A Brief Survey of Optical Wireless Communication

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Abstract

Optical wireless communication (OWC) technologies have been discussed and evaluated in a wide range of application scenarios, which is drawing increasing interest to keep pace with the growth in LED technologies. OWC has unique advantages to provide safe, secure, low-cost, and high-bandwidth communications. As a compensation for the existing radio frequency communications, OWC has huge potentials to be used for distributed applications from indoor to outdoor, from atmosphere to ground and underwater. In this paper, we conduct a brief survey of the most recent advances and research activities in OWC. We study the advantages and potential applications of OWC, and provide an overview of the techniques used to achieve OWC system.Some potential future research directions for OWC are also discussed.

Keywords: Optical wireless communication, light emitting diode, infrared wireless communication, visible light communication

1 Introduction

Optical wireless communication (OWC) transmits information through optical radiations in free space. Apart from the visible light spectrum (Komine & Nakagawa 2004*b*,*a*), the wavelengths utilized in OWC include infrared (IR)(Wong & O'Farrell 2000, Kahn & Barry 1997) and ultraviolet (UV)(Xu & Sadler 2008).

Communications using the visible light spectrum are also known as visible light communication (VLC). To make use of transmitters (or sources), OWC converts the electrical signal to an optical signal, which is received by a receiver (or a detector) (see Fig. 1). Light emitting diodes (LEDs) or laser diodes (LDs) can be used as optical transmitters, and LEDs or photodiodes (PDs) are adopted as receivers. Particularly, with the development of LED technology, a key component of OWC system, for solid-state lighting covers the entire visible spectral window (380-750 nm). VLC communication has drawn an increasing number of interests for its distinct benefits (Daukantas 2014, Tsonev et al. 2013).

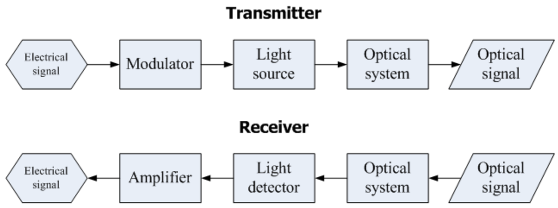

Figure 1: Basic components in a OWC system.

2 Advantages of optical wireless communication

It can be seen that radio frequency communication techniques dominate in the current wireless communications. Nevertheless, these techniques have their own limitations that can be overcome by OWC for the following reasons:

License-free operation Since the frequencies employed in OWC are different from traditional wireless communications such as sensor network, cellular communication service, Wi-Fi, etc., they are license-free and do not have any associated charges.

Unregulated huge bandwidth Point-to-point link data rates in OWC system using off-the-shelf components are continuous increased. Back in 1979, Gfeller and Bapst demonstrated the first IR system whose transmission speed is below 1 Mb/s based on a diffuse link (Gfeller & Bapst 1979). After that, an improved system operating at 50 Mb/s, is proposed by March and Khan in 1996 (Marsh & Kahn 1996). In 2000, Carruther and Kahn proposed a quasi-diffuse system achieving a data rate of 70 Mb/s (Carruther & Kahn 2000). Driven by progress in LED technology, a VLC system utilizing white LED lights is presented by Tanaka et. al., and data rate is reported up to 400 Mb/s according to the simulation experiment (Tanaka et al. 2003). Vučić et al. in 2010 reported a VLC system in which the point-to-point communication link can operate at 513 Mbit/s gross transmission rate. Data rates over 1 Gb/s in a VLC system have been shown using off-the-shelf LEDs (Khalid et al. 2012, Cossu et al. 2012, Azhar et al. 2013). Tsonev et. al. presented a VLC system based on a single 50-μm gallium nitride LED in 2014, which achieves a demonstration of wireless communication at speeds exceeding 3 Gb/s using a single LED (Tsonev et al. 2014) .

Low-cost front-ends Different form radiofrequency communication techniques, it is not necessarily using expensive RF units. As a key component for OWC, LEDs are often used as transmitters and receivers device, which is cheap, low power consumption, low heat radiation, and has small size, high brightness along with long lifetime.

Safty Radio-Frequency Interference (RFI), generated by radio waves, is known to disturbance an electrical circuit due to electromagnetic radiation or electromagnetic induction. These effects can range from a simple degradation of data to a total loss of data. Hence, potential sources of RFI including consumer electronic equipments (e.g. cell phones) are asked to turn off in airplanes and in hospitals. Furthermore, RFI has potentially dangerous in hazardous operations, such as power/nuclear generation or underground mine. In addition, the transmission power of radio waves is regulated below a certain level since there are serious health risks for human beings. By contrast, light, instead of radio waves, is used to transmit data in OWC systems, which does not create RFI. Thus, OWC systems are usually deployed in some places where traditional wireless communication is forbidden.

Security Because of the long wavelength of radio waves, they can easily penetrate walls, thus the messages transmitted by them can be intercepted and read anywhere in transit by third parties. Compared to radio waves, optical waves cannot penetrate objects in their path, and they are more likely to be reflected. Hence, OWC provides a secure data communication.

Illumination VLC systems, unlike other dispersive OWC systems, offer data transmission in addition to illumination through white-light LEDs. Making use of power line communication (PLC) technology, VLC system can use existing electrical wiring to interconnect the different white-light LED units and convey data to them. Moreover, distributed ceiling installations guarantee a dominant line-of-sight (LOS) component, tiny path loss and high data rate (Grubor et al. 2008).

3 Potential applications

Although the optical wireless communication techniques will not completely replace radio communication techniques such as the fourth-generation (4G) wireless whose peak download data rate at 100Mb/s for high-mobility and 1Gb/s for low-mobility, they tend to play a complementary role in some practical scenarios where other means of communication cannot be used for the distinguished advantages mentioned above. It has been commonly agreed that OWC technique can provide high throughput for low-mobility and short-range communication like indoor applications. Especially, VLC technology can be applied to the situations where illumination and data transmission is in joint demand to serve.

Aviation A promising scenario for OWC on airplanes is illustrated in Fig. 2. In this scenario, passengers can establish an Internet connection via reading lamps using white LEDs installed in the overhead, which can exchange data with wired base stations (BSs) in the aircraft cabin. In addition to transferring data, power of reading lamps and wired BSs are both provided by Power over Ethernet (PoE) technique likewise.

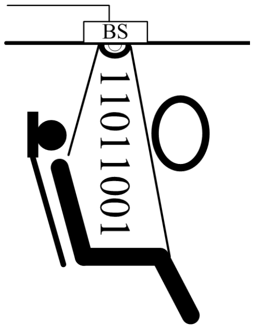

Figure 2: VLC system transmit data to passenger through reading lamp in the airplane.

Hospital In hospitals, it has been reported that various frequencies of radio waves induce strong electric field intensity, is prone to interference with electronic medical equipment, notably the respiratory and anesthesia area (Van Der Togt et al. 2008, Hanada et al. 2001, Hanada 2007). Therefore, the implement of OWC system have a lot of advantages in this area.

Real-time audio & video transmission system Because of the high data rate of OWC, OW techniques can be used to deal with the future demand of indoor wireless access to real-time bandwidth-intensive applications such as Voice over IP (VoIP), video conference, real-time video frequency monitoring, and network attached storage (NAS) (*802.11n: Next-Generation Wireless LAN Technology* 2009, He et al. 2013).

Smart traffic system As depicted in Fig. 3, in smart system, two vehicles can communicate with each other about rates and destinations of themselves to avoid traffic accidents and share traffic information which are unknown in advance. Besides, some infrastructures such as gas stations will inform their own state to passing vehicles to help them choose the right refueling locations and ensure road safety. Traffic lights and street lamps, as another examples, equipped with OWC, can both display informations using backlight and emit additional modulated information to vehicles (The NSF Smart Lighting Engineering Research Center (ERC) n.d.). Pang et. al., set up a VLC system for traffic light-based communications in 1999, and the data rate of the system is up to 128 kb/s (Pang et al. 2002). Moreover, CMOS image sensors (e.g. the camera of a Video Event Data Recorder (VEDR)) can be used to record video in a vehicle, and also locate its source (Visible Light Communications Consortium n.d.), helping to record the current position of the vehicle.

Dangerous and extreme environments In underground mine, using radio-frequency communication may cause explosion because of the transmission power. On the other hand, no wireless techniques except OWC can establish high-speed communication link underwater. Thus, OWC is a safe and high adaptability technology that provides illumination and data transmission simultaneously.

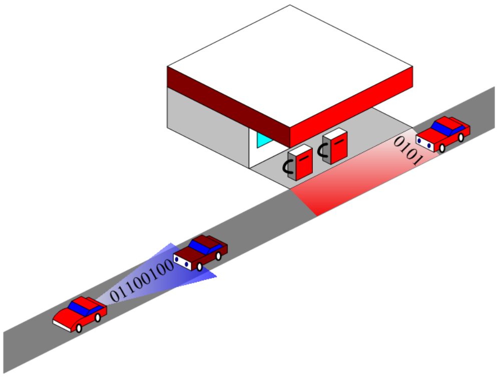

Figure 3: OWC systems exchange data between vehicles and infrastructures in Transportation.

4 The carriers of global OWC research activities

IEEE 802.15.7 Visible Light Communication Task Group
In early 2009, the task group IEEE 802.15.7 had been working on a VLC standard encompassing both new physical and medium access control layers based on a clean-slate approach. In November 2010 the P802.15.7 IEEE draft standard was published.

OMEGA, the Home Gigabit Access Project
OMEGA is an Integrated Project in the ICT area funded by the European Commission under the Seventh Research Framework Programme (FP7). The project was running between January 2008 and December 2010. The OMEGA project aimed to set a global standard for ultra broadband home area networks. The new standard will enable transmission speeds of one gigabit per second (1 Gbps) via heterogeneous communication technologies, including PLC, IR and visible light communications. PLC is used to provide a backbone within the home. SPiDCOM technologies lead the PLC work package in the OMEGA Project. A technology-independent MAC layer will be developed to control the network and provide services as well as connectivity to any number of access points in any room. Furthermore, this MAC layer will allow user to change their position from one access point to another point without losing the connectivity.

Visible Light Communication Consortium (VLCC)
The VLCC was built in 2003 with some major companies in Japan. It occupies a leading position in the field of VLC technology and have exhibited many potential applications in our daily life for this ubiquitous and human-interface technology. The organization dedicated to research, development, and standardization of VLC. Based on the recommendations of VLCC, Japan Electronics and Information Technology Industries Association (JEITA) issued two visible standards-based JEITA CP-1221 and JEITA CP-1222 in 2007. After that, in 2008, the VLCC began to cooperate with the Infrared Data Association (IrDA) and the Infrared Communication Systems Association (ICSA). The VLCC released a standard in 2009, which adopted and extended the IrDA Physical Layer. And then, with the help of VLCC, the ICSA proposed a standard for VLC local area network (LAN) based on full duplex using wavelength-division multi-plexing (WDM) (IR and visible).

Institutes and universities
Other institutes and universities, which are devoted to OWC research, include the NSF Smart Lighting Engineering Research Center (ERC) (America), the Center on Optical Wireless Applications (COWA) (America), the Ubiquitous Communication by Light (UC-Light) Center (America), Fraunhofer Heinrich Hertz Institute (Germany), university of Oxford (England), D-Light Project (England), Monash University (Australia), Fudan University(China) and Tsinghua University (China).

5 Typical indoor optical wireless communication system

A basic OWC system, as shown in Fig. 1, is comprised of a light transmitter and a light detector. In addition, free space is used as the optical signal propagation medium in the system. Electrical signals as input are modulated and passed to light source. Then the light source outputs the information into the free space controlled by an optical system in case the emitted radiation is too high to hurt eyes. Through the free space, the optical signal is received by an optical system of the receiver. An optical filter in the receiver will filter out the noise in the signal. Then the denoised optical signal is focused on the amplifier by a lens system or concentrator. The resulting photocurrent is amplified to facilitate the processing of electronic devices. Indoor OW communication system always relies on intensity modulation with direct detection (IM/DD) to realize inexpensive optical carrier modulation and demodulation. The instantaneous power of the optical carrier is modulated from the desired waveform, then the instantaneous power received by detector and generates a proportional current. Note that only the receiver can detect the intensity of the optical wave, without frequency or phase information.

LEDs or laser diodes (LDs) are usually used as optical sources and photodiodes (PDs) are equipped as detectors. Most indoor applications prefer LEDs as the light sources because of the relaxed safety regulations, low cost and high reliability compared to LDs. On the other hand, PIN PDs are favored because of the operation with an inexpensive low-bias voltage, lower cost and tolerance to wide temperature fluctuations compared to avalanche photodiodes (APDs). Stefan et. al., demonstrated a LED-to-LED VLC networks using LEDs as transmitters and receivers and the transmission speed is 800 b/s at a remarkable distance of more than 2 m (Schmid et al. 2013).

5.1 IR system

It has been demonstrated that IR indoor OWC systems preferably adopt the wavelengths range of 780 nm to 950 nm. In this range, not only inexpensive optical sources are already available but also the peak sensitivity of cheap photo diodes, as the main elements of a receiver, coincides with this band.

Gfeller and Bapst, in 1979, firstly proposed a IR system based on a diffuse link operating at about 950 nm and the data rate of it is 1 Mb/s (Gfeller & Bapst

1979). A faster IR system enables transmission speeds of 50 Mb/s that proposed by Marsh and Kahn in 1996 (Marsh & Kahn 1994, 1996). In quasi-diffuse systems, a data rate of 70 Mb/s was achived by Carruther and Kahn in 2000 (Carruther & Kahn 2000). Such link using non Line-of-sight paths, via illumination of the ceiling or walls, is more robust compared to LOS paths (Kahn & Barry 1997, Kahn et al. 1995).

5.2 VLC system with white LEDs

Due to the wavelength of visible light, the VLC generally utilizes the LOS link configurations. In addition, as the white LED technology is blooming developing, white LEDs are committed to be used in VLC for the potential of providing solid-state lighting and wireless data transmission simultaneously. Hence, VLC systems using white LEDs have been of great importance to both academia and industry. White LEDs used in VLC are usually divided into two categories: trichromatic LED and blue-chip LED.

Trichromatic LED Tanaka et. al., proposed trichromatic LEDs and demonstrated that the maximum data rate using trichromatic LEDs is up to 400 Mb/s (Tanaka et al. 2003).

Blue-chip LED With blue-chip LEDs, Vučić et. al., improved the traditional orthogonal frequency-division multiplexing (OFDM) modulation technique and setup a simulation with blue-chip LED, in which the transmission speed is considered higher than 500Mb/s (Vučić et al. 2010).

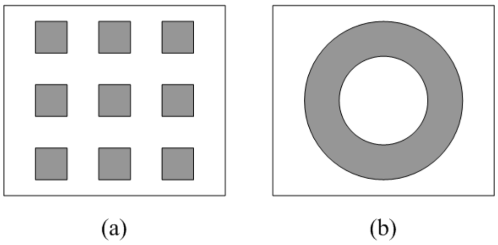

Figure 4: Two kinds of light source deployments located on the ceiling: (a) is square layout and (b) is round layout.

He et. al., investigated the illuminance distribution of LED system in two kinds of light source layout located on the ceiling (as shown in Fig. 4) (He et al. 2013). To provide sufficient visible light illumination, the frequency must be higher than the standard, i.e., 88 MHz, but such constraint would cause the wireless communication, to have a very high signal-to-noise ratio (SNR) (greater than 60 db through the entire room) (Grubor et al. 2008). Moreover, if the minimum SNR for the target bit error rate (BER) is obtained, then the dimming option of VLC is feasible, and full light intensity is not necessary.

Many demonstrations of VLC is only designed for broadcast information, i.e., there is no 'return' channel in the system. Using an existing RF channel to set up a bi-directional communication is investigated by Hou and O'brien in 2006 (Hou & O'brien 2006), to archive such kind of communications, Komine et al. proposed retro-reflecting modulators (Komine et al. 2003). Using LEDs as both transmitters and receivers is proposed by Schmid et al. (Schmid et al. 2013), the data rate is very slow.

Wu and Little observed that although signal reflection still exists, optical wireless communication technology suffers from a high path loss due to the absence of a direct path and data-rate is greatly limited (Wu & Little 2010). To provide continuous connectivity, two network solutions under LOS constraints are proposed, namely peer-to-peer protocol and peer-to-host protocol. Theoretical analysis and simulation of the two protocols showed that they both have advantages and disadvantages. Consequently, each solution will be selected based on the desired communication behavior.

6 Modulation techniques

The basic time unit in digital modulation techniques is a symbol made up of a segment of the sinusoidal waveform. If a digital modulation called a binary modulation, then there are two different symbols only. Single-carrier modulation techniques use only one sinusoidal wave at all times, on the contrast, multi-carrier modulation techniques use more than one sinusoidal waves are transmitted at the same time. Basic single-carrier modulation techniques modify only one of the three parameters: amplitude, frequency and phaseCof the sinusoidal wave.

6.1 Single-carrier pulsed modulation

In single-carrier (SC) pulsed modulation techniques, information are transmitted by time-dependent characteristics of the optical pulse, as a result, the modulation techniques can achieve high average power efficiency. There are two main schemes are utilized in the SC pulsed modulation techniques.

6.1.1 On-off keying

On-off keying (OOK), as one of the oldest modulation techniques, is a good tradeoff between complexity and performance, since hardware can easily implement and integrate such modulation technique. Therefore, it is applicable to any digital encoding scheme. The Infrared Data Association (IrDA) founded in 1993 by around 50 companies, uses OOK in optical communication systems (Infrared Data Association n.d.). In its simplest form, OOK uses the presence of a carrier in a specific duration to represent a binary one, the absence in the same duration to represent a binary zero. OOK is very sensitive to noise, hence, the most challenging problem could be how to optimise the tuning of the equalisers, i.e., the design of these components. Le et al., in 2009 built up an OOK data transmission using first-order analogue equalisers in which the data rate is up to 100Mb/s (Le Minh et al. 2009). Simplex and duplex transceiver prototypes have been demonstrated by Little et al. (Little et al. 2008) in which OOK was applied without observable flicker in the target modulation ranges.

6.1.2 Pulse-position modulation

Compared to OOK, pulse-position modulation (PPM) technique has higher signal bandwidth and power efficiency. In PPM, a single pulse in one of 2^m possible time-shifts encodes m message bits. This procedure takes t seconds, hence, the transmitted bit rate is $\frac{m}{t}$ bits per second. Receivers do not need to use a phase-locked loop (PLL) to track the phase of the carrier. Since the receivers should have the capacity to keep symbol-level and slot-level synchronization, the implement of PPM technique is more complex to constraint the propagation of errors between symbols. Another shortcoming of PPM is that the information is encoded in the time of arrival in the same or different length. The presence of one or more echoes can make it extremely difficult, if not impossible. To accurately determine the correct pulse position corresponding to the transmitted pulse when the receiver's signal contains one or more echoes of each transmitted pulse is difficult. Therefore, the PPM is the mainly used optical communications systems where no multipath interference exists.

For more details of SC pulsed modulation techniques, we refer to (Kahn & Barry 1997).

6.2 Multiple-subcarrier modulation

The bandwidth of time-dependent characteristics of the optical pulse modulation techniques is capped low, nonetheless, the signal to noise ratio of the modulation techniques is high. To increase the transmission speed, efforts are drawn on parallel communication, equalization and complex modulation. Ohtsuki Tomoaki firstly proposed multiple-subcarrier modulation techniques for optical wireless links (Ohtsuki 2003).

6.2.1 OFDM

Orthogonal frequency-division multiplexing (OFDM), as one of realization of multiple-subcarrier modulation, provides parallel data transmission through transmitting orthogonal subcarriers between transmitter and receivers.

OFDM systems can easily implement using Fast Fourier Transform (FFT), adapt to severe channel conditions not requiring complex time-domain equalization. Unlike PPM, they are not sensitive to time synchronization errors. Compared to other double sideband modulation schemes, OFDM techniques have high spectral efficiency, and are robust against narrow-band co-channel interference and intersymbol interference (ISI) along with fading caused by multipath propagation. Moreover, the techniques can adapt modulation to the quality of service (QoS) and the requested data rates of uplink/downlink (UL/DL). Also, any multiple access scheme can combine OFDM. Therefore, it is a good option to OW applications.

However, OFDM techniques still have some drawbacks such as sensitivity to Doppler shift and frequency synchronization problems. Linear transmitter circuitry, suffering from poor power efficiency, is important to high peak-to-average-power ratio (PAPR). Furthermore, these techniques require compensating for the nonlinear characteristics of the LEDs (Elgala et al. 2009*c*, Dimitrov & Haas 2010).

Since phase information detection can not be used in IM/DD optical systems, the OFDM of the system is different from that of RF communications. There are two unipolar OFDM that are used to realize OFDM IM/DD optical systems, namely DC-biased optical OFDM (DCO-OFDM) (Carruthers & Kahn 1996, Gonzalez et al. 2005, Elgala et al. 2009*a*) and asymmetrically clipped optical OFDM (ACO-OFDM) (Armstrong & Lowery 2006, Armstrong & Schmidt 2008). DCO-OFDM puts a DC bias into the signal and constellation size determines the optimum bias. After setting a proper DC operating point, the optical carrier intensity is modulated by bipolar time domain caused by DCO-OFDM. In contrast, there is no negative going signals in ACO-OFDM and the bipolar OFDM signal is clipped at the zero level. If the system modulates odd frequency subcarriers, then the even frequency subcarriers are set to zero. Thus, all of the clipping noise falls on the even subcarriers, the data conveyed by odd subcarriers are not hurt. For a more complete description of the OFDM, see (Armstrong 2009).

7 Medium Access Control (MAC) protocol layer implementation

The MAC protocol allows several terminals or network nodes to communicate within a multiple access network by providing addressing and channel access control mechanisms. Most physical networks are based on the addressing scheme used in early Ethernet implementations, through which data packets is delivered to destinations within a local network. The channel access control mechanisms provided by the MAC layer, on the other hands, allow multiple terminals sharing same physical medium to communicate with each other by detecting or avoiding data packet collisions.

The European community home gigabit access project (OMEGA project n.d.) tried to use IR and visible light communications to provide wireless communication. The system contains a technology-independent MAC layer providing connectivity to any number of access points in any room, the addressing scheme ensures the service will keep working when users change position from one access point to another. Another problem for connectivity is the shadowing when users moving in a room. It is already known that an optical wireless communication link is established base on a LoS path when the receiver moved out of path will lost the connection with transmitter. To improve the performance of MAC protocols, a polling protocol with blockage sensing is proposed by proposed by Hou et al., in 2003 (Hou & O'Brien 2003). Compared to classical time-division multiple access (TDMA) and polling type MAC protocols, the modified polling protocol improves both system throughput and average transfer delay .

Carrier Sense Multiple Access With Collision Detection (CSMA/CD) is a widespread multiple access control method that is utilized in the network collision domain. The method handles a carrier sensing scheme to detect whether another signal is transmitting in the shared medium before delivering a frame, if there is another terminal is transmitting data, then the method will wait for a random time interval before trying to resend the frame again. Nakagawa laboratories in Japan proposed a concept of a full duplex multi-access system for LED-based wireless communications base on CSMA/CD to ensure the compatibility with wire communications such as Ethernet networks (Lin & Hirohashi 2009).

Multiple access collision avoidance (MACA) is a slotted media access control protocol used in wireless network to avoid collisions. The protocol requires a terminal to make an announcement before sending a frame. If the receiver allows the transmission, it will reply a frame to confirm, and other terminals will keep silent to avoid collisions. MACA for Wireless (MACAW) is an extended edition of MACA for the original protocol cannot avoid transmission collisions completely. Chengottarasappan illustrated a simulator in 2004 to simulate several RF MAC protocols in an OW environment, and multiple access collision avoidance (MACA) is reported among protocols (Chengottarasappan 2004). The reported low throughput ($22C - 25\%$) owing to the protocol only allow two nodes to transfer data simultaneously.

8 Physical layer implementation

The physical layer includes the basic networking hardware transmission technologies of a network. In this paper, we focus on the details of how the physical layer to support multiple access and improve the transmission speed.

8.1 Multiple access techniques

Multiple access techniques conducted in the physical layer are used to permit multiple users to build up communication links simultaneously. There is a single optical access point (OAP) for a user or a room (single cell topology), or there are several OAPs with spatial overlap for multiple users (cellular topology). All these three topologies for indoor coverage is shown in Fig. 6 of (Elgala et al. 2011). Selecting a suitable topology needs to consider the room size, amount of users, users mobility, and/or the offered network services. A single cell topology for only one user does not need multiple access techniques since every user does not share resources with others. Single cell topologies are common, like in a aircraft cabin, every passenger has a reading lamp overhead as a OAP in VLC systems. A single cell topology for a room covers a larger area and a couple of users have to share a common OAP. While a cellular topology is capable to provide coverage in a big conference hall. Hence, both a single cell topology per room or a cellular topology will support multiple access by electrical multiplexing or optical multiplexing.

8.1.1 electrical multiplexing techniques

Time Division Multiple Access (TDMA)
TDMA allows different users to have different time slots in the same frequency channel based on the requested data rates and QoS to transmit their own data. TDMA is used in OWC systems, the digital 2G cellular systems, satellite systems and combat-net radio systems because of high power efficiency. However, the techniques limit the transmission capacity of each user (Kahn & Barry 1997).

Frequency Division Multiple Access (FDMA)
FDMA allocate each user one or more frequencies to transmit data. In a cellular system, the overall bandwidth is divided into nonoverlapping frequency bands and different OAP in the topology has a unique band. With the growth of the amount of subcarriers, the energy consumption of FDMA has a corresponding increase. Orthogonal frequency-division multiple access (OFDMA) is an enhanced version of OFDM for multiple users, where each user is assigned one or more OFDM symbols and subcarriers. Single carrier FDMA (SC-FDMA) using single carrier modulation and frequency domain equalization has lower peak-to-average power ratio without decreasing performances compared to the OFDMA system (Myung et al. 2006*b*,*a*). Li et al., developed a VLC proposed system in combination with the SC-FDMA system. And the simulation results showed a better performances than OFDM system in nonlinear channel. The system protects LED devices lifetime and humans eye from over bright as well (Li et al. 2010, 2011).

Code division multiple access (CDMA)
CDMA assigns each user a code and employs spread-spectrum technology to permit several users to share a band of frequencies. For optical CDMA systems, users can access the same channel using optical orthogonal codes (OOCs) as direct sequence spreading. In this case, users are allowed to transmit data at overlapping times and wavelengths and make it possible that to deploy hybrid optical systems such as WDMA/CDMA or TDMA/CDMA (Moosa et al. 2002, Stok & Sargent 2002, Fernando 2003, Alsaadi & Elmirghani 2009, Cui et al. 2013).

8.1.2 optical multiplexing techniques

Wavelength-Division Multiple Access (WDMA)
In WDMA, users can transmit data through a shared channel at the same time using different wavelengths. An optical tunable reception filter can be used to identify the data sent by one user from other wavelengths. A significant disadvantage of such a complex structure is that the hardware is costly. Some indoor OWC systems with WDMA techniques have been proposed (Khan et al. 2012, Wang et al. 2012, Cossu et al. 2012).

Space-Division Multiple Access (SDMA)
SDMA can use parallel spatial pipes next to higher capacity pipes through spatial multiplexing to offer enhanced performance. Considering that the optical signal can achieve high angular resolution for its short wavelength, SDMA can make use of alternative dispute resolution (ADR) to discriminate signals from different users and constrain co-channel interference (C-CI) in the same OPA (Carruther & Kahn 2000, Wu et al. 2012). Consequently, the complexity of the structure is accordingly increased.

8.2 Optical MIMO

Multiple-input multiple-output (MIMO) techniques deploy multiple antennas at both the transmitter and receiver to improve throughput. The techniques can improve the spectral efficiency and the link reliability. Hence, MIMO has been taken as an important part of modern wireless communication standards such as IEEE 802.11n, 3GPP Long Term Evolution, WiMAX, HSPA+ and so on. The high levels of signal power available from multiple transmitters offer the possibility of transmitting multiple data streams in OWC systems (Zeng et al. 2009).

Parallel single-input single-output (SISO) links
A MIMO system for OWC can be implemented using multiple parallel single-input single-output (SISO) links. Such parallel communication involves simultaneous sending of different data streams using a transmitter array. Transmitters and receivers should be accurate aligned so that each detector in the receiver array can receive data by a single source. Furthermore, interferences between different signals must be limited by appropriate settings of the array structures, the source beamwidth, and the detector field of view. Raleigh et al. shows OWC systems will experience benefits by employing spatio-temporal MIMO channel structures where the MIMO channel matrix is composed of SISO subblocks (Raleigh & Cioffi 1998).

Spatial multiplexing combining MIMO with OFDM forms another implementation of optical

MIMO systems. Zeng et al. proposed a spatial multiplexing indoor MIMO technique for VLC system using OFDM (Zeng et al. 2009). Experiment results showed that the channel is highly correlated. Therefore, different locations inside the room experience performance degradation. To enhance the performance, imaging diversity receivers technique is employed to decorrelate the MIMO channel matrix Azhar et al. demonstrating a Gigabit/s indoor wireless transmission using MIMO-OFDM VLC system with four transmitting signals at 250 Mb/s, a nine-channel imaging diversity receiver is used to detect the signals (Azhar et al. 2013).

Spatial modulation In order to relax the alignment requirement of a MIMO system, the spatial modulation (SM) technique is proposed to add in OWC system by Mesleh et al., (Mesleh et al. 2010). The active transmitter transmits a pulse with certain optical power. The index of the active transmitter is estimated at the receiver and used to encode the information bits. For the receiver side, a hard decision optimum decoder is used to estimate the active transmit unit and to retrieve the original information bits (Jeganathan et al. 2008).

9 Factors that interference high-speed transmission

Different link configuration will affect the induced signal degradation. Generally, according to the existence of a LOS path between the transmitter and the receiver along with the source beam-angle and detector field of view (FOV), Kahn and Barry defined six kinds of indoor link configurations (Kahn & Barry 1997). Only three of them are most commonplace configurations shown in Figs. 5 (a), (b) and (c) (Elgala et al. 2011), Yun and Kavehrad proposed another quasi-diffuse link configuration based on multispot diffusing (MSD) shown in Fig. 5 (d) (Yun & Kavehrad 1993).

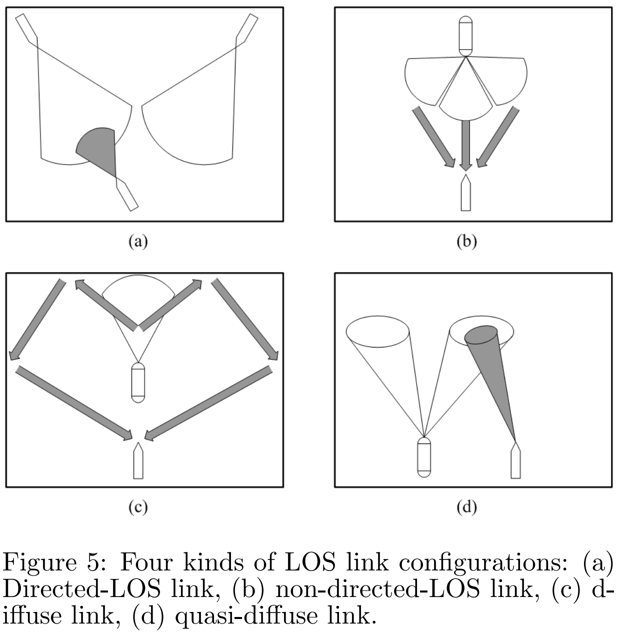

Figure 5: Four kinds of LOS link configurations: (a) Directed-LOS link, (b) non-directed-LOS link, (c) diffuse link, (d) quasi-diffuse link.

Furthermore, no matter how the OWC systems are deployed in indoor or outdoor environments, optical communications are inevitable interfered by nature light, i.e., ambient light noise. Thus, same to radio frequency, the signal strength of light wave will loss in a line-of-sight path through free space between transmitter and receiver. Such kind of loss is called free-space path loss(FSPL) and is proportional to the square of the distance between the transmitter and receiver. Hence it exists in all kinds of LOS link configurations. When the LOS link configurations are not directed, light rays fractionally travel along different paths and the propagation delays for each path are different. These multipath dispersions cause intersymbol interference (ISI) which is unwanted phenomenon for similar symbols acting as noise to each other, thus making the communication unreliable.

10 Open problems

1. The performance of OWC system is limited by the modulation bandwidth of the LEDs. To achieve high-speed data transmission, the poor performance of such LEDs must be mitigated through detecting only the blue peak of the emission spectrum of the white LED (Grubor et al. 2007, Foo & Kaehler 2009). Le-Minh et al., presented a multiple-resonant-driving equalization approach, in which each LED in a array is set a different frequency, and the careful selection of the different responses allows a high net bandwidth (Le Minh et al. 2008*b*, Le-Minh et al. 2008*a*). These are expected to yield further improvements in coverage area and error-performance by optimizing transmitter and receiver. Pre-equalisation and post-equalisation techniques are shown experimentally to significantly improve the bandwidth available for communications using white-light LEDs. The first-order equalizer used in the system is suitable for implementation in analogue electronics and will not increase the complexion too much (Zeng et al. 2008). More complex designs are likely to yield further improvements, and these are under investigation.

2. Nonlinearity has a significant impact on the performance of optical systems based on OFDM. Different from RF systems, in which the main source of nonlinearity is the power amplifier, the LED is the main source of nonlinearity in optical systems. In order to control the LED nonlinearity induced distortion, it is necessary to search for an optimum DC operating point and optimal OFDM signal power to modulate the LED intensity. Moreover, error-performance can be improved by considering an LED with low voltage-current slope characteristics. Elgala et al. demonstrated that the degradation can greatly be mitigated by using the proposed predistortion technique (Elgala et al. 2009*b*). A high peak-to-average power ration (PAPR) due to the addition of many independent frequency carriers will lead to nonlinear distortion. Reduction techniques are proposed to reduce power backoff levels to limit the distortion (Kang & Hranilovic 2008).

3. Broadcasting applications only require users to receive data from LED sources. However, if users need to transmit their requests back, uplink channels are necessary which is a challenging design task. One possible solution is through wavelength-division duplexing (WDD) using different IR wavelengths, so that alignment or tracking between transmitters and receivers are indispensable. Komine et al., take use of corner cube modulator to realize the uplink channel to

avoid these requirements in 2003 (Komine et al. 2003). The proposed system is promising for high-speed communication and it can avoid shadowing. Nevertheless, it still needs further investigation. An alternative solution is using the time-division duplexing (TDD) technique to separate the downlink and the uplink signals. Hou and O'brien even made use of RF, instead of light, to build up uplink in the communication system (Hou & O'brien 2006). Further study needs to be done to investigate other solutions and compare the performance of all these options.

4. In a VLC system, it is necessary to adjust brightness of LEDs as time changes. Another task is to minimize the degradation of the transmission performances when the level of illumination changes. Pulse Width Modulation (PWM) driver can be used to apply the electrical power to the WLED. Lopez-Hernandez et al. showed that in a VLC system with a PWM driver providing electrical power to the WLED (Lopez-Hernandez et al. 2006), the transmission capabilities can be implemented with minor changes and the data transmission archives 500 kb/s. Moreover, independent control of the LED power supply voltage and the data/dimming control block can overcome LED driver bandwidth limitations (Mirvakili & Koomson 2012). As other primary dimming techniques, analog dimming also needs to be further investigated.

5. OWC systems are required to allow for user mobility. However, the link can be lost due to movement or rotation of the OPAs. Hence, it is necessary and important to have link recovery as well as handover mechanisms to maintain the communications, such problems are challenging and need to be investigated.

6. One of the the most difficult challenges is to find where is the place for OWC in the next generation wireless landscape. There is no consensus on how to make use of OWC in specific scenarios in heterogeneous wireless communications.

11 Conclusion

Radio frequency communication technique as an incumbent technology apparently has an indefinite future. However, the limitations of radio frequency prevent it from being deployed in some scenarios. In next generation of wireless communication technologies, OWC techniques are promising supplemental technologies to radio frequency communication systems for both indoor or outdoor cases. The development of OWC is mostly contributed to the evolving of new LED materials and devices, which now are undoubtedly able to replace existing incandescent and fluorescent lights devices. In this paper, a brief survey is conducted on most advances in OWC. We investigated the potential scenarios that OWC can be deployed, main carriers of OWC research, technologies that a OWC system could uses, and open problems that need further study.

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