Challenges In Outdoor and Indoor Optical Wireless Communications

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Abstract

Optical wireless communications in the outdoor is capable of providing a broadband last mile access, and in the indoor environment it can be used to provide flexible interconnection through wireless distributed data communication systems to connect PCs, digital assistants, laptops, printers, digital cameras in offices, shopping areas, warehouses and manufacturing floors. Optical wireless communications, however, faces many challenges in its implementation because of high loss in the outdoor environment due to adverse weather conditions, maintaining line of sight link due to sway and vibration in the building, and eye safety and multipath effect in the indoor environment. Many solutions have been presented to overcome these challenges. This paper will review these challenges and discuss solutions for indoor and outdoor environments. A hybrid optical wireless/ RF link to overcome the effect of adverse weather conditions and improve link availability will also be discussed.

Keywords: Optical wireless communications, infrared communications, free space optics, hybrid FSO/RF communications

1.0 Introduction

Optical wireless communications is becoming an attractive alternative medium to optical fiber, and radio frequency (RF) communications, because of its high bandwidth, low cost, ease of implementation, license free spectrum and freedom from interference. The use of dedicated optical fiber to connect buildings in the outdoor environment involves trenching, laying fiber optic cables, securing rights of way and meeting environmental regulations. Radio frequency communications in the licensed band can provide higher capacity but spectrum licenses are expensive while RF in the unlicensed band is limited in bandwidth. Both RF technologies are relatively expensive, difficult to implement and suffers from interference from the existing RF systems. The indoor optical wireless systems uses light sources and photo-detectors which are cheaper than RF or wire-line systems, easy to implement, and free from interference from the other parts of the building. As the infrared does not pass through walls, it makes it easier to make cell-based secure networks by reusing the same wavelength in different rooms of an office building. The bandwidth of the optical wireless (optical beam) is about 10,000 times higher than the highest frequencies used by RF technology. Furthermore, more than 1000 independent data channels can be grouped into the air on a single optical beam using wavelength division multiplexing (WDM) thus providing a potential bandwidth ten million times that of any RF solution. Optical wireless will be the preferred medium of choice in both network and cellular, as user density and individual bandwidth needs increase as well as in new emergency situations created as a result of natural and man made disasters [1,2,3].

Outdoor optical wireless communications originally developed more than 30 years by the military and NASA, can be divided into long-range free space links and short-range links. The Long range free space links for networking a constellation of satellites or to relay the data rates up to G bits /sec has been investigated by the government agencies for decades. The current market is emerging mainly in the area of intersatellite links. The short-range links are used as a last or first mile access by bringing broadband to home as well as a high bandwidth bridge between the LANs, MANs and WANs. Most of the short-range links for connecting LANs between the high- rise buildings in the metropolitan area are commercially available for a distance of about 1 Km [1,4,5].

The outdoor optical wireless systems must transmit sufficient power to make the system available most of the time in the presence of adverse weather conditions without exceeding eye-safe limit. This requirement is further motivated by the need to preserve carrier class availability of 99.999%, because of signal attenuation in the outdoor optical link due to heavy fog, snow and smoke. A practical solution to this problem has been proposed [13, 30,31,32,33] by making use of a hybrid system where an RF link acts as a backup to the free space optical wireless system. Such a system is called a hybrid free space optics/radio frequency (FSO/RF) that employs a laser and a radio in tandem to obtain higher availability of communication link.

Indoor optical wireless communication was first proposed by Gfeller and Bapst [6], in 1979, and currently its applications have penetrated homes, offices and warehouses ranging from TV control to IrDA ports on portable electronic devices such as mobile phones, digital cameras, personal digital assistants and laptops. The current worldwide installed base of IrDA ports is over 200 million units, and is growing with an annual rate of 40%. In 1993 the Infrared Data Association (IrDA) established a standard [7] to create and promote interoperable low-cost IR data interconnection that support point- and shoot applications in ad-hoc mode. IrDA based standard uses diffuse optical communication link to overcome the limiting factors of shadowing and misalignment, which can disrupt communications. Diffused infrared LANs rely on wide field of view (FOV) emitted radiation being diffused from reflections from walls and ceilings. IrDA has produced standards for 115.2 k bits/sec and 4 M bits/sec and 16 M bits/sec. In April 1997, Hewlett-Packard Inc and IBM Corporation collaborated on a new IR standard [8], called Advanced Infrared (AIR) to incorporate provision of multiple-access use of IR medium missing in the earlier IrDa standard. IrDA devices communicate using infrared LED's at a wavelength of 875 nm +-30 nm. Infrared LANs use IEEE 802.11 standard at 780-950nm wavelengths, and a bit rate of 1 or 2Mbps. As the diffuse system architecture supports one to many, many to one communications, it can also be used in the establishment of ad-hoc- and local area networks [9].

In diffused indoor systems, light scatters off walls and ceilings creating multiple paths from the sources to the receiver. This mode of indoor communication lowers the power of the received signal due to absorption by the diffusing surface and reduces the data rate of the system. To overcome power limitations a Multi-Spot Diffusing (MSD) method is proposed which makes use of multiple directive diffusing spots from one or more transmitters and is easy to align [10,11,12].

Use of white light produced from light emitting diodes has recently been suggested as light sources for indoor wireless communications [13]. Kavehrad and Amirshahi [14] have shown that coupling white LEDs to low voltage power grids can deliver secure data in the indoor up to gigabit.

Despite the many advantages of optical wireless communications over the optical fiber and RF communication, there are challenges to overcome in order to fully implement such systems. This paper reviews some of the challenges and discusses their solutions. Section 2 discusses the challenges and the solutions of implementing short range outdoor links including wavelet diversity strategy approach to help optical wireless signals penetrate clouds, fog and other adverse weather conditions. Section 3 discusses the challenges and solutions of indoor diffused links and review multispot diffusing technique to combat some of the challenges. It also discusses an optimization technique based on annealing algorithm to improve system performance. Section 4 discusses the hybrid FSO/RF link for higher link availability and section 5 concludes the paper.

2.0 Challenges of Outdoor links

One of the main challenges of implementing outdoor short-range optical wireless links is the atmospheric attenuation caused due to absorption, scattering and shimmer of the optical signals in the atmosphere. Absorption of optical signals takes place due to the presence of water particles and carbon dioxide. Scattering in the presence of fog and haze, as well as rain and snow allows a portion of light traveling from a source to deflect away from the intended receiver. The nature of scattering depends on the wavelength of the optical signal used and the size of scattering element such as fog, rain or dust particles. Shimmer is caused by a combination of factors including light refraction, atmospheric turbulence, air density cloud cover and wind [15]. According to one estimate [16] the attenuation of optical beams as high as 300 dB/Km in heavy fog has been observed in some locations in the world. Several approaches as given below have been suggested to overcome these problems.

2.1 Adverse Weather Conditions and Scattering

As the transmitting conditions of optical wireless channel in the adverse weather conditions like channel availability and bandwidth are randomly time varying, its transmission requires a strategy where data to be transmitted can be found at different frequency bands, in order to allow for an efficient reception. In this case it is not required for the transmitter to change the transmission configuration, while the receiver makes the necessary changes to cope with the channel variations. Fractal modulation [17] has been used for signal transmission over time-varying channels where the spectral efficiency is kept constant over a broad range of rate-bandwidth ratios using a fixed transmitter configuration. This is achieved by embedding data in a homogeneous signal, which is a wavelet. Kavehrad et al [18] used this approach based on wavelet diversity strategy to help optical wireless signals penetrate clouds, fog and other adverse weather conditions. It employs multi-rate, ultra –short laser pulses with waveforms like dolphin chirps. The data to be transmitted is embedded in the optical ultra-short pulses, which are shaped like wavelets by using fractal modulation. The wavelets are generated and separated by holographic techniques and are transmitted at various rates [19].

Kedar and Arnon [20] found that the scattering effect of fog could instead be used to enhance the performance of the link. This is achieved by capturing some of the scattered light when the unscattered light is not received. As the power of the received signal depends upon the field of view of the receiver, a large FOV is obtained by using an array of detectors. In such a detector array the thermal noise produced by small detectors is much less than produced by a single larger detector having the same FOV. As a result detector array gives higher SNR and enables multi-user applications using the same hardware. The intersymbol interference produced as a result of multiple scattering can be reduced by the use of an adaptive decision equalizer. However, since the multiple scattering results into low power of the received signal, implementing adaptive decision equalizer will be challenging.

2.2 Line of Sight Alignment, Building Sway and Scintillation

Line-of-sight alignment between transmitter and receiver is another problem, which can influence the light traveling between the transceivers mounted on the buildings and thus leading to link failure. This misalignment is caused mainly due to the influence of wind, in which the high-rise buildings may sway in the alongwind and acrosswind directions, or twist due to torsion. Thermal expansion of building frame parts and weak earthquakes are other causes of misalignment. Earthquakes cannot be predicted but the thermal expansion may have a daily cycle and seasonal characteristics. Building sway is a source of pointing error at the beam steering stage and is a random process that affects system performance [20]. Izadpanah et al [21] proposed that the misalignments between the transceivers could be tackled by using auto-beam tracking capabilities of the system and increasing the optical power of the transceiver to increase the footprint of the coverage. Kedar and Arnon [20] suggests the methods for possible solutions of mitigating building sway and include adaptive laser array transmitter and adaptive or adaptive divergence beams.

Scintillation is a small random fluctuation in the received optical signal produced as a result of heated air rising from the earth or man-made devices such as heating ducts, which create temperature variations among different air pockets. Using a larger photodiode to ensure that the signal is never lost can reduce the wavefront distortion of the received optical signal caused by scintillation. The effect of scintillation is less significant at higher frequencies and a distance less than 500 meters.

2.3 Eye Safety in the Outdoor Lin

Eye safety is a concern because the cornea is transparent from the near violet to the near infrared range of wavelengths. As a result, the radiation at a wavelength of 875 nm +-30 nm used in IrDA devices can cause thermal damage if focused onto the retina. This happens because the eye does not protect itself from damage by closing the iris or closing the eyelid as this wavelength is outside the visible range of light. Outdoor point-to-point systems generally use high power lasers in the Class 3B band in order to achieve good power budget. Therefore stringent regulations such as ANSI Z-136 and IEC 825 series have been established to ensure eye safety [22]. The prescribed safety standard by the ANSI and International regulation recommends that the systems using lasers should be located where a beam cannot be intercepted or viewed accidentally by people. In order to avoid the hazardous exposure, these systems are often located on rooftops or on high walls.

Outdoor optical wireless systems using 1550 nanometer wavelength operates at higher power than those systems operating in the 780-920 nanometer range. The 1550 nm systems are entirely eye-safe and are more resilient to adverse weather conditions. The light beamed between telescopes in these systems can penetrate through most windows, which enables service providers to eliminate the need to negotiate rights to operate units on rooftops. A window-to-window optical wireless system does not carry the additional cost associated with hardening units against bad weather.

3.0 Challenges of Indoor links

In comparison to outdoor, indoor optical wireless systems are characterized with smaller distances free from environmental degradation such as fog, rain, snow and mist. The loss in the indoor link takes place only due to free space loss. There are two indoor optical wireless transmission techniques: Direct line of sight and diffused configuration. The direct line of sight configuration requires alignment between the transmitter and receiver to establish communication by transmitting optical signals from the transmitter to the receiver without any reflection. Such a system has superior power efficiency; low multipath dispersion and lower path loss and can achieve higher transmission rates. The drawback of this configuration is that it suffers from shadowing and a concern for eye safety that limits the average transmitter power, hence affecting overall power efficiency. Diffuse configuration does not require the alignment of transmitter-receiver in which the transmitters send optical signals in a wide angle to the ceiling and arrive at the receiver after one or several reflections. Diffuse configuration as a result is robust against shadowing and easy to use allowing more mobility. The diffused system, however, suffers from higher path loss and requires higher transmitter power levels and larger size photodetecting area at the receivers. It also suffers from multipath dispersion, which occurs when the transmitted signal follows different paths due to its reflection by ceiling, walls, and other objects in its way to the receiver. The multipath propagation of diffused systems gives rise to intersymbol interference and becomes critical at higher data rate.

The source of noise in indoor optical wireless systems is ambient light, which is a combination of incandescent light, fluorescent light and sunlight making it an important issue in achieving higher signal to noise ratio at the receiver. Kahn and Barry [23] found that the intensity of direct sunlight is greater than the incandescent and fluorescent lights and sunlight produces an interfering sinusoid signal of 100 Hz containing only a few harmonics. Other challenges in designing an indoor optical wireless system include the pulse shape of the received signal, permissible transmitted power considering the concern of eye safety, shadowing effect, and background interference.

3.1 Solutions Using Multi Spot Diffusion Technique

Jivkova, Kavehrad and Pakravan [24,25] suggested the use of multibeam transmitters technique to reduce multipath dispersion, reduce the shadowing effect and increase the transmitter power without jeopardizing eye safety. This technique is based on Multi-spot diffusing (MSD), first proposed by Yun and Kavehrad [12], which is a multi input, multi output (MIMO) system that utilizes multiple narrow-beam transmitters and a multi-branch angle-diversity receiver. The function of the transmitter is to generate several diffusing spots to cover a room ceiling with a uniform distributed optical signal. The receiver consists of several narrow FOV receiving elements aimed at different directions and its goal is to ensure that at most one diffusing spot lies within each receiver branch FOV. Diffusing spots can either be created by a separate laser beam projected on the ceiling using a conventional lens or by using a holographic optical element and a single laser to generate multiple beams. Jivkova et al [24] used a multibeam transmitter and employed uniform distribution of multiple diffusion spots, which illuminated the ceiling of a whole room. Such a system improved the performance at the expense of increased complexity.

Al-Ghamdi and Elmirghani [26,27] used a simple line strip multibeam transmitter and angle diversity detectors to reduce multipath dispersion and increase in the received optical power. It uses a less complicated multibeam transmitter, which is placed on the communication floor pointing upward and a holographic diffuser on the emitter. Such a structure produces multiple narrow beams, which illuminate multiple small areas forming a lattice of diffusing spots on the ceiling.

Garfield et al [9] used multiple spatially separated non-direct, non-LOS transceivers to overcome the power limitations and increase the data rate and spectral density. This approach is based on MIMO space-time coding technique to characterize the instantaneous state of the channel during a training period by independent data. Space-time codes were first introduced by Tarokh et al [28] in 1998 as a novel means of providing transmit diversity for the multiple antenna-fading channels. The characterization of the instantaneous state of the channel with each data transfer allows the intelligent processing of multiple independent received signal components, which combat channel variations and shadowing. The authors [9] used hardware implementation and experimentation of a flexible defined wireless MIMO test bed and characterized a low mobility indoor diffused matrix channel by implementing 2x2 Alamouti-type space –time code. The communication system consists of two identical transmitter units, whose spacing is limited only by the practical considerations. Each transmitter consists of an array of 6 high-speed infrared light emitting diodes and all infrared emitting diodes send the same information. The receiver consists of two units of 3 high-speed silicon PIN photodiodes, and their separation is limited only by practical consideration.

The results of their experimentation showed the implementation of space-time coding in hardware and it was demonstrated that by increasing the levels of diversity, bit error performance could be improved. It also showed that bit error performance varies as a function of transmitter array inter-element distance and transmitter to receiver distance. MIMO techniques have the potential to improve diffuse optical links with comparable data rates as RF but with less external interference [9].

3.2 Optimization of Diffusion Pattern For Improving System Performance

In order to improve the system performance, Wong et al [29] proposed a method of optimization of the diffusing pattern by making use of a simulated annealing algorithm (SA). The simulated annealing algorithm was proposed by Kirkpatrick [30] as a means of finding a global minimum in an optimization process and used by Yao et al [31], to optimize the hologram mask to convert a point source into an extended source with the lowest cost function. A model based on conventional square grid-type designs (shown in figure 3.1), with 8 different spot patterns, and 5 different receiver FOVs were used to determine the best results of combination of spot patterns and receiver FOV. The model consisted of a lambertian diffuse pattern for the transmitter and five other grid-based designs with different separation. Each pattern used 1 W of power equally distributed into all the spots. Five FOV of values 10, 20,30,45 and 90 were used. Having found the optimum FOV, the spot pattern was optimized using simulated annealing technique to obtain the optimum distribution of spots for a target parameter.

It was shown that simulated annealing technique resulted in an improvement of 19% as compared to the simple iterative method although SA took longer time to compute. To optimize the spot pattern obtaining minimum delay spread for the five different FOVs, a 93% reduction was observed in the standard deviation of the received signal power below that of the grid design, and 87.5% reduction over the uniform illumination pattern [31].

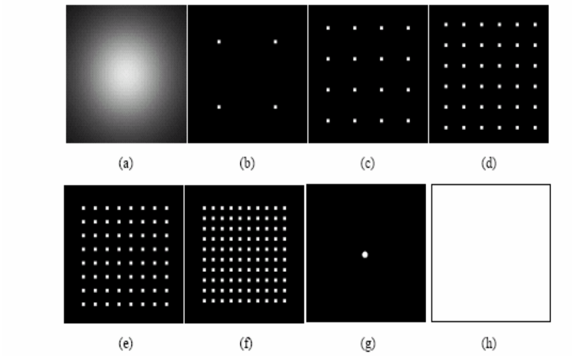

Figure 3.1 Spot patterns used in the conventional grid-type simulation (reference 27)
(a) Lambertian, (b) 2x2, (c) 4x4, (d) 6x6, (e) 8x8,(f) 10x10,(g) single point,(h) Uniform illumination

3.3 Eye Safety in the Indoor Link

For eye safety an acceptable power from point source according to International Electrotechnical Commission (IEC) must emit around 0.24 mW at 850 nm wavelengths (class 1M lasers). However, in an indoor optical wireless link a practical receiver design requires about 30 dbm of incident optical power, which translates to an individual light source (a laser) that emit approximately 10mW. Such a source power is far greater than the class 1 acceptable emission limit for a point source. Work has been done to devise holographic diffuser that would disperse power from a high power point source like a laser over a large area to enable eye-safe transmission for optical wireless networking.

Yao et al [29] created a holographic diffuser using a computer generated hologram. A computer-generated hologram does not require a physical template but uses a mathematical description using the Fraunhofer approximation. A computer based iterative process termed as simulated annealing first designs a desired holographic image. The image is then displayed on a spatial light modulator and its pattern is obtained on quartz by the illumination of HeNe laser. This quartz holographic diffuser is used in an optical setup along with a collimating lens and Fourier lens to diffuse the light in wireless networking. Such a diffuser can expand the size of the laser beam 10 times and spread the radiation pattern uniformly over an area of approximately 4x5 meter at a distance of 2 meter. This setup makes the high power laser safer to use as it reduces the power below 0.35 m W.

4.0 Hybrid Free Space/Radio Frequency (FSO/RF) links

Outdoor optical wireless communication has become a viable option to short- haul fiber link for distances of 4 Km or less and an alternative technology to last mile access. However the atmospheric attenuation of optical signals and unpredictability of weather conditions limits the distance and affects link availability. The link availability requirement for enterprise systems is generally greater than 99% and for carrier class it is considered to be 99.999%. To obtain such link availability a hybrid FSO/RF link can be used where RF link serves as a low-bandwidth backup to the primary optical link and can provide a carrier grade wireless system capable of ranges greater than 1 Km in all weather conditions [32].

Kim and Korevar [32] studied the distance limitation of FSO systems for both carrier and enterprise applications and showed that carrier – class availability can be achieved for much longer link distances if the free space optics link is combined with a radio frequency backup.

Akbulut et al [15] developed an experimental hybrid FSO/RF communication system shown in figure 4.1, between the two of five campuses of Ankra University located at different locations in the city. The optical link provided a 155 Mb/sec full duplex connection by using a laser source at 1550 nm up to 2.9 Km range. An unlicensed RF link in the ISM was used at 2.4 GHz linking the two terminals at 11 Mbps.

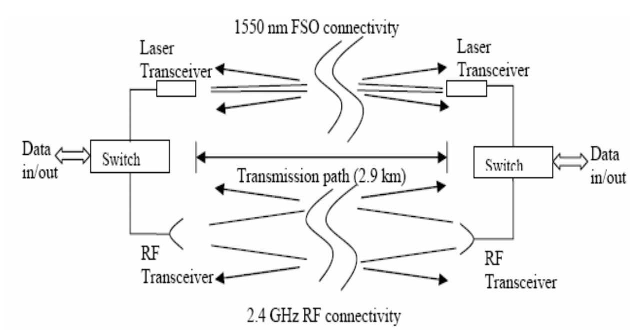

Figure 4.1 An Experimental FSO/RF link (ref. 15)

Izadpanah [33] reported design concept of broadband access utilizing millimeter wave and optical wireless high speed links to provide last mile access and networking solution to internet users in densely populated areas with homes and businesses. This approach is based on the combined and complimentary aspects of RF/microwave/millimeter-wave as well as free optical wireless links for integrated network operation.

Derenick et al [34] introduced FSO/RF mobile ad-hoc networks (MANET) for mobile robots, which can be deployed for disaster relief to provide carrier grade patches to metropolitan area network. The authors [32] also presented link acquisition and routing protocols by developing FSO/RF mobile area networks. The feasibility of link acquisition was established by deploying FSO link dynamically using a hierarchical vision/FSO based link system up to distances of about 45 meters [35].

5.0 Conclusion

Optical wireless communication is becoming an attractive alternate technology to optical fiber and RF communications for certain applications such as the last mile access in the outdoor and indoor connectivity of various computing and mobile devices in our homes and businesses. The challenges and problems for implementing indoor and outdoor short-range optical wireless links have been discussed. It shows new solutions to combat the problems of adverse weather in the outdoors links and ambient light and multipath effect in the indoor optical wireless links. New approaches based on wavelet diversity strategy to help optical wireless signals penetrate clouds, fog and other adverse weather conditions employing multi-rate, ultra –short laser pulses with waveforms like dolphin chirps have been studied. Multispot diffuse technique to reduce multipath dispersion, and the shadowing effect and increase the transmitter power without jeopardizing eye safety and optimization of diffusion pattern is also discussed. Finally a hybrid FSO/RF link is shown to provide carrier grade link availability capable of ranges greater than 1 Km in all weather conditions.

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