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Comparison of hard-decision and soft-decision channel coded *M*-ary PPM performance over free space optical links

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SUMMARY

Error control coded *M*-ary pulse position modulation (PPM) can be used over free space optical links to mitigate the atmospheric attenuations and the turbulence induced fading. In this paper, we present performance analysis for coded free space optics (FSO) communication systems operating over various atmospheric conditions. We justify the selection of higher state PPM as an appropriate modulation scheme for the links and provide a comparative analysis between hard decision decoded (Reed-Solomon, RS) and soft decision decoded (Turbo) channel coded PPM over varying link conditions. Simulation results strongly indicate RS-coded PPM as a robust and well-performing coded-modulation scheme for the FSO links. Copyright © 2008 John Wiley & Sons, Ltd.

1. INTRODUCTION

Free space optics (FSO) is a cost effective, high bandwidth alternative and complementary wireless scheme to the conventional RF systems, which has attracted interest in recent years [1–4]. With the potential high data rate capability, low cost, quick deployment, convenient reconfigurability and scalability, high security and particularly wide bandwidth on unregulated spectrum (as opposed to the limited bandwidth radio frequency (RF) counterpart), FSO systems have emerged as an attractive means not only for terrestrial point-to-point links as a supplement to fiber optics [2] but also for deep space and intersatellite communication and other applications including cellular backhauls and local area network segment interconnects.

In this paper we focus on terrestrial point-to-point short range line of sight links, that provide a viable solution to the last mile problem [5]. Such links however, suffer from intensity attenuation caused by fog, rain, snow and building sway, atmospheric turbulence induced fading and solar background light interference [6]. This requires an enhanced system design for the links to improve performance under severely adverse weather conditions. The problem of efficient data communication over free space optical links has driven much of the cross-disciplinary research on the adaptation of the principles of conventional electrical modem design to the optical intensity channels [7]. Current free space optical communication systems employ intensity modulation with direct detection (IM/DD) [8, 9] and use light emitting diodes (LED) or laser diodes as transmitters and PIN photodiode or avalanche photodetectors as receivers. These devices modulate and detect solely the intensity of the carrier and not its phase. Furthermore, biological safety reasons constrain the average radiated optical power, thereby constraining the average signal amplitude.

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The most reported modulation technique used for FSO is the on-off keying (OOK) which offers bandwidth efficiency but lacks power efficiency. Binary level signalling though the simplest and most common modulation schemes for the optical intensity channel, offer low power efficiency and high bandwidth efficiency [7]. Power efficiency as well as the improved system performance can be achieved by adopting pulse position modulation (PPM) schemes as in References [10–14]. *M*-ary PPM achieves high power efficiency at the expense of reduced bandwidth efficiency compared with other modulation schemes [13]. The optimal PPM order is high, since a higher order creates the higher peak power needed to overcome the weak average power [15]. *M*-ary PPM has been previously suggested as a suitable modulation scheme for FSO systems [16, 17].

In FSO PPM communication links, channel coding is needed to reduce the average transmitted optical power required for reliable communication and to keep the system bandwidth requirement low compared to that for uncoded PPM at a specific bit error rate [18]. Besides, coding provides a form of time diversity to combat turbulence induced fading. McEliece [19] has suggested the use of Reed-Solomon (RS) block codes in a noiseless PPM channel. Massey [20] has investigated the use of interleaved binary convolutional codes in a PPM channel. Divsalar *et al.* [21] have extended the application of RS codes to noisy optical PPM channels with background and photodetector noise. RS codes have long been used in combination with PPM as their alphabet sizes are easily matched to the PPM order, resulting in a one-to-one correspondence between code symbols and PPM symbols. However, a disadvantage of a RS code is that the decoder does not use the soft detector outputs, but instead operates on the decoded PPM symbols and erasures. There do exist methods for extracting soft information from the RS codes [22] but adapting such methods for utilisation and practical implementation excessively complicates the PPM modulated FSO system design. We thus have the motivation for using Turbo codes, which are already known to have outstanding performance in other applications and can operate on the soft counts directly rather than having to use explicit PPM symbol decisions. In fact, there have been attempts towards using Turbo codes for the turbulent FSO channels with IM/DD [9, 23] and Kiasaleh [24] has demonstrated appreciable coding gains possible through Turbo coded binary PPM.

In this paper, we propose a channel coded *M*-ary PPM scheme for terrestrial FSO systems that uses an efficient algorithm to extract soft information from the received PPM frames. A performance comparison is made between the soft-decision decoding (for Turbo codes) and the hard decision decoding (RS codes) for the proposed modulation scheme. The paper describes the channel modelling performed for testing the performance of the coded modulation scheme in Section 2, and follow it up with a theoretical justification of *M*-ary PPM as the modulation of choice in the next section. Section 4 forms the core of the work, providing a detailed comparative analysis between the Turbo-coded and RS-coded PPM. The paper concludes with some remarks and direction for future work.

2. CHANNEL MODELLING

To design an appropriate coded-modulation scheme, it is of prime significance to accurately model the terrestrial atmospheric propagation channel. The channel imposes interesting challenges to the system designer owing to all the different possible impairments [25–27]. The atmosphere interacts with the light due to its composition, which consists of different molecular structures and small suspended particles called aerosols. This interaction produces a variety of phenomena: frequency selective attenuation, absorption, scattering and scintillation. Sunlight may also affect system performance when the sun is co-linear with the free space optical link.

2.1. Ambient light

Ambient light can be physically interpreted as an additional unwanted electromagnetic radiation with flat frequency characteristic in the bandwidth of the detector [28]. We model ambient noise as an additive Gaussian noise with zero mean and standard deviation as a parameter, which determines the power of ambient light.

2.2. Fog

Mie scattering due to aerosol and fog droplet distribution is considered the major atmospheric element that attenuates the optical signal. The coded modulation require modelling fog attenuation for PPM symbol duration (in order of milliseconds for the physical world). In recent measurements in Graz [29], fog was measured at a time resolution of about 10 ms and no change was observed in the attenuation level over very long intervals of a few seconds. Thus, the coherence time of the attenuation is much greater than a PPM symbol period. Figure 1 shows the specific attenuation during one second in a fog event recorded in Graz [30]. The attenuation is clearly constant and this expresses a strong statistical dependence from one coded symbol to

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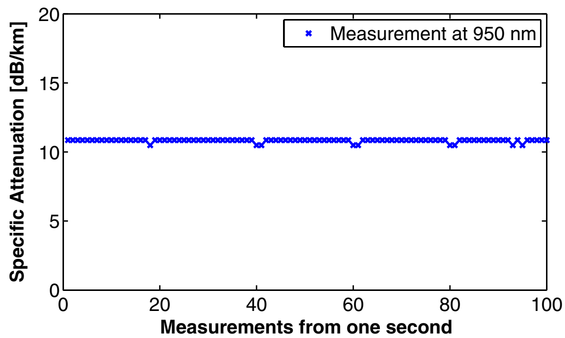

Figure 1. Specific attenuation during 1 second in the fog event.

the next, and the errors thus introduced would be bursty in nature. Fog increases the attenuation of the optical signal, so it can be modelled as a multiplicative distortion. The attenuation variation in a foggy period of a year roughly obeys the Gaussian distribution in dB scale [31]. So we model fog attenuation as multiplicative channel distortion with Gaussian distribution. The attenuation is taken constant for at least one modulation symbol; assuming a frozen atmospheric channel.

2.3. Scintillation

One of the major impairments on the FSO channel is the atmospheric turbulence or scintillation, which occurs as a result of the variations in the refractive index due to inhomogeneities in temperature and pressure fluctuation [32]. The atmospheric turbulence results in fluctuations at the received signal, i.e. signal fading. The length and the depth of the fades need be estimated. Averaged over different operating conditions, the scintillation fade was determined as 4 dB of attenuation depth and 20 ms of fade length, translating into very long but not very deep fades [5]. Henniger *et al*. [33] state that usually the fading time is much bigger than one bit duration and the data signal is affected by very slow fading, i.e. the mean duration of fades is much longer than the duration of one block code word.

In general, when an optical beam is exposed to clear air turbulence, the intensity of the optical beam experiences random fluctuations. The coherence length of such fluctuations is in the range of a few milliseconds to tens of milliseconds, justifying a frozen-atmosphere model for high-speed communications. We may estimate this as a slow-fading condition and considering the frozen-atmosphere scenario, the received signal impacted by turbulence can be assumed constant over a PPM slot duration [17].

The lognormal distribution is the most widely used model for the probability density function (pdf) of the irradiance [23]. However, this model is only applicable to weak turbulence conditions [34]. Many other statistical models have also been proposed over the years to describe atmospheric turbulence such as the K distribution, I-K distribution and Lognormal Rician channel [1]. In a recent series of papers on Scintillation theory [34–36], Andrews *et al*. introduced the modified Rytov theory and proposed gamma-gamma pdf based on a doubly stochastic theory of scintillation.

We use two different models, namely the lognormal and the exponential distribution function to predict the fluctuation of the intensity signal. In order to characterise the influence of fading, it is common practice to employ the scintillation index defined by

$$\chi_{\mathrm{sc}} := \frac{E[n_s^2]}{E[n_s]^2} - 1 \tag{1}$$

where n_s are the average number of signal photons. For lognormal models $\chi_{\mathrm{sc}} \in [0.0, 0.75]$, whereas for exponential models $\chi_{\mathrm{sc}} \geqslant 1.0$.

The related probability distribution for the lognormal model can be described as

$$f_I(n_s) = \frac{1}{\sqrt{2\pi\sigma_I^2 n_s}} e^{-\frac{(\ln n_s - \mu_I)^2}{2\sigma_I^2}} \tag{2}$$

The scintillation index is given by

$$\chi_{\mathrm{sc}} = e^{\sigma_I^2} - 1 \tag{3}$$

such that $\sigma_I^2 = \ln(1 + \chi_{\mathrm{sc}})$.

To cater for strong turbulent conditions, i.e. $\chi_{\mathrm{sc}} \geqslant 1.0$, we have utilised the exponential probability distribution which can be summarised by

$$f_I(n_s) = \frac{1}{\overline{n}_s} e^{-\frac{n_s}{\overline{n}_s}} \tag{4}$$

where $\overline{n}_s$ is the average number of signal photons according to the exponential model.

3. MODULATION

Most modulation schemes for data transmission on landline or wireless optical channels rely on binary levels to transmit data. The communication design problem is one of carefully designing a pulse set in order to meet the required amplitude constraints while at the same time ensuring that power

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and bandwidth efficiency targets are met. Schemes such as on-off keying and PPM depend on the use of two levels to transmit data. Multilevel modulation schemes can provide better bandwidth and power efficiencies because of their more complex signal constellations. Schemes such as L-PAM (pulse amplitude modulation) and QAM (quadrature amplitude modulation) achieve higher bandwidth efficiency at the expense of decreased power efficiency. M-ary PPM is a fundamentally different modulation scheme that achieves high power efficiency at the expense of reduced bandwidth efficiency [13]. Digital PPM is widely used in intensity-modulated optical communication systems, such as fibre optic and satellite systems, primarily because of its high average-power efficiency [19, 37, 38]. The abundance of bandwidth in these applications makes the poor bandwidth efficiency of PPM of little concern, the FSO environment represents a very similar situation, and PPM with its significantly better power efficiency seems the appropriate choice.

A k-bit source

$$\mathbf{a} = (a_1, a_2, \dots\dots\dots, a_k) \epsilon (0, 1)^k$$

when modulated with M-ary PPM, $M = 2^k$, yields a signal

$$X = (0, \dots, 0, 1, 0, \dots\dots, 0) \epsilon (0, 1)^M$$

which contains a single one in the position indicated by the binary representation of a. The transmission channel is a binary-input unconstrained-output memoryless channel. One use of the overall PPM-symbol channel consists of M serial uses of the binary input channel, and produces the received vector

$$\mathbf{Y} = (Y_1, Y_2, \dots, Y_M) \epsilon \mathbf{R}^M$$

Since PPM uses one pulse per M slots, it has a duty cycle of $1/M$ and a peak-to-average power ratio of M. It uses $\frac{\log_2(M)}{M}$ bits per slot, which for varying M results in a flexible trade-off between photon efficiency and bandwidth efficiency [15].

In a PPM scheme, each symbol interval of duration

$$T = \frac{1}{R_b} \log_2 M \tag{5}$$

is partitioned into M sub-intervals, or chips, each of duration $\frac{T}{M}$, and the transmitter sends an optical pulse during one and only one of these chips. PPM is similar to L-ary FSK, in that all signals are orthogonal and have equal energy.

A baseband AWGN channel model for optical wireless communications can be written as

$$y(t) = \int_{-\infty}^{\infty} x(\tau) h(t - \tau) \mathrm{d}\tau + n(t) \tag{6}$$

where $x(t)$ is the instantaneous transmitted optical power, $y(t)$ is the instantaneous received current, $h(t)$ the temporal dispersion and $n(t)$ the white Gaussian noise. $x(t)$ must satisfy

$$x(t) \geqslant 0 \quad \text{and} \quad \overline{x(t)} \leqslant P \tag{7}$$

where P is the average optical power constraint of the transmitter [39].

A PPM signal satisfying Equation (7) can be written as

$$x(t) = MP \sum_{k=0}^{M-1} c_k \, p(t - \frac{kT}{M}) \tag{8}$$

where $[c_0, c_1, c_2, \dots\dots, c_{M-1}]$ is the PPM codeword, P the average signal power and equals $\frac{1}{M} \sum_i \overline{x_i(t)}$ and $p(t)$ is a regular pulse of duration $\frac{T}{M}$ and unity height. The transmitter conveys information at a rate of R_b bits/s by transmitting one of the M non-negative signals every $T = \frac{\log_2 M}{R_b}$ seconds. All of the signals are equidistant, with

$$\begin{aligned} d_{\min}^2 &= \min_{i \neq j} \int_{-\infty}^{\infty} (x_i(t) - x_j(t))^2 \mathrm{d}t \\ &= 2MP^2 \frac{1}{R_b} \log_2 M \end{aligned} \tag{9}$$

where $d_{\min}$ is the minimum Euclidean distance between any pair of valid modulation signals. Therefore, the average power requirement is approximately

$$P_{\mathrm{PPM}} / P_{\mathrm{OOK}} \approx d_{\mathrm{OOK}} / d_{\min} = \sqrt{\frac{2}{M \log_2 M}} \tag{10}$$

$d_{\mathrm{OOK}} = \frac{2P}{\sqrt{R_b}}$ is the minimum distance between the two signals in OOK signal set. From Equation (10), we see that, for any M greater than 2, PPM requires less optical power than OOK. In principle, the optical power requirement of PPM can be made arbitrarily small by making M suitably large, at the expense of bandwidth, the bandwidth required by PPM to achieve a bit rate of R_b is approximately the inverse of one chip duration, $B = M/T = M \frac{R_b}{\log_2 M}$ [39]. It has been shown in Reference [13] and can be seen through Equation (10) that 2-PPM has same power efficiency as

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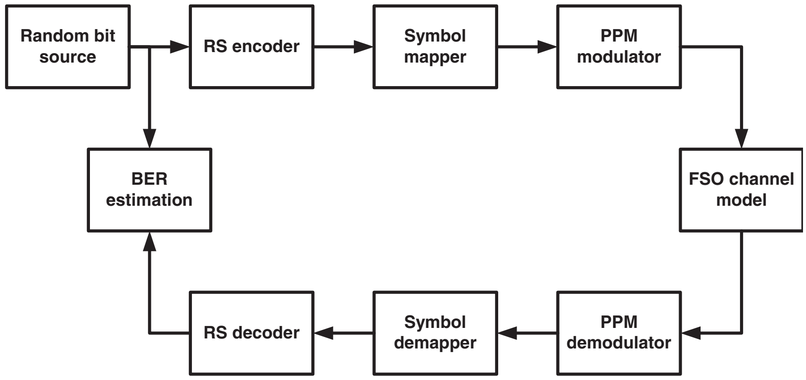

Figure 2. FSO communication system simulation model.

OOK but requires twice the bandwidth and 4-PPM requires 3.8 dB less optical power, and as M increases from 4 to 16, the bandwidth requirement doubles, while the sensitivity increases from 3 dB better than OOK to 7.5 dB better than OOK, and clearly increasing M improves the power efficiency for multilevel PPM. Though increasing M would continuously improve the power efficiency, but practical considerations like synchronisation and detection limits the implementation up-to a reasonable value.

The M-PPM system can also be viewed as a binary constant weight (n, d, w) code, where n, d and w are the length, minimum Hamming distance and weight of the codeword, respectively. The generic M-PPM will always have $n = M$, $d = 2$ and $w = 1$. Thus, M-PPM can be viewed as the rate $\frac{\log_2 M}{M}$ block code consisting of all binary M-tuples having unity Hamming weight [40]. However, a multipulse PPM scheme [41] may also be devised with varying values for the codeword parameters (n, d, w). The multipulse PPM system can outperform the single pulse scheme [41], but due to its complicated hardware implementation, we restrict our analysis only to the single pulse case. If λ denotes the average number of photons sent in a signal slot, then the transmission efficiency ζ can be defined as

$$\zeta = \frac{\ln M}{\lambda} \tag{11}$$

To prove our theoretical analysis, we simulated the performance curves for M-ary PPM with different values for M, under various operating conditions. Figure 2 shows the FSO communication system model utilised. For modulation analysis the RS channel coder in the model was deactivated. As perceived by the theoretical analysis of M-PPM modulation schemes with the same average power, the higher state PPM with more concentrated power performed significantly better. Figure 3 shows the performance curves tested under ambient light conditions, i.e. in the presence of only background light and no other attenuations, the 256-PPM showed an improvement of about 5 dB at a bit error rate (BER) of 10^{-6} over 2-PPM, which is very similar to the current technology of IM/DD or OOK.

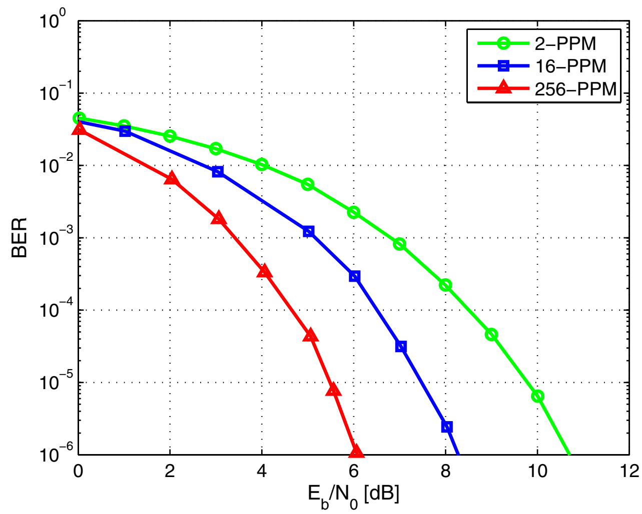

Figure 3. Performance comparison of 2-PPM, 16-PPM and 256-PPM.

4. CHANNEL CODING

A PPM signalling scheme seems to lend itself naturally to a RS code, whose alphabet size can be easily matched to the PPM order. This results in a one-to-one correspondence between RS code symbols and PPM symbols. Using a maximum count, or threshold hard decision rule [42], a single PPM error translates directly into a single RS-code symbol error.

RS codes can be applied to M-ary PPM to enhance the system performance. An (N, K) RS code can correct all patterns of up to $(N-K)$ symbol erasures. Assuming that a decoding error occurs when there are $(N-K+1)$ or more symbol erasures. In case of a decoding error, a fraction of $(N-K+1)/N$ of the K information symbols are decoded erroneously. The symbol error probability P_e is therefore

$$P_e = \frac{N-K+1}{N} \sum_{s=N-K+1}^{N} \binom{N}{s} \epsilon^s (1-\epsilon)^{N-s} \tag{12}$$

where ϵ is the probability of a symbol erasure given by

$$\epsilon = \left(1 - M^{-\frac{R_c}{\zeta}}\right)\left(M^{-\frac{R_c}{\zeta}}\right) \tag{13}$$

with code rate $R_c = K/N$ and the transmission efficiency, ζ.

Since RS codes cannot make full use of soft information, Turbo codes, well known for their exceptional coding gains, were chosen to provide a comparative analysis. Attempts towards utilising Turbo codes in combination with PPM for optical systems have been made earlier as well [24, 43, 44]. The primary difficulty of applying a Turbo code to an optical channel is that of matching Turbo codes symbols to the higher state PPM. A suitable PPM order for our application is 256 (Figure 3), whereas 256-ary Turbo codes are practically not feasible as Turbo decoding complexity is exponential in the symbol alphabet size, and it would introduce huge computational effort and intolerable decoding delays.

Soft information extraction necessary for Turbo decoding was accomplished by developing a low complexity algorithm. This algorithm calculates the soft information for each data bit based on the received power within each PPM time slot. Each PPM symbol represents the $k = \log_2 M$ bits long binary data vector $\mathbf{a} = (a_1, a_2, a_3, \ldots, a_k)$. Probability that data vector $\mathbf{a}$ was sent if the PPM symbol Y is received can be calculated by Reference [43]

$$P(\mathbf{a}|\mathbf{Y}) = \frac{\frac{p_s(y_a)}{p_n(y_a)}}{\sum_{i=1}^{M}\left(\frac{p_s(y_i)}{p_n(y_i)}\right)} \tag{14}$$

where $p_s(\cdot)$ and $p_n(\cdot)$ denote the pdf of the soft output of a signalling slot and a non-signalling slot, respectively. We propose calculating $P(\mathbf{a}|\mathbf{Y})$ which simply equals the power received in the ath PPM slot normalised with the total PPM symbol power [45].

$$P(\mathbf{a}|\mathbf{Y}) = \frac{y_a}{\sum_{i=1}^{M} y_i} \tag{15}$$

Having calculated $P(\mathbf{a}|\mathbf{Y})$, the probabilities that the particular bit in the data vector $\mathbf{a}$ is '1' or '0' at the received

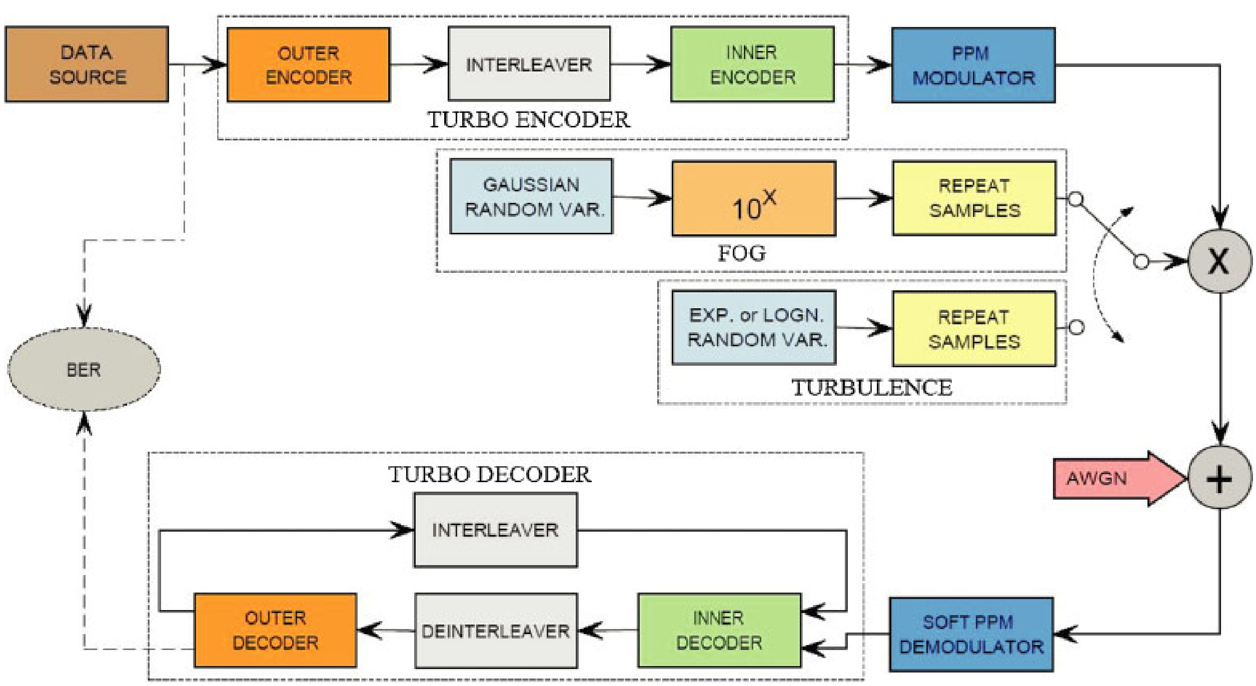

Figure 4. FSO communication system simulation model with Turbo-coded-PPM.

Table 1. Generator polynomials for Hamming codes.

n	k	Generator polynomoial
7	4	$X^3 + X^1 + 1$
15	11	$X^4 + X^1 + 1$
31	26	$X^5 + X^2 + 1$
63	57	$X^6 + X^1 + 1$

symbol Y can be determined, considering probabilities of all M possible vectors **a**. It was shown [45] that the proposed simplification does not impair the performance of the Turbo decoder.

Figure 4 shows the simulation setup utilised to obtain the Turbo coded PPM performance curves. Turbo product codes (TPC) with a pair of extended Hamming codes were designed with a matched random block interleaver structure. Binary extended Hamming codes with additional parity check bits were designed for the simulation setup. The generator polynomials for the Hamming codes utilised are specified in Table 1, and they were always used in the extended form as identical encoders without shortening. The iterative decoding required decoders with soft input and soft output (SISO). The decoder calculates the *a posteriori* value Λ_o for each bit in the data vector **a** based on the a priori information of previous decoder Λ_i and soft channel values. A maximum likelihood (ML) decoding algorithm for component decoding inside SISO decoders is complex, and the simulation setup utilised the sub-optimal Chase Pyndiah algorithm [46, 47].

This sub-optimum algorithm [46] is better for all block linear codes with known algebraic decoding algorithm, and has been extended for applications in SISO decoding of Turbo codes [47], where the analog weights are calculated using Euclidean distance. The reliability vector is calculated by

$$\Lambda(d_j) = \ln\left(\frac{P(e_j = +1|R)}{P(e_j = -1|R)}\right) \tag{16}$$

The soft outputs are calculated as

$$r'_j = \left(\frac{|R - C|^2 - |R - D|^2}{4}\right) d_j \tag{17}$$

where $|R - D|^2$ is the Euclidean distance between soft input value R and the hard decision codeword D and $|R - C|^2$ is the Euclidean distance between R and codeword C. d_j is the jth bit value of D and C is a competing codeword of D with jth bit inverse value $c_j \neq d_j$. If there are more such codewords then the one with the minimum Euclidean distance is selected.

To get a better insight into the performance of soft-decision and hard-decision channel codes, a detailed comparative analysis of RS-coded 16-PPM and Turbo-coded 16-PPM is provided. Results under different operating conditions on an $\frac{E_b}{N_0}$ scale are being provided for the simulated terrestrial FSO link. In radio communication systems, the SNR is defined as a ratio of average signal power to average noise power

$$\mathrm{SNR} = \frac{E_S/T_S}{N_0 B} = \frac{E_S/T_S}{N_0/T_S} = \frac{E_S}{N_0} \tag{18}$$

where E_S denotes the energy of received signal, B is signal bandwidth, T_S stands for PPM symbol duration and N_0 is the noise power spectral density. Assuming an M-PPM signal sampled once per PPM slot, the noise power spectral density N_0 is calculated as a sum of noise samples in each slot N_i normalised by signal bandwidth 1/M, thus the SNR yields

$$\mathrm{SNR} = \frac{E_S M}{\sum_{i=1}^{M} N_i} \tag{19}$$

The SNR is transformed to E_b/N_0 by considering number of transmitted data bits per symbol

$$\frac{E_b}{N_0}[\mathrm{dB}] = \mathrm{SNR}[\mathrm{dB}] - 10\log_{10}(R_c \log_2 M) \tag{20}$$

where R_c is coding rate. To depict a comprehensive picture, comparative performance curves for coded 16-PPM under ambient light, foggy weather and turbulent atmospheric conditions are produced.

Figure 5 shows the performance curves for coded 16-PPM under ambient light conditions. The rate $\frac{1}{2}$ RS (255,127) code provides very similar coding gain as the rate $\frac{4}{5}$ TPC (64,57). The rate $\frac{2}{3}$ TPC (32,26) performance is slightly inferior to the TPC (64,57). TPC (64,57) was simulated for different interleaver sizes variant by a factor of 10, but both provided the same performance. The operating conditions for these simulations of ambient light alone, meant that the channel errors could be classified as random, which may explain insignificant gain by increasing the interleaver size. The rate $\frac{1}{4}$ TPC (8,4) fail to provide any coding gains under the ambient light conditions.

Figure 6 provides the simulation results for coded 16-PPM performance under moderate fog conditions. The moderate fog attenuation has been added in a way that there is symbol-to-symbol independence between the

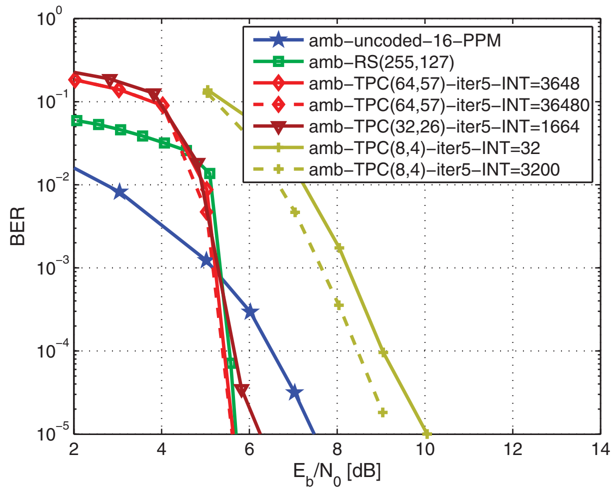

Figure 5. Coded 16-PPM under ambient light conditions.

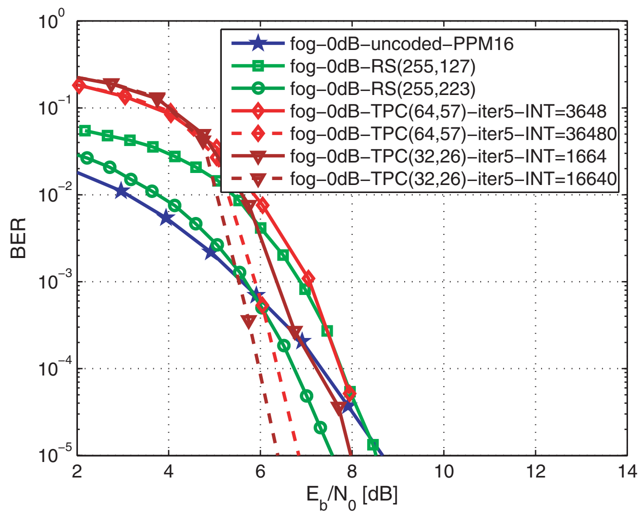

Figure 6. Coded 16-PPM under foggy weather conditions.

errors introduced but they are highly co-related per symbol, thus, causing short burst of errors. Heavy fog causes high levels of attenuation and very long error bursts mostly disrupting the FSO links altogether. The RS (255,223) code rate $\frac{7}{8}$ outperforms its counterpart RS (255,127) code with a code rate of $\frac{1}{2}$. The rate $\frac{4}{5}$ TPC (64,57) and the rate $\frac{2}{3}$ TPC (32,26) both give a performance enhancement of about 1.4 dB at 10^{-5} BER when their interleaver sizes are enhanced 10 fold. The spectral thinning introduced by longer interleavers allows the performance enhancement in the bursty errors introduced by fog attenuations. Further increasing the interleaver length would provide even better gains but introduce intolerable decoding delays. The rate

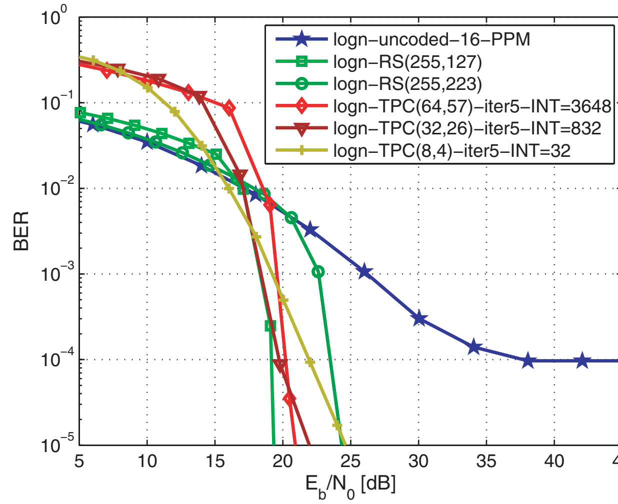

Figure 7. Coded 16-PPM under weak turbulent conditions.

$\frac{2}{3}$ TPC (32,26) with an interleaver size of 16 640 bits outperforms the RS (255,223) by about 1.2 dB and the TPC (64,57) with interleaver size of 36 480 bits by 0.7 dB at an operating BER of 10^{-5}. The Turbo codes prove their superior performance against bursty errors in these simulated results.

Figure 7 depicts the coded 16-PPM performance under weak turbulent conditions modelled as a lognormal distribution. Lognormal distribution is agreed upon to model weakly turbulent conditions [1] with the scintillation index $\chi_{sc} \in [0.0, 0.75]$. For the simulation, the lognormal distribution utilised represented a scintillation index χ_{sc} about 0.5. This result proves the real merit of applying channel coding, as it can be clearly seen that the coding gain provided by the codes below a BER of 10^{-4} is immense, as the uncoded PPM performance curve saturates. The coding gains for Turbo and RS codes are very similar in this case, and owing to their different code rates a direct comparison is not possible. However, the RS (255,127) performs better than all the other codes under the weakly turbulent atmospheric conditions.

Figure 8 shows the performance under strong turbulent conditions modelled as an exponential distribution. Strong turbulence conditions represent a scintillation index $\chi_{sc} \geqslant 1.0$. The uncoded curve saturates rather quickly owing to the strongly turbulent atmosphere. The coding rates seem to play a crucial role in the strongly turbulent atmospheric conditions. All the different simulated Turbo product codes provide very similar coding gains with all performing better than RS (255,223), however, worse than RS (255,127). The rate $\frac{1}{2}$ RS (255,127) codes again perform better than all of

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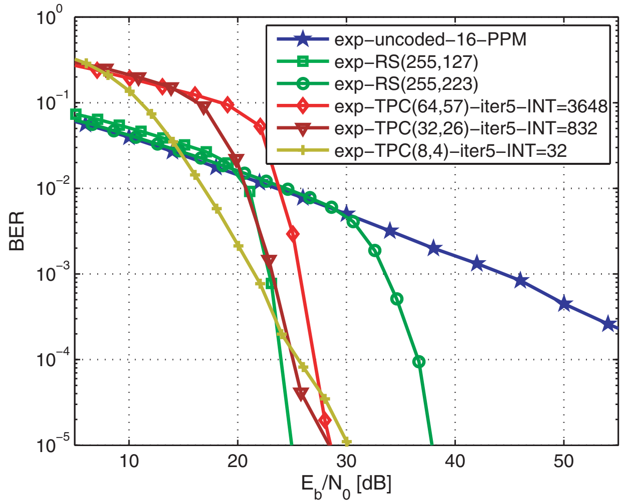

Figure 8. Coded 16-PPM under strong turbulent conditions.

the simulated Turbo codes. Though, not shown, we have also simulated the performance of Turbo codes with different interleaver sizes under turbulent conditions and longer interleavers do provide performance enhancement, however, the gains are not substantial (remaining well within a dB for a 10 times increase in the interleaver length).

The simulation results shown in the paper are rather difficult to interpret from a pure theoretical perspective since the code rates of the simulated codes are all different. The chosen code rates for the RS codes are $\frac{7}{8}$ for RS (255,223) and $\frac{1}{2}$ for RS (255,127) and for the Turbo product codes are $\frac{1}{4}$ for TPC (8,4), $\frac{2}{3}$ for TPC (32,26) and $\frac{4}{5}$ for TPC (64,57).

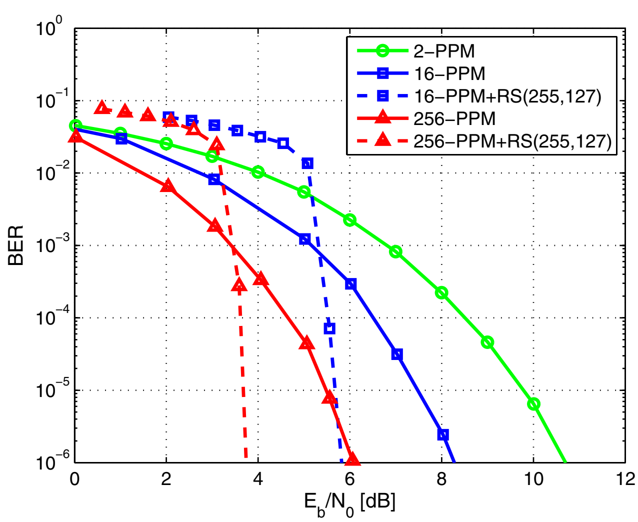

Figure 9. RS-coded PPM performance curves.

The selection of the codes has been motivated by the ease of their practical implementation. The Turbo codes chosen are those specified in Reference [48] and the decoding iterations for them have also been limited to five to keep the decoding delays within permissible limits for real world data applications [49]. Long interleavers introduce spectral thinning in Turbo codes by reducing the multiplicities of the low-weight codewords thus improving the performance but at the same time introduces large decoding delays by extending the block lengths of the codes. Introducing very long interleavers is thus not feasible as the decoding delays would reduce the acceptability of the free space optical technology in real time applications.

All in all, the analysis shows that RS coded PPM with a (255,127) code is quite a robust choice under most operating conditions, and when combined with 256-PPM, can provide a performance enhancement of about 6.8 dB over the current uncoded two level modulation schemes (Figure 9). The Turbo codes do provide coding gains, but the effort required to extract soft information and the decoding complexity involved may not be easily justifiable for FSO system design, so RS coded PPM might still be the preferable choice for practical world implementations.

5. CONCLUSIONS

In this paper, the modulation and channel coding design for terrestrial free space optical links was considered. Channel modelling for the terrestrial FSO links was discussed, followed by the proposal of higher state *M*-ary PPM as the modulation of choice for the future systems. The choice of *M*-ary PPM has been argued upon both theoretically and by simulation results. Appropriate channel codes to be coupled with *M*-ary PPM were discussed and a thorough comparative performance analysis has been provided between hard-decision decoded (RS) and soft decision decoded (Turbo) codes for varying atmospheric link conditions. In case of random errors alone (e.g. under ambient light addition), the rate $\frac{1}{2}$ RS codes perform better than all the different simulated Turbo codes. Turbo codes with long interleavers are the better choice when the errors are bursty (e.g. those introduced by foggy conditions). Under turbulent atmospheric conditions, both weak and strong, rate $\frac{1}{2}$ RS codes perform better than their counterpart Turbo codes. Channel coding plays a vital role under turbulent conditions as the uncoded PPM performance curve saturates, and thus coding provides substantial gains. Optimum interleaver sizes and code rates vary according to the turbulence strength. Long fades can be combated with matched interleaver concatenated coding.

Coded-modulation design is a challenging research problem for the atmospheric terrestrial free space optical channel. The implementation of an M-ary PPM modulation scheme can provide considerable performance enhancement. Coding offers extra link margin for combating attenuation and fading. The choice of channel codes may be driven by factors like tolerable decoding delays, and ease and cost of implementation. Our simulation results indicate that the RS codes provide a good compromise based on performance-complexity tradeoff, and perform well under most naturally occurring terrestrial FSO link conditions. An over all performance gain of up to 6.8 dB can be achieved by using RS coded 256-PPM as compared to the current systems under ambient light conditions.

Packet layer coding [50] alongside the current work on the physical layer will lead to better future systems. Real time signal estimation can be used to provide adaptive modulation and codes which will result in much better throughput performance.

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