Beyond 240 Gb/s per Wavelength Optical Transmission Using Coded Hybrid Subcarrier/Amplitude/Phase/Polarization Modulation

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***Abstract*—In this letter, we propose a low-density parity-check coded hybrid subcarrier/amplitude/phase/polarization (H-SAPP) modulation scheme suitable to achieve a 240-Gb/s single-channel transmission rate over optical channels. The proposed scheme doubles the aggregate transmission rate achievable by eight-quadrature amplitude modulation while providing 2-dB optical signal-to-noise ratio performance improvement at a bit-error-ratio (BER) of 10^{-6}. Moreover, H-SAPP can increase the aggregate rate of the hybrid amplitude/phase/polarization scheme while maintaining the BER performance intact.**

***Index Terms*—Coherent detection, high-speed optical transmission, hybrid subcarrier/amplitude/phase/polarization (H-SAPP) coded modulation, low-density parity-check (LDPC) codes, optical communications.**

I. Introduction

Achieving optical transmission beyond 100 Gb/s per wavelength has become the interest of many research groups in the last several years. This interest stems from the fact that the demand on transmission capacities is continuously increasing, due to the increasing popularity of the internet and multimedia. The major concerns while adapting to higher transmission rates are dealing with signal quality degradation due to various linear and nonlinear effects and escalated costs. To this end, in this letter, we propose a scheme that achieves beyond 240 Gb/s per wavelength transmission by upgrading currently available communication systems operating at lower speeds such as 50 GSymbols/s (GS/s).

The proposed scheme is a hybrid subcarrier/amplitude/phase/polarization (H-SAPP) modulation scheme. H-SAPP is composed of two or more hybrid amplitude/phase/polarization (HAPP) subsystems modulated with different subcarriers that are multiplexed together. At any symbol rate and code rate, H-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 the orthogonality among subcarriers is preserved. In this letter, coding is done using structured low-density parity-check (LDPC) codes [1]. Structured LDPC codes are chosen for this scheme to allow easier iterative exchange of the extrinsic soft bit reliabilities between the equalizer and the LDPC decoder, 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 three examples; 8-HAPP, 16-HAPP, and 20-H-SAPP consisting of two HAPP subsystems (4-HAPP and 16-HAPP modulated with different subcarriers). Using components operating at 50 GS/s with an LDPC code of rate 0.8, we achieve 120, 200, and 240 Gb/s, respectively.

II. H-SAPP Coded Modulation

The coded H-SAPP system is composed of two or more HAPP subsystems modulated with different subcarriers to exploit the full potential of the 3-D space. Using H-SAPP, we are able to increase the minimum distance between the constellation points in comparison to quadrature amplitude modulation (QAM) counterparts and so improve the BER performance. Moreover, H-SAPP allows a nonpower-of-two constellation to be utilized (such as 20-point H-SAPP). The HAPP modulation format is based on regular polyhedrons inscribed inside a Poincaré sphere. Since simple regular polyhedrons are not flexible in terms of number of vertices and number of faces, the number of points per constellation becomes limited especially since it has to be a power of 2 for binary systems. H-SAPP offers a more flexible utilization of the nice properties of these polyhedrons as it allows the combination of different polyhedrons, as will be shown later through the text.

Fig. 1(a) shows the block diagram of the H-SAPP system configuration. N input bit streams from different information sources are divided into L groups variable in number of streams per group. The selection process for the different groups $N_1, N_2, \cdots, N_L$ is governed by two factors, the required aggregate rate, and the polyhedron of choice. Each N_l, the number of streams in the lth group, is then used as input to an 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 fiber. At the receiver side, the signal is split into L branches and forwarded to the L HAPP receivers. In this letter, and without loss of generality, we clarify three simple examples for $N = 8$ and $N = 16$ where $L = 1$ and for $N = 20$ where $L = 2$.

Fig. 1(b) 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

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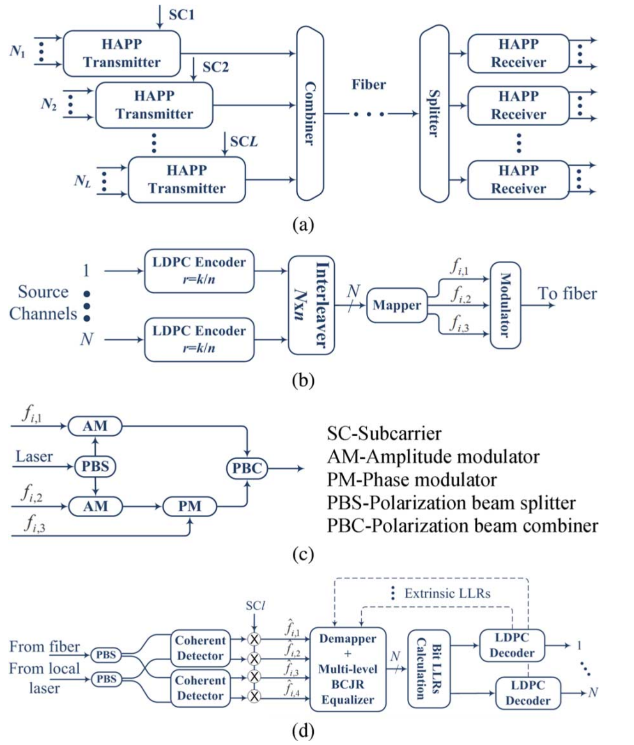

Fig. 1. H-SAPP bit-interleaved LDPC-coded modulation block diagrams: (a) H-SAPP system; (b) HAPP transmitter; (c) HAPP modulator; and (d) HAPP receiver configurations.

with code rate $r = k/n$, where k represents the number of information bits, and n represents the codeword length. The outputs of the encoders are then 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 in one bit-stream, 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). (Please note that the vertices of all the L polyhedrons define a regular polyhedron inscribed in the Poincaré sphere). The signal is then modulated by the HAPP modulator.

The HAPP modulator, shown in Fig. 1(c), is composed of three simpler modulators, two amplitude modulators (AMs) and one phase modulator (PM). Therefore, the LUT maps each N_l bits into a set of three voltages $(f_{1,i}, f_{2,i}, f_{3,i})$ needed to control the set of modulators. As the polyhedrons used are inscribed in a Poincaré sphere, Stokes parameters are used for the design. Stokes parameters, shown in [2, eq. (1)], are then converted into amplitude and phase parameters according to (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 $\phi_x = 0$ at all times, hence $\delta = -\phi_y$. This yields a system of three equations with three unknowns that can easily be solved. Using symmetrical geometric shapes results in closed form numbers for the

TABLE I
MAPPING RULE LOOKUP TABLE FOR $N_1 = 3$

Interleaver output	s_1	s_2	s_3	δ	a_x	a_y
000	$1/\sqrt{3}$	$1/\sqrt{3}$	$1/\sqrt{3}$	$\pi/4$	$\sqrt{\frac{1}{2}\left(1+\frac{1}{\sqrt{3}}\right)}$	$\sqrt{\frac{1}{2}\left(1-\frac{1}{\sqrt{3}}\right)}$
001	$1/\sqrt{3}$	$1/\sqrt{3}$	$-1/\sqrt{3}$	$-\pi/4$	$\sqrt{\frac{1}{2}\left(1+\frac{1}{\sqrt{3}}\right)}$	$\sqrt{\frac{1}{2}\left(1-\frac{1}{\sqrt{3}}\right)}$
			⋮			
111	$-1/\sqrt{3}$	$-1/\sqrt{3}$	$-1/\sqrt{3}$	$-3\pi/4$	$\sqrt{\frac{1}{2}\left(1-\frac{1}{\sqrt{3}}\right)}$	$\sqrt{\frac{1}{2}\left(1+\frac{1}{\sqrt{3}}\right)}$

TABLE II
MAPPING RULE LOOKUP TABLE FOR THE H-SAPP-20 SCENARIO

Group	*Interleaver output*	s_1	s_2	s_3
N_1	0000	$1/\sqrt{3}$	$1/\sqrt{3}$	$1/\sqrt{3}$
		⋮		
	1111	$-d/\sqrt{3}$	0	$-1/\sqrt{3}d$ *
N_2	00	0	$-1/\sqrt{3}d$	$d/\sqrt{3}$
		⋮		
	11	$-1/\sqrt{3}d$	$d/\sqrt{3}$	0

* d is the golden ratio: $(1+\sqrt{5})/2$

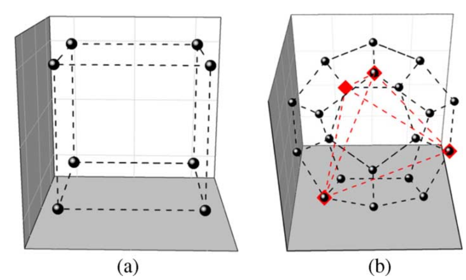

Fig. 2. Signal constellations for: (a) 8-HAPP and (b) 20-H-SAPP.

voltages as shown in Table I. Table I is the LUT for 8-HAPP. The constellation forms a cube inscribed inside the Poincaré sphere. Table II shows the LUT for the 20-H-SAPP with a constellation of a dodecahedron. This configuration utilizes two subcarriers; the first subcarrier is used to modulate the points on 16 out of the 20 dodecahedron vertices, and the other subcarrier is used for the remaining 4 vertices. The selection of vertices for a subcarrier is done to maximize the distance between the points on the same subcarrier. In the table, the top part corresponds to 16-HAPP ($N_1 = 4$), and the bottom portion corresponds to 4-HAPP ($N_2 = 2$). The constellation for the resulting two-subcarrier modulation 20-H-SAPP is shown in Fig. 2.

Fig. 2 shows the case for which (a) 8-HAPP, and (b) 20-H-SAPP, where different point color/shape represents a different subcarrier.

Fig. 1(d) shows the block diagram of the HAPP receiver. The signal from fiber is passed into two coherent detectors then to four branches, which contain all the information needed for the amplitudes and phases for both polarizations. This receiver configuration is essentially the same as a conventional polarization multiplexing receiver. The output of each branch is demodulated by the subcarrier specified for the corresponding HAPP receiver, then sampled at the symbol rate, then forwarded to the demapper

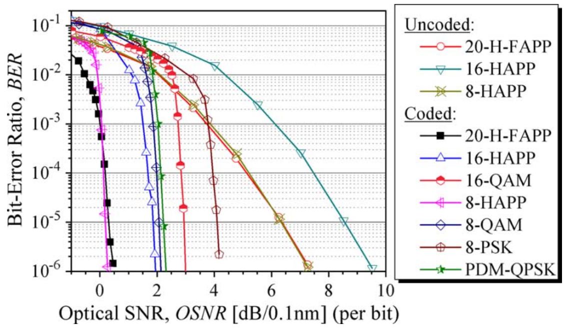

Fig. 3. BER performance versus the OSNR per bit.

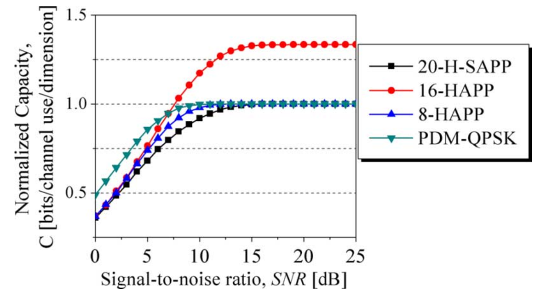

Fig. 4. Normalized channel capacity for different modulation formats.

and the multilevel Bahl, Cocke, Jelinek, Raviv algorithm based equalizer (BCJR equalizer). The multilevel BCJR equalizer [3] used in this scheme is a generalization of the original version of the BCJR algorithm presented in [4]. The output of the equalizer is then forwarded to the bit log-likelihood ratios (LLRs) calculator which provides the LLRs required for the LDPC decoding process. The LDPC decoder forwards the extrinsic LLRs to the BCJR equalizer, and the extrinsic information is iterated back and forth between the decoder and the equalizer until convergence is achieved unless the predefined maximum number of iterations is reached. This process is denoted by *outer iterations*, as opposed to the *inner iterations* within the LDPC decoder itself. The outer iterations help in reducing the BER at the input of the LDPC decoder so as it can efficiently decode the data within a small predefined number of inner iterations, without increasing the complexity of the system.

III. Performance Analysis

The proposed scheme is tested using VPITransmisionMaker, for a symbol rate of 50 GS/s, for 20 iterations of sum-product algorithm for the LDPC decoder, and 3 outer iterations between the LDPC decoder and the multilevel BCJR equalizer. The simulations are done assuming an amplified spontaneous emission (ASE) dominated channel scenario, and using an optical preamplifier, for both uncoded and LDPC coded bit sequences. The coded bit sequence uses LDPC(16935, 13550) code of rate 0.8, which yields an actual effective information rate of the system of $3 \times 50 \times 0.8 = 120$ Gb/s, 160 and 240 Gb/s for 8-HAPP, 16-HAPP, and 20-H-SAPP, respectively.

The results of these simulations are summarized in Fig. 3. We show the uncoded and coded BER performance versus the optical signal-to-noise ratio (OSNR) per information bit. As noticed from the figure, for the ASE-dominated scenario, the 8-HAPP scheme outperforms its QAM counterpart by 2 dB, while it outperforms the phase-shift keying (PSK) counterpart by 4 dB at a BER of 10^{-6}. Moreover, the 16-HAPP outperforms its QAM counterpart by 1.1 dB and the polarization-division-multiplexed quadrature PSK (PDM-QPSK), which transmits a total of 4 bits/symbol, and exploits both polarization, by 0.5 dB at a BER of 10^{-6}. On the other hand, the proposed scheme of H-SAPP increases the aggregate transmission rate by 80 Gb/s in comparison with 16-HAPP, and improves the performance by 1.75 dB at a BER of 10^{-6}. Furthermore, 20-H-SAPP doubles the aggregate transmission rate of 8-HAPP while keeping the BER performance of the system almost intact. On the other hand, utilizing M subcarriers requires M times the bandwidth of the HAPP system. To this end, a better utilization of the bandwidth can be achieved by employing larger constellation HAPP subsystems into the H-SAPP such as employing three 8-HAPPs for a 24-H-SAPP, rather than using two 4-HAPPs and a 16-HAPP and so on.

Fig. 4 shows the information rate curves normalized per dimension for the different modulation formats discussed in this letter. HAPP utilizes three orthogonal dimensions (Stokes coordinates), PDM-QPSK uses two dimensions/polarization, and H-SAPP utilizes three dimensions/subcarrier. As noticed, the curves are in agreement with the performance in Fig. 3.

IV. Conclusion

This letter presents a coded H-SAPP modulation that enables optical single-channel transmission of 240 Gb/s and beyond using the currently available commercial component operating at 40 and 50 GS/s. We show the performance of H-SAPP and its special case HAPP where only one subcarrier is in use. We show that 8-HAPP and 16-HAPP outperform the corresponding 8-QAM and 16-QAM by 2 and 1.1 dB, respectively. We also show that we can double the aggregate transmission rate of 8-HAPP and keep the BER performance intact by utilizing two different subcarriers in the form of 20-H-SAPP. This approach can be further modified to increase the number of constellation points and provide higher aggregate rates. One simple modification to the dodecahedron discussed in this letter that allows us to increase the total transmission per subcarrier to 200 Gb/s is to exploit the 12 faces of the dodecahedron. We can add 12 points to the constellation at the projection of the center of each face on the Poincaré sphere. This way the total number of constellation points increases to 32. Applying this configuration and utilizing five different orthogonal subcarriers allow a total aggregate rate of 1 Tb/s per wavelength that can be used as enabling technology for future 1-Tb/s Ethernet.

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