Wireless Optical Communications: A Survey

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ABSTRACT

The demand for wireless broadband communications has been growing steadily for last several years. The congestion and the limitations on bandwidths of the radio spectrum have inhibited unrestricted growth of radio wireless systems. Wireless optical, however, holds the promise of delivering data rates that can meet the broadband requirements. As a result, wireless optical is believed to be a viable long term option for many applications of wireless communications. Nevertheless, the advantages of optical wireless have not yet been fully exploited. Basic and applied research is needed at the laboratory and commercial levels to bring the performance of real-life wireless optical systems into higher levels. The Gb/s level data rate has been validated in laboratory, however, available indoor systems only realize a data rate of 155Mb/s. Current research in wireless optical concentrates on increasing the communication capacity and improving the performance. In this paper, we survey the wireless optical discipline emphasizing major design, performance, and safety issues. Research directions that have the potential to close the gap between theory and practice, in wireless optical communications, are also presented.

KEYWORDS
Wireless Systems, Wireless Optical Communications, Infrared Systems, RF Systems.

I. Introduction

Over the last two decades, wireless communications have gained enormous popularity. Wireless offers an attractive option for many personal as well as organizational communication needs because of flexibility, cost effectiveness, and mobility. Consider, for example, communication needs of a large company; it is estimated that 30 percent of LAN nodes are reallocated every year [1]. Wireless communication minimizes the cost of cabling and offers flexible installation leading to simpler network infrastructure. It requires fewer constraints on workplace architecture simplifying floor planning. Availability of ready installation made wireless networks a suitable solution for static, dynamic as well as temporary demand. Wireless provides extensibility options to wired counterparts that have reached cabling limits. Moreover, wireless communication is naturally suitable for mobile applications. The need for wireless communications, thus, cannot be overestimated.

Two transmission techniques for wireless communications have been deployed; *Radio Frequency (RF)* and *Infrared*. The well-established industry experience in radio frequency led to quick development of RF-based wireless technologies. The RF wireless systems offer a wide range of coverage and a host of compatible devices. The popularity of RF wireless communications has experienced exponential gain during the last decade. On the other hand, the growing demand of broadband applications and congestion of RF spectrum have fueled interest in the development of the infrared option.

The use of diffused infrared radiation in wireless communications was first proposed in [2]. The then-novel idea has led to growing interest in using optical signals in free space and has inspired related research and development. The Infrared Data Association (IrDA) was an outcome of the increased interest in the infrared option [3]. IrDA was founded to establish wireless optical standards vis-a-vis to propagate development of new optical wireless technologies. As wireless optical evolved, the IEEE 802.11 IR standard for wireless LANs was a result of realizing the importance of wireless optical.

Early research in wireless optical was focused on design issues related to infrared wireless technologies [1], [4]. As a result, six different types of infrared links were proposed based on the degree of directionality and Line of Sight (LOS) between the transmitter and receiver [5], [6], [7]. The effect of infrared radiation on the human eye was recognized as a research issue of significant concern and influenced the design of safe infrared devices [4], [8]. Performance issues have also caught attention of researchers. Power budget, light interference, and receiver sensitivity are examples of such issues [9], [10], [11], [12]. Advances in performance enhancement research have led to novel techniques including hybrid diffused-LOS and hybrid infrared-radio systems [13], [14].

Wireless optical has a lot to offer. It holds the promise of increasing the data rate by many orders of magnitude that has been validated in experimental laboratory systems [15]. Optical wireless systems with a data rate comparable to RF wireless systems already have been implemented. However, real-life indoor systems that realize the Gb/s level data rate have not yet seen the light due to cost and other commercial issues [11] (i.e. outdoor systems at the Gb/s level are commercially available). In a recent guest editorial in the IEEE Communications Magazine, it is stated that the current research in wireless optical focuses on increasing the bit rate and reducing the effect of impairments [16]. This area offers enormous

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opportunities for basic and applied research and development in the near future. In addition, research and development at commercial application level is needed. The field is therefore in need for a thorough assessment of its current state. This motivates us to survey the wireless optical field emphasizing major design, performance, and safety issues. We also identify research directions that possess the potential to close the gap between theory and practice in wireless optical.

II. Wireless Optical Systems

Wireless optical transmission can be classified according to the distance between the transmitter and receiver. Accordingly, two classes of wireless optical systems called *long and short distance systems* have been recognized. Long distance systems are used for outdoor wireless optical. While, short distance systems can be applied for both outdoor and indoor environments. A long distance system usually connects receivers and transmitters that are 100's of meters apart. An outdoor system is mainly used for bridging two different networks. As a result, long distance systems must offer a high bit rate, which conventionally requires the use of high optical power sources such as laser. However, a high power laser can represent a hazard to human eyes. Accordingly, transmitters and receivers are commonly mounted on buildings roofs or in safe places where humans cannot interrupt the beams. Yet, experiments have been successful using low power sources in outdoor systems leading to eye-safe designs [17].

Indoor systems are suitable for in-office and in-home LANs. An indoor optical wireless network comprises a number of cells, every cell commonly has a base station and a group of computing hosts. The indoor cells, in this regime, are supported by a fast backbone infrastructure where a fiber optics transmission is considered a good option. Due to technical implications of infrared signals, an indoor wireless optical cell is usually confined to a single room. Indoor and outdoor wireless optical systems share many design and performance issues. However, the atmospheric effect on indoor systems is almost non-existent [17]. Outdoor systems have a big advantage over indoor systems; the ability to operate high power emitters that may present hazards to the human eyes and thus cannot be used in indoor systems. High power emitters offer tempting data rates. The indoor transmission link within a cell is classified according to the degree of directivity and the existence of a line of sight between the transmitter and the receiver [6], [7]. There are three configurations of directionality; directed, hybrid, and non-directed. A directed link requires both the transmitter and receiver to be directed. On the other hand, line of sight links either exist or do not, this leaves only two possibilities; LOS and non-LOS. The combination of the two kinds of line of sight links and the three degrees of directionality yields six different types of indoor optical links. Among the six link forms, optical telepoint, also known as Line Of Sight (LOS), and diffused systems are the most commonly used. Optical telepoint systems implement directed line of sight links, while diffused systems have non-directed links with no line of sight. Conventionally, in an optical telepoint system, a satellite source (base station) of infrared signals is mounted to the ceiling. The base station and host terminals must keep line of sight links. The base station emits relatively confined beams covering a certain area. In diffused systems, a base station is also attached to the ceiling. However, there is no line of sight or direction constraints on the alignment of the base station and the terminals. In this system, a wide angle source emits beams that are allowed to reflect off physical objects within the cell. Terminals receivers have wide angle that cover the whole plane.

In general, power efficiency improves as the degree of directionality increases and/or line of sight exists because, in both cases, the path loss is minimized [18]. Accordingly, optical telepoint systems have better power efficiency than diffused systems. LOS systems can support higher data rates than diffused systems because energy is more confined in optical telepoint systems [1]. However, optical telepoint systems are more prone to blocking as the transmitter and receiver must be able to see each other at all times. Further, maintaining precise directions for transmitter and receiver is not trivial. On the other hand, diffused systems show more resistance to blockage due to the availability of more than one path between the transmitter and receiver. Diffused systems provide wider area of coverage than optical telepoint leading to a better mobility support. Though, mutlipath impairments affect the performance of diffused systems.

III. Why Wireless Optical?

Conventionally, wireless networks were implemented as RF systems because of the already available RF technologies. Moreover, the long experience with RF systems and the features RF presents had a great impact on the accelerated propagation of these systems. RF systems offer a wide range of coverage and have the ability to penetrate most physical obstructions resulting in high immunity to blocking. However, these "nice" features evaporate as the data rate increases because line of sight becomes essential at high frequencies limiting the coverage capability of RF systems. Furthermore, expensive components must be used to operate RF systems at high frequencies. As a result, some RF-based wireless systems operate at low carrier frequencies to avoid loss of the major RF advantages. Operating at low frequencies limits the data rate. Furthermore, the heavy demand on RF wireless systems has been pushing the RF spectrum to the limit. In addition, operations of RF systems, at some frequencies, require licenses from governmental agencies such as the Federal Communications Commission (FCC) [19] (i.e. operating radio systems at 2.4GHz, 5.8GHz, and 60GHz requires no licenses.). Obtaining such licenses is subject to technical and security issues. There is no doubt that RF wireless systems will continue to serve a large share of the wireless communications market but the stipulation of broadband applications and the need for an alternative to RF that overcomes the above problems are the main motives fueling the development of infrared wireless systems.

Advantage	Discussion
1. Unregulated Spectrum	Leads to virtually unlimited use of spectrum by individual networks.
2. Huge Bandwidth	Great support for high-speed applications.
3. No Strict Laws	License-free operation.
4. Optoelectronic Technology	Leads to manufacturing inexpensive components and little power consumption.
5. Less Interference	Facilitates system design and results in a significant cost savings.
6. Fading Immunity	Results in less power loss to attenuation.
7. Reusability	Enables use of same communication equipments and wavelengths by nearby systems.
8. Confinement	Results in simpler security measures and data encryption requirements.
9. Low Power Consumption	Leads to less energy requirements and cost savings.

TABLE I
ADVANTAGES OF WIRELESS OPTICAL

Contrary to RF wireless, infrared systems require no licenses, offer unregulated spectrum, and theoretically provide unlimited bandwidth. Consequently, optical technologies have the potential to be the wireless choice of the future, knowing that the congestion of the RF spectrum and the demand for broadband applications will be ever increasing. In addition to licensing and bandwidth, wireless optical has many other advantages. Infrared systems are manufactured using inexpensive components because of the simple technology needed for optoelectronic devices. These components consume little power compared to RF systems. Mobile technologies are expected to benefit the most as manufacturing optical-wireless-ready mobile devices becomes simpler and inexpensive. Infrared signals do not interfere with relatively nearby signals of the same nature as well as radio signals facilitating system design and resulting in a significant cost savings [18]. Moreover, infrared signals are more immune to fading than radio signals resulting in less expenditure dealing with this phenomenon and less power loss to attenuation. Infrared systems offer great reusability. The same communication equipments and wavelengths of one system can be reused in another nearby system, for example systems on another floor of the same building in indoor systems. Thus, the cost can be significantly alleviated. Furthermore, infrared systems are secure by nature. The inability to penetrate physical objects limits the coverage of infrared systems to the boundaries of the room in which the system is installed. Accordingly, the security measures and data encryption needed for wireless optical systems are reduced compared to those of RF systems leading to simpler design process and less overhead. Wireless optical requires low operating power leading to cost and energy saving. The advantages of wireless optical are summarized in Table I.

Despite the fact that wireless optical systems have great potential and offer a wide range of features, yet, optical wireless has disadvantages. Infrared signals can represent a hazard to the human eye. Strict regulations have been implemented to ensure safety. The common solution to comply with the eye-safe standards is to lower the level of power used. As a result, highly sensitive receivers are required thus increasing the complexity of system design. Wireless optical also suffers from blocking especially LOS systems. It imposes a design challenge to minimize the probability of blocking by setting up more than one emitting source and/or by insuring that clear path is rarely blocked. Infrared signals are prone to interference by natural and artificial light. Such noise as sun and fluorescent lights interfere with the infrared signals at receivers, affecting the performance of the system. Diffused infrared systems insure the availability of a signal path between the transmitter and receiver by allowing signal scattering and reflecting off physical objects. As a result, more than one path may exist between the transmitter and the receiver yielding a multipath deterioration. Table II summarizes these disadvantages.

Problem	Disadvantage
1. High Launch Power	Represents eye hazard.
2. Light Interference	Negatively affects system performance.
3. Blockage	Leads to design challenges.
4. Low Power Source	Requires high sensitive receivers.
5. Signal Scattering	Results in mutlipath impairment.
6. Alignment	Leads to more operation constraints.

TABLE II
DISADVANTAGES OF WIRELESS OPTICAL

A. *Wireless Optical vs Radio Frequency*

There has been a long ongoing discussion on use of RF vs infrared as a wireless option. The theoretically visualized great potential of infrared has been validated in laboratory with promising results. A one Gb/s transmission rate using infrared has already been achieved [15]. However, currently available commercial indoor systems only offer a data rate of 155 Mb/s. RF wireless systems have a long history of support by the industry, and to certain extent RF wireless data rates are still increasing. However, RF wireless networks are believed to be non-scalable [20]. Current research favors the optical option. Yet, the data rates of commercially available indoor wireless optical systems raise the question of why use wireless optical. These issues are discussed in [11]. It is clear that commercial issues are taking a toll on the progress to bridge the gap between laboratory achievements and real-life infrared systems. The cost of delivering the promised wireless optical data rate is one of the major issues. Expensive laser systems should be used to reach the desirable level of hundreds of megabits per second. Another engineering issue is room or cell size that is adversely proportional to data rate. Achieving one Gb/s may limit the cell size to less than one meter [11]. Such a size is not physically livable, and most probably users will not trade an amenable working environment with a one-meter cell just because they can get a one Gb/s data rate. Radio wireless cells can accommodate only a few number of broadband users because of the limited available bandwidth. As a result, many cells will be required to provide broadband service to an average number of users. However, RF signals are not confined to cell boundaries. Such scenario would yield overlapped cells with all security and interference consequences, a non feasible solution. Finally, the discussion concludes that for many applications wireless optical is the choice of the future due to its enormous capacity, and that optical and radio wireless should not compete rather complement [11].

IV. Design Issues

The design process of an wireless optical system is greatly affected by the environment where the system is installed. An indoor system has different design concerns than an outdoor system. For example, mobility support is a major issue for indoor systems, while the point-to-point nature of outdoor systems diminishes the role of mobility. Yet, outdoor and indoor systems share many of the design fundamentals and constraints. For instance, at the transmitter side, achieving good power budget is a design issue for both indoor and outdoor systems. However, the implementation might differ. In an outdoor system, a laser source can offer a good power budget. While a Light Emitting Diode (LED) is the option for indoor systems because of the hazards a laser source represents for indoor environments.

The main design issue for optical transmitters is the choice of a light source. There are two types of source emitters; laser and LED. Laser sources can launch high power transmissions leading to high speed communications. However, lasers can harm the eye retina because they are point-source emitters. Lasers are not always suitable for systems where the beams can be intercepted by humans. Accordingly, laser is typically used in outdoor systems. On the other hand, LEDs are the preferred choice for indoor systems. LEDs are wide area sources when reflected on the retina the exposure occupies much wider spot than that of point-source emitters, and the result is less hazardous effect. Yet, LEDs are naturally low power sources which limits the amount of bandwidth provided. However, the launch power of LEDs can be dramatically increased using LED arrays. Moreover, LEDs are manufactured of components more resistant to damage than lasers [18].

In general, wireless optical receivers must be able to tolerate high input capacitance. The use of transimpedance in receivers design, as in fiber optic networks, is not recommended because achieving high bandwidths with this configuration results in high noise degrading system performance [17]. Accordingly, a hybrid technique combining transimpedance and bootstrapping is frequently employed in wireless optical systems. Two different types of optical detectors have been propagated; PIN and avalanche photodiodes. The decision to implement either type is a major design consideration. PIN photodiodes are preferred in most of the systems especially indoor systems. PIN photodiodes are cost effective solutions with high tolerance to temperature changes [18] and require low power to operate. Although, avalanche photodiodes are more sensitive than their PIN counterparts, a decisive issue for high performance systems [17]. More discussion on wireless optical design can be found in [4], [11], [14], [17], [18], [20], [21].

V. Performance Issues

The research community agrees on the potential that wireless optical systems have and the many advantages they offer. Nevertheless, an wireless optical system is not perfect. wireless optical systems are affected by performance impairments. For example, atmospheric loss is a natural phenomenon that wireless optical cannot avoid especially for outdoor systems, yet this kind of loss can be minimized. Also, receiver sensitivity largely affects system performance, however it is an artificial issue imposed by the use of certain detectors. Light interference is one of the most studied degradation factors of wireless optical systems.

Wireless optical receivers detect designated signals as well as other signals in the form of either noise or interference. Ambient light is the main source of such signals. There are two types of light sources; natural and artificial. The sun light represents the natural source, while fluorescent and incandescent lamps represent the artificial source. The effect of light interference on wireless optical varies according to the environment of the system. While outdoor systems are mostly affected by daylight, artificial light is dominant in indoor environments. The effect of light on optical receivers is determined by the nature of the light source. The impairment induced by daylight is commonly considered as a *shot noise* because the variation in radiance is slow and can be considered steady, while artificial sources induce both noise and interference. A characterization of the artificial interference can be found in [9].

The degree of defacement that the atmosphere has on the performance of wireless optical systems is again a function of the system environment. Outdoor systems are intuitively more prone to path loss. While indoor systems are only affected by the free space loss, outdoor systems are also exposed to atmospheric conditions such as fog and rain. Four different sources of path loss have been recognized in [17]. First, free space loss represents the portion of power lost to space. Second, clear air similarly absorbs another portion. Third, scattering and refraction are the attenuation resulting from water drops. Finally, scintillation is a scattering effect resulting from solar energy. Geometrical and pointing losses also affect the performance of wireless optical systems. In general, path loss is tolerated by refining transmission power and reception sensitivity and averaging of receiver aperture [22].

Eye safety requires indoor transmitters to comply with the regulations governing the operation of optical sources in indoor environments. As a result, the performance of indoor wireless optical systems can be degraded by the safety regulations of the launch power. Operating low power sources demands the availability of sensitive receivers that can capture weak signals. Designing highly sensitive receivers is not straightforward. Some techniques have been devoted to this issue such as those presented in [10]. Yet, the sensitivity improvement has led to a bandwidth tradeoff. More discussion on the performance of wireless optical systems can be found in [5], [9], [10], [12].

VI. Safety Issues

The development of wireless optical systems has been motivated by the promise of huge bandwidth enabling broadband applications. It is true that wireless optical systems can reach data rates never thought of in the wireless domain. Nonetheless, real-life wireless optical systems are far behind these data rates. One of the main reasons is eye safety. High launch power is needed on the transmitter side to reach promised data rates. However due to the optical radiation of wireless optical systems, launching high power can be hazardous to humans, especially the eye. Direct exposure to an optical source can harm the cornea, retina, and skin. The peril level is determined by four main factors; *source type, radiation power, signal wavelength*, and *exposure time*. Accordingly, measures controlling these factors are necessary to ensure a safe operation. Several safety standards have been established worldwide such as ANSI Z136.1 and IEC 60825-1 [23], [24]. According to IEC 60852-1, the use of laser is classified based on the Accessible Emission Limit (AEL) into different classes of hazards. Every class is assigned an operating range of wavelengths, if maintained safety is ensured. In general, four classes of hazard level have been identified. Class 1 is considered safe and therefore can be operated without specific safety measures. Class 2 radiations are in the visible spectrum and can also be operated safely unless the exposure is direct and for a long period of time. Class 3 is further classified into classes 3a and 3b. Both classes 3a and 3b represent a hazard, however Class 3a is less severe. Class 4 is very hazardous and can even harm the skin.

Point source optical transmitters are much more dangerous than their wide-area counterparts. LEDs are preferred for indoor environments because high launch powers can be achieved while the operation remains safe. Outdoor systems, on the other hand, can even use hazardous lasers as long as it cannot be interrupted by humans (i.e. Class 3b). Several techniques to use lasers in indoor environments have been proposed. Holograms are probably one of the most attractive ideas [4], [25]. In this technique, a hologram is placed in front of a laser source. The laser beam is scattered by the hologram reducing its effect on the retina. Additional discussion on the operational safety of wireless optical can be found in [4], [8], [25].

VII. Research Directions

The wireless optical community has been growing steadily. The field has matured enough to face the new challenges imposed by the fast emerging applications of wireless systems. Yet, the need for further research and development is apparent. Current research focuses on increasing the bit rate capacity and reducing the effect of distortions [16]. We believe that the advantages of wireless optical have not been fully exploited yet. In the following, we present some major research directions that can help materialize the advantages of outdoor as well as indoor wireless optical systems.

The Internet has struck its 50-million user in a period of four years [26]. This record is due, in large, to the technological advances witnessed in the last decade. The computing power and accommodated pricing of most Hi-Tech devices are major contributors along with ease of communication. A current user of the Internet enjoys the luxury of fast data, voice, and video communications. Recently, wireless access to the Internet has been realized. Advances in the telecommunications and Internet context have been steadily growing and are expected to grow for decades to come. All-IP networks can be seen in the horizon. Much research is dedicated to enable such technology. As part of All-IP networks, wireless Internet is expected to serve a huge number of the Internet users. Free space optics provide a vital solution to the wireless Internet. The high data rates, which free space optics offer, match the need to increase the communication capacity in the wireless domain of the Internet. Yet, the nature of the Internet imposes several requirements on the deployment of wireless optical. Relevant research is highly realized. Topology flexibility and appropriate communication protocols are examples of areas of interest [20], [26].

Research in wireless optical has revealed that the first mile problem is a major area of research. The provision of broadband applications has captured researchers attention for a long time. Related research has identified two parties in a broadband system; *provider and client*. *Provider* represents network and service providers; while a *client* is a user of the service. We have witnessed successful achievements at the provider side. Optical fibers with enormous capacities have been developed. In the mean time, sophisticated techniques to increase the data rate on a fiber optic network continue to be designed. As a result, providers have the technology required to provide broadband applications to the end user through fiber optic networks. On user side, slower means of communications are still in use. Basically, financial issues are preventing laying fibers to users because providers are not certain of good return on the large investment needed for building such infrastructure, approximately a thousand dollars per household [20]. Instead, users are connected to the fiber optic networks via other means such as cable, DSL, or satellite. Thus, there is a bridging problem between the fast provider and the slow user. In literature, this is known as the *first mile* or (*last mile*) problem. A good discussion on this problem can be found in [20], where wireless optical is considered a potential solution because of the high speed offered and the affordable cost of installing an wireless optical system. Every household will need a transceiver that communicates with a central node covering a group of users. This is an example of an application where the long-term choice favors wireless optical. However, there is still a need for basic research for such a system to see the life.

Another research area is communications capacity. Increasing the capacity of wireless optical networks has always been a major research area, especially for indoor systems. This is because there exists a big gap between the advancement of the technology and the availability of commercial products with state-of-the-art capabilities. Several years ago, the Gb/s capacity was achieved in laboratory. Nevertheless, no indoor commercial products are yet available. The factors behind this situation are identified as both commercial and technical issues. For instance, increasing the communication rate of an wireless optical system results in cell size limitations [11]. Accordingly, the improvement in system capacity is at the expense of cell livability; a major challenge. We believe that more attention has to be paid to this issue. Research at commercial and technical levels is expected.

The design constraints at receiver side are considered a major research area [21], in a recent publication. In this context, the limitations imposed by the detector attendant capacitance have been considered a major design constraint. It is expected that developing a system that meets these constraints, with the current design techniques, would complicate the transceiver architecture. Thus, new designs are needed to enable the development of inexpensive uncomplicated transceiver components. Lately, wireless optical has been introduced to new applications and techniques that seek a wireless high data rate, from hybrid radio-wireless optical LANs [14] to topology-flexible wireless optical links [20] through wireless optical ad hoc networks using embedded systems [27].

VIII. Conclusions

In this paper, we review the wireless optical communications field and discuss major design, performance, and safety issues. The advantages of wireless optical ensure this technology a secure place in the future. However, the real capabilities of wireless optical have not yet been delivered to end users, more research is needed to commercially reach the promised capacity of communications. Free space optics is a promising extension to the wireless Internet; the need for new addenda and modifications to the current technology fuels relevant research.Outdoor wireless optical has the potential to solve the *first mile* problem due to its high capacity and cost savings, yet there is a need for additional research to implement such systems. Attention has to be paid to the design of inexpensive and simpler receivers that meet operational constraints. Operating high launch power sources safely in indoor environments is a major challenge that can help elevate the performance of wireless optical systems. In conclusion, our survey reveals that there are five major areas of research:

1) Free space optics as a wireless Internet solution.
2) Using wireless optical as a solution to the *first mile* problem.
3) Delivering the promised communication capacity to end users in indoor environments.
4) Designing inexpensive simple receivers that meet the imposed constraints.
5) Enabling the use of high launch power sources while ensuring human safety.

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