} = AC / 4$$

Where  $S_L$  = Signal power in lower side band frequency before demodulation.

 $S_U$  = Signal power in upper side band frequency before demodulation.

 $S_{bL}$  = Signal power in lower side band frequency after demodulation.

 $S_{bU}$  = Signal power in upper side band frequency after demodulation.

Since both lower and upper side band frequencies are identical before and after demodulation, they will add coherently in the demodulator to produce a total base band power  $S_b$  given by eqn. 1.7.

$$S_b = 2\left(S_{bL} + S_{bU}\right) = 2\left[\left(\frac{AC}{4}\right) + \left(\frac{AC}{4}\right)\right] = AC$$
(1.7)

Combining the expressions for  $S_b$  and  $N_b$ , we get the following relationship between  $S_b/N_b$  and (C/N).

$$\frac{S_b}{N_b} = \frac{C}{N} \tag{1.8}$$

Where  $N = N_o B$  with  $N_o$  being noise power spectral density in W/Hz and *B* being the receiver bandwidth.

However, this relationship is only valid for a modulation index of unity. The generalized expression for modulation index of *m* is given by eqn. 1.9.

$$\frac{S_b}{N_b} = m^2 \left(\frac{C}{N}\right) \tag{1.9}$$

So far, we have been talking about a single frequency modulating signal. In the case where the modulating signal is a band of frequencies, we would get a lower and an upper side band and we shall get a frequency spectrum such as the one shown in Figure 1.6. Incidentally, the spectrum shown represents a case where the modulating signal is the base band signal of telephony ranging from 300 to 3400 Hz.



Figure 1.6 Spectrum of the AM signal for a multi-frequency modulating signal.

### 1.2.2.4 Different Forms of Amplitude Modulation

We have seen in the preceding paragraphs that the process of amplitude modulation produces two side bands, each of which contains the complete base band signal information. Also, the carrier contains no base band signal information. Therefore, if one of the side bands was suppressed and only one side band transmitted, it would make no difference to the information content of the modulated signal. In addition, it would have the advantage of requiring only one-half of the bandwidth required as compared to the conventional double side band signal. Also, if the carrier were also suppressed before transmission, it would lead to a significant saving in the required transmitted power for a given power in the information carrying signal. That is why the single side band suppressed carrier mode of amplitude modulation is very popular. In the following paragraphs, we shall briefly outline some of the practical forms of amplitude modulation systems.

### 1.2.2.4.1 A3E System

This is the *standard AM* system used for broadcasting. It uses the double side band with full carrier. The standard AM signal can be generated by adding a large carrier signal to the Double Side Band Suppressed Carrier (DSBSC) or simply the DSB signal. The DSBSC signal in turn can be generated by multiplying the modulating signal m(t) and the carrier ( $\cos \omega_c t$ ). Figure 1.7 shows the arrangement for generating the DSBSC signal.

Demodulation of the standard AM signal is very simple and is implemented by using what is known as an envelope detection technique. In a standard AM signal, when the amplitude of the unmodulated carrier signal is very large, the amplitude of modulated carrier is proportional to the modulating signal. Demodulation in this case simply reduces to detection of envelope of modulated carrier regardless of the exact frequency or phase of the carrier. Figure 1.8 shows the envelope detector circuit used for demodulating the standard AM signal. Capacitor C filters out the high-frequency carrier variations.

Demodulation of DSBSC signal is carried out by multiplying the modulated signal by a locally generated carrier signal and then passing the product signal through a low pass filter.



Figure 1.8 Envelop detector for demodulating standard AM signal.

### 1.2.2.4.2 H3E System

This is the Single Side Band, Full Carrier system (SSBFC). H3E transmission could be used with A3E receivers with distortion not exceeding 5%. One method to generate an SSB signal is to first generate a DSB signal and then suppress one of the side bands by the process of filtering. This method, known as the Frequency Discrimination method, is illustrated in Figure 1.9. In practice, this approach poses some difficulty because the filter needs to have sharp cut-off characteristics.

Another method for generating an SSB signal is the phase shift method. Figure 1.10 shows the basic block-schematic arrangement. The blocks labelled  $-\pi/2$  are phase shifters that add a lagging phase shift of  $\pi/2$  to every frequency component of the signal applied at the input to the block. The output block can either be an adder or a subtractor. If m(t) is the modulating signal and m'(t) is the modulating signal delayed in phase by  $\pi/2$ , then the SSB signal produced at the output can be represented by eqn. 1.10.

$$x_{SSB}(t) = m(t)\cos\omega_c t \pm m'(t)\sin\omega_c t \tag{1.10}$$

The output with a + sign is produced when the output block is an adder and with – when the output block is a subtractor.

The difference signal represents the upper side band SSB signal while the sum represents the lower side band SSB signal. For instance, if m(t) is taken as  $\cos \omega_m t$ , then m'(t) would be  $\sin \omega_m t$ . The SSB signal in case of the minus sign would then be

$$\cos\omega_m t \cdot \cos\omega_c t - \sin\omega_m t \cdot \sin\omega_c t = \cos(\omega_m + \omega_c)t \tag{1.11}$$

In case of the plus sign, it would be

$$\cos\omega_m t \cdot \cos\omega_c t + \sin\omega_m t \cdot \sin\omega_c t = \cos(\omega_c - \omega_m)t \tag{1.12}$$



### 1.2.2.4.3 R3E System

This is the *Single Side Band Reduced Carrier* system, also called the *pilot carrier* system. Re-insertion of a carrier with a greatly reduced amplitude before transmission aims to facilitate receiver tuning and demodulation. This reduced carrier amplitude is 16 or 26 dB below the value it would have had it not been suppressed in the first place. This attenuated carrier signal, while retaining the advantage of saving in power, provides a reference signal to help demodulation in the receiver.

### 1.2.2.4.4 J3E System

This is the *Single Side Band Suppressed Carrier (SSBSC) system*. This system is usually referred to as SSB, in which a carrier is suppressed by at least 45 dB in the transmitter. It was not popular initially due to the requirement of high receiver stability. However, with the advent of synthesizer-driven receivers, it has now become the standard form of radio communication.

Generation of SSB signals was briefly described in the earlier paragraphs. Suppression of carrier in an AM signal is achieved in the building block known as the *Balanced Modulator*. Figure 1.11 shows the typical circuit implemented using FETs. The modulating signal is applied in push-pull to a pair of identical FETs as shown and as a result, the modulating signals appearing at the gates of the two FETs are 180° out of phase. The carrier signal, as is evident from the circuit, is applied to the two gates in phase. The modulated output currents of the two FETs produced as a result of their respective gate signals are combined in the centre-tapped primary of the output transformer. If the two halves of the circuit are perfectly symmetrical, it can be proved with the help of simple mathematics that the carrier signal frequency will be completely cancelled in the modulated output and the output would contain only the modulating frequency, sum frequency and difference frequency components. The modulating frequency component can be removed from the output by tuning the output transformer. Demodulation of SSBSC signals can be implemented by using a coherent detector scheme as outlined in case of demodulation of DSBSC signal in earlier paragraphs. Figure 1.12 shows the arrangement.

### 1.2.2.4.5 B8E System

This system uses two independent side bands with the carrier either attenuated or suppressed. This form of amplitude modulation is also known as Independent Side Band (ISB) transmission and is usually employed for point-to-point radio telephony.



Figure 1.11 Balanced modulator.



#### 1.2.2.4.6 C3F System

*Vestigial Side Band (VSB)* transmission is the other name for this system. It is used for transmission of video signal in commercial television broadcasting. It is a compromise between SSB and DSB modulation systems in which a vestige or part of the unwanted side band is also transmitted usually with a full carrier along with the other side band. The typical bandwidth required to transmit a VSB signal is about 1.25 times that of an SSB signal. VSB transmission is used in commercial TV broadcasting to conserve bandwidth.

VSB signal can be generated by passing a DSB signal through an appropriate side band shaping filter as shown in Figure 1.13. The demodulation scheme for the VSB signal is shown in Figure 1.14.

### 1.2.3 Frequency Modulation

In *Frequency Modulation*, the instantaneous frequency of the modulation signal varies directly as the instantaneous amplitude of the modulating or base band signal. The rate at which these frequency variations take place is of course proportional to the modulating frequency. If the modulating signal is expressed by  $v_m = V_m \cos \omega_m t$ , then instantaneous frequency, *f*, of an FM signal is mathematically expressed by eqn. 1.13.

$$f = f_c \left( 1 + K V_m \cos \omega_m t \right) \tag{1.13}$$

Where  $f_c$  = unmodulated carrier frequency

 $V_m$  = Peak amplitude of modulating signal  $\omega_m$  = Modulating frequency

K = Constant of proportionality

The instantaneous frequency is at a maximum when  $\cos \omega_m t = 1$  and minimum when  $\cos \omega_m t = -1$ . This gives:

$$f_{\max} = f_c (1 + KV_m) \text{ and } f_{\min} = f_c (1 - KV_m)$$
 (1.14)



Figure 1.15 Frequency modulation.

Frequency deviation,  $\delta$ , is one of the important parameters of an FM signal and is given by  $(f_{\text{max}} - f_c)$  or  $(f_c - f_{\text{min}})$ . This gives

Frequency deviation, 
$$\delta = KV_m f_c$$
 (1.15)

Figure 1.15 shows the modulating signal (taken as a single tone signal in this case), the unmodulated carrier and the modulated signal. An FM signal can be mathematically represented by eqn. 1.16.

$$v(t) = A\sin\left[\omega_{c}t + \left(\frac{\delta}{f_{m}}\right)\sin\omega_{m}t\right] = A\sin\left[\omega_{c}t + m_{f}\sin\omega_{m}t\right]$$
(1.16)

Where,  $m_f = Modulation index = \delta / f_m$ 

A is the amplitude of the modulated signal that in turn is equal to the amplitude of the carrier signal.

Depth of modulation in the case of an FM signal is defined as the ratio of frequency deviation,  $\delta$ , to maximum allowable frequency deviation. Maximum allowable frequency deviation is different for different services and is also different for different standards, even for a given type of service using this form of modulation. For instance, maximum allowable frequency deviation for commercial FM radio broadcast is 75 kHz. It is 50 kHz for the FM signal of TV sound in CCIR standards and 25 kHz for FM signal of TV sound in FCC standards.

### 1.2.3.1 Frequency Spectrum of the FM Signal

We have seen that an FM signal involves the sine of a sine. The solution of this expression involves the use of Bessel Functions. The expression for the FM signal can be rewritten as:

$$\nu(t) = A \begin{bmatrix} J_0(m_f)\sin\omega_c t + J_1(m_f)\{\sin(\omega_c + \omega_m)t - \sin(\omega_c - \omega_m)t\} \\ + J_2(m_f)\{\sin(\omega_c + 2\omega_m)t - \sin(\omega_c - 2\omega_m)t\} \\ + J_3(m_f)\{\sin(\omega_c + 3\omega_m)t - \sin(\omega_c - 3\omega_m)t\} + \dots \end{bmatrix}$$
(1.17)

Thus, the spectrum of an FM signal contains the carrier frequency component and an apparently infinite number of side bands. In general,  $J_n(m_f)$  is the Bessel function of the first kind and *n*th order. It is evident from this expression it is the value of  $m_f$  and the value of the Bessel functions that will ultimately decide the number of side bands having significant amplitude and therefore the bandwidth. The following observations can be made from eqn. 1.17.

### 1.2.3.2 Narrow Band and Wide Band FM

An FM signal, whether it is a *Narrow Band FM signal* or a *Wide Band FM signal*, is decided by its bandwidth and in turn by its modulation index. For a modulation index  $m_f$  much less than 1, the signal is considered the narrow band FM signal. It can be shown that for an  $m_f$  less than 0.2, 98% of the normalized total signal power is contained within the bandwidth. Bandwidth for narrow band FM is given by eqn. 1.18.

$$Bandwidth = 2(m_f + 1)\omega_m \approx 2\omega_m \text{ for } m_f \ll 1$$
(1.18)

where  $\omega_m$  is the sinusoidal modulating frequency.

In case of FM signal with an arbitrary modulating signal m(t) band limited to  $(\omega_M)$ , we define another parameter, called the Deviation Ratio (D) as D = (Maximum frequency deviation)/(Bandwidth of <math>m(t)). The deviation ratio, D, has the same significance for arbitrary modulation as the modulation index  $m_f$  for sinusoidal modulation. The bandwidth in this case is given by eqn. 1.19.

$$Bandwidth = 2(D+1)\omega_M \tag{1.19}$$

This expression for bandwidth is generally referred to as Carson's rule. In the case of D«1, the FM signal is considered a narrow band signal and the bandwidth is given by eqn. 1.20.

$$Bandwidth = 2(D+1)\omega_M \approx 2\omega_M \tag{1.20}$$

In the case where  $m_f \gg 1$  (for sinusoidal modulation) or  $D \gg 1$  (for arbitrary modulation signal band limited to  $\omega_M$ , the FM signal is termed the wide band FM and the bandwidth in this case is given by eqn. 1.21.

$$Bandwidth = 2m_f \omega_m \text{ or } 2D\omega_M \tag{1.21}$$

### 1.2.3.3 Noise in the FM Signal

As we shall see in the following paragraphs, frequency modulation is far less affected by presence of noise compared to the effect of noise on an amplitude modulated signal. Whenever a noise voltage with peak amplitude  $(V_n)$  is present along with a carrier voltage of peak amplitude  $(V_c)$ , the noise voltage amplitude modulates the carrier with a modulation index equal to  $(V_n/V_c)$ . It also phase modulates the carrier with a phase deviation equal to  $[\sin^{-1}(V_n/V_c)]$ . This expression for phase deviation results when a single frequency noise voltage is considered vectorially and the noise voltage vector is superimposed on the carrier voltage vector. In case of voice communication, an FM receiver is not affected by the amplitude change as it can be removed in the receiver in the limiter circuit. Also, an AM receiver will not be affected by the phase change. It is therefore the effect of phase change on the FM receiver and the effect of

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amplitude change on the AM receiver that can be used as the yardstick for determining the noise performance of the two modulation techniques. Two very important aspects that need to be addressed when we set out to compare the two communication techniques vis-à-vis their noise performance are the effects of modulation index and the signal-to-noise ratio at the receiver input. Without going into detailed analysis of effects of modulation index and signal-to-noise ratio, we can summarize that an FM system offers a better performance than an AM system provided that (1) the modulation index is greater than unity, (2) the amplitude of carrier is greater than maximum noise peak amplitudes and (3) the receiver is insensitive to amplitude variations.

### 1.2.3.3.1 Pre-Emphasis and De-Emphasis

Noise has a greater effect on the higher modulating frequencies than it has on lower ones. This is because of the fact that FM results in smaller values of phase deviation at the higher modulating frequencies, whereas the phase deviation due to white noise is constant for all frequencies. Due to this, *S/N* deteriorates at higher modulating frequencies. If the higher modulating frequencies above a certain cut-off frequency were boosted at the transmitter prior to modulation according to a certain known curve and then reduced at the receiver in the same fashion after the demodulator, a definite improvement in noise immunity would result. The process of boosting the higher modulating frequencies at the transmitter and then reducing them in the receiver are, respectively, known as pre-emphasis and de-emphasis. Figure 1.16 shows the pre-emphasis and de-emphasis curves.

Having briefly discussed noise performance of an FM system, it would be worthwhile presenting the mathematical expression that could be used to compute the base band signal-to-noise ratio at the output of the demodulator. Without getting into intricate mathematics, we can write the following expression for base band signal-to-noise ratio ( $S_b/N_b$ ).

$$\left(\frac{S_b}{N_b}\right) = 3\left(\frac{f_d}{f_m}\right)^2 \left(\frac{B}{2f_m}\right) \left(\frac{C}{N}\right)$$
(1.22)

Where  $f_d$  = Frequency deviation

 $f_m$  = Highest modulating frequency B = Receiver bandwidth C = Carrier power at receiver input N = Noise power (kTB) in bandwidth B.

The expression 1.22 does not take into account the improvement due to use of pre-emphasis and de-emphasis. In that case the expression gets modified to eqn. 1.23.



Figure 1.16 Pre-emphasis and de-emphasis curves.



Figure 1.17 LC oscillator-based direct method of FM signal generation.

$$\left(\frac{S_b}{N_b}\right) = \left(\frac{f_d}{f_1}\right)^2 \left(\frac{B}{f_m}\right) \left(\frac{C}{N}\right)$$
(1.23)



#### 1.2.3.4 Generation of FM Signals

Though there are many possible schemes that can be used to generate an FM signal, all of them depend simply on varying the frequency of an oscillator circuit in accordance with the modulating signal input. One of the possible methods is based on the use of a varactor (a voltage variable capacitor) as a part of the tuned circuit of an L-C oscillator. The resonant frequency of this oscillator will not vary directly with the amplitude of the modulating frequency as it is inversely proportional to square root of the capacitance. However, if the frequency deviation is kept small, the resulting FM signal is quite linear. Figure 1.17 shows the typical arrangement when the modulating signal is an audio signal. This is also known as the *direct method* of generating an FM signal as in this case, the modulating signal directly controls the carrier frequency.

Another direct method scheme that can be used for generation of an FM signal is the *reactance modulator*. In this, the reactance offered by a three-terminal active device such as an FET or a bipolar transistor forms a part of the tuned circuit of the oscillator. The reactance in this case is made to vary in accordance with the modulating signal applied to the relevant terminal of the active device. For example, in case of FET, the drain-source reactance can be shown to be proportional to the transconductance of the device, which in turn can be made to depend on the bias voltage at its gate terminal. The main advantage of using the reactance modulator is that large frequency deviations are possible and thus less frequency multiplication is required. One of the major disadvantages of both these direct method schemes is that carrier frequency tends to drift and therefore additional circuitry is required for frequency stabilization. The problem of frequency drift is overcome in crystal controlled oscillator schemes.

While crystal control provides a very stable operating frequency, the exact frequency of oscillation in this case mainly depends upon the crystal characteristics and to a very small extent on the external circuit. For example, a capacitor connected across the crystal can be used to change its frequency typically from 0.001 to 0.005%. The frequency change may be



Figure 1.18 Crystal control oscillator-based scheme for FM signal generation.

linear only up to a change of 0.001%. Thus, a crystal oscillator can be frequency modulated over a very small range by a parallel varactor. The frequency deviation possible with such a scheme is usually too small to be used directly. The frequency deviation in this case is then increased by using frequency multipliers as shown in Figure 1.18.

Another approach that eliminates the requirement of extensive chains of frequency multipliers in direct crystal controlled systems is an *indirect method* where frequency deviation is not introduced at the source of RF carrier signal; that is, the oscillator. The oscillator in this case is crystal controlled to get the desired stability of the unmodulated carrier frequency and the frequency deviation is introduced at a later stage. The modulating signal phase modulates the RF carrier signal produced by the crystal controlled oscillator. Since frequency is nothing but rate of change of phase, phase modulation of the carrier has the associated frequency modulation. Introduction of a leading phase shift would lead to an increase in the RF carrier frequency and a lagging phase shift results in a reduced RF carrier frequency. Thus, if the phase of the RF carrier is shifted by the modulating signal in a proper way, the result is a frequency modulated signal. Since phase modulation also produces little frequency deviation, a frequency multiplier chain is required in this case too.

### 1.2.3.5 Detection of FM Signals

Detection of an FM signal involves the use of some kind of a frequency discriminator circuit that can generate an electrical output directly proportional to the frequency deviation from the unmodulated RF carrier frequency. The simplest of the possible circuits would be the *balanced slope detector* that makes use of two resonant circuits; one off-tuned to one side of the unmodulated RF carrier frequency and the other off-tuned to the other side of it. Figure 1.19 shows the basic circuit. When the input to this circuit is at the unmodulated carrier frequency, the two off-tuned slope detectors (or the resonant circuits) produce equal amplitude but out-of-phase outputs across them. The two signals after passing through their respective diodes produce equal amplitude opposing DC outputs that combine to produce a zero or near-zero output. When the received signal frequency is towards either side of the centre frequency, one output has higher amplitude than the other to produce a net DC output across the load. The polarity of the output produced depends on which side of the centre frequency the received signal is. Such a detector circuit, however, does not find application for voice communication because of its poor linearity of response.

Another class of FM detectors, known as *quadrature detectors*, use a combination of two quadrature signals, that is, two signals 90° out of phase, to get the frequency discrimination property. One of the two signals is the FM signal to be detected and its quadrature counterpart is generated by using either a capacitor or an inductor. The principle of operation of quadrature



Figure 1.19 Basic circuit of balanced slope detector.



Figure 1.20 Foster-Seeley frequency discriminator.

detector forms the basis of two most commonly used FM detectors namely the Foster–Seeley FM Discriminator and the Ratio Detector.

In the *Foster–Seeley Frequency Discriminator* circuit of Figure 1.20, the two Quadrature signals are provided by the primary signal  $E_p$  as appearing at the centre tap of secondary and  $E_b$ . We can appreciate that  $E_a$  and  $E_b$  are 180° out of phase and also that  $E_p$  available at the centre tap of the secondary is 90° out of phase with the total secondary signal. Signals  $E_1$  and  $E_2$ , appearing across the two halves of the secondary, have equal amplitudes when the received signal is at the unmodulated carrier frequency as shown in the phasor diagram.  $E_1$  and  $E_2$  cause rectified currents  $I_1$  and  $I_2$  to flow in the opposite directions with the result that voltage across  $R_1$  and  $R_2$  are equal and opposite. The detected voltage is zero for  $R_1 = R_2$ . The conditions when the received signal frequency deviates from the unmodulated carrier frequency value are also shown in the phasor diagrams. In case of frequency deviation, there is a net output voltage whose amplitude and polarity depends upon the amplitude and sense of frequency deviation.

Another commonly used FM detector circuit is the *ratio detector*. This circuit has the advantage that it is insensitive to short term amplitude fluctuations in the carrier and therefore does not require an additional limiter circuit. The circuit configuration, as can be seen from Figure 1.21, is similar to the one given in case of Foster–Seeley discriminator circuit, except for a couple of changes. These are a reversal of diode connections and addition of a large capacitor  $C_3$ . The time constant  $[(R_1 + R_2)C_3]$  is much larger than the time period of even the lowest modulating frequency of interest. The detected signal in this case appears across the  $C_1$ – $C_2$  junction. The sum output across  $R_1$ – $R_2$  and hence across  $C_1$ – $C_2$  remains constant for a given



Figure 1.21 Ratio detector.



Figure 1.22 PLL-based FM detector.

carrier level, and also is insensitive to rapid fluctuations in carrier level. However, if the carrier level changes very slowly  $C_3$  would charge/discharge to the new carrier level. The detected signal therefore is not only proportional to the frequency deviation, it also depends upon average carrier level.

Yet another form of FM detector is the one implemented using a phase locked loop (PLL). A PLL, as we know, has a phase detector (usually a double balanced mixer), a low pass filter and an error amplifier in the forward path and a voltage controlled oscillator (VCO) in the feedback path. The detected output appears at the output of error amplifier as shown in Figure 1.22. A PLL-based FM detector functions as follows.

The FM signal is applied to the input of the phase detector. The VCO is tuned to a nominal frequency equal to unmodulated carrier frequency. The phase detector produces an error voltage depending upon frequency and phase difference between the VCO output and instantaneous frequency of input FM signal. As the input frequency deviates from the centre

frequency, the error voltage produced as result of frequency difference after passing through the low pass filter and error amplifier drives the control input of the VCO to keep its output frequency always in lock with the instantaneous frequency of the input FM signal. As a result, the error amplifier always represents the detected output. The double balanced mixer nature of phase detector suppresses any carrier level changes and therefore the PLL-based FM detector requires no additional limiter circuit.

A comparison of the three types of FM detectors would reveal that the Foster–Seeley type FM discriminator offers excellent linearity of response, is easy to balance and the detected output depends only on frequency deviation. But it needs high gain RF and IF stages to ensure the limiting action. The ratio detector circuit on the other hand requires no additional limiter circuit; detected output depends both on frequency deviation as well as on average carrier level. However, it is difficult to balance. The PLL-based FM detector offers excellent reproduction of modulating signal, is easy to balance and has low cost and high reliability.

## 1.2.4 Pulse Communication Systems

Pulse communication systems differ from continuous-wave communication systems in the sense that the message signal or intelligence to be transmitted is not supplied continuously as in case of AM or FM. In turn, it is sampled at regular intervals and it is the sampled data that is transmitted. All pulse communication systems fall into either of the two categories; namely, analogue systems and digital systems. Analogue and digital communication systems differ in the mode of transmission of sampled information. In case of analogue communication systems, the representation of sampled amplitude may be infinitely variable whereas in digital communication systems, a code representing the sampled amplitude to the nearest predetermined level is transmitted.

### 1.2.5 Analogue Pulse Communication Systems

Important techniques that fall in the category of analogue pulse communication systems include:

- 1) Pulse Amplitude Modulation
- 2) Pulse Width (or Duration) Modulation
- 3) Pulse Position Modulation

## 1.2.5.1 Pulse Amplitude Modulation

In the case of *Pulse Amplitude Modulation* (PAM), the signal is sampled at regular intervals and the amplitude of each sample, which is a pulse, is proportional to the amplitude of the modulating signal at the time instant of sampling. The samples, as shown in Figure 1.23, can have either a positive or negative polarity. In a single-polarity PAM, a fixed DC level can be added to the signal as shown in Figure 1.23(c). These samples can then be transmitted either by a cable or used to modulate a carrier for wireless transmission. Frequency modulation is usually employed for the purpose and the system is known as PAM-FM.

### 1.2.5.2 Pulse Width Modulation

In case of *Pulse Width Modulation* (PWM), as shown in Figure 1.24, the starting time of the sampled pulses and their amplitude is fixed. The width of each pulse is made proportional to the amplitude of the signal at the sampling time instant.





Figure 1.23 Pulse amplitude modulation: (a) modulating signal, (b) double polarity PM signal and (c) single polarity PAM signal.



Figure 1.24 Pulse width modulation.

### 1.2.5.3 Pulse Position Modulation

In case of *Pulse Position Modulation* (PPM), the amplitude and width of sampled pulses is maintained as constant and the position of each pulse with respect to the position of a recurrent reference pulse varies as a function of instantaneous sampled amplitude of the modulating signal. In this case, the transmitter sends synchronizing pulses to operate timing circuits in the receiver.

A pulse position modulated signal can be generated from a pulse width modulated signal. In a PWM signal, as we know, the position of leading edges is fixed, whereas that of trailing edges depends upon the width of pulse, which in turn is proportional to amplitude of modulating signal at the time instant of sampling. Quite obviously, the trailing edges constitute the pulse position modulated signal. The sequence of trailing edges can be obtained by differentiating the PWM signal and then clipping the leading edges as shown in Figure 1.25.



**Figure 1.25** Pulse position modulation: (a) modulating signal, (b) pulse width modulated signal, (c) differentiated pulse width modulated signal and (d) pulse position modulated signal.

Pulse width modulation and pulse position modulation both fall in the category of Pulse Time Modulation (PTM).

### 1.2.6 Digital Pulse Communication Systems

Digital pulse communication techniques differ from the analogue pulse communication techniques described in the previous paragraphs in the sense that, in the case of analogue pulse modulation, the sampling process transforms the modulating signal into a train of pulses with each pulse in the pulse train representing the sampled amplitude at that instant of time. This is one of the characteristic features of the pulse, such as amplitude in the case of PAM, width in the case of PWM and position of leading or trailing edges in the case of PPM, which is varied in accordance with the amplitude of the modulating signal. What is important to note here is that the characteristic parameter of the pulse, which is amplitude or width or position, is infinitely variable. As an illustration, if in case of pulse width, then 5.23 and 5.24 V amplitudes would be represented by 5.23 and  $5.24 \mu$ s, respectively. Further, there could be any number of amplitudes between 5.23 and 5.24 V. It is not the same in the case of digital pulse communication techniques, each sampled amplitude is transmitted by a digital code representing the nearest predetermined level.

Important techniques that fall in the category of digital pulse communication systems include:

- 1) Pulse Code Modulation (PCM)
- 2) Differential PCM
- 3) Delta Modulation
- 4) Adaptive Delta Modulation.

### 1.2.6.1 Pulse Code Modulation

In *Pulse Code Modulation* (PCM), the peak-to-peak amplitude range of the modulating signal is divided into a number of standard levels, which in case of binary system is an integral power of 2. The amplitude of the signal to be sent at any sampling instant is the nearest standard level. For example, if at a particular sampling instant, the signal amplitude is 3.2 V, it will not be sent as a 3.2 V pulse as might have been in case of PAM or a  $3.2 \,\mu$ s wide pulse as in case of PWM; instead it will be sent as the digit-3 if 3 V is the nearest standard amplitude. And in a case where the signal range has been divided into 128 levels, it will be transmitted as 0000011. The coded waveform would be like that shown in Figure 1.26(a). This process is known as *quantizing*. In fact, a supervisory pulse is also added with each code group to facilitate reception. Thus, the number of bits for  $2^n$  chosen standard levels per code group is n + 1. Figure 1.26(b) illustrates the quantizing process in PCM.

As is evident from Figure 1.26(b), the quantizing process distorts the signal. This distortion is referred to as quantization noise, which is random in nature as the error in the signal's amplitude and that actually sent after quantization is random. Maximum error can be as high as half of the sampling interval, which means if the number of levels used were 16, it would be 1/32 of the total signal amplitude range. It may be mentioned here that it would be unfair to say that a PCM system with 16 standard levels will necessarily have a signal-to-quantizing noise ratio of 32:1; because neither the signal nor the quantizing noise will always have its maximum value. Signal-to-noise ratio depends upon many other factors too and also its dependence on the number of quantizing levels is statistical in nature. Nevertheless, an



Figure 1.26 The quantization process: (a) coding waveform and (b) actual and quantized signals.

increase in number of standard levels does lead to an increase in signal-to-noise ratio. In practice, for speech signals, 128 levels are considered adequate. Also, the greater the number of levels, the greater the number of bits to be transmitted and therefore the higher the required bandwidth. In binary PCM where a binary system of representation is used for encoding various sampled amplitudes, the number of bits to be transmitted per second would be given by  $nf_s$  where  $n = \log_2 L$ , L = number of standard levels. Also,  $f_s \ge f_m$  where  $f_m =$  message signal bandwidth.

Assuming that PCM signal is a low pass signal of bandwidth,  $f_{PCM}$ , then the required minimum sampling rate would be  $2f_{PCM}$ .

Therefore, 
$$2f_{PCM} = nf_s$$
 or  $f_{PCM} = \left(\frac{n}{2}\right)f_s$  (1.24)

Generating a PCM signal is a complex process. The message signal is usually sampled and first converted into a PAM signal, which is then quantized and encoded. The encoded signal can then be transmitted either directly via a cable or used to modulate a carrier using analogue or digital modulation techniques. PCM-AM is quite common.

### 1.2.6.2 Differential PCM

*Differential PCM* is similar to conventional PCM. The difference between the two lies in the fact that, in differential PCM, each word or code group indicates a difference in amplitude





Figure 1.27 (a) Delta modulator and (b) output waveform.

(positive or negative) between the current sample and the one immediately preceding. Thus, it is not the absolute but the relative value that is indicated. The bandwidth required as a consequence is lower compared to that required in the case of normal PCM.

### 1.2.6.3 Delta Modulation

*Delta modulation* has various forms. In one of the simplest forms, only one bit is transmitted per sample just to indicate whether the amplitude of the current sample is greater or smaller than the amplitude of the immediately preceding sample. It has extremely simple encoding and decoding processes but then it may result in tremendous quantizing noise in case of rapidly varying signals.

Figure 1.27(a) shows a simple delta modulator system. The message signal m(t) is added to a reference signal with the polarity shown. The reference signal is integral of the delta modulated signal. The error signal e(t) produced is fed to a comparator. The output of the comparator is  $(+\Delta)$  for e(t) > 0 and  $(-\Delta)$  for e(t) < 0. The output of the delta modulator is a series of impulses

with the polarity of each impulse depending upon the sign of e(t) at the sampling time instance. Integration of delta modulated output  $x_{DM}(t)$  is a staircase approximation of message signal m(t), as shown in Figure 1.27(b).

The delta modulated signal can be demodulated by integrating the modulated signal to get the staircase approximation and then passing it through a low pass filter. The smaller the step size  $\Delta$ , the better the reproduction of the message signal. However, small step size must be accompanied by a higher sampling rate if the slope overload phenomenon is to be avoided. In fact, to avoid slope overload and associated signal distortion the following condition should be satisfied.

$\Delta_{=}$	$\left[\frac{dm(t)}{dm(t)}\right]$	(1.2	25)
$T_s$	$d(t) \rfloor_{\max}$		

Where  $T_s$  = time between successive sampling time instants.

### 1.2.6.4 Adaptive Delta Modulator

This is a type of delta modulator. In delta modulation, the dynamic range of amplitude of message signal m(t) is very small due to threshold and overload effects. This problem is overcome in an adaptive delta modulator. In adaptive delta modulation, the step size  $\Delta$  is varied according to the level of message signal. The step size is increased as the slope of the message signal increases to avoid overload. The step size is reduced to reduce the threshold level and hence the quantizing noise when the message signal slope is small. In case of adaptive delta modulation, however, the receiver also needs to be adaptive. The step size at the receiver should also be made to change to match the changes in step size at the transmitter.

### 1.2.7 Sampling Theorem

During our discussion on digital pulse communication techniques such as pulse code modulation, delta modulation and so on, we have noticed that the three essential processes of such a system are sampling, quantizing and encoding. *Sampling* is the process in which a continuous time signal is sampled at discrete instants of time and its amplitude at those discrete instants of time are measured. *Quantization* is the process by which the sampled amplitudes are represented in the form of a finite set of levels. The *encoding* process designates each quantized level by a code. Digital transmission of analogue signals has been made possible by sampling the continuous time signal at a certain minimum rate, which is dictated by what we call *sampling theorem*.

Sampling theorem states that a band limited signal with the highest frequency component as  $f_M$  Hz can be recovered completely from a set of samples taken at the rate of  $f_s$  samples per second provided that  $f_s \ge 2f_M$ . This theorem is also known as the *Uniform Sampling Theorem* for base band or low pass signals. The minimum sampling rate of  $2f_M$  samples per second is called the *Nyquist rate* and its reciprocal is the *Nyquist interval*. For sampling of band pass signals, lower sampling rates can sometimes be used.

The sampling theorem for band pass signals states that if a band pass message signal has a bandwidth of  $f_B$  and an upper frequency limit of  $f_u$ , then the signal can be recovered from the sampled signal by band pass filtering if  $f_s = (2f_u/k)$  where k is the largest integer not exceeding  $(f_u/f_B)$ .

### 1.2.8 Shannon–Hartley Theorem

The *Shannon-Hartley theorem* describes the capacity of a noisy channel (assuming that the noise is random). According to this theorem,

$$C = B\log_2\left[1 + \left(\frac{S}{N}\right)\right] \text{bits/second}$$
(1.26)

Where *C* = Channel capacity in bits/second

B = Channel bandwidth in Hz

S/N = Signal-to-noise ratio at the channel output or receiver input.

The Shannon–Hartley theorem underlines the fundamental importance of bandwidth and signal-to-noise ratio in communication. It also shows that, for a given channel capacity, we can exchange increased bandwidth for decreased signal power. It may be mentioned that increasing the channel bandwidth by a certain factor does not increase the channel capacity by the same factor in a noisy channel, as would be suggested by Shannon–Hartley theorem apparently. This is because increasing the bandwidth also increases noise, thus decreasing *S*/*N* ratio. However, channel capacity does increase with increase in bandwidth; the increase will not be in the same proportion.

### 1.2.9 Digital Modulation Techniques

Base band digital signals have significant power content in the lower part of the frequency spectrum. Because of this, these signals can be conveniently transmitted over a pair of wires or coaxial cables. At the same time, for the same reason, it is not possible to have efficient wireless transmission of base band signals as it would require prohibitively large antennas, which would not be a practical or feasible proposition. Therefore, if base band digital signals are to be transmitted over a wireless communication link, they should first modulate a CW high-frequency carrier. Three well-known techniques available for the purpose include:

- 1) Amplitude Shift Keying (ASK)
- 2) Frequency-Shift Keying (FSK)
- 3) Phase Shift Keying (PSK)

Each one of these is described in the following paragraphs. Of the three techniques used for digital carrier modulation, PSK and its various derivatives such as Differential PSK (DPSK), Quadrature PSK (QPSK) and Offset Quadrature PSK (O-QPSK) are the most commonly used ones; more so for satellite communications because of certain advantages they offer over others. PSK is therefore described in a little more detail.

### 1.2.9.1 Amplitude Shift Keying (ASK)

In the simplest form of ASK, the carrier signal is switched ON and OFF depending upon whether a 1 or 0 is to be transmitted (Figure 1.28). For obvious reasons, this form of ASK is also known as *ON-OFF Keying* (OOK). The signal in this case is represented by:

 $X_{c}(t) = A \sin \omega_{c} t$  for bit 1 and  $X_{c}(t) = 0$  for bit 0.

ON-OFF keying has the disadvantage that appearance of any noise during transmission of bit 0 can be misinterpreted as data. This problem can be overcome by switching the amplitude of



Figure 1.29 Two-amplitude shift keying.

the carrier between two amplitudes, one representing a 1 and the other representing a 0 as shown in Figure 1.29. Again, the carrier can be suppressed to have maximum power in information carrying signals and also one of the side bands can be filtered out to conserve the bandwidth.

### 1.2.9.2 Frequency Shift Keying (FSK)

In FSK, it is the frequency of the carrier signal that is switched between two values, one representing bit 1 and the other representing bit 0, as shown in Figure 1.30. The modulated carrier signal in this case is represented by:

 $X_{c}(t) = A \sin \omega_{c1} t \text{ for bit 1 and}$  $X_{c}(t) = A \sin \omega_{c2} t \text{ for bit 0.}$ 

In the case of FSK, when modulation rate increases, the difference between the two chosen frequencies to represent a 1 and a 0 also needs to be higher. Keeping in view the restriction in available bandwidth, it would not be possible to achieve bit transmission rate beyond a certain value.



Figure 1.30 Frequency shift keying.

### 1.2.9.3 Phase Shift Keying (PSK)

In PSK, the phase of the carrier is discretely varied with respect to either a reference phase or to the phase of the immediately preceding signal element in accordance with the data being transmitted. For example, when encoding bits, the phase shift could be 0° for encoding a bit 0 and 180° for encoding a bit 1, as shown in Figure 1.31. The phase shift could have been -90° for encoding a bit 0 and +90° for encoding a bit 1. The essence is that representations for 0 and 1 are a total of 180° apart. Such PSK systems in which the carrier can assume only two different phase angles are known as Binary Phase Shift Keying (BPSK) systems. We can appreciate that in BPSK systems each phase change carries one bit of information. This, in other words, means that bit rate equals the modulation rate. Now if the number of recognizable phase angles were increased to four, then two bits of information could be encoded into each signal element.

Coming back to BPSK, the carrier signals used to represent 0 and 1 bits could be expressed as:

$$X_{c0}(t) = A\cos(\omega_c t + \theta_0)$$
$$X_{c1}(t) = A\cos(\omega_c t + \theta_1)$$

Since the phase difference between two carrier signals is 180°; that is,  $\theta_1 = \theta_0 + 180^\circ$ Then,  $X_{c0}(t) = A\cos(\omega_c t + \theta_0)$  and  $X_{c1}(t) = -A\cos(\omega_c t + \theta_0)$ .

### 1.2.9.4 Differential Phase Shift Keying (DPSK)

Another form of PSK is *DPSK*. Instead of an instantaneous phase of carrier determining which bit is transmitted, it is the change in phase that carries message intelligence. In this system, one logic level (say 1) represents a change in phase of carrier and the other logic level (i.e., 0) represents a no change in phase. In other words, if a digit changes in the bit stream from 0 to 1 or 1 to 0, a 1 is transmitted in the form of change in phase of carrier signal. And in case, there is no change, a 0 is transmitted in the form of no phase change in carrier.

The BPSK signal is detected using a coherent demodulator where a locally generated carrier component is extracted from received carrier by a PLL circuit. This locally generated carrier assists in the product demodulation process where the product of the carrier and the received



Figure 1.31 Binary phase shift keying.



Figure 1.32 Block-schematic arrangement of a typical QPSK modulator.

modulated signals generate the demodulated output. There could be difficulty in successfully identifying the correct phase of regenerated signal for demodulation. DPSK takes care of this ambiguity to a large extent.

### 1.2.9.5 Quadrature Phase Shift Keying (QPSK)

QPSK is the most commonly used of all forms of PSK. A QPSK modulator is nothing but two BPSK modulators operating in quadrature. The input bit stream ( $d_0$ ,  $d_1$ ,  $d_2$ ,  $d_3$ ,  $d_4$ ...) representing the message signal is split into two bit streams, one with, say, even numbered bits ( $d_2$ ,  $d_4$ ...) and the other with odd numbered bits ( $d_1$ ,  $d_3$ ,  $d_5$ ,...). Also, in QPSK, if each pulse in the input bit stream has a duration of *T* seconds, then each pulse in the even/odd numbered bit streams has a pulse duration of 2 *T* seconds. Figure 1.32 shows the block-schematic arrangement of a typical QPSK modulator. One of the bit streams  $d_i(t)$  feeds the in-phase modulator while the other bit stream  $d_q(t)$  feeds the quadrature modulator. The modulator output can be written as eqn. 1.27.

$$x(t) = \frac{1}{\sqrt{2}} \left[ d_i(t) \cos(\omega_c t + \pi/4) \right] + \frac{1}{\sqrt{2}} \left[ d_q(t) \sin(\omega_c t + \pi/4) \right]$$
(1.27)



Figure 1.33 Conceptual diagram of QPSK.



Figure 1.34 QPSK phase diagram.

This expression can also be written in a simplified way as  $x(t) = \cos[\omega_c t + \theta(t)]$ .

The in-phase bit stream represented by  $d_i(t)$  modulates the cosine function and has the effect of shifting the phase of the function by 0 or  $\pi$  radians. This is equivalent to BPSK. The other pulse stream represented by  $d_q(t)$  modulates the sine function thus producing another BPSK like output that is orthogonal to the one produced by  $d_i(t)$ . The vector sum of the two produces a QPSK signal given by  $x(t) = \cos[\omega_c t + \theta(t)]$ . Figure 1.33 illustrates it further.

 $\theta(t)$  will have any of the four values of 0°, 90°, 180° and 270° depending upon the status of pair of bits having one bit from  $d_i(t)$  bit stream and the other from the  $d_q(t)$  bit stream. Four possible combinations are 00, 01, 10 and 11. Figure 1.34 illustrates the process further. It shows all possible four phase states. The in-phase bits operate on the vertical axis at phase states of 90° and 270° whereas the quadrature-phase channel operates on horizontal axis at phase states of 0° and 180°. The vector sum of the two produces each of the four phase states as shown. As mentioned earlier, phase state of QPSK modulator output depends upon a pair of bits. The phase states in the present case would be 0°, 90°, 180° and 270° for input combinations 11, 10, 00 and 01, respectively.



Figure 1.35 Offset QPSK waveform.

Since each symbol in the case of QPSK comprises of two bits, symbol transmission rate is half of bit transmission rate of BPSK, the bandwidth requirement is halved. The power spectrum for QPSK is same as that for BPSK.

### 1.2.9.6 Offset QPSK

The *Offset QPSK* is similar to QPSK with the difference that the alignment of the odd/even streams is shifted by an offset equal to *T* seconds as shown in Figure 1.35. In the case of QPSK, as explained earlier, carrier phase change can occur every 2*T* seconds. If neither of the two streams changes sign, the carrier phase remains unaltered. If only one of them changes sign, carrier phase undergoes a change of  $+90^{\circ}$  or  $-90^{\circ}$  and both change sign, the carrier phase undergoes a change of  $+90^{\circ}$  or  $-90^{\circ}$  and both change sign, the carrier phase undergoes a change of  $+90^{\circ}$  or  $-90^{\circ}$  and both change sign, the carrier phase undergoes a change of  $+90^{\circ}$  or  $-90^{\circ}$  and both change sign, the carrier phase undergoes a change of  $+90^{\circ}$  or  $-90^{\circ}$  and both change sign, the carrier phase undergoes a change of  $+90^{\circ}$  or  $-90^{\circ}$  and both change sign, the carrier phase undergoes a change of  $180^{\circ}$ . In such a situation, the QPSK signal no longer has a constant envelope if the QPSK signal is filtered to remove spectral side lobes. If such a QPSK signal is passed through a nonlinear amplifier, the amplitude variations could cause spectral spreading to restore unwanted side lobes, which in turn could lead to interference problems. Offset QPSK overcomes this problem. Due to staggering of in-phase and quadrature-phase bit streams, the possibility of the carrier phase changing state by  $180^{\circ}$  is eliminated as only one bit stream can change state at any time instant of transition. A phase change of  $+90^{\circ}$  or  $-90^{\circ}$  does cause a small drop in the envelope but it does not fall to near zero as in the case for QPSK for  $180^{\circ}$  phase change.

### 1.2.10 Multiplexing Techniques

Multiplexing techniques are used to combine several message signals into a single composite message so that they can be transmitted over a common channel. The multiplexing technique ensures that the different message signals in the composite signal do not interfere with each other and that they can be conveniently separated out at the receiver end. The two basic multiplexing techniques in use include:

- 1) Frequency Division Multiplexing (FDM)
- 2) Time Division Multiplexing (TDM)

While *FDM* is used with signals that employ analogue modulation techniques, *TDM* is used with digital modulation techniques where the signals to be transmitted are in the form of a bit stream. The two techniques are briefly described in the following paragraphs.

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Figure 1.36 Frequency division multiplexing.

### 1.2.10.1 Frequency Division Multiplexing

In the case of *Frequency Division Multiplexing* (FDM), different message signals are separated from each other in frequency. Figure 1.36 illustrates the concept of FDM showing simultaneous transmission of three message signals over a common communication channel. As is clear from the block-schematic arrangement shown, each of the three message signals modulates a different carrier. The most commonly used modulation technique is the single side band (SSB) modulation. Any type of modulation can be used as long as we ensure that the carrier spacing is sufficient to avoid a spectral overlap. On the receiving side, band pass filters separate out the signals, which are then coherently demodulated as shown. The composite signal formed by combining different message signals after they have modulated their respective carrier signals may be used to modulate another high-frequency carrier before it is transmitted over the common link. In that case, these individual carrier signals are known as sub-carrier signals.

FDM is used in telephony, commercial radio broadcast (both AM and FM), television broadcast, communication networks and telemetry. In the case of commercial AM broadcast, the carrier frequencies for different signals are spaced 10 kHz apart. This separation is definitely not adequate if we consider a high-fidelity voice signal with a spectral coverage of 50 Hz–15 kHz. Because of this reason, AM broadcast stations using adjacent carrier frequencies are usually geographically far apart to minimize interference. In case of FM broadcast, the carrier frequencies are 200 kHz apart. In the case of long-distance telephony, 600 or more voice channels, each with a spectral band of 200 Hz–3.2 kHz, can be transmitted over a coaxial or microwave link using SSB modulation and a carrier frequency separation of 4 kHz.

### 1.2.10.2 Time Division Multiplexing

*Time Division Multiplexing (TDM)* is used for simultaneous transmission of more than one pulsed signals over a common communication channel. Figure 1.37 illustrates the concept. Multiple pulsed signals are fed to a type of electronic switching circuitry called the *commutator* in the figure. All the message signals, which have been sampled at least at the Nyquist rate (the sampling is usually done at 1.1 times the Nyquist rate to avoid aliasing problem), are fed to the commutator. The commutator interleaves different samples from different sampled message signals so as form a composite interleaved signal. This composite signal is then transmitted



Figure 1.37 Time division multiplexing.

over the link. In the case where all message signals have same bandwidth, one commutation cycle will contain one sample from each of the messages. But in case signals have different bandwidths, then one would need to transmit more number of samples per second of the signals with a larger bandwidth. As an illustration, if there are three message signals with respective sampling rates of 2.4, 2.4 and 4.8 kHz, then each cycle of commutation will have one sample each from the first two messages and two samples from the third message.

At the receiving end, the composite signal is de-multiplexed using a similar electronic switching circuitry that is synchronized with the one used at the transmitter. TDM is widely used in telephony, telemetry, radio broadcast and data processing. If T is the sampling time interval of the time multiplexed signal of *n* different signals each with a sampling interval of  $(T_s)$ , then  $T = T_s/n$ . Also, if the time multiplexed signal is considered a low pass signal with a bandwidth of  $f_{TDM}$  and  $f_m$  is the bandwidth of individual signals, then  $f_{TDM} = nf_m$ .

#### **Communication Transmitters and Receivers** 1.3

Having discussed different analogue and digital modulation and the corresponding demodulation techniques, in the following paragraphs we shall briefly describe (with the help of block-schematic arrangements) different types of transmitters and receivers that use these modulation and demodulation schemes.

#### 1.3.1 **Elements of the Communication System**

The basic communication system - irrespective of whether it is an analogue or digital communication system, microwave communication system or the one operating at relatively lower carrier frequency, point-to-point communication or broadcast communication, the message signal to be transmitted is audio, video or data - has three essential elements, namely the Transmitter, the Transmission or Communication Channel and the Receiver. Extending it further, the communication systems would have Source of Message Signal and Input Transducer preceding the transmitter and Output Transducer following the receiver. Figure 1.38 shows the block-schematic arrangement of a generalized

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Figure 1.38 Block-schematic arrangement of a generalized communication system.

communication system. The block marked Noise/Interference represents the noise and interference that gets introduced into the transmitted signal as it propagates through the communication channel.

The *source of information* or message signal generates the information or message signal to be transmitted. It could be audio, video or data. The *input transducer* is used only in cases where the message signal to be transmitted is not electrical in nature. The transducer converts the non-electrical message signal into a time varying electrical signal. A microphone used to convert sound waves into an equivalent electrical signal is an example of transducer. The function of the *transmitter* is to process the electrical signal from different aspects. The primary function of transmitter is modulation, which is the process of changing one of the properties (amplitude, frequency or phase) of the high-frequency carrier signal in accordance with the message signal. The message signal may need to be processed before modulation. Processing may involve filtering such as restricting the range of audio frequencies in an AM radio broadcast transmitter, signal amplification and so on. The term *channel* means the medium through which the message travels from the transmitter to the receiver. In other words, we can say that the function of the channel is to provide a physical connection between the transmitter and the receiver.

Communication channels provide the physical medium for transmission of signals from one point to another. Communication channels are either point-to-point channels such as microwave links, wired lines, optical fibres or broadcast channels where a single transmitter signal reaches a large number of receivers; an example being the one provided by a satellite in geostationary orbit covering about one-third of Earth's surface. As the signal propagates through the communication channel, the signal gets distorted due to noise. Though noise may creep into the signal at any point, it adversely affects the signal the most while it is propagating through the channel. The *receiver* receives the noise-affected signal and reproduces the message signal from the distorted modulated signal by a process called demodulation or detection. The *output transducer* restores the demodulated electrical signal representing the message to its original form.

### 1.3.2 Classification of Transmitters

Radio transmitters are generally classified on the basis of operating carrier frequency, type of modulation techniques used by the transmitter and the nature of service provided by the transmitter. On the basis of operating frequency, they are classified as Medium Frequency (MF) transmitters, High-Frequency (HF) transmitters, Very High Frequency (VHF) transmitters and Ultra-High Frequency (UHF) transmitters. On the basis of type of modulation, they are classified as Amplitude Modulated (AM) transmitters, Frequency Modulated (FM) transmitters, Phase Modulated (PM) transmitters, Amplitude Shift Keying (ASK) transmitters,
Frequency-Shift Keying (FSK) transmitters and Phase Shift Keying (PSK) transmitters and different variants. According to the nature of service or function provided by the transmitter, we have radio telegraph transmitters, television transmitters, radar transmitters, navigation transmitters and so on.

*MF transmitters* operate over the 300 kHz–3 MHz frequency band. MF transmitters are used for AM radio broadcast services that employ the 535-1705 kHz band, maritime and aircraft navigation, amateur radio, cordless phones and so on. HF transmitters that operate over the HF band (3-30 MHz) and use the ionosphere as a means of electromagnetic wave propagation (commonly known as sky wave propagation) are particularly suitable for long-distance communication across intercontinental distances. The band is extensively used by international shortwave broadcasting stations as the entire short waveband of frequencies (2.310-25.820 MHz) falls within the HF band. Other examples of HF transmitter use include aviation communication, such as HF radios used on board aircraft to provide effective communication over long-distance oceanic and transpolar routes, weather stations and amateur radio and citizens' band services. Amateur radio relates to use of radio frequency spectrum for voice, text, image and data communication for non-commercial purposes such as wireless experimentation, radio sport, training, emergency services and so on. It is allocated one band in the MF (Medium Frequency) band and several bands in the HF band. The Citizens' Band (CB) Radio Service that is allocated 40 channels in the 26.965–27.405 MHz frequency band is a private, two-way, short-distance voice communications service for the personal or business activities of the general public. It may also be used for voice paging. VHF transmitters operate over the VHF band (30-300 MHz) and use space wave line-of-sight propagation. The radio horizon is slightly longer than the geometric line-of-sight horizon due to bending of electromagnetic waves by the atmosphere. VHF transmitters are commonly used for FM radio broadcasting employing the 87.5-108 MHz frequency band with a few exceptions such as 76-90 MHz used in Japan and 65-74 MHz used in the Eastern Bloc of the erstwhile Soviet Republic, television broadcasting, two-way land mobile radio systems for various private, business, military and emergency services, long-range data communication, amateur radio and marine communications. Air traffic control communications and air navigation systems are other applications. UHF transmitters operate over the UHF-band (300 MHz-3 GHz). UHF transmitters find applications in a large number of communication services, which include television broadcasting, cell phone communication, cordless phones, satellite communication, WiFi and Bluetooth services and so on.

On the basis of type of modulation used, transmitters are classified as AM transmitters, FM transmitters and PM transmitters, ASK transmitters, FSK transmitters and different variants of PSK transmitters. *AM transmitters* employ amplitude modulation. These transmitters are used in medium wave (MW) and short wave (SW) frequency bands for AM broadcast. Based on the transmitted power levels, AM transmitters use a high-level modulation scheme where the transmitted power needs to be of the order of kilowatts and low-level modulation where only a few watts of power need to be transmitted. *FM transmitters* employ frequency modulation. One of the most common applications of FM transmitters is in FM broadcasting, which is nothing but radio broadcasting using frequency modulation. FM broadcasting first began in 1945 and is now used worldwide to provide high-fidelity voice and music over broadcast radio. FM broadcasting employs the VHF band of 30–300 MHz. FM broadcast range is limited by optical visibility. Range doesn't increase linearly with transmitted power. An Effective Radiated Power (ERP) of 30 W would give a coverage range of about 15 km and an ERP of 300 W would probably give a range of 45 km, provided it is not limited by optical visibility. In addition to FM broadcasting, other important applications of FM transmitters

include telemetry, radar, two-way radio systems and medical diagnostics. *PM transmitters* employ phase modulation. Phase modulation and frequency modulation are closely linked together (frequency is rate of change of phase) and it is often used in many transmitters and receivers such as two-way radios and mobile radio communications including maritime mobile radio communications.

Like the AM, FM and PM transmitters that use analogue modulation techniques, we have transmitters such as ASK, FSK and PSK transmitters employing digital modulation techniques. *ASK modulation* is commonly used in LED transmitters for transmission of digital data through optical fibres. Other applications of ASK transmitters include remote control operations and security systems. *FSK transmitters* are also used for remote control and security systems. Integrated circuits that can generate different forms of ASK and FSK signals are commercially available for these applications. ASK and FSK transmitters operate in the VHF/UHF bands. *PSK transmitters* employ any of the different forms of phase shift keying, which include Phase Shift Keying (PSK), Binary Phase Shift Keying (BPSK), Quadrature-Phase Shift Keying (QPSK), 8 Point Phase Shift Keying (8 PSK), 16 Point Phase Shift Keying (16 PSK), Quadrature Amplitude Modulation (QAM), 16 Point Quadrature Amplitude Modulation (16 QAM) and 64 Point Quadrature Amplitude Modulation (64 QAM). PSK is particularly suited to data communications. PSK in its different forms is extensively used for wireless LANs, Radio Frequency Identification (RFID) and Bluetooth communication.

Based on the function performed by transmitter, they are classified into Television Transmitters, Radar Transmitters, Radio Control Transmitters, Navigation Transmitters and so on. *Television transmitters* use AM transmitters for transmission of picture information and FM transmitters for transmission of sound. *Radar transmitters* may be one of two types; namely the Continuous-Wave Radar Transmitter and Pulsed Radar Transmitter. *Radio Control Transmitters* are used for remote control operations. Navigation Transmitters and Receivers are used as navigational aids for sea and air navigation.

### 1.3.3 Continuous-Wave (CW) Transmitter

The CW transmitter makes use of a radio communication technique that uses an undamped continuous-wave signal of constant amplitude and frequency. The signal is obviously a sinusoidal waveform. The CW transmitter is principally used for radiotelegraphy; that is, for the transmission of short or long pulses of RF energy to form the dots and dashes of the Morse code characters. A significant advantage of CW transmission is its narrow bandwidth, which not only reduces output power requirement on the part of the transmitter but also makes the communication immune to noise and interference.

Figure 1.39 shows the simplified block-schematic arrangement of a CW transmitter. It comprises an RF oscillator that generates the sinusoidal waveform at the desired frequency; a buffer or preamplifier to amplify the oscillator output to a level sufficient to drive the power amplifier; a power amplifier that amplifies the RF oscillations to power level to get the desired range; a device to turn the RF output on and off, a process known as keying, in accordance with the intelligence to be transmitted and a power supply to operate different sections of the transmitter and an antenna to radiate keyed RF signal. The buffer also serves the purpose of isolating the amplifier stages from the oscillator. Variations in source voltage or/and changes in amplifier due to keying would vary the load on the oscillator and hence change the frequency. A buffer stage ensures that the oscillator sees a constant load.

There is currently no commercial traffic using Morse code characters, but it is still popular with amateur radio operators. Another application area where information is transmitted using Morse code characters is in non-directional beacons used for air navigation.



Figure 1.39 Block-schematic arrangement of a CW transmitter used for wireless telegraphy.



Figure 1.40 CW receiver used in wireless telegraphy.

## 1.3.4 CW Receiver

A CW receiver is used for detection of continuous-wave communication signals. Figure 1.40 shows a simplified block-schematic arrangement of a *direct conversion receiver* that can be used for detection of CW signals such as those transmitted in wireless telegraphy using Morse code. The incoming RF signal is passed through a Band Pass Filter (BPF) with its centre frequency equal to the transmitted carrier frequency. The band pass filter ensures that the signal fed to the *RF amplifier*, and subsequently to the *product detector*, is very close in frequency to the carrier frequency and that unwanted frequencies are eliminated. The incoming signal after passing through the band pass filter is mixed with the output of a Beat Frequency Oscillator (BFO) in the product detector. The product detector converts the incoming signal from RF frequencies to audio frequencies. It is simply another mixer whose output is the difference between the BFO frequency and the received carrier RF frequency. The BFO has a frequency very close to that of the RF input so that the output signal of the product detector is in the audio range. For CW, the difference between the input frequency and the BFO frequency is kept to about 800 Hz. This 800 Hz tone is then amplified in an *audio amplifier* and fed to a *loudspeaker*. This is the tone we hear when we listen to CW. Since the BFO can mix with two different frequencies, one above and one below the received carrier frequency to get the same output tone, for this reason the input RF signal is band pass filtered so as to contain only a narrow range of frequencies. This keeps the audio output cleaner with fewer undesired signals.

# 1.3.5 Amplitude Modulated (AM) Transmitter

As outlined in an earlier paragraph, AM transmitters are broadly classified as those employing *low-level modulation* and those employing *high-level modulation*. While detailing the amplitude modulation technique, we discussed different forms of amplitude modulation including Double Side Band (DSB) with full carrier, also known as Standard AM or A3E, Double Side Band with Suppressed Carrier (DSBSC), Single Side Band (SSB) with full carrier known as H3E, Single Side Band with Reduced Carrier (R3E) and Single Side Band with Suppressed Carrier (SSBSC) known as J3E. In the following paragraphs, we shall discuss AM transmitters employing low-level and high-level modulation schemes, which will be followed by a brief description of standard AM broadcast transmitters and SSB transmitters.

## 1.3.5.1 Low-Level AM Transmitter

In the case of low-level modulation, amplitude modulation of the carrier signal takes place at a much lower power level of the carrier signal and the modulated signal is then amplified in a chain of linear amplifiers to raise the power required for transmission. Figure 1.41 shows a block-schematic arrangement of a low-level amplitude modulated transmitter. The RF oscillator generates the carrier signal of desired frequency. The *buffer* is nothing but an amplifier stage required to raise power level of carrier signal before it is fed to *modulator*. This ensures that we don't draw too much power from the oscillator that could lead to change in its frequency. The modulating signal, which is an audio signal in case of AM broadcast, is also amplified to the desired level before it is fed to the modulator. The modulator is also a kind of amplifier operating in the nonlinear region. As its output, it produces a double side band full carrier signal. The modulated signal is then amplified in the *driver amplifier* and the *power amplifier* to raise the power to desired level as required for transmission by antenna. It should be mentioned that all amplifiers following the modulator must be linear. That is, they are either Class A amplifiers or Class B push-pull amplifiers. The advantage of low-level amplitude modulation is that not much audio power is required. The disadvantage is reduced efficiency due to use of linear amplifiers. Low-level amplitude modulation is usually used in low power transmitters such as those in Walkie-Talkies.

## 1.3.5.2 High-Level Amplitude Modulated Transmitter

In the case of high-level modulation, the carrier signal is modulated at a much higher power level equal to the power to be transmitted. The carrier signal here is amplified in a chain of Class C amplifiers to raise the power to the level required for transmission. Figure 1.42 shows a block-schematic arrangement of a high-level amplitude modulated transmitter. The RF oscillator generates the carrier signal of the desired frequency. The buffer is nothing but an



Figure 1.41 Block-schematic of a low-level amplitude modulated transmitter.



Figure 1.42 Block-schematic of a high-level amplitude modulated transmitter.



Figure 1.43 Block-schematic arrangement of a superheterodyne AM broadcast receiver.

amplifier stage required to raise the power level of carrier signal before it is fed to modulator and serves the same purpose as the one in case of low-level modulation. The modulating signal, which is an audio signal in case of AM broadcast, is also amplified to the desired level before it is fed to the power amplifier where the modulation takes place. As outlined before, all amplifiers used to amplify the carrier signal can be high efficiency Class C amplifiers as they have to amplify only a pure sinusoidal signal. This is the key advantage of high level modulation. The disadvantage is that the modulating signal needs to be amplified to a high level to be able to modulate a high-power carrier. High level modulation is generally used in high power AM transmitters used at broadcast stations and also in high power amateur transmitters operating in the AM mode only.

## 1.3.6 AM Receiver

The *superheterodyne receiver* is the receiver of choice in modern AM receivers. Figure 1.43 shows block-schematic arrangement of a superheterodyne AM receiver. The RF amplifier amplifies the entire band of frequencies, such as the broadcast band in the case of an AM broadcast transmitter or the amateur band in case of an amateur radio transmitter, received by the antenna. The amplified RF signal is fed to the mixer, which is a nonlinear device. The mixer is also fed with the signal from a local oscillator. The local oscillator frequency is kept higher than the received RF signal frequency by an amount equal to intermediate frequency. The intermediate frequency is 455 kHz in case of an AM broadcast receiver. While tuning in different radio stations operating at different carrier frequencies, the resonant frequencies of tuned circuits of RF amplifier and local oscillator are simultaneously varied to maintain this constant

difference of 455 kHz. The signal at the output of the mixer is also an amplitude modulated signal with its side band information intact, except for the fact that the carrier frequency is now 455 kHz. In fact, in an AM broadcast receiver, it will be 455 kHz irrespective of the station tuned in to. An intermediate frequency amplifier comprises a cascade arrangement of several stages of amplification. Different stages of IF amplification are sharply tuned to 455 kHz with the desired bandwidth. Most of signal amplification occurs in IF amplifiers. The signal is then demodulated. The amplified modulated signal at intermediate frequency is demodulated in the envelope detector. It is a diode detector with a low pass filter to filter out the high-frequency carrier. The audio amplifier stage amplifies the demodulated signal before it is fed to the loudspeaker. The audio amplifier is a two-stage amplifier comprising a preamplifier and a power amplifier.

One of the problems of superheterodyne receivers arises from the image frequency. Image frequency is the signal frequency that would produce the same intermediate frequency as the desired signal frequency. For example, if the desired signal frequency is 1600 kHz, then the local oscillator frequency would be 2055 kHz. The image frequency in this case is 2510 kHz and also produces a 455 kHz signal frequency at the output of the mixer. Therefore, it is likely to interfere with the desired frequency. The image frequency signal, if lying within the broadcast band, is substantially attenuated in the tuning stage of the RF amplifier. Also, radio broadcast stations operating in the same area are assigned frequencies to avoid such a situation.

Some receivers such as amateur receivers have two intermediate frequencies. These are 10.7 MHz (first IF) and 455 kHz (second IF). While the first IF is produced by a variable frequency local oscillator; generation of second IF employs fixed frequency local oscillator. Use of two intermediate frequencies enhances selectivity further.

Sensitivity, selectivity, fidelity and noise performance are the important characteristics of an AM broadcast receiver. *Sensitivity* is a measure of a receiver's ability to produce the desired *S/N* ratio for weak received signals. It is measured as received signal strength in microvolts to produce a signal-to-noise ratio of 10 dB. *Selectivity* is the ability of the receiver to reject unwanted signals at the input of receiver. The *fidelity* of a receiver is its ability to accurately reproduce at its output the signal that appears at its input. A broader receiver bandwidth produces high fidelity. This is in contrast to the requirement of narrower bandwidth for better selectivity. Most receivers are a compromise between good selectivity and high fidelity. *Noise* limits the usable input signal of the receiver. A noise level of 0 dB is ideal.

### 1.3.7 Single Side Band (SSB) Transmitter

SSB modulation as outlined earlier is a type of amplitude modulation in which one of the side bands, either the upper side band or lower side band, is suppressed and only one side band is transmitted. SSB modulation and SSBSC (Single Side Band Suppressed Carrier) modulation techniques offer more efficient use of transmitter bandwidth and power. Figure 1.44 shows the block-schematic arrangement of an SSB transmitter. The modulator combines the modulating signal input, which is an audio signal, and the carrier signal input to produce the modulated signal with carrier and two side bands. The filter selects the desired side band and suppresses the other one. The filter pass band can also be so chosen as to suppress the carrier along with one of the side bands. In most cases, SSB generators operate at very low frequencies as compared to the normally transmitted frequencies. The filter output is translated to the desired frequency in the mixer stage. The mixer is fed with the filter output and the carrier generator output after its frequency is multiplied in the frequency multiplier. The output from the mixer is fed to a linear power amplifier to raise the signal power to the desired level for transmission.



Figure 1.44 Block-schematic arrangement of an SSB transmitter.



Figure 1.45 Block-schematic of an SSBSC transmitter using the phase shift method.

Another method of generating the SSB signal is the phase shift method. Figure 1.45 shows the block-schematic arrangement of an SSB transmitter based on the phase shift method. The phase shift technique uses two balanced modulators. One of the balanced modulators is fed with modulating signal, which is the audio signal, and the high-frequency carrier signal. The other balanced modulator is fed with modulating signal and the carrier signal with both phases shifted by 90°. Both balanced modulators produce the product of the two signals fed at the inputs. If the carrier and modulating signals are respectively expressed by  $V_c \cos \omega_c t$  and  $V_m \cos \omega_m t$ , then the output of first balanced modulator will be  $1/2[\cos(\omega_c - \omega_m)t - \cos(\omega_c + \omega_m)t]$ . The output of second balanced modulator that is fed with phase shifted signals is given by  $1/2[\cos(\omega_c - \omega_m)t + \cos(\omega_c + \omega_m)t]$ . The two signals present at the outputs of balanced modulators are summed up to produce the difference frequency component only. That is, the output contains only the lower side band and the carrier is also suppressed. The output is therefore an SSBSC signal.

### 1.3.8 SSB Receiver

An SSB receiver is also a superheterodyne receiver, discussed in Section 1.3.6, comprising an RF amplifier, a mixer along with a local oscillator, intermediate frequency amplifier stage, a





Figure 1.46 Block-schematic of an SSB receiver.



Figure 1.47 Block-schematic of a double conversion SSB receiver.

detector, an audio amplifier stage and a loudspeaker. Figure 1.46 shows the simplified blockschematic of an SSBSC receiver. One difference between the standard AM broadcast receiver and the SSBSC receiver is that the carrier signal needs to be reinserted at the detector for the detection process to occur. This may be done by using another oscillator called a *carrier insertion oscillator*. In a case where a pilot carrier is transmitted, it may be separated or removed from the signal at the output of IF amplifier using a filter, amplified and then reinserted at the detector. The receiver will also have AGC (Automatic Gain Control) and AFC (Automatic Frequency Control) circuits, not shown in the block diagram. The AGC circuit controls gain of RF and IF amplifiers and AFC controls the frequency of local oscillator. Functions of different sections have been explained in the case of an AM broadcast receiver.

Double conversion superheterodyne receiver configuration is also used for SSB receivers. In this case, the AFC, again not shown in the diagram for the sake of simplicity, controls the frequency of second local oscillator. Figure 1.47 shows the block-schematic of a double conversion SSB receiver.

## 1.3.9 Frequency Modulated (FM) Transmitter

In the case of a frequency modulated signal, the carrier frequency is varied in accordance with the amplitude of modulating signal with the amplitude of carrier signal remaining nearly constant. Figure 1.48 shows the block-schematic arrangement of an FM transmitter that employs a direct method of generation of FM signals. The *carrier oscillator* generates a stable sinusoidal signal at the centre frequency, also called the rest frequency, of the carrier oscillator. It is the frequency of the carrier oscillator when no modulating signal is applied to it. The *buffer* 



Figure 1.48 Block-schematic arrangement of an FM transmitter.

amplifier acts as a constant high impedance load on the oscillator to help stabilize the oscillator frequency. The buffer amplifier may have a small gain. The *pre-emphasis circuit* is used to boost the amplitudes of higher frequencies, generally 2–15 kHz, in the modulating signal. This is done to increase signal-to-noise ratio. It increases intelligibility and fidelity. The reactance modulator changes the carrier oscillator frequency on application of a modulating signal. The greater the peak-to-peak amplitude of the modulating signal, the larger the frequency deviation of the carrier frequency from its rest value. A reactance modulator is a circuit whose reactance, capacitive or inductive, is connected across the resonant circuit of the carrier oscillator. The reactance and hence the oscillator frequency is made to vary by the changing amplitude of the modulating signal. A *frequency multiplier* multiplies the frequency and is used to increase frequency deviation. Frequency multipliers are tuned-input, tuned-output RF amplifiers in which the output resonant circuit is tuned to a multiple of the input frequency. Multiplication factors of 2, 3 and 4× are common. The output of frequency multiplier feeds the driver amplifier, which in turn feeds the power amplifier to raise the RF power to a level desired for transmission. The power amplifier output feeds the transmitting antenna through an impedance matching network.

In the direct method of generating an FM signal, frequency stability of the carrier oscillator is a concern. This shortcoming is overcome in the *indirect method* that attempts to generate FM signal from a phase modulated signal. FM and PM signals are interrelated: one cannot exist without the other. In the indirect method, also known as *Armstrong's method*, the information signal is first integrated and then used to phase modulate a crystal controlled oscillator thereby achieving exceptionally high-frequency stability of the centre frequency. The modulated signal is a narrow band FM signal. A frequency multiplier is used to transform it to a wide band FM signal.

### 1.3.10 FM Receiver

Figure 1.49 shows a block-schematic arrangement of a superheterodyne FM receiver. An *RF amplifier* amplifies the signal intercepted by the antenna. The amplified signal is fed to the *mixer*. The second input to the mixer is from the *local oscillator*. The intermediate frequency signal is amplified by a chain of *IF amplifiers*. The *limiter* following the IF stage removes noise



Figure 1.49 Block-schematic of an FM receiver.

from the received modulated signal and produces a constant amplitude FM signal at an intermediate frequency. The output of the limiter circuit is applied to the FM demodulator circuit. FM demodulator circuits such as the Foster-Seeley discriminator and ratio detector have been discussed in Section 1.2.3. A phase locked loop also makes a very good FM demodulator. In a PLL-based FM demodulator, the incoming FM signal can be fed into the reference input and the VCO drive voltage used to provide the demodulated output. Then there is the quadrature FM detector. A quadrature FM detector comprises a phase shift network, a mixer and a low pass filter. The FM signal and the phase shifted FM signal are applied to the mixer. The mixer output feeds a low pass filter. The output of low pass filter is the demodulated signal. The demodulated output is *de-emphasized* to attenuate the high-frequency components. This is done to bring them back to their original amplitudes as these are boosted prior to transmission. The de-emphasized signal is fed to the *audio amplifier* stage comprising a driver amplifier and a power amplifier. A limiter circuit is required only in the case where an FM discriminator is used as an FM demodulator. In the case of a ratio detector, a limiter circuit is not required as the ratio detector limits the amplitude of the signal. An automatic frequency control (AFC) circuit is required to have a stable local oscillator frequency.

# 1.3.11 Phase Modulated (PM) Transmitter and Receiver

Frequency modulated and phase modulated signals are interrelated. Therefore, a PM transmitter and an FM transmitter have similar structures. The difference between the two lies in the type of modulator used. While frequency modulators encode information by changing the frequency of the carrier wave in accordance with amplitude variations of information signal, phase modulators do so by changing the phase of the carrier wave again in accordance with the amplitude variations of information signal. The PM receiver and FM receiver also have similar structures, except for the fact that a PM receiver doesn't have a de-emphasis stage following the demodulator. Because of this, in the case of a PM transmitter, no pre-emphasis stage is needed to boost the high-frequency components of the modulating signal.

# 1.3.12 Amplitude Shift Keying (ASK) Transmitter

Various digital modulation techniques have been discussed in terms of their operational principle, merits and demerits earlier in Section 1.2.9. In this sub-section and the following Section 1.3 sub-sections, we shall discuss transmitters and receivers for ASK, FSK and different forms of PSK. As outlined earlier, in the case of ASK, the high-frequency sinusoidal carrier signal is given two or more discrete amplitude levels depending upon the number of levels adopted by the digital message. In the case of Binary ASK the message sequence has two levels, one of which is typically zero. The data rate is a sub-multiple of the carrier frequency. One of the disadvantages is that it doesn't have a constant envelope, which makes processing such as power amplification

more difficult. Another disadvantage is that ASK is sensitive to atmospheric nose, distortions and propagation conditions. However, demodulation is relatively easier. ASK digital modulation scheme is used to transmit digital data over optical fibres, point-to-point military communication applications and so on. Figure 1.50 shows a simplified block-schematic of a binary ASK modulator. The diagram is self-explanatory. The sinusoidal carrier is applied to the input of a controlled electronic switch. The message sequence is fed to the control input of the switch. Logic 1 closes the switch thereby passing the carrier signal on to the output. The switch remains open for logic 0, thereby blocking the carrier from appearing at the output.

# 1.3.13 ASK Receiver

Figure 1.51 shows use of a simple product detector for demodulation of a binary ASK signal. The product detector multiplies the modulated signal and locally generated carrier signal. The product detector works like a frequency mixer. The output of product detector contains the message signal frequency component and twice the carrier frequency component. The output of low pass filter is the message signal. In the case of the schematic in Figure 1.51, frequency and phase of the locally generated carrier signal must be matched to those in the case of a transmitted carrier signal. A more sophisticated receiver makes use of two product detectors. The modulated signal is fed to one of the inputs of both product detectors. While the other input to one of the product detectors is the carrier signal, the other input of the second product detector is fed with a carrier signal that is phase shifted by 90°. The outputs of the two product detectors are combined to produce a demodulated output.

# 1.3.14 Frequency Shift Keying (FSK) Transmitter and Receiver

FSK is a digital modulation technique in which digital information is transmitted through discrete frequency changes of a carrier wave. The simplest FSK is binary FSK (BFSK) that uses a pair of discrete frequencies to transmit binary information. In the case of BFSK, two frequencies



used to transmit 1 (MARK) and 0 (SPACE) are equal to integral multiples of bit rate. Figure 1.52 represents the basic block-schematic arrangement of a BFSK transmitter. The binary sequence to be encoded is applied to two mixers; directly to one of them and through an inverter to the other. The two mixers are fed at the other input by carrier waves of two discrete frequencies. The outputs of two mixers are combined to produce the BFSK output. As is self-explanatory, when 1 is being transmitted, the output is the carrier wave at frequency  $f_1$  and when a 0 is being transmitted, the output is the carrier wave at frequency  $f_2$ .

There are two broad categories of FSK demodulators, namely the FM detector type demodulators and filter-type demodulators. In the case of FM detector type FSK demodulators, the FSK signal is treated as an FM signal with binary modulation. The FSK signal is fed to a band pass filter to remove out-of-band interference and then to a limiter to remove AM interference. The amplitude limited signal is then demodulated using an FM detector such as the Foster– Seeley FM discriminator or ratio detector. The demodulated signal is low pass filtered to remove interference at frequencies above the baud rate. The decision-making circuit finally converts all positive voltages into binary 1 s and all negative voltages into binary 0 s. Figure 1.53 shows the simplified block-schematic, which is self-explanatory. This category of FSK demodulators, though simple to implement, are non-optimal.

In the category of filter-type FSK demodulators, we have the non-coherent FSK demodulators and the coherent FSK demodulators. Figure 1.54 shows a simplified block-schematic of a non-coherent filter-type FSK demodulator. The information bits from an FSK signal are demodulated by subtracting the amplitude of the detected SPACE component from the amplitude of the detected MARK component. When the difference is above a certain threshold level, a MARK is assumed to be sent. If the difference is less than the threshold, a SPACE is assumed to be sent. The two-band pass filters are centred on the Mark and Space frequencies, respectively.



Figure 1.52 Generation of a BFSK signal.



Figure 1.53 FM detector-type FSK demodulator.



Figure 1.54 Noncoherent filter type FSK demodulator.



Figure 1.55 Coherent filter type FSK demodulator.

Figure 1.55 shows a simplified block-schematic of a coherent filter-type FSK demodulator. In the FSK demodulator of Figure 1.54, the detectors operate on base band signals. With the base band approach, the input signal is mixed by locally generated coherent MARK and SPACE carrier frequencies. The two base band signals present at the outputs of mixers are then filtered by identical low pass filters. The low pass filtered MARK and SPACE signals are combined and fed to the decision circuit. The output of decision circuit is the data. The base band approach is easily adaptable to moving MARK and SPACE frequencies without needing to change data filters. However, different low pass filters are needed when the baud rate changes.

## 1.3.15 Phase Shift Keying (PSK) Transmitters and Receivers

PSK is a digital modulation scheme that encodes data by changing the phase of a carrier wave. There are a number of PSK modulation schemes such as BPSK, DPSK, Quadrature-Phase Shift Keying (QPSK) and Offset QPSK and so on. These digital modulation schemes have been discussed in Section 1.2.9 previously. Different PSK modulation schemes use a finite number



Figure 1.58 Block-schematic of a QPSK transmitter.

of phases, each assigned a unique pattern of binary digits. Each pattern of bits representing a certain phase forms a symbol. On the receiver side, the demodulator determines the phase of the received signal and maps it back to the symbol it represents to recover the transmitted data.

In the case of BPSK, a carrier signal can assume only two values of phase. Each phase value therefore carries one bit of information and the bit rate is same as the modulation rate. Figure 1.56 shows a simplistic BPSK transmitter. In the figure,  $E_b$  is transmitted signal energy per bit;  $T_b$  is time interval between adjacent bits, n is a fixed integer and ( $f_c = n/T_b$ ) is the carrier frequency.

Figure 1.57 shows the basic BPSK receiver. The received BPSK signal is multiplied with a locally generated coherent reference carrier signal. The output of the mixer is low pass filtered and fed to a decision circuit where it is compared with a threshold of 0 V. The receiver produces 1 for the filter output greater than zero and a 0 for filter output less than zero.

In QPSK, also known as quaternary PSK, 4-PSK or 4-QAM, the information is encoded in phase states of the carrier, which takes on one of four equally spaced values such as  $\pi/4$ ,  $3\pi/4$ ,  $5\pi/4$  and  $7\pi/4$ . Figure 1.58 shows a simplified block-schematic of a QPSK transmitter. The input binary sequence b(t) is de-multiplexed into two separate binary sequences comprising odd and even numbered input bits denoted by  $b_1(t)$  and  $b_2(t)$ .  $b_1(t)$  and  $b_2(t)$  are used to modulate two carrier signals that are in phase quadrature. The two binary PSK signals produced as a result are added to produce the desired QPSK signal.

Figure 1.59 shows a block-schematic of a QPSK receiver. The QPSK signal is applied to a pair of correlators, each comprising a cascaded arrangement of a mixer and a low pass filter.







The two mixers are also fed with locally generated carrier signals  $c_1(t)$  and  $c_2(t)$ . The outputs  $x_1$  and  $x_2$  of two low pass filters are each compared with a threshold of 0 V. The decision circuit takes the decision in favour of 1 for x ( $x_1$  and  $x_2$ ) greater than 0 V and 0 for x ( $x_1$  and  $x_2$ ) less than 0 V. These two channels are combined in a multiplexer to get the original binary output.

DPSK, a common form of phase modulation encodes data by changing the phase of the carrier wave. In the case of DPSK, as outlined in Section 1.2.9.4, the information is encoded by change in phase. While logic state 1 is represented by a change in phase of the carrier, logic level 0 is represented by no change in phase. Figure 1.60 illustrates the generation of DPSK signal. The binary sequence to be encoded is applied to one of the inputs of an X-NOR gate. The second input to the X-NOR gate is the output fed back via a 1-bit delay circuit. The resulting bit stream is applied to the balanced modulator to produce a DPSK signal. In the DPSK demodulator (Figure 1.61), the DPSK signal is passed to the balanced modulator directly and also through a 1-bit delay circuit. The resulting signal feeds a low pass filter. The output of the low pass filter is applied to a decision circuit, which produces binary data.

# 1.4 Antennas, Transmission Media and Propagation Modes

Antennas and transmission lines constitute a vital interface between the transmitter output and free space, and also between the propagating medium and receiver input. Transmission lines and waveguides constitute transmission media. Transmission media are primarily used in communication systems to carry signals from transmitter output to the input of transmitting antenna and from receiving antenna to the input of receiver. A waveguide does the same job at microwave frequencies as the transmission lines usually do at relatively lower radio frequencies. The mode of propagation of electromagnetic waves through the propagating medium is largely governed by the operating frequency. In this section, we shall discuss principles and applications of transmission lines, waveguides and antennas. Different propagation modes are briefly touched upon towards the end of the section.

## 1.4.1 Transmission Line Fundamentals

# 1.4.1.1 Transmission Line Equivalent Circuit

As outlined before, transmission lines are used in communication systems to carry signals from the transmitter output to the input of the transmitting antenna and from the receiving antenna to the input of the receiver. They are also used to for other applications such as impedance matching. Principle of operation of a transmission line can be best understood with the help of its electrical equivalent circuit. Figure 1.62 shows the lumped component equivalent network of a radio frequency (RF) transmission line supporting a transverse electromagnetic (TEM) mode. In the equivalent network shown, R and L are the equivalent series resistance and equivalent series inductance, respectively, per unit length of the line. G and C are equivalent shunt conductance and equivalent shunt capacitance, respectively, per unit length of the line. In an ideal lossless transmission line, R = G = 0. The incremental length here is chosen to be the one that is much smaller than the wavelength of the propagating signal. It should be mentioned here that transmission lines support two types of modes at microwave frequencies: (1) TEM and (2) non-TEM modes of propagation. The four basic parameters characterizing a TEM mode are the characteristic impedance  $Z_0$ , the phase velocity  $n_p$ , the attenuation constant a and the peak power handling capability  $P_{max}$ . In case of transmission lines supporting a non-TEM mode, these four parameters also depend upon the type of supported mode in addition to depending upon the geometrical features and material properties of the transmission line.

## 1.4.1.2 Transmission Line Losses

The three major sources of losses in RF transmission lines include: (1) copper losses (also referred to as  $I^2R$  losses), (2) dielectric losses and (3) radiation losses. Copper loss or  $I^2R$  loss is due to the resistance associated with the conductors constituting the transmission line. This loss appears in the form of heat. This loss is frequency dependent and increases with an increase in frequency. Dielectric loss also appears in the form of heat and increases with an increase in



Figure 1.62 Equivalent circuit of a transmission line.

frequency. This loss is due to leakage through the dielectric. Radiation loss is due to radiation of RF power to free space or nearby circuits. Although transmission lines are not lossless, for all practical purposes they can be assumed to be so.

### 1.4.1.3 Transmission Line Propagation Modes

Two types of modes propagating in transmission lines are: (1) the TEM mode and (2) non-TEM modes. In the TEM mode (also called the principal mode), the electric and magnetic field vectors are perpendicular to one another and transverse to the direction of propagation of the signal. The TEM mode has no cut-off frequency. Besides the fundamental TEM mode or principal TEM mode, transmission lines can also support various non-TEM higher-order modes referred to as  $TE_{mn}$  (transverse electric) and  $TM_{mn}$  (transverse magnetic) modes. In the case of TE modes, there is no electric field component in the direction of propagation, and for TM modes, there is no magnetic field component in the direction of propagation. The subscript *m* signifies the number of full-period variations of the radial component of the field in the angular direction and *n* denotes the number of half-period variations of the angular component of the field in the radial direction.

### 1.4.1.4 Transmission Line Parameters

Important transmission line parameters include: (1) characteristic impedance, (2) propagation constant, (3) reflection coefficient, (4) standing wave ratio, (5) input impedance, (g) return loss and (7) mismatch loss.

*Characteristic impedance* of a transmission line is its input impedance if it was infinitely long. Refer to the transmission line equivalent circuit of Figure 1.62. It can be proved with

simple mathematics that the characteristic impedance of this line is given by  $Z_0 = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}$ . Where R = distributed resistance per unit length

*L* = distributed inductance per unit length

G = distributed shunt conductance per unit length

C = distributed shunt capacitance per unit length.

In a lossless transmission line, R = 0 and G = 0, so the expression for characteristic impedance line reduces to  $Z_0 = \sqrt{\frac{L}{C}}$ .

Characteristic impedance, as is clear from its definition and the relevant mathematical expression, is characteristic of the line and is independent of the length of the line. As all practical transmission lines are going to be of finite length, the significance of this parameter arises from the fact that if a finite line is terminated in a load impedance equal to the characteristic impedance of the line, its input impedance in that case will also equal the characteristic impedance.

The *propagation constant*,  $\gamma$ , is a measure of the attenuation and the phase shift of the incident waves travelling from the source to the load end of the transmission line. The propagation constant, for practical purposes, is a complex quantity having a real part known as attenuation constant  $\alpha$  and an imaginary part called as phase shift constant  $\beta$ . The propagation of a wave along a transmission line can be mathematically expressed as  $\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$ . For a lossless line,  $\gamma = j\omega\sqrt{LC}$ , which gives  $\alpha = 0$  and  $\beta = \omega\sqrt{LC}$ .

When a transmission line is terminated in load impedance that is not equal to its characteristic impedance, part of the signal energy sent down the line is reflected back. The ratio of the reflected signal amplitude to the incident one is defined as the *reflection coefficient*. It may be expressed as a magnitude only and denoted by  $\rho$  or as a complex value having both a magnitude and a phase and denoted by  $(\Gamma)$  with  $\rho = |\Gamma|$ . Reflection coefficient is expressed as  $\rho = |\Gamma| = |(Z_L - Z_0)/(Z_L + Z_0)|$ .

Whenever a signal travelling along a transmission line comes across a discontinuity or whenever the line is terminated in a load other than the characteristic impedance of the line, a part of the whole incident energy is reflected back. Under such circumstances, we have two counter-propagating waves in the transmission line. At all those points, where the waves are in phase, they add producing a signal maximum, and at all those points where they are out of phase, they produce a signal minimum. Thus, we have points of signal maxima and signal minima along the line except for the case where there is no discontinuity and where the line is terminated in its characteristic impedance. VSWR, an abbreviation for *voltage standing wave ratio*, is the ratio of  $E_{max}$  to  $E_{min}$ . It is a measure of the mismatch at the discontinuity. VSWR of unity implies a zero reflection coefficient and thus a perfect match. VSWR is expressed as  $VSWR = (1 + \rho)/(1 - \rho)$ . Also,  $\rho = (VSWR - 1)/(VSWR + 1)$ .

Input impedance of a section of transmission line of length (*l*), characteristic impedance ( $Z_0$ ) and terminated in a load impedance  $Z_L$  is expressed as  $Z_{in} = Z_0[(Z_0 + Z_L \tanh \gamma l)/Z_L + Z_0 \tanh \gamma l]$ . In the case of an ideal transmission line, the expression reduces to  $Z_{in} = Z_0[(Z_0 + Z_L \tanh \beta l)/Z_L + Z_0 \tan \beta l]$ . Further, the expressions for  $Z_{in}$  for short circuited and open circuited lines, respectively, would be  $Z_{in} = jZ_0 \tan \beta l$  and  $Z_{in} = -jZ_0 \cot \beta l$ . Another interesting observation is that, for lines whose length is an odd integral multiple of  $\lambda/4$ , impedance inversion takes place from load to the source and such a line can then be used as an impedance transformer. It can be verified that for such a line,  $Z_{in}$ .

The *return loss* signifies the total round trip loss of the signal and is defined as the ratio of the incident power to the reflected power at a point on the transmission line. It is expressed in decibels. Return loss,  $L_{\Gamma} = -20 \log \rho$ , where  $\rho$  is the magnitude of reflection coefficient.

*Mismatch loss* is the loss due to reflection from a mismatch. It is defined as the ratio of incident power to the difference of incident and reflected power expressed in decibels.

Mismatch loss,  $L_m = -10\log(1-\rho^2)$ .

#### 1.4.2 Types of Transmission Lines

The two commonly used types of transmission lines on radio frequencies include *open-wire lines*, also known as parallel wire lines and the *coaxial lines*. In the category of open-wire lines, the two-wire balanced configuration, whose cross-section is shown in Figure 1.63(a), is more common. A coaxial transmission line [Figure 1.63(b)] comprises a conducting shell and a solid tape or a braided conductor surrounding an isolated concentric inner conductor. The inner conductor is either solid or stranded. Open-wire lines suffer from radiation losses and cross-talk. Radiation losses become prohibitively large at microwave frequencies. Coaxial lines, however, have much better shielding properties and therefore much lower radiation losses.



Figure 1.63 (a) Open wire line and (b) coaxial line.

Coaxial lines are, however, unbalanced lines. TEM is the dominant mode. Referring to the two-wire balanced transmission line of Figure 1.63(a), characteristic impedance of the line is given by  $Z_0 = (260/\sqrt{\varepsilon_r})\log_{10}(2H/d) \Omega$ . Referring to the coaxial line in Figure 1.63(b), characteristic impedance of the line is given by  $Z_0 = (138/\sqrt{\varepsilon_r})\log_{10}(b/a) \Omega$ .

### 1.4.3 Impedance Matching using Transmission Lines

Impedance matching is an important requirement in microwave circuit design in order to ensure that there is maximum transfer of power from source to load, that amplitude and phase imbalances are reduced in power distribution networks and that power loss in feed lines is minimized. Use of a transmission line to provide an impedance match involves a transmission line section of characteristic impedance  $Z_0$  and length l, which depend upon the nature of impedances to be matched. The transmission line section used for matching is connected in either of the different possible configurations again depending upon the matching requirement. A typical matching problem, in practice, involves matching complex impedance, which could be either input or output impedance of a device, to real impedance. The commonly used configurations include use of stubs and quarter-wave transformers. In stub matching, again there is a single stub matching technique and a double stub matching technique. Single stub matching technique uses either a shunt stub or a series stub. Various techniques outlined here are briefly described in the following paragraphs.

### 1.4.3.1 Single Stub Matching

A stub is basically a shorted or open section of a transmission line used in conjunction with transmission lines to provide impedance match and cancel out reflections if any. As the shorted and open transmission line sections present pure reactance, their introduction does not absorb any power. Figure 1.64 illustrates the use of a single stub, a shunt stub as it is connected across the main transmission line, to provide an impedance match. Here, a transmission line having characteristic impedance of  $Z_0$  is shown terminated in a complex load admittance of  $(g_L + jb_L)$ . As a first step, we locate a point on the transmission line where the normalized admittance is  $(1+jb_L)$ . It may be mentioned here that  $(g_L+jb_L)$  is also the normalized load. In the second step, put a stub across the transmission line at that point with the stub designed to offer a susceptance of  $-jb_L$ . Thus, the transmission line with a characteristic impedance of  $Z_0$  gets matched to a complex load. It is usual practice to use shorted stubs rather than open ones as it is impossible to get a perfect open. An open stub if used will always be terminated in free-space impedance. Figure 1.65 shows the use of series stub. Again, in the first step, we locate a point on the transmission line where the normalized impedance looking towards the load end is (1 + jX). At that point, a stub is added with the stub offering a normalized reactance of -jX. As is clear from Figure 1.65, the feed line needs to be cut for insertion of series stub. This technique is therefore not commonly used as it is difficult to fabricate in coaxial and strip lines.

**Figure 1.64** Single stub matching using a shunt stub.





#### 1.4.3.2 Double Stub Matching

With the single stub matching of the type discussed in Section 1.4.3.1, it is sometimes impractical to put the stub at the intended location, more so in coaxial lines and waveguides. In such cases, a double stub matching technique is preferred. In double stub matching, as shown in Figure 1.66, the two stubs are put across the main line at fixed points spaced  $3\lambda/8$  or even closer. These stubs have adjustable shorting plungers that can be adjusted to cancel out most of the reflections.

#### 1.4.3.3 Quarter-Wave Transformer

A quarter-wave transformer ( $\lambda/4$  long line) can be used to match both real as well as complex load impedance to a transmission line. If the main line characteristic impedance is  $Z_0$  and it is to be matched to a load with a resistance  $R_L$ , the characteristic impedance of the quarter-wave section required for matching would be  $\sqrt{R_L.Z_0}$ . Figure 1.67 shows the interconnection. If the load impedance is complex, say ( $R_L + jX_L$ ), it should first be converted into real impedance by means of an additional length l of a line to cancel out the reactive component. If  $R_L$  is the real impedance looking into the input of this additional length towards the load end, then the characteristic impedances of the quarter-wave line section are given by  $Z_T = \sqrt{R_L.Z_0}$ .

The interconnections are shown in Figure 1.68. The reactive part of the load can also be tuned out by using a stub as shown in Figure 1.69. In this case, the complex load impedance can be made to present the real impedance  $R_{L}$ ' to the quarter-wave line section by means of an  $(n\lambda/8)$  length of a line having characteristic impedance equal to the magnitude of the load impedance.



### 1.4.4 Waveguide Fundamentals

A waveguide does the same job with microwaves that the transmission lines usually do at relatively lower frequencies. At microwaves, it is more convenient to talk in terms of electric and magnetic fields propagating in the transmission medium rather than voltages and currents we are familiar with in the case of transmission lines. At relatively lower frequencies, extending up to say 100 MHz or so, the AC circuit theory is very well developed and almost all electronic functions can be implemented with available lumped components such as resistors, capacitors, inductors and so on, interconnected with wires to form a circuit. This approach of the AC circuit theory, which is nothing but an approximation to the field theory explained by Maxwell's equations and the wave equation, however, breaks down as we operate at higher frequencies exceeding 1 GHz or so. At those frequencies, it is more relevant to talk in terms of electromagnetic fields. The reason for this is very simple. At microwave frequencies, where the corresponding wavelengths are typically few tens of centimetres or lower, the size of lumped circuit elements and interconnecting wires becomes comparable to the wavelength and they behave like antennas. Because of this, the electromagnetic energy instead of remaining confined to the circuit gets radiated. The waveguide is the transmission medium of choice at higher frequencies.

### 1.4.4.1 Types of Waveguides

A waveguide is nothing but a conducting tube through which energy is transmitted in the form of electromagnetic waves. The waveguide can be considered to be a boundary that confines the waves to the space enclosed by boundary walls. An ideal waveguide would perform this task without any loss of energy or any distortion of the propagating wave. Actual waveguides, however, only approximate to this ideal condition. The waveguide can assume any shape theoretically, but the analysis of irregularly shaped guides becomes very difficult. Two popular types of waveguides are rectangular and circular waveguides, and again out of the two, the former is more extensively used. Less commonly used waveguide types include elliptical, cylindrical, and irregular waveguides. Figure 1.70(a) and (b) shows the outlines of rectangular and circular waveguides, respectively. A rectangular waveguide is characterized by its internal diameter (d).



Figure 1.70 Types of waveguides. (a) Rectangular waveguide and (b) circular waveguide.



Figure 1.71 Waveguide modes.

#### 1.4.4.2 Waveguide Modes

There will, in general, be infinite number of possible electric and magnetic field configurations inside the waveguide if there was no upper limit for the frequency of the signal to be transmitted. Each of these field configurations is called a mode. There are two types of modes: transverse magnetic (TM) modes and transverse electric (TE) modes. In TM modes, magnetic lines are entirely transverse to the direction of propagation of the electromagnetic wave. The electric field has a component in that direction. In TE mode, the electric field lines are entirely transverse to the direction of propagation whereas magnetic field has a component along the direction of propagation. Various propagation modes, both TM and TE, are designated by two subscripts. The first subscript indicates the number of half-wave variations of the electric field in the wide dimension of the waveguide whereas the second subscript indicates the number of half-wave variations along the narrow dimension of the waveguide. For instance, in TE10 mode, which is the simplest mode, there is only one-half-wave variation of electric field along the wide dimension and there is no electric field variation along the narrow dimension. Refer to Figure 1.71. It may be mentioned that this subscript notation is only for rectangular waveguides. In circular waveguides, the subscripts are there but they do not carry the same meaning as they do in case of rectangular waveguides.

The *dominant mode* propagating in a waveguide is one which has the highest cut-off wavelength for a waveguide of given dimensions. The cut-off wavelength of a waveguide is the highest signal wavelength that can propagate in a given waveguide. It will be seen that TE10 mode is the dominant mode in rectangular waveguides. Now, if we choose the guide dimensions in such a way that the signal wavelength is less than the cut-off wavelength for TE10 mode and greater than the cut-off wavelength at all other modes, which is easily achievable, we can ensure that only TE10 mode propagates. That is why TE10 mode is called the dominant mode. Even if a higher mode gets excited due to a discontinuity in the waveguide; it would soon die out as the guide would not support that mode. TE11 mode has the highest cut-off wavelength in a circular waveguide and we can always choose a diameter so that only TE11 mode propagates. This should then be the dominant mode in circular guides. However, due to the unsymmetrical nature of this mode, as shown in Figure 1.72(a), and due to the symmetrical nature of a circular guide, this mode is not the most popular because a bend or a discontinuity



Figure 1.72 Circular waveguide modes. (a) TE11 mode, (b) TM01 mode and (c) TE01 mode.

in the guide might twist the mode leading to propagation with the wrong polarization. TM01 and TE01 modes, however, are symmetrical as shown in Figure 1.72(b) and (c), respectively. TM01 mode is used where symmetry is important whereas TE01 is used for long-distance waveguide runs as it has the least attenuation of all the commonly used modes in circular waveguides. Also, its attenuation decreases as frequency increases and is thus useful at higher microwave frequencies.

#### 1.4.4.3 Waveguide Parameters

Important waveguide parameters include; (1) cut-off wavelength, (2) guide wavelength, (3) group and phase velocities and (4) characteristic wave impedance. Each of these parameters is briefly described in the following paragraphs.

As already outlined, there are a number of possible electric field and magnetic field configurations (called modes) that can exist in a waveguide. The modes that can exist and sustain in a waveguide are a function of waveguide dimensions and the frequency of the propagating signal. Each mode has a cut-off wavelength, that is, for a particular mode to sustain the wavelength corresponding to the signal frequency must be less than the cut-off wavelength for that mode. The *cut-off wavelength* for rectangular guides for both TE<sub>mn</sub> and TM<sub>mn</sub> is given by  $\lambda_c = 2/\sqrt{(m/a)^2 + (n/b)^2}$  where *a* is the wide dimension and *b* is the narrow dimension of the waveguide. The cut-off wavelength of a circular waveguide with an internal diameter *d* is given by  $\lambda_c = (\pi d/K_r)$ , where  $K_r$  is the solution of a Bessel function equation. The values of  $K_r$ for the TE<sub>01</sub>, TE<sub>11</sub>, TE<sub>21</sub>, TE<sub>02</sub>, TE<sub>12</sub> and TE<sub>22</sub> modes are 3.83, 1.84, 3.05, 7.02, 5.33 and 6.71, respectively. The values of  $K_r$  for TM<sub>01</sub>, TM<sub>11</sub>, TM<sub>21</sub>, TM<sub>02</sub>, TM<sub>12</sub> and TM<sub>22</sub> modes are 2.4, 3.83, 5.14, 5.52, 7.02 and 8.42, respectively.

*Guide wavelength*, that is, the wavelength of the travelling wave propagating inside the waveguide, is always different from the free-space wavelength  $\lambda$ . The guide wavelength  $\lambda_{g}$ , the cut-off

wavelength  $\lambda_c$  and the free-space wavelength  $\lambda$  are interrelated by  $\lambda_g = \lambda / \sqrt{[1 - (\lambda/\lambda_c)^2]}$ .

The velocity of propagation in a waveguide is the product of guide wavelength  $\lambda_g$  and frequency *f*. As  $\lambda_g > 1$ , it appears as if *phase velocity*  $v_p$  is greater than the speed of light. This appears to contradict the law that no signal can be transmitted faster than the speed of light. Also, in waveguides, it is found that intelligence or modulation does not travel at a velocity  $(v_p)$ . When a modulated carrier travels through a waveguide, the modulation envelope travels with a velocity far lower than that of the carrier and even lower than the speed of light. The velocity of modulation envelope is called *group velocity*  $v_g$ . As  $v_g$  is less than  $v_p$ , the modulation keeps slipping backwards with respect to the carrier as the modulated signal travels in a waveguide. In an air-filled or hollow waveguide, the phase and group velocities are related to speed of light by  $v_p = (\lambda_g/\lambda)c$  and  $v_g = (\lambda/\lambda_g)c$ , which gives  $v_pv_g = c^2$ .

*Characteristic impedance* is another important waveguide parameter. The generalized expression for the characteristic impedance  $Z_0$  of waveguide for TE modes is given by  $Z_0 = 377 \times (\sqrt{\mu/\varepsilon}) \times (b/a) \times (\lambda_g/\lambda)$ . The generalized expression for the characteristic impedance  $Z_0$  of waveguide for TM modes is given by  $Z_0 = 377 \times (\sqrt{\mu/\varepsilon}) \times (b/a) \times (\lambda_g/\lambda)$ . For rectangular waveguides, *a* is the wide dimension and *b* is the narrow dimension. For circular waveguides, a = b.

# 1.4.5 Antenna Fundamentals

An antenna is a structure that transforms guided electromagnetic waves into free-space electromagnetic waves and vice versa. The guided electromagnetic waves look more appropriate when the feeder connecting the output of the transmitter and the antenna or the input of the receiver and the antenna is a waveguide, which is generally true when we talk about microwave frequencies and microwave antennas. In case of other antennas such as those at high frequency (HF) and very high frequency (VHF), the term guided electromagnetic waves mentioned previously would be interpreted as a guided electromagnetic signal in the form of current and voltage. Sometimes, an antenna is considered a system that comprises everything connected between the transmitter output or the receiver input and free space. This includes, in addition to the component that radiates other components such as the feeder line, balancing transformers and so on. An antenna is a reciprocal device, that is, its directional pattern as receiving antenna is identical to its directional pattern when the same is used as a transmitting antenna provided; of course, it does not employ unilateral and nonlinear devices such as some ferrites. Also, reciprocity applies, provided the transmission medium is isotropic and the antennas remain in place with only transmit and receive functions interchanged. Antenna reciprocity also does not imply that antenna current distribution is the same on transmission as it is on reception.

## 1.4.5.1 Radiation Mechanism

When a radio frequency (RF) signal is applied to the antenna input, there is current and voltage distribution on the antenna that lead to the existence of an electric and a magnetic field. The electric field reaches its maximum coincident with the peak value of the voltage waveform. If the frequency of the applied RF input is very high, the electric field does not collapse to zero as the voltage goes to zero. A large electric field is still present. During the next cycle, when the electric field builds up again, the previously sustained electric field gets repelled from the newly developed field. This phenomenon is repeated again and again and we get a series of detached electric fields moving outwards from the antenna. According to laws of electromagnetic induction, a changing electric field produces a magnetic field and a changing magnetic field produces an electric field. It can be noticed that when the electric field is at its maximum, its rate of change is zero and when the electric field is zero, its rate of change is maximum. This implies that the magnetic field's maximum and zero points correspond to the electric field's zero and maximum points, respectively. That is, the electric and magnetic fields are at right angles to each other and so are the detached electric and magnetic fields. The two fields add vectorially to give one field that travels in a direction perpendicular to the plane carrying mutually perpendicular electric and magnetic fields.

## 1.4.5.2 Characteristic Parameters

Important basic characteristic parameters of antennas relevant to all types of antennas used in various types of communication systems, radar systems and satellites include; (1) antenna reciprocity, (2) directive gain, (3) power gain, (4) effective isotropic radiated power, (5) directional pattern, (6) beam width, (7) bandwidth, (8) polarization, (9) impedance and (10) aperture.

An antenna is a *reciprocal device*. That is, its directional pattern as a receiving antenna is identical to its directional pattern when the same is used for transmitting antenna; provided that, of course, it doesn't use any unilateral and nonlinear devices such as some ferrites. Also, reciprocity applies provided that the transmission medium is isotropic and the antennas remain in place with only transmit and receive functions interchanged. Antenna reciprocity also doesn't imply that antenna current distribution is the same on transmission as it is on reception.

The *directive gain* in a given direction is defined as the ratio of the power density of the radiated electromagnetic energy in that direction to the power density in the same direction and at the same distance due to an isotropic radiator with both antennas radiating the same total power. Directive gain is always specified for a given direction and would have maximum value in the direction of maximum radiation. This maximum directive gain is termed the *directivity* and is usually expressed in decibels (dB). An antenna with a directivity of 20 dB would produce a power density at a given distance in the direction of maximum radiation when radiating a certain total power that would be 100 times the power density resulting from an isotropic radiator at the same point when radiating the same total power. The generalized expressions for directive gain are given by  $4\pi P(\theta, \phi)/P_R$ . Directivity is expressed by  $4\pi [P(\theta, \phi)]_{max}/P_R$ . P( $\theta, \phi$ ) = Power radiated in the direction ( $\theta, \phi$ ),  $P_R$  is isotropic radiated power and [ $P(\theta, \phi)]_{max}$  is the maximum radiated power of a directive antenna.

*Power gain* is defined as the ratio of the power density at a given distance in the direction of maximum radiation intensity to the power density at the same distance because of an isotropic radiator of the same total power fed to the two antennas. The definition of power gain is similar to that of directive gain or directivity, except that it is not the power radiated by the antenna but the power fed to the antenna that is considered while computing the gain. It takes into account the antenna losses and thus is of greater practical importance. The generalized expression for power gain is given by: power gain =  $4\pi [P(\theta, \phi)]_{max}/P_{in}$ .  $P_{in}$  = Input power =  $P_R + P_L$ ;  $P_L$  = power loss and  $P_R$  = isotropic radiated power.

The *Effective Isotropic Radiated Power* (EIRP) is the more appropriate figure of merit of the antenna. It is given by the product of transmitter power and antenna gain. An antenna with a power gain of 40 dB and a transmitter power of 1000 W would mean an EIRP of 10 MW. That is, 10 MW of transmitter power, when fed to an isotropic radiator, would be as effective in the desired direction as 1000 W of power fed to a directional antenna with a power gain of 40 dB in the desired direction.

The antenna directional pattern or radiation pattern is a normalized distribution plot of electromagnetic energy in a three-dimensional (3D) angular space. The parameters to be plotted could be radiation intensity, which is the power per unit solid angle or the power density. A more commonly used representation of directional pattern is the two-dimensional (2D) plot. There are, again, various types of 2D plots. One of the types is the polar plot of radiation intensity or power density shown in Figure 1.73 that we are all quite familiar with. Another is the principal plane elevation pattern as shown in Figure 1.74. This is the pattern drawn by sectioning the 3D pattern with a vertical plane through the peak of the beam and a zero azimuth angle. A similar pattern called the *principal plane azimuth pattern* could be drawn by sectioning the 3D pattern through the peak of the beam and a zero elevation angle. Though the 2D patterns obtained by sectioning with planes other than the principal planes (called cardinal planes) can also be drawn, the azimuth and elevation patterns usually suffice in most of the cases. The main beam of the pattern is called the main lobe and the beams in directions other than the direction of maximum radiation are called sidelobes. High sidelobe levels, with a few exceptions, are always undesirable. The sidelobe level of an antenna pattern is usually specified in terms of relative sidelobe level, which is the peak level of the highest sidelobe relative to the peak of the main lobe. For instance, a relative sidelobe level of 20 dB means that the peak power density in the side lobe is l/100th of the peak power density in the main lobe.



Figure 1.73 Polar plot.



Figure 1.74 Principle plane elevation pattern.

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Figure 1.75 Beam width. (a) Power density radiation pattern and (b) field intensity radiation pattern.

The common types of antenna radiation patterns include the (1) omnidirectional (azimuth plane), beam, (2) pencil beam, (3) fan beam and (4) shaped beam. The *omnidirectional beam* is commonly used in communication and broadcast applications for obvious reasons. The azimuth plane pattern is circular and the elevation pattern has some directivity to increase the gain in horizontal directions. A *pencil beam* is a highly directive pattern whose main lobe is confined to within a cone of a small solid angle and it is circularly symmetric about the direction of maximum intensity. A *fan beam* is narrow in one direction and wide in the other. A typical application of such a pattern would be in search or surveillance radars in which the wider dimension would be vertical and the beam is scanned in azimuth. The last application would be in height-finding radar where the wider dimension is in the horizontal plane and the beam is scanned in elevation. There are applications that impose beam-shaping requirements on the antenna. One such requirement, for instance, is to have a narrow beam in azimuth and a shaped beam in the elevation such as in case of air search radar.

Beam width gives the angular characteristics of radiation pattern. It is taken as the angular separation either between the half power points on its power density radiation pattern [Figure 1.75(a)] or between 3 dB points on the field intensity radiation pattern [Figure 1.75(b)]. It is measured in degrees and with reference to the main lobe. Antennas also have 6-dB beam widths and null-to-null beam widths. Null-to-null beam width is the width of the response between the minima surrounding the main lobe and is approximately twice the 3-dB beam width for most antenna responses. The parameter is particularly relevant to the antennas producing narrow beams such as those in tracking radars. An antenna's power gain  $G(\theta,\phi)$  is related to its beam width in the azimuth direction (in radians) and  $\Delta\phi$  is the beam width in the elevation direction (in radians).

Antenna bandwidth is in general the operating frequency range over which the antenna gives a certain specified performance. Antenna bandwidth is always defined with reference to a certain parameter such as gain or input impedance or standing wave ratio (SWR). It is generally taken as the frequency range around the nominal centre frequency over which power gain falls to half of the maximum value. When referenced to the SWR, one may specify a 2:1 SWR bandwidth and so on. The lower the operating frequency, the narrower the bandwidth. It follows from the rule that in case of a resonant circuit, for a given quality factor Q, the bandwidth is directly proportional to the centre frequency.

Antenna polarization, whether it is transmitting or receiving, is the direction of electric field vector with respect to the ground. While receiving, it is considered for the orientation of

electromagnetic wave that the antenna responds best to. From antenna reciprocity, we can say that the antenna would respond most optimally to an electromagnetic wave that would have the same polarization as that of the transmitted wave radiated from the same antenna. It is a normal practice to consider the antenna itself as being polarized. The polarization of the antenna is the same as that of the electromagnetic wave it radiates or best responds to. The polarization of an antenna can be classified into two broad categories: linear polarization and elliptical polarization. *Linear polarization* could be either horizontal polarization or vertical polarization. *Circular polarization* is a special case of *elliptical polarization*. In linear polarization, the electric vector lies in a plane. If the plane is horizontal, it is horizontally polarized and if the plane is vertical, it is vertically polarized. An inclined plane leads to what may be referred to as *slant polarization*. Slant polarization is a general case of linear polarization having both horizontal and vertical components. It is called linear polarization because the direction of the resultant E vector is constant with respect to time. In the generalized case of a linearly polarized wave, the two mutually perpendicular components of the E vector are in phase. When the two components of the E vector are not in phase, it can be verified that the tip of the resultant traverses an ellipse as the RF signal goes through one complete cycle. This is called *elliptical* polarization. This polarization could have right-hand sense or left-hand sense depending upon whether the E vector moves clockwise or anticlockwise when viewed as a wave receding from the observation point in the direction of propagation. Elliptical polarization has two orthogonal linearly polarized components. When the magnitudes of these components become equal and the phase difference between the two becomes 90°, polarization becomes circular polarization. Again, we have either right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP).

*Cross polarization* is the component that is orthogonal to the desired polarization. For instance, a horizontally polarized antenna may also radiate vertical polarization in some directions of propagation or a vertically polarized antenna may radiate horizontal polarization in some directions. The other example could be that of an RHCP antenna also radiating LHCP and an LHCP antenna also radiating RHCP. A well-designed antenna should have a cross-polarized component at least 20 dB below the desired polarization in the direction of the main lobe and 5–10 dB below the desired polarization in the direction of side lobes.

If the received electromagnetic wave is of a polarization different from the one the antenna is designed for, a polarization loss results. This loss in decibels in the case of linear polarization is given by Polarization loss =  $20\log(1/\cos\phi)$ . Here,  $\phi$  is the angle between the polarization of the received wave and that of the antenna.

The *antenna impedance* at a given point in the antenna is given by the ratio of voltage to current at that point. As the magnitude of voltage and current vary along the antenna length, the impedance also varies being minimum at the point of the voltage node or minima, such as the centre point of a half-wave dipole and maximum at the point of the current node, such as the centre point of a full-wavelength long antenna. The input impedance of an antenna is of considerable importance to engineers as it is desirable to supply the maximum amount of transmitter power to the antenna. For this, the characteristic impedance of the feeder line must match the antenna input impedance at the chosen feed point. The antenna impedance is resistive if it is resonant at the operating frequency. The antenna resistance further comprises of two components, namely, the radiation resistance  $R_r$  and the  $R_d$  loss resistance. Radiation resistance is basically the resistance that, if the antenna is terminated, would dissipate the same power as that being radiated by the antenna. It is given by the radiated power divided by square of feed current. The loss resistance is contributed to by factors such as eddy current losses in metallic objects lying in the vicinity of induction field of antenna, losses in imperfect dielectrics, corona effects and so on. Antenna efficiency is defined as  $\eta = R_r/(R_r + R_d)$ .

The antenna aperture is the physical area of the antenna projected on a plane perpendicular to the direction of the main beam or the main lobe. In the case where the main beam axis is parallel to the principal axis of the antenna, it is the same as the physical aperture of the antenna itself. For a given antenna aperture A, the directive gain of the antenna at an operating wavelength of 1 is given by  $(4\pi A/\lambda^2)$ . This expression is valid only when the aperture A is uniformly illuminated. Typical antennas are not uniformly illuminated and have a tapered illumination, the maximum being at the centre and lower towards the edges. This is done to reduce the sidelobe level. Because of this nonuniform illumination, the antenna gain falls from its maximum value of  $(4\pi A/\lambda^2)$ . This is where the term effective aperture  $A_e$  of the antenna comes into the picture. It is that aperture area that, when uniformly illuminated, gives the same gain as that offered by a nonuniformly illuminated antenna of aperture A. Thus, the gain of a practical antenna is given by  $(4\pi A_e/\lambda^2)$ . Here A and  $A_e$  are interrelated by  $A_e = \eta A$  and  $\eta$  is the aperture efficiency (or effectiveness).

# 1.4.6 Types of Antennas

In the paragraphs to follow, we shall briefly describe the operational aspects of major types of antennas. Different types of antennas include the following.

- 1) Hertz antenna
- 2) Marconi antenna
- 3) Dipole antenna
- 4) Yagi-Uda antenna
- 5) Rhombus antenna
- 6) Reflector antenna
- 7) Lens antenna
- 8) Horn antenna
- 9) Helical antenna
- 10) Log periodic antenna
- 11) Phased array antenna
- 12) Microstrip antenna.

## 1.4.6.1 Hertz, Dipole and Marconi Antennas

A *Hertz antenna* is a straight length of a conductor that is a half-wave long. It may be placed vertically to produce vertically polarized waves [Figure 1.76(a)] or in horizontal position to produce horizontally polarized waves [Figure 1.76(b)]. A *dipole antenna* is also a straight radiator usually fed at the centre and producing the maximum of radiation in a place perpendicular to the antenna axis. A dipole that is a half-wavelength long is called a half-wave dipole [Figure 1.76(c)].

The vertical antenna that is a quarter-wave long and is fed against an infinitely large perfectly conducting plane is called a quarter-wave monopole or *Marconi antenna*. It has the same radiation characteristics above the plane as the half-wave dipole antenna in free space. The Marconi antenna has an edge over the Hertz antenna when it is to be used as a transmitting antenna at low frequencies, as its length is half of the required length of Hertz antenna for a given transmission frequency. Also, a Marconi antenna produces vertically polarized waves, ideally suited for transmission and propagation of relatively lower frequency RF signals. The radiation resistance of the half- and quarter-wave monopoles can be determined to be equal to 73  $\Omega$  and 36.5  $\Omega$ , respectively. The generalized expressions for the impedance are given  $0.609\eta I_{RMS}^2/2\pi$  (monopole) and  $0.609\eta I_{RMS}^2/\pi$  (dipole). Here,  $I_{RMS}$  is the RMS value of antenna current and  $\eta$  is the characteristic impedance of medium = 377  $\Omega$  for free space.

A modification of the half-wave dipole is the folded dipole suitable for TV reception purposes. A folded dipole [Figure 1.76(d)] comprises two half-wave dipoles connected at the ends and one of them fed at the centre. It may be constructed by folding a full-wave long conductor. The second element gets its excitation from the field produced by the driven element. The folded dipole electrically behaves in the same fashion as a straight dipole, physical construction being the only difference. Addition of this second element increases the input impedance of the antenna, which is given by  $Z_{in} \times$  [(Cross-sectional area of all conductors)/Cross-sectional area of driven element].

### 1.4.6.2 Yagi-Uda Antenna

A Yagi-Uda antenna comprises a half-wave dipole with parasitic elements to enhance the directionality of the radiation pattern. It is the most commonly used antenna type for HF and VHF communications. The simplest Yagi antenna would be a three-element array with a centre-fed half-wave dipole as the driven element, one parasitic element smaller in length than the driven element by about 4% called the director is placed in front of the driven element and another parasitic element longer in length than the driven element by about 5%, called the reflector, is placed behind the driven element (Figure 1.77). The director enhances the directivity of the radiation pattern and the reflector suppresses the radiation in the backwards direction; that is, when used as a receiving antenna it does not receive from that direction thus improving the front-to-back ratio. The director–dipole spacing is approximately  $0.12\lambda$  whereas the reflector–dipole spacing is  $0.2\lambda$ .



### 1.4.6.3 V-Antenna and Rhombic Antenna

These are long-wire antennas. In a *V-antenna*, the conductors are arranged to form a V-shape and they are fed in phase opposition at the apex [Figure 1.78(a)]. Such an arrangement produces a high gain bidirectional pattern as shown in Figure 1.78(b). If the antenna is to be used as a wideband antenna, the apex angle is a compromise between an optimum for the lowest and the highest frequencies in terms of number of half wavelengths in each leg. In a *rhombic antenna*, conductors are arranged to form a rhombus. It is a combination of two long-wire V-antennas [Figure 1.78(c)]. In this case too, the length of the legs and the apex angle control the shape and directivity of the pattern. The gain of a rhombic antenna, whose individual legs are of the same lengths as those of a V-antenna, will be approximately double. The resonant rhombic antenna produces a bidirectional radiation pattern as shown in Figure 1.78(d).

### 1.4.6.4 Reflector Antennas

A reflector antenna is made in different types, shapes and configurations depending upon the shape of the reflector and the type of feed mechanism. It is by far the most commonly used antenna type in all those applications that require high gain and directivity. High gain and a highly directional radiation pattern, which are antenna parameters that are essentially the same, are the characteristics typical of both terrestrial and satellite-based communication links, radar systems, direction-finding systems and so on. While communicating in the UHF and microwave frequency bands, it is important to have narrow beam width to avoid interference with other transmissions. In a radar system such as tracking radar, accuracy and resolution of measurement of angular information are equally important. Angular resolution, which is the ability to discriminate between two targets located close to each other, again depends upon the narrowness of the beam width. The narrower the beam, the higher the angular resolution. Now the gain or the directivity of the antenna is directly proportional to the size of the antenna. The antenna dimensions need to be much larger than the operating wavelength for achieving high directivity, a requirement that would not be practicable at relatively lower frequencies. At UHF and above it does become practicable. For example, at 10 GHz,  $\lambda = 3$  cm with a 3-m diameter dish would give a dimension that is 100 times the operating wavelength. Of course, there is a small overlap region between VHF (30 - 300 MHz) and UHF (300 - 3000 MHz) and some of the antenna types to be used for higher-end VHF and lower-end UHF are common.



Figure 1.78 (a) V-antenna. (b) Directional pattern of a V-antenna. (c) Rhombic antenna. (d) Directional pattern of a rhombic antenna.



**Figure 1.79** Reflector antennas: (a) Focal point fed parabolic antenna. (b) Offset-fed sectioned parabolic antenna. (c) Cassegrain fed antenna. (d) Array-fed cylindrical reflectors. (e) Symmetrical Cassegrain antenna. (f) Offset Cassegrain antenna.

A reflector antenna, in essence, comprises a reflector and a feed antenna. As mentioned earlier, depending upon the shape of the reflector and the feed mechanism, there are different types of reflector antennas suitable for different applications. The reflector is usually parabolic, also called parabolic reflector, or a section of parabolic or cylindrical reflectors. A cylindrical reflector has a parabolic surface in one direction only. The feed mechanisms include the feed antenna placed at the focal point of the parabolic reflector or the feed antenna placed off the focal point. Another common feed mechanism is the Cassegrain feed. Cylindrical reflectors are fed by an array of feed antennas. The feed antenna is usually a dipole or a horn. These antennas are thus available in many types and configurations, some of the more commonly used ones include; (1) a focal point fed parabolic reflector [Figure 1.79(a)], (2) an offset fed sectioned parabolic reflector [Figure 1.79(b)], (3) a Cassegrain fed reflector [Figure 1.79(c)] and (4) an array fed cylindrical reflector [Figure 1.79(d)]. Power gain of a focal point fed parabolic reflector antenna is given by  $(4\pi A_e/\lambda^2)$ . Here,  $A_e$  is the effective aperture area and  $\lambda$  is the operating wavelength. If D and h are the mouth diameter of the reflector and aperture efficiency, respectively, then power gain is given by  $(\pi \eta^2 D/\lambda^2)$ . The 3-dB beam width of such an antenna is given by  $70(\eta/D)$ .

If the feed antenna beam width is excessive, it causes a spill over producing an undesired antenna response in that direction. And if it is too small, only a portion of the reflector is illuminated with the result that antenna produces a wider beam and a consequent lower gain. Focal length is another important design parameter. A long focal length reflector antenna would produce more error at the feed than that produced by a short focal length reflector. However, focal length cannot be increased arbitrarily as long focal length reflectors need a larger support structure for the feed and hence a greater aperture blockage.

The directional pattern of the feed determines the illumination of the reflector. The angle subtended by the feed antenna at the edges of the reflector is given by  $4 \tan^{-1}[1/(4f/D)]$ . According to a rule of thumb, the 3 dB beam width should be equal to 0.9 times the subtended angle.

Feed together with its support is one of the major causes of aperture blockage, which is further one of the major causes of sidelobes. In applications where the feed antenna is rather large so as to block a portion of the reflector aperture with significant effects on the radiated beam in terms of increased sidelobe content, an offset fed parabolic reflector antenna is one of the solutions. The shortcomings of the focal point fed parabolic reflector antenna, such as aperture blockage and lack of control over main reflector illumination, can also be overcome by adding a secondary reflector. The contour of the secondary reflector determines the distribution of power along the main reflector thereby giving control over both amplitude and phase in the aperture. The Cassegrain antenna derived from telescope designs is the most commonly used antenna using multiple reflectors. The feed antenna illuminates the secondary reflector, which is a hyperboloid. One of the foci of the secondary reflector and the focus of the main reflector are coincident. The feed antenna is placed on the other focus of the secondary reflector. The reflection from the secondary reflector illuminates the main reflector. Figure 1.79(e) shows the arrangement. Symmetrical Cassegrain systems usually produce a large aperture blockage, which can be minimized by choosing the diameter of the secondary reflector equal to that of the feed. Blockage can be completely eliminated by offsetting both the feed as well as the secondary reflector as shown in Figure 1.79(f). Such an antenna is capable of providing a very low sidelobe level.

A cylindrical parabolic antenna uses a reflector that is a parabolic surface only in one direction and is not curved in the other. It is fed by an array of feed antennas, which gives it much better control over reflector illumination. Electronic steering of the output beam is also more convenient in an array fed cylindrical antenna. Symmetrical parabolic cylindrical reflectors, however, suffer from a large aperture blockage. A cylindrical reflector fed from an offset placed multiple element line source offers excellent performance.

#### 1.4.6.5 Lens Antenna

Like reflector antennas such as parabolic reflectors, lens antennas are another example of application of rules of optics to microwave antennas. In the case of former, it is the laws of reflection; the lens antennas depend on refraction phenomenon for their operation. Lens antennas are made of dielectric material and Figure 1.80(a) explains the principle of operation. A point source of operation is placed at the focal point of the lens. Due to the curvature of the lens, rays close to the edges are refracted more than the rays close to the centre. This explains why the rays get collimated and become parallel to the lens axis after passing through the lens, though they are inclined in the space between the lens and the point source. Similarly, on reception, the rays arriving parallel to the lens axis get focused onto the focal point where the feed antenna is placed. Another way of explaining the operation of a lens antenna is as follows. Refer to Figure 1.80(b). Spherical waves emitted by the point source get transformed to plane



**Figure 1.80** Lens antenna: (a) principle of operation using a ray diagram and (b) principle of operation using a wave front.



Figure 1.81 Zoned lenses.

waves during transmission and the reverse process occurs during reception. This happens as the spherical waves travelling closer to the centre are slowed down more than those travelling away from the centre. Same reasoning explains the reverse process during reception. Also, for efficient operation of a lens antenna, the thickness of the lens antenna at the centre should be much larger than the operating wavelength. This makes a lens antenna less attractive at operating frequencies less than 10 GHz. Even at frequencies around 10 GHz, there are serious thickness and weight issues, which are overcome by using what are known as Fresnel or zoned lenses. Two types of zoned lenses are shown in Figure 1.81. Zoning not only overcomes the weight problem, it also absorbs less energy. A thicker lens would absorb a higher proportion of the radiation. The thickness t of each step in a zoned lens is related to wavelength to ensure that phase difference between the rays passing through the centre and those passing through adjacent section is  $2\pi$  radians or an integral multiple of it. A zone lens, because of its thickness being related to operating wavelength, has a small operational frequency range.

#### 1.4.6.6 Horn Antennas

If the abrupt discontinuity of a waveguide is transformed to a more gradual one, we get the *horn antenna*. It may be mentioned here that a transmission line or a waveguide open circuited at the load end would radiate electromagnetic energy into the atmosphere very inefficiently, mainly due to the impedance mismatch between the transmission line or waveguide and the atmosphere. Making the discontinuity more gradual only improves the impedance match and thereby the coupling of electromagnetic energy to the atmosphere. There are various types of horn antennas such as the *sectoral horn* [Figure 1.82(a)] where the

flare is only on one side, the *rectangular pyramidal horn* [Figure 1.82(b)] where the flare is on both sides and the *conical horn* [Figure 1.82(c)], which is a natural extension of a circular waveguide.

The important design parameters of a horn antenna include flare length and flare angle [Figure 1.82(d)]. If the flare angle is too small, the antenna has low directivity and also emitted electromagnetic waves are spherical and not planar. Too large a flare angle also leads to loss of directivity due to diffraction effects. Horns could have simple straight flares or exponential flares. These are commonly used as feed antennas for reflector type antennas. When more demanding antenna performance is desired in terms of polarization diversity, low sidelobe level, high radiation efficiency and so on, the feeds also become more complex. Segmented, finned and multimode horns may be used. Some combinations of horn antennas and parabolic reflectors such as Cass-Horn and Hog-Horn antennas have gain and beam width specifications matching those of parabolic reflectors of comparable dimensions.

**Figure 1.82** (a) Sectoral horn. (b) Rectangular pyramidal horn. (c) Conical horn. (d) Flare length and flare angle.



**Figure 1.83** The helical antenna. (a) Helical antenna. (b) photograph of a representative helical antenna.



#### 1.4.6.7 Helical Antenna

A *helical antenna* is a broadband VHF and UHF antenna. Most of its applications are due to the circularly polarized waves it produces. VHF and UHF propagation undergoes a random change in its polarization as it propagates through the atmosphere due to various factors like Earth's magnetic field, ionization of different regions of atmosphere and so on, Faraday rotation being the main cause. The propagation gets more severely affected in case of trans-ionospheric communications such as those involving satellites. Circular polarization is, to a great extent, immune to these polarization changes. On the other hand, horizontally polarized waves would not be received at all if its polarization was rotated by 90° and became vertically polarized. Figure 1.83(a) shows a typical helical antenna. Figure 1.83(b) shows a photograph of a representative helical antenna. The ground plane is a wire mesh. The antenna has two operating modes with the one producing a

circularly or elliptically polarized broadside pattern with the emitted wave perpendicular to the helical axis and the other producing a circularly polarized end fire pattern with emitted wave along the helical axis. For the first mode, the helix circumference is much smaller than operating wavelength whereas for the second mode, it is approximately equal to operating wavelength. The second mode is the more common of the two.

# 1.4.6.8 Log Periodic Antenna

## 1.4.6.9 Phased Array Antennas

A *phased array antenna*, or more appropriately a phase steered array antenna, is where the radiated beam (or the axis of the main lobe of the radiated beam) can be steered by feeding the



Figure 1.84 (a) Using straight dipoles. (b) Using bent dipoles.
elements of the array with signals having a certain fixed phase difference between adjacent elements of the array during transmission. On reception, they work exactly the same way and instead of splitting the signals among elements, the elemental signals are summed. Receive steering uses the same phase angles as transmit steering from antenna reciprocity principle. Phased array antennas are extensively used in different types of radars including those used for surveillance, tracking, air defence and so on and don't have much relevance to military communications.

### 1.4.6.10 Microstrip Antennas

A *microstrip* consists of a thin strip sitting on a dielectric that rests on a ground plane. A microstrip when used as a transmission line has a tendency to radiate from irregularities and sharp corners, which indicates that such a component could possibly be used as an antenna. Microstrip antennas radiate efficiently as devices on microstrip printed circuit boards and the microstrip antenna arrays consist of microstrip elements, feed mechanisms, phasing networks and any other microstrip devices. The most commonly used microstrip antenna element is a rectangular element photo-etched from one of the sides of a double-sided printed circuit board with the other side used as a ground plane as shown in Figure 1.85. The element is fed from a coaxial feed. The length L here is the most critical device dimension and is slightly less than half the operating wavelength in the dielectric substrate material. Length L is expressed by  $L = (0.49\lambda_0/\sqrt{\varepsilon_r})$ . Here  $\varepsilon_r$  is the relative dielectric strength of printed circuit substrate material. The thickness t is in the order of  $0.01\lambda$ . The selected value of thickness is based on the desired bandwidth and commercially available thickness. The width W must be less than a wavelength in the dielectric substrate material so that higher-order modes are not excited. However, this is not the constraint if multiple feeds are used to eliminate higher-order modes. Width W decides the input impedance of the antenna element. The expected bandwidth (in MHz) can be computed from  $(50 \times f \times t)$  where f is operating frequency in GHz and t is thickness in cm. The input impedance can be computed from  $60\lambda_0/W$  (for  $\lambda/2$  element) and  $120\lambda_0/W$  (for  $\lambda/4$  element).

### 1.4.7 Propagation Modes

The subject of electromagnetic wave propagation is of immense importance to all those associated with radio communications, be it two-way radio communications links, point-to-point radio communications or radio broadcasting or be it mobile radio communications, as electromagnetic wave propagation is significantly affected by the media it travels through in terms of the quality of received signal. It is therefore important to know the electromagnetic wave propagation characteristics likely to be encountered. There is a number of different mechanisms by which electromagnetic waves travel through media and the resultant signal may comprise a combination of several signals that have travelled by different paths. These signals may either add constructively or combine destructively, thereby causing an increase in signal strength in some places and complete loss of signal in others. Also, signals travelling via different paths may be delayed causing distortion of the resultant signal. In the following sections, we shall discuss the different regions of the atmosphere that are of great importance to the propagation





of electromagnetic waves followed by a brief discussion on different modes of electromagnetic wave propagation.

#### 1.4.7.1 Different Regions of the Atmosphere

The different regions of the atmosphere based on their properties may be classified as the *troposphere*, a region extending to altitudes of about 10km above the surface of Earth; the *stratosphere* extending from 10 to 50km and the *mesosphere*, located between 50 and 80km above Earth's surface and ionosphere extending from 60 to about 1000km. There are other classifications depending upon which properties one is interested in. From the viewpoint of radio propagation, the two main regions of interest are the troposphere and ionosphere.

The troposphere is the lowest region of the atmosphere. What we term 'weather' occurs in this region with low clouds occurring at altitudes of up to 2km, medium clouds occurring at altitudes of up to 4 km and the highest clouds occurring at 10 km or so. Within the troposphere, the temperature steadily falls with height. The troposphere plays an important role in radio wave propagation, particularly in VHF and UHF frequency ranges. Tropospheric propagation refers to the lower atmosphere of the Earth causing bending, scattering and/or reflection of electromagnetic waves, thereby sometimes enhancing their usable communication range by letting them propagate over the horizon, but also compounding interference-related problems. The tendency of electromagnetic waves to bend towards the surface of Earth occurs due to varying index of refraction in the troposphere, which is further due to varying propagation velocity at different altitudes in the troposphere. Different propagation velocities are due to different air density values. The refractive index is the highest near the surface of Earth and decreases with increase in altitude. This produces a tendency for electromagnetic waves to bend towards the surface of Earth. The troposphere scatters electromagnetic waves over a vast range. The effect is more pronounced at UHF and microwave frequencies. An electromagnetic wave beamed slightly above the horizon can get scattered up to several miles. This makes overthe-horizon communications possible. A related effect is that of *ducting*. Under certain specific conditions of the troposphere, when a cool air mass is overlain by a warm air mass, the electromagnetic waves striking the boundary at a near grazing angle from beneath can propagate over hundreds and sometimes to thousands of miles due to waves alternately bouncing off the frontal boundary and the Earth's surface.

The *ionosphere* extends from 60 to 1000km above the surface of Earth. It is the layer of the Earth's atmosphere that is ionized by solar and cosmic radiation. It is formed by ionization of the Earth's atmosphere by high energy from the Sun and from cosmic rays. The radiation interacts with the molecules to produce free electrons and positive ions. It is found that the level of free electrons varies throughout the ionosphere and, as a result of this, electromagnetic waves are affected more in certain regions than others. These regions are often known as layers, which are given designations D, E and F1, F2.

The *D layer* is the lowest in altitude of all the regions extending from 60 to 90 km. The D layer is present during the day only when radiation is being received from the Sun. After sunset, in the absence of solar radiation to retain ionization levels and because of density of molecules at this altitude, free electrons and ions quickly recombine resulting in the vanishing of the D layer. The D layer has the effect of attenuating radio signals passing through it. The attenuation decreases with increase in frequency. For example, the medium wave broadcast band may not be heard in the regions beyond the ground wave coverage during the day. The same may be heard at further-off distances during night in the absence of the D layer when the signals are reflected from higher layers of ionosphere. The E layer extends from 100 to 125 km. The *E layer* reflects radio signals while they undergo some attenuation. The E layer too significantly reduces in strength after sunset due to recombination of free electrons and positive ions, though some

ionization remains. The *F layer* is above both the D and E layers. It is the most important region for long-distance HF communications. During the day it often splits into two regions known as the F1 and F2 layers with the F1 layer being the lower in altitude of the two. At night, the two layers combine to give one layer called the F2 layer. The characteristics of the F layer are significantly affected by the time of day, season and the state of the Sun. Summer and winter time altitudes of F1 and F2 layers are 300 km and 400 km (summer) and 200 km and 300 km (winter). Night time altitude of the F layer may be 250 - 300 km. These are only approximate values. In the case of the F layer too, during night time, the ionization density reduces like in the D and E layers; the process of recombination of free electrons and positive ions that causes reduction in ionization strength is, however, much slower in the case of the F layer due to lower air density at higher altitudes. As a consequence of this, the F layer is able to support night time radio communications.

#### 1.4.7.2 Modes of Propagation

Electromagnetic waves, after being radiated by transmitting antennas, may be divided into various parts. One part travels along the surface of Earth and is known as the *ground wave*. The other part moves upwards and is known as the *sky wave* (Figure 1.86). The ground wave further comprises the *surface wave* and *space wave*. The surface wave travels in contact with the surface of Earth. The space wave travels in the space just above the surface of Earth. It is composed of the *direct wave* and *reflected wave*. To summarize, the ground wave comprises the surface wave, direct wave and reflected wave (Figure 1.87).

Ground waves propagate along the boundary between the Earth's surface and the atmosphere. In the case of a vertical antenna, ground waves leave the antenna in all directions. In the case of horizontal antennas, they leave the antenna mainly from the broad side. Since the



Figure 1.86 Different modes of propagation.



Figure 1.87 Components of a ground wave.

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Figure 1.88 Space wave propagation.

ground is a good conductor, ground waves are always vertically polarized as horizontally polarized ground waves would get shorted out by the conductivity of the ground. Ground waves are attenuated as they propagate along Earth's surface as the Earth is not a perfect conductor. The attenuation is more pronounced at higher frequencies, which limits the usefulness of the ground wave propagation mechanism to frequencies to below 3 MHz. It is, however, the preferred propagation type for long-distance communication for frequencies below 3 MHz. Since sea water has higher conductivity, ground waves can propagate over longer distances over sea.

Space waves propagate directly between the transmitting antenna and receiving antenna, which necessitates there is a line-of-sight path between the two (Figure 1.88). The maximum geometric line-of-sight distance between the two antennas depends upon the heights of them and is mathematically expressed by  $D(\text{in km}) = 3.57 \times \left| \sqrt{H_t} + \sqrt{H_r} \right|$  where  $H_t$  and  $H_r$ , respectively, are the heights of transmitting and receiving antennas in metres. In practice, the radio waves don't travel in straight lines. Instead, due to refractive effects of atmospheric layers, they experience bending towards the surface of Earth, thereby effectively increasing the radio horizon distances by a factor approximately equal to 1.15 (increase of 15%) under normal weather conditions. As a result, this expression gets modified to  $D(\ln \text{ km}) = 4.12 \times |\sqrt{H_t} + \sqrt{H_r}|$ . Space waves also have the characteristic of bouncing off hard objects, which can lead to total blockage of the signal if there is an obstacle between the two antennas. In general, what reaches the receiving antenna is the combined effect of the direct wave and reflected wave. The reflection could be from Earth's surface from an adjacent object such as a building. The two waves, that is the direct and reflected waves, reach the receiving antenna with a certain phase difference leading to reduction in signal strength. In the case where the direct and reflected signals become out of phase with each other, they cancel each other out. However, if they arrive at the receiving antenna in phase, they add up.

Sky waves make use of the ionosphere for communication. Ionospheric propagation allows radio signals to be received at much longer distances. Reflection from the ionosphere is called a 'hop'. The radio signal after reflection from the ionosphere travels back towards Earth and is received by the receiving antenna. The radio signal may bounce off the Earth's surface again and get reflected from the ionosphere again only to be received on Earth's surface at a further distance. There can be several reflections between Earth's surface and ionosphere in what is known as multi-hop transmission (Figure 1.89).

The preferred mode of propagation is determined by the frequencies involved and the distance to be covered. Ground wave propagation, which is mainly dominated by the surface wave, is useful only for short-distance communication. Surface waves attenuate rapidly as they propagate due to Earth being a good conductor and there comes a point where the signal strength of the surface wave becomes too weak to be received and detected. As outlined earlier, higher frequencies suffer greater attenuation. Thus, a higher frequency wave travels considerably smaller distances than a lower frequency wave. Therefore, ground wave propagation is effective for short-distance communication at low frequencies. At higher frequencies, the only



Figure 1.89 Sky wave propagation.

alternative is to use space waves. To avoid a cancellation effect, their path difference may get considerably increased by increased heights of transmitting and receiving antennas. For long-distance communication, sky wave propagation is the preferred mode. In this, highfrequency signals get reflected from the ionosphere and reach the Earth. In the vicinity of the point where the waves reach after reflection, the signal is considerably stronger.

# 1.5 Optical Communication

Communication technology has experienced a continual development to higher and higher carrier frequencies, starting from a few hundred kilohertz in Marconi's time to several hundred terahertz since we employed lasers in fibre systems. The main driving force was that the usable bandwidth and the consequently the transmission capacity increased in direct proportion to carrier frequency. Another asset comes into play in free-space point-to-point links. The minimum divergence obtainable with a freely propagating beam of electromagnetic waves scales proportional to the wavelength. The jump from microwaves to light waves therefore means a reduction in beam width by orders of magnitude, even if we used transmit antennas of much smaller diameter. The reduced beam width does not only imply increased intensity at the receiver site but also reduced cross-talk between closely operating links and less chance for eavesdropping. Space communication, as employed in satellite-to-satellite links, is traditionally performed using microwaves. For more than 25 years, however, laser systems are being investigated as an alternative. One hopes that mass, power consumption and size of an optical transceiver module will be smaller than that of a microwave transceiver. Also, fuel consumption for satellite attitude control when quickly redirecting antennas should be less for optical antennas. On the other hand, a new set of problems would need to be addressed in connection with the extreme requirements for pointing, acquiring and tracking the narrow-width laser beams.

## 1.5.1 Advantages and Limitations

Optical communication is a communication technology that uses light propagating in the communication medium to transmit data for telecommunications or computer networking. The communication media could be free space, which means air, outer space, vacuum or something similar, water as is the case in underwater communication or an optical transmission line such as optical fibre cable. Key advantages of using optical communication, fibreoptic/free space or underwater include high achievable data transmission rates, low bit error rates, immunity to electromagnetic interference, full duplex operation, higher communication security and no necessity for a Fresnel zone. Also, the light beam can be very narrow, which makes it hard to intercept.

Key disadvantages include beam dispersion particularly in free space and underwater communication applications, signal attenuation due to atmospheric absorption and adverse weather conditions, scintillation and signal swamping when the Sun goes exactly behind the transmitter. These factors cause an attenuated receiver signal and lead to higher bit error ratio (BER). To overcome these issues, designers have found some solutions such as multi-beam or multipath architectures, which use more than one sender and more than one receiver. Some state-of-the-art devices also have larger fade margin (extra power, reserved for rain, smog, fog). To keep an eye-safe environment, good free-space optical communication systems have a limited laser power density and support laser classes 1 or 1M. Attenuation due to atmospheric conditions, which are exponential in nature, limits practical range of free-space optical communication (FSO) devices to several kilometres. In the following paragraphs two common modes of optical communication are described at length; namely, free-space communication and fibreoptic communication.

#### 1.5.2 Free-Space Communication

Free-space optical communication is a communication technology that makes use of light as the carrier to transmit intelligence. Free space here means air, outer space, vacuum or something similar. The other common form of optical communication in use is optical fibre communication that makes use of an optical transmission line such as optical fibre cable. The technology is useful where physical connections are impractical due to high costs or other considerations. In addition, there is a host of other advantages that come along with use of optical communication. These have already been outlined in the previous paragraph. Figure 1.90 shows the basic block-schematic arrangement of a free-space optical communication link. The diagram is self-explanatory.

Practical free-space point-to-point optical links are usually implemented by using infrared laser light, although low-data-rate communication over short distances is possible using LEDs. Maximum range for terrestrial links is in the order of 2-3 km, but the stability and quality of the link is highly dependent on atmospheric factors such as rain, fog, dust and heat.



Figure 1.90 Block-schematic arrangement of a free-space optical communication link.

Data transmission rates approaching 1 Gbps have been demonstrated in the case of free-space optical communication, though not for terrestrial links.

Preferred wavelengths for free-space optical communication are 850 and 1550 nm. Operation in  $3-5 \,\mu\text{m}$  and  $8-14 \,\mu\text{m}$  bands has also been used due to excellent atmospheric transmission characteristics in them. Selection of optimum wavelength for free-space communication depends upon many factors, which include required transmission distance, eye-safety considerations, availability of components, cost and so on. Recent studies have revealed that operation in the  $3-5 \,\mu\text{m}$  and  $8-14 \,\mu\text{m}$  bands does not offer a significant advantage as compared to 850 and 1550 nm bands to counteract scattering losses. Also, availability of sources and detectors is limited in mid-infrared and far-infrared bands. Another advantage of 1550 nm comes in its eye-safety feature. Regulatory agencies allow approximately 100 times higher laser power levels for 1550 nm compared to 850 nm. In general, choice of a specific wavelength is not so important as long as it is not strongly absorbed in the atmosphere.

In outer space, the communication range of free-space optical communication is currently in the order of several thousand kilometres, but can be extended to cover interplanetary distances of millions of kilometres using optical telescopes as beam expanders. Use of optical communication technology involving detection and emission of laser light by space probes has been done several times in the past. A two-way distance record for communication was set by the Mercury laser altimeter instrument aboard the *Messenger* (an acronym for MErcury Surface, Space ENvironment, GEochemistry and Ranging) spacecraft. This infrared diode-pumped neodymium laser, designed as a laser altimeter for a Mercury orbit mission and known as Mercury Laser Altimeter (MLA), set a record of two-way communication across a distance of 24 million km, as the craft neared Earth on a fly-by in May, 2005.

The space-based free-space optical communication concept has been around for many years and particularly in the last few years, significant advances have been made for the concept to fructify in both civilian and government funded non-classified and classified applications. The primary market of free-space optical communication today is that of Inter-Satellite Links (ISL). There is scope in providing space-earth optical communication links in spite of the discouraging atmosphere related issues. For example, lot of R&D activity is known to be funded to develop a satellite to submarine optical communication link, which mainly interests military strategists. In such a link of course, problems are encountered not only from atmospheric issues but also from issues concerning propagation of lasers through turbulent waters of the oceans.

Coming back to the primary application of free-space optical communication links in today's world, that is, inter-satellite links (ISLs), it may be mentioned here that inter-satellite communications are mainly used for networking of a satellite constellation. The involved data rates could vary from hundreds of Mbps to several Gbps. ISLs are in use for all types of satellite orbits including low earth orbits (LEO), medium earth orbits (MEO), geosynchronous earth orbits (GEO) and even highly elliptical orbits (HEO). Though there are currently operational satellite constellations employing RF inter-satellite links, examples being the Iridium satellite system and NASA's TDRSS (Tracking and Data Relay Satellite System), the future definitely belongs to optical ISLs. This is supported by the fact that most of the commercial satellite constellations being announced now will use optical ISLs. The SILEX optical communication system is another example. SILEX payload embarked on the European Space Agency's *Artemis* (Advanced Relay and Technology Mission Satellite) spacecraft and also on the French Earth observation satellite SPOT-4. It uses GaAlAs laser diodes as the source and is used to transmit data at 50 Mbps from a low earth orbit to geostationary orbit.

The TSAT (Transformational Satellite System) is yet another example of a contemporary satellite constellation employing laser intersatellite links. The system is designed to provide a



Figure 1.91 The TSAT satellite constellation.

protected, secure Internet-like communication system that integrates space, air, ground and sea networks. The TSAT programme is composed of three segments and a systems engineering and integration function. The Space Segment will consist of five satellites in geosynchronous orbits interconnected by high-data rate laser cross links. TSAT will use internet-like technology to connect war fighters all over the world in a global information network with unprecedented carrying capacity, accessibility, reliability and immunity to jamming, eavesdropping and nuclear effects. It is the backbone of twenty-first-century net-centric warfare and is projected to revolutionize military communications. Figure 1.91 shows a photograph of the TSAT satellite constellation.

#### 1.5.3 Fibreoptic Communication

Fibreoptic communication is also a form of optical communication and it differs from the freespace communication in respect to transmission medium, which in this case is a fibreoptic cable rather than free-space. While the advantages of optical communication discussed in the previous paragraphs in the case of free-space communication equally hold good for fibreoptic communication, some of the key limitations of free-space optical communication encountered due to atmospheric propagation issues are overcome in fibreoptic communication. In practice, laser-based communication today is dominated by fibreoptic transmission. Earlier, the life times of semiconductor diode lasers and the fibre losses were too high to make laser-based fibreoptic communication an attractive alternative to other forms of communication. With advances in both semiconductor diode laser and fibre technologies, these shortcomings have been overcome. State-of-the-art semiconductor diode lasers have life times of greater than 10<sup>7</sup> hours and fibre loss is as small as a small fraction of dB/km. Today, fibreoptic communication links are a reality for both intra-city and trunk telephone lines, video data links and computerto-computer communications.

The semiconductor diode laser is the natural choice for fibreoptic communication as these are suitably small and have a configuration for efficient coupling into the small-diameter core



Figure 1.92 Basic block-schematic of a fibreoptic communication link.

of an optical fibre cable. Semiconductor diode lasers operating at CW power levels of a few milliwatts are suitable for fibreoptic communication. These lasers can be easily modulated by drive current modulation up to frequencies in the gigahertz range.

Laser wavelengths in use for fibreoptic communication are 0.85, 1.3 and 1.55  $\mu$ m. The first practical fibreoptic communication systems employed 0.85  $\mu$ m as it matched the available AlGaAs lasers. With advances in fibre technology and the opening up of lower loss windows first at 1.3  $\mu$ m and then at 1.55  $\mu$ m, these became the preferred wavelengths for long-distance, high performance systems. Corresponding semiconductor diode laser and detector types for these operational wavelengths are AlGaAs and silicon for 0.85  $\mu$ m, InGaAsP and InGaAs or Germanium for 1.3  $\mu$ m and InGaAsP and InGaAs for 1.55  $\mu$ m. Typical fibre losses at these wavelengths are 2 dB/km at 0.85  $\mu$ m, 0.5 dB/km at 1.3  $\mu$ m and 0.2 dB at 1.55  $\mu$ m.

Figure 1.92 shows a typical fibreoptic communication link. The laser is pulse code modulated with intelligence to be transmitted through drive current modulation and is coupled into the fibre. On the receiver side, laser light is detected and the intelligence signal is recovered. Optical amplifiers are used to reinforce the signal strength every few km of fibre cable length to counter signal degradation caused by various loss mechanisms such as absorption, scattering and modal and chromatic dispersion. To summarize, the process of fibreoptic communication involves generating the optical signal modulated with intelligence to be transmitted using a transmitter, relaying the signal along the fibre making sure that the signal does not become too distorted or weak, receiving the optical signal and converting it back into an electrical signal representing the original intelligence signal.

In terms of choice of different components for fibreoptic communication, preferred types of laser sources and detectors for the commonly used wavelength bands were briefly discussed in an earlier paragraph. To summarize, fibres with loss figures of 2 dB/km at 0.85  $\mu$ m, 0.5 dB/km at 1.3  $\mu$ m and 0.2 dB/km at 1.55  $\mu$ m are available. Also, fibres with bandwidth-distance products approaching 3000 MHz/km are available. Semiconductor diode lasers with 10 mW power levels and modulation rates approaching 10 GHz with a life time of 10<sup>7</sup> hours are also available. LEDs providing 0.1 mW into the fibre with a modulation rate of 200 MHz and life time in the order of 10<sup>6</sup>–10<sup>7</sup> are also available. PIN type photo diodes with responsivity and NEP figures of 0.5 A/W and 10<sup>-12</sup> W/ $\sqrt{Hz}$ , respectively, are used. Also, more sensitive APDs with responsivity and NEP figures of 80–100 A/W and 10<sup>-14</sup> W/ $\sqrt{Hz}$  are commercially available for the purpose. Couplers and splices with insertion loss in the range of 0.1–0.5 dB are available for use. Splices are usually added to the link to allow fibre cable repair in case of need.

We have seen four generations of fibreoptic communication and currently we are in the fifth generation. This first-generation system operated at 0.85 µm wavelength at a bit rate of 45 Mbps and repeater spacing of up to 10km. In April 1977, General Telephone and Electronics sent the first live telephone traffic using fibreoptics at a 6 Mbps data rate in Long Beach, California. The second generation of fibreoptic communication operated at  $1.3 \,\mu\text{m}$  and used InGaAsP semiconductor lasers. These fibreoptic systems were initially limited by dispersion of multimode fibres. The advent of single-mode fibres in 1981 significantly improved system performance. Third-generation fibreoptic systems operated at 1.55 µm. The difficulty faced earlier in terms of pulse spreading at  $1.55\,\mu m$  was largely overcome by using dispersion-shifted fibres designed to have minimal dispersion at  $1.55\,\mu m$  or by limiting the laser spectrum to a single longitudinal mode. The features of third-generation systems allowed commercial fibreoptic systems to operate at 2.5 Gbit/s with repeater spacing in excess of 100 km. The fourth generation of fibreoptic communication systems used optical amplification to reduce the need for repeaters. It also explored use of wavelength-division multiplexing to increase data capacity. These features brought revolutionary improvements to the performance of fibreoptic systems. In fact, since 1992, the data rate has doubled every six months until it reached a figure of 10 Tbps after 2000. In 2006, a bit rate of 14 Tbps was reached over a single 160 km line using optical amplifiers.

In the fifth generation of fibreoptic communications systems, the focus is on extending the wavelength range over which a WDM system can operate. The conventional wavelength window, known as the C band, covers the wavelength range  $1.53-1.57 \mu m$ . The dry fibre promises an extension of that range to  $1.30-1.65 \mu m$ . Other features of fifth generation fibreoptic systems include the concept of optical solitons, which involves use of pulses of a specific shape that helps them preserve their shape by counteracting the effects of dispersion with the nonlinear effects of the fibre.

### 1.6 Software-Defined Radio

There are diverse areas in which communications devices and systems are put to use by a large cross-section of users in civilian and military sectors. Also there are many ways by which one would like communicate, which principally include voice, video and data communications. Others include broadcast messaging, command and control communications, emergency response communications and so on. Conventionally, it wouldn't be feasible for a generic hardware platform to fit all these application scenarios. Software-Defined Radio (SDR) allows a common platform to be used across a number of areas. The basic concept of the SDR is that the functions to be performed by the radio can be totally configured or defined by the software. In addition to defining radio configuration, there is also the possibility that it can be reconfigured in case its scope of operation is changed or it is to be employed for another role or as the existing

standards get the upgrades. The concept of SDR is equally applicable to both military as well as commercial sectors. Joint Tactical Radio System (JTRS), a radio intended for military applications and briefly discussed in an earlier section in the chapter, has been a major initiative in the military domain. JTRS allowed the use of a single hardware platform to communicate in different application scenarios by simply reloading or reconfiguring the software required for the intended application. One of the common applications applicable to the commercial world is the ease with which frequently occurring upgrades of standards can be incorporated, such as at cellular base stations by using a generic platform. These changes such as those from *Universal Mobile Telecommunications System* (UMTS), a third-generation mobile cellular system based on the GSM (*Global System for Mobile*) communication standard to *High-Speed Packet Access* (HSPA) and on to *Long Term Evolution* (LTE) technology, a standard used for wireless transmission of high-speed data for mobile phones and data terminals, could be incorporated simply by uploading new software and reconfiguring it without any hardware changes irrespective of the fact that different operating frequencies and modulation schemes are used.

There are two main categories of radio using software, which include the software controlled radio and SDR. The SDR Forum, working in collaboration with the Institute of Electrical and Electronic Engineers (IEEE) P1900.1 group defines the two categories of radio as follows. *Software controlled radio* is the one in which software is used to control some or all of the physical layer functions of the radio that are fixed within the radio. That is, the functions performed by the radio are not software defined or reconfigurable; instead the software is used to only control the predefined functions. In the case of software-defined radio, some or the entire physical layer functions of the radio. The SDR is configured around a generic hardware platform comprising digital signal processors as well as general-purpose processors to implement transmit and receive radio functions. The hardware platform is used to operate in different application scenarios and offer a range of performance specifications as defined by the software is used to reconfigure the hardware platform for various applications.

#### 1.6.1 Different Tiers of SDR

Different tiers of SDR in essence define the different levels of SDR that may exist. It may be mentioned here that it may not always be practically feasible for an SDR to have all possible features in one radio. Different tiers describe the level of software definability of the radio in terms of what is configurable and what is not. Different tiers include Tier 0, Tier 1, Tier 2, Tier 3 and Tier 4. Each one of them is briefly described in the following paragraph.

Tier 0 is the level assigned to anon-configurable hardware radio. That is, no changes can be made to the radio by software. Tier 1 is a software controlled radio where limited functions are controllable. In the case of Tier 1 SDR, control functionality is implemented in software, but change of attributes such as type of modulation and operating frequency band cannot be implemented without changing hardware. These may be power levels, interconnections and so on, but not mode or frequency. Tier 2 SDR is more of a software controlled radio (SCR) though there is significant proportion of the radio that is software to provide variety of modulation techniques, wideband or narrow band operation, and communications security functions. The RF front-end still remains hardware based and nonreconfigurable. Tier 3 SDR is the ideal SDR. It possesses all of capabilities of software-defined radio, but eliminates analogue amplification and heterodyne mixing prior to A/D conversion and after D/A conversion. It could be said to have full programmability. Tier 4 is the ultimate software radio (USR) and is a stage further on from the Ideal Software Radio (ISR). Not only does this form

of software-defined radio have full programmability, but it is also able to support a broad range of functions and frequencies at the same time. It is the ideal software-defined radio on a chip that requires no external antenna and doesn't have any frequency restrictions. It can perform a wide range of adaptive services.

### 1.6.2 Advantages of SDR

The key advantages of SDR originate mainly from its capability to reconfigure its common hardware platform using software and the waveform portability.

- 1) The concept of SDR allows implementation of a family of radios using a common hardware architecture, thereby facilitating quick introduction of many a new product into the market. Software re-usage across a range of radio products reduces costs and remote re-programming enables fixing bugs in radios while they are in service. For the service providers, the use of a common hardware platform for multiple applications significantly reduces logistical support and operating expenditures. Remote software downloads can be used to increase capacity.
- 2) SDR waveform portability when ensured by incorporating certain steps at the early stages of design lends interoperability. In addition to the capability of an SDR to reconfigure itself, another major advantage is that of waveform portability. Capability of reusing waveforms for various applications leads to huge savings in cost. It also mitigates obsolescence as the existing waveforms get transferred to newer platforms with the development of technology.

### 1.6.3 SDR Hardware Architecture

There are different tiers or levels of SDR, as outlined previously. The complexity of the hardware platform and associated control and management software to an extent varies with the level the radio belongs to. Irrespective of the hardware platform and software complexity, there are certain basic functional blocks that are present in the architecture of SDR. Figure 1.93 shows the block-schematic arrangement of an ideal SDR highlighting the basic functional blocks.

The first basic functional block is that of *RF amplification*, which includes power amplification of the signal present at the output of digital-to-analogue converter (DAC) on the transmit side and low noise amplification of received antenna signal on the receive side. A power amplifier raises the level of the RF signal to the required power suitable for transmission and



Figure 1.93 Block-schematic arrangement of an ideal SDR.

the low noise amplifier amplifies the received antenna signal before it is further passed onto the analogue-to-converter (ADC). An ideal SDR digitally codes and modulates the data that's going to be communicated in a baseband processor before transmitting it. Also, the digital output of the ADC is processed in a baseband processor to recover the originally transmitted signal. In the case of an ideal SDR, the antenna connects directly to the low noise amplifier (LNA) and the ADC or the power amplifier and the DAC. It is the baseband processor that handles all radio functions. In many designs, some analogue processing may be required, which would typically involve converting the signal to and from the final radio frequency. Some intermediate frequency processing may also be present.

A digital-to-analogue converter (DAC) on the transmit side and analogue-to-digital converter (ADC) on the receive side constitute *digital conversion* building block. It is at this stage that the signal is converted between the digital and analogue formats. While on transmit side digital conversion, the maximum frequency and the required power level are the some of the key issues to be addressed, on the receive side, the maximum frequency and number of bits to give the required quantization noise are of great importance.

The *baseband processor* is at the very centre of SDR. It performs all radio functions including filtering, up/down conversion, modulation/demodulation and digital baseband. One of the key issues of the baseband processor is the amount of processing power required. The greater the processing power, higher would be the current consumption, which in turn requires additional cooling. This is particularly important if size were a limitation.

Most wireless activity is above the VHF and UHF frequency band and well into the microwave region. Though it may be feasible to realize an ideal SDR at relatively lower frequencies, it is not so at frequencies normally encountered in the case of practical SDRs. As a consequence of this, modern SDRs need to use mixers in the front-end to perform analogue up-conversion and down conversion. Figure 1.94 shows the block-schematic arrangement of a practical SDR.



Figure 1.94 Block-schematic arrangement of a practical, modern SDR.

A mixer following the low noise amplifier in the receive channel downconverts the received RF signal to an intermediate frequency (IF) that can be handled by today's ADCs. In the transmission channel, an up-convert mixer up-converts the DAC signal to the final transmission frequency before it is fed to the power amplifier for subsequent transmission. As is evident from the block diagram, I/Q mixer format has been used to preserve phase and frequency information contained in most digital modulation schemes.

Digital Up Conversion (DUC) is employed in the transmission channel to boost the lower set of frequencies to an intermediate frequency that is closer to transmit frequency. Digital Down Conversion (DDC) is commonly used in the receive channel after the ADC to further lower the data rate so that memory requirements may be relaxed and processing speeds are more moderate. Ideally, we would have liked to have ADC and DAC to be fast enough to eliminate these conversions so that all baseband processing is performed digitally. But that is not the case as yet. Though these devices come as individual ICs, their functions also can be implemented in the baseband processor. The baseband processors may be fast standard processors like those found in PCs, laptops, programmable DSPs or FPGAs. Modern SDRs typically use both a DSP and an FPGA, with the processing duties divided up as appropriate to the capabilities of each.

### 1.6.4 SDR Security

While the emergence of SDRs has added many new features such as re-configurability, waveform portability and interoperability to both military and commercial radios, it has also triggered new sets of security problems not encountered by conventional radios. It is important to understand security requirements of a communication network in general before we look at the security risks that affect these networks in an adverse manner. SDRs and cognitive radios should have capabilities to address various security risks that can undermine the following security requirements. Different security requirements that are applicable to almost all communication networks including SDRs and cognitive radios encompass a *controlled access to resources* allowing one to access information or resources only when authorized for the same; robustness to provide the specified communicated data while guaranteeing integrity of a system and also that of stored and communicated data; *compliance to a regulatory framework; accountability or non-repudiation* implying that the system entities own the responsibility for any of their performed actions and system capability to establish and *verifying the claimed identity* of any player in the network.

Different types of security threats are briefly described as follows. These threats are broadly classified as threats that are common to both conventional radios and SDRs and those that are specific to SDRs. *Insertion of malicious software* is a type of threat similar to mobile malware and relates to introduction of malicious software on an SDR. *Alteration or destruction of configuration data* is a threat that identifies the alteration or destruction of configuration data leading to corruption or removal of this data from the SDR platform and needed by it to perform its intended functions. *Artificial consumption of resources* is a type of threat that identifies the abnormal increase in processing or memory resources of the SDR platform and may be caused by various things such as insertion of malicious software, alteration or destruction of configuration data or even physical failure. *Alteration or destruction of waveform code* is a type of threat that relates to alteration or destruction of the waveform code required to support a radio access technology or air interface, thereby affecting one or more radio waveforms but not the SDR itself. *Alteration or destruction of a real-time operating system* alters or destruction of the software framework is a threat relating to alteration or destruction of elements of the

software framework and middleware, which support the waveforms and applications. *Alteration or destruction of user data* relates to alteration or destruction of user data. *Software failure* relates to failure of any of the components of the real-time operating system, the software framework, waveforms or applications. *Hardware failure* is a type of threat identifying a generic hardware failure in the hardware platform. *Extraction of configuration data, waveform data* and *user data* are eavesdropping threats where the attacker collects configuration data, waveform data and user data, respectively, which can be used in subsequent attacks. Yet another type of security threat relates to *download and activation of a malicious software waveform* or application can access or use services of the SDR platform without proper access level. *Data repudiation* or rejection relates to the possibility of repudiating or rejecting access or provision of data and services.

# 1.7 Network-Centric Warfare

*Network-centric warfare* (NCW) is a military doctrine that uses networking of sensors, planners and decision makers and shooting platforms to create enhanced shared awareness of the battle space. Shared awareness of battle space for the armed forces increases synergy for command and control, which leads to superior decision making and an ability to coordinate complex military operations spread over a wide geographical coverage to give an overwhelming military advantage. Coordinated efforts and synchronized operations result in greater inflicted lethality on the adversary forces and increased survivability of own forces.

There are slight variations in how network-centric warfare is known and interpreted in different countries. The United States uses the term *Network-Centric Warfare* (NCW), which is characterized by the ability of geographically dispersed forces to create a high level of shared battle space awareness that can be exploited through various network-centric operations to execute commander's intent. In the United Kingdom, the term *Networked Enabled Capability* (NEC) is used. The NEC concept is based on use of three elements namely *sensors* to gather information, *network* to fuse and disseminate sensor data and *strike assets* to deliver the military effect. In Australia, the term *Network Enabled Operations* (NEO) was initially used. The concept was derived its power from effectively linking different elements to conduct military operations. Under the NEO concept, platforms are treated as nodes of a network. They all collect, share and access information, which is used to create a common, real-time battlespace picture. This allows a greater level of situational awareness, coordination and offensive potential than is currently the case. The use of the term NEO has been discontinued and the US terminology of NCW has been adopted instead.

### 1.7.1 OODA Loop

In order to understand the role of different components of NCW in improving the overall efficacy of military engagement, we must first understand the complete sequence of events that must take place in a military engagement. This is best described by the US Air Force strategist John Boyd's *OODA* (*Observation-Orientation-Decision-Action*) loop. The OODA loop is fundamental to all military operations at both tactical and strategic levels as the adversary must be observed to gather information, the attacker must orient himself as per the situation or context, take decision and then act accordingly. With everything else being equal, the player with faster OODA loop would have a distinctive edge over his opponent by preempting or blocking any move that the opponent with relatively sluggish OODA loop intends to execute.

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The OODA loop as outlined here has four components. It is imperative that all four components are accelerated to achieve an overall higher operational tempo. While the first three of the four components relate to information processing and therefore largely governed by networking capabilities, the fourth component is the kinetic component of the loop and is associated with movement and application of fire power. The first three components of observation, orientation and decision are all about gathering and distributing information, analysing it and then deciding how to act upon it. Networking accelerates the observation and orientation phases thereby facilitating the decision phase.

However, efficient networking capability only is not the solution to all problems. Overall combat effectiveness is linked to the kinetic phase of the OODA loop. NCW scholars have tried to use the well-established laws such as the Metcalfe's law and Amdahl's law from commercial domains to military operations. While Metcalfe's law presents a best possible scenario for distribution of information gathered by platform sensors by stating that utility of a network increases as a function of square of number of nodes or platforms in the network, Amdahl's law explains the limits to the gains achieved in networked systems arising from decision and action phases of the OODA loop. According to Amdahl's law, increasing the number of assets in the system increases the achieved effect at best only by the number of assets added as the real improvement is constrained by queuing effects observed in positioning of the assets or platforms that perform engagements. Another important aspect of NCW operations is that the networking does permit a significant improvement in operational tempo in all those cases where the targeting information is lacking such as in close air support operations against highly mobile ground targets. On the contrary, networking would have very little impact in cases where the targeting information is well-known or where the operation is constrained by number of platforms in use.

### 1.7.2 Advantages and Shortcomings

The salient features of the network-centric warfare doctrine as outlined in the previous paragraphs highlight the advantages it brings to the modern battlefield. To summarize, key advantages expected from application of the NCW doctrine to military operations include the following.

- 1) The NCW doctrine with its networking capabilities allows deployment of relatively smaller size units with fewer platforms and supplies without the need for a tight formation. This enables accomplishment of a given mission with greater efficacy and lower cost. Also, networking allows use of new tactics. It gives to the troops far greater battle space awareness and ability to track movements of fellow soldiers when they are spread over a large coverage area in small independent units. Swarm tactics involving the use of a decentralized force against the adversary with focus on mobility, communication, coordination and unit autonomy used by the US Armed Forces during Operation Iraqi Freedom is an example. Another example of use of networking and communications capabilities has been during the US Operation Enduring Freedom in Afghanistan when Special Forces on the ground could execute a coordinated operation between them and the air support through use of data and voice links provided by communications satellites thereby enabling attack aircraft destroy targets laser designated by ground forces.
- 2) The networking capability of NCW allows individual units benefit from the experiences of experts located far away from war scene in case situation demands.
- 3) The NCW doctrine exploits the shared battle space awareness of the Armed Forces to achieve strategicand tactical objectives through close coordination not only in a specific theatre of operations, but also of dispersed forces on a global level.

4) Implementation of the NCW doctrine significantly reduces sensor-to-shooter time by allowing soldiers in the field conduct an on-site analysis of raw intelligence available from sensors on platforms to facilitate quick action.

Though NCW is essential to modern-day military operations, it has issues that must be addressed to take full advantage of this military doctrine. Technological innovations come with both pros and cons. Implementation of new concepts in warfare can create a new set of vulnerabilities an adversary can seek to exploit. NCW is no exception. Some of the key problem areas include the following.

- 1) NCW's heavy reliance on technology and infrastructure runs the risk of crippling military operations in the event of failure of technology or incapacitation of infrastructure through attack by adversary; should there be no alternative warfare strategy in a non-network-centric operational scenario. Widespread use of GPS jammers capable of blocking GPS signals that are central to navigation and precision guidance capabilities strengthen the point.
- 2) Another flaw in NCW, if one may say so, is the premise that machine intelligence and analysis is superior and therefore can be used to replace the soldier in the loop, though there is no viable proof to substantiate the claim. There are numerous instances of massive communication, information, security and processing failures of commercial computer networks. While such failures to a certain degree may be acceptable in case of commercial networks, the same would not be true for networks dictating military operations. Information and networking alone are therefore no substitutes for combat manoeuvre and the massing of Armed Forces. NCW is akin to a chess game where situational awareness alone is not enough to win you the game, making a move by instead anticipating the enemy's next move is the key.

# 1.8 C4ISR

C4ISR is an acronym for Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance. The C4ISR concept encompasses all systems, technologies and procedures that are used to gather and disseminate information. C4ISR systems allow military commanders to understand their operational environment, identify mission-critical factors and control their assets. It is a highly multi-disciplinary concept involving application of command and control, communications, intelligence, surveillance and reconnaissance systems and technologies. Command and control functions involve planning, directing, coordinating and controlling operations for accomplishment of intended mission. These functions are performed through an arrangement of personnel, equipment, communications and facilities. Creation of situational awareness is an essential element of command and control systems, which they provide by fusing data streams from multiple sensors and feeding the decision support software. Other software components as applied to C4ISR systems include programmes and algorithms used to ensure interoperability among disparate communication systems, encryption algorithms to ensure security of communications, communications networking protocols and inertial navigation. Threat warning systems and electronic countermeasures such as jamming techniques and counter-countermeasures such as decoys are also included in the command and control domain. Communications and computing technologies process and transport information and are the enabling technologies that support command and control (C2) and intelligence, surveillance and reconnaissance (ISR) functions. ISR functions involve use of remote optical, infrared and radar sensors placed on platforms such as satellites and unmanned vehicles.

### 1.8.1 Command and Control

*Command and control*, communications and information infrastructure, data fusion and information management systems, radar, infrared and optical sensors, electronic warfare, cyber security and space-based surveillance constitute important elements of C4ISR. Command and control systems give the Armed Forces the decisive advantage by enabling concurrent and not serial planning and decision making, thereby keeping Armed Forces ahead of their adversaries in accelerated operational environments. The *Theatre Battle Management Core System* (TBMCS) developed by Lockheed–Martin is one such command control system. It is the primary system for planning and executing the joint air campaign, coordinating and directing flying operations from a wide range of airborne platforms such as F-16 fighters, refuelling tankers, helicopters, unmanned aerial vehicles and even cruise missiles. TOPLITE from Rafael, a highly stabilized, multi-role, multi-sensor optronic payload, is a day/night surveillance and targeting system configured for naval, air and ground surveillance and targeting systems. It is designed for a wide range of missions, from law enforcement observation through surveying and fire-control to missile targeting.

### 1.8.2 Communications

Next-generation communication networks need to be secure, resilient and adaptable. The Universal Communications Platform (UCP) from Lockheed–Martin is one such system. The UCP integrates any radio communications systems using existing communications infrastructure to form a cost-effective, dedicated network for complete communications including voice, video and data. The Warfighter Information Network–Tactical (WIN-T) by the same company is a tactical tele-communications system for the army. The WIN-T network provides mobile, secure and seamless C4ISR capabilities capable of supporting multimedia tactical information systems. C4I-CONNECT from Rafael, a voice communication system developed for Air Force is another example. The SEA-COM system again from Rafael is a state-of-the-art communications suite for naval platforms.

### 1.8.3 Intelligence, Surveillance and Reconnaissance

ISR systems, as outlined earlier, use thousands of sensors housed on manned and unmanned landbased, airborne, sea-based and space-based military platforms. Data from sensors is processed, analysed, fused to generate and disseminate mission-critical information. *P-3 Orion* from Lockheed–Martin is one such ISR platform. It is a premier multi-mission maritime long-endurance aircraft that performs air, surface and subsurface patrol and reconnaissance tasks over extended periods. SEA SPOTTER, infrared Stabilized Stare and the Track (IRS<sup>2</sup>T) system, developed by Rafael, enable situational awareness and the automatic, passive detection of sea skimming missiles, air-to-surface smart bombs, fast strike aircraft, helicopters, marine vessels and rubber boats.

### 1.8.4 Cyber Security and EW Systems

Sophisticated *cyber solutions* are used to defend networks and systems from advanced persistent threats. Electronic warfare systems include *Naval EW systems* are used to intercept signals that identify both imminent and potential threats and even protect vessels from anti-ship missile attacks, *Ground EW Systems* such as the *Symphony Counter – Improvised Explosive Device* (*C – IED*) *Defeat* system and *Airborne EW Systems* such as the *Electronic Support Measures* (*ESM*), *Radar Warning Receivers* (*RWR*), *COMINT* (*Communications Intelligence*) and *ELINT* (*Electronic Intelligence*) systems.

C-PEARL from Rafael is a compact, lightweight state-of-the-art ESM system enabling automatic detection and identification of threats in complex electromagnetic environments. C-PEARL has military, naval and homeland security applications.

### 1.9 Representative Military Communications Equipment

In the following paragraphs, we shall briefly discuss salient features and capabilities of some representative devices and systems under the categories of smart phones, radios including ground mobile radios, SDRs and cognitive radios and C4ISR systems including command and control, communications and ISR systems. Representative EW systems are covered in Chapter 6 on *Electronic Warfare*.

#### 1.9.1 Smart Phones

Smart phones and tablets are becoming increasingly popular with the Armed Forces, particularly as the associated security concerns have been addressed to a large extent. An increasing number of smart phones certified for military use are now commercially available. Some common types include *LG G5* using Android OS version 6.0.1 and *LG V10* using Android OS version 5.1.1, Motorola's *AME 1000 secure mobile telephony system* configured around *ES400 Enterprise smart phone, Solarin* from Sirin Labs and the *Boeing Black Smartphone*.

The United States' *National Information Assurance Partnership* (NIAP) for compliance in meeting international security standards in corporate environments has certified model G5 and V10 from LG Electronics for military use. It may be mentioned here that NIAP employs a Common Criteria Evaluation and Validation Scheme for certification for security conformance and is recognized by the governments of 25 Common Criteria member countries including, Canada, France, Germany, India, Japan, South Korea and the UK. LG V5 and G10 smart phones feature LG's *GATE (Guarded Access to Enterprise)* technology for enhanced platform, network, and application security.

The LG G5 employs GSM/HSPA/LTE/CDMA networking technology and is powered by Qualcomm MSM8996 Snapdragon 820 octa-core chip set that runs on Android OS, v6.0.1 (Marshmallow). It comes with a 5.3-inch 1440 × 2560 pixel touch screen display, 4GB of RAM and 32 GB of internal storage. Solarin packs a 23.8-megapixel primary camera on the rear and an 8-megapixel front camera. Connectivity options include WiFi, GPS, Bluetooth, NFC, radio, an infrared port and USB. The phone includes fingerprint technology, accelerometer, gyro, proximity, compass, barometer and colour spectrum sensors. The LG V10 employs GSM/HSPA/CDMA/EVDO/LTE networking technology and is powered by a Qualcomm MSM8992 Snapdragon 808Hexacore chip set that runs on Android OS, v5.1.1 (Lollipop), upgradable to v6.0 (Marshmallow). It comes with a 5.7-inch 1440 × 2560 pixel touchscreen display, 4GB of RAM and 32/64 GB of internal storage. It has a 16-megapixel primary camera and 5-megapixel duo secondary camera. Connectivity options include WiFi, GPS, Bluetooth, NFC, radio, infrared port and USB. The phone includes fingerprint technology, accelerometer, gyro, v6.0 (Marshmallow). It comes with a 5.7-inch 1440 × 2560 pixel touchscreen display, 4GB of RAM and 32/64 GB of internal storage. It has a 16-megapixel primary camera and 5-megapixel duo secondary camera. Connectivity options include WiFi, GPS, Bluetooth, NFC, radio, infrared port and USB. The phone includes fingerprint technology, accelerometer, gyro, proximity, compass, barometer and colour spectrum sensors.

Motorola's *AME-1000 Secure Mobile Telephony Solution* combines hardware- and softwarebased security that meets federal information security standards and also provides National Security Agency (NSA)-approved Suite B encrypted voice communications. The AME-1000 is configured around the ES400 enterprise smart phone (Figure 1.95). It comprises an ES400 with a CRYPTR micro encryption module, Apriva Voice software and an Apriva gateway infrastructure. It employs GSM/HSPA networking technology and is configured around the Qualcomm



Figure 1.95 Motorola's ES400 smart phone.

MSM7627 chip set that runs on the Microsoft Windows Mobile 6.5.3 Professional operating system (OS). It has a 3.0-inch 480 × 640 pixel resolution touch screen display. Connectivity options include WiFi, Bluetooth, radio, GPS and USB. It includes fingerprint technology and accelerometer sensors.

Solarin from Sirin Labs (Figure 1.96) is yet another smart phone designed for military use and other applications where security and privacy are highly desirable. It was launched in May 2016. Reportedly, it is equipped with the most advanced security features and incorporates privacy technology currently unavailable in other secure smart phones. The smart phone includes military grade encryption embedded in its hardware and also has built-in security software. In addition, it comes with a physical security switch, which can be used to put the phone into a shielded mode for making secure phone calls. This special switch at the back flips it into a cyber-secure mode, thereby allowing only outgoing voice calls and securely encrypted messaging.

Solarin is powered by an octa-core Qualcomm Snapdragon 810 processor that runs on the Android 5.1 operating system (OS). It comes with a 5.50-inch 1440 × 2560 pixel touchscreen display, 4 GB of RAM and 128 GB of internal storage. Solarin packs a 23.8-megapixel primary camera on the rear and an 8-megapixel front camera. The SirinSolarin is a single SIM (GSM) smart phone that accepts a Nano-SIM. Connectivity options include WiFi, GPS, Bluetooth, NFC and 4G. The phone includes a proximity sensor, ambient light sensor, accelerometer and gyroscope.

Figure 1.96 Solarin smart phone.



Figure 1.97 Boeing Black smart phone.



The *Boeing Black* smart phone (Figure 1.97) with its security and modularity features allows use of the same mobile platform across a range of missions and configurations. The smart phone employs specific hardware and software architecture for various configurations depending on the intended mission. Security features include Embedded FIPS 140–2 Key Storage, Hardware Inhibits, Trusted Modules and Configurable OS Security Policies. Major device specifications include a 4.3-inch qHD display with 540×960 pixel resolution, Bluetooth v2.1 + EDR enabled connectivity, a dual 1.2 GHz ARM Cortex-A9 processor, dual SIM support that allows users to switch between government and commercial networks, micro-SD card slot and Android OS with enhanced software security configuration allowing users to configure the device for maximum mission productivity and security.

#### 1.9.2 Tactical Radios

*Tactical radios* are widely used to deliver secure, reliable and mission-critical information to the intended recipients on the battlefield. Tactical handheld and manpack radios for individual soldiers and radios mounted on ground vehicles and aerial platforms such as fixed or



Figure 1.98 JTRS-HMS AN/PRC-155 Manpack Radio.

rotary-wing aircraft and unmanned aircraft systems deliver high-speed multiband voice, data and video to provide enhanced situational awareness enabling soldiers to switch waveforms and networks on-the-move as per the requirements of the intended mission. A large number of tactical radios including handheld radios, manpack radios, HF radios, VHF radios, UHF radios, VHF/UHF radios and multiband radios to name a few are available from leading international companies such as Thales, General Dynamics, Motorola and the Harris Corporation. Some representative tactical radios are briefly covered as regards their salient features in the following paragraphs. These include the *JTRS-HMS (Joint Tactical Radio System – Handheld Manpack Small form fit) Rifleman Radio* Type *AN/PRC-154* and *Manpack radio Type AN/PRC-155* by Thales and General Dynamics, the *AN/VRC-118 (V) 1* developed under MNVR (Mid-tier Networking Vehicular Radio) US Army programme by the Harris Corporation, the *Falcon-III AN/PRC-152A* wideband networking handheld radio and *Falcon-III RF-7850A-MR* multichannel networking radio from the Harris Corporation, the *SRX-2200* combat radio from Motorola.

JTRS-HMS is a family of software-programmable and hardware configurable digital radios designed to provide increased flexibility, adaptability and interoperability to support military communications requirements of diverse missions of the Army, Marine Corps, Navy and Air Force. The JTRS-HMS family includes essentially any portable ground radio unit not mounted on vehicles. Different variants of JTRS family of tactical radios include the Handheld Rifleman Radio Type AN/PRC-154 and Two-channel Manpack Radio Type AN/PRC-155 (Figure 1.98) and forms suitable for integration on platforms requiring a small form fit radio. The AN/ PRC-154 Rifleman Radio is an individual soldier's radio that is used to simultaneously transmit voice and data utilizing the UHF-band (225-450 MHz) and L band (1250-1390 MHz, 1750-1850 MHz) and the Soldier Radio Waveform (SRW). It brings secure squad-level communications to the soldier by encrypting unclassified information (NSA, Type-2). The AN/PRC-155 Manpack Radio is two-channel networking software-defined radio operating in the 30-2200 MHz (banded) frequency range. The PRC-155 Manpack is the only tactical radio to demonstrate the successful use of all three networking waveforms including Soldier Radio Waveform (SRW), Wideband Networking Waveform (WNW) and Mobile User Objective System (MUOS) waveform. The SRW delivers secure networked voice and data communications for individual soldiers. The WNW provides the backbone function needed to seamlessly transport large amounts of data across the tactical network. The MUOS is a military satellite communications system that enables secure, mobile networked communications. The MUOS waveform enables satellite communications and leverages advanced wireless technology that is similar to terrestrial cellular communications. The AN/PRC-155 Manpack delivers secure communications using NSA Type-1 encryption of classified information. With two channels, the Manpack can run different waveforms simultaneously, eliminating the need for more than one radio at any location.

*AN/VRC-118 (V)1* was developed by the Harris Corporation under the US Army's Mid-tier Networking Vehicular Radio (MNVR) programme. This programme provides software-programmable digital radios to support army tactical communications requirements from company through to brigade. AN/VRC-118 (V) 1 provides a dynamic, self-forming and self-healing wireless network for both mobile and stationary forces. The radio utilizes two high-bandwidth waveforms namely the SRW and the WNW, which increases overall connectivity and network capability by operating as a node. Mission-critical information gets routed from sender to receiver using the best possible route through various hops from one AN/VRC-118(V)1 MNVR to another. The MNVR also provides a terrestrial data path if or when SATCOM is denied. It can also exchange mission-critical data with Army Aviation platforms through an Airborne Maritime Fixed station (AMF) Small Airborne Networking Radio (SANR). It is interoperable with Falcon, SINCGARS (Single Channel Ground and Airborne Radio System) and other legacy radio systems. SINCGARS is a new family of VHF-FM combat net radios that can operate in a hostile environment by means of its Electronic Counter Countermeasure (ECCM) features. It provides the primary means of command and control for Infantry, Armour and Artillery Units.

*Falcon-III AN/PRC-152A* by the Harris Corporation is handheld wideband networking radio that provides simultaneous voice and high-speed networked data with NSA-certified security using the Harris Sierra-II encryption module. The radio delivers secure, IP-based mobile adhoc networking to dismounted frontline operators, thereby putting enhanced connectivity in the hands of warfighters. Falcon-III AN/PRC-152A seamlessly connects dismounted and upper echelon networks to provide situational awareness and data-on-demand for faster decision making. The *Falcon-III RF-7850A-MR* multichannel networking radio, also from the Harris Corporation, extends the tactical network into the aerial tier. The radio facilitates ground-toair communications between command posts and the frontline forces by simultaneously delivering mission-critical voice, high-speed IP-networked data and full motion video. The radio is airborne certified for fixed and rotary winged aircraft. It is fully interoperable with legacy waveforms and all radios in the Falcon family. It is easily integrable on a range of military platforms to support multiple missions, waveforms and modes of operation.

The *FlexNet-One* (Figure 1.99) from Thales is a compact vehicular V/UHF (30–512 MHz) software-defined radio equipped with features such as mobile ad-hoc networking that is



Figure 1.99 FlexNet-One.



self-healing and self-organizing allowing automatic routing upon mobile nodes, open architecture that is fully compliant with Software Communications Architecture (SCA) to ensure waveform portability and accommodate customized requirements and upgraded functionality, interoperability that allows the radio to be immediately reconfigured to provide interoperability with the PR4G standard that makes it form/fit compatible with the worldwide operated Thales PR4G vehicular tactical radio and other standard and national waveforms, easy integration with IP networks and applications and embedded or external high level encryption including customer specific encryption.

Motorola's *SRX 2200 Combat Radio* (Figure 1.100) operates in the 700/800 MHz (763–776 MHz, 851–870 MHz), VHF (136–174 MHz) and UHF Range-1 (380–470 MHz). It is designed specifically for tactical and base personnel, equipped with host of battlefield-tested and military-trusted features. Salient features of the SRX 2200 include embedded Individual Location Information (ILI), night vision goggle compatibility, tactical inhibition, Federal Information Processing Standard (FIPS) 140–2 Level-3 validated encryption capability for secure voice and data communications and radio-to-radio text messaging allowing deployment in most sensitive operations, forwards and backwards compatibility with all Motorola mission-critical radios including the most recent Project-25 (P-25) standards of interoperability and its compliance to rigorous MIL-810 environmental specifications and IP67 submersion specifications.

*Cognitive radio* is a radio communications technology that uses knowledge about environment, internal state and any predefined objectives to decide the relevant operational parameters thereby allowing the most efficient use of radio spectrum for the prevailing conditions. Cognitive radios have the ability to monitor, sense and detect the conditions of their operating environment, and dynamically reconfigure their own characteristics to best match those conditions. A cognitive radio is able to look at the spectrum, detect available or free frequencies and then implement the best form of communication for the required conditions by selecting the frequency band, the type of modulation and power levels most suited to the requirements, prevailing conditions and the geographic regulatory requirements. The xMAX system by xG Technology Inc. is one such cognitive radio network solution that provides end-to-end Internet Protocol (IP) network solution incorporating xG's patented cognitive radio technologies to deliver the first fully mobile Voice over Internet Protocol (VoIP) and broadband network that also supports any smart phone, tablet and other commercial WiFi or IP-enabled devices.

Figure 1.100 SRX-2200 combat radio.

#### 1.9.3 C4ISR Systems

C4ISR systems discussed in this section include the *Theatre Battle Management Core System* (TBMCS) developed by Lockheed–Martin and *TOPLITE* from Rafael (Command and Control), the *Universal Communications Platform* (UCP) and *Warfighter Information Network–Tactical* (WIN-T) from Lockheed–Martin, *C4I-CONNECT* and *SEA-COM system* from Rafael (Communications) and *P-3 Orion* from Lockheed–Martin and *SEA SPOTTER* developed by Rafael (ISR).

Developed and fielded by Lockheed–Martin, the *Theatre Battle Management Core System* (TBMCS), a set of hardware and software application tools, is the primary air warfare tool used for planning and execution of theatre air battle plan for intelligence and operations personnel at force and unit levels. It is the workhorse engine of the Air Operations Centre (AOC) for coordinating and directing flying operations from a wide range of airborne assets such as fighter jets, refuelling tankers, helicopters, unmanned aerial vehicles and even cruise missiles. TBMCS feeds real-time, decision-quality information to a cross-section of users from the Joint Forces Air Commander to the staff at an Air Operations Centre and further on to pilots and weapons control officers on the battlefield. TBMCS horizontally integrates numerous stove-piped systems, often developed in isolation with disregard to how it might be integrated with future technologies, to provide mission-critical information in real time to users across the battlefield accelerating the decision cycle to enable forces to act faster and decisively. Developed and fielded by Lockheed–Martin, TBMCS is resident at Air Operations Centres and Navy ships around the globe.

Physical elements of TBMCS include workstations running the core *Contingency Theatre Automated Planning System* (CTAPS), *Combat Intelligence System* (CIS), *Wing Command and Control System* (WCCS) and *Command and Control Information Processing System* (C2IPS) *software applications* at various nodes of the Theatre Air Control System (TACS). There are other elements such as *Air Force Mission Support System* (AFMSS), *Navy/Marine Joint Maritime Command and Control Information Processing System* (JMCIS), *Army/Marine Advanced Field Artillery Tactical Data System* (AFATDS) that are not considered core systems. These systems are also equally important in the integrated system for command and control of joint air operations. Each element of the system exchanges information with the *Joint Forces Air Component Commander* (JFACC) and the staff through automated links to TBMCS. TBMCS functionality supports the command and control of joint air operations regardless of the JFACC's Service affiliation.

TOPLITE Electro-Optic System (EOS) from Rafael (Figure 1.101) is a multirole, multi-sensor optronic payload that can be configured for military, airborne, naval and homeland security applications. It is a derivative of Rafael's state-of-the-art LITENING targeting and navigation pod. TOPLITE EOS systems support defence and homeland security applications ranging from missile targeting and guidance for precision-guided weapons to fire-control and law enforcement observation. It is used for day/night target observation, detection, identification and recognition of targets in adverse weather conditions for guidance of precision-guided weapons. Different subsystems of TOPLITE payload include 4-axis Gimbals (360° continuous or  $\pm 165^{\circ}$  azimuth coverage,  $\pm 85^{\circ}$  to  $-35^{\circ}$  or  $-85^{\circ}$  to  $\pm 35^{\circ}$  elevation coverage, up to 90°/s slew rate, up to 100°/s<sup>2</sup> LOS acceleration and better than 20 micro-radian LOS stabilization on a manoeuvring helicopter flight), third-generation (3–5 µm) Focal Plane Array (FPA) with  $320 \times 240$  pixel resolution (TOPLITE-II) and  $640 \times 480$  pixel resolution (TOPLITE-III) or second generation and third-generation 8–12 micron FPA, B/W or colour CCD, eye-safe laser rangefinder, Laser designator (optional), NVG (Night Vision Goggle) compatible 0.808 µm Laser Marker and Advanced correlation tracker. TOPLITE systems are currently operational



Figure 1.101 TOPLITE EOS system. (Source: Courtesy of Konflikty.pl.)

on land-based, airborne and sea-based platforms in the United States, Israel, Australia and many other countries across the worldfor weapons guidance and control and in surveillance, detection and identification systems.

The Universal Communications Platform (UCP) from Lockheed-Martin integrates fixed and mobile radio systems thereby transforming any radio system into a fully IP-based network. With the new generation of IP communications technologies and protocols, the UCP enables nearly any type of existing radio system to perform with state-of-the-art IP features. It enables interoperability with other communications and data-related systems, and allows monitoring, control and dispatch from any location with a network connection and a smart phone, laptop, Personal Computer (PC) or a Personal Digital Assistant (PDA). The communications platform has been designed on an open-architecture framework, which allows the UCP to be easily and seamlessly integrated and deployed to a wide range of government and civilian applications, including first responder, law enforcement and counterterrorism. The Tactical Deployable Unit (TDU) version of UCP integrates land mobile radio units, LTE, Tactical Communications and WiFi in a seamless operation. It is a self-contained, portable system that includes fully capable communications for operation centres, mobile units and the Department of Defence and Department of Homeland Security applications. It supports a large number of tactical radios including the Thales MBITR/JEM, Harris PRC 117F/150/152, General Dynamics URC-200, PSC-5, Collins GRC-171, Harris R-2368, Harris RF-590A, Harris RF-1310A, Harris RF-5800M-HH, Harris RF-5800H-MP and Harris RF-310M-HH; Ground Mobile radios including the Motorola P25, Tetra, Harris P25, Open Sky, EF Johnson P25, TDMA, Thales P25 and Thales Liberty; Cellular Radios including the GSM 2/3G, CDMA and Satellite Radios including BGAN, Iridium and Thuraya. TDU enables first responders to set up for operation at any place and at any time in less than 15 minutes. Network Interface Unit (NIU), Radio Control Unit (RCU) and Multi-Radio Unit (MRU) are the other UCP products from Lockheed-Martin. NIU provides an IP-based gateway for communications interoperability. It allows up to four separate audio devices to be accessed remotely through a LAN or WAN using a common IP language and supports any device that supports two- or four-wire analogue audio. A Radio Control Unit (RCU) enables IP-based remote control radios worldwide. It provides access and



Figure 1.102 WIN-T Increment 2 communication node.

control of embedded radios through an IP Network either in conjunction with or independent of NIU and MRU products. This allows all radios connected to the RCU to be remotely controllable from any client device including PC, laptop, PDA, cellular smart phones, SIP phones, iPhones and iPads. MRU connects multiple radio transceivers. The unit works in conjunction with NIU and RCU to provide IP access and control of up to four separate portable radio transceivers. It can be configured and tuned remotely with the most commonly used web browsers via the web-based interface.

The Warfighter Information Network - Tactical (WIN- T) developed by General Dynamics Mission systems is a telecommunications network backbone that delivers voice and data communication services without the need for any fixed infrastructure. WIN-T Increment 1 provides voice and data communications at the halt. It began to be fielded in 2004 and is currently in use by the US Army, National Guard and Army Reserves. It was used to support combat missions during Operation Enduring Freedom and Operation Iraqi Freedom where it provided a high-speed, interoperable voice and data communications network down to the battalion level. WIN-T Increment 2 provides connectivity to the soldiers on the move. It does so through tactical communication nodes that provide mobile communications infrastructure on the battlefield, thereby maintaining network connectivity even after the fixed infrastructure has been removed. Figure 1.102 shows the mobile communications infrastructure on a vehicle. WIN-T Increment 2 is a completely adhoc, self-forming network that enables commanders and select staff to manoeuvre anywhere on the battlefield and maintain connectivity to the network. This makes them far less vulnerable to attack as there is no need for them to stop and set up communications. The 10<sup>th</sup> Mountain Division of the US Army reportedly was the first to get equipped with this capability in July 2013 when deployed in Afghanistan. WIN-T Increment 3 is the research and development component of the WIN-T programme and is aimed at improving the capability of all increments of the network. The objective of WIN-T Increment 3 is that the network keeps pace with advances in technology and that the entire WIN-T portfolio remains cyber secure with ongoing upgrades and Type-1 encryption for the network. Another objective is to expand the reach of the network so as to be able to support a highly dispersed force over isolated areas.



Figure 1.103 The P-3 Orion. (Source: Courtesy of the US Navy).

*C41 CONNECT* from Rafael is a Radio/Voice-over-IP (RoIP/VoIP) communication system leveraging the most advanced industry standard technologies such as IP, VoIP and RoIP. It is designed for the specific needs of battlefield command and control (C2) applications. A distinctive feature of the C4I CONNECT is its seamless interoperability, which provides seamless access to various types of UHF, VHF, HF and SATCOM radios and to any legacy telephony system. Other key features include built-in IP-PBX capability that supports advanced telephony features such as call transfer, caller ID and call waiting indication; an embedded conference bridge with capabilities to run an unlimited number of broadcast or conference calls; secure voice communication that ensures that all voice sessions are protected and only authorized users are allowed to participate in a session; user/officer mobility that allows the user to be located anywhere in the country and still be able to participate in a mission taking place elsewhere and a built-in digital recording system that records all voice, data and video sessions over the tactical network.

The SEA-COM system developed by Rafael is a state-of-the-art, IP-based communication suite for naval platforms such as ships and submarines. SEA-COM fully integrates internal communication including voice, data and video and external communication systems including HF, V/UHF and SATCOM. The SEA-COM communication suite maintains continuity of operations in the harsh environmental conditions of the sea due to use of a redundant IP network and an automatic reconfiguration management system.

The P-3 Orion (Figure 1.103) from Lockheed–Martin is a multi-mission maritime aircraft designed to perform air, surface and subsurface patrol and reconnaissance tasks over extended periods of time. It is a long-endurance aircraft capable of performing designated tasks far from support facilities. P-3 Orion is fitted with sophisticated detection equipment including Infrared and long-range electro-optical cameras and a special imaging radar that allow it to monitor activity from a comfortable distance. The P-3 Orion can carry a variety of weapons in its large internal weapons bay and a number of external weapons hard points. The P-3 airborne platform is used for a variety of missions including submarine hunting, over-land peacekeeping and surveillance operations, protection of shipping lanes, prevention of illegal immigration, anti-terrorism missions, providing warning of potential threats

to ground convoys and so on. Lockheed–Martin's Mid-Life Upgrade (MLU) programme ensures that P-3 Orion continues to evolve and remains mission ready for decades to come. P-3 Orion has provided support for *Operation Unified Assistance*, a humanitarian mission of the US military in the wake of Tsunami that struck South-East Asia in December 2004; *Hurricane Katrina* that struck the Gulf Coast of the United States in August 2005; the ongoing *Operation Atlanta* that started in December 2008, a counter-piracy military operation in the Gulf of Aden and the *BP Horizon oil rig disaster*, also known as the *Deep Water Horizon Oil Spill* that started in the Gulf of Mexico in April 2010 and capped in July 2010. No other aircraft is better suited for these missions and Lockheed–Martin's P-3 Mid-Life Upgrade Programme will help ensure the P-3 is mission ready for decades to come. It is mainly used by the US Navy, NASA, Canadian Armed Forces, Royal Australian Air Force and Royal New Zealand Air Force.

The *Sea Spotter* from Rafael is a third-generation infrared staring and tracking system that is capable of automatically locating both surface and airborne targets including surface-to-surface missiles, supersonic and subsonic sea skimming missiles, combat aircraft, gliding bombs, ARM weapons, helicopters, ships, rubber boats and small target vessels such as submarine periscopes. Based on infrared sensors, Sea Spotter is a completely passive system, which makes it invisible to the adversary's sensors unlike traditional radar sensors that give away a vessel's location. It has high probability of detection and an extremely low false alarm rate due to use of a continuously staring infrared sensor coupled with unique image-processing algorithms like 'track before detect' and 'multiple target tracking'. This is unlike the Infrared Search and Track (IRST) systems of the previous generation that used scanning sensors.

# **Illustrated Glossary**

- **A3E System** This is the Standard AM system used for broadcasting. It uses double side band with a full carrier.
- Adaptive Delta Modulation This is a type of delta modulator. In delta, the dynamic range of amplitude of message signal m(t) is very small due to threshold and overload effects. In adaptive delta modulation, the step size ( $\Delta$ ) is varied according to the level of message signal. The step size is increased as the slope of the message signal increases to avoid overload. The step size is reduced to reduce the threshold level and hence the quantizing noise when the message signal slope is small.
- **AME-1000** A secure mobile telephony solution from Motorola. It combines hardware and software-based security that meets federal information security standards and also provides National Security Agency (NSA)-approved Suite B encrypted voice communications. AME-1000 is configured around ES400 enterprise smart phone and comprises ES400 with a CRYPTR micro encryption module, Apriva Voice software and an Apriva gateway infrastructure.
- **Amplitude Modulated (AM) Transmitters** AM transmitters employ amplitude modulation. These transmitters are used in medium-wave (MW) and short-wave (SW) frequency bands for AM broadcast. Based on the transmitted power levels, AM transmitters use high level modulation scheme where the transmitted power needs to be of the order of kilowatts and low-level modulation where only a few watts of power needs to be transmitted.
- **Amplitude Modulation** This is the analogue modulation technique in which the instantaneous amplitude of the carrier signal varies directly as the instantaneous amplitude of the modulating signal. The frequency of the carrier signal remains constant.

- **Amplitude Shift Keying (ASK)** This is a digital modulation technique. In the simplest form of ASK, the carrier signal is switched ON and OFF depending upon whether a 1 or 0 is to be transmitted. This is also known as ON-OFF keying. In another form of ASK, the amplitude of the carrier is switched between two different amplitudes.
- **Amplitude Shift Keying (ASK) Transmitters** ASK transmitters use ASK modulation commonly used in LED transmitters for transmission of digital data through optical fibres. ASK transmitters operate in the VHF/UHF-band. Other applications of ASK transmitters include remote control operations and security systems.
- **Antenna** An antenna is a structure that transforms guided electromagnetic waves into freespace electromagnetic waves and vice versa.
- AN/VRC-118 (V) 1 A vehicular radio developed by the Harris Corporation under the Mid-tier Networking Vehicular Radio (MNVR) programme of the US Army. The MNVR programme provides software-programmable digital radios to support Army tactical communications requirements from company through brigade. AN/VRC-118 (V) 1 provides a dynamic, self-forming and self-healing wireless network for both mobile and stationary forces.
- **B8E System** This system uses two independent side bands with carrier either attenuated or suppressed. This form of amplitude modulation is also known as independent side band (ISB) transmission and is usually employed for point-to-point radio telephony.
- **Bandwidth (Antenna)** Antenna bandwidth is, in general, the operating frequency range over which the antenna gives a certain specified performance. Antenna bandwidth is always defined with reference to a certain parameter such as gain or input impedance or standing wave ratio (SWR).
- **Beam Width (Antenna)** This gives the angular characteristics of radiation pattern. It is taken as the angular separation either between the half power points on its power density radiation pattern or between 3 dB points on the field intensity radiation pattern
- **Boeing Black** This is a smart phone from Boeing. With its security and modularity features, it allows use of the same mobile platform across a range of missions and configurations. The Boeing Black smart phone employs specific hardware and software architecture for various configurations depending on the intended mission.
- **C3F System** Also known as Vestigial Side Band transmission. This is used for transmission of video signal in commercial television broadcasting. It is a compromise between SSB and DSB modulation systems in which a vestige or part of the unwanted side band is also transmitted usually with a full carrier along with the other side band. The typical bandwidth required to transmit a VSB signal is about 1.25 times that of an SSB signal.
- **C4I CONNECT** The C4I CONNECT from Rafael is a Radio/Voice-over-IP (RoIP/VoIP) communication system leveraging the most advanced industry standard technologies such as IP, VoIP and RoIP. It is designed for the specific needs of battlefield command and control (C2) applications.
- **C4ISR** An acronym for Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance. C4ISR concept encompasses all systems, technologies and procedures that are used to gather and disseminate information. C4ISR systems allow military commanders to understand their operational environment, identify mission-critical factors and control their assets.
- **Characteristic Impedance (Transmission Line)** This is its input impedance if it was infinitely long. Characteristic impedance is characteristic of the line and is independent of the length of the line.
- **Characteristic Impedance (Waveguide)** This is another important waveguide parameter. The generalized expression for the characteristics impedance  $Z_0$  of waveguide for TE modes is given

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by  $Z_0 = 377 \times \sqrt{(\mu/\varepsilon)} \times (b/a) \times (\lambda_g/\lambda)$ . The generalized expression for the characteristic impedance  $Z_0$  of waveguide for TM modes is given by  $Z_0 = 377 \times \sqrt{(\mu/\varepsilon)} \times (b/a) \times (\lambda/\lambda_g)$ . For rectangular waveguides, a is the wide dimension and b is the narrow dimension. For circular waveguides, a = b.

- **Citizens Band (CB)** The CB Radio Service that is allocated 40 channels in 26.965–27.405 MHz frequency band is a private, two-way, short-distance voice communications service for personal or business activities of the general public and may also be used for voice paging.
- **Cognitive Radio** This refers to an array of technologies that allow radios self-reconfiguration in terms of operating mode selection, optimal power output and dynamic spectrum access for interference management. Cognitive radios have the ability to monitor, sense and detect the conditions of their operating environment, and dynamically reconfigure their own characteristics to best match those conditions.
- **Continuous-Wave (CW) Receiver** The CW receiver is used for detection of continuouswave communication signals. A direct conversion receiver used for detection of CW signals, such as those transmitted in wireless telegraphy using Morse code, is a CW receiver.
- **Continuous-Wave (CW) Transmitter** The CW transmitter makes use of a radio communication technique that uses an undamped continuous-wave signal of constant amplitude and frequency. The CW transmitter is principally used for radiotelegraphy; that is, for the transmission of short or long pulses of RF energy to form the dots and dashes of the Morse code characters.
- **Cross-Polarization (Antenna)** This is the component that is orthogonal to the desired polarization.
- **Cut-off Wavelength (Waveguide)** This is the highest wavelength that can propagate through the waveguide. Cut-off wavelength for rectangular guides for both  $TE_{mn}$  and  $TM_{mn}$  is given by  $\lambda_c = 2/\sqrt{(m/a)^2 + (n/b)^2}$  where *a* is the wide dimension and *b* is the narrow dimension of the waveguide. The cut-off wavelength of a circular waveguide with an internal diameter *d* is given by  $\lambda_c = \pi d / K_r$  where  $K_r$  is the solution of a Bessel function equation.
- **Delta Modulation** This has various forms. In one of the simplest forms, only one bit is transmitted per sample just to indicate whether the amplitude of the current sample is greater or smaller than the amplitude of the immediately preceding sample.
- **Differential PCM** This is similar to conventional PCM. The difference between the two lies in the fact that in differential PCM, each word or code group indicates difference in amplitude (positive or negative) between the current sample and the immediately preceding one.
- **Differential Phase Shift Keying** This is another form of PSK. In this, instead of instantaneous phase of carrier determining which bit is transmitted, it is the change in phase that carries message intelligence. In this system, one logic level (say 1) represents a change in phase of carrier and the other logic level (i.e., 0) represents a no change in phase.
- **Dipole Antenna** This is also a straight radiator usually fed at the centre and producing maximum of radiation in a place perpendicular to the antenna axis.
- **Directional Pattern (Antenna)** The antenna Directional Pattern or Radiation Pattern is a normalized plot of distribution of electromagnetic energy in a three-dimensional (3D) angular space. The parameters to be plotted could be radiation intensity, which is the power per unit solid angle or the power density.
- **Directive Gain (Antenna)** Directive gain in a given direction is defined as the ratio of the power density of the radiated electromagnetic energy in that direction to the power density in the same direction and at the same distance due to an isotropic radiator with both antennas radiating the same total power.

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**Dominant Mode (Waveguide)** Dominant mode propagating in a waveguide is one which has the highest cut-off wavelength for a waveguide of given dimensions.

- **Effective Isotropic Radiated Power (EIRP)** This given by product of transmitter power and antenna gain. An antenna with a power gain of 40 dB and a transmitter power of 1000 W would have an EIRP of 10 MW. That is, 10 MW of transmitter power when fed to an isotropic radiator would be as effective in the desired direction as 1000 W when fed to a directional antenna with 40 dB power gain in desired direction.
- **Falcon-III AN/PRC-152A** This is a handheld wideband networking radio from the Harris Corporation. It provides simultaneous voice and high-speed networked data with NSA-certified security using the Harris Sierra-II encryption module.
- **Falcon-III RF-7850A-MR** This is a multichannel networking radio from Harris Corporation. It extends the tactical network into the aerial tier. The radio facilitates ground-to-air communications between command posts and the frontline forces by simultaneously delivering mission-critical voice, high-speed IP-networked data and full motion video.
- **Fidelity (Communication Receiver)** This refers to its ability to accurately reproduce at its output the signal that appears at its input. Broader receiver bandwidth produces high fidelity. This is in contrast to the requirement of narrower bandwidth for better selectivity.
- FlexNet-One This is a compact vehicular software-defined radio from Thales.
- **Frequency Division Multiplexing** In the case of FDM, different message signals are separated from each other in frequency. FDM is used in telephony, commercial radio broadcast (both AM and FM), television broadcast, communication networks and telemetry.
- **Frequency Modulated (FM) Transmitters** These employ frequency modulation. One of the most common applications of FM transmitters is in FM broadcasting, which is nothing but radio broadcasting using frequency modulation. FM broadcasting first began in 1945 and is now used worldwide to provide high-fidelity voice and music over broadcast radio. FM broadcasting employs the VHF band at 30–300 MHz.
- **Frequency Modulation** This is the analogue modulation technique in which the instantaneous frequency of the modulation signal varies directly as the instantaneous amplitude of the modulating or base band signal. The rate at which these frequency variations take place is of course proportional to the modulating frequency.
- **Frequency-Shift Keying** FSK is the frequency of the carrier signal that is switched between two values, one representing bit '1' and the other representing bit '0'.
- **Frequency-Shift Keying (FSK) Transmitters** FSK transmitters employ FSK modulation and operate in the VHF/UHF-band. They are generally used for remote control and security systems available for these applications.
- **Ground Wave** This is that part of propagating electromagnetic wave that travels along the surface of Earth. The ground wave further comprises the surface wave and space wave. A surface wave travels in contact with the surface of Earth. A space wave travels in the space just above the surface of Earth. It is composed of a direct wave and reflected wave. Space waves propagate directly between transmitting antenna and receiving antenna, which necessitates there is a line-of-sight path between the two.
- **Guide Wavelength (Waveguide)** This is the wavelength of the travelling wave propagating inside the waveguide. The guide wavelength  $\lambda_g$ , the cut-off wavelength  $\lambda_c$  and the free-space

wavelength ( $\lambda$ ) are interrelated by  $\lambda_g = \lambda / \sqrt{1 - (\lambda / \lambda_c)^2}$ .

H3E System This is the single side band, full carrier AM system.

**Helical Antenna** This is a broadband VHF/UHF antenna. Most of its applications are due to the circularly polarized waves it produces.

- **Hertz Antenna** This is a straight length of a conductor that is half-wave long. It may be placed vertically to produce vertically polarized waves or in horizontal position to produce horizontally polarized waves.
- **High-Frequency (HF) Transmitters** HF transmitters operate over the HF band (3–30 MHz) and use ionosphere as means of electromagnetic wave propagation that is commonly known as sky wave propagation are particularly suitable for long-distance communication across intercontinental distances. The band is extensively used by international short wave broadcasting stations as the entire short wave band of frequencies (2.310–25.820 MHz) falls within the HF band.
- **High Level Amplitude Modulated Transmitter** This employs high level modulation. In a case of high level modulation, the carrier signal is modulated at a much higher power level equal to the power to be transmitted. The carrier signal here is amplified in a chain of Class C amplifiers to raise the power to the level required for transmission.
- **Horn Antenna** This is a simple development of the waveguide transmission line. It is essentially a section of waveguide where the open end is flared to provide a transition to the areas of free space. The horn antenna is used in the transmission and reception of RF microwave signals. The antenna is normally used in conjunction with waveguide feeds.
- **Impedance (Antenna)** Antenna impedance at a given point in the antenna is given by the ratio of voltage to current at that point. As the magnitude of voltage and current vary along the antenna length, the impedance also varies being minimum at the point of voltage node or minima such as the centre point of half-wave dipole and maximum at the point of current node such as the centre point of full-wave length long antenna.
- **Ionosphere** This is a region of atmosphere extending from 60 km to about 1000 km. The ionosphere further comprises of different layers designated as D, E, F1 and F2 layers.
- **J3E System** This is the Single Side Band Suppressed Carrier system. This is the system usually referred to as SSB, in which carrier is suppressed by at least 45 dB in the transmitter.
- **JTRS-HMS** This is a family of software-programmable and hardware configurable digital radios designed to provide increased flexibility, adaptability and interoperability to support military communications requirements of diverse missions of the Army, Marine Corps, Navy and Air Force. The JTRS-HMS family includes essentially any portable ground radio unit not mounted on vehicles. Different variants of JTRS family of tactical radios include the Handheld Rifleman Radio Type AN/PRC-154 and Two-channel Manpack Radio Type AN/PRC-155 and form suitable for integration on platforms requiring a small form fit radio.
- **LG G5** This is a smart phone from LG Electronics. It uses Android OS version 6.0.1 and is certified by National Information Assurance Partnership (NIAP) for military use.
- **LG V10** This is smart phone from LG Electronics. It uses Android OS version 5.1.1 and is certified by National Information Assurance Partnership (NIAP) for military use.
- **Log Periodic Antenna** This is a broadband VHF/UHF antenna capable of providing enormous bandwidth.
- **Low-Level Amplitude Modulated Transmitter** This employs low-level modulation. In the case of low-level amplitude modulation, amplitude modulation of carrier signal takes place at a much lower power level of the carrier signal and the modulated signal is then amplified in a chain of linear amplifiers to raise the power required for transmission.
- **Marconi Antenna** This is the vertical antenna that is a quarter-wave long and is fed against an infinitely large perfectly conducting plane.
- **Medium Frequency (MF) Transmitters** MF transmitters operate over the 300 kHz–3 MHz frequency band and are used for AM radio broadcast services that employ (535–1705) kHz band, maritime and aircraft navigation, amateur radio, cordless phones and so on.

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**Mesosphere** This is a region of atmosphere located between 50 and 80km above Earth's surface. **Microstrip Antenna** This consists of a thin strip sitting on a dielectric that rests on a ground plane.

- **Mid-tier Networking Vehicular Radio Programme (MNVR)** The MNVR programme aims to provide software-defined, multichannel networking radios for a wide variety of Army tactical vehicles to meet the Army's requirement for a mid-tier wideband networking capability. It provides self-forming and self-healing communication networks from the brigade to the platoon level throughout the full range of military operations.
- **Mismatch Loss (Transmission Line)** This is the loss due to reflection from a mismatch. It is defined as the ratio of incident power to the difference of incident and reflected power expressed in decibels.
- **Mobile Ad-Hoc Network (MANET)** MANET is a type of ad-hoc network that can change locations and configure itself on the fly. MANETs can be networked to interconnect multiple mobile phones within a specified coverage area offering greater bandwidth and better connectivity.
- **Network-Centric Warfare (NCW)** NCW is a military doctrine that uses networking of sensors, planners and decision makers and shooting platforms to create enhanced shared awareness of the battle space.
- **Offset QPSK** This is similar to QPSK with the difference that the alignment of the odd/even streams is shifted by an offset equal to *T* seconds, which is the pulse duration of the input bit stream.
- **OODA Loop** This describes sequence of events that must take place in a military engagement. The OODA loop is fundamental to all military operations at both tactical and strategic levels as the adversary must be observed to gather information, the attacker must orient himself as per the situation or context, take decision and then act accordingly.
- **P-3 Orion** The P-3 Orion from Lockheed–Martin is a multi-mission maritime aircraft designed to perform air, surface and subsurface patrol and reconnaissance tasks over extended periods of time.
- **Phased Array Antenna** A Phased Array Antenna or, more appropriately, a phase steered array antenna is the one where the radiated beam (or the axis of the main lobe of the radiated beam) can be steered by feeding the elements of the array with signals having a certain fixed phase difference between adjacent elements of the array during transmission. On reception, they work exactly the same way and instead of splitting the signals among elements, the elemental signals are summed.
- **Phase Modulated (PM) Transmitters** PM transmitters employ phase modulation. Phase modulation and frequency modulation are closely linked together (frequency is rate of change of phase) and is often used in many transmitters and receivers such as two-way radios and mobile radio communications including maritime mobile radio communications.
- **Phase Shift Keying (PSK)** In PSK, the phase of the carrier is discretely varied with respect to either a reference phase or to the phase of the immediately preceding signal element in accordance with the data being transmitted. For example, when encoding bits, the phase shift could be 0° for encoding a bit 0 and 180° for encoding a bit 1. The phase shift could have been  $-90^{\circ}$  for encoding a bit 0 and  $+90^{\circ}$  for encoding a bit 1.
- **Phase Shift Keying (PSK) Transmitters** PSK transmitters employ any of the different forms of phase shift keying, which include Phase Shift Keying (PSK), Binary Phase Shift Keying (BPSK), Quadrature-Phase Shift Keying (QPSK), 8-Point Phase Shift Keying (8-PSK), 16-Point Phase Shift Keying (16-PSK), Quadrature Amplitude Modulation (QAM), 16-Point Quadrature Amplitude Modulation (16-QAM) and 64-Point Quadrature Amplitude Modulation (64-QAM). PSK is particularly suited to data communications. PSK in its

different forms is extensively used for wireless LANs, Radio Frequency Identification (RFID) and Bluetooth communication.

- **Polarization (Antenna)** Antenna polarization is the direction of electric field vector with reference to ground in the radiated electromagnetic wave while transmitting and the orientation of the electromagnetic wave again in terms of the direction of electric field vector the antenna responds best to while receiving.
- **Power Gain (Antenna)** This is defined as the ratio of the power density at a given distance in the direction of maximum radiation intensity to the power density at the same distance due to an isotropic radiator for the same total power fed to the two antennas.
- **Propagation Constant (Transmission Line)** The propagation constant,  $\gamma$ , is a measure of the attenuation and the phase shift of the incident waves travelling from the source to the load end of the transmission line. Propagation constant, for practical reasons, is a complex quantity with a real part known as the attenuation constant,  $\alpha$ , and an imaginary part called the phase shift constant,  $\beta$ .
- **Pulse Amplitude Modulation (PAM)** In PAM, the signal is sampled at regular intervals and the amplitude of each sample, which is a pulse, is proportional to the amplitude of the modulating signal at the time instant of sampling.
- **Pulse Code Modulation (PCM)** In PCM, the peak-to-peak amplitude range of the modulating signal is divided into a number of standard levels, which in case of binary system is an integral power of 2. The amplitude of the signal to be sent at any sampling instant is the nearest standard level. This nearest standard level is then encoded into a group of pulses. The number of pulses (*n*) used to encode a sample in binary PCM equals  $\log_2 L$  where *L* is number of standard levels.
- **Pulse Position Modulation (PPM)** In the case of PPM, the amplitude and width of sampled pulses is maintained as constant and the position of each pulse with respect to the position of a recurrent reference pulse varies as a function of instantaneous sampled amplitude of the modulating signal.
- **Pulse Width Modulation (PWM)** In the case of PWM the starting time of the sampled pulses and their amplitude is fixed. The width of each pulse is made proportional to the amplitude of the signal at the sampling time instant.
- **Quadrature-Phase Shift Keying (QPSK)** QPSK is the most commonly used of all forms of PSK. A QPSK modulator is nothing but two BPSK modulators operating in Quadrature. The input bit stream  $(d_0, d_1, d_2, d_3, d_4...)$  representing the message signal is split into two bit streams, one with, say, even numbered bits  $(d_0, d_2, d_4...)$  and the other with odd numbered bits  $(d_1, d_3, d_5....)$ . The two bit streams modulate the carrier signals, which have a phase difference of 90° between them. The vector sum of the output of two modulators constitutes the QPSK output.
- **Quarter-Wave Transformer (Transmission Line)** This is  $\lambda/4$  long line. It can be used to match both real as well as complex load impedance to a transmission line.
- **R3E System** This is the single side band reduced carrier type AM system also called the pilot carrier system.
- **Reflection Coefficient (Transmission Line)** When a transmission line is terminated in load impedance which is not equal to its characteristic impedance, part of the signal energy sent down the line is reflected back. The ratio of the reflected signal amplitude to the incident one is defined as the reflection coefficient. It may be expressed as a magnitude only and denoted by  $\Gamma$  or as a complex value having both a magnitude and a phase and denoted by  $\rho$ , with  $\rho = |\Gamma|$ .
- **Reflector Antenna** This comprises of a reflector and a feed antenna. Depending upon the shape of the reflector and the feed mechanism, there are different types of reflector antennas suitable for different applications. The reflector is usually a parabolic, also called a

parabolic reflector, or a section of parabolic or cylindrical reflectors. A cylindrical reflector has a parabolic surface in one direction only. The feed mechanisms include the feed antenna placed at the focal point of the parabolic reflector or the feed antenna placed off the focal point. Another common feed mechanism is the Cassegrain feed. Cylindrical reflectors are fed by an array of feed antennas. The feed antenna is usually a dipole or a horn.

- **Return Loss (Transmission Line)** This signifies the total round trip loss of the signal and is defined as the ratio of the incident power to the reflected power at a point on the transmission line.
- **Rhombic Antenna** This is a long-wire antenna. In a rhombic antenna, conductors are arranged to form a rhombus. It is a combination of two long-wire V-antennas.
- **Sampling Theorem** This states that a band limited signal with the highest frequency component as  $f_M$  Hz can be recovered completely from a set of samples taken at the rate of  $f_s$  samples per second provided that  $f_s \ge 2f_M$ .
- **SEA-COM** This system developed by Rafael is state-of-the-art, IP-based communication suite for naval platforms such as ships and submarines. SEA-COM fully integrates internal communication including voice, data and video and external communication systems including HF, V/UHF and SATCOM.
- **Sea Spotter** Sea Spotter from Rafael is a third-generation infrared staring and tracking system that is capable of automatically locating both surface and airborne targets including surface-to-surface missiles, supersonic and subsonic sea skimming missiles, combat aircraft, gliding bombs, ARM weapons, helicopters, ships, rubber boats and small target vessels such as a submarine periscope.
- **Selectivity (Communication Receiver)** This is the ability of a receiver to reject unwanted signals at the input of receiver.
- **Sensitivity (Communication Receiver)** This is a measure of a receiver's ability to produce the desired signal-to-noise (S/N) ratio for weak received signals. It is measured as received signal strength in microvolts to produce a signal-to-noise ratio of 10 dB.
- **Shannon–Hartley Theorem** Shannon–Hartley theorem describes the capacity of a noisy channel (assuming that the noise is random). According to this theorem,  $C = B\log_2[1+(S/N)]$  bits/second

The Shannon–Hartley theorem underlines the fundamental importance of bandwidth and S/R ratio in communication. It also shows that for a given channel capacity, we can exchange increased bandwidth for decreased signal power.

- **Single Side Band (SSB) Receiver** The SSB is also a superheterodyne receiver comprising an RF amplifier, a mixer along with a local oscillator, intermediate frequency amplifier stage, a detector, an audio amplifier stage and a loudspeaker. One difference between the standard AM broadcast receiver and the SSBSC receiver is that the carrier signal needs to be reinserted at the detector for the detection process to occur.
- **Single Side Band (SSB) Transmitter** An SSB transmitter employs single side band modulation, a type of amplitude modulation in which one of the side bands, either upper side band or lower side band, is suppressed and only one side band is transmitted. SSB modulation and SSBSC (Single Side Band Suppressed Carrier) modulation techniques offer more efficient use of transmitter bandwidth and power.
- **Sky Wave** These make use of the ionosphere for communication. Ionospheric propagation allows radio signals to be received at much longer distances.
- **Smart Phone** This is a mobile phone that is capable of performing many of the functions of a computer with its touch screen interface, internet access and an operating system capable of running downloaded applications.
- **Software-Defined Radio (SDR)** SDR is the radio in which some or all of the physical layer functions are software defined. Software in this case can be used to alter the specifications and functions of the radio. The SDR is configured around a generic hardware platform comprising digital signal processors as well as general-purpose processors to implement transmit and receive radio functions.
- **Software Reprogrammable Payload (SRP)** SRP is a satellite-rooted technology with its down-to-earth communication potential. It is an adaptation of a small radio receiver designed for space applications into a full-fledged radio frequency system initially targeted for UAS (Unmanned Airborne System) communications.
- **SOLARIN** This is a smart phone developed by Sirin Labs designed for military use and other applications where security and privacy are highly desirable. The smart phone includes military grade encryption embedded in its hardware and also has built-in security software. In addition, it comes with a physical security switch, which can be used to put the phone into a shielded mode for making secure phone calls.
- **Soldier Radio Waveform (SRW)** SRW is an open-standard voice and data waveform used to extend wideband battlefield networks to the tactical edge. It is designed as a mobile ad-hoc waveform and it functions as a router within a wireless network. It is used to transmit vital information over long distances and elevated terrains including mountains and other natural or manmade obstructions and allows communication without a fixed infrastructure.
- **SRX-2200** This is a combat radio from Motorola. It operates in the 700/800 MHz (763–776 MHz, 851–870 MHz), VHF (136–174 MHz) and UHF Range-1 (380–470 MHz). It is designed specifically for tactical and base personnel, equipped with host of battlefield-tested and military-trusted features.
- Stratosphere This is a region of atmosphere extending from 10 to 50 km.
- **Stub (Transmission Line)** Basically, this is a shorted or open section of a transmission line used in conjunction with transmission lines to provide impedance match and cancel out reflections.
- **Superheterodyne Receiver** This is one of the most commonly used types of receiver in a variety of applications from broadcast receivers to two-way radio communications links as well as many mobile radio communications systems. It uses frequency mixing to convert the received radio frequency (RF) signal to a fixed intermediate frequency (IF) which can be more conveniently processed than the original carrier frequency. Basic building blocks of a superheterodyne receiver include RF amplifier, mixer, local oscillator, IF amplifier, suitable detector, audio amplifier and loudspeaker.
- **Tablet** This is a wireless, portable personal computer with a touch-screen interface with a form factor typically smaller than a notebook computer but larger than a smart phone.
- **Theatre Battle Management Core System (TBMCS)** The TBMCS, developed and fielded by Lockheed–Martin, is a set of hardware and software application tools. It is the primary air warfare tool used for planning and execution of theatre air battle plan for intelligence and operations personnel at force and unit levels.
- **Time Division Multiplexing (TDM)** TDM is used for simultaneous transmission of more than one pulsed signals over a common communication channel and different message signals are separated from each other in time. TDM is widely used in telephony, telemetry, radio broadcast and data processing.
- **TOPLITE** This is an electro-optic system from Rafael. It is a multirole, multi-sensor optronic payload that can be configured for military, airborne, naval and homeland security applications. It is a derivative of Rafael's state-of-the-art LITENING targeting and navigation pod.

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- **Transmission Line** This is a communication medium used in communication systems to carry signals from transmitter output to the input of transmitting antenna and from receiving antenna to the input of receiver. They are also used to for other applications such as impedance matching.
- **Troposphere** This is a region of atmosphere extending to altitudes of about 10 km above the surface of Earth.
- **Ultra-High Frequency (UHF) Transmitters** UHF transmitters operate over the UHF-band (300 MHz–3 GHz). UHF transmitters find applications in a large number of communication services, which includes television broadcasting, cell phone communication, cordless phones, satellite communication, WiFi and Bluetooth services and so on.
- **Universal Communications Platform (UCP)** The UCP from Lockheed–Martin integrates fixed and mobile radio systems, thereby transforming any radio system into a fully IP-based network to meet the demanding requirements of rapidly changing tactical and emergency situations.
- **V-antenna** This is a long-wire antenna. In a V-antenna, the conductors are arranged to form a V-shape and they are fed in phase opposition at the apex.
- **Very High Frequency (VHF) Transmitters** VHF transmitters operate over the VHF band (30–300 MHz) and use space wave line-of-sight propagation. The radio horizon is slightly longer than the geometric line-of-sight horizon due to bending of electromagnetic waves by the atmosphere. VHF transmitters are commonly used for FM radio broadcasting employing 87.5–108 MHz frequency band with few exceptions such as 76–90 MHz used in Japan and 65–74 MHz used in Eastern Bloc of the former Soviet Republic, television broadcasting, two-way land mobile radio systems for various private, business, military and emergency services, long-range data communication, amateur radio and marine communications. Air traffic control communications and air navigation systems are other applications.
- Warfighter Information Network Tactical (WIN-T) This is a telecommunication network backbone developed by General Dynamics Mission systems. It delivers voice and data communication services without the need for any fixed infrastructure. WIN-T Increment 1 provides voice and data communications at the halt. WIN-T Increment 2 provides connectivity to the soldiers on the move. WIN-T Increment 3 is the research and development component of the WIN-T programme and is aimed at improving the capability of all increments of the network.
- **Waveguide** This is nothing but a conducting tube through which energy is transmitted in the form of electromagnetic waves. The waveguide can be considered to be a boundary that confines the waves to the space enclosed by boundary walls.
- **Wideband Networking Waveform (WNW)** WNW is the next-generation high throughput military waveform, developed under the Joint Tactical Radio System (JTRS) Ground Mobile Radio (GMR) programme. It uses the Orthogonal Frequency Division Multiplexing (OFDM) Physical Layer. With its mobile ad-hoc networking (MANET) capabilities, the waveform is designed to work well in both urban landscape as well as a terrain-constrained environment, since it can locate specific network nodes and determine the best path for transmitting information.
- **xMAX system** This is a cognitive radio network solution from xG Technology Inc. It provides end-to-end Internet Protocol (IP) network solution incorporating xG's patented cognitive radio technologies to deliver the first fully mobile Voice over Internet Protocol (VoIP) and broadband network that also supports any smart phone, tablet and other commercial WiFi or IP-enabled devices.
- **Yagi-Uda Antenna** This comprises of a half-wave dipole with parasitic elements to enhance the directionality of the radiation pattern.

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