Wireless Infrared Communications

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I. Introduction

Wireless infrared communications refers to the use of free-space propagation of light waves in the near infrared band as a transmission medium for communication(1-3), as shown in Figure 1. The communication can be between one portable communication device and another or between a portable device and a tethered device, called an access point or base station. Typical portable devices include laptop computers, personal digital assistants, and portable telephones, while the base stations are usually connected to a computer with other networked connections. Although infrared light is usually used, other regions of the optical spectrum can be used (so the term "wireless optical communications" instead of "wireless infrared communications" is sometimes used).

Wireless infrared communication systems can be characterized by the application for which they are designed or by the link type, as described below.

A. Applications

The primary commercial applications are as follows:

- short-term cable-less connectivity for information exchange (business cards, schedules, file sharing) between two users. The primary example is IrDA systems (see Section 4).
- wireless local area networks (WLANs) provide network connectivity inside buildings. This can either be an extension of existing LANs to facilitate mobility, or to establish "ad hoc" networks where there is no LAN. The primary example is the IEEE 802.11 standard (see Section 4).
- building-to-building connections for high-speed network access or metropolitan- or campus-area networks.
- wireless input and control devices, such as wireless mice, remote controls, wireless game controllers, and remote electronic keys.

B. Link Type

Another important way to characterize a wireless infrared communication system is by the "link type", which means the typical or required arrangement of receiver and transmitter. Figure 2 depicts the two most common configurations: the point-to-point system and the diffuse system.

The simplest link type is the point-to-point system. There, the transmitter and receiver must be pointed at each other to establish a link. The *line-of-sight* (LOS) path from the transmitter to the receiver must be clear of obstructions, and most of the transmitted light is *directed* toward the receiver. Hence, point-to-point systems are also called *directed LOS systems*. The links can be temporarily created for a data exchange session between two users, or established more permanently by aiming a mobile unit at a base station unit in the LAN replacement application.

In diffuse systems, the link is always maintained between any transmitter and any receiver in the same vicinity by reflecting or "bouncing" the transmitted information-bearing light off reflecting surfaces such as ceilings, walls, and furniture. Here, the transmitter and receiver are *non-directed*; the transmitter employs a wide transmit beam and the receiver has a wide field-of-view. Also, the LOS path is not required. Hence, diffuse systems are also called *non-directed non-LOS systems*. These systems are well suited to the wireless LAN application, freeing the user from knowing and aligning with the locations of the other communicating devices.

C. Fundamentals and Outline

Most wireless infrared communications systems can be modeled as having an output signal $Y(t)$ and an input signal $X(t)$ which are related by

$$Y(t) = X(t) \otimes c(t) + N(t) \qquad (1)$$

where $\otimes$ denotes convolution, $c(t)$ is the impulse response of the channel and $N(t)$ is additive noise. This article is organized around answering key questions concerning the system as represented by this model.

In Section 2, we consider questions of optical design. What range of wireless infrared communications systems does this model apply to? How does $c(t)$ depend on the electrical and optical properties of the receiver and transmitter? How does $c(t)$ depend on the location, size, and orientation of the receiver and transmitter? How do $X(t)$ and $Y(t)$ relate to optical processes? What wavelength is used for $X(t)$? What devices produce $X(t)$ and $Y(t)$? What is the source of $N(t)$? Are there any safety considerations? In Section 3, we consider questions of communications design. How should a data symbol sequence be modulated onto the input signal $X(t)$? What detection mechanism is best for extracting the information about the data from the received signal $Y(t)$? How can one measure and improve the performance of the system? In Section 4, we consider the design choices made by existing standards such as IrDA and 802.11. Finally, in Section 5, we consider how these systems can be improved in the future.

II. Optical Design

A. Modulation and demodulation

What characteristic of the transmitted wave will be modulated to carry information from the transmitter to the receiver? Most communication systems are based on phase, amplitude, or frequency modulation, or some combination of these techniques. However, it is difficult to detect such a signal following nondirected propagation, and more expensive narrow-linewidth sources are required(2). An effective solution is to use *intensity* modulation, where the transmitted signal's intensity or power is proportional to the modulating signal.

At the demodulator (usually referred to as a detector in optical systems) the modulation can be extracted by mixing the received signal with a carrier light wave. This *coherent detection* technique is best when the signal phase can be maintained. However, this can be difficult to implement and additionally, in nondirected propagation, it is difficult to achieve the required mixing efficiency. Instead, one can use *direct detection* using a photodetector. The photodetector current is proportional to the received optical signal intensity, which for intensity modulation, is also the original modulating signal. Hence, most systems use intensity modulation with direct detection (IM/DD) to achieve optical modulation and demodulation.

In a free-space optical communication system, the detector is illuminated by sources of light energy other than the source. These can include ambient lighting sources, such as natural sunlight, fluorescent lamp light, and incandescent lamp light. These sources cause variation in the received photocurrent that is unrelated to the transmitted signal, resulting in an additive noise component at the receiver.

We can write the photocurrent at the receiver as

$$Y(t) = X(t) \otimes Rh(t) + N(t)$$

where R is the responsivity of the receiving photodiode (A/W). Note that the electrical impulse response $c(t)$ is simply R times the optical impulse response $h(t)$. Depending on the situation, some authors use $c(t)$ and some use $h(t)$ as the impulse response.

B. Receivers and Transmitters

A transmitter or *source* converts an electrical signal to an optical signal. The two most appropriate types of device are the light-emitting diode (LED) and semiconductor laser diode (LD). LEDs have a naturally wide transmission pattern, and so are suited to nondirected links. Eye safety is much simpler to achieve for an LED than for a laser diode, which usually have very narrow transmit beams. The principal advantages of laser diodes are their high energy-conversion efficiency, their high modulation bandwidth, and their relatively narrow spectral width. Although laser diodes offer several advantages over LEDs that could be exploited, most short-range commercial systems currently use LEDs.

A receiver or *detector* converts optical power into electrical current by detecting the photon flux incident on the detector surface. Silicon *p-i-n* photodiodes are ideal for wireless infrared communications as they have good quantum efficiency in this band and are inexpensive(4). Avalanche photodiodes are not used here since the dominant noise source is background light-induced shot noise rather than thermal circuit noise.

C. Transmission Wavelength and Noise

The most important factor to consider when choosing a transmission wavelength is the availability of effective, low-cost sources and detectors. The availability of LEDs and silicon photodiodes operating in the 800 nm to 1000 nm range is the primary reason for the use of this band. Another important consideration is the spectral distribution of the dominant noise source: background lighting.

The noise $N(t)$ can be broken into four components: photon noise or shot noise, gain noise, receiver circuit or thermal noise, and periodic noise. Gain noise is only present in avalanche-type devices, so we will not consider it here.

Photon noise is the result of the discreteness of photon arrivals. It is due to background light sources, such as sun light, fluorescent lamp light, and incandescent lamp light, as well as the signal-dependent source $X(t) \otimes c(t)$. Since the background light striking the photodetector is normally much stronger than the signal light, we can neglect the dependency of $N(t)$ on $X(t)$ and consider the photon noise to be additive white Gaussian noise with two-sided power spectral density $S(f) = qRP_n$ where q is the electron charge, R is the responsivity, and P_n is the optical power of the noise (background light).

Receiver noise is due to thermal effects in the receiver circuitry, and is particularly dependent on the type of preamplifier used. With careful circuit design, it can be made insignificant relative to the photon noise(5).

Periodic noise is the result of the variation of fluorescent lighting due to the method of driving the lamp using the ballast. This generates an extraneous periodic signal with a fundamental frequency of 44 kHz with significant harmonics to several MHz. Mitigating the effect of periodic noise can be done using high-pass filtering in combination with baseline restoration(6), or by careful selection of the modulation type, as discussed in Section 3.1.

D. Safety

There are two safety concerns when dealing with infrared communication systems. Eye safety is a concern because of a combination of two effects: the cornea is transparent from the near violet to the near IR. Hence, the retina is sensitive to damage from light sources transmitting in these bands. However, the near IR is outside the visible range of light, and so the eye does not protect itself from damage by closing the iris or closing the eyelid. Eye safety can be ensured by restricting the transmit beam strength according to IEC or ANSI standards(7,8).

Skin safety is also a possible concern. Possible short-term effects such as heating of the skin are accounted for by eye safety regulations (since the eye requires lower power levels than the skin). Long-term exposure to IR light is not a concern, as the ambient light sources are constantly submitting our bodies to much higher radiation levels than these communication systems do.

III. COMMUNICATIONS DESIGN

Equally important for achieving the design goals of wireless infrared systems are communications issues. In particular, the modulation signal format together with appropriate error control coding is critical to achieving power efficiency. Channel characterization is also important for understanding performance limits.

A. Modulation Techniques

To understand modulation in IM/DD systems, we must look again at the channel model

$$Y(t) = X(t) \otimes c(t) + N(t)$$

and consider its particular characteristics. First, since we are using intensity modulation, the channel input $X(t)$ is optical intensity and we have the constraint $X(t) \geq 0$. The average transmitted optical power P_T is the time average of X(t). Our goal is to minimize the transmitted power required to attain a certain probability of bit error P_e, also known as a bit error rate (BER).

It is useful to define the signal-to-noise ratio SNR as

$$SNR = \frac{R^2 H^2(0) P_t^2}{R_b N_0}$$

where $H(0)$ is the d.c. gain of the channel, i.e. it is the Fourier transform of $h(t)$ evaluated at zero frequency, so

$$H(0) = \int_{-\infty}^{\infty} h(t)\, dt.$$

The transmitted signal can be represented as

$$X(t) = \sum_{n=-\infty}^{\infty} s_{a_n}(t - nT_s).$$

The sequence $\{a_n\}$ represents the digital information being transmitted, where a_n is one of L possible data symbols from 0 to $L-1$. The function $s_i(t)$ represents one of L pulse shapes with duration T_s, the symbol time. The data rate (or bit rate) R_b, bit time T, symbol rate R_s, and symbol time T_s are related as follows: $R_b = 1/T$, $R_s = 1/T_s$, and $T_s = \log_2(L)T$.

There are three commonly used types of modulation schemes: on-off keying (OOK) with non-return-to-zero pulses, OOK with return-to-zero pulses of normalized width δ (RZ-δ) and pulse position modulation with L pulses (L-PPM). OOK and RZ-δ are simpler to implement at both the transmitter and receiver than L-PPM. The pulse shapes for these modulation techniques are shown in Figure 3. Representative examples of the resulting transmitted signal $X(t)$ for a short data sequence are shown in Figure 4.

We compare modulation schemes in Table 1 by looking at measures of *power efficiency* and *bandwidth efficiency*. Bandwidth efficiency is measured by dividing the zero-crossing bandwidth by the data rate. Bandwidth efficient schemes have several advantages– the receiver and transmitter electronics are cheaper, and the modulation scheme is less likely to be affected by multipath distortion. Power efficiency is measured by comparing the required transmit power to achieve a target probability of error P_e for different modulation techniques. Both RZ-δ and PPM are more power efficient than OOK, but at the cost of reduced bandwidth efficiency. However, for a given bandwidth efficiency, PPM is more power efficient than RZ-δ, and so PPM is most commonly used. OOK is most useful at very high data rates, say 100 Mb/s or greater. Then, the effect of multipath distortion is the most significant effect and bandwidth efficiency becomes of paramount importance(9).

B. *Error Control Coding*

Error control coding is an important technique for improving the quality of any digital communication system. We concentrate here on forward error correction channel coding, as this specifically relates to wireless infrared communications; source coding and ARQ coding are not considered here.

Trellis-coded PPM has been found to be an effective scheme for multipath infrared channels(10,11). The key technique is to recognize that although on a distortion-free channel, all symbols are orthogonal and equidistant in signal space, this is not true on a distorting channel. Hence, trellis-coding using set partitioning designed to separate the pulse positions of neighboring symbols is an effective coding method. Coding gains of 5.0 dB electrical have been reported for rate 2/3-coded 8-PPM over uncoded 16-PPM, which has the same bandwidth(11).

C. *Channel impulse response characterization*

Impulse response characterization refers to the problem of understanding how the impulse response $c(t)$ in Equation (1) depends on the location, size, and orientation of the receiver and transmitter. There are basically three classes of techniques for accomplishing this: measurement, simulation, and modeling. Channel measurements have been described in several studies(9,12,2), and these form the fundamental basis for understanding the channel properties. A particular study might generate a collection of hundreds or thousands of example impulse responses $c_i(t)$ for configuration i. The collection of measured impulse responses $c_i(t)$ can then be studied by looking at scatter plots of path loss versus distance, scatter plots of delay spread versus distance, the effect of transmitter and receiver orientations, robustness to shadowing, and so on.

Simulation methods have been used to allow direct calculation of a particular impulse response based on a site-specific characterization of the propagation environment(13,14). The transmitter, receiver, and the reflecting surfaces are described and used to generate an impulse response. The basic assumption is that most interior surfaces reflect light diffusely in a Lambertian pattern, i.e. all incident light, regardless of incident angle, is reflected in all directions with an intensity proportional to the cosine of the angle of the reflection with the surface normal. The difficulty with existing methods is that accurate modeling requires extensive computation.

A third technique attempts to extract knowledge gained from experimental and simulation-based channel estimations into a simple-to-use model. In

(15), for example, a model using two parameters (one for path loss, one for delay spread) is used to provide a general characterization of all diffuse IR channels. Methods for relating the parameters of the model to particular room characteristics are given, so that system designers can quickly estimate the channel characteristics in a wide range of situations.

IV. STANDARDS AND SYSTEMS

We examine the details of the two dominant wireless infrared technologies, IrDA and IEEE 802.11, and other commercial applications.

A. Infrared Data Association Standards (IrDA)

The Infrared Data Association(16), an association of about one hundred member companies, has standardized low-cost optical data links. The IrDA link transceivers or "ports", appear on many portable devices including notebook computers, personal digital assistants, and also computer peripherals such as printers.

The series of IrDA transmission standards are described in Table 2. The current version of the physical layer standards is IrPHY 1.3. Data rates from 2.4 kb/s to 4 Mb/s are supported. The link speed is negotiated by starting at 9.6 kb/s.

Most of the transmission standards are for short-range, directed links which an operating range from 0 m to 1 m. The transmitter half angle must be between 15 and 30 degrees, and the receiver field-of-view half angle must be at least 15 degrees. The transmitter must have a peak-power wavelength between 850 nm and 900 nm.

B. IEEE 802.11 and wireless LANs

The IEEE has published a set of standards for wireless LANs, IEEE 802.11 (17). The IEEE 802.11 standard is designed to fit into the structure of the suite of 802 LAN standards. Hence, it determines the physical layer (PHY) and medium-access control layer (MAC) leaving the logical-link control (LLC) to 802.2. The MAC layer uses a form of carrier-sense multiple access with collision avoidance (CSMA/CA).

The original standard supports both radio and optical physical layers with a maximum data rate of 2 Mb/s. The 802.11b standard adds a 2.4 GHz radio physical layer at up to 11 Mb/s and 802.11a standard adds a 5.4 GHz radio physical layer at up to 54 Mb/s.

The two supported data rates for infrared 802.11 LANs are 1 Mb/s and 2 Mb/s. Both systems use PPM but share a common chip rate of 4 Mchips/s, as explained below. Each frame begins with a preamble encoded using 4 Mb/s OOK. In the preamble, a three-bit field indicates the transmission type, either 1 Mb/s or 2 Mb/s (the six other types are reserved for future use). The data is then transmitted at 1 Mb/s using 16-PPM or 2 Mb/s using 4-PPM. 16-PPM carries $\log_2(16)/16{=}1/4$ bits/chip, and 4-PPM carries $\log_2(4)/4 = 1/2$ bits/chip, resulting in the same chip time for both types.

The transmitter must have a peak-power wavelength between 850 nm and 950 nm. The required transmitter and receiver characteristics are intended to allow for reliable operation at link lengths up to 10 m.

C. Building-to-building systems

Long range (greater than 10 m) infrared links must be directed LOS systems in order to ensure a reasonable path loss. The emerging products for long-range links are typically designed to be placed on rooftops(18,19), as this provides the best chance for establishing line-of-sight paths from one location to another in an urban environment. These high data rate connections can then be used for enterprise network access or metropolitan- or campus-area networks.

There are several design issues specific to these systems that are unique to these long-range systems(3). The first is atmospheric path loss, which is a combination of clean-air absorption from the air and absorption and scattering from particles in the air, such as rain, fog, and pollutants. Secondly, an effect called scintillation, which is caused by temperature variations along the LOS path, causes rapid fluctuations in the channel quality. Finally, building sway can affect alignment and result in signal loss unless the transceivers are mechanically isolated or active alignment compensation is used.

D. Other Applications

Wireless infrared communication has found several markets in and around the home, car, and office which fall outside the traditional telecommunications markets of voice and data networking. These can either be classified as wireless input devices, or as wireless control devices, depending on one's perspective. Examples include wireless computer mice and keyboards, remote controls for entertainment equipment, wireless video-game controllers, and wireless door keys for home or vehicle access. All such devices use infrared communication systems due to the attractive combination of low cost, reliability, and light weight in a transmitter/receiver pair that achieves the required range, data rate, and data integrity required.

V. TECHNOLOGY OUTLOOK

In this section, we discuss how competition from radio and developments in research will impact the future uses of wireless infrared communication systems.

A. Comparison to radio

Wireless infrared communication systems enjoy significant advantages over radio systems in certain environments. First, there is an abundance of unregulated optical spectrum available. This advantage is shrinking somewhat as the spectrum available for licensed and unlicensed radio systems increases due to modernization of spectrum allocation policies.

Radio systems must make great efforts to overcome or avoid the effects of multipath fading, typically through the use of diversity. Infrared systems do not suffer from time-varying fades due to the inherent diversity in the receiver. This simplifies design and increases operational reliability.

Infrared systems provide a natural resistance to eavesdropping, as the signals are confined within the walls of the room. This also reduces the potential for neighboring wireless communication systems to interfere with each other, which is a significant issue for radio-based communication systems.

Inband interference is a significant problem for both types of systems. A variety of electronic and electrical equipment radiates in transmission bands of current radio systems; microwave ovens are a good example. For infrared systems, ambient light, either man-made or natural, is a dominant source of noise.

The primary limiting factor of infrared systems is their limited range, particularly when no good optical path can be made available. For example, wireless communication between conventional rooms with opaque walls and doors cannot be accomplished; one must resort to using either a radio-based or a wireline network to bypass the obstruction.

B. Research Challenges

A variety of techniques have been considered to improve upon the performance of wireless infrared communication systems.

At the transmitter, the radiation pattern can be optimized to improve performance characteristics such as range. Some optical techniques for achieving this are diffusing screens, multiple-beam transmitters, and computer-generated holographic images.

At the receiver, performance is ultimately determined by signal collection (limited by the size of the photodetector) and by ambient noise filtering. Optical interference filters can be used to reduce the impact of background noise; the primary difficulty is in achieving a wide-field-of-view. This can be done using non-planar filters or multiple narrow FOV receiving elements.

Some recent developments and research programs are described in (20), and an on-line resource guide is maintained in (21).

VI. CONCLUSIONS

Wireless infrared communication systems provide a useful complement to radio-based systems, particularly for systems requiring low cost, light weight, moderate data rates, and only requiring short ranges. When LOS paths can be assured, range can be dramatically improved to provide longer links.

Short-range wireless networks are poised for tremendous market growth in the next decade, and wireless infrared communications systems will compete in a number of arenas. Infrared systems have already proven their effectiveness for short-range temporary communications and in high data rate longer range point-to-point systems. It remains an open question whether infrared will successfully compete in the market for general-purpose indoor wireless access.

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Cross-references

Wireless Optical Communications. See Wireless Infrared Communications.

Optical Wireless Communications. See Wireless Infrared Communications.

Infrared Wireless Communications. See Wireless Infrared Communications.

IrDA. See Wireless Infrared Communications.

TABLES

Modulation Type	P_e	ZC-Bandwidth
On-Off Keying	$Q(SNR^{1/2})$	R_b
OOK RZ-δ	$Q(\delta^{-1/2}SNR^{1/2})$	$\frac{1}{\delta}R_b$
L-PPM	$Q\left((0.5L * \log_2(L))^{1/2}SNR^{1/2}\right)$	$\frac{L}{\log_2 L}R_b$

TABLE I

Comparison of Modulation Schemes on Ideal Channels.

Version	Link Type	Link Range	Data Rate	Modulation
1.3	Point-to-Point	1 m	2.4 – 115.2 kb/s	RZ-3/16
1.3	Point-to-Point	1 m	576 kb/s 1152 kb/s	RZ-1/4 RZ-1/4
1.3	Point-to-Point	1 m	4 Mb/s	4-PPM
VFIR/1.4	Point-to-Point	1 m	16 Mb/s	OOK
AIR/proposed	Network	4 m 8 m	4 Mb/s 250 kb/s	

TABLE II

IrDA data transmission standards.

FIGURES

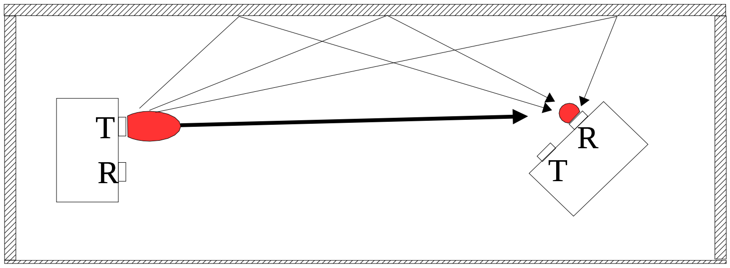
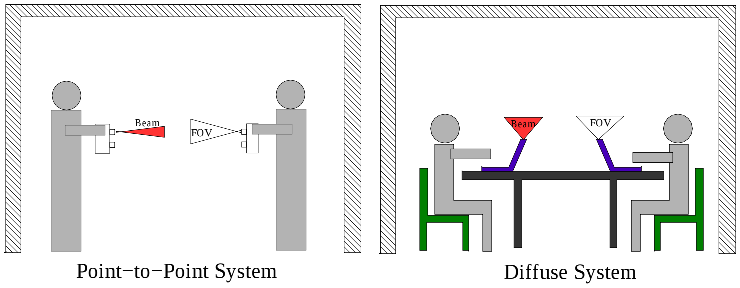


Fig. 1. A typical wireless infrared communication system



Point−to−Point System

Diffuse System

Fig. 2. Common types of infrared communication systems.

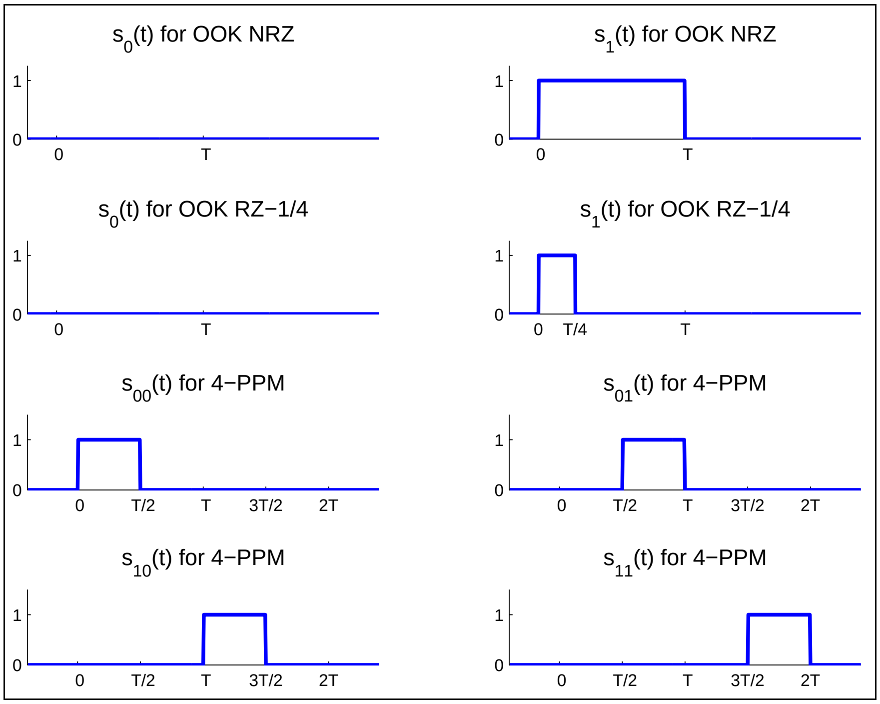


Fig. 3. The pulse shapes for OOK, RZ-0.25, and 4-PPM.

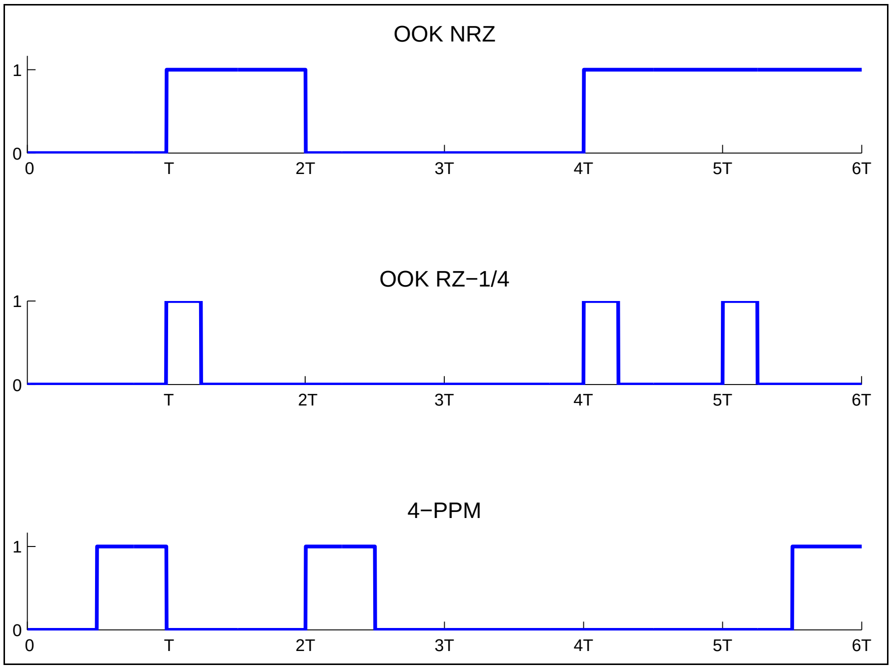


Fig. 4. The transmitted signal for the sequence 010011 for OOK, RZ-0.25, and 4-PPM.