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Introduction

In this book, we present state-of-the-art and next-decade technologies for optical and related microwave transmission in telecom applications, high-speed long distance as well as last-mile and in-house communication. Furthermore, we have learned a lot about the needs of companies producing state-of-the-art systems. They use practical systems in order to compete in the market for such products. They want a complete solution to their demands, and they do not care if fiber optics are part of the solution or not. Consequently, nowadays, further physical techniques have to be developed: Wireless applications open up a new field of data transmission. High-speed wireless LED transmission offers short-range data transmission without EMI/EMC problems. Visible light communication using high power LEDs is an interesting technique. The first aim of using these light sources is to illuminate a room. However, at the same time, they can be modulated to transmit a data signal (Figure 1.6). Thus, optical and non-optical solutions, microwave-, Radio over Fiber- or even RADAR-systems have to be developed.

All these systems working in common will offer high-speed up- and downloads for offices, labs and private homes, and also for transportation systems such as cars, airplanes and ships.

Since the beginning of the 1960s, there has been a light source which yields a completely different behavior compared to the sources we had before. This light source is the LASER, **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Basic work had been published already, in 1917 by Albert Einstein [1.1]. The first laser realized was the bulk-optic ruby laser, a solid state laser [1.2] developed by Theodor Maiman in 1960. A short time after this very important achievement, diode lasers for use as optical transmitters were developed [1.3]. At the beginning they were difficult to operate. They had to be cooled using nitrogen at -169°C . It took until 1970 to drive semiconductor diode lasers in a continuous wave (CW) mode at room temperature [1.4]. Parallel to that accomplishment, the use of dielectric optical waveguides as media for transmission systems was suggested. Charles Kao and George Hockam [1.5] can be regarded as inventors of fiber-optic transmission systems, as well as Manfred Börner [1.6]. Nowadays, their invention would not be regarded as anything remarkable. Take a light source as a transmitter, an optical fiber as a transmission medium, and a photodiode as a detector (Figure 1.1)! Yet, in the 1960s it was a revolution, because the attenuation of optical glass was in the order of 1000 dB/km corresponding to a factor of 10^{-100} over one kilometer. This was totally unrealistic for use in practical systems.

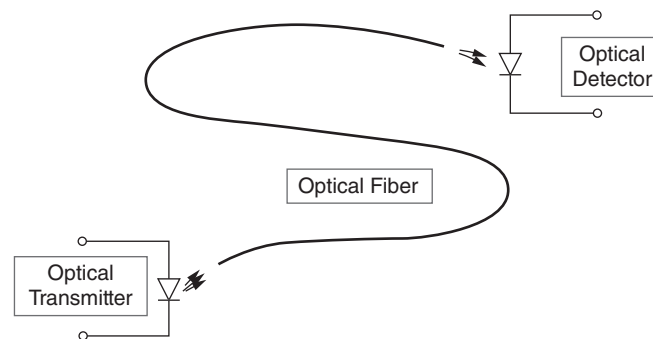


Figure 1.1 Basic arrangement of a fiber-optic system

In the early 1970s, physicists and engineers in research laboratories developed the first optical glass fiber with sufficient low attenuation to transmit electromagnetic waves in the near infrared region (Corning Glass Works [1.7]). They achieved a value of about 20 dB/km, that is, after one kilometer there is still 1% of light at the detector from the light which was coupled into the fiber by the transmitter. Today's fibers have an attenuation of below 0.2 dB/km, which means the 1% value is still achieved after 100 km of the fiber.

The development of optical detectors started much earlier. Already in 1876, W. Adams and R. Day proved the separation of charge carriers in Selenium [1.8] by illumination of light. They discovered the inner photo effect, also named the photovoltaic effect. This effect is still the fundamental process exploited in modern photo detectors. First experiments with silica solar cells took place in the early 1950s, and new developments for practical use to transmit a data signal started in 1970 [1.9]. Thus, systems could be developed using optoelectric (O/E) and electrooptic (E/O) components for transmitters and receivers, as well as a fiber in the center of the arrangement. The main fields of application of such systems are found in the area of fiber-optic transmission and fiber-optic sensors (Figure 1.2).

In the beginning, in both areas exclusively, the intensity of light was of interest. In analog as well as in digital systems, signal transmission is realized by modulation of the laser power. At the fiber end, an intensely sensitive receiver is used exclusively to detect the data signal. Regarding sensor systems, the measurement of the physical quantity of interest is also exclusively concerned with the power of the light. In this case the optical power is varied by exploiting a change of the fiber attenuation or other system components. Modern more sophisticated systems make use of the fact that an electromagnetic wave also carries information on frequency, phase and polarization.

The media to transport the propagation of light is named the waveguide. The most common waveguide is a glass fiber. The geometrical shape does not need to be strictly circular like a fiber, but can also be rectangular forming a planar waveguide. This was suggested by Stewart Miller in 1969 and thus the new field of integrated optics was born [1.10]. The aim of this technology is to integrate a maximum of components onto a single chip such as an integrated circuit – elements with a variety of different functions within the smallest space to avoid macro-optic devices like mirrors and lenses. Some integrated optic components are able to influence all parameters of an optical wave: amplitude (intensity), frequency, phase and polarization. However, the first optical transmission is much older. Native Americans for instance, were

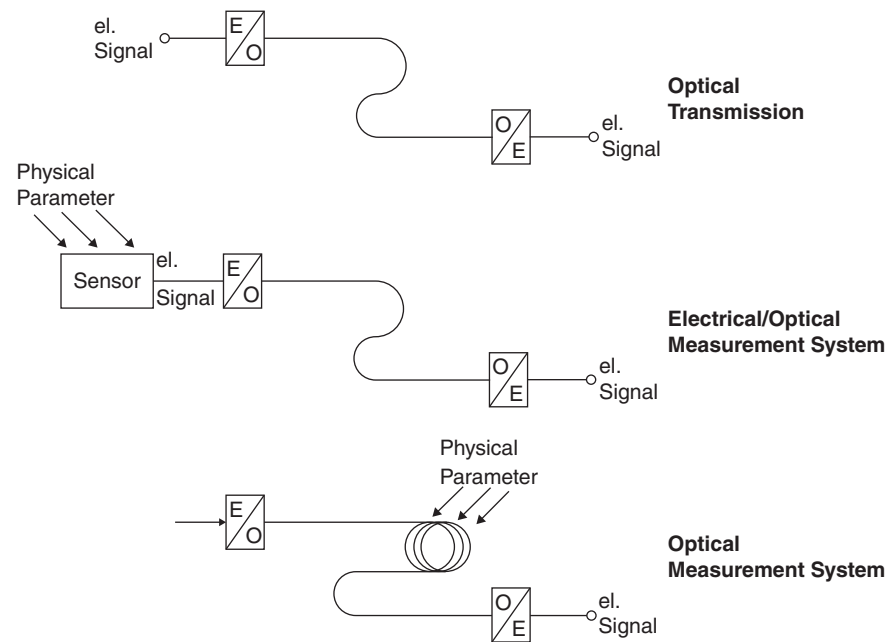


Figure 1.2 Application of fiber-optic systems

already communicating with smoke signals a long time ago [1.12,1.13]. Furthermore, it was a very sophisticated and modern system, because it was already a digital system, consisting of “binary 1” and “binary 0” (smoke/no smoke) (Figure 1.3).

Thus digital systems have already existed for a long time, providing the basics for information technologies, information processing and transmission. However, analog techniques are still of interest – physical quantities at the origin and the reception (e.g. human reception). But as soon as they are processed or transmitted nowadays, almost exclusively digital techniques are used. A further free space transmission has also been developed, the optical telegraph realized by Claude Chappe. He invented a semaphore set-up by means of movable bars able to produce several signs. But free space transmission on Earth suffers from atmospheric disturbance [1.11]. This also holds for free space laser transmission on Earth, which came to light in the 1960s after the invention of the laser. There are exceptions in outer space applications and for short distance air transmissions (Chapter 9.3).

The real breakthrough of optical data transmission systems came with the glass fiber, which had sufficient low attenuation for propagation of electromagnetic waves in the near infrared region. This low value of attenuation is one of the most attractive advantages of fiber-optic systems compared to conventional electrical ones.

Figure 1.4 depicts the attenuation behavior. In particular, we observe independence of the modulation frequency of fiber-optic systems in contrast to electrical ones which suffer from the skin effect. Yet it has to be confessed that there are different problems leading to a frequency limit, the dispersions: modal, chromatic and polarization mode dispersions must be mentioned (Chapter 3). Solutions of how to deal with these problems with sufficient success will be

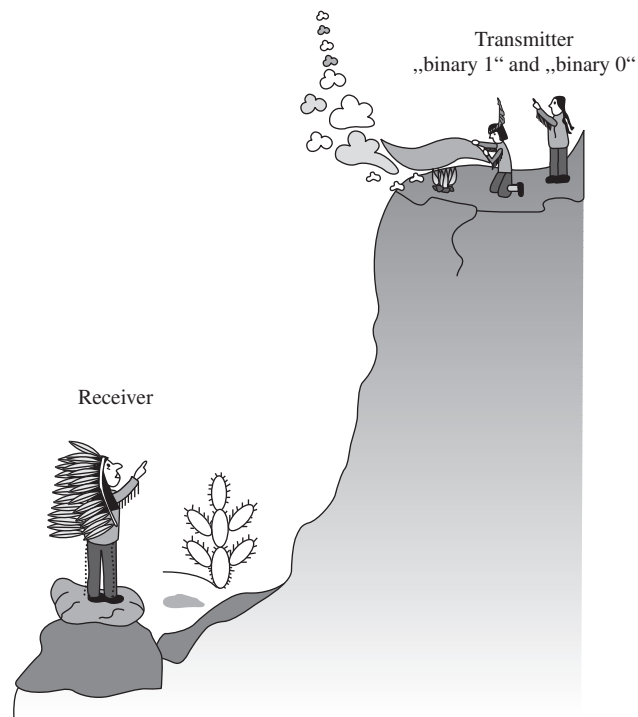


Figure 1.3 Digital optical transmission by use of smoke signals

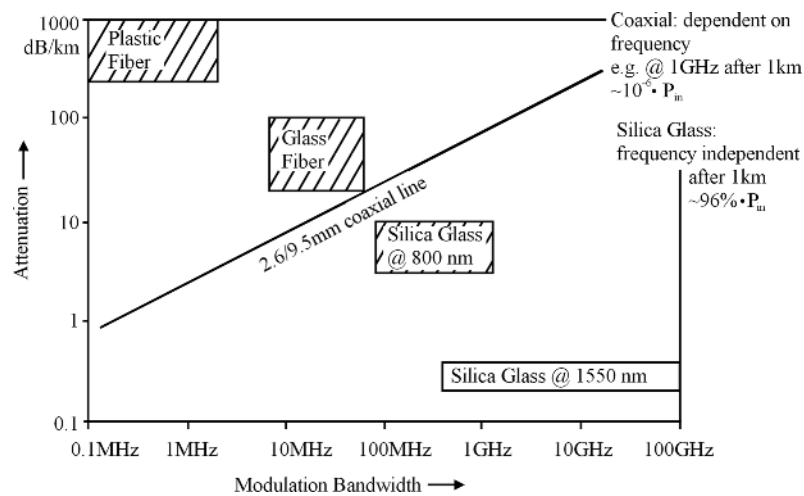


Figure 1.4 Attenuation of coaxial cables and optical fibers

presented. In the end, the enormous achievable bandwidth must be highlighted. That leads to a high transmission capacity in terms of the product of achievable fiber bandwidth B and length L , also named *transmission capacity*, C_t . It is a figure of merit, as one of the most important goals is to maximize this product for every kind of data transmission with respect to the demands concerning its application.

$$C_t = B \cdot L = \text{Max!} \quad (1.1)$$

where:

B maximum achievable bandwidth and

L maximum achievable link length

In addition, low weight, small size, insensitivity against electromagnetic interference (EMI, EMC), electrical insulation and low crosstalk must be mentioned.

Glass fiber systems are used in the near infrared range, right above the wavelengths we can see with our eyes. As optoelectronic components for light sources, we apply GaAlAs (Gallium-Aluminium-Arsenide) LEDs and laser diodes for wavelengths in the 850 nm region and InGaAsP (Indium-Gallium-Arsenide-Phosphide) devices for the long wavelengths of about 1200 nm to over 1600 nm. Photodiode materials of interest are well known, Si for 850 nm, and Ge and InGaAsP for the long wavelength range (Figure 6.40). However, an optical communication system is more than a light source, a fiber, and a photodiode. There is a laser driver circuit necessary to provide a proper high-bit-rate electric signal; this driver, combined with a laser or an LED, builds the optical transmitter. Also the photodiode (pin or APD – Avalanche Photodiode), together with the front-end amplifier, forms the optical detector, also called the optical receiver. This front-end amplifier consists of a very highly sophisticated electric circuit. It has to detect a high bandwidth operating with very few photons due to a large fiber length and it is struggling with a variety of noise generators. In addition, there are further electric circuits to be taken into account, such as circuits for coding, scrambling, error correction, clock extraction, temperature power-level, and gain controls. If the desired link length cannot be realized, a repeater consisting of a front-end amplifier and a pulse regenerator will be inserted. This pulse regenerator is necessary to restore the data signal before it is fed to a further laser driver followed by another laser (Figure 9.2). Alternatively, an optical amplifier can be used, in particular the Erbium-doped fiber amplifier is a great success (Figure 8.2).

Moreover, instead of unidirectional systems, we need bi-directional ones (Figure 9.9); that is, it is not sufficient that for a telephone link a person at one side of the link is able to speak, but at the other side another person can only listen; the system does not operate the other way round. To overcome this inconvenient situation, optical couplers on both sides of the link are inserted (Figures 4.53 and 4.54). The two counter propagating optical waves superimpose undisturbed, and they separate at the optical couplers on the other side of the link and reach the according receivers. To improve the transmission capacity drastically, wavelength selective couplers are applied, called multiplexers and demultiplexers. Several laser diodes operating at different wavelengths are used as transmitters; their light waves are combined by the multiplexer and on the other link end they are separated by the demultiplexer. This set-up is named the wavelength division multiplex system (WDM). If we apply this arrangement again in the two counter propagating directions, we achieve a bi-directional WDM system. The

transmission capacity then rises by the number N of the channels transmitted over one single fiber.

For about 20 years now, last mile communication has been discussed. The idea of fiber to the home (FTTH) has also been discussed, but until now this did not happen because it was too expensive. Latest improvements could help to achieve this special communication. All-plastic PMMA-fibers (poly methyl methacrylate) have been developed, named *Polymer Optical Fibers* (POF), which feature in contrast to the previous PMMA-fibers at a considerably lower attenuation [1.17] (Chapter 10.2). As an economic alternative to the application of semiconductor lasers, another important step is the development of cheap high-speed LEDs [1.18] or low-cost VCSELs (Vertical Cavity Surface Emitting Lasers) [3.1], which can be modulated fast enough.

Combinations of fiber-optic with mm-waves systems or coaxial cable systems have been developed for the local area network as a possible alternative. As another alternative to cable systems, the declared dead free space transmission could be also revived with distances in the 100 m range. For this purpose, the light emerging from a fiber is fed to a lens and formed into a parallel beam. At the reception site it is again coupled into a fiber or directly to a detector.

This conjunction of fiber-optic transmission and free space may successfully be used in sky scraper areas, where air distances lie in the 100 m range and cable systems would need to be in kilometres. Wireless data transmission is also an interesting option for distances in the 10 m range. Connections between, for example, a PC, printer, scanner or adjacent participants in intranets (LANs, *Local Area Networks*, see below) should not be bridged by interfering electrical cables. Further developments in the microwave range have been developed, such as the recent well-known *Bluetooth systems*.

Moreover, besides typical point-to-point connections, network systems are necessary. In nearby zones, for example inside a business house, the commonly used term is LANs (*Local Area Networks*); in the local net or metro region it is MANs (*Metropolitan Area Networks*), [9.85–9.87]. The network topologies are bus, star or ring structures (Chapter 9.5.3).

Furthermore, free space transmission is gaining a particular renaissance in outer space, because outside of the Earth's atmosphere typical problems such as natural disturbances by fog, rain, snow or artificially caused impurities do not inherently exist. Therefore, laser free space connections between satellites have been already tried and tested successfully (Chapter 9.3).

In the last 10 years, communication in automotive systems became of great interest (Chapter 11.1). Currently, optical data buses in vehicles are almost exclusively used for infotainment (information and entertainment) applications. The Media Oriented Systems Transport (MOST) is the optical data bus technology used nowadays in cars with a data rate up to 150 MBit/s (Figure 11.5 [1.14]). The development of infotainment applications in cars began with a radio and simple loudspeakers. Today's infotainment systems in cars include but are not limited to ingenious sound systems, DVD-changers, amplifiers, navigation and video functions. Voice input and Bluetooth interfaces complement these packages. Important and basic logical links of these single components are already well known from a simple car radio. Everybody probably knows the rise of volume in the case of road traffic announcements. However, the integration of more and more multimedia and telematic devices in vehicles led to a large increase in data traffic demands. In particular, for luxurious classes, a huge need for network capacity and higher complexity by integration of various applications have to be taken into account. MOST



Figure 1.5 Lightning strike in an airplane [1.22]. Source: Reproduced with permission of Denny Both, Piranha.dl 3d Animation, Berlin

150 operates with LEDs, a POF and silicon photodiodes. However, to enable the next step towards autonomous driving, new bus systems with higher data rates will be required.

Another serious challenge arises in protecting new generation aircrafts, particularly against lightning strikes [1.15]. This is because new airplanes will be built using carbon-fibers to reduce the weight of the fuselage. Therefore, these airplanes will lose their inherent Faraday cage protection against lightning, cosmic radiation and further electrostatic effects (Figure 1.5).

In order to avoid failures in signal transmission in the physical layer, the electrical copper wires should be well protected. But this solution is too expensive and increases the weight of the cables [1.15]. A reasonable solution is to use glass or plastic fibers as transmission media in these new airplanes. Since the FlexRay bus protocol [1.16] is more adequate for avionic applications, it should be adapted for this kind of transmission. Thus, this solution is cost-efficient and offers more safety in the aviation domain. A promising solution for higher sophisticated systems could be the use of optical data transmission based on new laser types, such as VCSELs and the application of Polymer Cladded Silica (PCS) fibers. This enables EMC compatibility and paves the way for the future.

In this book we mainly give an introduction to optical transmission. Emphasis is on fiber transmission systems, working with basic components. The reader should be familiar with

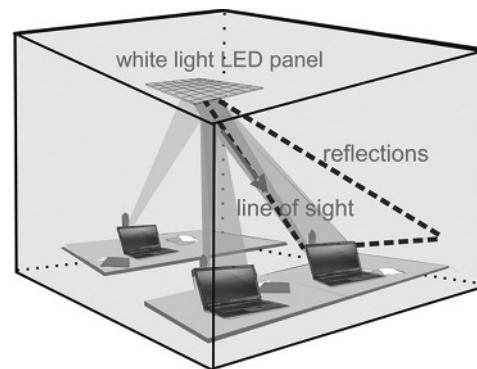


Figure 1.6 Room lighting with inherent data modulation and transmission

the fundamental optical techniques for communication systems. Moreover, for more comprehensive considerations there are further components to be dealt with, for example the optical amplifier to enhance the link length. In order to achieve this, Erbium and Raman amplifiers (Chapter 8) [8.1,8.2] have been developed to overcome the problem of attenuation in fibers. Due to the above-mentioned dispersions, there are signal distortions in optical fibers. The systems suffer from pulse broadening (Figure 3.21) leading to bandwidth reduction with impact on the transmission capacity, the product of bandwidth and fiber length. Solutions to overcome or at least to reduce these problems are discussed in Chapter 3.2.

Furthermore, wireless applications open new fields for data transmission [1.19]. High speed wireless LED transmissions offer short and middle range data transmission without EMI/EMC problems (Figure 1.6). Higher bandwidths than non-optical wireless applications will offer high-speed up- and downloads in offices, labs and private homes.

Also, car-to-car communication could be an interesting scenario (Figure 11.1 [1.20]). In particular, safety relevant applications are of great interest (Iizuka 2008, [1.20]). The catchword is “Pre-crash safety” by VL-ISC: Visible Light Image Sensor Communication. Human reaction time is a problem in security, as in difficult circumstances it could last much longer than a sensor does. The vehicle in front might suddenly start braking. Thus, depending on the brake pressure, immediately its stoplights will give information to the following vehicle. In critical cases the following vehicle will automatically start emergency braking to avoid a collision or at least to avoid serious damage.

A further new development is shown in Figure 11.2, a red-light-to-car communication. In this case, the red light tells a waiting driver that he will get a green signal in 50 seconds. Another example would be that a car is approaching a red light and the driver gets the information 10 seconds before he can even see it. While the driver is waiting at the red light, the system receives the red interval from the traffic light in order to take the decision to stop the engine. The outcome would be a gas-mileage and CO₂ reduction of more than 5% (November 2008). In addition, the driver does not have to fix his eyes on the traffic light permanently. These systems can predict idling intervals with accuracy to solve unnecessary engine stops and starts. Including information about the green, amber and red time zones, the traffic volume can be better regulated.

Moreover, a new industry standard, named communication in automation engineering, has been developed. Applying this technology has opened up new perspectives for data linking between tooling machines and a central control unit: Industry 4.0 is a collective term for technologies and concepts of value chain organization (Chapter 9.6).

Finally, non-optical techniques have to be taken into account (Chapters 10.5 and 11.2). For example, WLAN and even RADAR systems can be used in automotive application, to guarantee more safety in limited optical visibility situations like heavy rain, fog or snow.

As mentioned above, it has to be underlined that nowadays the user wants a complete solution for his demands and he does not stop to ask if that is fiber optics or whatever. Moreover, he also wants combinations of other physical techniques with or without fibers, so Optical wireless communications, Optical and Non-Optical Solutions, and Microwaves in Radio over Fiber (RoF) have to work together.

