

12.1: Introduction to optical communication links

12.1.1: Introduction to optical communications and photonics

Optical communications is as ancient as signal fires and mirrors reflecting sunlight, but it is rapidly being modernized by *photonics* that integrate optics and electronics in single devices. Photonic systems are usually analyzed in terms of individual photons, although wave methods still characterize the guidance of waves through optical fibers, space, or other media. This chapter introduces optical communications and applications of photonics in Section 12.1. It then discusses simple optical waveguides in Section 12.2, lasers in Section 12.3, and representative components of optical communications systems in Sections 12.4, including photodetectors in 12.4.1-2, multiplexers in 12.4.3, interferometers in 12.4.4, and optical switches in 12.4.5.

12.1.2: Applications of Photonics

Perhaps the single most important application of photonics today is to optical communications through low-loss glass fibers. Since 1980 this development has dramatically transformed global communications. The advantage of an optical fiber for communications is that it has a bandwidth of approximately one terahertz, and can propagate signals over continental and even global distances when assisted by optical amplifiers. These amplifiers are currently separated more than ~ 80 km, and this separation is steadily increasing as technology improves. In contrast, coaxial cable, wire-pair, and wireless links at radio frequencies still dominate most communication paths of bandwidth < 2 MHz, provided the length is less than ~ 1 –50 km.

One broadband global wireless alternative to optics is microwave communications satellites in geosynchronous orbit⁶⁶ that can service ships at sea and provide moveable capacity addressing transient communications shortfalls or failures across the globe; the satellites simply point their antenna beams at the new users, who can be over 10,000 km apart. The greatest use of satellites, however, is for broadcast of entertainment over continental areas, either to end-users or to the head ends of cable distribution systems. In general, the limited terrestrial radio spectrum is more efficiently used for broadcast than for one-to-one communications unless there is re-use of spectrum as described in Section 10.4.6. Optical techniques are disadvantaged for satellite-ground links or ground-to-ground links through air because of clouds and fog, which restrict such links to very short distances or to cases where spatial diversity⁶⁷ offers clear-air alternatives.

⁶⁶ Geosynchronous satellites at 22,753-mile altitude orbit Earth once every 24 hours and can therefore hover stationary in the sky if they are in an equatorial orbit.

⁶⁷ Spatial diversity involves use of spatially distinct communications links that suffer any losses independently; combining these signals in non-linear ways improves overall message reliability. Optical links also have great potential for very broadband inter-satellite or diversity-protected satellite-earth communications because small telescopes easily provide highly focused antenna beams. For example, beamwidths of telescopes with 5-inch apertures are typically one arc-second⁶⁸, corresponding to antenna gains of $\sim 4\pi \times (57 \times 3600)^2 \cong 5 \times 10^{11}$, approximately 5000 times greater than is achievable by all but the very best radio telescopes. Such optical links are discussed in Section 12.1.4.

⁶⁸ One arc-second is $1/60$ arc-minutes, $1/60^2$ degrees, $1/(57.3 \times 3600)$ radians, or $1/60$ of the largest apparent diameters of Venus or Jupiter in the night sky.

Optical fibers are increasingly being used for much shorter links too, simply because their useable bandwidth can readily be expanded after installation and because they are cheaper for larger bandwidths. The distance between successive amplifiers can also be orders of magnitude greater (compare the fiber losses of Figure 12.2.6 with those of wires, as discussed in Section 7.1.4 and Section 8.3.1). The bandwidth per wire is generally less than ~ 0.1 GHz for distances between amplifiers of 1 km, whereas a single optical fiber can convey ~ 1 THz for 100 km or more. Extreme data rates are now also being conveyed optically between and within computers and even chips, although wires still have advantages of cost and simplicity for most ultra-short and high-power applications.

Optical communication is not the only application for photonics, however. Low-power lasers are used in everyday devices ranging from classroom pointers and carpenters' levels to bar-code readers, laser copiers and printers, surgical tools, medical and environmental instruments, and DVD players and recorders. Laser pulses lasting only 10^{-15} second (0.3 microns length) are used for biological and other research. High power lasers with tens of kilowatts of average power are used for cutting and other manufacturing purposes, and lasers that release their stored energy in sub-picosecond intervals can focus and compress their energy to achieve intensities of $\sim 10^{23}$ W/m² for research or, for example, to drive small thermonuclear reactions in compressed pellets. Moreover, new applications are constantly being developed with no end in sight.

12.1.3: Link equations

The link equations governing through-the-air optical communications are essentially the same as those governing radio, as described in Section 10.3. That is, the received power P_r is simply related to the transmitted power P_t by the gain and effective area of the transmitting and receiving antennas, G_t and A_e :

$$P_r = (G_t P_t / 4\pi r^2) A_e \text{ [W]} \quad (\text{optical link equation}) \quad (12.1.1)$$

The gain and effective area of single-mode optical antennas are related by the same equation governing radio waves, (10.3.23):

$$G = 4\pi A / \lambda^2 \quad (12.1.2)$$

Some optical detectors intercept multiple independent waves or modes, and their powers add. In this case, the gain and effective area of any single mode are then less relevant, as discussed in Section 12.1.4.

The maximum bit rate that can be communicated over an optical link is not governed by the $E_b > \sim 10^{-20}$ Joules-per-bit limit characteristic of radio systems, however, but rather by the number of photons the receiver requires per bit of information, perhaps ~ 10 for a typical good system. Each photon has energy $E = hf$ Joules. Thus to receive R bits/second might require received power of:

$$P_r = E_b R \cong 10hfR \text{ [W]} \quad (\text{optical rate approximation}) \quad (12.1.3)$$

where h is Planck's constant (6.624×10^{-34}) and f is photon frequency [Hz]. Clever design can enable many bits to be communicated per photon, as discussed in the following section.

12.1.4: Examples of optical communications systems

Three examples illustrate several of the issues inherent in optical communications systems: a trans-oceanic optical fiber cable, an optical link to Mars, and an incoherent intra-office link carrying computer information.

First consider a trans-oceanic optical fiber. Section 12.2.2 discusses losses in optical fibers, which can be as low as ~ 0.2 dB/km near 1.5-micron wavelength ($f \cong 2 \times 10^{14}$ Hz). To ensure the signal (zeros and ones) remains unambiguous, each link of an $R = 1$ -Gbps fiber link must deliver to its receiver or amplifier more than $\sim 10hfR$ watts, or $\sim 10 \times 6 \times 10^{-34} \times 2 \times 10^{14} \times 10^9 \cong 1.2 \times 10^{-9}$ watts; a more typical design might deliver $\sim 10^{-6}$ watts because errors accumulate and equipment can degrade. If one watt is transmitted and 10^{-6} watts is received, then the associated 60-dB loss corresponds to 300 km of fiber propagation between optical amplifiers, and perhaps ~ 20 amplifiers across the Atlantic Ocean per fiber. In practice, erbium-doped fiber amplifiers, discussed in Section 12.3.1, are now spaced approximately 80 km apart.

Next consider an *optical link* communicating between Earth and astronauts on Mars. Atmospheric diffraction or “seeing” limits the focusing ability of terrestrial telescopes larger than ~ 10 cm, but Mars has little atmosphere. Therefore a Martian optical link might employ the equivalent of a one-square-meter optical telescope on Mars and the equivalent of 10-cm-square optics on Earth. It might also employ a one-watt laser transmitter on Earth operating at 0.5 micron wavelength, in the visible region. The nominal link and rate equations, (12.1.1) and (12.1.3), yield the maximum data rate R possible at a range of $\sim 10^{11}$ meters (approximate closest approach of Mars to Earth):

$$R = P_r / E_b \cong (G_t P_t / 4\pi r^2) A_e / 10hf \text{ [bits s}^{-1}\text{]} \quad (12.1.4)$$

The gain G_t of the transmitter given by (12.1.2) is $G_t \cong 4\pi A / \lambda^2 \cong 5 \times 10^{11}$, where $A \cong (0.1)^2$ and $\lambda \cong 5 \times 10^{-7}$ [m]. The frequency $f = c/\lambda = 3 \times 10^8 / [5 \times 10^{-7}] = 6 \times 10^{14}$. Therefore (12.1.4) becomes:

$$R \cong \left\{ [5 \times 10^{11} \times 1] / [4\pi (10^{11})^2] \right\} \left\{ 1 / [10 \times 6.624 \times 10^{-34} \times 6 \times 10^{14}] \right\} \cong 1 \text{ Mbps} \quad (12.1.5)$$

Table 11.4.1 suggests that this data rate is adequate for full-motion video of modest quality. The delay of the signal each way is $\tau = r/c = 10^{11} / [3 \times 10^8]$ seconds $\cong 5.6$ minutes, impeding conversation. This delay becomes several times greater when Mars is on the far side of the sun from Earth, and the data rate R would then drop by more than a factor of ten.

This 1-Mbps result (12.1.5) assumed 10 photons were required per bit of information. However this can be reduced below one photon per bit by using *pulse-position modulation*. Suppose $\sim 10^6$ 1-nsec 10-photon pulses were received per second, where each pulse could arrive in any of 1024 time slots because the ratio of pulse width to average inter-pulse spacing is 1024. This timing information conveys ten bits of information per pulse because $\log_2 1024 = 10$. Since each 10-photon pulse conveys 10 bits of

information, the average is one bit per photon received. With more time slots still fewer photons per bit would be required. If a tunable laser can transmit each pulse at any of 1024 colors, for example, then another factor of 10 can be achieved. Use of both pulse position and pulse-frequency modulation can permit more than 10 bits to be communicated per photon on average.

The final example is that of a 1-mW laser diode transmitting digitally modulated light at $\lambda = 5 \times 10^{-7}$ [m] isotropically within a large office over ranges r up to 10 meters, where the light might travel directly to the isotropic receiver or bounce off walls and the ceiling first. Such optical communications systems might link computers, printers, personal digital assistants (pda's), and other devices within the room. In this case $G_t = 1$ and $A_e = G\lambda^2/4\pi = (5 \times 10^{-7})^2/4\pi \cong 2 \times 10^{-14}$ [m²]. The maximum data rate R can again be found using (12.1.4):

$$R = P_r/E_b \cong (1 \times 10^{-3}/4\pi 10^2) (2 \times 10^{-14}) / (10 \times 6.6 \times 10^{-34} \times 6 \times 10^{14}) \cong 0.004 \text{ [bits s}^{-1}\text{]} \quad (12.1.6)$$

The fact that we can send 10^6 bits per second to Mars with a one-watt transmitter, but only 4 millibits per second across a room with a milliwatt, may conflict with intuition

The resolution of this seeming paradox lies in the assumption that the receiver in this example is a single mode device like that of typical radio receivers or the Martian optical receiver considered above. If this room-link receiver were isotropic and intercepted only a single mode, its effective area A_e given by (12.1.2) would be 2×10^{-14} [m²]. The tiny effective area of such low-gain coherent optical antennas motivates use of incoherent photodetectors instead, which respond well to the total photon flux from all directions of arrival. For example, intraroom optical links of this type are commonly used for remote control of many consumer electronic devices, but with a much larger multimode antenna (photodiode) of area $A \cong 2 \times 10^{-6}$ [m²] instead of 2×10^{-14} . This "antenna" is typically responsive to all photons impacting its area that arrive within roughly one steradian. That is, a photodetector generally intercepts all photons impacting it, even though those photons are incoherent with each other. Thus the solution (12.1.6) is increased by a factor of $10^{-6}/10^{-14}$ if a two-square-millimeter photodetector replaces the single-mode antenna, and R then becomes 0.4 Mbps, which is more capacity than normally required. In practice such inexpensive area detectors are noisier and require orders of magnitude more photons per bit. Better semiconductor detectors can achieve 10 photons per bit or better, however, particularly at visible wavelengths and if stray light at other wavelengths is filtered out.

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