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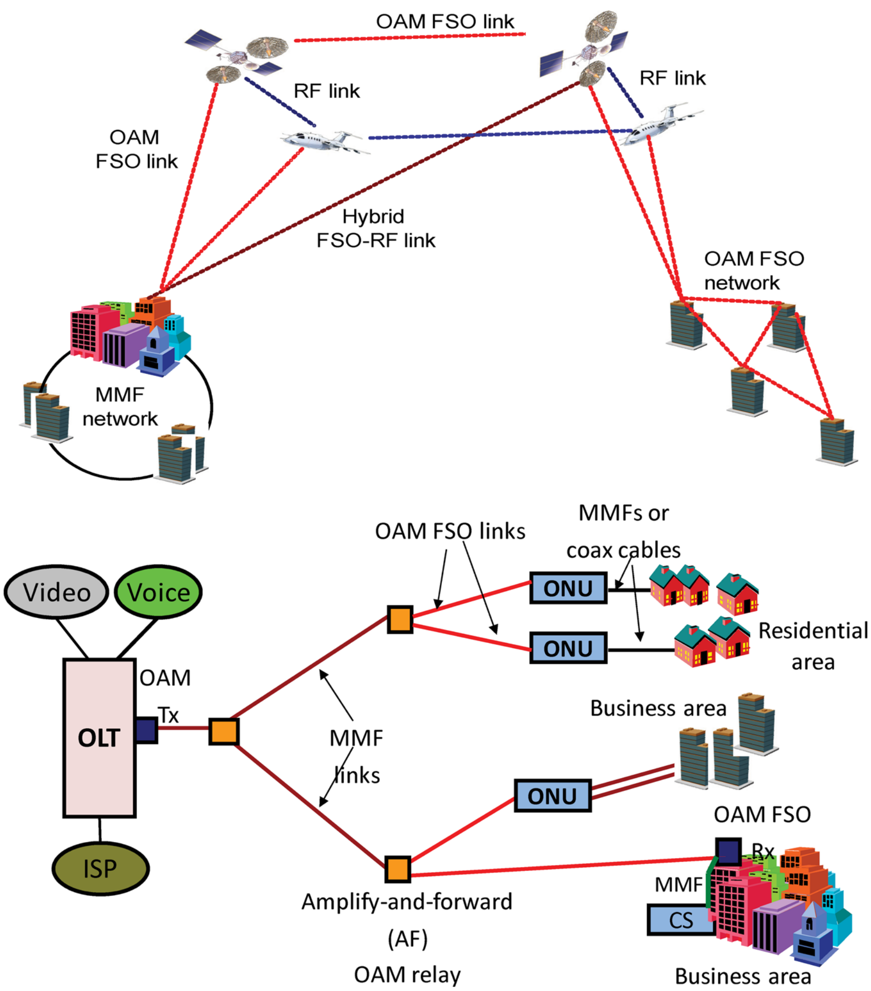

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Heterogeneous Transparent Optical Networking Based on Coded OAM Modulation

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Abstract: In this paper, we propose a coded orbital angular momentum (OAM)-based heterogeneous transparent optical networking scenario. The OAM is associated with the azimuthal phase dependence of the complex electric field. Because OAM eigenstates are orthogonal, they can be used as basis functions for multidimensional signal constellations. From Shannon's theory, we know that information capacity is a linear function of a number of dimensions and a logarithmic function of signal-to-noise ratio (SNR). Therefore, through multidimensional signal constellations, we can dramatically improve the overall aggregate data rate per single wavelength. The ability to generate the OAM modes, such as Bessel and Laguerre-Gaussian (LG) modes, in both multimode fibers (MMFs) and free-space optical (FSO) links will allow the realization of heterogeneous transparent FSO-fiber-optics communication networks, composed of MMF and FSO links, with ultrahigh bits-per-photon efficiencies. We perform Monte Carlo simulations to demonstrate the feasibility of the proposed heterogeneous optical networking scenario. We demonstrate the high potential of the proposed network to solve high-bandwidth demands and interoperability problems simultaneously. Finally, we prove that a dramatic improvement in spectral efficiency is possible by employing this OAM-based multidimensional signaling scheme.

Index Terms: Orbital angular momentum (OAM) modulation, heterogeneous free-space optical multimode fiber (FSO-MMF) optical networking, low-density parity-check (LDPC) codes, coded-modulation.

1. Introduction

The invention of the Internet has fundamentally changed the underlying information communication infrastructure and has led to the worldwide telecom boom in the late 1990s and early 2000s [1], [2]. The volume of Internet traffic continues to grow rapidly, fueled by the emergence of new applications, such as IP-TV, VoIP, and YouTube, thus increasing the demand for higher bandwidths. The exponential Internet traffic growth projections (e.g., by CISCO [1]) place enormous transmission rate demand on the underlying information infrastructure at every level: from the core to access networks. The major technical issue in achieving such high transmission rates is degradation of the signal quality due to various linear and nonlinear effects in optical channels. In addition to high-bandwidth traffic requirements, the future optical networks should allow the interoperability of radio frequency (RF), fiber-optic, and free-space optical (FSO) technologies. However, the incompatibility of RF and optical technologies is an important limiting factor in efforts to further increase transport capabilities of such hybrid networks. Additionally, typical data rates in FSO communications are much lower than those in fiber-optic networks. Moreover, the modulation formats used in FSO and fiber-optic networks are different causing an interoperability problem for future heterogeneous optical networking.

As a solution to high-bandwidth problems, in a series of articles (e.g., [3]), we proposed the use of multidimensional coded-modulation schemes. The key idea behind these papers is to exploit various degrees of freedom already available for the conveyance of information on a photon. These degrees of freedom include frequency, time, phase, amplitude, and polarization. The goal is to improve the photon efficiency while keeping the system cost reasonably low. On the other hand, it is well known that photons can carry spin angular momentum (SAM), which is associated with polarization, and orbital angular momentum (OAM), which is associated with azimuthal phase dependence of the form $\exp(il\phi)(l = 0, \pm 1, \pm 2, \ldots ; i^2 = -1)$. The ability to generate and analyze states with different OAMs by using interferometric or holographic methods [4]–[6] allows the realization of optical communication systems, which are both FSO- [4], [5] and multimode fiber (MMF)-based [6]–[11], with ultrahigh photon efficiencies. Unfortunately, FSO communications links suffer from atmospheric turbulence, and their quality of service (QoS) depends on weather conditions. On the other hand, various dispersion and nonlinear effects in MMFs can lead to deterioration of initial orthogonality of OAM states.

In order to solve high-bandwidth demands and interoperability problems, in this paper, we propose a low-density parity-check (LDPC)-coded OAM-based heterogeneous transparent optical networking scenario. Because OAM eigenstates are orthogonal, they can be used as basis functions for multidimensional signal constellations, as indicated above. From Shannon's theory, we know that information capacity is a linear function of number of dimensions and a logarithmic function of signal-to-noise ratio (SNR). Therefore, through multidimensional signal constellations, we can dramatically improve the overall aggregate data rate per single wavelength. On the other hand, the ability to generate the OAM modes, such as Bessel and Laguerre-Gaussian (LG) modes, in both MMF (see [6]–[8] and references therein) and FSO links [4], [5] will allow the realization of heterogeneous communication networks, which are composed of FSO and MMF links, with ultrahigh bits-per-photon efficiencies. Because OAM-based modulation formats can be used in both FSO and MMF links, the interoperability problem can be solved. In addition, the proposed networking scenario is transparent to various modulation formats and data rates. As a proof-of-concept demonstration, we perform Monte Carlo simulations to demonstrate the feasibility of the proposed heterogeneous optical networking scenario and confirm the high potential of the proposed network. We also demonstrate that dramatic improvement in spectral efficiency is possible by employment of this OAM-based multidimensional signaling scheme.

This paper is organized as follows. In Section 2, we describe the proposed OAM-based heterogeneous transparent optical networking architectures. In Section 3, we describe the proposed OAM-based multidimensional coded-modulation scheme. Performance evaluation is provided in Section 4. Some important concluding remarks and a discussion of future research topics is provided in Section 5.

2. Heterogeneous Transparent Optical Network Architectures Based on OAM Modulation and Multiplexing

The corresponding hybrid networking architecture is shown in Fig. 1(a), in which we can identify three ellipses representing core, edge, and access networks. The links in edge network are OAM MMF based, while the links in access networks are OAM FSO based. The core network links are single-mode fiber (SMF) based. An example of a hybrid network is shown in Fig. 1(b). This particular example includes inter-satellite links and connection to aircraft. The fiber-optic portion of network could be a part of a mobile area network or a wireless area network, with corresponding links being OAM MMF based. The OAM FSO network portion should be used whenever the pulling the ground fiber is expensive (in rural areas) or takes too much time for licensing and deployment (in urban areas). Communication between a ground-station and satellites can be envisioned by using a hybrid (OAM FSO–RF) communication scenario. For example, several satellites can serve

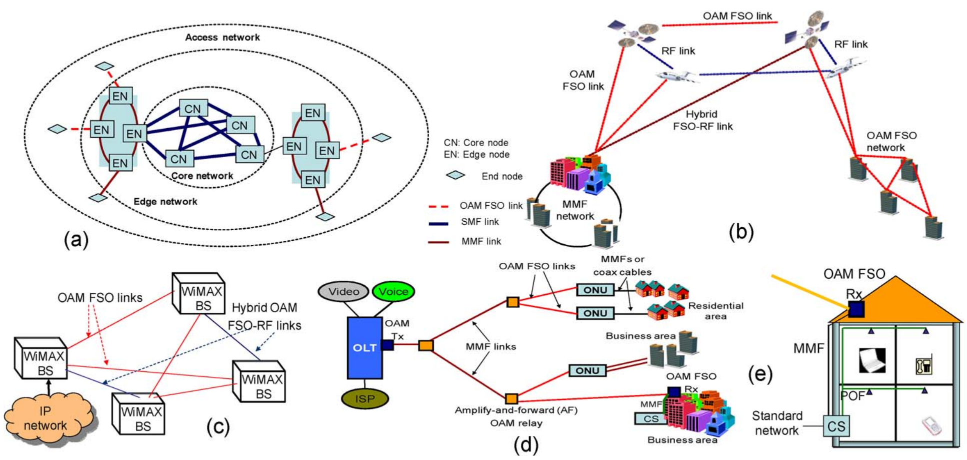

Fig. 1. Heterogeneous transparent (FSO-MMF) OAM-based communication systems/networks. (a) Heterogeneous networking architecture. (b) Satellite-to-ground/ground-to-satellite, intersatellite, and satellite-to-aircraft/aircraft-to-satellite OAM communications. (c) OAM mesh-networking scenario, (d) OAM distribution system. (e) Indoor OAM communications. CS: central station; OLT: Optical line terminal; ONU: Optical network unit.

as nodes of mesh network, and links among satellite nodes can be established by using OAM FSO links. Satellite-to-ground communication can be established by using OAM FSO or hybrid links. Communication between aircraft can be based on RF links, while communication between aircraft and satellite nodes can either be based on OAM FSO or RF links. Finally, for military applications, communication from satellite to submarines can be established by using OAM FSO or hybrid links.

Some other applications of interest of proposed OAM modulation-based heterogeneous systems/networks, which are depicted in Fig. 1, include i) to establish the connection between mobile telephone switching office and base stations (BSs) in cellular systems; ii) to extend the coverage and reliability by connecting WiMAX BSs with OAM FSO or hybrid links in WiMAX-like systems [see Fig. 1(c)]; iii) to increase data rate and reduce system cost and deployment time in access networks [see Fig. 1(d)]; and iv) to enable ultrahigh-speed Internet to an end user [see Fig. 1(e)]. To reduce system installation and maintenance costs for indoor applications, the MMFs can be used from OAM FSO Rx to central station (CS) unit, while within the building, plastic optical fiber (POF) can be used. The OAM communication system is also an excellent candidate to be used instead of passive optical network (PON) applications to substitute various SMF links, as shown in Fig. 1(d). With OAM MMF/FSO links being used as transmission media, OAM access networks (OAM-ANs) can offer higher bandwidth and better energy efficiency, while supporting various communication services. Instead of optical couplers used in PONs, we can use amplify-and-forward (AF) OAM relays, as is illustrated in Fig. 1(d).

3. Description of Coded OAM Modulation

In this section, we describe our approach to simultaneously increase the photon and spectral efficiencies in both FSO and MMF links based on *N*-dimensional OAM coded-modulation. The *N* dimensions correspond to *N* *orthogonal* OAM states; see [4]–[8] for more details. (For few-mode MMF design, see [11].) By increasing the number of dimensions, we can increase the aggregate data rate of the system, while enabling reliable transmission at these higher speeds by using LDPC codes at each level. Previously, we studied the use of volume hologram-based multidimensional FSO communication [5], with system architecture being shown in Fig. 2(a), for completeness of presentation. In this architecture, the *N* independent data-carrying TEM_{00} modes were shown on a series of volume holograms; each programmed to one out of *N* OAM modes in use. The

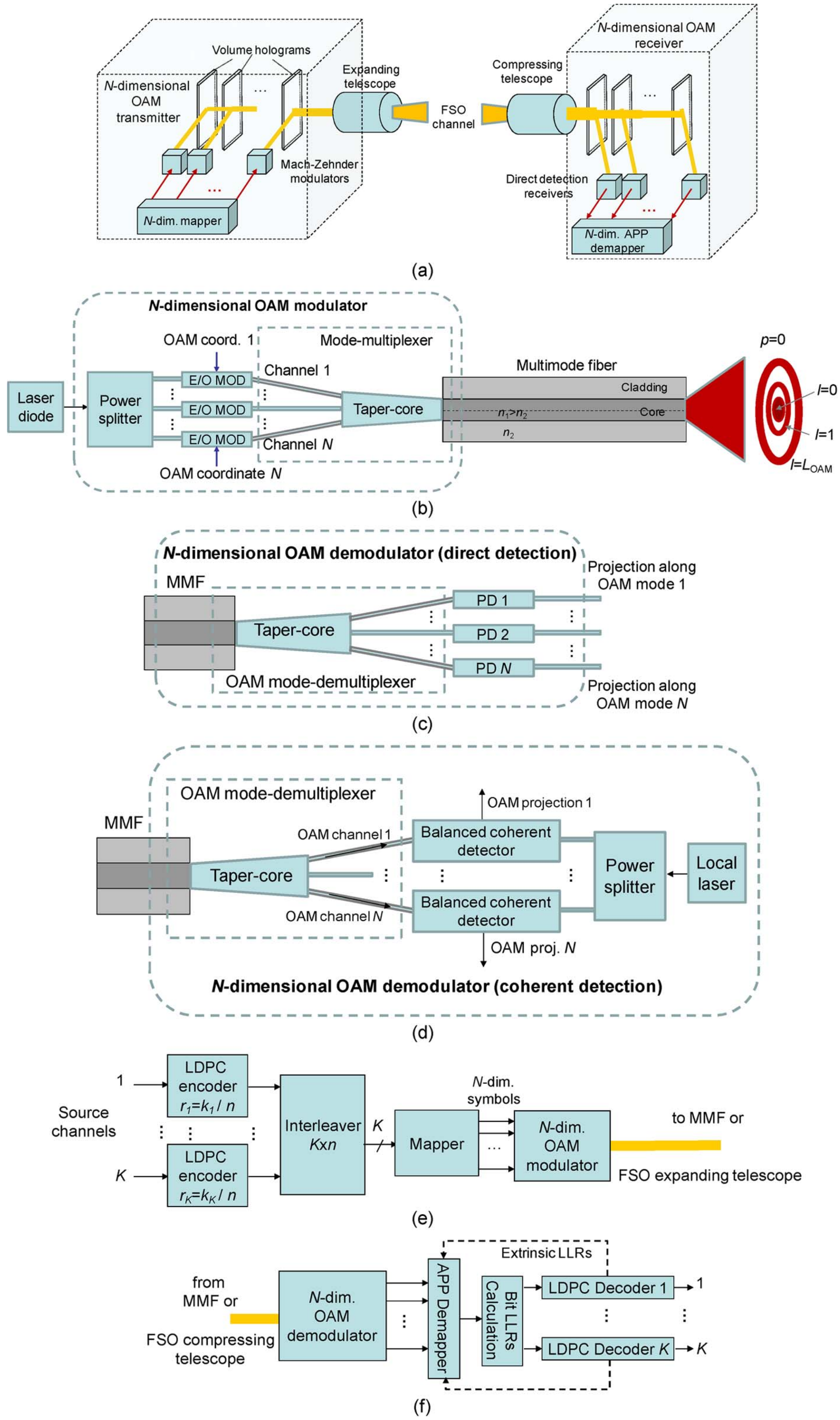

Fig. 2. OAM-based N-dimensional coded-modulation. (a) Volume holograms based OAM FSO system configuration. (b) MMF-based OAM system configuration and N-dimensional OAM modulator. (c) N-dimensional OAM demodulator with direct detection. (d) N-dimensional OAM demodulator with coherent detection. (e) OAM transmitter. (f) OAM receiver. [The excited OAM modes $l = 0, 1, \ldots, L_{OAM}$ in MMF are illustrated in (b).]

corresponding diffraction angles were properly adjusted to enable coaxial propagation of outgoing OAM beams, and the resulting superposition beam was expanded by a telescope. On the receiver side, the same set of volume holograms was used to separate different OAM beams. Here we propose, instead of using a set of volume holograms to perform mode (de-)multiplexing, to use MMF-based mode multiplexer/demultiplexer shown in Fig. 2(b)–(d). In the MMF-based mode multiplexing scheme, shown in Fig. 2(b), a continuous-wave laser diode signal is split into N branches by using a power splitter (such as $1:N$ star coupler) to feed N electrooptical modulators (EO MODs), each corresponding to one of the N OAM modes. The jth input to the jth EO MOD, i.e., $1 \le j \le N$, corresponds to the jth coordinate of the signal to be modulated. Notice that jth coordinate can be 1-D (when one Mach–Zehnder modulator (MZM) per OAM state is sufficient), 2-D (when I/Q modulator can be used), or 4-D (when two I/Q modulators and two polarization beam splitters/combiners are needed; see [3] and [12] for more details). To keep receiver complexity reasonable low, in particular for indoor applications, we assume in the rest of the paper that 1-D modulators (MZMs) are used. The mode demultiplexer can be implemented by propagating the multimode signal in opposite direction [see Fig. 2(c) and (d)]. The overall system configuration for transmission over MMFs is shown in Fig. 2(b). It is evident that transmitter configuration up to the compressing telescope or MMF is identical in both subsystems (either FSO or MMF based). The receiver configuration, after the compressing telescope or MMF, is also the same for both systems. Notice that when OAM transmitter and receiver are implemented as shown in Fig. 2(b)–(d), it would be quite challenging to distinguish between OAM modes with azimuthal mode numbers of the same magnitude but of opposite sign $(\exp(\pm jl\phi))$, which is not a problem when holographic-based OAM (de-)multiplexers are used. Nevertheless, distinguishable azimuthal modes $l = 0, 1, \ldots, L_{\mathrm{OAM}}$ (for fixed p) are still orthogonal (see [4] and [8]). The mode detector shown in Fig. 2(c) can also be implemented based on integrated ring-shaped detector with N-different p-i-n regions to capture different l-modes, as illustrated in Fig. 2(b) for $p = 0$. Namely, for $p = 0$, the intensity of an LG mode is a ring of radius proportional to $\sqrt{|l|}$, and as such, it can easily be detected. This mode detector will have N outputs that correspond to N-projections along OAM modes. A coherent detection-based N-dimensional OAM demodulator is shown in Fig. 2(d). We first perform OAM mode-demultiplexing in OAM-demux block, whose outputs are projections along N OAM states. The nth OAM projection is used as input to the balanced coherent detector [the second input is the corresponding output that originates from local laser, as shown in Fig. 2(d)]. The balanced coherent detectors' outputs are after digital-to-analog conversion used as inputs to an *a posteriori* probability (APP) demapper, which is shown in Fig. 2(f).

After this generic description of OAM-based FSO and MMF subsystems, we provide more details of OAM transmitter and receiver. As shown in Fig. 2(e), K different bit streams coming from different information sources are encoded using (n, k) LDPC codes. The outputs of the encoders are interleaved by the $K \times n$ block interleaver. The block interleaver accepts bits from the encoders row-wise and outputs bits column-wise to the mapper, which accepts K bits at each symbol interval i. The mapper determines the corresponding M^N-ary signal constellation point by

$$s_i = C_{N,M} \sum_{j=1}^{N} \varphi_{i,j} \Phi_j; \;\; i = 1, \ldots, M^N \tag{1}$$

where M is the number of amplitude levels per OAM state, and $C_{N,M}$ is the normalization constant. The set $\{\Phi_1, \Phi_2, \ldots, \Phi_N\}$ represents a set of N orthogonal OAM basis functions, and $\varphi_{i,j}$ are signal constellation point coordinates. The signals are then modulated, mode multiplexed, and sent over the FSO/MMF channel [see Fig. 1(a) and (b)]. The number OAM modes N to be used is determined by the desired final rate and FSO/MMF channel conditions. The simplest OAM-based coded-modulation scheme with direct detection can be described by the following set of constellation points for $N = 3$ and $M = 2: \{(0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), (1,1,1)\}$. (For the coherent detection version, zeros need to be replaced by -1.) The

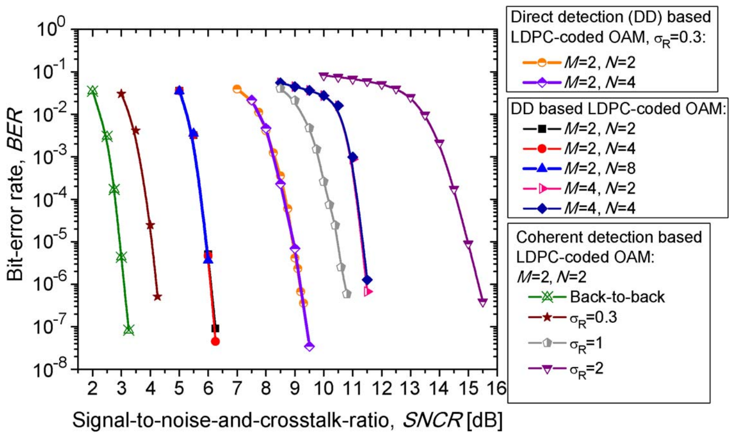

Fig. 3. BER performance of proposed coded OAM modulation systems.

N-dimensional signal constellation can be obtained as the N-dimensional Cartesian product of a 1-D signal constellation originating from pulse-amplitude modulation (PAM)

$$X^N = \underbrace{X \times X \times \cdots \times X}_{N\,\text{times}} = \{(x_1, x_2, \ldots, x_N) | x_d \in X,\ 1 \leq d \leq N\} \tag{2}$$

where $X = \{2m - 1 - M | m = 1, 2, \ldots, M\}$. At the receiver side, as shown in Fig. 2(f), after OAM demodulation (mode demultiplexing) and photodetection (or coherent detection), the outputs of the N branches of the demodulator are sampled at the symbol rate, and the corresponding samples are forwarded to the APP demapper. The orthogonality among OAM modes in realistic FSO or MMF subsystems can be reestablished by various multiple-input–multiple-output (MIMO) and equalization techniques. The demapper provides the bit log-likelihood (LLRs) required for iterative LDPC decoding [see Fig. 2(f)]. The aggregate data rate of proposed system (per single wavelength) is given by $\log_2(M^N) \times R_s \times R$, where R_s is the symbol rate, and R is the code rate.

4. Performance Evaluation

In order to illustrate the high potential of proposed OAM-based transparent heterogeneous networking, in Fig. 3, we show BER versus signal-to-noise-and-crosstalk ratio (SCNR) plots for information symbol rate of 12.5 GS/s. The LDPC (4320,3242) code used in simulations is a quasi-cyclic LDPC code of girth 8 and column-weight 4, which is designed as described in [13]. For $M = 2$ and $N = 8$, the aggregate data rate of 100 Gb/s is obtained, indicating that the proposed system is compatible with 100 Gb/s Ethernet and beyond. In simulations, we assume that OAM crosstalk distribution follows the Gaussian distribution (the same assumption was used in [4] and [5]), which motives the use of SCNR instead of SNR. We show BER performance both in the presence of atmospheric turbulence (corresponding to FSO links) and in the absence of atmospheric turbulence (corresponding to MMF links).

It is evident that system is scalable to arbitrary aggregate data rate, as long as the orthogonality of the OAM states is preserved. In the presence of atmospheric turbulence, for the direct detection-based receiver, in the weak turbulence regime (for Rytov standard deviation $\sigma_R = 0.3$; see [5] for the definition), the system is facing about 3.14 dB degradation at a BER of 10^{-7}. In the strong atmospheric turbulence regime, the direct detection version of OAM exhibits error floor phenomenon (not shown in the figure) so that the use of repetition MIMO processing [14] is needed. On the other hand, when coherent detection is used, the proposed system is able to operate even in strong atmospheric turbulence for reasonable values of SCNR, even without employing MIMO techniques. Coherent detection system faces 1.15-dB degradation in the weak turbulence regime (for $\sigma_R = 0.3$) with respect back-to-back configuration at a BER of 4×10^{-7}, while it faces 7.72-dB degradation in the medium turbulence regime ($\sigma_R = 1.0$) (at the same BER). From Fig. 3, is clear that in order to increase the aggregate data rate, it is more energy-efficient to increase the number of dimensions instead of the number of amplitude levels.

5. Conclusion and Future Work

We proposed LDPC-coded OAM modulation-based heterogeneous transparent optical networks, in which various optical links are composed of either FSO or MMF links. Proposed systems can be used to solve various problems that current optical networking is facing: i) to enable ultrahigh-speed transmission to end-users; ii) to allow interoperability of various RF and optical technologies; iii) to reduce installation costs; iv) to reduce deployment time; and v) to improve the energy efficiency of a communication link. The proposed scheme is based on multidimensional signal constellations, in which OAM states are used as basis functions. It is compatible with both FSO and MMF subsystems, which allows interoperability of FSO and MMF links and realization of heterogeneous optical networks. Because OAM modes can be generated in both FSO and MMF links, the proposed networking scenario is transparent to various modulation formats and data rates. Since the channel capacity is a linear function of a number of dimensions, the aggregate data rate per single wavelength can be dramatically improved. Monte Carlo simulations show that for fixed number of amplitude levels, the increase in number of dimensions leads to negligible BER performance degradation, as long as the orthogonality among OAM states is preserved. For $M = 2$, during propagation over atmospheric turbulence channels, in a weak turbulence regime, N-dimensional signal constellations are facing 3.14-dB degradation for direct detection and 1.15 dB for coherent detection.

There are many interesting research topics to be addressed in the foreseeable future, such as i) integration of the mode-multiplexer and EO MODs into a single chip; ii) integration of a mode-demultiplexer and a series of photodetectors into a single mode detector; iii) compensation of OAM crosstalk introduced by atmospheric turbulence in FSO links and mode coupling in MMF links; and iv) experimental proof-of-concept demonstrations.

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