Abstract

Pulse position modulation (PPM) has many attractions for optical communication over deep space and for intersatellite communications. This paper describes a variate of PPM, known as differential pulse position modulation (DPPM) which can double the data throughput relative to PPM. We begin this paper with a survey of various laser sources and laser modulation techniques used in modern space optical communications. We then discuss the advantages of the combination of DPPM and Reed-Solomon (RS) codes.

I. INTRODUCTION

For the past decade the maturation of laser technology has inspired a great deal of efforts in making lasers a new tool in free-space communication. It is believed that in the future laser communications will be widely applied in all fields of space communications, either in satellite to satellite or in deep space communication. Laser communication has many advantages. First, the laser beams is a very narrow EM wave, so it is very difficult to jam. Second, because both spatial and temporal distributions of the laser beam are very narrow, the signal can propagate in a high peak power concentrated in a small area, and hence only a small antenna is needed. Third, optical modulation provides a very wide bandwidth, up to Gbits per second could be reached. This makes Laser communication more superior than the traditional RF communication.

We will discuss various laser sources used in optical communications in Section 2. In Section 3, we present popular laser modulation techniques. Section 4 introduces differential PPM. Section 5 presents the performance of RS coded PPM system. Section 6 discusses the symbol synchronization in DPPM. Section 7 summarizes the results and conclusion.
2. LASERS SOURCES

Different lasers can be chosen to optimize the system performance for different applications. Among all possible laser sources, the most popular candidate are AlGaAs diode lasers, AlGaAs diode-pumped Nd:YAG (Nd doped yttrium aluminum garnet) lasers (1.064 μm), and AlGaAs diode-pumped doubled Nd:YAG lasers (0.532 μm).

Laser diode technology has been very much improved in the past five to ten years by applying the techniques of molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD). Laser diodes have the advantage of easy direct modulation and the potential of reaching the 30 GHz range [1]. A very high conversion efficiency (i.e., the ratio of optical output power to electrical input power) of nearly 50 percent can be obtained. Also their small size and light weight make them suitable for space-based applications. However, the limitation for using laser diodes as direct source for laser communication has been addressed [2]. The output power of the laser beam is low and the beam divergence is wide, making laser diodes somewhat limited in their ultimate data rate and range compared to diode-pumped solid state lasers. If weight and efficiency considerations outweigh these limitation, the laser diodes can be considered for some special applications.

Most conventional solid-state lasers are pumped with a flashlamp. The idea of diode-pumped solid state lasers was first proposed in early 60s [3]. The progress of laser diode technology in the past decade made the use of diode- pumped solid state lasers feasible in fulfilling the needs of space communications. There are many advantages of diode pumping when compared with the conventional flashlamp pumping for a solid state laser. The output spectrum of a diode laser can be precisely matched to the absorption line of the solid state lasing material. The pumping energy can be mode matched into the lasing material. Diode pumping also reduces electrical input power, reduces waste heat, and increases reliability. Also as size, weight, and power efficiency are concerned, diode pumping is definitely more preferable to flashlamp pumping [4]. Extensive lists of references on diode-pumped solid state lasers can be found in several excellent reviews [5][6].

Another commonly used source is the frequency doubled diode- pumped Nd:YAG laser which has a wavelength of 0.532 μm. There are two advantages of this beam source. Firstly, the angular spread of a laser beam is proportional to its wavelengths, so the shorter wavelength will decrease the propagation loss. Secondly, the quantum efficiency of most photodetectors is low, and is greatly improved at 0.532 μm. Both advantages lead to a reduction of overall link loss. The frequency doubling (also is called second harmonic generation) is achieved by inserting an optically nonlinear crystal in the laser cavity. The
best nonlinear crystal for second harmonic generation is KTiOPO4 (KTP) because its relatively higher efficiency and higher damage threshold.

3. LASER MODULATION TECHNIQUES

Different laser pulse modulation techniques are used for different lasers and modulation frequencies. For semiconductor laser diodes, the direct modulation applied on the injection current can reach up to 30 GHz bandwidth. With the mode locking technique, an even higher bandwidth up to 100 GHz could be obtained [7].

For diode-pumped solid state lasers, the most popular modulation techniques are Q-switching, cavity dumping, and mode locking [8], each with its own bandwidth limit. The basic design of a laser cavity should have a mirror system as a photon resonator, and an amplifying medium to provide population inversion (i.e., the population of the excited atom at higher energy level is higher than that at lower energy level). The quality factor Q is defined as the ratio of energy stored in the cavity to the energy loss per cycle. Lasing will occur when the cavity Q exceeds a threshold. In Q-switching technique, energy is stored in the amplifying medium by optical pumping while cavity Q is kept low to prevent lasing. As the population inversion grows up and reaches a level far above the threshold for normal lasing action, the cavity Q is switched to some high value, and the stored energy is suddenly released in a form of very short pulse of light. The pulse duration generated by Q-switching is in the order of 10 ns. The peak power is normally very high, e.g., up to few hundreds KW is possible depending upon specific laser characteristics. The Q-switching technique is extremely effective for low pulse repetition rate (<1 KHz). Peak power decreases rapidly for pulse repetition rates higher than 3 KHz. However, average power which is a measure of idly for pulse repetition rates higher than 3 KHz. However, average power which is a measure of overall efficiency, increases and approaches the maximum CW power output at repetition rate above 10 KHz. This implies that higher pulse repetition rate gives higher power efficiency for the system, but pays the price for reducing its peak power. The upper limit of pulse repetition rate for the Q-switching is set by the finite buildup time of the field inside the laser cavity and the time required to repump the population inversion. For Q-switched Nd:YAG laser, the upper limit is of the order of 50 KHz.

Cavity dumping operates at modulation frequencies between 100 KHz to 30 MHZ [9]. Unlike Q-switching to store energy in the atomic population inversion, cavity dumping accumulates and stores energy between output pulses primarily in the optical field. The cavity dumping modulation technique in the application of space communication has been analyzed and calculated in Ref.[9].
4. Pulse Position Modulation Laser Communications

In optical communications, information signal is encoded with laser pulses by modulating source laser as discussed in Section 3. This can often be improved by pulsing the laser, and encoding the resulting light pulses. The laser source is pulsed on or off at a prescribed pulse repetition frequency (PRF), producing a light pulse with fixed width \( \tau \) and peak power \( P_{\text{peak}} \) every \( 1/\text{PRF} \) sec. The laser, therefore, operates at an average power \( P_r \) satisfying

\[
P_{\text{peak}} \tau = P_r / \text{PRF}
\]

At the receiver the detected pulse SNR (signal to noise ratio) after photodetection is [11]

\[
\text{SNR} = \frac{K_s^2}{K_s + K_b + K_n}
\]

where \( K_s \) = Average number of signal counts per slot,

\( K_b \) = Average number of background noise counts per slot,

\( K_n \) = Average number of effective detector noise counts per slot.

The symbol error rate in terms of \( K_s \) and \( K_s + K_b + K_n \) is calculated in Appendix 1.

In an M-bit PPM system the laser pulse is delayed into one of \( 2^M \) possible locations (called a frame) during each pulse period, and M bits are sent with each pulse (Fig. 1). It is possible to start a new frame immediately after the last pulse (Fig. 2). The resulting signal waveform is called DPPM [12]. DPPM has the advantage that

1. the throughput of DPPM is doubled compared with PPM (Appendix 2).

It has the disadvantage that

2. channel errors might cause symbol slip or insertion that error correction codes are not conventionally able to decode.

We will discuss this problem and propose a solution to it in Section 6.
5. Reed-Solomon Coded PPM system

In a Reed-Solomon code $RSm(n,k)$, $m$ message bits form a message symbol, and $k$ message symbols are combined with $r = n - k$ redundant symbols to form encoded blocks of $n$ symbols. $r/k$ is called the redundancy percentage. It can be shown that using a symbol length $m$ and a block length $n < 2^m$, a Reed-Solomon code can be constructed that has Hamming distance $r+1$ and thus corrects $t = \lfloor r/2 \rfloor$ symbol errors [13]. Further, if the errors occur at not more than $r$ symbol “erasure” positions, all of which are known by some method (e.g., a loss of signal amplitude) external to the decoder, then the code can correct up to $r$ symbol errors. The general rule is that a $RS(n,k)$ code can correct up to $t$ symbol errors and $s$ erasures if $t+s \leq n-k$ [13]. Note that error correction applies equally to message and parity symbols. DPPM symbol structure tends to produce error statistics at the symbol level rather than the bit level. This is an ideal arrangement for RS codes where the number of bits per RS symbol is identical to the number of DPPM symbol. RS codes also have the following advantages:

1. they provide good performance with less redundancy.

2. RS codes perform best in the bursty error or jamming environment.

We now define two important parameters which are important for coded systems

1. Code cost based on code rate $R$:

The percentage of information bits in a coded block is called the code rate. If the code rate of a coded system is $R$, then the code cost for that system is:

$$\text{code cost (in dB)} = -10.0 \times \log_{10} R.$$  

In other word, code cost is a measure of extra power spent for redundancy in a coded system.

2. Coding gain (CG) based on output bit error rate:

For a desired output bit error rate, the difference of required minimum average numbers of photons per slot between uncoded ($ANP_u$) and coded ($ANP_c$) system is called the coding gain:

$$\text{coding gain (in dB)} = 10.0 \times \log_{10} ANP_u - 10.0 \times \log_{10} ANP_c.$$  

Therefore, coding gain is a measure of power saving in a coded system.
For example, in order to transmit 800 information bits, suppose that an uncoded PPM system requires power:

\[ P_{\text{uncoded}} = \left(\frac{800}{M}\right)\left(\frac{P_r}{PRF}\right) \]

to achieve a certain output bit error rate. Then a coded system needs

\[ P_{\text{coded}} = \left(\frac{800}{RM}\right)\left(\frac{P_r \times CG}{PRF}\right) \]

to achieve the same bit error rate where \( R \) is the code rate and \( CG \) is the coding gain. Therefore, the total power is reduced (or increased) by \( CG(dB) - R(dB) \) in terms of dB.

We now show by two concrete examples how Reed-Solomon coding can help PPM system to reduce the total power for transmitting and avoid suffering from burst or fading noise simultaneously. Two 8-bit PPM using RS\(_8\)(255,100) and RS\(_8\)(200,100) are examined. Performances based on signal photon counts and noise photon counts (assuming \( \gamma = 1.0 \)) are presented in Figure 1 through 2. Table 1 lists the code costs and coding gains for our two examples. From this table, we can conclude that RS(200,100) can save the total power up to 3.0 dB. Higher savings are possible through more complicated coding schemes [14].

6. Block Synchronization in Coded DPPM Systems

The most common block synchronization aid is the block marker. The block marker is a short pattern of bits that the transmitter inserts periodically into the data stream. The receiver must know the pattern and the insertion interval. We will discuss block synchronization in 6.1. As we mentioned before, DPPM systems are most vulnerable to symbol slip or symbol insertion due to channel errors. In Section 6.2, we will present a rescue routine for this situation.

6.1 Codeword Block Synchronization

The synchronization between the codewords and the decoder can be achieved by periodic insertion of sync patterns. For example, a RS\((n,k)\) m-bit code has \( nm \) bits per codeword block. We can insert a sync pattern (usually, it is an m-bit symbols with good auto-correlation property) once every \( nm \) bits. At the receiving side, bits are input to a sync pattern detector providing an m-bit window sliding along the received data stream. We set up an input address counter modulo \((n+1)m\). Each address that holds an input bit also holds
a sync score for that location. As each bit is entered, the sync score is updated: incremented when the m-bit window matches the sync pattern, decremented otherwise. When any location’s score is greater than a preset threshold, we declare that to be the SYNC location.

6.2 Symbol Slip or Symbol Insertion Recovery

If the sync detector finds a sync pattern at the location either one symbol before or one symbol after the declared SYNC location. There is a strong indication that a symbol slip happened in the previous codeword block. The decoder certainly can not successfully decode the following codeword blocks. Eventually the system will ask the sync detector to revert to the resync state and all codeword blocks before the next SYNC is declared will be lost. We now propose an algorithm which would eliminate this infrequent disaster if one and only one symbol slip happened in the codeword with high probability.

We subdivide the codeword block into several subblocks of equal length and insert a second sync pattern T between any two consecutive subblocks (Figure 2).

If a symbol slip is detected in a subblock, do the following:

1. Insert an extra symbol after the [\((k-1)/2\)]-th received symbol in that subblock, where k is the number of symbols in each subblock. (delete the \([(k+2)/2\)]-th symbol for a symbol insertion)

2. Erase the inserted symbol and send the whole codeword block to the decoder.

Note that a symbol insertion at the wrong location will cause extra symbol errors. For example suppose the last symbol in a subblock has a symbol slip and an extra symbol is inserted before the first symbol of that subblock. This will cause all symbols in that subblock wrong. Observing all possible combinations of symbol slip and symbol insertion locations, we find that the best location for inserting an extra symbol is at the location after the \([k/2]\)-th received symbol in that subblock. An example for \(k = 6\) is given in table 2 that shows a symbol insertion after symbol 2 or 3 will cause the least number of extra symbol errors on average. Second, since we know the inserted symbol might be wrong (with probability \(= (2^m-1)/2^m\)), we therefore erase the inserted symbol in order to improve the chance that the decoder might correct the codeword. This strategy also works for symbol insertions and can be easily extended to multisymbol slip and insertion situations.
7. Conclusion

This paper has presented an overview of various laser source and modulation techniques used in laser communication systems. Performance of Reed-Solomon coded PPM systems is presented in terms of total power reduced and signal photon counts to noise photon counts. It shows that a saving in total power of up to 3.0 dB is possible. We also present the advantage and disadvantage of using DPPM for optical communications and propose a synchronization algorithm to overcome the symbol slip or insertion problem in coded DPPM systems. The authors thank Mr. Jerry Walker and Mr. Colum Keelaghan for many helpful suggestions.

Appendix 1. Uncoded PPM performance calculation

The correct pulse slot in an M-slot PPM system is selected based on the maximum slot count per PPM frame. The correct pulse slot has an average count of $K_s + K_d$ and the incorrect slot has an average count of $K_d$. It can be shown that the symbol error rate is

$$SER = 1 - \int_{-\infty}^{\infty} \left( \int_{-\infty}^{\nu} P(\nu | K_s) d\nu \right)^{M-1} d\nu$$

We first assume that the count detected at an optical receiver over a time interval has a Poisson distribution, in which the probability that the count is $n$ (an integer) is given by

$$P(n) = \frac{K^n}{n!} e^{-K}$$

where $K$ is the mean interval count.

Base on this probability distribution function, it can be shown that the symbol error rate (SER) of an M-bit PPM system is

$$SER = 1 - \sum_{n=0}^{\infty} \frac{(K_s + K_d)^n e^{-(K_s + K_d)}}{n!} \left( \sum_{m=0}^{n-1} \frac{K_d^m e^{-K_d}}{m!} \right)^{(2^n - 1)}$$

where $K_s =$ mean count of signal photons.

$K_d =$ mean count of noise photons.
$K_d$ is relatively large, we can treat the photon count as a Gaussian random process and the signal photon count as additive. Then it can be shown that the symbol error rate in this case is

$$SER = 1 - \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{(x - SNR)^2}{2} \right) \left( 1 - erfc \left( \frac{x}{\sqrt{2}} \right) \right)^{M-1} dx$$

where

$$erfc \left( \frac{x}{\sqrt{2}} \right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp \left( -\frac{t^2}{2} \right) dt$$

Therefore

$$SNR = \frac{K_s^2}{K_n} = \left( \frac{GE_s}{hf} \right)^2$$

$K_s$ and $K_n$ are numbers of signal and noise photons produced due to incident signal energy $E_s$ and noise energy $E_n$ respectively. Additionally,

$$E_s = \frac{P_r}{PRF}$$

Appendix 2. Throughput of DPPM

Define $M$: number of bits per pulse. $D$: guard time. $T$: bin time. $R$: code rate = percentage of information bits per coded block.

On average, we can transmit

$$\frac{1}{D + \left( \frac{2^M + 1}{2} \right)T}$$

pulses per second (Figure 2). Therefore, each information bit needs
seconds and the data rate for DPPM system can be expressed as

\[ \text{datarate} = \frac{\frac{MR}{D + \left(\frac{2^M + 1}{2}\right)T}}{D + \left(\frac{2^M + 1}{2}\right)T} \]

Set

\[ \alpha = \frac{T}{D} \]

where \( \alpha \) is a system constraint which is imposed upon the design. Then

\[ \text{datarate} = \frac{\frac{MR}{D + \alpha \left(\frac{2^M + 1}{2}\right)D}}{D + \alpha \left(\frac{2^M + 1}{2}\right)D} = \frac{\left(\frac{R}{D}\right) \frac{M}{1 + \alpha \left(\frac{2^M + 1}{2}\right)}}{1 + \alpha \left(\frac{2^M + 1}{2}\right)} \]

It can be shown that the data rate has maximum value if

\[ \alpha = \frac{1}{M 2^{M-1} \log 2 - 2^{M-1} - \frac{1}{2}} \]

which can be approximated by

\[ \alpha \approx \frac{10}{2^M (7M - 10)} \]

if \( M \) is large. For comparison purpose, we define

\[ \text{normalized datarate} = \text{datarate} \left(\frac{D}{R}\right) \]

It can be shown that the maximum value of the normalized data rate is

\[ M - \frac{1}{\log 2} \left(1 + \frac{1}{2^M}\right) \]
which can be approximated by

\[ M - 1.44 \]

if \( M \gg 1 \).

REFERENCES


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<th>RS(255,100) 8-bit symbol</th>
<th>RS(200,100) 8-bit symbol</th>
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Table 1 Evaluation of Coded 8-bit PPM Systems based on Poisson Channel Model
Table 2. Extra symbol errors caused by symbol insertions

Figure 1. an Example of 3-bit PPM

Figure 2. an Example of 3-bit DPPM
Figure 3. Uncoded 8-bit PPM Performance
Figure 4. Coded 8-bit FPM Performance assuming the Average Number of Noise Photons Per Slot is 1.0.

Figure 5. subblocks of a codeword block

6 5 1 2 3 4 5 6 1 2 3 4 5 6 T