Transfer Transmission Performance of Differential Multi-pulse
Position Modulation in Optical Communication

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Abstract
To needs the requirement of space optical communication network, a high speed laser communication in satellite
links is necessary, and the modulation technology is the basis of large capacity and wide band communication.
In this paper, a novel differential multi-pulse position modulation scheme is proposed to reduce the bandwidth
requirement and increase the transmission rate. Firstly, based on the theory of pulse position modulation,
combined with the characteristic of differential pulse position modulation (DPPM), a differential multi-pulse
position modulation (DMPPM) scheme model is established by introducing the multi-pulse position modulation
(MPPM) mode. Based on the character of the symbol structure of the model, the unit transmission rate equation
of DMPPM is derived, and the bandwidth requirement model is established according to Gauss channel
Shannon formula. Finally, based on the established model, the transmission characteristics of the new scheme
are simulated, and the results are compared with other schemes. The research results show that, in terms of the
unit rate of transmission and bandwidth demand, when N is small, DMPPM scheme is similar to that of other
schemes, with the gradual increase of N, the performance of the new scheme quickly exceed the others, and has
obvious advantages. The results of this study can be applied to the new optical communication modulation
technology, which can achieve higher transmission rate in case of large bit number information.

Key words: Free Space Optical Communication, Differential Multi-Pulse Position Modulation, Unit Rate Of
Transmission, Bandwidth Requirement, Transmission Efficiency.

1. INTRODUCTION
With the continuous development of laser communication technology, space laser communication network
has become one of the key researches. In the field of space communication, compared with traditional
microwave communication, laser communication has the characteristics of high secrecy, high transmission rate
and high power utilization. However, with the increasing demand of information capacity in daily life, the
performance of the laser device severely restricts the rapid development of laser communication technology.
Under the premise of the slow development of laser devices, in order to achieve a higher rate of transmission,
the modulation scheme with high transmission rate and low bandwidth requirement is necessary. Therefore, it is
an urgent need to design a new modulation scheme and improve the bandwidth utilization of the present laser.

2. STATE OF THE ART
At present, the most widely used in laser communication technology is the intensity modulation/direct
detection (IM/DD) technology (Eric, 2010; Colin, 2012; Mohamed, 2014). One of the most simple method is to
on-off keying (OOK), which easy to realize, but the anti-interference performance is poor. With the
development of laser modulation technology, phase modulation, pulse width modulation (PWM) and pulse
position modulation (PPM) has been proposed in succession (Selvi and Murugesan, 2012). Among them, PPM has become one of the research focused in the research of laser communication modulation technology, due to its excellent anti-interference ability. In order to further improve the transmission rate of the pulse position modulation, the multi-pulse position modulation (MPPM) and the differential pulse position modulation (DPPM) have been invented based on the classical PPM theory (Xu and Zhou, 2011; Gopal and Jain, 2014). The bandwidth utilization of DPPM has been greatly improved, but its error rate is high. Xu et al. established a packet error rate (PER) model, the simulation of the model shows that when the signal-to-noise ratio (SNR) is constant, DPPM the PER of DPPM is 2 orders of magnitude higher than that of PPM (Xu and Zhou, 2011). MPPM can effectively control the bit error rate (BER) and improve the stability of the system, but its bandwidth utilization is poor. Michael Bacher set up a relative power model, in order to obtain the relationship between the relative power of various modulation schemes and the original data rate (Bacher and Arnold, 2014). An equivalent noise parameter is set in the simulation, and the simulation results show that when the relative power is -5dB, the raw data rate of PPM reached saturation 500Mbps. At the same time, the raw data rate of 4-MPPM is 600Mbps, and it can continuously rise with the increasing of the relative power, finally reach 900Mbps. Pooja Gopal et al compared the waveform of PPM, DPPM, MPPM and other modulation methods, the simulation shows that the bandwidth utilization of PPM and MPPM is the same, but much lower than that of DPPM (Gopal and Jain, 2014). The research results show that DPPM does not need clock synchronization, can improve the utilization rate of bandwidth, but will produce a great deal of error; while MPPM can expand the information capacity, has high reliability, but cannot improve the bandwidth utilization. Consequently, in this paper, DPPM scheme is designed based on DPPM by introducing MPPM, to integrate the advantages of them, and improve the transmission rate under the premise of system stability.

The remainder of this paper is organized as follows. Section 3 studies the symbol structure of PPM, DPPM, MPPM and DMPM. Then the formula of the unit rate of transmission is derived, and the model of bandwidth requirement is established. Section 4 analyzes the unit transmission rate and the bandwidth requirement based on the results of the simulation. Conclusions are summarized in Section 5.

3. METHODOLOGY

Different symbol structure determines its modulation performance has great differences. Based on the characteristics of the model of the four modulation schemes, the unit rate of transmission formula is derived, and the bandwidth requirement model is established according to Gauss channel Shannon equation. The results show that two indicators, the unit rate of transmission and bandwidth requirement, are related to their symbol structure, and shows a large difference in performance with the symbol parameter p and N.

3.1. Model of the Modulation Scheme

The principle of PPM modulation is to describe the information by the pulse position in a time period. But different modulation schemes have different symbol structure, which lead to different modulation performance.

Classical PPM theory is to divide one information period $T$ into $m$ time slots, the width of each time slot is $\tau = T/m$. The modulator only occurs one optical pulse signal in one of the time slot, and the position of the pulse represents one bit information. With the increasing of time slots number, the power utilization of this modulation method is far more than that of OOK, but the bandwidth requirement will rise. DPPM is an improvement of PPM, by deleting all the “off” behind the “on” time slot (Gopal and Jain, 2014). As the symbol length of DPPM decreases, its duty cycle increases, so the power utilization ratio is improved. MPPM is to send several pulses in one information period, which can describe information of several bits by using less time slots. In order to facilitate the expression, it usually denoted as $[N, p]_{\text{MPPM}}$. Where N denotes the bit number of information, and $p$ represent the pulse number in symbol. In order to improve the modulation performance, the DMPM scheme is proposed in this paper. Based on MPPM, all the “off” behind the last pulse of the symbol is removed, and the other time slots are reserved. Since the symbols of DMPM and DPPM are both ended by a pulse signal, so they do not need frame synchronization, which greatly reduce the demodulation difficulty. At the same time DMPM has the same characteristics of MPPM that, the information period is significantly shorter than others.

The symbol structure and the symbol length is given in Table 1.

From Table 1, when the signal source is a 3 bits binary number, the classical PPM modulation requires an information frame period which contains 8 slots, and only one pulse in the period. The symbol length of DPPM is obviously shorter than that of PPM, because the “off” slots behind the pulse in the period are removed. The symbol length of MPPM is also shorter than PPM, for it can describe information with multiple pulses in one information period. The pulse number in Table 1 P=2, with the increasing of $p$, the symbol length can be further shorten. The symbol length of DMPM is shorter than MPPM.
Table 1. Symbol in variety modulation schemes

<table>
<thead>
<tr>
<th>Signal source</th>
<th>PPM</th>
<th>DPPM</th>
<th>MPPM(p=2)</th>
<th>DMPPM(p=2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>1000,0000</td>
<td>1</td>
<td>00110</td>
<td>0011</td>
</tr>
<tr>
<td>001</td>
<td>0100,0000</td>
<td>01</td>
<td>01001</td>
<td>01001</td>
</tr>
<tr>
<td>010</td>
<td>0010,0000</td>
<td>001</td>
<td>00101</td>
<td>00101</td>
</tr>
<tr>
<td>011</td>
<td>0001,0000</td>
<td>0001</td>
<td>00011</td>
<td>00011</td>
</tr>
<tr>
<td>100</td>
<td>0000,1000</td>
<td>0000,1</td>
<td>11000</td>
<td>11</td>
</tr>
<tr>
<td>101</td>
<td>0000,0100</td>
<td>0000,01</td>
<td>10100</td>
<td>101</td>
</tr>
<tr>
<td>110</td>
<td>0000,0010</td>
<td>0000,001</td>
<td>10010</td>
<td>1001</td>
</tr>
<tr>
<td>111</td>
<td>0000,0001</td>
<td>0000,0001</td>
<td>01100</td>
<td>011</td>
</tr>
</tbody>
</table>

As the signal source is a N bits binary number, the symbol length of PPM is \( l_{PPM} = 2^N \).
Due to symbol length of DPPM and DMPPM is not constant, the average symbol length is analyzed below.

The minimum symbol length of DPPM is 1, and the maximum length is M, then
\[
\frac{l_{DPPM}}{2} = \frac{l_{PPM} + 1}{2}.
\]
The minimum symbol length of DMPPM is \( p \), and the maximum length is \( \frac{l_{MPPM}}{2} \), then
\[
\frac{l_{DMPPM}}{2} = \frac{l_{MPPM} + p}{2}.
\]
Where the symbol length of MPPM should satisfy that \( \log_2 C_{\text{wouv}}^{p} \geq N \).

3.2. Unit rate of Transmission

The unit rate of transmission can be derived from the symbol structure above, which indicates the bit number transmitted per second, and it is an important parameter for comparing the transmission efficiency of different modulation schemes (Gong and Guo, 2015). The rate of transmission is expressed by \( \nu \),
\[
\nu = R/B(\text{bit/s}^{-1} \cdot \text{Hz}^{-1}),
\]
in which \( R \) is the transmission rate (\( \text{bit/s}^{-1} \)), \( B \) is the signal bandwidth. For various modulation schemes, the information frame period is \( T \). The duration of the information frame is \( T_{\text{slot}} \). Pulse duration is \( \tau \). Usually, the laser operates in a pulse state, its corresponding bandwidth \( B = 1/\tau \). The analysis of this paper is carried out under the ideal conditions, that is, pulse duration \( \tau = T_{\text{slot}} \), then \( B = 1/T_{\text{slot}} \). Set the information transmission rate \( R_b \), the unit transmission rate of PPM is:
\[
\nu_{PPM} = \frac{R_b}{B_{PPM}} = \frac{N}{T} \cdot \frac{1}{T_{\text{slot}}} = \frac{N}{l_{ppm}} = \frac{N}{2^N}.
\]
(1)

Similarly, the unit rate of transmission of DPPM, MPPM and DMPPM are:
\[
\nu_{DPPM} = \frac{N}{2^N + 1}
\]
(2)
\[
\nu_{MPPM} = \frac{N}{m}
\]
(3)
\[
\nu_{DMPPM} = \frac{2N}{m + p}
\]
(4)

3.3. Bandwidth Requirement

The bandwidth requirement can be reduced based on the Gaussian channel theory, which is also decided by the model of the modulation scheme analysis above.

Gaussian channel produces Shannon equation \( C_s = \lim_{T \to \infty} C = W \log \left( 1 + \frac{P}{N_0 W} \right) \text{(bit/s)}, \) \( (P_s \text{ is signal average power, } N_0 W \text{ is the average power of white } \text{Gaussian noises in bandwidth } W, \text{ power spectral density is } N_0/2) \) (Liu, 2010).

In Gaussian channel, channel capacity (the maximum amount of information that can be transmitted in the channel) is related to the bandwidth and SNR. When the bandwidth tends to infinity, the amount of information tends to the limit. For the modulation scheme, the less the transmission bandwidth of each frame, the larger the total transmission, the greater the bandwidth of the Shannon equation.

For different modulation schemes, under the same conditions of \( N \), the bandwidth requirement is the reciprocal of the slots duration time. The bit rate is recorded as \( R_b \) (bits transmitted per second bit/s), and the bandwidth requirement of the PPM modulation is:
Similarly, the bandwidth requirements of DPPM, MPPM and DMPPM are:

\[
B_{\text{DPPM}} = \frac{f_{\text{DPPM}}}{N/R_b} = \frac{2^N + 1}{2N} R_b
\]

(6)

\[
B_{\text{MPPM}} = \frac{f_{\text{MPPM}}}{N/R_b} = \frac{m}{N} R_b
\]

(7)

\[
B_{\text{DMPPM}} = \frac{f_{\text{DMPPM}}}{N/R_b} = \frac{m + p}{2N} R_b
\]

(8)

4 RESULT ANALYSIS AND DISCUSSION

The unit rate of transmission and bandwidth requirement is researched by simulation. The results show that the related parameters of different modulation schemes have great differences. In MPPM and DMPPM, the value of \( N \) and \( p \) are important parameters which can decide the unit rate of transmission and bandwidth requirement. They have great significance to the system performance.

4.1. Comparison of the Unit Rate of Transmission

In 3.2, based on the symbol structure character, the four unit rate of transmission formular is derived. According to these formular, the unit rate of transmission varies with the parameter \( N \) and \( p \). The simulation is shown as Figure 1.

Figure 1. The comparison of unit rate of transmission.

Figure 1.(a) shows the curve of that the unit rate of transmission of PPM, DPPM, MPPM and DMPPM (the pulse number \( p = 2 \)) varies with the bit number \( N \) of each symbol. Figure 1.(b) shows the curve of that the unit rate of transmission of MPPM and DMPPM varies with the bit number \( N \) when the pulse number \( p = 2 \) and \( p = 3 \). Figure 1.(c) shows the curve of that the unit rate of transmission of MPPM and DMPPM varies with the pulse number \( p \) when the bit number \( N \) is 10.

From Figure 1.(a), it can be found that the unit rate of transmission of PPM and DPPM gradually reduced when \( N \geq 2 \). In special circumstances, the unit rate of transmission of PPM are the same when \( N = 1 \) and \( N = 2 \).

The unit rate of transmission of \([N, 2]\)MPPM gradually increases when \( 1 \leq N \leq 3 \), and gradually reduces when \( 3 \leq N \). It reaches peak when \( N = 3 \). The unit rate of transmission of \([N, 2]\)DMPPM gradually increases when \( 1 \leq N \leq 5 \), and gradually reduces when \( 5 \leq N \). It reaches peak when \( N = 5 \). With vertical comparison, we
can find the unit rate of transmission of \([N, 2]DMPPM\) is the largest of all when \(3.2 \leq N\), the unit rate of transmission of \([N, 2]MPPM\) ranks second. The unit rate of transmission of PPM is the least, which is a bit less than that of DPPM. And regardless of the value of the \(N\ (3.2 \leq N\), the relationship will remain.

The Figure1.(b) shows that the unit rate of transmission of \([N, 3]MPPM\) gradually increases when \(1 \leq N \leq 5\); and gradually reduces when \(5 \leq N\). It reaches peak when \(N = 5\). The unit rate of transmission of \([N, 3]DMPPM\) gradually increases when \(1 \leq N \leq 5\), and gradually reduces when \(8 \leq N\). It remains maximum and constant when \(5 \leq N \leq 8\). The unit rate of transmission of \([N, 2]MPPM\) is higher than that of \([N, 3]MPPM\) when \(1 \leq N \leq 2\), and keeps the same with that when \(2 \leq N \leq 3\), it is lower than that of \([N, 3]MPPM\) when \(3 \leq N\). The unit rate of transmission of \([N, 2]DMPPM\) is higher than that of \([N, 3]DMPPM\) when \(1 \leq N \leq 4\). The unit rate of transmission of \([N, 3]DMPPM\) is higher than that of \([N, 2]DMPPM\) when \(4 \leq N\). The unit rate of transmission of \([N, 2]MPPM\) is higher than that of \([N, 3]MPPM\) when \(1 \leq N \leq 8\), and lower when \(8 \leq N\).

Figure1.(c) shows that when the bits per symbol is certain (suppose \(N=10\)), the unit rate of transmission of \([N, p]MPPM\) and \([N, p]DMPPM\) increases rapidly to its maximum value with the increasing of the number of pulses per symbol, and then slowly decreases.

The unit rate of transmission of \([N, p]MPPM\) keeps constant and the maximum value when \(5 \leq p \leq 8\). The unit rate of transmission of \([N, p]MPPM\) and that of \([N, p]DMPPM\) tend to be the same if the pulse number keeps growing. In addition, before the unit rate of transmission of \([N, p]DMPPM\) and \([N, p]MPPM\) increases to its maximum value, the former is much higher than the later.

Based on the analysis above, the unit rate of transmission of \([N, p]DMPPM\) is significantly higher than that of \([N, p]MPPM\), DPPM and PPM when \(N\) is a large number \((N \geq 3)\) and \(p\) is constant. When \(N\) and \(p\) is constant, the unit rate of transmission of DMPPM is higher than that of MPPM. In addition, when \(N\) is constant, there is an optimum pulse number that makes the unit rate of transmission of \([N, p]MPPM\) and \([N, p]DMPPM\) reach the maximum.

4.2. Comparison of the Bandwidth Requirement

In 3.3, the bandwidth requirement model of four kinds of modulation is established based on Gauss channel theory Shannon’s equation. According to model, the bandwidth requirement varies with the parameter \(N\) and \(p\). The simulation is shown as Figure 2.

![Figure 2](image-url)
Figure 2. (a) shows the curve that normalized bandwidth requirement of DPPM and PPM varies with the bit number of each symbol, the curve that normalized bandwidth requirement of MPPM and DMPPM varies with the bit number of each symbol when p=2. In order to make the graph clearer, Figure 2. (b) shows the logarithm of normalized bandwidth requirement. The curves in Figure 2. (c) show the normalized bandwidth requirement of MPPM and DMPPM varies with the bit number of each symbol when the pulse number p=2 and p=3, Figure 2. (d) shows the normalized bandwidth requirement of MPPM and DMPPM varies with the pulse number in each symbol when the symbol number corresponding to each symbol N=10.

From Figure 2. (a)-2. (b), when 2 ≤ N , the bandwidth requirement of PPM and DPPM increases with the increasing of N. When 3 ≤ N , the bandwidth requirement of [N, 2]MPPM and [N, 2]DMPPM increases with the increasing of N. There is a minimum of bandwidth requirement in these modulation methods, but in practical application, the bit number of each symbol is relatively large. In addition, by comparing, when 3 ≤ N , the bandwidth requirement of these modulation methods are in order: \[ B_{[N,2]}^{MPPM} \leq B_{[N,2]}^{DMPPM} \leq B_{DPPM}^{P} \leq B_{PPM}. \]

From Figure 2. (c), when 1 ≤ N ≤ 5 , the bandwidth requirement of [N, 3]MPPM and [N, 3]DMPPM decreases with the increasing of N. When 5 ≤ N , the bandwidth requirement of [N, 3]MPPM and [N, 3]DMPPM increases with the increasing of N. When 1 ≤ N ≤ 2 , the bandwidth requirement of [N,2]MPPM is less than that of [N, 3]MPPM. When 2 ≤ N ≤ 3 , the bandwidth requirement of [N,2]MPPM and [N, 3]MPPM are same. When N ≥ 3 , the bandwidth requirement of [N,2]MPPM is larger than that of [N, 3]MPPM. When 1 ≤ N ≤ 4 , the bandwidth requirement of [N,2]DMPPM is less than that of [N, 3]DMPPM. When 4 ≤ N , the bandwidth requirement of [N, 2]DMPPM is larger than that of [N, 3]DMPPM. When 1 ≤ N ≤ 8 , the bandwidth requirement of [N, 2]DMPPM is less than that of [N, 3]MPPM. When 8 ≤ N , the bandwidth requirement of [N, 2]DMPPM is larger than that of [N, 3]MPPM.

From Figure 2. (d), when N remains invariant, the bandwidth requirement of [N, p]MPPM and [N, p]DMPPM first rapidly decrease and then increase slowly with the increasing of p. There is an optimal number of pulses that can make the bandwidth requirement of [N, p]MPPM and [N, p]DMPPM minimum.

Figure 2. shows that when N ≥ 3 , \[ B_{[N, p]}^{MPPM} \leq B_{[N, p]}^{DMPPM} \leq B_{N, p}^{DPPM} \leq B_{N, p}^{PPM}, \] and the bandwidth requirement of [N, p]MPPM and [N, p]DMPPM are much less than that of PPM and DPPM, especially when N is large. Moreover, for [N, p]MPPM and [N, p]DMPPM, there is an optimal number of pulses that can make the bandwidth requirement minimum.

5. CONCLUSIONS

In order to achieve a higher information transmission rate within the laser output bandwidth limit, the advantages and limitations of various modulation schemes are studied. Starting with the basic principle of PPM, the modulation performance is analyzed based on the symbol structure of various modulation schemes. Based on the classical PPM theory, a new type of DMPPM modulation scheme is designed combined with the characteristics of MPPM and DPPM, and simulation analysis is carried out on the unit transmission rate and bandwidth requirement.

Finally the following conclusions were obtained:

1. The bit number of information N and the pulse number per frame period p are significant parameters in MPPM and DMPPM scheme. When N is relative small, the performance of these two schemes is not obviously different from that of the others. With the increasing of N, the introduction of multiple pulses in the frame period can significantly improve the transmission rate and reduce the bandwidth requirement.

2. The simulation results of the unit rate of transmission and the bandwidth requirement show that, if N is constant, with the increasing of p, the unit rate of transmission of DMPPM showed a trend of slow decline after a sharp rise, and its bandwidth requirement rise slowly after a sharp decline. Taking N=10 as an example, when 4 ≤ p ≤ 6 , the unit rate of transmission reaches its peak value, and its bandwidth requirement is the lowest. Therefore, for DMPPM, an appropriate pulse number p can greatly improve the performance.

3. For the information source, in which the bit number N is relative large, DMPPM has a great performance advantage. When N ≥ 6 , its unit rate of transmission is far greater than other modulation schemes, and the bandwidth requirement is much smaller than others. This shows that DMPPM has advantages in large capacity data transmission, and more suitable for the future communication demands.

In this study, a new modulation scheme is proposed by combining the theory MPPM with DPPM. The DMPPM scheme is designed to have higher transmission rate and lower bandwidth requirement for large bit number information, which is of great significance for the future high rate laser communication. However, due to the performance is influenced by the bit number N, the optimal parameter p is not obtained in this paper. In the future, the scheme should be fixed and combined with the actual needs of the system, the modulation performance of DMPPM can be further improved.
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