Chapter 1

Introduction

A communication system transmits information from one place to another, whether
represented by a text file or an image. Communication systems can be
classified by their electromagnetic carrier waves: frequency (RF) waves
being used in terrestrial high-speed networks. Optical communication
systems use high carrier frequencies (\(\sim 1000 \text{ THz}\)) to utilize the
valuable spectrum at the far end of the electromagnetic spectrum. They
are sometimes called high-speed systems or terahertz wireless
communication systems, where carrier frequency is typically
modulated by time series of magnitude \(\sim 1 \text{ GHz}\). Other optical
communication systems use high-speed systems that
employ optical fibers for information transmission.
Such systems have been deployed worldwide since 1970s
and have revolutionized the field of telecommunications.
Indeed, lightwave technology, together with microelectronics, led to
the advent of the "information age" during the 1990s.

This book describes these optical communication
systems in a comprehensive manner. The chapters are
organized to provide a comprehensive
overview of the field of optical communication systems. Section
1.1 gives an historical overview
of the development of optical communication systems. Section
1.2 covers

1.1 Historical Perspectives

The use of light for communication purposes dates back to antiquity in
ancient technologies. Light waves carry information, such as
sound waves. However, the use of light to convey a simple
form of information (such as a message in a word) essentially
the same idea was used in the second half of the eighteenth century
through signal lamps, flags, and other communication devices. The
idea was extended further, following a suggestion of Claude Chappe in 1792,
by means of mechanically encoded telegraphy over longer distances
\(\sim 1000 \text{ km}\) by the use of

1.1.2 Modern Perspectives
Figure 1.1: Schematic illustration of the optical telegraph and telegraphist, June 1844. (From Morse’s 1844 Annual Address, Annual Address of the American Association for the Advancement of Science, reprinted with permission.)

mowen the basic telegraphally. The first major "mechanical telegraphy" was put into service between Paris and Lille (from Luneville via Strasbourg, 230 miles apart) on July 19, 1856. By 1870, the network had expanded throughout France [11]. The role of light in each telegraph was simply to sense the encoded signal and relay it to an operator.

The first mechanical telegraph systems of the nineteenth century were inherently slow. In modern-day terminology, these systems had a maximum speed of less than 1 bit per second (1 bps).

11.1 Need for Reliable Telegraph Communication

The advent of telegraphy in the 1840s replaced the use of light, by electricity, and began the era of electrical communication [11]. The first uses of electricity began in 1800, by the use of telegraphic technologies, such as the Morse code. The first use of telegraphic relays to create electrical communication over long distances (-10,000 km) occurred in 1870. Indeed, the first successful transatlantic telegraph cable went into operation in 1858. Telegraphy was essentially a digital scheme through time with electrical pulses at different locations (dots and dashes of the Morse code). The invention of the telephone in 1876 brought a major change in communication and electric signals were transmitted ion analog form through a continuously varying electric current [12]. Analog electrical techniques were not suitable for digital communication systems for a century or so.

The development of worldwide telegraph networks during the nineteenth century led to many advances in the design of electrical communication systems. The use of coaxial cables in place of wire provided increased system capacity considerably. The first coaxial cables were tested in 1890, with a 30-MHz system capable of transmitting 3000 words per minute over a single telegraph line. This bandwidth of such systems was limited by the frequency-dependent cable losses, which increased rapidly for frequencies beyond 10 MHz. This limitation led to the development of microwave communication systems for which the electromagnetic carrier wave with frequencies in the range of 10 GHz is used to transmit the signal by using suitable modulation techniques.
The first underwater submarine system operating at the carrier frequency of 4 GHz was put into service in 1934. Since then, both terrestrial and underwater submarine systems have increased considerably and are able to operate at high rates (~100 kbps). The modern submarine communication system was put into service in 1945 and approached a bit rate of 224 kbps. A severe characteristic of such high-speed submarine systems is their overall transmission capacity (~1000 bps), which makes these systems relatively expensive to operate. High-speed submarine communication systems generally operate at a lower frequency spectrum, but this is not made for ultra-modern line-of-sight submarine communication systems.

It was realized during the second half of the twentieth century that an increase of several orders of magnitude for the transmission speed of travelled distances was needed in this century. However, neither a sufficient bandwidth nor a suitable transmission medium was available during the 1950s. The invention of the laser and its communication in 1960 solved the first problem [3]. Additionally, there were several other limiting factors for optical communication. For example, the amount of light for transmission during the 1960s [6], the amount of light for transmission during the 1980s [7], the amount of light for transmission during the 1990s [8], the amount of light for transmission during the 2000s [9], and the amount of light for transmission during the 2010s [10].
Figure 1.3c: Increase in the capacity of lightwave systems since the first 1960s. The dotted line indicates an exponential growth in the bit rate for both theoretical and commercial systems. Note the change in the slope after 2000.

It was suggested in 1966 that optical fibres might be the best choice [3], as they were expected to provide the high bandwidth similar to the guidance of electrons in copper wires. This main proposition was the high losses of optical fibres. Fibre available during the 1960s had losses in excess of 10000 dB/km. A breakthrough occurred in 1970 when fibre losses could be reduced to below 200 dB/km in the wavelength region near 1 µm [36]. As shown in section 1.2, this improvement in performance made it possible to develop optical fibres into a widespread optical fibre communication systems [43]. Figure 1.3c shows the increase in the capacity of lightwave systems mentioned since 1960 through several generations of development [36]. As seen there, the commercial development of lightwave systems followed the research and development phases closely. This progress has involved losses until a level where maximum data rates for the bit rate can be achieved at 1000000000 bits per second at 10 km or less than 70 cm.

1.1.5. Evolution of Lightwave Systems

The research phase of lightwave communication systems started around 1975. The continuous progress continued over the 25-year period starting from 1975 to 2000, and the progress into several distinct generations. Figure 1.4 shows the increase in the capacity of lightwave systems within these time periods as quantified through various laboratory experiments [13]. This straight line corresponds to a doubling of the bit rate every ten years. In every
The first generation of lightwave systems operated near 0.85 μm and used linear semiconductor lasers. After several field trials during the period 1977-1980, such systems became available commercially in 1980 [14]. They operated at a bit rate of 44.7 billion and allowed operating wavelengths of up to 10 km. The longer distance required compared with the 1-km spacing of coaxial systems was an important motivation for system designers to decrease the installation and maintenance costs associated with such spacing.

It was clear during the 1970s that the receiver spacing could be increased considerably by operating the lightwave system in the wavelength region near 1.3 μm, where fiber losses are below 0.4 dB/km. Furthermore, optical filters exhibited minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of indium-arsenide semiconductor lasers and detectors operating near 1.3 μm. The second generation of fiber-optic communication systems became available in the early 1980s, but the bit rate of early systems was limited to below 100 Mbits/s because of dispersion in multimode fibers [15]. This limitation was overcome by the use of active-mode filters.

A laboratory experiment in 1981 demonstrated transmission at 3 Gbits/s over 64 km of single-mode fiber [16]. The introduction of commercial systems soon followed. By 1987, second-generation lightwave systems, operating at bit rates of up to 1.5 Gbits/s with a receiver spacing of about 50 km, were commercially available.

The next decade saw the fourth generation lightwave systems, operating near 1.55 μm (typical 980 nm diode). However,
of Chinese characters becomes unrecognizable over 1.5% gain. Conversely, at 0.2% difference lines were read.

However, the introduction of third-generation Lightwave systems operating at 1.55 µm was exceptionally difficult by even higher difference levels. Correspondingly, the spectrum of transmitters could not be verified because of pulse spreading occurring as a result of simultaneous modulation of several long-haul channels. The dispersion provided to the transmitters relied only by making longtransmissions with different filters designed for lower minimum difference levels near 1.55 µm and by combining the laser systems into a single long-haul channel. Early approaches were unsatisfactory until the 1980s. By 1985, laboratory experiments indicated that the possibility of short-term difference in bit rates of up to 2-3 Mbit/s could be achieved by coming up to 1020 km [118].

Third-generation Lightwave systems operating at 1.55 µm took over commercially in the mid-1980s. These systems were expensive and operating at a rate that was not yet the 10 Gbit/s [119].

The first transceivers in commercial use; they were designed to work with long-haul channels while lowering overdispersion in a single long-haul channel.

A disadvantage of third-generation 1.55 µm systems is that they could be reconfigured periodically by using electronic tungsten systems with gain typically by 60-70 dB level. The approach operating was the introduction by replacing the transmission or a few hundred mm to hundreds of transmitters between the measurement and the constant wavelength separation. Such systems were reconfigured to an extended Lightwave systems. Commercial systems were needed developing several wavelengths cladding the 1980s, and their practical use was demonstrated in many transceivers [120]. However, commercial introduction of such systems was postponed with the advent of fiber optic switches in the 1990s.

The fourth generation of Lightwave systems requires much less electronic equalization for increasing the optical receivers and the wide-signal wavelength spreading (GW100) line increasing the bit rate. As seen from Figures 1.9 and 1.1, the advent of those fiber-optic systems in 1992 started a revolution that continues to demanding all the system complexity in terms of increased bandwidth and increased linearity. One of the main market areas for the modern Lightwave systems operating on a bit rate of 10-100 Gbit/s by 2000. The main fiber-optic systems, which are based on concatenated periodically by extending reaches of the transceivers operating up to 100 Gbit/s [121].

Early optical communications over 10 Gbit/s and longer were uneconomical commercially before the advent of fiber-optic switches in the 1990s.

Figure 1.9 shows that the introduction of digital and electronic systems was prepared in 1982 [29]. Three 25 Gbit/s line filter optical channels established the global bandwidth between two Gbit/s [120]. The system is capable of transceivers in the 1980s, which combines the optical and electronic channels in several transceivers. The first Digital Optical Systems (DOS) were developed in 1988 [121]. The rate was increased to 10 Gbit/s and later to 40 Gbit/s and 100 Gbit/s. The 100 Gbit/s technology was developed in the 1990s [122]. The performance of these systems was enhanced by the advent of fiber-optic switches in the 1990s.

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The changes in the shape of dotted lines in Figure 0.8, occurring around 2000, indicates this reality.

The complexity of modern WDM hybrid systems is on increasing their capacity by transmitting more and more channels through the WDM technology. With increasing signal bandwidth, it is often not possible to amplify all channels using a single configuration. As a result, new amplification schemes (such as distributed linear amplification) have been developed for connecting the spectral region extending from 1.44 μm to 1.62 μm. The approach used in 2000 was to 3.25 Gbps expansion in which 162 channels, each operating at 40 Gbps, were transmitted over 2800 km. Within a year, this system capacity could be increased to nearly 61 Tbps (975 WDM channels, each operating at 64 Gbps) and the transmission distance was extended to 1070 km [39]. In another network configuration, 300 channels, each operating at 116 Gbps, were transmitted over 2300 km, resulting in a total bandwidth of more than 39,000 Gbps [37]. Commercial systems with the capacity of 20 Tbps, transmitting 60 channels (each at 40 Gbps) with the use of erbium amplification, were available by the end of 2003. Given that the first-generation systems had a capacity of 40 Gbps in 1990, it is remarkable that the capacity increased by a factor of more than 200,000 over a period of 25 years.

The fifth generation of fiber optic communication systems is expected to extend the wavelength range over which a WDM system can operate simultaneously. The conventional wavelength windows, known as the C band, cover the wavelength range 1.53-1.56 μm. In the future, development of both the long- and short-wavelength windows, resulting in the L and S bands, respectively. These new amplification techniques can be used for signals in all these wavelength bands. Moreover, a new kind of fiber, known as the sky fiber has been developed with the property that it can transmit signals over the entire wavelength range extending from 1.26 to 1.65 μm [28]. Availability of such fibers and new amplification techniques may lead to hybrid systems with channels over 800 Gbps.
The focus of current fifth-generation systems is on increasing the spectral efficiency of WDM systems. Thus, the aim is to improve interchannel and intrachannel interference in WDM systems. Although each channel were developed and are used communally for different purposes, data rates that lightwave systems achieved record over the range of 2000s. As these advancements have been achieved, the spectral efficiency, typically defined in terms of the bit rate, became a core factor. This is due to the following reasons: First, as the spectral efficiency becomes higher, the data rate increases. Second, as the bit rate increases, the data rate per second increases. Third, as the bit rate increases, the data rate per second increases. Fourth, as the bit rate increases, the data rate per second increases. Fifth, as the bit rate increases, the data rate per second increases.

1.2 Biometric Communications

Biometric communication is a new biometric concept emerging in all communication systems. It can be described as a description of analog and digital signals and their digital communication over analog signals. This can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital. Since the conversion from analog to digital is a conversion from analog to digital, it can be converted into digital.
...are characterized by their handbreadth, which is a measure of the spectral content of the signal. The signal bandwidth represents the range of frequencies contained within the signal and is determined mathematically through its Fourier transform.

A sampling signal can be converted from digital form by sampling it at regular intervals of time [11, 12]. Figure 1.7 shows the conversion method mathematically. The sampling rate is determined by the bandwidth $\Delta f$ of the analog signal. According to the sampling theorem [13], a bandlimited limited signal can be fully represented by discrete samples, without any loss of information, provided that the sampling frequency $f_s$ satisfies the Nyquist criterion $[13, 14]: f_s \geq 2\Delta f$. The first step consists of sampling the analog signal at the right frequency. The sampled values can take any value in the range $0 \leq A \leq A_{\text{max}}$, where $A_{\text{max}}$ is the maximum amplitude of the given analog signal. Let us assume that $A_{\text{max}}$ is divided into $2^N$ discrete values (most commonly equally spaced) $A_k$. Each sampled value is represented by one of these discrete values. Obviously, this procedure leads to an additional noise, known as quantization noise, which adds to the noise already present in the analog signal.

The effect of quantization noise can be minimized by altering the number of discrete levels such that $N' \geq A_{\text{max}}/A_k$, where $A_k$ is the least significant quantization amplitude of the analog signal. The ratio $A_{\text{max}}/A_k$ is called the dynamic range and is related to the signal-to-noise ratio (SNR) by the relation

$$\text{SNR} = 10 \log_{10}(A_{\text{max}}/A_k),$$

where $\text{SNR}$ is expressed in decibels (dB) units. Any noise $N$ can be converted into equivalent noise by using the general definition $10 \log_{10}(N)$ (see Appendix A). Equation (1.2.1)
contains a factor of 20 in place of 10 simply because the SNR for electrical signals is defined with respect to the electrical power, whereas it is related to the electric current (or voltage).

The quantized sampled values can be converted into digital format by using suitable conversion techniques. For this scheme, however, we must introduce quantization, which is the process of converting the sampled values into a discrete set of values. In practical terms, this means that each sampled value is rounded to the nearest integer. These techniques are usually used in practical optical communications systems, where it is difficult to maintain the pulse position or pulse width to high accuracy during propagation inside the fiber. One technique used almost universally, known as pulse-code modulation (PCM), is based on a binary scheme in which information is conveyed by the presence or absence of pulses that are otherwise identical. A binary code is used to convert each sampled value into a sequence of 1 and 0 bits. The number of bits required to encode each sample is related to the number of quantized signal levels by the relation:

\[ A_{digital} = 2^{k_{bits}} \quad \text{or} \quad x = \log_2 \text{levels} \]  

(1.2.2)
II.2. Receiver Circuits

The bit rate associated with the PCM digitized signal is given by

$$B = -\log_2 P > (2A_f) \log P A_f$$

(1.2.3)

where the Nyquist criteria hold for $A_f > 2A_f$, necessitating a Nyquist rate. By noting that $P > A_{max}/A_f$ and noting $\log P > 1$, (1.2.11) becomes valid for $P > 100 \approx 3.32$.

$$B > (A_f/3) \log P A_f$$

(1.2.4)

where the SNR is expressed in decibels (dB) units.

Equation (1.2.4) provides the minimum bit rate required for digital representation of an analog signal at bandwidth $A_f$ and a specific SNR. With SNR $> 130$ dB, the required bit rate exceeds $10^6 A_f$, indicating that the required bit rate is too high for the bandwidth requirements of digital signals. Despite this requirement, the analog signal is almost always used for optical communication systems. Thus, choice for results here is off the assumption practicality of digital transmission systems. All higher-speed systems utilize novel new components in the system for signal transmission (by a factor $10^6$). Compared with microwave systems, these new components are far more bandwidth-efficient, even for simple harmonic systems.

As an illustration of Eq. (1.2.4), consider the digital representation of an analog signal processed in a telecommunication. The analog signal is subject to noise in the form of $0.01 B$ levels, with a bandwidth $A_f$ : 50 MHz will have an SNR of 100 dB, and same for a $1$ MHz noise level $B = 10$. This requirement indicates that a digital signal with information $B > 1$ MHz is required for the transmission of information.

A transmission bandwidth of $1000$ MHz, for example, requires a transmission bandwidth of $1000$ MHz, which in turn requires a transmission bandwidth of $1000$ MHz.

II.2.2: Channel-based Multiplexing

An aspect in the preceding discussions, a digital voice channel requires a bandwidth of 6 kHz. Most fiber-optic communication systems are capable of accommodating all under seven channels in 1 GHz. This implies that system complexity is limited, in its necessity to transmit many channels simultaneously through multiplexing. This can be accomplished through time-division multiplexing (TDM) or frequency-division multiplexing (FDM). In the case of TDM, time samples of each channel are transmitted at the same frequency, whereas in FDM, different channels are transmitted at different frequencies. This can be illustrated, for example, in the case of a telephone using a telephone system consisting of 240 channels. These smaller channels can be multiplexed through TDM or FDM. The bit rate of each channel in a 240-channel system is displayed by $B \text{ bits}$. Figure 1.2(b) shows the multiplexing for 240 channels simultaneously at a transmission bit rate of 3200 bits.

In the case of FDM, the channels are spaced apart in the frequency domain. Each channel is expanded for its own carrier wave. The carrier frequency is spaced evenly across the entire bandwidth to allow the carrier signal to be transmitted without overlap, as shown in Figure 1.2(a). FDM is suitable for both analog and digital signals used in transmission-a bandwidth of carriers and transmission elements. TDM is necessary for digital signals and is communally used for telephonecommunication systems. It is independent of carrier frequency.
TDM and FDM can be implemented in both the electrical and optical domains. Optical TDM is sometimes referred to as WDM. Channelization is done in the optical domain using multiplexing techniques. While wavelength-division multiplexing (WDM) is employed in optical communications, it can also be utilized in electrical communications into a single electrical data stream.

The concept of TDM can be traced back to the time of the ancient Egyptians. In their ancient world, the first level corresponds to channeling information into separate channels with a composite bit rate of 1.544 Mbps (intermediate 1638-2), whereas the higher 320 channels are multiplexed, resulting in a composite bit rate of 2.048 Mbps. The bit rate of each multiplexed signal is slightly larger than the simple product of the bit rate with the number of channels because each channel contains bits that are specific for each channel (demultiplexing), the channels at the receiving end, the normal level multiplexing is performed by multiplexing 4 1638-2 TDM channels. This results in a bit rate of 63.12 Mbps (intermediate 643-2) for 64 TDM channels for 2.048 Mbps. This procedure is continued for other higher-level multiplexing channels. For example, at the fifth level of multiplexing, the bit rate becomes 565.6 Mbps for 32 channels and 2.048 Gbps for 8 channels.

The lack of an international standard in the telecommunications industry caused the TDM and FDM to be used on a more experimental, short duration when compared to optical multiplexed systems (CSMD). In the optical domain, the optical multiplexing technique is present in multiplexing networks up to 3200 CH (OC-12). It is also present in multiplexing time-division multiplexing (TDM) optical systems. This leads to...
Building block of the SDU4FC has a bitrate of 31.25 Mbit/s. The corresponding optical signal is referred to as OCS-1, where OCS stands for optical carrier. The basic building block of the SDU1 has a bitrate of 155.52 Mbit/s and is referred to as SONET-1, where SONET stands for synchronous transport protocol. A useful feature of the SDU1 and SDU4F is that higher levels have a bitrate that is an exact multiple of the basic bitrate. Table 1.1 lists the correspondence between SDU1-SDU4FC and SONET levels for several levels. The SDU1 provides an interconnection standard that resembles in the serial optical. Indeed, lightwave systems operating at the SDU1-OC-3 level (256 Mbit/s) were available since 1992 [10]. Commercially SDU1-2.5G (OC-12/36) systems operating near 40 Gbit/s became available by 2002.

11.2.3 Nonlinear Phenomena
The first stage in the design of an optical communications system is to decide how the electrical signal would be converted into an optical bit stream. traditionally, the output of an optical source such as a semiconductor laser is modulated by applying the electrical signal either directly to the optical source or to an external modulator. These are two distinct classes for the modulation format of the resulting optical bit stream. These are shown in Figure 11.1 and are known as the intensity-on-off (I2O) and intensity-on-off (POL) formats. In the M2O format, each optical pulse representing bit 1 is stronger than the bit 0, and its amplitude reduces for each bit before the bit duration is over. In the MLO format, the optical pulses remain constant throughout the bit time and the amplitude decreases only between the bit streams. As a result, the pulse width varies depending on the bit position, whereas it remains the same for the case of the I2O format. An advantage of the I2O format is that the bandwidth associated with the bit time is smaller than that of the POL format by about a factor of 2, which becomes even more pronounced at higher frequency channels. However, the use requires higher channel count; the pulse width must be small to reduce power-dependent effects in the optical signal propagation during transmission. The POL format is often used in practice because of its smaller signal bandwidth associated with it.

The use of the POL format in the optical channel began in the first generation of 1999 when it was found that the use may help in the design of high-capacity lightwave systems [14]. By using the POL format in more channels simultaneously, the SONET channels can be assigned to operate at 40 Gbit/s or more. An example of the benefits of the POL format is provided by the use of parallel precursors [37] that employ a relatively slow opti-
The optical coherence tomography (OCT) technology is based on the interference of light waves. The interference pattern is captured by a detector, which generates an image representative of the tissue being scanned. OCT technology allows for high-resolution imaging of tissues, particularly in the eye, providing valuable information for clinical diagnosis and monitoring.

**Mathematical Representation**

The optical coherence function (OCF) is given by the following equation:

\[ \text{OCF}(f) = \mathcal{F}\{\text{correlation}(\phi, \psi)\} = \mathcal{F}\{\text{amplitude}(\phi, \psi)\} \]

where \( f \) is the frequency, \( \phi \) and \( \psi \) are the optical fields, and \( \mathcal{F} \) denotes the Fourier transform. This function captures the correlation between the two fields, providing information about the tissue's optical properties.

**Applications**

OCT technology finds applications in various fields, including ophthalmology, where it is used for imaging the retina and detecting early signs of diseases like macular degeneration. It is also used in skin imaging for dermatological applications.

Until recently, OCT technology was less common due to its reliance on specialized equipment. However, advancements in miniaturization have made OCT devices more accessible, increasing their use in clinical and research settings.
Although the use of PSK and QPSK schemes was explored during the 1950s in the context of coherent high-speed systems [225], these schemes were largely abandoned during the 1960s because of the complexities associated at the receiving end. The situation changed after 1980 when it was realized that the use of PSK in essence provides frequency-division multiplexing efficiency of WDM/SWDM systems. By contrast, PSK/SWDM systems carry frequency-division multiplexed modulation formats in which information is encoded using both the amplitude and phase of the optical carrier [229]. The basic idea behind these formats can be understood by employing the complex notation for the electric field, i.e., \( E(t) e^{j2\pi f t} \) and introducing the so-called phase shifts \( \Delta \phi \). Figure 1.11 illustrates four modulation formats in the constellation diagrams, where the real and imaginary parts of \( E(t) \) are plotted along the real and imaginary axes, respectively. The first two configurations represent the standard binary ASK and PSK formats in which either the amplitude or the phase of the optical field takes two values: real or imaginary. The third one shows the quadrature PSK (or QPSK) format in which the optical phase takes three possible values. This case, discussed in considerable detail in Chapter 3, uses both quadrature channels during each time slot, and the effective bit rate is halved. Moreover, from the microsecond communication standpoint, the effective bit rate is called the symbol rate (or baud). The last example in Figure 1.11 shows how the symbol concept can be extended to modulated signals in which each symbol carries 4 bits, meaning that the additional two bits can be placed in one transmission over orthogonally polarized symbols simultaneously during each symbol slot.
1.3 Optical Communication Systems

As mentioned earlier, optical communication systems differ in principle from microwave systems only in the frequency range of the carrier waves used to carry the information. The optical carrier frequencies are typically ~200 THz, in contrast with the microwave carrier frequencies (~1 GHz). An increase in the information capacity of optical communication systems by a factor of up to 10,000 is expected simply because of the high carrier frequencies used for lightwave systems. This increase can be understood by noticing that the bandwidth of the modulated carrier can be made to a few percent of the carrier frequency. Taking, for illustration, 1% as the limiting value, optical communication systems have the potential of carrying information at bit rates ~10 Tbps in our current potential bandwidth of optical communication systems that is the driving force behind the worldwide development and deployment of lightwave systems. Current state-of-the-art systems operate at bit rates ~10 Gbps, indicating that there is considerable room for improvement.

Figure 1.12 shows a generic block diagram of an optical communication system. It consists of a transmitter, a communication channel, and a receiver, the three elements common to all communication systems. Optical communication systems can be classified into four broad categories: guided and unguided. As the name implies, in the case of guided lightwave systems, the optical beam emitted by the transmitter remains spatially contained. This is realized in practice by using optical fibers, as discussed in Chapter 7. Since all guided optical communication systems currently use optical fibers, the commonly used term for them is fiber optic communication systems. The term lightwave system is also used for fiber optic communication systems, although it should generally include both guided and unguided systems.

In the case of unguided optical communication systems, the optical beam emitted by the transmitter travels in space, similar to the operation of microwave systems. However, unguided optical systems are best suitable for near-infrared applications than microwave systems because optical beams are not confined in the thousand directions as a result of the inherent wavelength. There are generally two types of unguided systems: ground-based and space-based. The former is the most common type of unguided system used in space communications. In the case of propagation, the signal in unguided systems can experience considerable loss due to scattering within the atmosphere. This problem, of course, disappears in free space communication where the earth atmosphere (e.g., interstellar communications). Although line-of-sight optical communication-
Optical Transmitter \hspace{5em} Communication Channel \hspace{5em} Optical Receiver

**Figure 1.12:** A generic optical communication system.

Optical systems are well suited for certain applications and have been studied extensively. However, most commercial applications involve use of fiber-optic communications systems. This trend shows great promise for optical communications systems.

The applications of fiber-optic communications in geophysics in many areas that require transmission of information from one place to another. Nevertheless, these systems are difficult to develop and only recently have been identified as two distinguishable applications. Fiber-optic communications systems in geophysics in terms of establishing by large-scale applications. High-speed systems are capable of operating at higher bit rates and over longer distances. Varieties of applications of the optical system by many researchers in recent years have made them very exciting for many potential applications. For instance, the use of WDM within optical communication has revolutionized the cost and services to increasing applications. As stated in Chapter 1.3, a large number of transmitters and receivers systems have already been installed to ensure international fiber-optic networks.

Small-scale telecommunications systems offer lower cost and lower-speed networks. These systems typically operate at lower bit rates over shorter distances than those in WDM. The use of single-channel fiber-optic systems for such applications is most cost-effective. From this reason, the use of WDM has become increasingly popular for short-distance systems. With the advent of the Internet in the 1990s, data traffic involving transmission of video and still images has become more prevalent as commercial usage, by more such traffic, continues through the Internet. The use of multiwavelength involving packet switching is increasing continuously. Only newer fiber-optic WDM systems can meet the rapidly growing bandwidth requirements. Multiplexed Lightwave systems and their applications are discussed in Chapter 6.

**1.4 Lightwave System Components**

The generic block diagram of Figure 1.12 applies to a fiber-optic communication system. The only difference being that the communication channel is a single-fiber cable. The other three components, the optical transmitter and the optical receiver, are designed...
to meet the needs of such a specific communication channel. In this section we discuss the general issues related to the role of optical fibers as a communication channel and the design of transmission and reception. The objectives in the previous and introductory exercises, as the three components are discussed in detail in Chapters 2–4.

1.4.1 Optical Fibers as a Communication Channel

The role of a communication channel is to transmit the optical signal from transmitters to receivers without distortion. In optical fiber systems, the optical fibers act as the communication channel because light propagates through fibers as well. In practice, however, optical power reaches to only 1% of the input power. This means that the power delivered to the fiber decreases significantly as the distance increases. Consequently, it becomes necessary to increase the optical signal with higher power. This problem occurs in the case of multimode fibers, where power spreads rapidly (typically at a rate of 0.1 dB/km) because of differential mode dispersion associated with different fiber numbers. As its result, because the couplings between communication systems need to be nearly equal, the frequency distribution of the electrical source still results in pulses traveling (typically < 0.1 m/km), and it is small enough to be acceptable for most applications and can be resolved using by compensating the spectral width of the optical source. Nevertheless, as discussed in Chapter 4, chromatic dispersion may cause light waves and the transmission distance of fiber optic communication systems.

1.4.2 Optical Transmitters

The goal of an optical transmitters is to convert the electrical signal into optical form and to launch the resulting optical signal into the optical fibers. Figure 1.4.2 shows the block diagram of an optical transmitter. It consists of an electrical source, a modulator, and an optical amplifier. The modulator converts the light output of an electrical source into the optical source. Although it can be advantageous to modulate the electrical source, several amplifiers are needed to achieve optical compatibility with the optical fiber communication channel. These are discussed in detail in Chapter 3. The optical signal is processed by modulating the optical carrier wave. Although an optical modulator in communication, it is the optical signal itself that is transmitted. The optical signal contains the information that needs to be transmitted. Such a signal is typically a quadrature amplitude modulation that contains the information that needs to be transmitted. The optical signal contains the information that needs to be transmitted. The information is typically a quadrature amplitude modulation that contains the information that needs to be transmitted.
Appendix A):

\[ \text{power (dBm)} = 10 \log_{10} \left( \frac{\text{power}}{1 \text{ mW}} \right). \]  

Then, 1 mW is 0 dBm, but 1 pW corresponds to -30 dBm. The fractional power is rather low (<10 dBm), but semiconductor lasers can launch powers \( \sim 10 \text{ mW} \). As light-emitting diodes are also limited in their modulation capabilities, most lightwave systems use semiconductor lasers as optical sources. The bandwidth of optical transmitters is often limited by electronics rather than by the semiconductor laser itself. While laser design, optical transmitters can be made to operate at a bit rates of up to 40 Gbps. Chapter 3 contains a complete description of optical transmitters.

II.4.3 Optical Receivers

An optical receiver converts the optical signal received at the output end of the optical fiber back into the original electrical signal. Figure II.14 shows the block diagram of an optical receiver. It consists of a detector, a amplifier, and a demodulator. The detector converts the received optical signal into the photoelectrons. Semiconductor photodiodes are used as photodetectors because of their compatibility with the whole system, they are discussed in Chapter 4. The design of the demodulation elements can be the modulation format used by the lightwave system. The use of RZK and NRZ format generally requires heterodyne or homodyne demodulation techniques discussed in Chapter 10. These lightwave systems employ a scheme referred to as "coherent modulation with direct detection" (CDMD). Demodulation in this case is done by a decision circuit that identifies bits as 1 or 0, depending on the amplitude of the electrical signal. The accuracy of the decision circuit depends on the SNR (signal-to-noise ratio) at the photoelectrons.

The performance of a digital lightwave system is characterized through the bit error rate (BER). Although the BER can be defined as the number of erroneous symbols received, much a definition makes the BER bit-rate dependent. It is customary to define the BER as the average probability of bit error rate. Therefore, a BER of 10^-9 corresponds to an average one error per million bits. Most lightwave systems specify a BER of 10^-9 as the operating requirement, some even require a BER as small as 10^-11.
An important parameter for any receiver in the sensor sensitivity. It is usually defined as the minimum average optical power required to reach a SNR of 10^{-3}. Receiver sensitivity depends on the SNR, which in turn depends on various factors including the state of the semiconductor itself. This is reflected in the quantum limits in the form of a set of formulae. Optical receiver performance is governed by the quantum limits and the sensitivity of the receiver. The practical receiver operates at the quantum noise limit because of the presence of several other noise sources. Some of these sources include thermal noise and shot noise.

Oftentimes the system in the communication theory can be visualized by the absorption. For instance, any amplification of the optical signal along the transmission line means that the power in the fundamental process of quantum noise emission. Coherent dispersion in optical fibers can add additional noise through phenomenon such as cross-phase modulation and mode partitioning. The receiver sensitivity is determined by a cumulative effect of all possible noise mechanisms that degrade the SNR at the decision point. In general, it also depends on the line noise at the contribution of various noise sources (e.g., shot noise) increases in proportion to the signal bandwidth. Chapter 6 is devoted to noise and sensitivity issues of optical receivers by considering the SNR and the BER in digital communication systems.

**Problem 1.1**
Calculate the center frequency for optical communication systems operating at 600 nm, 1.3, and 1.55 pm. What is the photon energy (in eV)? In each case?

**Problem 1.2**
Calculate the transmission distance over which the optical power will attenuate by a factor of 10 through fibers with losses of 0.5, 200, and 3000 dB/km. Assuming that the optical power decreases in exp{(-x/λ)}, calculate in (in km) for these three fibers.
1.3 Assume that a digital communication system can be operated at a bit rate of up to 100,000 bits per second. How many pulses can be transmitted or received under those conditions at 1000 Hz, and at a speed equal to 1000 Hz per second?

1.4 A 1000 Hz data transmission rate in digital form is transmitted over a television channel at a frequency of 6 MHz and an optical channel at 1.2 MHz per sec.

1.5 A 1.2 MHz digital communication system operating at 1.2 MHz can be transmitted at a rate of 1000 000 bits per second. Assuming that 1 and 0 bits are equally likely to occur, calculate the number of photons transmitted within each second.

1.6 An analog signal has a half-wave peak-to-peak voltage of 200 mV and is disturbed by noise, resulting in a signal-to-noise ratio of 20. What is the corresponding digital signal in a system of 1 and 0 bits, assuming a 4-bit representation for each sample?

1.7 Sketch the variation of output power with time in a digital 1000 Hz bit stream 01010101010101 by assuming a bit rate of 2.5 Gbps. What is the duration of the standard and roundtrip optical pulses?

1.8 A 1.2 MHz digital communication system is transmitting digital signals over 1000 km at 200 km/sec. The transmission loss is 1 mW and the average power flux is 300 bits per second. These two values result in a link loss of 12 bits per second. Assume that 0 bits carry no power, while 1 bits carry more than 300 bits of average power. What is the duration of the standard and roundtrip optical pulses?

1.9 A 0.8-mc optical receiver module at 0.1000 photodiodes is required for a 1000 000 bits per second optical communication system designed to transmit data at 1000 000 bits per second. The fiber loss is 2.0 dB/km at 0.8 microns. Assume that 0 bits carry no power and a maximum optical pulse width.

1.10 A 1.3 mm optical transmission is used to obtain a digital bit stream at a bit rate of 2 Gbps. Calculate the number of photons contained in a single 1 bit transmitted as average power emitted by the transmitter in 1000 W. Assume that the 0 bits carry no energy.

References:
