Spectral Analysis of (Multi-) Pulse-Position Modulation

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Abstract—Nowadays, laser communication has received great achievements owing to its advantages, e.g., large channel capacity, easy miniaturization of communication system and strong anti-interference ability in different conditions. Pulse position modulation (PPM), as an important modulation technology in laser communication system that transmit signal with lower power, is attracting much attention. However, the performance of the modulation scheme highly depends on the bandwidth of transmission. To remedy this defect of PPM, the multi-pulse position modulation (MPPM) scheme is proposed to increase the accuracy and bandwidth limit. This modulation scheme has stronger anti-interference ability than PPM. Therefore, there has been rising interest in studying the characteristics of the multi-PPM. In this article, we developed an appropriate mathematical model to represent a PPM transmission, analyzed the spectrum of the transmission and characterized the bandwidth of this transmission. Compared with benchmarks of MPPM scheme, its performance has been discussed. According to the analysis, MPPM strongly increases band-utilization efficiency, however PPM has a better bit error rate (BER) performance than MPPM.

1. Introduction
Contemporarily, following the development of Internet of Things (IoT), Deep Space Communication System and medical robots [1-4], communication systems are required to work more stably in challenging conditions. However, traditional modulation schemes, such as Amplitude Shift Keying (ASK) can be easily disturbed by noise or transmission loss. To tackle this issue, in 1989, Sugiyama H and Nosu K [1] first introduced the MPPM modulation scheme, which can increase the bandwidth efficiency by increasing the number of pulses and charging the position of pulse. In the next 30 years, MPPM modulation is widely used in the laser communication system [2]. The system required optical quantum detector has the resolution to distinguish single quantum [3]. Therefore, MPPM are always chosen to be the modulation method of the system because its higher optical power utilization as well as frequency band utilization, and can improve the anti-interference ability of transmission channel, increase communication distance and many other advantages [4]. In this paper, an mathematical model is developed to represent MPPM modulation. Using the model, we analyzed the spectrum of the transmission and compared the performance of MPPM with PPM. We also added noise to the transmission channel to simulate a real-life modulation environment. This paper will show
the spectral analysis result and the performance comparison of MPPM scheme with some other existing modulation schemes.

The main aspects of this work can be summarized as two parts. We developed an appropriate mathematical model that represent MPPM transmission and applied the mathematical model to MATLAB for spectral analysis.

We use MPPM for modulation in MATLAB. We chose a random signal as the modulated signal, and compared the signal correlations between original signal, modulated signal, signal pass channel and demodulated signal, to find out the transmission characteristics of MPPM like the bandwidth of the signal for one or more pulse shapes. Then, we compare the same transmission characteristics of PPM and ASK to study the difference in transmission efficiency and accuracy of these models. According to the results, the conclusions about the relative superiority of MPPM scheme and what conditions is most suitable for MPPM modulation [5-8] are drawn.

The rest of the paper is organized as follows: In section 2, 2 signal’s spectrum (Ideal 4-PPM signal and 4-PPM signal with noise) are analyzed, which shows the relationship of spectrum with frequency or time [6]. In section 3, the difference of 4-PPM and PPM modulation are be shown and analyzed based on the Bit Error Rate (BER), Signal to Noise Ratio (SNR) and the Quality factor (Q Factor) [9, 10]. Finally, section 4 gives a brief summary.

2. Methods

In order to find out the relative superiority of MPPM, the spectrum of the MPPM has to be analyzed to observe the spectral characteristics of MPPM modulation scheme. One way to perform spectral analysis is to use program analysis, because signal is always combined with random noise in the area of telecommunications, and it is impossible to observe, by eye, the underlying pulse signal. The signal in the channel would be completely random and comprised of noise. However, based on fast Fourier transformation (FFT), one can check the Discrete Fourier Transform (DFT) of the signal, to see if any spectral peak exists. Moreover, in order to utilize the FFT function for spectral analysis, a mathematical model for MPPM modulation scheme has to be derived and performed. Thus, the spectral analysis for MPPM can be separated into two parts, one is to develop a mathematical model for MPPM and the other is to compute the DFT, IDFT of the model and use them for spectrum filtering to get the power spectral density (PSD), spectral resolution and other important parameters. Subsequently, to check the advancement of MPPM compared to PPM, and verify the applicability of MPPM in telecommunication field, it is required to modulate the same signal using PPM and MPPM and pass it through a channel with random noise, and check some of the important quantified indicators of performance. Figure 1 shows the overall framework of our analysis on MPPM.

2.1. Spectral analysis

2.1.1. Mathematical model

To choose an appropriate mathematical model for a MPPM transmission, the PPM modulation scheme should be simplified. Related to the basic working principle of PPM scheme, the only parameter that keeps changing in PPM scheme is the position of the pulses. Therefore, it is quite important for us to
characterize the offset in the PPM mathematical model. Besides, we can refer to the mathematical model for data pulse sequence, which can be formulated as:

\[ s_i(t) = \sum_k a_i g(t - kT) \]

(1)

where \( T \) indicates the sampling period and \( a_i g(t - kT) \) represents the amplitude of the \( k \)th sampled pulse.

MPPM, unlike PPM, maps \( n \)-bit binary bits to a PPM symbol composed of \( M \) information timeslots according to certain rules, in which there are signal pulses in at least two out of \( M \) information timeslots. Figure 2 illustrates the schematic diagram of MPPM modulation.

\[ \text{Fig. 2 The schematic diagram of MPPM modulation} \]

2.1.2. Spectrum analysis

Based on the obtained mathematical model, we first use Simulink in MATLAB to simulate the MPPM modulation. This step shows us simulation of the MPPM modulation of a message signal that we randomly create. Then, by employing the simulation result to the spectrum analyzer in Simulink, one obtains the spectrum of this certain MPPM scheme. Finally, to make the simulation result more relate to real-life scenario, noises are added to the transmission channel to acquire the signal spectrum with noise for comparison in next step.

2.2. Key characteristics of MPPM and PPM

Because the development of MPPM is to compensate some of the backbones of PPM, e.g., its lower band-utilization efficiency. It is worthwhile to investigate whether such improvement in efficiency would also bring some improvement in Bit Error Rate (BER), Signal to Noise Ratio (SNR) and the Quality factor (Q Factor). Therefore, the same analog signal in MATLAB is modulated by PPM and MPPM modulation scheme respectively. Afterward, the modulated signal is passed through a noisy channel and then demodulate it. Therewith, those quantified parameters mentioned above are compared, which will be done for multiple pairs of input signal with different signal types to add reliability to the research.

3. Experiment

In order to analyze of the experiment simpler, 4PPM modulation scheme is utilized, which is also an MPPM scheme that allows 4 signal pulses to exist among \( M \) information time slots. Using 4PPM won’t affect the accuracy of the comparison, meanwhile this can increase the efficiency of our experiment.
Fig. 3 The message signal and the signal after PPM modulation

Fig. 4 The message signal and the signal after 4PPM modulation

Figures 3 and 4 is a comparison of the simulation result of the same signal under PPM modulation and 4PPM modulation scheme. According to the results, only one pulse is obtained in each sampling period PPM modulation scheme, while 4 pulses are observed in the 4PPM modulation scheme. Compared with the PPM scheme, 4PPM strongly increases the band-utilization efficiency.
Figures 5 and 6 are the spectrum analysis of the 4PPM and PPM signal modulation scheme, it is obvious that using 4PPM the transmission bandwidth could be reduced to about half that of conventional PPM modulation scheme at the same information rate.

Fig. 7 The 4PPM modulated signal through noisy channel
Fig. 8 The PPM modulated signal through noisy channel

Fig. 9 The autocorrelation function of 4PPM modulated signal through noisy channel

Fig. 10 The autocorrelation function of PPM modulated signal through noisy channel
Figures 7~12 displays the performance of 4PPM and PPM scheme in noisy environment. Based on these results, PPM has a better performance in bit-error rates (BERs) than MPPM at the same information rate and allowing different bandwidth utilizations.

4. Conclusion
In summary, the spectrum results of PPM modulation and MPPM modulation are presented through the basic model of PPM and MPPM communication system. After comparing and analyzing the bandwidth of the two, it is verified that the transmission bandwidth required by MPPM is narrower than the bandwidth required by PPM. However, in terms of BER PPM outperforms MPPM, which means the use of MPPM will decrease the reliability of the transmission.

In the future, there are still many problems ought to be further investigated, e.g., more suitable reliability coding for PPM to enhance the reliability of information transmission, synchronization algorithm that is easy to implement and simple to operate, and the selection and application of synchronization algorithm in practical engineering. Additionally, it is promising to propose an updated version of MPPM that can fix the problem of increased error rate. These results offer a guideline for future study on the functionality of other newly-developed signal transmission modulation schemes.
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