Short-Range Optical Wireless Communications for Indoor and Interconnects Applications

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Abstract

Optical wireless communications have been widely studied during the past decade in short-range applications, such as indoor highspeed wireless networks and interconnects in data centers and high-performance computing. In this paper, recent developments in high-speed short-range optical wireless communications are reviewed, including visible light communications (VLCs), infrared indoor communication systems, and reconfigurable optical interconnects. The general architecture of indoor high-speed optical wireless communications is described, and the advantages and limitations of both visible and infrared based solutions are discussed. The concept of reconfigurable optical interconnects is presented, and key results are summarized. In addition, the challenges and potential future directions of short-range optical wireless communications are discussed.

Keywords

indoor infrared communications; optical wireless communications; reconfigurable optical interconnects; visible light communications

1 Introduction

B roadband access networks have been widely deployed, mainly using the passive optical network (PON) architecture, and high-speed connectivity has been provided to door steps of users' premises [1]. Therefore, high-speed communications within personal working/living spaces are highly demanded. The popularity and availability of high-performance portable communication devices such as smartphones and tablets has brought more demands on wireless connectivity that supports mobility than those based on wired connections.

Several technologies have been investigated to provide over gigabit-per-second wireless connections to users in indoor environments. The millimeter-wave (mm-wave) system using the 60 GHz range is a promising solution which utilizes the several GHz license-free bandwidth available [2], [3]. One advantage of 60 GHz mm-wave systems is the possibility of realizing compact integrated transceivers, including mixers, phase - lock loops, amplifiers and phased-array antennas, by using complementary metal-oxide-semiconductor (CMOS), which is the dominant technology in the semiconductor industry. However, the distribution of 60 GHz mm-wave signals to indoor scenarios is challenging, mainly due to the high free-space propagation loss and the line-of-sight propagation requirement. Typically, it is also challenging to realize broadband CMOS based mm-wave transceivers. Therefore, the license-free bandwidth available needs to be divided into several sub-bands and the data to be transmitted needs to be fit into a limited sub-band. This results in the use of comparatively complicated modulations and signal processing algorithms. Another type of widely investigated high-speed indoor wireless communication technology is the ultra-wideband (UWB) based system, which has low power spectral density (PSD) spread over a wide range of frequencies and can share the RF spectrum with other existing communication systems [4], [5]. However, there is a fundamental trade-off between the bit rate and the communication distance that can be achieved.

In addition to mm-wave and UWB systems, the optical wire-

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less technology has also been widely studied to realize highspeed indoor communications, where the optical signal propagates through the free-space directly to the subscriber side [6]– [8]. Based on the carrier wavelength, indoor optical wireless systems can be divided into two broad categories, namely visible light communication (VLC) systems and infrared systems [9], [10]. In VLC systems, LEDs are used as light sources and they can be used for illumination and data transmission simultaneously. In infrared systems, the light source is typically laser which has much broader modulation bandwidth and higher cost compared to LEDs. In this paper, both systems will be discussed.

The optical wireless technology has also been applied in another short-range scenario-board-to-board optical interconnects in data centers and for high-performance computing [11]-[13]. With the rapid development of semiconductor integrated circuits such as processors and with the increasing data-intensive applications such as high-definition video in demand, high -speed interconnects are highly needed and the use of optical interconnects have been widely studied. According to the data transmission distance, optical interconnects can be divided into chip-to-chip, board-to-board, and rack-to-rack interconnects. The silicon photonics technology has been widely used in chip-to-chip interconnects, and high-speed transmissions have been realized through silicon waveguides [14]-[17]. For rack-to-rack interconnects, single-mode optical fiber is considered to increase both transmission speed and distance [18], [19]. Several solutions based on polymer waveguides, multimode fiber ribbons and free-space optics are considered for board-to-board optical interconnects [11]-[13], [20]-[22]. Compared with other solutions to board-to-board optical interconnects, the optical wireless based scheme is capable of providing the reconfigurability and flexibility through free - space beam steering. This scheme will be discussed in this paper.

2 High-Speed Indoor Optical Wireless Communications

2.1 Typical System Architecture and Model

Indoor optical wireless communication systems are typically modeled by the architecture shown in **Fig. 1**. The data to be transmitted (in the electrical domain) is first converted to the optical domain through an electrical-optical (E-O) conversion unit, where either LEDs or lasers can be used. Then the modulated optical signal passes through an optical assembly to generate the desired beam pattern for free-space propagation. The optical assembly can be used to generate collimated beams, fully diffusive beams, partially diffusive beams, or other special patterns such as multiple beam spots [6]. Then the optical signal propagates through the free-space link before being collected at the receiver side.

Optical signals arrive at the receiver side via two possible



Figure 1. Typical model of indoor optical wireless communication systems.

links: the direct line-of-sight link and the non line-of-sight (multipath) link [23]. The multipath signal is mainly due to the reflections of physical shadowing items, such as walls, ground, ceiling, and cubicle partitions. For high-speed operations, the direct line-of-sight signals are always preferred because the multipath signals limit the channel bandwidth due to different propagation delays. However, when the direct line-of-sight link is blocked, multipath signals can be used to maintain wireless connections, although at much lower communication speed.

In addition to line - of - sight and multipath signals, background light is also collected at the receiver end. Both sunlight and illuminating lamps contribute to the collected background light. In order to reduce the impact of background light, optical bandpass filters are used at the receiver side to reject most of the out-of-band (signal band) background light. However, the in -band background light cannot be avoided and results in additional noise and performance degradation in the optical wireless communication system [24], [25].

In typical indoor optical wireless communication systems, an optical assembly is used at the receiver side for signal collection and focusing. The signal is converted back to the electrical domain by an optical-electrical (O-E) converter for further signal processing and characterization. It is desirable that the receiving optical assembly can collect large signal power with minimum multipath dispersion and background light power, and provide high optical gain to the O-E converter. In order to provide mobility to end users, a reasonable field - of - view (FOV) is also required for the receiving optical assembly. However, there is a trade-off between the FOV and the optical gain [23]. The receiver with a large FOV also collects high background light power. In addition, a large FOV may result in the collection of substantial multipath signals, limiting the system communication bandwidth [26]. To overcome this limitation, a number of advanced receiver designs have been proposed and investigated, such as angle-diversity receivers [27], imaging receivers [28], single-channel imaging receivers [29], [30], and steering - mirror assisted receivers [31], [32]. These solutions

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use different mechanisms to limit the FOV of receiving elements (or each element). They can reduce the impact of background light, improve the optical gain, and enhance the transmission channel bandwidth. However, the cost is more complicated structure and operation.

Air turbulence is another possible source of performance degradation in indoor optical wireless communications. Although the indoor channel status is typically stable, turbulence still exists due to local environmental changes such as the change of local temperature because of air-conditioners or heaters. The scintillation and beam wandering effects are negligible in indoor short - range applications due to the relatively weak turbulence and short link distance, although these effects are limiting factors in outdoor long-range optical wireless systems. Turbulence also changes the polarization status of the optical signal at the receiver side. In general, the power penalty due to polarization dependent loss in indoor optical wireless systems is minimal.

Compared with RF based wireless communication systems such as Wi-Fi, mm-wave and UWB systems, indoor optical wireless communication systems have unique advantages. First of all, almost unlimited license-free bandwidth is available in optical wireless systems, ranging from ultra-violet (UV) and visible to infrared bands (the UV band is typically not used in indoor applications). Therefore, high-speed communications can be realized without spectrum limitations. Moreover, optical wireless systems are immune to electromagnetic interferences (EMIs). As a result, the optical wireless technology can be used in RF hostile environments, such as in hospitals or on aircrafts.

According to the link configuration, indoor optical wireless communication systems can be divided into two categories, namely directed systems and diffusive systems [23], as shown in **Fig. 2a** and **Fig. 2b**. In directed systems, a narrow signal beam is used to establish a point - to - point link between the transmitter and the receiver. Such a system has minimum multipath dispersion and can achieve high data transmission rate. In addition, the energy efficiency is high as well. However, strict alignment between transceivers is required in the directed system, which limits the mobility of end users. In diffusive systems, the entire room is covered by diffusive signal beams to provide full mobility to end users. However, the severe multipath dispersion limits the communication bandwidth and the energy efficiency is low. Therefore, hybrid partial diffusive systems (**Fig. 3c**) have been proposed and demonstrated. In a hybrid system, the partial diffusive signal beam covers the user's location and surrounding areas to realize limited mobility and simultaneously maintains broad channel bandwidth and relatively high energy efficiency [33], [34].

Special Topic

2.2 Visible Light Communications

In indoor optical wireless communication systems, the use of visible wavelength range has been widely investigated [9], [35]–[55]. VLC systems generally use the wavelength range from 380 nm to 780 nm and LEDs serve as the light source in the systems. Because LEDs are more energy efficient compared with traditional illumination lights and widely deployed as headlights, the possibility of using LEDs for data transmissions has attracted intensive research interests. Different types of LEDs have been used for data transmission and they have different modulation bandwidths, ranging from a few tens of MHz (phosphorus LEDs), to about 100 MHz (RGB LEDs), and up to a few hundreds of MHz (resonant cavity enhanced LEDs). At the receiver (user) side, a photodiode (PD) or photodiode array is typically used for signal detection.

LEDs are incoherent light sources and transmitting information can only be realized by the optical intensity change. Therefore, intensity modulation and direct detection (IM/DD) is used in VLC systems. This also implies that the signal used to modulate LEDs needs to be real-valued, non-negative, and unipolar.

LEDs in VLC systems have limited modulation bandwidth, and other techniques are therefore needed to provide high speed wireless connections to end users. A number of potential solutions have been proposed and investigated.

When the phosphor-based LED is used, a blue optical filter can be added at the receiver side to remove the yellow component that has slower frequency response, with the cost of higher link attenuation [36]. The communication speed can also be improved by using equalizations at the transmitter, receiver, or both sides [36]–[42]. The transmitter equalization is used to compensate for the LED fast roll-off frequency response, improving the modulation bandwidth. The equalization can also be applied at the receiver side to achieve higher data rates.

In addition, advanced modulation formats with better spectral efficiency can be used in VLC systems to further enhance the channel capacity [43], [44]. One widely used advanced

> modulation is the orthogonal frequency division multiplexing (OFDM). However, conventional OFDM signals are bipolar and complex, and cannot be directly applied to VLC systems with IM/DD scheme. Therefore, modifications are required, such as discrete multitone (DMT) modulation [45], [46], direct current optical OFDM (DCO - OFDM) [47], and asymmetrically clipped optical OFDM (ACO-OFDM) [48]–[50]. Another way to increase





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the VLC system speed is the Multi-Input Multi-Output (MIMO) technique. This technique uses an array of LEDs and an array of photodiodes and can realize parallel communications [51], [52].

The VLC system is an attractive option for realizing highspeed indoor wireless communications, because it is able to provide illumination and data transmission simultaneously. Several solutions to its bandwidth limit have been proposed and the achievable bit rate has been significantly enhanced to well beyond 1 Gb/s. More detailed review on VLC systems can be found in [53]–[55].

2.3 Indoor Infrared Optical Wireless Communication Systems

Indoor optical wireless communication systems also use the near-infrared bands including 850 nm, 980 nm, and 1510 nm regions. In this type of systems, the laser is used as the light source. The laser has much broader modulation bandwidth compared with the LED. Therefore, high-speed operation can be achieved even using the simplest on-off-keying (OOK) modulation format without equalizations. The vertical cavity surface emitting laser (VCSEL) is a low-cost option for the optical transmitter. However, because of the laser eye and skin safety regulations, the transmission power is generally limited.

Considerable research attention has been devoted to the diffusive indoor infrared communication systems [23], [26]–[32]. Here, high-power laser is used to cover the entire room, providing full mobility to end users. However, the inherent multipath dispersion in the system results in limited channel bandwidth. A large FOV is also typically required at the receiver side, which also collects a large amount of background light. Furthermore, the high power laser leads to safety concerns. In order to overcome these limitations, a number of advanced schemes have been studied. At the transmitter side, the multi-

spots technique has been proposed to provide better channel bandwidth, and at the receiver side, the diversity scheme has been employed for better channel impulse response and smaller collected background light [28]–[31], [56]. Adaptive power and beam spots/angular allocation mechanism based on the user location has also been investigated, with which over gigabitper - second data rates become possible [57], [58].

In the previously mentioned VLC and diffusive indoor infrared communication systems, the light sources, either LEDs or lasers, are always placed inside each room and the distribution of data to each room is challenging, especially when the data is in the electrical domain. Although optical fibers can be used for signal distribution, additional optical-electricaloptical (O-E-O) conversion unit is needed at each transmitter, which results in additional cost and control issues. In addition, complicated mechanisms, possibly advanced modulation format, MIMO, equalizations, advanced transceivers, and adaptive allocation schemes, are needed in the previously discussed systems to achieve high-speed data transmission.

To overcome these challenges, we have proposed a hybrid indoor optical wireless communication system using the near-infrared wavelength range in previous studies, and its basic architecture is shown in Fig. 3 [7], [34]. Here, a centralized architecture is utilized where a central office (CO) serves multiple rooms through the in-building fiber distribution network. All expensive components and complicated control functions are placed in the CO, so the cost and complexity can be shared by multiple rooms and users. Inside each room, the ceiling mounted fiber transmitter is used and partially diffusive optical beam is used for data transmission. The beam covers the user location and surrounding areas to provide limited mobility. The fiber transmitter mainly consists of a fiber end connected with the CO, a lens for controlling the beam divergence angle, and MEMS-based steering mirrors to change the orientation of optical signal according to the user location. After free-space propagation, the optical signal from direct line-of-sight link is collected and detected. The simplest subscriber unit is a nonimaging receiver, which consists of a non-imaging compound parabolic concentrator (CPC) and a photodiode.

In this system, the user location is required to provide limited mobility. The user tracking function is also needed to change the beam orientation and to maintain high-speed wireless connectivity. The indoor localization function has been realized by using a number of technologies, such as RF based, imaging sensor based, infrared beams based and pyro-electric sensors based systems [59]–[62]. The indoor localization function can also be realized based on the optical wireless technolo-



▲ Figure 3. Centralized architecture of the hybrid indoor infrared optical wireless communication system.

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gy, using either VLC or infrared systems. The optical wireless indoor localization is out of the scope of this paper, and more details can be found in [63]–[65].

Similar with VLC systems, the background light is also a fundamental limiting factor in hybrid indoor infrared communication systems [25]. Advanced receivers, such as the single channel imaging receiver and the steering mirrors assisted receiver, are used to reduce the impact of background light (Fig. 4) [29]–[32]. The single-channel imaging receiver mainly consists of an imaging lens for signal collection and focusing, and a small photo-sensitive area PD placed on a 2-axis actuator at the back focal plane of the lens [29], [30]. The actuator can be voice-coil based and move the PD on the focal plane to search for the focused signal spot. The receiver FOV is further limited due to the small size of PD, and this receiver is capable of rejecting most of the background light and improving the system performance. A similar concept is applied in the steering mirrors assisted receiver, where steering mirrors are used in front of the simple non-imaging receiver [31], [32]. The mirrors are steered according to the user location to reduce the incident angle of signal light into the CPC. Therefore, smaller FOV CPCs can be utilized which have higher optical gain and lower collected background light power. In addition, the steering mirrors further limit the receiver FOV for better system performance.

3 Reconfigurable Board-to-Board Optical Interconnects

Traditionally, electrical cables are used to realize board-toboard interconnects in data centers and for high performance computing. However, the electrical cables encounter a number of fundamental limitations with high-speed operations, including limited bandwidth, high transmission loss and latency, and weight and heat dissipation problems. To overcome these issues, optical interconnects based on polymer waveguides and multi-mode fiber ribbons have been proposed and investigated [20]–[22]. These proposed solutions are capable of high-speed data transmission between fixed ports/boards. However, high-



▲ Figure 4. Advanced receivers for hybrid indoor infrared optical wireless communication system.

speed O-E-O conversions are required for data re-routing to other destinations.

Special Topic

The optical wireless technology has been studied for realizing reconfigurable and flexible board-to-board optical interconnects [11]–[13], [66]–[70]. **Fig. 5** shows a typical architecture of optical wireless based interconnects. The electrical data to be transmitted first modulates optical transmitters, and lowcost VCSELs or VCSEL arrays are good choices for optical transmitters. Then the modulated optical beams pass through optical assemblies for collimation. A link selection block is then used which can dynamically change the beam orientation to different receivers according to requirements. After free space propagation, signal beams arrive at the receiver side and are collected and focused by receiving optical assemblies. Optical signals are finally converted back to the electrical domain with photodiodes or photodiode arrays.

It can be seen that the flexibility and reconfigurability in optical wireless interconnects are realized by the link selection block, which dynamically steers signal beams to different destinations in the optical domain. The link selection block has been realized by using liquid crystal on silicon or opto Very Large Scale Integrated Circuits (opto-VLSIs) [66], [67]. However, both the solutions are based on optical signal diffractions and the beam steering range is limited. Furthermore, high order diffractions need to be used for large beam steering angles, which results in considerably large signal loss. To overcome these limitations, a link selection block based on MEMS steering mirrors has been proposed and investigated [68]-[70]. MEMS mirrors have simple link reconfiguration mechanism based on signal reflections. In addition, the signal loss after passing through such the link selection block is minimal because the MEMS mirrors reflection efficiency can be high through coating. Furthermore, the large beam steering range can be easily realized with the link selection block based on MEMS steering mirrors.

Multiple wavelength channels through wavelength division multiplexing (WDM) and multiple parallel free-space channels with the same operation wavelengths are used to realize ultrahigh-speed board-to-board interconnections. Compared with the WDM solution, the solution based on multiple parallel



▲ Figure 5. Typical architecture of reconfigurable board-to-board optical interconnects based on the optical wireless technology.

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free-space channels has the advantages of lower cost and simpler operation, because precise wavelength control circuits and wavelength multiplexers/demultiplexers are not needed. Therefore, the solution based on parallel channels is typically utilized.

Based on multiple parallel channels and MEMS steering mirrors, we have proposed and experimentally demonstrated a reconfigurable board - to - board optical interconnects [68]-[70]. The proposed interconnects architecture is shown in Fig. 6. One dedicated optical interconnect module is integrated onto each electronic card, which is typically a printed circuit board (PCB). Inside the optical interconnect module, a VCSEL array serves as the light sources for optical interconnects, and each VCSEL element is directly modulated by the data to be transmitted. The generated optical beams pass through a micro-lens array for collimation before being steered by the link selection block based on MEMS steering mirrors along arbitrary directions to the destinations. After free-space propagation, the optical beams are steered with another MEMS mirror array towards corresponding receivers, which consist of a micro-lens array for optical beam focusing and a photodiode array for detection.

To further increase the data rate of optical wireless based interconnects, advanced modulation formats can be used. However, this modulation format needs to support direct modulation of VCSELs and simple signal processing for keeping the low cost and low complexity of the system. The carrierless-amplitude-phase (CAP) modulation format can satisfy these requirements and have been applied in reconfigurable free-space optical interconnects. Up to 3–40 Gb/s interconnects have been experimentally demonstrated with 16-CAP [71].

In free-space based reconfigurable board-to-board optical interconnects, moderate or even strong turbulence exists due to the heat generated by electronic components and the fans for heat dissipation. The air turbulence results in refractive index fluctuations along the optical interconnection path and leads to signal scintillation, beam wandering and beam broadening effects [72]. Experimental results show that the power penalty is about 0.5 dB with moderate turbulence and about 1.6 dB with comparatively strong turbulence [73].

4 Discussions

The application of optical wireless technology in short-range applications has attracted considerable research attention and achieved significant advances during the past years. High speed data transmissions have been demonstrated in both VLC, infrared and interconnect systems. However, there are still considerable aspects that require further innovative research efforts and some of these are discussed in this section.

4.1 Hybrid Indoor Optical Wireless Communication Systems with Multiple Users

In previous studies of hybrid high-speed indoor optical wireless communication systems with partial diffusive beams, especially systems using the infrared wavelength region as discussed in Section 2.3, typically the scenario with only one user is considered. However, in practical personal working/living spaces, multiple users may need to be connected simultaneously. Therefore, further studies on multiple users' scenarios are needed.

With safety considerations, partial diffusive beams are required and transmission power is limited. In this way, high speed wireless connectivity can only be provided to a limited area. When multiple users are located in the same area of a room that can be covered by the signal beam, providing data transmission to all users can be achieved by simply using the time-division-multiplexing (TDM) scheme. However, when the multiple users are located in different areas inside the room, providing wireless connections becomes challenging. The TDM scheme can still be used by steering the signal beam to different users at different time slots. However, the throughput is reduced significantly due to the limited MEMS mirrors steering speed (in the millisecond or tens of milliseconds scale). In addition, the use of TDM decreases the data transmission speed to each user, and the situation becomes worse when the number of users increases. Therefore, other solutions are demand-



◄ Figure 6. Architecture of proposed reconfigurable board-toboard optical interconnects with MEMS mirrors and parallel channels.

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ed and some of the possible candidates include the spatial-division-multiplexing scheme with which multiple fiber transmitters are used to connect different users or user groups, and the WDM scheme that uses different wavelengths to cover multiple users or user groups. However, detailed investigations are necessary, especially taking the cost into consideration. Furthermore, corresponding media access control (MAC) protocols need to be considered.

4.2 Dimming Requirements in VLC Systems

In VLC systems, LEDs are used for illumination and data transmission simultaneously, and typically a higher illumination level results in faster wireless connectivity. However, in practical applications, the LEDs may be preferred to be operated at a low illumination level, such as during day time where the sunlight is sufficient for illuminations. In this case, both the data transmission distance and bit rate are affected [74]–[77]. Therefore, further studies are needed using advanced techniques, such as the pulse width modulation (PWM) mechanism.

4.3 Indoor Optical Wireless Communication Systems with Physical Link Blocking

In indoor optical wireless communication systems, line-ofsight link is generally required for high-speed operations. However, in practice, the line - of - sight free - space link can be blocked, resulting in communication interruptions. Therefore, novel solutions are needed to maintain wireless data transmissions. Several schemes have been proposed and investigated, such as using the diffusive signal to maintain connectivity in case the line-of-sight link is blocked. Nevertheless, the data rate needs to be reduced significantly. Recently, we have proposed and demonstrated a space-time-coding based solution by exploiting the spatial diversity [78]. However, the system is more complicated and additional hardware is needed, leading to the cost concern. Another possibility is using the existing RF indoor communication systems, such as Wi-Fi systems, as the lower-speed backup, and switching data transmissions to the RF backup channel when the optical wireless line-of-sight link is blocked. However, the handover also requires further investigations.

4.4 Extending Optical Wireless Interconnection Range

In an optical wireless system for board-to-board interconnects, one fundamental limiting factor is the beam divergence during the free-space link propagation, which results in much larger beam size. Since high data density is required in interconnects applications, the VCSEL, PD and micro-lens arrays typically have a pitch size of a few hundred micro-meters. Therefore, after the free - space propagation, only a small amount transmitted by VCSELs can be collected by receiving micro-lenses for further signal detection, which limits the interconnection range. For larger scale applications, the interconnection range needs to be extended and this requires further studies.

Special Topic

5 Conclusions

In this paper, the basic concepts and recent developments on short-range optical wireless communication systems have been reviewed and summarized. Modulated optical beams in optical wireless systems can directly propagate through the free space towards receivers to provide wireless connectivity. The optical wireless technology has been proposed to be applied in indoor personal area communications as well as in interconnects for data centers and high-performance computing. In indoor optical wireless communication systems, both VLC and infrared systems have been widely investigated and highspeed wireless data transmissions have been demonstrated in both types of systems. In optical wireless interconnects, the freespace signal propagation has been utilized to provide link reconfiguration capability through beam steering. In addition to the exciting achievements in this area, several aspects that require further research attention have been discussed as well.

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