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Subcarrier Intensity Modulated Optical Wireless Communications: A Survey from Communication Theory Perspective

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Abstract

Subcarrier intensity modulation with direct detection is a modulation/detection technique for optical wireless communication systems, where a pre-modulated and properly biased radio frequency signal is modulated on the intensity of the optical carrier. The most important benefits of subcarrier intensity modulation are as follows: 1) it does not provide irreducible error floor like the conventional on-off keying intensity modulation with a fixed detection threshold; 2) it provides improved spectral efficiency and supports higher order modulation schemes; and 3) it has much less implementation complexity compared to coherent optical wireless communications with heterodyne or homodyne detection. In this paper, we present an up-to-date review of subcarrier intensity modulated optical wireless communication systems. We survey the error rate and outage performance of subcarrier intensity modulations in the atmospheric turbulence channels considering different modulation and coding schemes. We also explore different contemporary atmospheric turbulence fading mitigation solutions that can be employed for subcarrier intensity modulation. These solutions include diversity combining, adaptive transmission, relay assisted transmission, multiple-subcarrier intensity modulations, and optical orthogonal frequency division multiplexing. Moreover, we review the performance of subcarrier intensity modulations due to the pointing error and synchronization error.

Keywords

Atmospheric turbulence fading; optical wireless communications; subcarrier intensity modulation

1 Introduction

In the last two decades, wireless communication systems have experienced a major evolution. Various smart wireless devices, such as smartphones, laptops and tablets, are equipped with various data-intensive multimedia applications such as wireless video surveillance, mobile TV, live streaming of high definition video, online gaming, social networking, and cloud storage. The direct implication of such evolution of wireless communications is an exponential surge of data traffic that the wireless communication channels need to transport with a small latency. Recent studies predict that there will be a several hundred-fold increase of data traffic volume in the next ten years along with a ten times increase of connected devices. The ability to support such an exponential growth of data traffic with diverse quality-of-service (QoS) requirements will be the key success factor for the future generation wireless networks [1]. Since there is a fundamental limit on the capacity of the existing radio-frequency (RF) wireless networks, and the existing RF spectrum is heavily licensed, the upper portion of the electromagnetic spectrum needs to be utilized for future generation wireless networks [2]. In recent years, optical wireless communication (OWC) has drawn a significant attention as a complementary technology to the conventional RF wireless communication systems. OWC is a broadband wireless communication system that uses optical carrier (visible, infrared or ultra-violet), which is propagated through the unguided transmission mediums (atmosphere or space), in order to transmit the information signal from one end to another. OWC systems have a significantly higher data rate than RF wireless communication systems. Cost effective rapid deployment, enhanced security and avoidance of interference (thanks to the narrow beam width of the optical carrier), protocol transparency, and freedom from spectrum licensing regulations are the additional benefits of the OWC systems [3], [4]. Besides theoretical investigations on the performance of OWC systems, several successful demonstrations of OWC systems supporting 10 Gbps or higher throughput are reported in recent years [5]. Moreover, the OWC system supporting 1.25 Gbps over a link distance of 500 m to 2 km is also available on the market. The anticipated benefits of the OWC systems from the theoretical investigations and the successful field trials strongly support the OWC systems technology for becoming an important candidate for future generation wireless networks.

In the last decade, due to the development of the optoelectronic devices, and due to increasing demand of the higher bandwidth, OWC has earned much research attentions. At present, OWC is used in various civilian applications. The most important application of OWC is as a cost-effective solution (because of its freedom from spectrum licensing regulations) to the so called "last-mile" problem by bridging end-users with the existing fiber-optic infrastructure. OWC can also be used to connect multiple campus buildings or enterprise buildings with the server building (connected to the backbone network), and can realize super high-speed local area networks (LAN) without installing expensive fiber cable among the buildings. Moreover, because of high data speed and flexible deployment feature, OWC can be used to facilitate high definition (HD) quality video transmission in wireless video surveillance networks, and broadcasting HD video signal to the temporary video studios (which are connected to the central studios via satellite uplink). One such example is the use of OWC technology by BBC to transport the HD video signals among the temporary studios located at Cape Town, South Africa during the 2010 FIFA World Cup event [2]. Moreover, because of the rapid deployment feature, OWC is an attractive solution for temporary communications during a disaster recovery period. For example, OWC was used in the post recovery period of the 9/11 terrorist attack on the world trade centers, New York, USA. It was reported in [6] that the OWC system can achieve at least 99.99% availability when the link range is below 300 m. In the future cloud-based small cell networks, the distance between nearby low power base stations (BTSs) will be on the order 100 m, and a wireless backhaul solution will be required in order to connect the BTSs with each other because these low power BTSs will be deployed randomly in a plug-and-play fashion. Since an OWC system is not licensed and can provide high data rate over a short distance (on the order of 100 m), it can be a potential candidate of wireless backhaul solution for cloud based mobile networks [7]. In addition, because of inexpensive and rapid deployment feature, OWC is also a potential solution for connecting different remote rural parts of the world to the internet in a cost-effective way. In fact, one of the most prominent applications of OWC in the coming years will be the use of OWC by the Facebook Inc. in its internet.org project that aims to provide internet connectivity to more than 4 billion people who are not yet online [8].

For an outdoor OWC system both intensity modulation with direct detection (IM/DD) and coherent modulation with homodyne/heterodyne detection were proposed in the literature. The coherent modulation with homodyne/heterodyne detection allows long-range transmission and improves background noise rejection. However, most of the practical OWC systems employ IM/DD due to its low-complexity implementation. Recently, IM/DD-based subcarrier intensity modulation (SIM) was proposed in the literature as a suitable alternative to the conventional on-off keying (OOK) and pulse-position modulation (PPM) based intensity modulations. In a SIM OWC system, a pre-modulated and properly biased RF subcarrier is used to modulate the intensity of the optical carrier. Commercial RF technology is relative mature and inexpensive, and the use of SIM can benefit an OWC system in two ways. First, SIM OWC system uses multiple subcarriers to carry the information, which essentially increases the throughput. This transmission technique is known as multiple subcarrier intensity modulation (MSIM) which will be discussed in Section 4. Second, a SIM OWC system can be seamlessly integrated with a fiber optic network where subcarrier modulation is already in use in conjunction with wavelength division multiplexing. An experimental setup of the seamless integration of fiber optics and OWC is provided in [9]. In the last five years or so, a number of research works have been published towards analyzing performance of SIM OWC systems. Since SIM is an important modulation/detection technique for the future OWC systems, an up-to-date survey exclusively on SIM OWC systems will be beneficial to the OWC research community as well as a broad range of audience. In this paper, we focus on the SIM OWC systems from a communication theory point of view. We discuss the performance of the different modulation and channel coding techniques for a single channel SIM OWC system in the presence of atmospheric turbulence induced fading. Since atmospheric turbulence induced signal fading is the most deleterious source of channel impairments for the outdoor OWC systems, appropriate fading mitigation solutions are required to improve the performance of the OWC systems. Therefore, we also explore different approaches, namely, diversity combining, adaptive transmission, relay assisted transmission, multiple-subcarrier intensity modulation, and optical orthogonal frequency division multiplexing (O-OFDM) for improving the performance of a SIM OWC system impaired by fading. Performance of a SIM OWC system can also be impaired by other channel and system impairments such as the pointing error and carrier phase synchronization error. Therefore, we also provide a review of the performance of a typical SIM OWC system with these channel and system impairments. We discuss different approaches for modeling those impairments, performance of different SIM systems in those impairments, and potential solutions to mitigate such impairments. Finally, we provide some future research directions on the SIM OWC systems.

2 OWC Channel Impairments and SIM System Model

2.1 OWC Channel Impairments

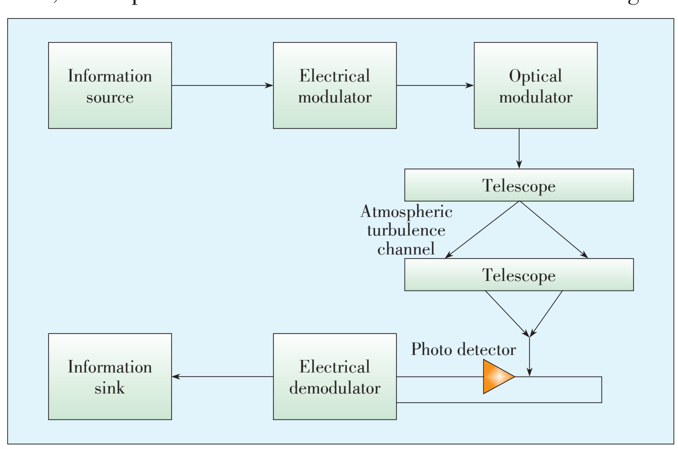
A typical outdoor OWC system exhibits three different types of channel impairments, namely, geometrical and misalignment loss, background radiation, and atmospheric loss. The geometrical loss happens due to divergence of the transmitted optical beam, and it can be quantified as a function of transmitter and receiver lens diameters, beam divergence angle, and link distance. The misalignment, also known as the pointing error, occurs when the transmitted optical beam deviates from its desired direction at the receiver plane. Different models of the pointing error and the performance loss due to the pointing error will be discussed in Section 5.1. The performance degradation of OWC systems due to background radiation and geometrical loss can be found in [2] and [6], respectively.

In a clear weather, the most detrimental atmospheric loss to the outdoor OWC system comes from the atmospheric turbulence induced fading or scintillation. Because of solar heating and wind, inhomogeneity in both temperature and wind takes place and results in the random atmospheric refractive index variation. Temperature changes in the air on the order of 1 K cause refractive index change on the order of several parts per million [4]. The resulting refractive index variations along the transmission path cause random fluctuations in both the amplitude and the phase of the received optical signal. Typically a deep fade may last up to 1-100 msec and result in loss of 10^9 consecutive information bits for a transmission rate of 10 Gbps. As fading severely degrades the performance of an outdoor OWC system, appropriate fading mitigation solutions must be employed, especially, for long-distance OWC systems. Since atmospheric turbulence fading is a random phenomenon, appropriate statistical models are necessary in order to theoretically analyze the impact of fading. Over the years, several statistical models have been proposed in order to describe the scintillation. The lognormal distribution is an important fading model for a weak turbulence condition. However, lognormal fading cannot describe the irradiance fluctuation caused by the moderate to strong turbulence fading. Different extensions of the lognormal distribution, such as log-exponential and log-Rice distributions, are proposed in order to describe atmospheric turbulence fading beyond the weak turbulence regimes. K-distribution is proposed to describe the strong atmospheric turbulence fading for an OWC system that has a link length more than 1 km. Negative exponential distribution is used to describe the atmospheric turbulence fading in the saturation regimes. Gamma-Gamma distribution is a widely accepted atmospheric turbulence fading model that describes a wide range of turbulence fading conditions from weak to strong [10]. Moreover, both K-distribution and negative exponential distributions can be obtained as the special cases of Gamma-Gamma distribution. Recently, a generalized distribution, namely, M-distribution has been proposed and it includes lognormal, Gamma-Gamma, shadowed-Rician, K-distribution, and negative exponential as the special cases [11]. Besides, two other statistical models of atmospheric turbulence fading, namely, double Gamma-Gamma distribution and exponential-Weibull (EW) distribution, have also been proposed in [10] and [12], respectively. Double Gamma-Gamma distribution is more accurate than the Gamma-Gamma distribution for strong turbulence regimes considering spherical wave propagation, and for moderate turbulence regimes considering plane wave propagation. EW distribution is also more accurate compared to the conventional Gamma-Gamma distribution when aperture averaging is considered.

2.2 System Model of SIM OWC

Fig. 1 shows a block diagram of a conventional SIM OWC system where the information bit stream, obtained from the information source block, is first modulated on a RF subcarrier using a conventional electric modulator block. Both phase and/or amplitude modulators are used as the electrical modulator block. The pre-modulated RF subcarrier is then used to drive the intensity of an optical source. Usually for the outdoor OWC system, semiconductor laser diode is used as an optical source. Since the input of the semiconductor laser diode must be non-negative, the pre-modulated RF subcarrier is added with a DC bias before driving the laser diode. The output of the laser diode is transmitted to the atmosphere via a transmit telescope. At the receiver, a second telescope is used in order to collect the transmitted optical beam. The receiver telescope focuses the received optical signal to the photodetector which is placed at the focal point of the receiver telescope. The photodetector converts the received an optical signal into an electric one. After removing the DC bias from the electrical signal (through a bandpass filter), the electric signal is passed to the electric demodulator and detector, and the output of electrical demodulator/detector is collected at the information sink.

Typically in a SIM system, two types of photodetectors, positive-intrinsic-negative (PIN) and avalanche photodiode (APD), are used. The PIN photodetector works well with an OWC system operating over a few kilometers. APD photodetector is suitable for long range OWC systems because it provides an extra gain to the output current for the impact ionization effect. However, the impact ionization also increases the noise current gen-



▲**Figure 1. A typical SIM OWC system.**

erated by the APD. As a result, for a given received optical power, the gain of an APD needs to be optimized in order to maximize the received signal-to-noise ratio (SNR) [13]. In addition, to facilitate the impact ionization, APD requires a higher reverse bias which eventually increases the circuit complexity and electrical power consumption. In a SIM OWC system, the noise generated from the receiver depends on the type of the photodetector used in the system. The noise current generated from the PIN photodetector is dominated by thermal noise. However, PIN also generates non-negligible shot noise when the background radiation is sufficiently high. On the other hand, the noise current generated from the APD photodetector is usually dominated by shot noise. In addition, depending on the load resistor, APD also adds some non-negligible thermal noise. Both thermal noise and shot noise can be modeled by zero mean additive white Gaussian noise (AWGN) processes

2.3 Advantages and Challenges of SIM OWC

Compared to the conventional modulation/detection schemes (e.g. OOK IM/DD, PPM, and coherent modulation) used in the OWC systems, SIM OWC improves error performance over the atmospheric turbulence fading and reduces implementation complexity. SIM OWC system does not suffer from the irreducible error floor like OOK IM/DD with fixed detection threshold as reported in [14]. Moreover, SIM does not suffer from poor bandwidth efficiency like PPM. Both PPM and coherent modulation with heterodyne and/or homodyne detection techniques require complex transceiver design compared to SIM[1]. The reason is that PPM requires a tight symbol and slot synchronization, and coherent modulation requires synchronization of the local oscillator's phase, frequency, and polarization with the transmitted optical carrier's phase, frequency, and polarization. In addition, SIM allows multiple subcarriers to transmit the information signal, which improves the throughput. SIM OWC is also capable of coping with existing fiber optic cable networks employing sub-carrier multiplexing technique [2].

SIM OWC experiences mainly two challenges. The first challenge is the poor power efficiency due to addition of DC bias with the pre-modulated RF subcarrier signal. This effect becomes worse in the case of multiple subcarriers. However, the power efficiency of a SIM with multiple subcarriers can be improved, which will be discussed in Section 4.4. Moreover, when coherent RF modulation is used (i.e., coherent phase-shift keying (PSK)/coherent quadrature-amplitude modulation (QAM)) for pre-modulating the RF subcarrier, an accurate synchronization of carrier phases is required in order to obtain the optimal performance of a SIM system. The impact of imperfect carrier phase synchronization on the performance of SIM will be discussed in Section 5.2.

[1]The performance comparison of coherent and SIM for a typical outdoor OWC over the Gamma-Gamma atmospheric turbulence channels is performed in [27]. Because of improved error rate performance, achievable data rate, and back ground noise rejection capability, coherent OWC is preferred to SIM OWC for long haul communication. However, SIM OWC is a suitable candidate for a short range communication with a simple transceiver design requirement.

3 Modulations and Channel Coding Techniques for SIM OWC

3.1 Modulation Schemes for SIM OWC

In this section, we present a brief literature review on the error rate performance of SIM OWC systems by using different modulation schemes over the atmospheric turbulence channels. SIM was first introduced in [15] where the bit-error rate (BER) performance of a SIM OWC system was investigated over a lognormal atmospheric turbulence fading channel employing differential PSK (DPSK), binary PSK (BPSK) and M-ary PSK (MSPK) modulations. A theoretical analysis of the superior error-rate performance of PSK SIM over OOK IM/DD with fixed detection threshold was presented in [14]. For an OOK IM/DD with fixed detection threshold, both information carrying signals and the response of the atmospheric turbulence fading to the non-zero DC bias (non-information signal) are the baseband random processes. Consequently, it is difficult for the receiver to differentiate between these two baseband random processes, and the demodulation of the information signal is always disturbed by the presence of non-information baseband random process. On the other hand, in a PSK SIM system, the information signal and the response of the atmospheric turbulence fading to the non-zero DC bias do not overlap in the frequency domain. As a result, the receiver can easily filter out the non-information signal which allows PSK SIM to have a superior demodulation performance. For this reason, in atmospheric turbulence condition, PSK SIM offers superior error rate performance compared to OOK IM/DD with fixed detection threshold. Following [14], the error rate performance of PSK SIM in different atmospheric turbulence conditions was extensively investigated in. In particular, the authors in [16] showed that the diversity order of the PSK SIM OWC over Gamma-Gamma turbulence channel depends only on the smaller channel parameter of the Gamma-Gamma turbulence fading. The authors in [17] showed that diversity orders of SIM OWC over both K-distributed and negative-exponential turbulence fading are 0.5. Moreover, the asymptotic analysis used in [17] also revealed the performance gap between the binary coherent and non-coherent modulated SIM in high signal-to-noise ratio (SNR) regimes. For example, the performance gaps between BPSK and DPSK SIMs over the K-distributed and negative-exponential turbulence channels are 3.92 dB in the high SNR regimes. This result is interesting because DPSK and BPSK have a 3 dB performance gap in the Rayleigh fading channels as reported in the RF literature. Different higher order PSK constellations were also used in the existing literature because of their improved spectral efficiency [18], [19]. In particular, both numerical and analytical results of [19] showed that the performance gap between BPSK and binary DPSK (BDPSK) modulations is 0 dB over the lognormal turbulence channels. Since the lognormal fading applies for many short-range OWC systems, such a theoretical result supports the use of differential constellations in practical SIM systems.

Compared to the PSK modulation, the QAM modulation has a better error rate performance over the fading channels. Therefore, it has also gained attention for the SIM OWC systems. The average symbol error rate (ASER) performance of a generalized rectangular QAM (R-QAM) based SIM over the lognormal, Gamma-Gamma, K-distributed, and negative exponential turbulence channels turbulence fading channels was presented in [20], [21]. In these aforementioned works, PIN photodetector aided photo detection was considered. However, these works cannot be directly applied to the cases in which APD photodetectors are used because the expressions of the SNR are different in PIN and APD aided photo detection process. In particular, the instantaneous SNR in a PIN aided photo detection process is directly proportional to the square of the fading random variable, while the instantaneous SNR in an APD aided photo detection process is an algebraic function of the fading random variable. Since APD photodetectors are particularly useful for the long range OWC systems, it is also imperative to investigate BER performance of a SIM OWC employing APD photodetectors. The BER performance of a gray-coded generalized R-QAM based SIM over the lognormal and Gamma-Gamma turbulence channels and by using APD photodetectors was investigated in [22]. The results showed that the BER performance is sensitive to the gain of the APD photodetectors, and the optimal gain (for which minimum BER is obtained) of the APD photodetectors depends on the turbulence condition and link range. Moreover, when the gain of the APD photodetectors is carefully selected, the BER performance of an R-QAM SIM employing APD photodetectors outperforms the BER performance of an R-QAM SIM employing PIN photodetectors.

3.2 Channel Coding Techniques for SIM OWC

In order to improve the error rate performance of SIM over atmospheric turbulence channels, different forward error correction (FEC) channel coding techniques have been considered for the SIM OWC systems. A typical FEC channel coding technique adds redundant bits into the transmitted sequence so that the receiver can correct a limited number of errors in the received message. For OWC over atmospheric fading channel, channel coding is a useful fading mitigation solution for weak atmospheric turbulence condition. Channel coding can also be used to mitigate moderate to strong atmospheric turbulence fading when it is combined with other fading mitigation solutions [2], which will be discussed in Section 4. The FEC code for the IM/DD system was introduced in [23]. The BER performance of a convolutional coded BPSK SIM was studied in [14]. These research works confirmed the performance improvement on the order of several dBs of the convolutional coded BPSK in atmospheric turbulence condition compared to the coded OOK IM/DD with fixed detection threshold. Using bit-by-bit interleaving, convolutional coded BPSK-SIM over the Gamma-Gamma was investigated in [24]. Since OWC channel experiences a quasi-static fading, and the data rate of a typical OWC system is on the order of Gbps; bit-by-bit interleaving requires the implementation of a large interleaver and it may not be suitable for the practical SIM OWC systems. Consequently, the authors in [24] also investigated the BER performance of a convolutional coded BPSK SIM when block interleaving is considered. Results of this work confirmed the superior error rate performance of the block interleaving compared to the case having no interleaving in the atmospheric turbulence condition[2]. Recently, bit-interleaved coded modulation (BICM) was also considered for OWC systems because of the high spectral efficiency [25]. In a BICM system, the channel encoder is separated from the modulator by a bit interleaver, and it supports to choose code rate and modulation order independently. The results presented in this work show that significant gain in the error rate performance can be achieved by using interleaver/deinterleaver blocks in the system. The asymptotic analysis reveals that diversity order of a BICM SIM over the Gamma-Gamma turbulence channels depends on the smaller channel parameter of the Gamma-Gamma turbulence as well as the free distance of the convolutional code.

[2] It should be noted that interleaving introduces latency on the order of milliseconds or more; however, such latency can be reduced. The researchers at MIT Lincoln LAB have achieved the reduction of latency during the implementation of channel coding and interleaver for a 5.4 km long OWC link having data rates of 2.66 Gbps and 10 Gbps [26].

4 Fading Mitigation Solutions for SIM OWC Systems

In this section we discuss some common atmospheric turbulence fading mitigation schemes considered in the literature for SIM OWC systems. These schemes include diversity combining, adaptive transmission, relay assisted transmission, multiple-subcarrier intensity modulation, and O-OFDM.

4.1 Diversity Combining

Since atmospheric turbulence fading severely degrades both error rate performance and data rate performance of OWC systems, proper fading mitigation solutions are necessary for outdoor OWC systems. Maximum likelihood sequence detection (MLSD) is an earlier fading mitigation solution found in the literature. However, the optimal MLSD technique requires large computational complexity, and consequently, only suboptimal MLSD technique can be employed in practice. Aperture averaging is another fading mitigation solution where a lens of large aperture is used at the receiver end to average the received irradiance fluctuations. However, this approach has some limitations. First, the aperture of the receiver should be at least larger than the fading correlation length. This is some-times difficult, especially for long-range OWC systems (because the fading correlation length increases with the link distance). Second, a lens of a large aperture requires a photodetector of large area, which increases the parasitic capacitance of the photodetector and the device delay in the end. Diversity combining, which was originally proposed for fading mitigation in RF wireless communications, is a suitable alternative to the aforementioned fading mitigation solutions. In a diversity combining scheme, the information signal is transmitted through multiple laser transmitters, and/or received by multiple photodetectors where each photodetector has a small aperture area. The earlier work of diversity combining with multiple-input and multiple-output (MIMO) configuration in OWC systems can be found in [26]. The performance of the considered OWC systems was evaluated for three different diversity combining schemes, namely, maximal ratio combining (MRC), equal gain combining (EGC), and selection gain combining. It was reported that the performance gain of EGC is almost equal to that of MRC over the lognormal turbulence channels. This result is interesting because EGC usually has much less implementation complexity compared to MRC. Following this result, diversity transmission and/or reception techniques are extensively considered for improving the performance of SIM OWC systems. BER performance and outage probability were studied of a MIMO SIM (with repetition coding) over the Gamma-Gamma turbulence channels by considering all three diversity combining schemes, namely, MRC, EGC, and selection gain combining [27], [28]. The asymptotic analyses of these works revealed that the diversity order of a MIMO SIM is $MN\beta/2$ where M is the number of the transmit apertures, N is the number of the receive apertures, and β is the smaller channel parameter of the Gamma-Gamma turbulence. In addition to repetition coding (by which same information is repeatedly transmitted from all the transmitters in a given transmission slot), orthogonal STBC (OSTBC) is considered for MIMO OWC systems. Different from OSTBC for RF communications, the OSTBC for OWC systems uses non-negative real signal instead of complex conjugates. Therefore, an optimized OSTBC for the IM//DD OWC was proposed. The error rate performance comparison was performed for a MIMO SIM OWC employing repetition coding and OSTBC across laser terminals with BPSK and MPSK modulations [28]. The asymptotic high SNR analysis shows both OSTBC and repetition coding achieve full diversity order in atmospheric turbulence; however, repetition coding outperforms the OSTBC.

The aforementioned works on spatial diversity assume that each diversity branch exhibits an independent channel fading. However, such an assumption is only valid when a sufficient spacing (larger than the fading correlation length) exists between the two neighboring transceivers. The fading correlation length increases with the increase of link distance as well as that in fading severity. For example, the fading correlation lengths for a 500 m link in a moderated turbulence environment and a 1500 m link in a strong turbulence environment were reported as 6.4 cm and 37 cm, respectively [2]. Therefore, it is not always possible to ensure sufficient spacing between the transceivers, especially for the OWC systems that have transmitter and/or receiver of compact sizes. As a result, in practical condition, OWC systems experience spatially correlated fading that degrades the diversity and coding gain. The BER performance of a single-input multiple-output (SIMO) BPSK SIM with spatial correlation over lognormal turbulence fading channels was reported in [29]. With three photodetectors, the correlation coefficients of 0.3 and 0.6 result in 2.7 dB and 5 dB SNR penalty for a target BER of 10^{-6}, respectively.

In addition to spatial diversity, time diversity or subcarrier delay diversity (SDD) was also introduced in order to improve the error rate performance of a SIM OWC system in atmospheric turbulence condition. In a SDD scheme, different subcarriers of different frequencies are used to transmit the delayed version of the original data, and they are combined at the receiver by using an EGC combiner. The error rate performance of a BPSK SIM system over lognormal turbulence channel using SDD was presented in [30]. However, in order to achieve an optimal performance by using SDD, the delay between consecutive subcarriers should be larger than the channel coherence time so that each subcarrier experiences independent channel fading. Since the atmospheric turbulence channel varies slowly with a coherence time on the order of milliseconds, SDD can introduce several delays in the system that may eventually outweigh the benefits of SDD in terms of the improved error rate performance. For this reason, SDD is not recommended for those OWC applications where delay is an important design concern.

4.2 Adaptive Transmission

Although spatial diversity is an effective fading mitigation technique, it imposes some limitations on system design. Increasing the number of transmit or the receive apertures will increase the implementation cost. Since outdoor OWC requires a line-of-sight communication link, maintaining alignment between multiple transmitters and receiver terminals requires a complicated tracking system [6]. Moreover, the effectiveness of a spatial diversity is restricted by the spatial correlation among multiple receivers. Adaptive transmission is a suitable alternative fading mitigation solution where transmission parameters (rate, power etc.) are varied according to the channel states in order to make efficient utilization of the channel capacity. The adaptive transmission solutions were originally proposed for RF wireless communications. In order to implement adaptive transmission over the fading channels, the channels should vary slowly. If the channel is fast changing, frequent feedback from the receiver to the transmitter will be needed. Moreover, frequent update of transmission parameters will also be required, which will significantly increase the system complexity and degrade the performance. Because an OWC channel has a slow fading process with channel coherence time from 0.1-100 msec, the implementation of adaptive transmission over OWC channel does not require frequent channel feedback from the receiver to the transmitter. Therefore, adaptive transmission is a feasible fading mitigation solution for the outdoor OWC systems. For SIM OWC systems, a variable-rate, constant-power adaptive transmission scheme was proposed by considering MPSK and R-QAM based SIM over the Gamma-Gamma and lognormal turbulence channels [31], [32]. In this scheme, the transmission power was kept constant, and the rate was varied by adapting the modulation order based on the received SNR (i.e., a higher order modulation was transmitted when the received SNR is high, a lower order modulation was transmitted when the received SNR is low, and transmission is suspended when received SNR falls below a cutoff value). The results of this work show that an adaptive transmission scheme significantly improves spectral efficiency compared to the non-adaptive BPSK while maintaining a target BER. Following [31] and [32], an adaptive transmission scheme for parallel OWC (employing PSK SIM) and millimeter wave communications was investigated in [33]. OWC and millimeter wave communications are complimentary: the performance of an OWC link is mainly degraded by fog and atmospheric turbulence, and that of the millimeter wave communication link is mainly degraded by the heavy rainfall. Consequently, the proposed adaptive transmission scheme in [33] offers an improved throughput and link availability in all weather conditions compared to the adaptive rate SIM OWC systems proposed in the previous studies.

4.3 Relay Assisted Transmission

Atmospheric turbulence induced fading severely degrades the performance of a SIM OWC system with a link longer than 1 km. Relay assisted transmission can improve the performance of such a SIM OWC system in two ways. First, a multi-hop relay assisted transmission (also known as the serial relaying) can enhance the coverage (i.e., the link range) of SIM OWC systems. Second, a parallel relaying scheme can create N independent fading links (where N is the number of parallel relays employed in the system) between source and destination nodes which eventually create a virtual multiple aperture system, and can offer a diversity gain (also known as the cooperative diversity gain). In particular, the shorter length hops created by a multi-hop relaying scheme help improve the performance (in terms of diversity gain) of a relayed-OWC system because of the distance-dependent behavior of the atmospheric turbulence fading. This is different from conventional RF wireless communications since multi-hop transmission does not provide any diversity gain for RF wireless communications over the fading channels. Recently, a mixed RF/OWC relaying scheme was introduced in order to facilitate radio over free space optical (RoFSO) communications. In the uplink direction, the mixed RF/OWC relaying scheme facilitates the multiplexing of a large number of RF devices into a single OWC link. Such a system can transmit maximum possible RF messages over OWC links (since an OWC link has much higher capacity compared to a RF link), and increase the end-to-end throughput. The outage performance of an asymmetric dual-hop relay transmission was investigated in [34]. A dual branch transmission system composed of a direct RF transmission link and fixed gain RF/OWC mixed relay aided dual hop link with SIM was considered in [35]. The simulation results show that the diversity combining scheme improves the outage and BER performance compared to a single RF link based transmission scheme.

4.4 Multiple-Subcarrier Modulation

In OWC systems, multiple-subcarrier modulation (MSM) refers to the modulation of information data onto multiple electrical subcarriers which are then modulated onto a single optical carrier [36]. Due to simplicity, the electrical subcarriers are usually modulated onto the intensity of the optical carrier, and the system is referred as the multiple-subcarrier intensity modulation. For an OWC system, multiple-subcarrier intensity modulation offers a number of advantages. Multiple-subcarrier intensity modulation is more bandwidth efficient compared to the OOK and M-ary PPM based IM/DD, and it also offers an opportunity of multiplexing multiple user data onto a single optical carrier. Moreover, multiple-subcarrier intensity modulation can minimize the inter symbol interference (ISI) because several narrowband subcarriers are used, and can also provide immunity to fluorescent-light induced noise [37]. As a result, multiple-subcarrier intensity modulation can be used in indoor OWC applications where optical signals suffer reflection and scattering from multiple objects, and the system performance is limited by ISI and fluorescent-light induced noise. Multiple-subcarrier intensity modulation was first proposed for non-directed infrared wireless communications in [38]. The performance of multiple-subcarrier intensity modulated OWC in atmospheric turbulence was investigated in [37]. The major challenge of multiple-subcarrier intensity modulation is poor optical average power efficiency. In particular, since the input to the optical intensity modulator must be non-negative, a sufficient DC-bias should be added with the electrical subcarriers that have both negative and positive parts. Adding DC-bias with the electrical subcarriers reduces the power efficiency of multiple-subcarrier intensity modulation. Moreover, the amount of required DC-bias increases as the number of subcarriers increases, and the power efficiency of multiple-subcarrier intensity modulation worsens as the number of subcarriers increases. Because of eye-safety and power consumption of the portable transmitter, the transmit power of a typical OWC system must be limited within some threshold value. As a result, due to poor power efficiency, multiple-subcarrier intensity modulation is forced to use a small number of subcarriers, which may degrade the data rate performance. BPSK and quadrature PSK (QPSK) modulations were used and two techniques were proposed in [39] to improve the power efficiency of multiple-subcarrier intensity modulation employing. The first technique uses block coding between the information bits and modulated symbols on the subcarriers so that the minimum value of electrical subcarriers increases and the required DC bias is reduced. However, this technique results in the expansion of the required bandwidth. The second technique introduces a symbol-by-symbol DC adaptive bias replacing the fixed DC bias, and this technique does not require bandwidth expansion. These two techniques can be used separately or together in order to improve the power efficiency of multiple-subcarrier intensity modulation.

4.5 Optical-Orthogonal Frequency Division Multiplexing

O-OFDM is a special case of the multiple-subcarrier intensity modulation, and in recent years it has gained attention for both outdoor and indoor OWC systems. OFDM is one of the most popular fading mitigation solutions for RF wireless communications due to its excellent resistance capability of multipath induced ISI. Moreover, OFDM uses inverse fast Fourier transform (IFFT)/fast Fourier transform (FFT) blocks at the transceiver and supports cost effective implementation. However, the OFDM signal used in RF wireless communications cannot be directly applied to the OWC systems. The main difference between these two systems is that the OFDM signal for RF wireless communications is a bipolar signal and that for an OWC system has to be unipolar signal (the O-OFDM signal cannot contain negative parts because it is modulated on the intensity). However, the use of unipolar signals reduces power efficiency of the O-OFDM system. The power efficiency of O-OFDM worsens as the number of subcarrier increases. In addition, the channel between the transmitter IFFT input and receiver FFT output is linear in RF wireless communication system. However, the linearity of channels does not hold in an OWC system since the receivers in the system employ square law detectors and introduce non-linear signal distortion [40]. In order to successfully apply OFDM to OWC, several modifications to the original OFDM signals were proposed. Examples of these modified OFDM signals are DC-biased O-OFDM (DCO-OFDM), asymmetrically clipped O-OFDM (ACO-OFDM), and flipped-OFDM. Subcarrier based PSK and QAM modulated O-OFDM were employed in IM/DD OWC systems in order to transport the WiMAX traffic to densely populated area where RF signal exhibits severe attenuation and multipath distortion [41]. The theoretical BER and outage performance were studied for subcarrier PSK and QAM based O-OFDM using IM/DD over Gamma-Gamma and M-turbulence channels considering transmitter non-linearity, inter-modulation distortion, and non-linear clipping [42], [43]. Results of these research works suggest that, due to laser diode non-linearity, the number of subcarriers and the optical modulation index for SIM need to be carefully chosen in order to minimize the performance loss due to non-linear signal distortion. Powerful error correction coding schemes with interleaving such as low-density-parity-check (LDPC) were also considered for IM/DD OWC employing O-OFDM technique in order to mitigate the scintillation effect [44].

In **Table 1**, we present a summary of different techniques that are useful for mitigating turbulence fading effects in SIM OWC systems.

5 SIM OWC Systems Subject to Various Channel and System Impairments

In addition to atmospheric turbulence induced fading, OWC systems also experience other system and channel impairments. We present a brief review of the pointing error and carrier phase synchronization error, and the impact of these impairments on the performance of SIM OWC systems.

5.1 Performance of SIM OWC in Presence of Pointing Error

Outdoor OWC systems are typically installed on the top of buildings, and a pointing error (i.e., the misalignment between

▼Table 1. Atmospheric turbulence induced fading mitigation solutions for SIM OWC

Fading mitigation solutions	Literatures	Advantage	Challenges
Spatial diversity	[27], [28], [29]	Improves BER and outage performance through diversity combining	Increases system cost and complexity with the increase of terminals; Performance is affected by spatial correlation among multiple terminals.
Subcarrier delay diversity	[30]	Improves BER and outage performance through combining subcarriers that have different delays	Increases end-to-end delay
Adaptive transmission	[31]–[33]	Improves spectral efficiency while maintaining a target BER requirement, and thus utilizes channel capacity in an efficient way	Requires ideal feedback on CSI from the receiver; Performance degrades when there is a feedback delay and transmission parameters are adapted based on outdated CSI.
Relay assisted transmission	[34], [35]	Improves BER and outage performance through cooperative diversity and facilitates non-line-of-sight communications	Synchronization of multiple distributed relay nodes for cooperative diversity gain is challenging.
Multiple-subcarrier intensity modulations	[36]–[39]	Offers high data rate, and provides immunity to fluorescent-light induced noise for the indoor OWC	Poor power efficiency
Optical-orthogonal frequency division multiplexing	[40]–[44]	Offers high data rate, and mitigates ISI in the scattered propagation environment	Signal distortion due to non-linearity of the transceivers

BER: bit-error rate　CSI: channel state information　OWC: optical wireless communication the transmitter and receiver terminals) may occur in such OWC systems due to building sway caused by the thermal expansion, wind load, small earthquake, and building vibration. Since the optical beam usually has a narrow beam width and the receiver has a narrow field of view, the pointing error may lead to the beam deviation at the receiver plane, which will significantly degrade the received SNR performance and link outage.

A pointing error consists of boresight and jitter. Boresight refers to the fixed displacement of the beam center from the detector center at receiver. Although typical OWC systems are installed with zero boresight, random thermal expansion may result in non-zero boresight. Jitter refers to the random vibration of the beam center around the center of detector, and it is mainly caused by building sway and building vibration. Different pointing error models are proposed in the literature.

Assuming zero boresight error and identical jitter in both horizontal and vertical directions, Farid and Hranilovic proposed an analytical pointing error model that has been widely used [45]. Using this model, the same authors proposed a closed-form expression for the probability density function (PDF) of composite channel impaired by the lognormal turbulence, and an integral expression for the PDF of the composite channel impaired by the Gamma-Gamma turbulence fading. Later, using the same model, a closed-form PDF expression of the composite channel impaired by the Gamma-Gamma turbulence was proposed in [46]. Assuming non-identical jitter in horizontal and vertical directions, a pointing error model was derived in [47] where the authors modeled the PDF of the composite channel using Hoyt distribution. Moreover, assuming non-zero boresight and identical jitter in both horizontal and vertical directions, a generalized pointing error model was presented in [48].

The performance of SIM OWC in the presence of pointing error and atmospheric turbulence was first analyzed in [49] where the authors used the pointing error model developed in [45]. The asymptotic high SNR analysis reveals that it is possible to make the diversity order of the SIM systems independent of the pointing error by choosing the equivalent beamwidth larger than $2\sigma_s\sqrt{\min(\alpha,\beta)}$, where σ_s is the jitter standard deviation, and α,β are the two channel parameters of the Gamma-Gamma turbulence fading. Besides, the authors showed that the pointing error severely degrades the performance of a SIM OWC system if an appropriate tracking is not employed. It was shown that diversity order of the system scales up with the number of transmitters and receivers, and consequently, the average BER performance improves by employing spatial diversity with pointing error. Relay assisted transmission (cooperative diversity) was also considered for investigating the performance of SIM OWC in the presence of pointing error. Outage probability and BER performance of a mixed RF/OWC system using an AF relay and SIM OWC was reported in [50] by considering both Gamma-Gamma turbulence and a zero boresight pointing error.

5.2 Performance of SIM OWC in Presence of Carrier Phase Synchronization Error

Most SIM OWC systems use coherent digital modulation schemes; therefore, carrier phase needs to be tracked at the receiver for demodulating the received signal. In these systems, the received optical signal is first being converted to an electrical signal, and then the phase of modulated signal is tracked by a phase locked loop (PLL). An error in phase tracking, known as carrier phase recovery error (CPE), degrades the error rate performance of a SIM OWC system. The BER performance of SIM OWC employing PSK over the lognormal turbulence channels with CPE was analyzed in [51]. The authors modeled the PDF of CPE using a Trikhonov distribution. The asymptotic analysis reveals that for lognormal turbulence fading, the performance loss of BPSK SIM due to CPE is 0 dB. The asymptotic performance loss of MPSK SIM (M >2) due to CPE was also quantified in this work, and it reveals that the performance loss increases as the value of M (modulation order) increases or the value of PLL SNR coefficient decreases.

6 Conclusions

SIM OWC is an excellent candidate for next generation IM/DD OWC systems because it improves the error rate performance when compared to conventional OOK IM/DD OWC with fixed detection threshold, and it is able to offer a larger data transmission rate by using multiple subcarriers. In this review article, we provide a comprehensive survey of the recent research works on SIM OWC systems. This survey covers three important aspects of the state-of-the-art research on SIM OWC systems, namely, modulation schemes and channel coding techniques, fading mitigation solutions, and performance of the SIM OWC systems with pointing error and carrier phase synchronization error.

Several interesting options can be carried out to further the research on SIM OWC systems. One is to further explore the adaptive SIM systems. In particular, the proposed adaptive SIM OWC considers the transmission parameters adaptation based on the instantaneous SNR that requires an increased channel feedback rate. Since atmospheric turbulence experiences a slow fading process, adaptation of transmission parameters based on the average SNR instead of instantaneous SNR is of practical interest, because the former has the potential to reduce the channel feedback rate. Another interesting topic is to design energy-efficient multiple subcarrier intensity modulations. Since one major disadvantage of multiple subcarrier intensity modulation is the poor power efficiency, a potential research topic is to develop joint power and rate allocation for multiple subcarrier intensity modulations in order to maximize the energy efficiency subject to transmit power constraint and other QoS constraints. The joint power and rate allocation schemes proposed for RF multi-carrier communications cannot be applied here because those schemes were proposed based on the assumption that the system can achieve Shannon capacity, and such an assumption is not applicable to SIM systems. Therefore, it is necessary to take into account the underlying properties of multiple-subcarrier intensity modulation for developing joint power and rate allocation for the multiple subcarrier intensity modulations. Finally, in almost all the aforementioned works, only physical layer performance metrics of SIM OWC are investigated. However, it is also important to analyze different cross-layer queuing performance metrics, such as the packet drop rate, packet delay, and effective capacity (the achievable traffic arrival rate in order to support a given delay bound). Therefore, developing an appropriate queuing model and analyzing different queuing performance metrics for SIM OWC in atmospheric turbulence fading and pointing error is a potential research direction.

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