Performance Analysis of All-optical PPM-mQAM Communication Systems

Abbas Sattar Abdulzahrah and Jassim K. Hmood
Laser and Optoelectronics Engineering Department, University of Technology, Baghdad, Iraq
*Corresponding author: jassim.k.hmood@uotechnology.edu.iq

Abstract. Increasing the spectral efficiency of transmission has increased interests in hybrid optical communication systems. However, these systems suffer from the nonlinear fiber impairments that produce nonlinear phase noise (NPN). In this paper, we investigate all-optical coding m-ary quadrature amplitude modulation (mQAM) by pulse position modulation (PPM) in a single channel optical communication system to increase the transmission capacity and reduce the NPN. The system performance that optically modulates the data by hybrid PPM-mQAM format is numerically investigated by simulation. The results show that the transmission capacity is duplicated and NPN is significantly moderated when PPM-4QAM and PPM-16QAM are used. At bit error rate (BER) of 10^{-4}, the transmission distances of PPM-4QAM is increased by about 33%, in comparison to 4QAM system. In addition, the required optical signal-to-noise ratios (OSNRs) for achieving BER of 1×10^{-4} are decreased by 4.7 dB and 7.5 dB for the PPM-4QAM and PPM-16QAM schemes, respectively.

1. Introduction
These days, optical transmission systems have been technologically advanced for encountering the requirements of customers universally due to advances in smart phones, multimedia applications and personal computers [1-4]. This progress is increasing rapidly, which requires higher capacity communication systems. These systems, which can carry information for lengthier distances with reasonable signal-to-noise ratio (SNR), have been reported [5-7]. Optical transport systems are able to obtain these needs, especially; developed multichannel transmission systems such as time division multiplexing, wavelength division multiplexing, orthogonal frequency division multiplexing and quadratic amplitude modulation (QAM) are widely used in modern telecommunications systems [8-12].

The position of the optical PPM is modified to increase the spectral efficiency of the fiber-optics transmissions schemes [13-16]. The optical pulses of PPM can be sent in blocks, each block involves single light pulse. The transmitted data at the light pulse position is determined each signal block. Because of this feature, optical PPM is candidate for employing in optical transmission schemes when the transmitted power is sternly limited, for example, the connections between satellites using optical PPM. The period of occurred pulse is narrow for raising total of transmitted data [13, 17, 18]. However, this also increases the required bandwidth. In order to increase the spectral efficiency of the coherent communication systems, pulse-position
modulation (PPM) has been combined with multi-level modulation formats [15]. Though, the transmitted signal has been electronically generated, limiting the transmission speed of the systems.

Commonly, optical transmission systems suffer from NPN produced by nonlinear fiber impairments, resulting low signal quality. Fiber nonlinearity such as self-phase modulation (SPM) induces NPN [11, 19]. The nonlinear impairments can interact with spontaneous noise inside amplifiers, conducting stochastic NPN [6, 20]. The NPN, which results from nonlinear fibrous linearity in addition to amplified spontaneous emission noise (ASE), is the major difficult facing the researchers in fiber-optics communication schemes [5, 11, 20]. Many factors contribute for increasing NPN, namely, greater signal power, lengthier transmission reaches, and higher amplifiers number [7, 12]. Appropriately, it is recognized in the past, the performance of the communication system, in terms of BER, OSNR and reachable transmission distances, is restricted by the NPN [21-22].

In this paper, we investigate an all-optical combination between the PPM and mQAM modulation formats to increase the transmission capacity and, in same time, to improve performance of the communication system by reducing the effect of NPN. This is achieved by shaping the envelope of mQAM symbols and allocating the pulses corresponding to the incoming data to PPM. The PPM modulator comprises two Mach Zehnder Modulators (MZMs) is employed for forming mQAM wave with sinc shape and positioning the resulted pulse. The analytical model and results expose that the NPN that induced by SPM is reduced to 42.4% of the phase noise of mQAM scheme. Additionally, the system performance is spectrally efficient and better than conventional mQAM system.

2. The System Modelling

In this section, we present an analytical model describing the interacting of between SPM with ASE noise. Nonlinear effects have been reported to be important in optical transport systems [12]. Phase degradation due to SPM, XPM, and FWM has been extensively studied for both systems with and without dispersion [19]. At end of link, the optical field of the signal can be expressed as:

\[ u(z,t) = u(0,t) \exp(j\phi) + n(t) \]  

(1)

Here \( u(0,t) \) is the transmitted signal and \( u(z,t) \) is the propagated signal at distance of \( z \), \( n(t) \) represents the noise of optical amplifier, and \( \phi \) symbolizes phase distortion by the Kerr effects and dispersion and it can be written as[19]:

\[ \phi = \phi_{\text{DIS}} + \phi_{\text{SPM}} + \phi^r_{\text{SPM}}, \]  

(2)

where \( \phi_{\text{DIS}} \) and \( \phi_{\text{SPM}} \) indicate the phase changes by affecting both dispersion and SPM phenomena, respectively. Here, \( \phi^r_{\text{SPM}} \) symbolizes the phase distortion due to interaction of SPM with ASE noise. In this paper, we model the NPN that produced by interacting SPM with amplifier noise for PPM-mQAM system and compare it with mQAM system. Firstly, the envelope of conventional mQAM wave that launched to optical fiber can be described by:

\[ u(0,t) = \sum_{k=1}^{\infty} \sqrt{\frac{P_i}{2}} A_k \text{rect} \left( \frac{t - k T_s}{T_s} \right), \]  

(3)

where \( T_s \) are the symbol period, \( P_i \) is the input optical power, the complex amplitude of \( k^{th} \) symbol is specified by \( A_k = a_k + j b_k \), and it is related to mQAM constellation. The rectangular function is:
For duplicating the spectral efficiency of the conventional mQAM communication system, we proposed a forming the envelope of the mQAM symbol according to the PPM pulse shape. Hence, the PPM-mQAM wave occupies part of the symbol and centered at first or second half of the symbol regarding to the data. In other words, one bit of data is coded the PPM modulator and assign the position of the pulse within the symbol period. Here, we investigate the performance of the proposed system with sinc pulses and the PPM-mQAM signal can be represented as:

\[ u(0, t) = \sum_{k=0}^{M} \sqrt{\frac{P}{2}} A_k \text{sinc} \left( \frac{\pi (t - k T_s)}{T_s} \right) \]

We develop analytic equations to estimate the NPN that produced by SPM effect, including interaction with ASE noise. Light signal it travels through multi-extension optical fibers where each period consists of an optical amplifier and optical fibers. At the output of each amplifier, an ASE noise field is added sub-conveyor, which is suitably designed as added Gaussian noise with variance of \( \sigma^2 \). Typically, in the long-haul fiber-optics system, the spans are identical and the equal fiber length, \( L \), and optical amplifiers with the ASE noise, \( n(t) \) described as:

\[ n(t) = \sum_{m} n_m(t) \]

The transmitted signal spread through \( M \) identical spans. Hence, the loss in the power of the propagated wave is periodically compensated by optical amplifier in each span. Thus, the NPN is collected over \( M \)-spans and it is expressed as:

\[ \phi_{\text{NL,SPA}} = \gamma L_{\text{eff}} \sum_{m} \left| \mu(0, t) + \sum_{n=1}^{m} n_n(t) \right|^2 \]

where \( \gamma \) is the nonlinear coefficients and \( n_n(t) \) is the noise of optical amplifier in \( n^{th} \) span. Here, \( L_{\text{eff}} = (1 - e^{-\alpha L}) / \alpha \), where \( \alpha \) characterizes optical fiber attenuation coefficient. Analyzing term in right side of Eq. (7), yields:

\[ \phi_{\text{NL,SPA}} = \gamma L_{\text{eff}} \sum_{m} \left[ \mu(0, t) \right]^2 + 2\Re \left\{ \mu(0, t) \sum_{n=1}^{m} n^*_n(t) \right\} \left[ \sum_{n=1}^{m} n_n(t) \right]^2 \]

where \( x^* \) and \( \Re \{x\} \) indicate phase-conjugated and the real of complex number, \( x \), respectively. The last terms on the right-hand side of Eq. (8) represents the interaction of noise with itself, which has no effect on phase noise. The first term represents the interaction of the signal with itself. This interaction induces SPM noise, which is expressed by:

\[ \phi_{\text{NL,SPA}} = \gamma L_{\text{eff}} \sum_{m} \left| \mu(0, t) \right|^2 \]

The second term denoted the random phase noise due to interacting SPM distortion with noise of amplifiers and it can be described as:

\[ \phi_{\text{NL,SPA}} = 2\gamma L_{\text{eff}} \sum_{m=1}^{M} \Re \left\{ \mu(0, t) \sum_{n=1}^{m} n^*_n(t) \right\} \]
The power of QAM signal is $P_i A_i^2 / 2$. As a result, the nonlinear phase noise variance of interaction ASE noise with SPM distortion is estimated by [19]:

$$\sigma_{SPM,QLM}^2 = \frac{M(M+1)}{2} \gamma^2 L_{eff} P_i A_i^2 \sigma^2$$

(11)

In PPM-mQAM communication system, the average power of the transmitted signal is:

$$\mu(0,t) = \frac{P_i}{2T_s} |A_i|^2 \int_0^T \sin^2 (t-T_s/4) dt$$

$$= \frac{2P_i}{3\pi} |A_i|^2$$

(12)

The variance of NPN for the PPM-mQAM signal can be described as:

$$\sigma_{SPM,PPM-mQAM}^2 = \frac{2M(M+1)}{3\pi} \gamma^2 L_{eff} P_i A_i^2 \sigma^2$$

(13)

From last equation, it is clear that the NPN variance of PPM-4QAM signal is reduced to be 42.4% times that of 4QAM signal.

3. Hybrid PPM-mQAM System Setup

In this section, we describe setup of a hybrid PPM-mQAM scheme as shown in Fig. 1. The setup of the proposed hybrid PPM-mQAM system includes three subsystems: transmission, and receiving the link. In the transmitter side, the laser diode supplies an optical carrier at frequency of 193.1 THz. The laser ray is straightly delivered to complex modulator that exploits two Mach-Zehnder modulators (MZMs) for generating mQAM signal. Sequentially, the modulating signal applied to PPM coder to produce a hybrid PPM-mQAM signal. The PPM coder is driven by corresponding pulses generated according to the data.

The PPM-mQAM signal is then released into long-haul link contain multi-span. All spans are identical and contain single-mode fiber (SMF), dispersion compensating fiber (DCF) and Erbium-doped fiber amplifier (EDFA). The parameters of SMF and DCF are listed in Table 1. The attenuation is fully compensated with optical amplifiers as well as the dispersion is totally compensated by DCF for maintaining the system's throughput as depicted in Fig. 1.

| Parameters                  | SMF | DCF |
|-----------------------------|-----|-----|
| Attenuation coefficient     | 0.2 | 0.5 |
| Dispersion coefficient      | 16  | -160|
| Nonlinearity coefficient    | 1.3 | 5.2 |
| Length                      | 60  | 3   |

Table 1. SMF and DCF parameters
4. Result and discussions

In this section, we consider the impact of the use of PPM-4QAM and PPM-16QAM on the performance and spectral efficiency of optical transmission systems. The system is numerically simulated in a split-step Fourier method. The 4QAM or 16QAM optical signals are initially modulated, then; they are optically coded with PPM with symbol rate of 20Gsymbol/s. To know the suppression of phase noise, the EVM is obtained and plotted against the channel power and transmission distance. Additionally, the BER is drawn against the OSNR and communication reach to explore the system performance.

In order to display the influence of combining PPM with 4QAM and 16QAM on EVM, the power of the optical carrier is varied and the EVM is estimated. Further, a comparison is made between the 4QAM and PPM-4QAM to show the advantage of coding with PPM. Figure 2 (a) depicts changing EVM with the power of optical carrier for both PPM-4QAM and 4QAM. During the calculation, the optical link length is adjusted to 1200km (20 spans × 60km). In general, EVM for PPM-4QAM and 4QAM are primarily diminished when optical power increases because the optical signal-to-noise ratio (OSNR) is raised. Nevertheless, the EVM increases for the power
higher than 3dBm and -1dBm for PPM-4QAM and 4QAM, respectively. The lowest EVM records 0.094 for PPM-4QAM while the lowest EVM accounts 0.132 for 4QAM signal. Likewise, in contrast to 16QAM modulation format, PPM-16QAM records lower EVM as displayed in Fig. 2 (b). Moreover, lowest EVM occurs at the power of 4dBm and 1dBm for PPM-16QAM and 16QAM, respectively.

Figure 2. Influence of combining PPM with mQAM on the phase noise: (a)PPM-4QAM versus 4QAM, (b) PPM-16QAM versus 16QAM.

Figure 3 shows the BER as a function of transmission distance at optimum optical carrier power, which produces the minimum EVM. For each transmission having a numerical distance, the corresponding sub-carrier power that gives is indicated by reference to Fig. 3(a), that the modulation formula PPM-4QAM is better than the traditional 4QAM coordination along the transmission distance. Furthermore, the system performance is greatly enhanced because it is able to transfer data in excess of 5200 km fibers at BER of $1 \times 10^{-4}$, representing approximately 33% increase in comparing with 4QAM system. High-order modulation formats such as 16QAM needs high OSNR to overcome NPN. Hence, propagation lengths are significantly shorter for using the 16QAM signal format or PPM-16QAM format as shown in Fig. 3(b). As expected, in BER from $1 \times 10^{-4}$, the signal reach is enlarged from 100 km to 450 km when PPM-16QAM is used instead of 16QAM. However, the performances of 16QAM and PPM-16QAM systems are restricted by the laser noise. Generally, in coherent detection systems, laser noise plays an important role in degrading system performance.
Finally, the receiver sensitivity for both PPM-mQAM and mQAM are investigated and compared. Figure 4(a) illustrates BER versus OSNR, which indicates the receive sensitivity for both PPM-4QAM and 4QAM systems. The result is obtained at a symbol rate of 20 G symbol/s and fiber length of 1200 km. From the figure, it can conclude that PPM-4QAM system shows better sensitivity to the received signal. At BER = $10^{-4}$, the PPM-4QAM signal requires a lower OSNR than 4QAM by about 4.7 dB. Regarding to Fig. 4 (b), the PPM-16QAM system exhibits superior performance in comparing to 16QAM system where the required OSNR is reduced by 7.5 dB at BER of $10^{-4}$.

Figure 4. BER versus OSNR: (a) PPM-4QAM versus 4QAM, (b) PPM-16QAM versus 16QAM.
5. Conclusions
In this paper, we investigate the performance of combining PPM with mQAM optical fiber transmission system. The spectrally efficient PPM-mQAM format is able to duplicate the system capacity as well as mitigate the fiber impairments. The PPM-mQAM signal has been optically generated where the envelope of mQAM has been shaped and positioned according to the incoming data. The numerical model has been established for illustrating the influence of use PPM-mQAM format on suppressing the NPN. The simulation results show that the system performance has been considerably improved due to reducing the NPN although the system capacity has been doubled. In contrast to 4QAM system, OSNR of PPM-4QAM system has been enhanced by 4.7dB and the propagation distance is lengthened by 33%. It can show same behavior when the PPM-16QAM system is examined, where the NPN is highly mitigated and the signal reach is considerably raised.

Acknowledgment
The authors thank the staff of the Laser and Optoelectronics Engineering Departments, University of Technology.

Reference
[1] Hamed, E.K., Munshid, M.A. and Hmood, J.K. 2020 Opt. Fiber Technol, 57, p 102230.
[2] Sakaguchi, J., Puttnam, B.J., Klaus, W., Awaji, Y., Wada, N., Kanno, A., Kawanishi, T., Imamura, K., Inaba, H., Mukasa, K. and Sugizaki, R. 2012, J Lightwave Technol., 31, pp 554-562.
[3] Qiu, M., Zhuge, Q., Chagnon, M., Gao, Y., Xu, X., Morsy-Osman, M. and Plant, D.V. 2014, Opt. Express, 22, pp 18770-18777.
[4] Kudo, R., Kobayashi, T., Ishihara, K., Takatori, Y., Sano, A. and Miyamoto, Y. 2009, J Lightwave Technol., 27, pp 3721-3728.
[5] Hmood, J.K. and Harun, S.W. 2019, Opt. Commun., 437, pp 237-245.
[6] Hamed, E.K., Hmood, J.K. and Munshid, M.A. 2020, Opt. Eng., 59, p 056105.
[7] Du, L.B., Morshed, M.M. and Lowery, A.J. 2012, Opt. Express, 20, pp 19921-19927.
[8] Yue, L., Li, Y., Qiu, J., Hong, X., Guo, H., Zuo, Y. and Wu, J. 2020. Opt. Commun., 455, p 124362.
[9] Wang, D., Huo, L., Li, Y., Wang, L., Li, H., Jiang, X., Chen, X. and Lou, C. 2017, Opt. Commun., 403, pp 87-91.
[10] Hmood, J.K., Noordin, K.A., Arof, H. and Harun, S.W. 2015, Opt. Fiber Technol, 25, pp 88-93.
[11] Zheng, Z., Lv, X., Zhang, F., Wang, D., Sun, E., Zhu, Y., Zou, K. and Chen, Z. 2016, J Lightwave Technol., 34, pp 2182-2187.
[12] Hmood, J.K. and Radhi, S.S. 2018, Opt. Commun., 428, pp 113-119.
[13] Lu, Y., Li, X., Pang, X., Hu, L., Wang, X., Bi, M. and Chen, J. 2020, Opt. Fiber Technol, 57, p. 102201.
[14] Sahoo, P.K., Prajapati, Y.K. and Tripathi, R. 2018, IET Commun, 12, pp 2158-2163.
[15] Tian, B., Zhang, Q., Ma, J., Tao, Y., Shen, Y., Wang, Y., Zhang, G., Zhou, W., Zhao, Y. and Pan, X. 2018, Opt. Commun., 419, pp 59-66.
[16] Khallaf, H.S., Morra, A.E., Elfiqi, A.E., Shalaby, H.M. and Hranilovic, S. 2019, Appl. Opt, 58, pp 9757-9767.
[17] Morra, A.E., Shalaby, H.M., Hegazy, S.F. and Obayya, S.S. 2015, Opt. Commun., 357, pp 86-94.
[18] Khallaf, H.S., Shalaby, H.M., Garrido-Balsells, J.M. and Sampei, S. 2017, J. Opt. Commun., 9, pp 161-171.
[19] Hmood, J.K., Harun, S.W., Emami, S.D., Khodaei, A., Noordin, K.A., Ahmad, H. and Shalaby, H.M. 2015, Opt. Express, 23, pp. 3886-3900.
[20] Ellis, A.D., Le, S.T., McCarthy, M.E. and Turitsyn, S.K. 2015, 17th Int. Conf. on Transparent Optical Networks (ICTON), pp 1-4.
[21] Essiambre, R.J., Tkach, R.W., Ryf, R., Kaminow, I., Li, T. and Willner, A.E. 2013, Optical Fiber Telecommunications VI B, (Academic Press), pp 1-37.
[22] Golani, O., Pilori, D., Guiomar, F.P.P., Bosco, G., Carena, A. and Shtaif, M., 2019, J Lightwave Technol., 38, pp 1148-1156.