Analysis on improving channel capacity of MPPM

Xinran Ke *
University College London, London, United Kingdom
* Corresponding Author Email: zceexke@ucl.ac.uk

Abstract. Nowadays, optical wireless communication has been widely applied and various techniques are used to achieve signals with higher quality and higher efficiency. Pulse position modulation (PPM) is a commonly used modulation scheme. However, PPM suffers from its low bandwidth efficiency and Multiple pulse position modulation (MPPM) is generated to improve the performance of signals. Further research can be carried out to figure out ways to further improve channel capacity of communication systems by combining modulation techniques together. In this paper, three different schemes are introduced, including LDPC-coded MPPM UWOC system, MIMO-MPPM WOC system, and PSM-MPPM system. Fundamental principles of these three techniques are mentioned before going through the methods used to carrying out experiments. Both simulations derived from numerical analysis and experiment results are obtained to support the results. In LDPC-coded and MIMO research, turbulence effects are considered by adopting different statistical distributions. The aim of the paper is to compare properties of three recent research and discuss how they can be applied in different scenarios to improve the communication systems.

Keywords: MPPM, channel capacity, MIMO, PSM, LDPC.

1. Introduction

Internet of Things (IOT) has been introduced to make life easier, and communication systems with better performance is supposed to achieve [1]. The information is supposed to be transmitted over a long distance with less noise attenuation and higher accuracy, especially in harsh conditions[2]. In order to meet the requirement, digital communication is applied instead of traditional analogue modulation, such as Pulse-Amplitude-Modulation (PAM). One of the digital modulation techniques is Pulse-position-modulation (PPM), which is used in digital communication systems to transmit data by varying the position of a pulse in a time slot [3]. Even though PPM has superior performance in transmission efficiency, it causes an increase in required transmission bandwidth. In order to mitigate the defect, MPPM (Multi-Pulse-position-modulation) was proposed by Hisayoshi and Kiyoshi (1989), an advanced modulation scheme based on PPM coding system and multiple pulses are used in a time slot to represent a single symbol. The method can halve the bandwidth required for the case in PPM and keep the transmission efficiency unchanged [4].

In order to achieve high efficiency in receiving information, channel capacity is aimed to improve, which is a concept introduced by Shannon in 1948. He described the channel as “the medium used to transmit the signal from transmitter to receiver.” Channel is defined as “that part of a communication system that the designer is unable or unwilling to change” so that it is easier to represent the physical communication system by applying mathematical theories. Based on the definitions, Shannon showed that the maximum rate at which information can be transmitted over a communication channel with a given level of reliability is limited by the channel capacity. This limit is determined by the noise and interference present in the channel [5]. The concept of channel capacity revolutionized the field of communication engineering and set the foundation for the development of modern communication systems. Shannon’s work established a theoretical framework for understanding the fundamental limits of communication systems and provided guidelines for designing communication systems that can achieve optimal performance [6].

Over the years, researchers have made significant progress in improving the channel capacity of MPPM communication systems. One of the key breakthroughs was the introduction of error-correcting codes, such as Convolutional Codes, Turbo Codes, and Low-Density Parity-Check (LDPC) Codes. In 2022, Hongyan et al. proposed applying MPPM together with LDPC code to mitigate the negative effect of Turbulence-induced fading, which is present in Underwater Wireless Optical communication (UWOC) systems. After investigating and comparing BER performance of different modulation systems, including OOK, PPM and MPPM, it was found that the UWOC performs better when applying LDPC code and MPPM instead of other modulation schemes. LPDC was also verified to be efficient in improving communication system with much better BER performance compared with BER performance of uncoded systems [7].

Researchers have also focused on developing advanced modulation and coding techniques, such as Multiple-Input Multiple-Output (MIMO) systems, to further improve communication systems' channel capacity. MIMO has played a key role in wireless communication, such as WiFi-networks, long term evolution (LTE). It has recently been widely applied in fifth-generation (5G) technology [8]. MIMO is a technique that uses multiple antennas at the transmitter and receiver to improve the performance of wireless communication systems to exploit multipath propagation. MIMO systems can also reduce fading effects and improve signal quality effectively, which means that bit error rate (BER) can be reduced [9]. In 2015, Haitham et al. analyzed the performance of MPPM-coded multiple-input multiple-output free space optical (MIMO-FSO) communication systems for overcoming atmospheric turbulence. It has been concluded that MIMO systems have better SER performance than SISO systems, assuming the same average power, data rates and channel states. Further research shows that MPPM scheme could benefit the MIMO-FSO communication systems more when MIMO systems were less correlated [10]. In 2020, the BER performance and Ergodic channel capacity of MPPM-coded wireless optical communication (WOC) MIMO systems over correlated fading channel suffering from negative impacts of atmospheric turbulence, atmospheric attenuation, and pointing error were investigated by Yue et al. [11].

Other modulation schemes are proposed to improve MPPM systems further. In 2019, Feng et al. investigated the performance of MPPM-QPSK modulation signals in FSO communication systems. The relation between BER performance and received optical power with various atmospheric turbulence was analyzed and compared by using QPSK, 2PPM-QPSK, 4PPM-QPSK and 8PPM-QPSK modulation schemes, respectively [12]. In 2022, Yifan et al. proposed to figure out how pulse shape modulation (PSM) could benefit the system and minimize inter-symbol interference (ISI). Frequency characteristics and BER performance of different pulse shapes are compared, and it was concluded that Gaussian monocycle and Scholz's monocycle presented good performance [13].

After discussing progress of modulation schemes and recent research about improving MPPM performance briefly, Some preliminary principles about MPPM such as work principles are discussed, then some theories related to research areas are mentioned. In the main part, three different communication systems are discussed respectively with detailed information including models used, how signals are processed in the system, data obtained through experiments and analysis based on measurements. Then, three modulation schemes are compared in different aspects such as application, techniques used, disturbance factors taken into consideration and properties of methods.

2. Principle/Theoretical Analysis

2.1. MPPM

Multi-Pulse-Position Modulation (MPPM) is based on the principle that the signal information is conveyed by the position of pulses in a given time slot. "Multi" means that the pulse number generated in the given time slot is larger than 1. The first letter 'M' can also indicate the number of pulses in each information time slot, which means that it can represent 2^M different levels of digital data. A mathematical formula can represent the (N,M) MPPM modulated signal during transmission, shown as eq 1. The code block can be represented as: $[a_0, a_1, \dots, a_{N-1}]$. The equation shows that there are N intervals in each time slot T. There are M open slots and N-M blocked slots among the code block. a_m value for each slot need to be designed to map the binary source to binary bitstream [14].

$$s_{(t)} = \sum_{m=0}^{N-1} a_m g\left(t - \frac{mT}{N}\right) \tag{1}$$

2.2. Channel capacity

The principle of channel capacity, also known as the Shannon-Hartley theorem, is a fundamental concept in information theory. It represents the theoretical maximum rate at which information can be reliably transmitted over a communication channel without errors due to noise or interference.

The Shannon-Hartley theorem can be expressed as:

$$C_t = Blog_2\left(1 + \frac{S}{N}\right) \tag{2}$$

Where C_t represent the channel capacity in b/s, B represents the bandwidth of the channel in Hertz, S is the average received signal power in watts and N is the average power of noise in watts. $\frac{S}{N}$ is signal-to-noise ratio which is in dB. By observing equation (2), it can be noticed that C_t is affected by B, S and N. C_t can be enhanced by improving the signal-noise ratio and increasing bandwidth. The defect of increase in required transmission bandwidth can be reduced by applying MPPM.

Assume that the channel is in an ideal case and the noise source is only contributed by additive white Gaussian noise (AWGN). Average power of noise (N) can be replaced by:

$$N = n_0 B \tag{3}$$

Where n_0 is the single-sided power spectral density in W/Hz, and B is the channel bandwidth in Hz. Substitute N into equation (2):

$$C_t = Blog_2\left(1 + \frac{S}{n_0 B}\right) \tag{4}$$

Through approximating B to infinity, it can be derived that:

$$C_t \approx 1.44 \frac{S}{n_0} \tag{5}$$

This result shows the limitation of improvement in channel capacity when increasing bandwidth [15].

2.3. LDPC

Low-density parity-check codes (LDPC) are error-correcting codes that can be used in MPPM communication systems to improve channel capacity. The data can be encoded by adding redundancy so that the receivers are able to detect and correct errors in the transmission. The LDPC code is represented by a sparse parity-check matrix H, which indicates the relation between information data bits and parity bits.

The encoding process can be expressed as:

$$c = [x, p] = xH \tag{6}$$

Where x is data vector, p is parity vector, and H is parity-check matrix.

The decoding process can be expressed as:

$$Hy = s \tag{7}$$

Where y is the received vector and s is the syndrome vector. Various algorithms can be used to decode LDPC codes. The performance can be optimized for operating conditions such as signal-to-noise ratio (SNR), modulation scheme or channel characteristics [16].

2.4. MIMO

Multi-input multi-output (MIMO) is an advanced technique that can help improve wireless communication systems by increasing the system's channel capacity. With multiple antennas used for both transmission and reception, MIMO systems can transmit and receive the same signals with different phases and amplitudes. Better performance is achieved by exploiting the spatial diversity and multipath propagation. For example, as shown in Figure 1, if signals with average transmitter power

P are transmitted through the MIMO systems and there are N_t number of transmitters. Then the signal strength transmitted by each antenna is $\frac{P}{N_t}$. When N_r number of receivers are used, then each sub-receiver can receive signal power of $\frac{P}{N_r}$ and the original data sequence can be regenerated through some signal-processing techniques. $h_{i,j}$ represents the fading coefficient transmitting from i-th channel to j-th channels .

After applying MIMO techniques in the MPPM systems, the communication system is able to transmit multiple symbols through various antennas. For example, if 2 receiving antennas and 2 transmitting antennas are used, 4 different symbols can be transmitted simultaneously, boosting the rate of information transmission and channel capacity greatly [14].

Fading effect is a non-negligible consideration that can affect the data quality and channel capacity correspondingly, leading to a failure of desirable performance. During propagation, signals experience attenuation, reflection and interference due to atmospheric conditions or obstacles. Then interference exists due to the attenuation and phase shift of each sub-signal. MIMO systems make use of the spatial diversity and various fading effects of each sub-channel to mitigate the overall fading effect. Overall data stream quality can be enhanced consequently, reducing SNR and increasing channel capacity [9].

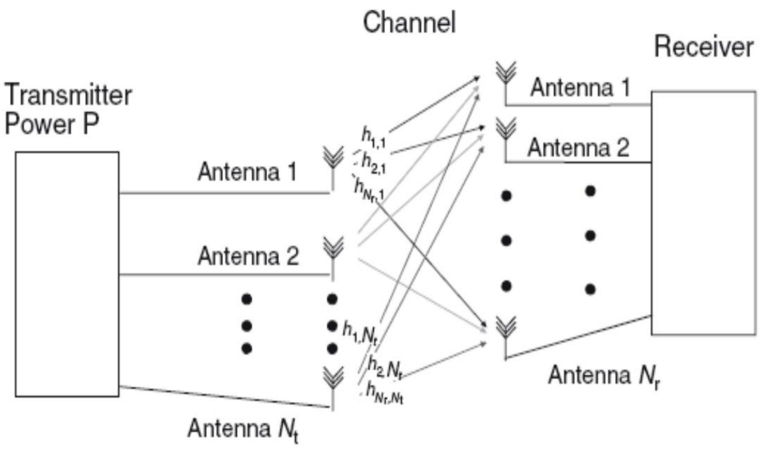

Fig 1. MIMO system [17]

2.5. pulse shaping

Pulse shaping modulation (PSM) is a technique used in communication systems to reduce inter-symbol interference (ISI) and improve channel capacity. ISI is a common problem in communication systems where multiple signals transmitted through a channel overlap and interfere, causing signal reception errors. PSM helps to reduce ISI by shaping the transmitted pulse to match the characteristics of the channel, resulting in a clearer and more reliable signal. PSM works by modifying the shape of the transmitted pulse to minimize interference with adjacent pulses. Several pulse shaping techniques exist, including Nyquist, raised cosine, and Gaussian pulse shaping. Each of these techniques has its advantages and disadvantages, depending on the characteristics of the channel and the data being transmitted.

PSM can benefit channel capacity a lot. Available channel capacity can be used more efficiently with lower ISI caused by better PSM, which means that a larger amount of information can be transmitted. This can be especially useful in high-speed communication systems like digital video and audio transmission. Another benefit of PSM is its ability to improve the reliability of communication systems. By reducing ISI, PSM can help prevent signal reception errors, which can lead to improved signal quality and fewer dropped connections. PSM also offers benefits in terms of power efficiency. By shaping the pulse to match the characteristics of the channel, PSM can reduce the amount of energy required to transmit a signal [18].

3. Key concepts of three modulation schemes

Three research about analysis of recent techniques used to improve MPPM communication systems further. Different techniques are combined with MPPM to improve the performance and effectiveness is figured out through experiments.

3.1. LDPC-coded MPPM UWOC systems

UWOC plays a key role in communication systems due to its security, high energy efficiency and fast communication. However, UWOC systems face a lot of challenges due to their complex nature, such as tide, surf or underwater obstacles. When transmitting underwater, received signals suffer from attenuation, delay spread and fading. Those impacts result from absorption and scattering due to suspended particles in the water, and turbulence effects. The turbulence effect represents the unstable intensity of optical signals due to the fluctuating refractive index of water. The effects mentioned above greatly influence UWOC performance. Since scattering and absorption are inevitable during the transmission, methods to undermine the fading effects over turbulence channels were proposed to investigate.

Various mathematical models can be applied to simulate different fading models, while the reference [7] adopted the Generalized-Gamma (GG) and exponentiated Weibull (EW) model to match the turbulence. Figure 2.1 presents a simplified flow block diagram of LDPC-coded MPPM UWOC systems over turbulent channels. Bits are LDPC-encoded before carrying out MPPM modulation. Then the electrical signal is converted into optical signal in the form of laser. Beam expander-and-collimator (BEC) and aperture averaging lens (AAL) are adopted at the transmitter side and receiver side, respectively to simulate different effects present in underwater scenarios, such as temperature gradients, salinity variation and air bubbles. After experiencing degradation caused by turbulence effects during transmission, optical signals are converted back to electrical signals through a photodetector (PD). Signals are regenerated after demodulation and recoding.

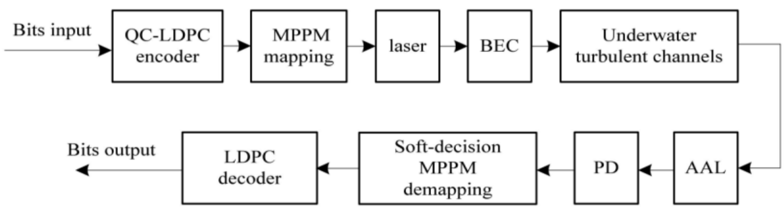

Fig 2. general block diagram of LDPC-coded MPPM UWOC systems over turbulent channels [7]

This reference [7] examined how LDPC codes could mitigate the effects of turbulence-induced fading by comparing the BER performance of a coded and uncoded MPPM UWOC system under various fading scenarios modeled by using GG distribution. GG and EW were adopted for the statistical distribution and were compared to observe the impact caused by different distributions.

(5,2) MPPM UWOC system was used to investigate the effectiveness of LPDC-code by observing the relation between average BER and average SNR in dB. The performance of LPDC-coded MPPM UWOC systems with different turbulence strength is investigated, and the scintillation index expresses the turbulence strength σ^2. Larger scintillation index (σ^2) represented stronger turbulence of the channel. The result (Fig 2.2) showed that coded system had better BER performance when the LDPC code was used in the MPPM UWOC system. The systems with different turbulence strengths showed the same characteristics, proving that the LDPC code can improve the UWOC MPPM systems regardless of the turbulence strength. It can be observed that the BER performance of LDPC-coded systems could be improved greatly when SNR is reasonably large, such as 6 dB 10dB and 14 dB, respectively, for weak, intermediate and strong turbulence. After exceeding those threshold values mentioned above, curves with a much larger gradient can be observed. Also, when comparing three coded curves with different turbulence strengths, it could be concluded that a much larger SNR ratio was required for a system with larger turbulence effects to achieve the same BER performance.

Another experiment was carried out using (6,3) MPPM UWOC system with different statistical distributions, such as log-normal, gamma- gamma, EW and GG, to consider the effects of the change in distributions may bring. The four distributions were used in the same UWOC systems. According to the result shown in Fig 2.3, it can be observed that the uncoded UWOC systems with four different distributions showed similar BER performances when SNR ratio was small, while the difference in BER performance became non-negligible when SNR was large enough. For coded UWOC systems, the same BER performance could be observed regardless of the magnitude of SNR ratio. It could be used to verify further that LDPC code can improve the UWOC systems effectively over channels with turbulence fading effects.

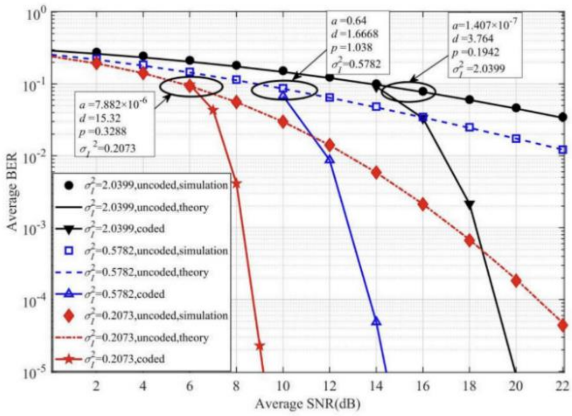

Fig 3. BERs of the (5,2) MPPM UWOC system with/without LDPC code in GG distributed fading channel with different scintillation indexes [7]

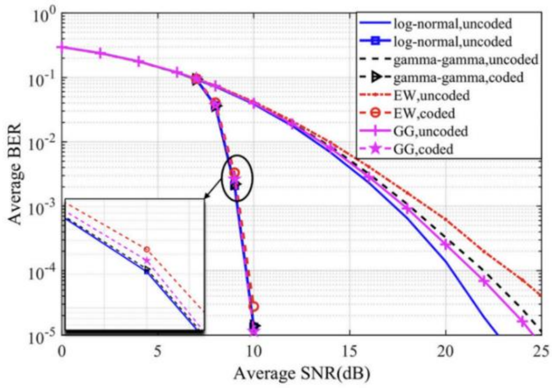

Fig 4. BERs of the (6,3) MPPM UWOC system with/without LDPC code in the same weak turbulence channel modeled by different statistical distribution [7]

3.2. PSM-MPPM

PSM-MPPM is an advanced modulation scheme that is based on MPPM communication system to improve optical communication systems further. It was proposed to investigate how pulse shape can affect signal transmission performance. A (2,5) MPPM was used for the basic modulation scheme and various PSM techniques would be combined with MPPM, including Manchester monocycle, Gaussian pulse, Gaussian monocycle, Scholtz's monocycle, step pulse, sine pulse, sawtooth pulse, triangular pulse and rectangular pulse. The effectiveness of different PSM was determined by BER performance in AWGN and the spectrum characteristics of transmitted signals. Those results were compared to figure out the impact of PSM-MPPM on overcoming noise distortion and improving BER performance. The experiment was simulated in MATLAB and AWGN channel was considered for the communication system. During simulation in MATLAB, a random message sequence with length of 1500 was generated, then the message signals were mapped to pulse sequence after carrying out (2,5) MPPM. PSM schemes reshaped pulses to different pulse shapes. The noise was added to the transmission side of the system to simulate the realistic condition. FFT was used to transform the signal from time domain to frequency domain to analyze spectrum characteristics. BER performance can be calculated by comparing the original signal at the transmission side and the demodulated transmitting signal.

According to the result shown as Fig 2.4, it can be concluded that PSM greatly affects the signal quality of the optical communication system. ISI is non-negligible with reasonably large pulses in the side-lobe, when Manchester monocycle, step pulse and sawtooth pulse are used for transmission. Among these PSM, sawtooth pulse presents the least desirable performance in ISI. Gaussian pulse and Scholtz's monocycle show low ISI, leading to less bit error during transmission. Therefore, BER performance can be improved by using suitable PSM. Besides ISI, channel capacity can be improved with higher bandwidth efficiency and more information transmission. Therefore, signals with lower bandwidth are preferred. Gaussian pulse has the narrowest bandwidth, while the Gaussian monocycle and Scholtz's monocycle have a much wider bandwidth than others. Apart from frequency spectral analysis, attenuation is another factor that needs to be considered. If the signal is not relatively large compared to the noise (low SNR ratio), it is more likely to lead to error. Rectangular pulse can generate signals with the largest amplitude in the frequency domain.

SNR is a factor that can influence BER performance. With a higher SNR ratio, the communication system has the After calculating BER performance of demodulated signals, it is concluded that Gaussian pulse and triangular pulse have the best BER performance, and sawtooth pulse shows the worst BER performance.

Different PSM can benefit the MPPM system in various aspects and a compromise should be made to choose a relatively suitable pulse shape for the PSM-MPPM schemes [19].

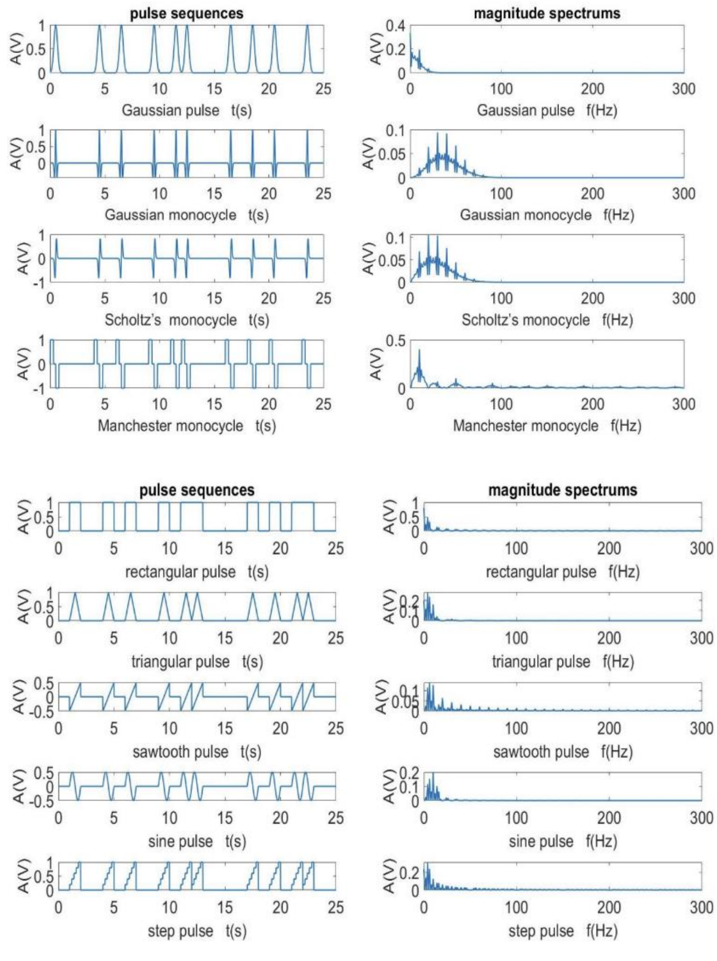

Fig 5. signal spectrum in time domain (left) and frequency domain (right) after PSM-(2,5)MPPM [19]

3.3. MPPM-coded WOC MIMO system over correlated fading channel

Wireless optical communication (WOC) combines the benefits of optical fiber links and wireless communications, making it an attractive field of research. However, WOC faces significant challenges, including channel fading caused by atmospheric attenuation and turbulence and pointing error caused by dynamic wind loads, thermal expansion, and vibrations. To address these issues, much research has focused on using multiple-input multiple-output (MIMO) technology to improve system performance. H.S. Khallaf et al. compared the performance of both correlated and uncorrelated systems when adopting SISO and MIMO separately and found that MIMO can improve SER performance greatly. However, previous investigations have neglected the spatial correlation of MIMO subchannels, which can limit the benefits of multiple lasers in practical applications. Additionally, background radiation is a major noise source in WOC MIMO links, and modulation formats such as on-off keying (OOK) and pulse position modulation (PPM) have limitations.

To address these issues, the reference proposed an MPPM-coded WOC MIMO system and analyzed its performance in the presence of atmospheric attenuation, turbulence, pointing error, spatial correlation, and background radiation. Approximate expressions were derived for the system's symbol error rate and ergodic channel capacity to achieve a practical performance bound. Numerical simulations using the Monte Carlo method confirm the effectiveness of the proposed system.

According to result shown as Fig 2.5, it can be concluded that the MPPM-MIMO system is more effective on uncorrelated channels, since uncorrelated systems showed better BER performance. The figure indicates that (5,4) MPPM has better performance than PPM schemes over uncorrelated channels. While for correlated channel, similar BER performance can be observed for both PPM and MPPM channels. Independent (2,5) MPPM shows the best BER performance among all the channels. (CE: the condition of combined effects, iid: independent identically distributed, cor: correlated channel, r: correlation coefficient)

Results about ergodic channel capacity can be found in fig 2.6. The relation between channel capacity and energy of signal can be observed on the plot. The curve increases gradually and stabilizes when signal energy increases 60dB.8-PPM channel show a similar channel capacity at 0.4 bits/channel use, which are worse than all the other channels. 4-PPM channels have better channel capacity at 1.4 bits/channel use and (2,5) MPPM has the highest capacity with 3.4 bits/channel values. It also can be concluded that the channel capacity is independent of the correlation efficiency [11].

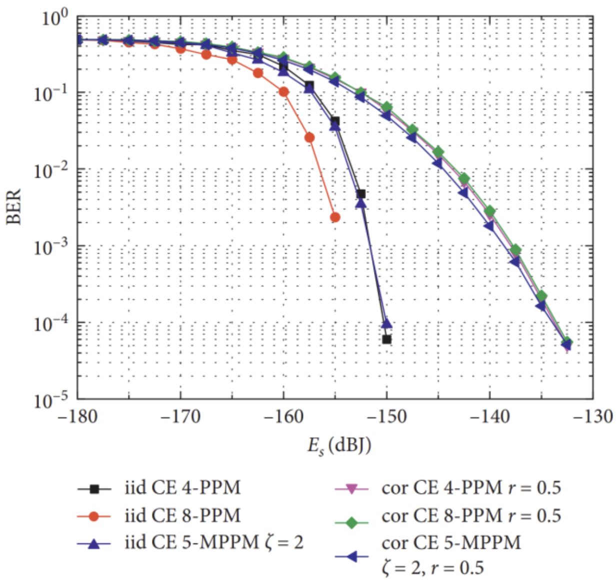

Fig 6. BER performance of different MPPM modulation methods in a 2 × 2 WOC MIMO system [11]

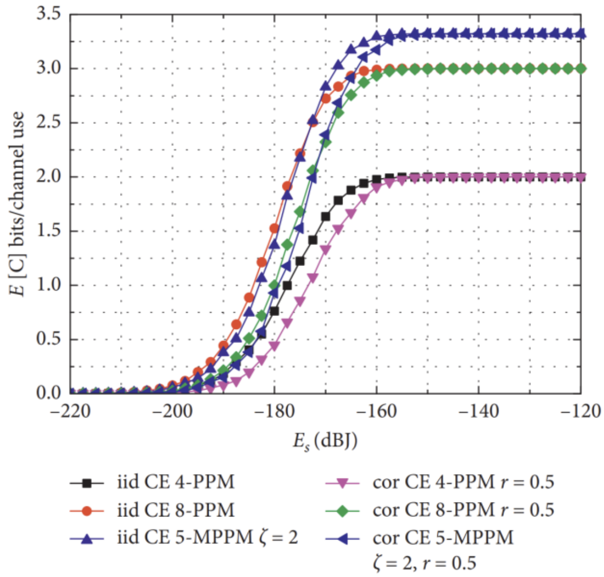

Fig 7. Ergodic channel capacity of different modulation methods in a 2× 2 MIMO system [11

3.4. Comparison between three schemes

Table 1. Comparison Between Three Schemes

Modulation schemes	Application scenario	Channel considered	Ways to improve channel capacity	Effect of Correlation of channel
LDPC-coded MPPM UWOC system	Underwater wireless optical communication	Turbulence UWOC channel	Better BER performance	Uncorrelated channels show better BER performance
PSM-MPPM system	No specific application scenario	AWGN channel	Less ISI & higher bandwidth efficiency	No multichannel used
MIMO-MPPM WOC system	Atmospheric wireless optical communication	Correlated fading channel	Better SER performance	Uncorrelated channels show better BER performance

Table 1 compares some key aspects of recent research focusing on three different methods: LDPC-code MPPM, PSM-MPPM and MIMO-MPPM. They can be used to improve the channel capacity of optical communication systems in different ways. Those three methods focus on different scenarios. For LDPC-coded MPPM, it was proposed to utilize in UWOC systems, which means that turbulence fading effects need to be considered. Different statistical distributions were adapted to fit different disturbances imposed on the signals. For PSM-MPPM, AWGN channel is used for simulating the modulation scheme. Advanced research with a more sophisticated modeling method is required for more accurate results. For MIMO-MPPM, it can be used for WOC, so atmospheric attenuation is considered, and numerical expressions are used to represent the combined effects of attenuation. For first and third methods, a result can be verified that modulation schemes can improve uncorrelated channels greatly with better BER performance compared to that obtained from correlated channels.

All in all, MIMO-MPPM provides higher channel capacity and better BER performance than LDPC-coded MPPM UWOC and PSM-MPPM in multi-user scenarios. However, its implementation is more complex and requires multiple antennas and sophisticated signal processing. LDPC-coded MPPM UWOC has lower complexity and better performance in underwater optical communication scenarios with high levels of noise and distortion. PSM-MPPM is a promising approach for satellite communication with higher data rates, but it may be less robust in the presence of atmospheric turbulence and other types of interference.

4. Conclusione

In conclusion, the three methods discussed in this essay, LDPC-coded MPPM, MPPM-MIMO, and PSM-MPPM, are effective in improving the capacity of MPPM channels. LDPC-coded MPPM is useful for improving the BER performance of MPPM signals, and MPPM-MIMO is also helpful in bettering the BER performance. PSM-MPPM can effectively reduce the ISI effects and enhance bandwidth efficiency of MPPM signals. In addition, it is figured out that correlation efficiency of channels can affect the effectiveness of MPPM. Channels with higher independence can generate better quality of signals after using MIMO-MPPM or LDPC-MPPM schemes. However, each method has its advantages and disadvantages, and the choice of method depends on the specific requirements of the application. In general, combining these techniques can lead to further improvement in the capacity of MPPM channels. Future research should focus on optimizing these methods to achieve higher capacity, reducing implementation complexity, and evaluating their performance in practical applications.

References

[1] D. Evans, "Connections the quarterly journal.," *Connections the quarterly journal*, 01-Jan-1970. [Online]. Available: https://connections-qj.org/article/internet-things-how-next-evolution-internet-changing-everything-white-paper. [Accessed: 18-Mar-2023].

[2] S. Gu, C. Liang, and J. Zhang, "Spectral analysis of (multi-) pulse-position modulation," *Journal of Physics: Conference Series*, vol. 2093, no. 1, p. 012024, 2021.

[3] N. Yu, P. Wang, and Z. Zhuang, "Design of digital pulse-position modulation system," *Journal of Physics: Conference Series*, vol. 2093, no. 1, p. 012030, 2021.

[4] H. Sugiyama and K. Nosu, "MPPM: A method for improving the band-utilization efficiency in optical PPM," *Journal of Lightwave Technology*, vol. 7, no. 3, pp. 465–472, 1989.

[5] I. P. Kaminow, T. Li, and A. E. Willner, in *Optical Fiber Telecommunications Volume VIB: Systems and Networks*, Elsevier Science, 2013, pp. 1–43.

[6] "A mathematical theory of Communication | Nokia Bell Labs journals ..." [Online]. Available: https://ieeexplore.ieee.org/document/6773024. [Accessed: 18-Mar-2023].

[7] H. Jiang, N. He, X. Liao, W. Popoola, and S. Rajbhandari, "The BER performance of the LDPC-coded MPPM over turbulence UWOC channels," *Photonics*, vol. 9, no. 5, p. 349, 2022.

[8] R. Chataut and R. Akl, "Massive MIMO systems for 5G and beyond networks-overview, recent trends, challenges, and future research direction," *MDPI*, 12-May-2020. [Online]. Available: https://www.mdpi.com/1424-8220/20/10/2753. [Accessed: 18-Mar-2023].

[9] B. Wu, "Analysis on theory of MIMO and research on channel capacity of MIMO System," *Journal of Physics: Conference Series*, vol. 1738, no. 1, p. 012002, 2021.

[10] H. S. Khallaf, J. M. Garrido-Balsells, H. M. H. Shalaby, and S. Sampei, "SER analysis of MPPM-coded MIMO-FSO system over uncorrelated and correlated gamma-gamma atmospheric turbulence channels," *Optics Communications*, vol. 356, pp. 530–535, 2015.

[11] Y. Zhang, H. Wang, M. Cao, and Z. Bao, "Performance evaluation of MPPM-coded wireless optical MIMO system with combined effects over correlated fading channel," *International Journal of Antennas and Propagation*, 18-Aug-2020. [Online]. Available: https://www.hindawi.com/journals/ijap/2020/7983812/. [Accessed: 18-Mar-2023].

[12] F. Wang, G. Hu, T. Du, Y. Sun, X. Hao, J. Chen, and P. Wu, "Performance research of MPPM-QPSK modulation signal for Free Space Optical Communication," *Optics Communications*, vol. 457, p. 124646, 2020.

[13] Y. Liu and C. Wang, "The research on transmission effect of different pulse shapes in MPPM," *2022 14th International Conference on Computer Research and Development (ICCRD)*, 2022.

[14] "Performance Analysis of MIMO Wireless Communications Over Fading Channels." [Online]. Available: https://www.rroij.com/open-access/performance-analysis-of-mimo-wirelesscommunications-over-fading-channels--areview.pdf. [Accessed: 18-Mar-2023].

[15] M. A. Parker, "12.8 Shannon Capacity and Limit Theorems," in *Digital Signal Processing 101 everything you need to know to get started*, Oxford, United Kingdom: Newnes, an imprint of Elsevier, 2017.

[16] S. Borwankar and D. Shah, "Low density parity check code (LDPC codes) overview," *arXiv.org*, 18-Sep-2020. [Online]. Available: https://arxiv.org/abs/2009.08645. [Accessed: 18-Mar-2023].

[17] W. Abbas, N. Abbas, and U. Majeed, "Efficient STBC for the data rate of MIMO-OFDMA - Researchgate," MIMO. [Online]. Available: https://www.researchgate.net/profile/Waseem-Abbas-12/publication/293811680_EFFICIENT_STBC_FOR_THE_DATA_RATE_OF_MIMO-OFDMA/links/56bb6bc008ae3f9793152b38/EFFICIENT-STBC-FOR-THE-DATA-RATE-OF-MIMO-OFDMA.pdf. [Accessed: 18-Mar-2023].

[18] T. Numata and H. Habuchi, "Figure 3 from an optical MPPM-PSM scheme for increasing data transmission rate: Semantic scholar," *2011 8th International Conference on Information, Communications & Signal Processing*, 01-Jan-1970. [Online]. Available: https://www.semanticscholar.org/paper/An-optical-MPPM-PSM-scheme-for-increasing-data-rate-Numata-Habuchi/9f3df44a30d0251f2f124536cacf1b89ace4457e/figure/2. [Accessed: 18-Mar-2023].

[19] Y. Liu and C. Wang, "The research on transmission effect of different pulse shapes in MPPM: Semantic scholar," *2022 14th International Conference on Computer Research and Development (ICCRD)*, 01-Jan-1970. [Online]. Available: https://www.semanticscholar.org/paper/The-Research-on-Transmission-Effect-of-Different-in-Liu-Wang/de3267babd617724c99c04c18c0e624077b69803. [Accessed: 18-Mar-2023].