Generalized Hybrid Subcarrier/Amplitude/Phase/Polarization LDPC-Coded Modulation Based FSO Networking

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ABSTRACT

In this paper, we propose a generalized hybrid subcarrier/amplitude/phase/polarization (GH-SAPP) modulation based free-space optical (FSO) communication network. By using 32-GH-SAPP modulation and mature 10 Gb/s technology the aggregate rate of 110 Gb/s can be achieved, which represents an FSO scheme compatible with 100G Ethernet. The 32-GH-SAPP coded-modulation scheme can operate even under strong atmospheric turbulence regime while still carrying 100G traffic. The corresponding polarization-multiplexed 16-QAM scheme can only operate under weak turbulence regime with aggregate data rate of only 80 Gb/s. The proposed scheme represents a cost effective solution to current high-bandwidth demands.

Keywords: Generalized hybrid subcarrier/amplitude/phase/polarization (GH-SAPP) modulation, free-space (FSO) optical networking, low-density parity-check (LDPC) codes, coherent detection.

1. INTRODUCTION

Future Internet technologies should be able to support a wide range of services containing a large amount of multimedia over different network types at high transmission speeds. The future optical networks should allow the interoperability of radio frequency (RF), fiber-optic and free-space optical (FSO) technologies [1]. However, the incompatibility of RF/microwave and optical technologies is an important limiting factor in efforts to further increase future transport capabilities of such hybrid networks. Because of its flexibility, the FSO communication is the technology that can potentially solve incompatibility problems between RF and optical technologies. Moreover, the FSO can address any type of connectivity needs in optical networks. To elaborate, in metropolitan area networks (MANs), the FSO can be used to extend the existing MAN rings; in enterprise, the FSO can be used to enable local area network (LAN)-to-LAN connectivity and intercampus connectivity; and, last but not least, the FSO is an excellent candidate for the last-mile connectivity. In FSO communication, we are concerned with power efficiency rather than spectral efficiency. Power-efficient modulation schemes such as multilevel pulse position modulation (PPM) [2], which have very low spectral efficiencies, are widely adopted. The very large bandwidth of FSO links (compared to RF links) has made the low spectral efficiency of PPM less of a concern. The spectral efficiency of PPM can be slightly improved using various modulation formats such as: differential PPM, overlapping PPM, di-code PPM [3], and multi-pulse PPM. Unfortunately, typical data rates in FSO communication are much lower than those in fiber-optic networks causing an interoperability problem for future heterogeneous optical networking.

In order to satisfy high-bandwidth demands of future optical networks and solve interoperability problems, while keeping the system cost and power consumption reasonably low, in this paper we propose to use the multidimensional coded modulation schemes, initially proposed for fiber-optic networks [4]. The key idea behind our proposal is to exploit various degrees of freedom already available for the conveyance of information on a photon such as frequency, time, phase, amplitude and polarization to improve the photon efficiency, while keeping the system cost reasonably low. The proposed scheme is a generalized hybrid subcarrier/amplitude/phase/polarization (GH-SAPP) modulation. The GH-SAPP is composed of three or more hybrid amplitude/phase/polarization (HAPP) subsystems modulated with different subcarriers that are multiplexed together. At any symbol rate and code rate, GH-SAPP is capable of achieving the aggregate rate of the individual HAPP systems it is composed of, without introducing any bit-error ratio (BER) performance degradation, as long as orthogonality among subcarriers is preserved. In this paper, coding is done using quasi-cyclic (QC) low-density parity-check (LDPC) codes. The QC LDPC codes are chosen to simplify decoder implementation, and to reduce the encoding complexity in comparison to the random codes, as encoding is done using linear shift register circuitry. The proposed technique is demonstrated by 32-GH-SAPP, which in combination with commercially available 10Gb/s equipment achieves the aggregate data rate of 110 Gb/s, thus representing the 100G Ethernet enabling FSO technology.

2. GENERALIZED H-SAPP MODULATION BASED FSO SYSTEM ARCHITECTURES

Various applications of interest of proposed GH-SAPP modulation based FSO systems, depicted in Figs 1-2, include: (i) in cellular systems to establish the connection between mobile telephone switching office and base stations (BSs), (ii) in WiMAX to extend the coverage and reliability by connecting WiMAX BSs with FSO or hybrid (FSO-RF) links (Fig. 1-left), (iii) in ultra wideband (UWB) communications to extend the wireless coverage range (Fig. 1-right), (iv) in access networks (Fig. 2-left) to increase data rate and reduce system cost and deployment time, (v) in ground-to-satellite/satellite-to-ground FSO communications to increase the data rate (Fig. 2-right), (vi) in intersatellite FSO communications (Fig. 2-right), and (vii) in aircraft-to-satellite/sattelite-to-aricarft communications (Fig. 2-right). To reduce system installation and maintenance costs for indoor applications, the plastic optical fiber (POFs) or MMFs can be used from residential gateway to either fixed or mobile wireless units inside the building. The proposed systems offer many advantages with respect to wireless such as low attenuation loss, large bandwidth, improved security, reduced power consumption, and easy installation and maintenance. The FSO communication system is also an excellent candidate to be used instead of passive optical network (PON) applications, to substitute various MMF or SMF links as shown in Fig. 2, while reducing system cost and speeding up the installation process. With the FSO link being used as the transmission media, free-space optical access networks (FSO-ANs) can offer much 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) FSO relays based on semiconductor optical amplifiers, which is illustrated in Fig. 2. FSO-ANs have many advantages compared to other conventional access technologies: (i) improved bandwidth efficiency, (ii) unique flexibility in dealing with bandwidth resource sharing and virtualization, (iii) protocol independence and service transparency, (iv) scalability, (v) cost-effectiveness, and (vi) it can operate with simple medium access control (MAC) with low overhead.

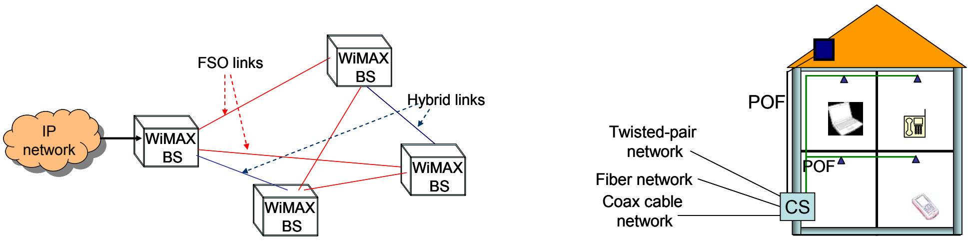

Figure 1. Possible GH-SAPP FSO communication systems: (left) a hybrid WiMAX-FSO mesh-networking scenario, (right) radio over FSO distribution system. POF: plastic optical fiber.

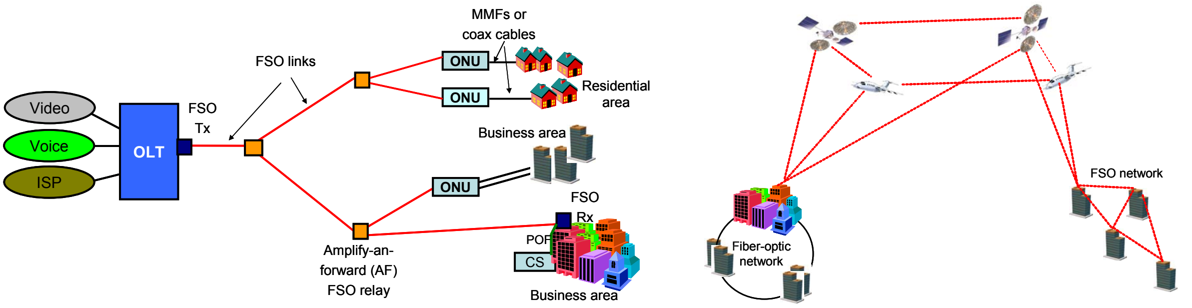

Figure 2. GH-SAPP FSO based networks: (left) an FSO access network, and (right) satellite-to-ground/ground-to-satellite, intersatellite, and satellite-to-aircraft/aircraft-to-satellite FSO communications. CS: central station, OLT: optical line terminal, ONU: optical network unit.

3. DESCRIPTION OF PROPOSED LDPC-CODED GH-SAPP MODULATION

In a GH-SAPP system, N input bit streams from different information sources are divided into L groups of bit streams with N_l streams per lth group. The selection process for $N_1,N_2,\cdots,N_L$ is governed by two factors, the required aggregate rate, and the polyhedron of choice. Each of N_l streams in the lth group is then used as input to a HAPP transmitter, where it is modulated with a unique subcarrier. The outputs of the L HAPP transmitters are then forwarded to a power combiner in order to be sent over the FSO channel. At the receiver side, the signal is split into L branches and forwarded to the L HAPP receivers. Figure 4a shows, without loss of generality, the block diagram of the 32-H-SAPP system configuration where $N = 11$ and $L = 4$. N_1, N_2, N_3 and N_4 are 4, 2, 2 and 3 respectively. N_1 and N_2 represent a dodecahedron of 20 vertices and 12 faces, and N_3 and N_4 represent the dual icosahedron of 12 vertices. Figure 4b shows the block diagram of the coded HAPP transmitter. N_l input bit streams from l different information sources, pass through identical encoders that use structured LDPC codes with code rate $r=k/n$ where k represents the number of information bits, and n represents the codeword length. As shown in the figure, the outputs of the encoders are interleaved by an $N_l \times n$ bit-interleaver where the sequences are written row-wise and read column-wise. The output of the interleaver is sent N_l bits at a time instant i, to a mapper. The mapper maps each N_l bits into a 2^{N_l}-ary signal constellation point on a vertex of a polyhedron inscribed in a Poincaré sphere based on a lookup table (LUT). The ensemble of all the vertices of the HAPP systems forms the vertices of the regular polyhedron and its dual in GH-SAPP. The signal is then modulated by the HAPP modulator. The HAPP modulator, shown in Fig. 4c, is composed of two amplitude modulators and one phase modulator. The three voltages ($f_{1,i}, f_{2,i}, f_{3,i}$) needed to control these modulator are defined in an LUT based on equation (2) below. Since the designed polyhedrons are inscribed in a Poincaré sphere, Stokes parameters are used to define the coordinates of the vertices. Stokes parameters shown in equation (1) from [4], are then converted into amplitude and phase parameters according to equation (2).

$$s_1 = a_x^2 - a_y^2,\ s_2 = 2a_x a_y \cos(\delta),\ s_3 = 2a_x a_y \sin(\delta),\ \delta = \phi_x - \phi_y. \tag{1}$$

where

$$E_x = a_x(t)e^{j(\omega t + \phi_x(t))},\ E_y = a_y(t)e^{j(\omega t + \phi_y(t))}. \tag{2}$$

Without loss of generality, we can assume that $\phi_x = 0$ and hence $\delta = -\phi_y$. This yields a system of three equations with three unknowns that can easily be solved. Figure 1d shows the block diagram of the HAPP receiver. The signal from FSO channel is passed into two coherent detectors as shown in the figure, the four outputs of the detectors provide all the information needed for the amplitudes and phases for both polarizations. These outputs are then demodulated by the subcarrier specified for the corresponding HAPP receiver, then sampled at the symbol rate to be forwarded to the a posteriori probability (APP) demapper. The output of the APP demapper is then forwarded to the bit log-likelihood ratios (LLRs) calculator which provides the LLRs required for the LDPC decoding process. The extrinsic information is then iterated back and forth between the LDPC decoder and the APP demapper to improve BER performance.

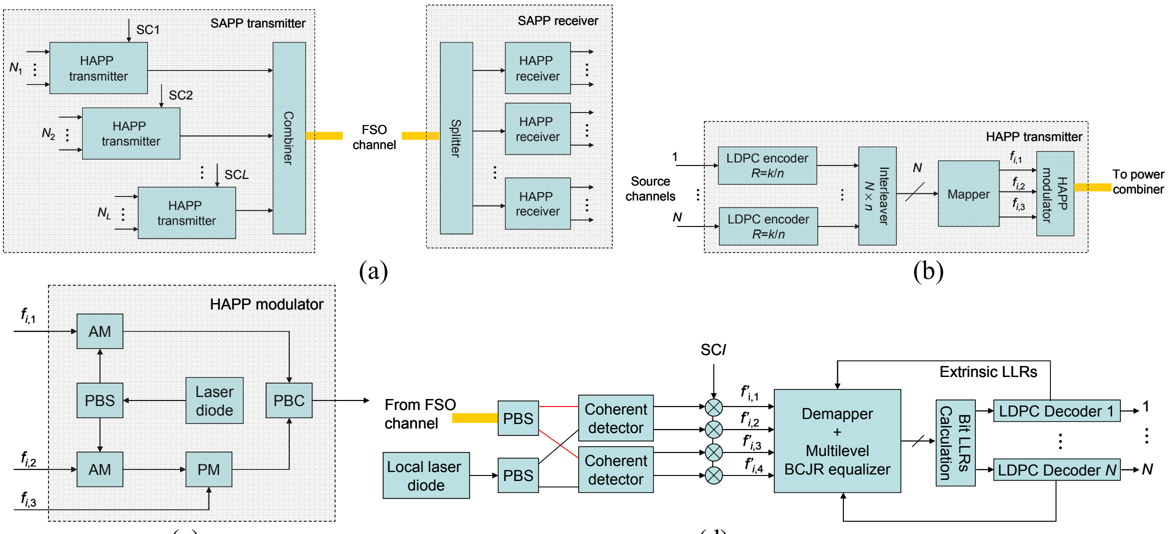

Figure 3. GH-SAPP bit-interleaved LDPC-coded modulation block diagrams: (a) 32-H-SAPP system, (b) HAPP transmitter (c) HAPP modulator and (d) HAPP receiver configurations. SC: Subcarrier, AM: Amplitude modulator, PM: Phase modulator, PBS: Polarization beam splitter and PBC: Polarization beam combiner.

The 32-GH-SAPP constellation diagram, shown in Fig. 4, has constellation points placed in vertices of a dodecahedron (Fig. 4-left) and its dual (Fig. 4-right). This configuration utilizes four subcarriers; the first two subcarriers are used to modulate the points of the dodecahedron vertices, and the other two subcarriers are used vertices of the dual (icosahedron). The 32-GH-SAPP that uses 11-bitstream input, grouped into four groups. The first group maps the input from the first four bitstreams onto 16 points of the 20 of the dodecahedron. The second group maps the input of two bitstreams onto the four vertices that form a tetrahedron. The selection of vertices for a subcarrier is done to maximize the distance between the points on the same subcarrier. The third group maps the input from the two bitstreams onto 4 points of the 12 of the icosahedron, while the fourth group maps the input of the remaining three bitstreams onto the remaining eight vertices. By using 11 different 9.1 Gb/s data streams the aggregate rate of 100.1 Gb/s can achieved, and 100G Ethernet can be delivered to different nodes in FSO network.

In Fig. 5 we show the BER performance of proposed 32-GH-HAPP scheme in weak, medium and strong atmospheric turbulence regimes, characterized by Rytov variance [1] $\sigma_R^2 = 1.23\ C_n^2\ k^{7/6} L^{11/6}$, where $k = 2\pi/\lambda$ is wave number, λ is the wavelength, L is propagation distance, and C_n^2 is the refractive index structure parameter. Weak fluctuations are associated with $\sigma_R^2 < 1$, moderate with $\sigma_R^2 \approx 1$ and strong with $\sigma_R^2 > 1$. The proposed scheme is compared against 32-QAM and polarization-multiplexed (PolMUX) 16-QAM. It is interesting to notice (see Fig. 5-left) that both 32-QAM and PolMUX 16-QAM exhibit BER floor phenomenon even in the weak turbulence regime, while the proposed scheme do not exhibit the error floor in observed region of SNRs (up to 35 dB) even under strong turbulence regime. Notice that for symbol rate of 10 Giga symbols/s (10 GS/s), the aggregate rate of 32-QAM is $R_D = 50$ Gb/s, the aggregate rate of PolMUX 16-QAM is 80 Gb/s, while the aggregate rate of proposed 32-GH-SAPP is 110 Gb/s. The comparison of proposed scheme was done with conventional modulation schemes having the same number of constellation points, so that the comparison is fare with respect to the atmospheric turbulence influence. Therefore, only the proposed scheme is compatible with 100G Ethernet while employing commercially mature 10 Gb/s technology. In Fig. 5-right, we provide simulation results for LDPC-coded scenario, obtained for 25 LDPC decoder iterations and three APP demapper-LDPC decoder iterations. The proposed scheme is able to operate in any atmospheric turbulence regime (ranging from weak to strong), PolMUX 16-QAM can only operate in weak turbulence regime, while 32-QAM cannot operate even in weak turbulence regime due to error floor phenomenon.

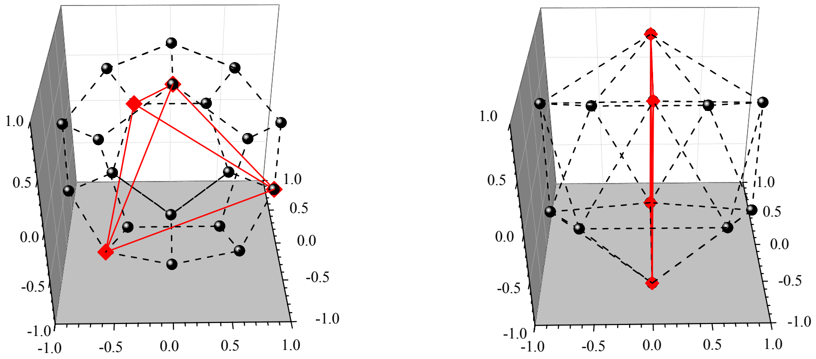

Figure 4. 32-GH-SAPP constellation points corresponding to: (left) dodecahedron and (right) icosahedron.

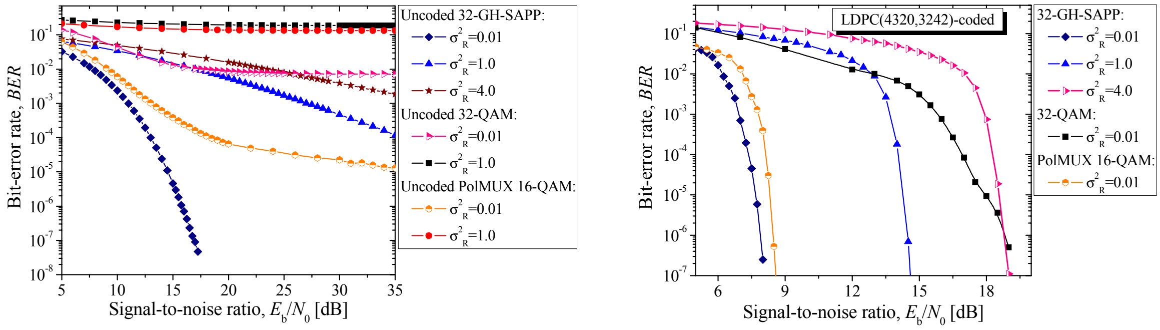

Figure 5. BER performance of proposed 32-GH-SAPP FSO system in weak (σ^2_R=0.01), medium (σ^2_R=1) and strong (σ^2_R=4) turbulence regimes: (left) uncoded and (right) QC LDPC(4320,3242)-coded cases.

4. CONCLUSIONS

The proposed GH-SAPP can be used to solve various problems that current optical networking is facing. It can be used to: (i) enable ultra-high-speed transmission to end-users, (ii) allow interoperability of various RF and optical technologies, (iii) reduce installation costs, (iv) reduce deployment time, and (v) improve the energy efficiency of a communication link. The 32-GH-SAPP modulation, which employs mature 10 Gb/s optical technology, is 100G Ethernet enabling technology. The proposed scheme can operate under various atmospheric turbulence regimes (ranging from weak to strong) while still enabling 100 Gb/s traffic. The corresponding PolMUX 16-QAM scheme can only operate under the weak turbulence regime with aggregate data rate of 80 Gb/s.

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