INDOOR OPTICAL WIRELESS COMMUNICATIONS
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Abstract

In the last few years, there has been a growing interest in optical wireless communications for indoor and outdoor applications. The high cost of reconfiguring and maintaining wired networks makes wireless an economical and flexible alternative to wired systems. Lately, two major transmission technologies have been used to achieve indoor wireless communication: RF and infrared. For many reasons, infrared is preferred in certain cases. For example, infrared links provide high bandwidth at low cost, infrared is immune to radio interference, the spectrum is freely available, and infrared components are inexpensive, small and consume little power. This article presents an up-to-date review of the optical wireless communication system features for indoor use. Benefits and limitations of infrared links are explained, as well as advantages and disadvantages of infrared compared to microwave and other radio systems. Design fundamentals and different possible configurations are described. Different sources of infrared noise are explained. Optical safety issues for optical wireless systems are presented. Finally current indoor infrared systems are reviewed, and future trends are visualised.

Introduction

Usually, one may see that computer terminals are clustered within office environments, labs, conference rooms, education institutions, libraries, hospitals and production floors. In all these environments, the inconvenience and high cost of maintaining and reconfiguring wired systems has lead to the alternative use of wireless communications. Wireless offers flexibility in the placement of terminals in work environments, and avoids the waste of time and cost that reconfiguring a wired system imply.

A way to achieve high-speed, indoor wireless communication is by using infrared radiation. The idea of using infrared as a medium to communicate in-house environments was first proposed about two decades ago [1][2], but it has been in the last few years that the interest in optical wireless communications has grown [19]-[23].

As optical systems operate in the near-infrared part of the spectrum, they make use of very low cost optoelectronic components available today. These components are generally small, and consume little power, which is very important when manufacturing mobile terminals for telecommunications in large quantities.

Comparison of Infrared with Radio Systems

Infrared radiation appears to be a viable alternative to radio for wireless communications. This is because, for indoor short-range communication applications, infrared presents certain advantages when compared with radio-frequency systems. Radio-frequency transmission is regulated by the FCC (Federal Communications Commission) [3] in the USA, and the Radio Communications Agency in the UK [24], and licenses are obtained with difficulty because of the increasing congestion of the frequency bands. The infrared region of the spectrum, on the other hand, offers huge bandwidth potential that is unregulated all over the world.

Infrared radiation, just like visible light, is confined to the room in which it is generated, so it cannot be detected outside, securing transmissions against eavesdropping. Also, infrared radiation does not interfere with systems of the same nature operating in neighbouring rooms and does not interfere with the radio frequency spectrum either.

Another advantage is that infrared components are inexpensive, small and consume little power, very important for mobile terminal systems.
Table 1. Comparison of radio and infrared properties for indoor wireless communications

<table>
<thead>
<tr>
<th></th>
<th>Radio</th>
<th>Infrared</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC/RCA regulation</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Security</td>
<td>possible</td>
<td>high</td>
</tr>
<tr>
<td>RF interference</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Technology Cost</td>
<td>variable</td>
<td>potentially</td>
</tr>
<tr>
<td>Main noise source</td>
<td>other user interference</td>
<td>ambient</td>
</tr>
<tr>
<td>Coverage</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>Mobility</td>
<td>yes</td>
<td>some configurations</td>
</tr>
<tr>
<td>Bandwidth limitation</td>
<td>Regulatory</td>
<td>photodetector/ preamplifier, diffuse channel</td>
</tr>
<tr>
<td>Multipath dispersion</td>
<td>yes</td>
<td>some configurations</td>
</tr>
<tr>
<td>Multipath fading</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Path loss</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>

In spite of the advantages presented by infrared over radio medium for different applications, it has some drawbacks as well. Infrared may suffer from blocking from persons and objects, resulting in problems on the communication link. Generally, optical wireless systems operate in noisy indoor environments due to incandescent, fluorescent lighting or sunlight that contribute to the noise in the detector. In infrared systems the transmitted power level is limited due to eye safety considerations, and this implies that the range of the system is restricted as well. Table 1 shows a comparison of the infrared and radio medium characteristics for indoor applications.

It is possible to conclude that radio and infrared technologies can operate in a complementary way, but one may be preferred over the other depending on the application. Radio is the most convenient medium when transmission over long ranges and high mobility are necessary, and infrared media is favoured in short-range applications where high “per-link” bitrate is required.

System Configurations

The different kinds of links for indoor optical wireless communications have been classified, depending on the existence of a line-of-sight (LOS) path between the transmitter and the receiver, and the degree of directionality (directed, non-directed or hybrid) [4][5]. The six basic configurations are shown in Fig. 1.

![Fig. 1 Configurations of infrared links](image)

LOS link systems improve power efficiency and minimise multipath distortion. Non-LOS links, on the other hand, increase link robustness as they allow the system to operate even when obstacles are placed between the transmitter and receiver, and alignment is not required.

Directed links also improve power efficiency as the path loss is minimised, but this kinds of systems need alignment of the transmitter, the receiver, or both, making them less convenient to use for certain applications.

Directed-LOS link systems improve power efficiency because the transmitted power is concentrated into a narrow optical beam, making possible the use of narrower field-of-view (FOV) receivers, and an improved link budget. Also, this kind of system does not
suffer from multipath distortion, and a predetermined maximum transmission distance can always be assured for a given optical power, independently of the reflective properties or the shape of the room, as far as the line of sight is not interrupted. Thus, the drawback of this configuration is that it is susceptible to blocking, and it requires aiming of the transmitter or receiver. A special case of this topology is the tracked system. This configuration presents the advantages of maximum power efficiency, and high coverage.

Hybrid-non-LOS systems do not present the blocking problem, but suffer from multipath distortion that increases as the area is increased.

One of the most attractive configurations is the nondirected-non-LOS, or diffuse. Systems working under this configuration do not require a direct line of sight, or alignment, between the optical transmitter and the receiver because the optical waves are spread as uniformly as possible in the room by making use of the reflective properties of the walls and the ceiling. This kind of link has the advantage that it can operate even when barriers are placed between the transmitter and the receiver. This makes it the most robust and flexible configuration. In spite of the advantages of the diffuse configuration, this kind of system suffers from multipath dispersion and higher optical losses than LOS and hybrid-LOS.

Current Infrared Communication Systems

Since the use of infrared radiation was proposed to achieve optical wireless communication, many manufacturers have developed different systems to communicate within indoor and outdoor environments.

Most of the manufacturers of indoor infrared systems nowadays base their designs on the directed-LOS and hybrid-LOS configurations, being these the topologies that allow higher bit rates (sometimes above 100 Mb/s), as they are free from multipath distortion. Besides, this systems can be developed at very low costs because the receivers are simple and consume little power. This is a very important consideration, taking into account that this kind of system cannot recover its cost by call tariffs.

Different manufacturers have taken advantage of the properties of Directed and LOS links, making the Directed-LOS configuration one of the most popular currently. An example of this kind of system is the FiRLAN point-to-point system manufactured by A.T. Schindler Communications Inc [6]. Directed and non-directed-LOS systems typically transmit

<table>
<thead>
<tr>
<th>Date</th>
<th>Organisation</th>
<th>Configuration</th>
<th>Bit rate</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>IBM</td>
<td>Diffuse</td>
<td>64 - 125 kb/s</td>
<td>100 mW, 950 nm, BPSK [1][2]</td>
</tr>
<tr>
<td>1983</td>
<td>Fujitsu</td>
<td>LOS</td>
<td>19.2 kb/s</td>
<td>15 mW, 880 nm, FSK [26]</td>
</tr>
<tr>
<td>1985</td>
<td>Hitachi</td>
<td>Hybrid</td>
<td>0.25 - 1 Mb/s</td>
<td>300 mW, FSK [27]</td>
</tr>
<tr>
<td>1985</td>
<td>Fujitsu</td>
<td>Hybrid</td>
<td>48 kb/s</td>
<td>880 nm, BPSK [13]</td>
</tr>
<tr>
<td>1985</td>
<td>HP Labs</td>
<td>Directed LOS</td>
<td>1 Mb/s</td>
<td>165 mW, 880 nm [28]</td>
</tr>
<tr>
<td>1986</td>
<td>Motorola</td>
<td>Wide LOS</td>
<td>50 kb/s</td>
<td>16 mW, 950 nm, RZ OOK [29]</td>
</tr>
<tr>
<td>1987</td>
<td>Bell Labs</td>
<td>Directed LOS</td>
<td>45 Mb/s</td>
<td>1 mW, 800 nm, OOK [14]</td>
</tr>
<tr>
<td>1988</td>
<td>Matsushita</td>
<td>Hybrid</td>
<td>19.2 kb/s</td>
<td>880 nm, FSK [30]</td>
</tr>
<tr>
<td>1992</td>
<td>MPR Teletech Ltd</td>
<td>non-Directed</td>
<td>230.4 kb/s</td>
<td>DPSK, 800/950 nm [31]</td>
</tr>
<tr>
<td>1993</td>
<td>BT Labs</td>
<td>Cellular</td>
<td>50 Mb/s</td>
<td>[23]</td>
</tr>
<tr>
<td>1994</td>
<td>Berkeley</td>
<td>Diffuse</td>
<td>50 Mb/s</td>
<td>475 mW, 806 nm, OOK [32]</td>
</tr>
<tr>
<td>1994</td>
<td>BT Labs</td>
<td>Cellular</td>
<td>155 Mb/s</td>
<td>40 mW</td>
</tr>
</tbody>
</table>

Table 2. Chronology of indoor optical wireless communication research

using just one LED, which emits an average power of several tens of mW at wavelengths between 850 and 950 nm, to optimise performance for the responsivity peak of p-i-n photodiodes at these wavelengths. This kind of transmitter usually has a FOV of 15 - 30°. Hybrid-LOS systems use hemispherical concentrators to maintain a wide FOV (about 60°) and to concentrate the received light. Hybrid-LOS links present higher coverage areas than the LOS, but the power efficiency is reduced and they suffer blocking problems. A good example of this kind of configuration (Hybrid-LOS links) is the ViPSLAN-10 system manufactured by JVC [7]. Directed-LOS links use an optical concentrator that allows a narrower FOV, but provides a higher degree of concentration. There are also some systems based on the diffuse configuration. A natural application for this kind of system may be a group of mobile, hand-held terminals within a room with access to a host computer via a base station located in the ceiling. The Spectrix Corporation has produced a system called SpectrixLite™ [8] that works under the diffuse configuration. This employs arrays of LEDs oriented in different directions, to provide diversity of propagation.
paths. The operation wavelengths of this system are typically 850 and 900 nm, and the transmitted power is in the range of 100 - 500 mW.

Diffuse systems can employ one or several silicon p-n detectors orientated in different directions to achieve a wider FOV. These detectors are, in most cases, encapsulated in hemispherical lenses, which allow a wide FOV and provide high concentration. A typical application for optical communication is an infrared wireless LAN. This wireless LAN can provide service in different environments and it can operate under different configurations. In diffuse systems, several mobile terminals are clustered in a room, and connected to a satellite (transceiver) via a duplex infrared link. The satellite is installed in the ceiling at the centre of the room and it uses an array of LEDs and photodetectors to provide transmission and reception. The mobile transceiver terminals can have one or several LEDs to transmit to the satellite, and one or more photodetectors. The satellite may be connected to a server via a fiber optic backbone that is shared with other satellites in different rooms.

For high speed optical wireless applications the receiver must have good sensitivity to get a maximum power margin. It must also have wide bandwidth and large dynamic range to be able to receive the different power level present in indoor environments.

Even when imaging and non-imaging concentrators have been used to increase the effective area of the photodetectors, large area photodetectors are still needed to maximise the power budget of the system. These photodetectors have the problem that they present a high capacitance at the input of the receiver that requires a positive feedback circuit technique to make possible an appropriate bandwidth and avoid the decrease of the sensitivity. Table 2 shows the chronology of published indoor optical wireless communication research.

**Transmitter options**

The two more commonly used sources for IR transmitters are: light emitting diodes (LEDs) and laser diodes (LDs). LEDs are usually cheaper and harder to damage than laser diodes, what makes them the preferred choice for different manufacturers. Also, LEDs achieve higher power capability. Laser diodes, on the other hand, can be used at higher modulation rates than LEDs.

As explained before, operation of these devices is in the near-infrared region, utilising the wavelengths of relevance of 850 nm, 950 nm, 1300 nm, 1480 nm and 1550 nm, where suitable devices are commonly available. The closer to the visible part of the spectrum, the safer that the wavelengths are.

**Receiver options**

The two more common detector types for the different configurations are: PIN diodes and avalanche photodiodes. The PIN detector is preferred in most of the systems, because of its low-bias-voltage requirement and its tolerance to temperature fluctuations. However, PIN detectors are about 10 to 15 dB less sensitive than avalanche photodiodes [14],[15].

Avalanche photodiodes, on the other hand, provide a more robust communication link due to their increased power margin. This reduces the problem of accurate alignment of lenses and allows for reduction of preamplifier noise, laser power and miscellaneous losses.

**Concentrators**

Optical concentrators are used to improve the collection efficiency of the receptors by transforming light rays incident over a large area into a set of rays that emerge from a smaller area [18]. This implies that smaller photodiodes can be used, which decreases the capacitance, the cost, and improves receiver sensitivity. A further advantage is that the transmitted power level can be decreased, which avoids the problems related to optical safety considerations and reduces power consumption. One of the most widely used concentrators is a truncated spherical lens, but different kind of concentrators such as the compound parabolic, have also been investigated [25].

**Data transmission limitations**

There are basically three factors that limit the data transmission rate in indoor optical wireless systems: ambient light, multipath distortion, and LED transient time.

In most of the indoor communication systems environments, the receiver photodiode is not just exposed to the infrared radiation of the transmitter, but also to ambient light from lamps. These lamps have a fraction of light in the infrared part of the spectrum, which introduces noise in the receiver. There are basically three sources of ambient light present in indoor environments, and these are: fluorescent lamps, incandescent lamps and daylight. Fig. 2 shows the spectral power densities of these light sources [2].
Fluorescent light has just a small amount of infrared radiation, but daylight and incandescent light present a higher amount of infrared radiation, tungsten being the worst source. Fluorescent light has a low power density at the wavelengths used by photodetectors. Most of the offices and indoor environments where optical systems are employed use fluorescent light instead of incandescent light, but the light emitted by a fluorescent lamps flickers on and off at the line frequency and causes spectral lines in the resulting photodetector current at multiples of the line frequency. This can be seen in fig. 3 [16]. The interference generated from these spectral lines can be avoided by modulating the transmitted signal.

![Fig. 3](image)

**Fig. 3.** Measured power spectrum at output of photodetector in the presence of fluorescent lights [16].

Daylight may be a problem just when terminals operate near windows, and it can be suppressed by using a with a silicon photodiode they perform jointly as a bandpass filter. Figure 4 shows the spectral sensitivity of a silicon photodiode and the transmittance of two infrared filters [2]. Band pass filters are the other option to reduce ambient light in optical receivers. As this type of filter greatly depends on the receiver incident angle, it must be used with an adequate concentrator to be suitable for diffuse systems. Band pass filters are constructed of superposed dielectric slabs, and can achieve narrow optical bandwidths. Another problem with infrared systems is the high noise level generated by fluorescent lighting during switch on. The effects of this noise source can be minimised using subcarrier modulation, or by using a narrowband optical filter before the photodetector that allows just the infrared frequencies used by the transmitter to hit the detector. This kind of filters, however, have a narrow field of view, what makes them inappropriate for diffuse configurations. The effect of the three sources of light can be considerably reduced by restricting the field of view of the receiver and by using optical filters before detection by the photodiode. These filters can be either bandpass or longpass. Long pass filters are the most commonly used in commercial infrared systems, as their transmission characteristics are greatly independent of the angle of incidence. Basically, these kind of filters restrict the passage of light before the cutoff frequency, and, when combined with a data coding scheme with a suppressed spectrum at low frequencies. Another important factor that limits the transmission speed in some IR links is multipath dispersion. When a system is used in indoor environments, the optical signal bounces from different reflectors to travel from the transmitter to the receiver, suffering from temporal dispersion, which leads to multipath fading. This effect, when viewed in the time domain, shows that the optical channel spreads the transmitted signal and leads to ISI. Thus, the configuration that suffers more from this effect is the diffuse, because the large beamwidth will result in more light reflected from the different reflectors. It has been shown that, for diffuse systems, the
maximum transmission speed is 260 Mbit/s for a typical room size of 10 m x 10 m x 3 m [2]. One more limitation to the data transmission rate is due to the rise and fall times of light emitting diodes.

**Eye safety**

For many indoor optical wireless applications, eye safety is probably the most important restriction for the emitted power level of the sources. Infrared radiation can damage the retina and the cornea of the eye when used inappropriately. The damage produced by an infrared source will depend on the exposure time, the wavelength, and the power of the signal. The limits of the output power levels of the lasers are set by the International Electrotechnical Commission (IEC) [9], which describes the allowable exposure limits (AEL). This AEL ensures that the system is safe under all circumstances of use and it does not require warning labels. The limits are a function of the size of the optical sources, the wavelength of the optical signal and the viewing time. The sources are classified depending on if the eye can focus the source (point source), or if the source form an extended image on the retina (extended or large area sources).

<table>
<thead>
<tr>
<th>Class</th>
<th>850 nm</th>
<th>1310 nm</th>
<th>1380 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>&lt; 10 mW</td>
<td>&lt; 8.8 mW</td>
<td>&lt; 0.2 mW</td>
</tr>
<tr>
<td>Class 2</td>
<td>Only applies to visible sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 3A</td>
<td>10 - 50 mW</td>
<td>8.8 - 45 mW</td>
<td>1.5 - 5 mW</td>
</tr>
<tr>
<td>Class 3B</td>
<td>50 - 300 mW</td>
<td>45 - 300 mW</td>
<td>5 - 500 mW</td>
</tr>
</tbody>
</table>

**Table 2. Safety classification for a laser source**

optical source for indoor wireless systems. Also, an array of LEDs may be used as the optical source to increase the transmitted power level.

A way to reduce the danger of damage in the retina is to use a diffusing screen placed after the laser, to change the point into a large area source. A very important contribution to overcome the problem of eye safety for laser sources is the hologram [10]. It breaks up the optical beam, thus diffusing the image of the laser spot on the retina. Another advantage of the use of holograms is that they give the system designer control over the shape of the transmitted optical beams, what is not possible with diffusing screens. Thus, transmitters using holograms achieve high optical power, control and safe distribution. Fig. 5 shows hologram cells with their far field distributions [18].

**Fig.5 Hologram cells with far-field distribution below [18]**

In 1993 an international organisation called the IrDA (Infrared Data Association) [11] was created to provide standards for the software and hardware used in infrared communication links. This organisation has over 160 members drawn from major software, hardware, components, peripherals, systems, and communication manufacturers, automobile and service providers, and telephone and cable companies.

The first standards of the IrDA were released in 1993 and 1994. The IrDA Data protocols consist of a set of mandatory and a set of optional protocols. The mandatory protocols are: PHY (Physical Signalling Layer), IrLAP (Link Access Protocol) and IrLMP (Link Management Protocol and Information Access Service (IAS)).
The idea of the IrDA standards is to provide interoperability between low cost and low power devices of all types. The IrDA standard defines the following parameters for the Physical IrDA Data Signalling: very short range (theoretically from 0 to 1 m), data rates from 128 kb/s to 4 Mb/s, 30° cone from the transmitter that equates to a 50 cm beam diameter at the receiver FOV, and very wide receiver FOV.

Conclusions

It is possible to conclude that, in spite of the advances achieved so far, there is still a lot of work to be done to exploit completely the advantages and the potential offered by the optical medium.

For indoor wireless system applications, the use of optical communications offers an important alternative for the growing area of mobile computers and communications. Thus, techniques to improve the operation and speeds of infrared wireless systems within room environments have still to be found, while trying to decrease the cost of the systems as much as possible. Researchers and manufacturers are also trying to find ways to improve the data bit rates and the range offered by current systems. That is why much effort has been spent on trying to reduce the problems associated with multipath distortion, improving the electronic components involved in the systems to achieve higher SNRs, reducing their power consumption, and optimising the coverage of the systems.

References