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Research Paper

Review of Modulation and Performance Analysis Methods for FSO Communication Systems

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ABSTRACT: *This paper reviews the modulation techniques and performance evaluation methods used in free-space optical (FSO) communication technology. The paper discusses modulation techniques such as the on-off keying, pulse position modulation and subcarrier intensity modulation. The merits and demerits of each modulation method are discussed and comparisons are made between them. Methods used to evaluate the performance of FSO communication systems are highlighted in this paper and the suitability of each method for performance estimation is discussed.*

KEYWORDS: *Free-space optical communication, Modulation, Performance analysis*

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I. MODULATION

Modulation refers to the process of changing some property (or properties) of a carrier wave in order to encode data (i.e. the information to be sent) on (in this work) an optical signal at the transmitter before onward transmission through the channel (i.e. atmosphere) [1]. Since the receiver is responsible for decoding the sent information, it is essential that it understands the modulation method used at the transmitter. Various modulation methods exist but methods involving intensity modulation (IM) at the transmitter and direct detection (DD) at the receiver (known as IM/DD) are commonly used in FSO links because they are easily implementable and also sufficient for many of the data rates presently used [2].

1.1 On-off keying (OOK)

On-off keying (a special case of amplitude shift keying (ASK)) is the most popular modulation format used in optical communication systems due to its simple implementation [3]. This simplicity also extends to performance calculations. In OOK, a 1 bit is encoded when the transmitter is turned on and a 0 bit is encoded when the transmitter is turned off. OOK modulation can be achieved by directly adjusting the transmitter (i.e. turning it on and off to represent the 1 and 0 encoded bits respectively) or by making use of an external modulator to achieve the same purpose. The use of an external modulator is preferred in long-distance high-speed fibre communication systems because it reduces dispersion penalty from chirp (not a problem in FSO communication systems) [1, 2] and facilitates a better extinction ratio. When the optical signal reaches the receiver, a decision is made to determine the transmitted bit. A 1 bit is determined to have been sent if the received signal level is above a decision threshold (i.e. presence of light) and a 0 bit is determined to have been sent if the received signal level is below the decision threshold (i.e. absence of light) [1]. While this method is very acceptable for optical fibre communication systems (at least until reaching $\approx$ 40 Gb/s), it is known to be particularly vulnerable (compared to other methods such as PPM) in FSO communication systems due to the power fluctuations caused by atmosphere turbulence when a non-adaptive threshold is used at the receiver. In order to obtain an optimal performance when the OOK modulation format is used in FSO communication systems, an adaptive decision threshold (which can be practically realised with a Kalman filter [4]) that can constantly track the power fluctuations is required at the receiver [3, 5]. The OOK modulation format is being used in commercial FSO applications designed by organisations such as the Infrared Data Association (IrDA) [3].

The OOK modulation method can be actualised either as return-to-zero (RZ) or non-return-to-zero (NRZ). In NRZ-OOK, a 0 bit is described by 'no pulse' across the bit interval and for a 1 bit; the pulse duration is equal to the bit duration [1, 3]. In a work by Ijaz *et al.*; where they experimentally compared the performances of the OOK-RZ and the OOK-NRZ modulation formats in a turbulent channel, the OOK-RZ was shown to perform better (at the expense of increased bandwidth demands [6]) than the OOK-NRZ. In a work by Elganimi, it was shown that the OOK-RZ requires less power and signal-to-noise ratio (SNR) than the OOK-NRZ to achieve the same bit error rate (BER) performance [6]. Also, since the OOK-RZ has a higher peak-to-average power ratio, it provides a better Q-factor and BER performance than the OOK-NRZ [7].

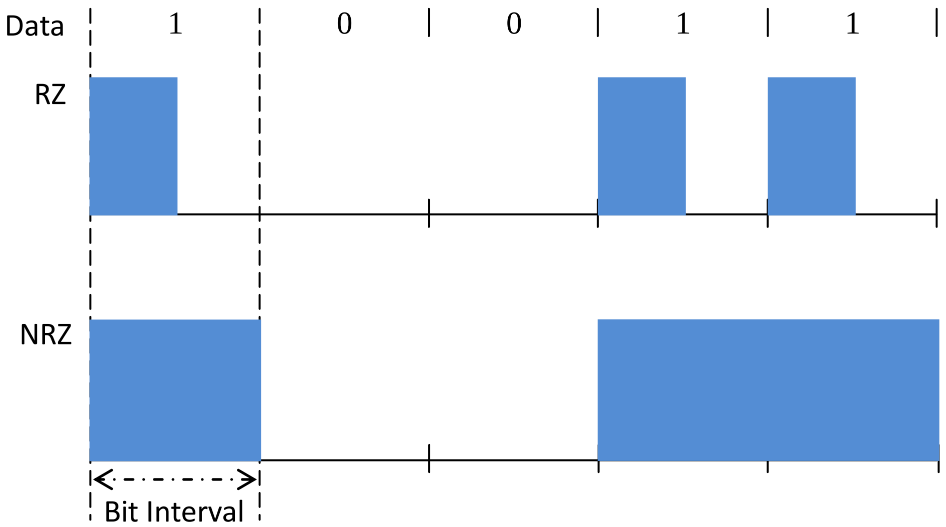

Fig. 1: Diagrammatic representation of RZ and NRZ OOK modulation scheme

1.2 Pulse position modulation (PPM)

PPM is a type of modulation scheme consisting of n possible time slots arranged sequentially within a frame. Each frame consists of l bits where $n = 2^l$. For a particular frame, the pulse containing the information to be sent is positioned in the slot having the same number as the decimal value of the l bits and the remaining slots in the frame are left empty. In other words, the position of the pulse represents the type of information that is being sent. The n -PPM scheme is shown diagrammatically in Fig. 2. At the receiver (i.e. while assuming that the transmitter and the receiver are always synchronised), a scan takes place across all the available slots to obtain the energy in each slot. The slot with the highest energy is then selected as the transmitted pulse position [8, 9]. Note that increasing the value of l would result in a decrease in the power requirement (leading to better BER performance) and an increase in the bandwidth requirement [10, 11].

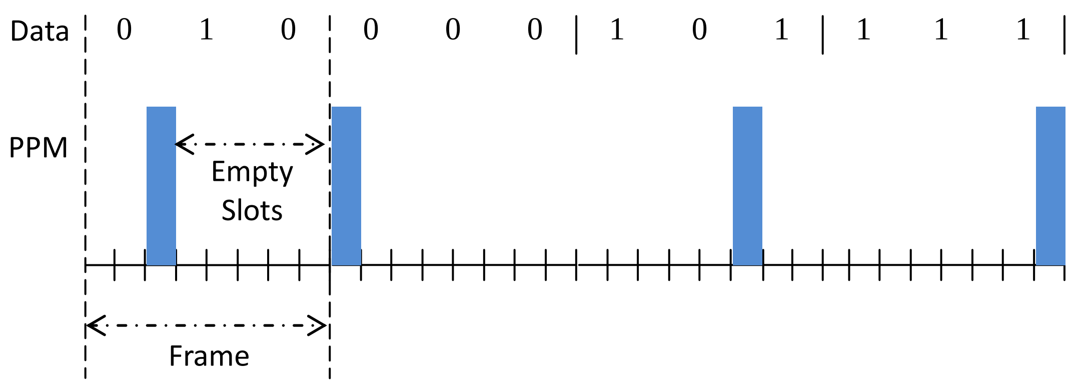

Fig. 2: Diagrammatic representation of 8-PPM scheme (l = 3, n = 8)

1.3 Subcarrier intensity modulation (SIM)

Subcarrier intensity modulation (SIM) (i.e. a variant from the popular multiple carrier RF communication) is a modulation scheme that has recently found usefulness in FSO communication systems [8]. In SIM with IM/DD, the intensity of the optical source is modulated by a sum of frequency division multiplexed RF subcarrier signals; each of which has been separately modulated with an information signal. Each subcarrier can be modulated with RF modulation schemes such as phase shift keying (PSK), frequency shift keying (FSK), amplitude shift keying (ASK) and quadrature amplitude modulation (QAM). Direct detection takes place at the receiver followed by the demodulation of each subcarrier, filtering, noise reduction, decision circuit processing and the subsequent recovery of the sent information signal [8, 12, 13]. A diagrammatic representation of a SIM powered FSO communication system is shown in Fig. 3.

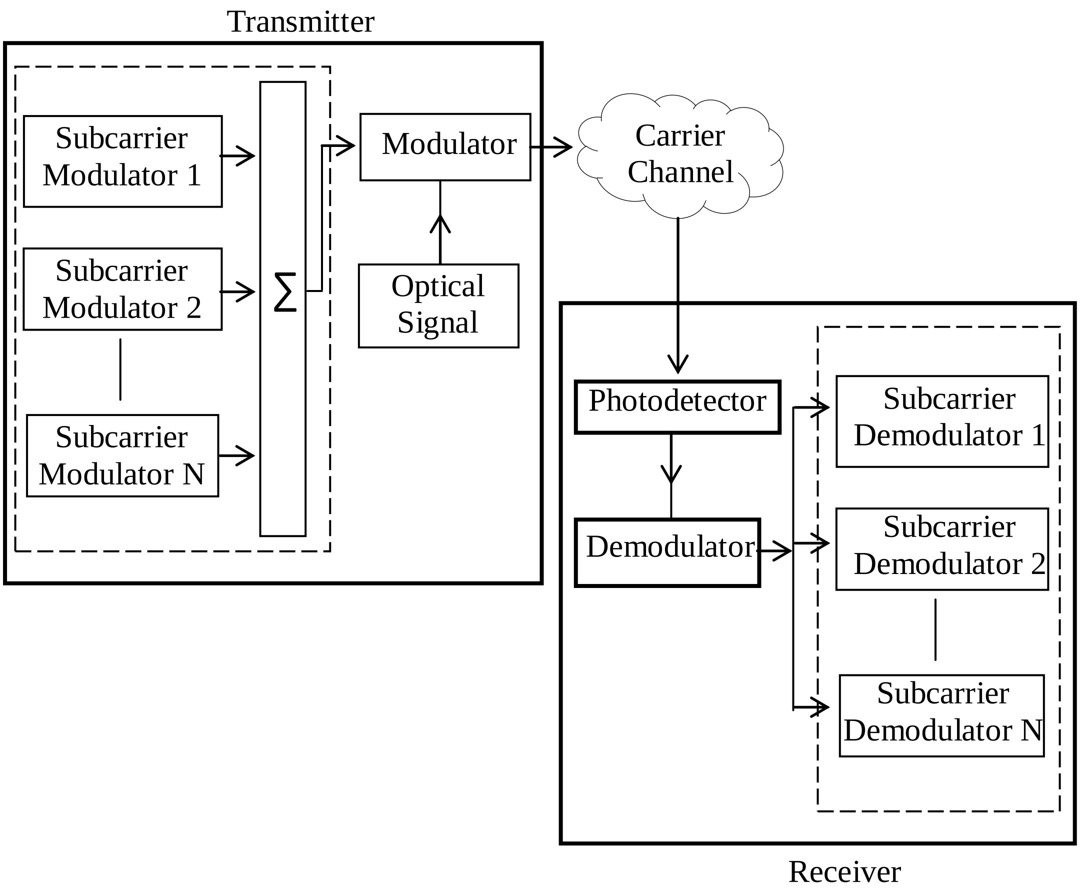

Fig. 3: Configuration of a SIM powered FSO communication system (Modified and redrawn from [8])

1.4 Comparison of various modulation formats

The choice of modulation scheme to adopt depends on factors such as bandwidth capacity, ease of operation and power requirements [3]. Unlike the OOK modulation, PPM and SIM do not require an adaptive decision threshold because they are not affected by the power fluctuations due to atmospheric turbulence [8, 14, 15]. Even though PPM is a modulation of choice in a wide range of applications due to its power efficiency, its execution is more complicated and it requires more bandwidth than the OOK [16, 17]. SIM has a lesser bandwidth demands than PPM and also capable of transmitting more information as a result of incorporated subcarriers. However, compared to the OOK and PPM, SIM is less power efficient, requires sufficient receiver synchronisation and prone to clipping and non-linearity [8]. Table 1 shows a broad comparison of various modulation formats.

Table 1: Comparison of various modulation formats [3].

Modulation Format	Cost	Power Efficiency	Signal to Noise Ratio	Bandwidth Efficiency
OOK-NRZ	Low	Lower than PPM and RZ	Moderate	Higher than PPM and RZ

OOK-RZ	Low	Higher than NRZ	Moderate	Lower than NRZ
PPM	Moderate	Higher than OOK	Low	Lower the OOK
SIM	Moderate to High	Lower than OOK and PPM	Moderate to High	Lower than PPM
Amplitude Modulation	Low	Low-moderate	Low-moderate	High
Frequency/Phase Modulation	Moderate	Moderate	Moderate	Moderate
Digital	High	High	High	Low

II. PERFORMANCE ANALYSIS

The goal of a system designer is to have a receiver that correctly demodulates and retrieves the transmitted information with minimal errors [1]. The optical signal arriving at the receiver is usually impaired due to reasons such as intersymbol interference, background radiations, signal distortions and power loss. It can also be affected by amplified spontaneous emission (ASE) noise in systems with optical amplifiers (OAs). The optical receiver itself also introduces noise currents such as thermal noise. These impairments affect how the receiver decodes the transmitted information. The performance of FSO communication systems can be evaluated with methods such as determining the outage probability for a target instantaneous BER [18] and the average BER [19]. For instance, if an optical receiver demodulating OOK signals detects a 1 bit for a transmitted 0 bit, an error is detected. The BER; which gives a ratio of the incorrectly detected bits to the total number of bits is the key performance attribute commonly used for digital communication system analysis [1]. While various methods are used to model the BER, the Gaussian Approximation (GA) is widely used due to its speed of operation and simplicity [1]. Other methods that can be used to estimate the BER include moment generating functions (MGF) methods such as the Chernoff Bound (CB), Modified Chernoff Bound (MCB), and the Saddle Point Approximation (SPA) [20, 21].

2.1 BER evaluation with the Gaussian Approximation

By making a GA assumption for the noise signals and assuming that the transmitted 1 and 0 bits have equal probability of occurrence (i.e. $P(1) = P(0) = 1/2$), the BER can be given as [21, 22]

$$BER_{GA} = \frac{1}{2}\left[P(0\mid 1) + P(1\mid 0)\right] \quad (1)$$

where the conditional probabilities, $P(0\mid 1)$ and $P(1\mid 0)$ are the probabilities of receiving a 0 bit when a 1 bit is transmitted and the probability of receiving a 1 bit when a 0 bit is transmitted respectively. By making an assumption that the noise present in the 1 and 0 bits are zero mean Gaussian with variances σ_1^2 and σ_0^2 respectively when sampling takes place in the receiver, the conditional probabilities in (1) can be re-written in terms of the Gaussian distribution probability density function (PDF) with continuous random variable y_x as [22, 23]

$$BER_{GA} = \frac{1}{2}\left[\frac{1}{\sqrt{2\pi\sigma_1^2}}\int_{-\infty}^{i_D}\exp\left(-\frac{(i_1 - y_1)^2}{2\sigma_1^2}\right)dy_1 + \frac{1}{\sqrt{2\pi\sigma_0^2}}\int_{i_D}^{\infty}\exp\left(-\frac{(y_0 - i_0)^2}{2\sigma_0^2}\right)dy_0\right] \quad (2)$$

where i_x represents the noise-free signal current level (and thus the mean of the signal and noise combination) at the sampling instant for transmitted data bits, $x \in \{0,1\}$. By applying the $\text{erfc}(\ )$ function (used in Gaussian statistics to calculate the area in the tails of the PDFs), the BER is given as [23]

$$BER_{GA} = \frac{1}{2}\left[\frac{1}{2}\text{erfc}\left(\frac{i_1 - i_D}{\sqrt{2\sigma_1^2}}\right) + \frac{1}{2}\text{erfc}\left(\frac{i_D - i_0}{\sqrt{2\sigma_0^2}}\right)\right] \quad (3)$$

where $i_x = RP_x$, P_x represents the input power and i_D represents the decision threshold. Note that for a preamplified receiver, $P_x = GP_{OAin_x}$ where P_{OAin_x} represents the OA input power and G is the OA gain. For a binary symmetric channel (BSC), $P(0\mid 1) = P(1\mid 0)$, an 'optimal' decision threshold can be obtained as [24]

$$i_D = \frac{i_1\sigma_0 + i_0\sigma_1}{\sigma_1 + \sigma_0} \quad (4)$$

It is known that the decision threshold value obtained from (4) is not exactly optimal (especially when ASE noise is present) but it leads to a valid Q factor and BER value [1]. With this 'optimal' decision threshold, the BER can be re-written as [21]

$$BER_{GA} = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right)\right] \tag{5}$$

where the Q factor, Q is given as

$$Q = \frac{i_1 - i_0}{\sigma_1 + \sigma_0} \tag{6}$$

2.1.1 Limitations of the Gaussian Approximation

Even though the total photocurrent PDFs for the 1 and 0 bits in the earlier section were treated as Gaussian, it is well known that the GA is not always completely accurate and further suffers from an inability to accurately give an optimum decision threshold when there is significant ASE. Firstly, the photocurrent PDFs are not strictly Gaussian in optically preamplified receivers due to the presence of ASE beat noises. Also, in a non-amplified optical receiver where the dominant thermal noise is Gaussian, the shot noise (which also makes a contribution to the PDF) is not strictly Gaussian. Hence, a PDF containing both noises is not strictly entirely Gaussian [25, 26]. Also, experimental evidence has shown that when ASE beat noises are present, the PDFs for the 1 and 0 bits are non-Gaussian [27]. While some other BER estimation methods will be used in this work, the main focus is on the GA due to its ease of use.

2.2 BER evaluation with moment generating function methods

The use of MGF methods to approximate the BER has been shown to give more accurate estimates compared to the GA because they give better representations of the signal and noise components [21, 24]. The MGF methods considered in this section include the CB, MCB and SPA. While the actual BER is not known, the CB provides an upper bound on the BER and can be regarded as being more accurate than the GA because there is uncertainty about when the GA values are higher or lower than the actual BER. The MCB, which is similar to the CB but regarded as more reliable in predicting the performance of FSO communication systems, also provides an upper bound on the BER [21, 24]. The SPA is similar to the MCB but more complicated and slower because it involves taking the second derivatives of the MGF [20, 24]. Now, an MGF of an optical signal (which takes the ASE noise into consideration) is given as [20, 21]

$$M_{Y_x}(s) = \frac{\exp\left(\dfrac{RGsP_{in_x}}{1-(RN_0 s/T)}\right)}{\left(1-(RN_0 s/T)\right)^L} \tag{7}$$

where s represents a standard parameter in the MGF transform domain, $L = B_{opt} m_t T$ and T represents the bit period. A more elaborate definition of the MGF, that includes the effect of receiver thermal noise, is given as [20, 21]

$$M_{Z_x}(s) = M_{th}(s) M_{Y_x}(s) \tag{8}$$

where the thermal noise MGF, $M_{th}(s) = \exp\left(\sigma_{th}^2 s^2/2\right)$. By assuming that the transmitted 1 and 0 bits have equal probability of occurrence, the BER can be given as [21, 22]

$$BER_{em} = \frac{1}{2}\left[P(0\,|\,1) + P(1\,|\,0)\right] \tag{9}$$

for $em \in \{CB, MCB, SPA\}$. The CB on the BER is then given as [20, 21, 24]

$$BER_{CB} \le \frac{1}{2}\left[\exp(s_0 i_D) M_{Z_0}(-s_0) + \exp(s_1 i_D) M_{Z_1}(-s_1)\right] \quad s_0 < 0, s_1 > 0 \tag{10}$$

The MCB on the BER is given as [20, 21, 24]

$$BER_{MCB} \le \frac{1}{2}\left[\frac{\exp(s_0 i_D) M_{Z_0}(-s_0)}{s_0\sqrt{2\pi\sigma_{th}^2}} + \frac{\exp(s_1 i_D) M_{Z_1}(-s_1)}{s_1\sqrt{2\pi\sigma_{th}^2}}\right] \quad s_0 < 0, s_1 > 0 \tag{11}$$

The SPA of the BER is given as [20, 24]

$$BER_{SPA} = \frac{1}{2}\left[\frac{\exp(s_0 i_D) M_{Z_0}(-s_0)}{s_0\sqrt{2\pi\psi_0''(s_0)}} + \frac{\exp(s_1 i_D) M_{Z_1}(-s_1)}{s_1\sqrt{2\pi\psi_1''(s_1)}}\right] \quad s_0 < 0, s_1 > 0 \tag{12}$$

where functions ψ_0 and ψ_1 are given as

$$\psi_0 = \ln\left[\frac{\exp(s_0 i_D) M_{Z_0}(-s_0)}{s_0}\right] \quad s_0 < 0 \tag{13}$$

$$\psi_1 = \ln\left[\frac{\exp(s_1 i_D) M_{Z_1}(-s_1)}{s_1}\right] \quad s_1 > 0 \tag{14}$$

The decision threshold i_D can be obtained by differentiating the CB BER with respect to the threshold and equating the result to zero as follows [21, 24]

$$\frac{\partial(BER_{CB})}{\partial i_D} = 0 \tag{15}$$

Even though the separate optimisation of s_0 and s_1 gives the tightest bounds, it is acceptable to set $s = -s_0 = s_1$ for easier computation [21, 24]. The CB optimum threshold (which can be applied to the MCB and SPA) is obtained as

$$i_D = \frac{\ln\left(M_{Y_0}(s)/M_{Y_1}(-s)\right)}{2s} \tag{16}$$

With this optimum decision threshold, (10), (11) and (12) can be re-written as [20, 21, 24]

$$BER_{CB} = M_{th}(s)\sqrt{M_{Y_0}(s)M_{Y_1}(-s)} \quad s > 0 \tag{17}$$

$$BER_{MCB} = \frac{M_{th}(s)\sqrt{M_{Y_0}(s)M_{Y_1}(-s)}}{s\sqrt{2\pi\sigma_{th}^2}} \quad s > 0 \tag{18}$$

$$BER_{SPA} = \frac{M_{th}(s)\sqrt{M_{Y_0}(s)M_{Y_1}(-s)}}{2s\sqrt{2\pi}}\left[\frac{1}{\sqrt{\psi_0''(-s)}} + \frac{1}{\sqrt{\psi_1''(s)}}\right] \quad s > 0 \tag{19}$$

III. CONCLUSION

This paper reviewed some of the modulation techniques used in FSO communication systems. The OOK, PPM and SIM modulation methods were discussed and even though OOK is widely used in FSO links due to its simplicity and bandwidth efficiency, its power inefficiency and need for an adaptive threshold in turbulent channels makes PPM a better choice in applications where power efficiency is paramount and the overhead expense of an adaptive threshold needs to be avoided. It was also shown that SIM is beneficial in applications where information carrying capacity is paramount at the expense of increased implementation cost. The methods used to measure the performance of FSO links were also discussed in this paper. The GA is computationally convenient and gives an acceptable measure of performance but some MGF based methods provides tighter bounds on the BER and can be used to confidently describe the performance of FSO communication systems.

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