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New adaptive link layer protocol using optimal packet length for free space optical communications

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ABSTRACT

In this paper, the authors propose a new link layer protocol that adapts packet length and modulation and coding scheme (MCS) to propagation conditions for free space optical communications (FSO). In conventional FSO systems, only the MCS has been adapted with respect to propagation condition. For low signal to noise ratio (SNR), we reduce packet length and use robust modulation such as On Off Keying (OOK) and low rate channel coding. While, at high SNR, we increase packet length and use large modulation constellation. A significant enhancement in throughput is observed: the proposed link layer protocol offers 1–2 dB gain compared to the conventional one where all packets are transmitted with the same length.

1. Introduction

Radio Frequency (RF) communications are used in many standards such as Universal Mobile Telecommunications Service (UMTS), Long Term Evolution (LTE), LTE Advanced and WiMax and offers low data rates with respect to optical systems [1–5]. Actual optical systems incur substantial costs related to the digging up of sidewalks to install fiber links. To circumvent this problem, a new technology known as FSO Communication can be used [1–8]. FSO allows high data rates (10 Gbps), line of sight and license-free communications. FSO communications can be used for applications requiring high data rate such as HDTV, internet games, military applications, satellite communications, last mile access, …FSO communications is a potential solution to solve the spectrum scarcity problem encountered in RF communications. There are many advantages of FSO communications such as very simple installation, high capacity, high interference immunity as well as security … [1–8]. The Quality of Service (QoS) of FSO communications can be degraded due to atmospheric turbulence (rain, fog, dust, and heat) or pointing errors. Pointing errors are due to misalignment between transmitter and receiver caused by building sway. Pointing errors are due to wind or weak earthquakes. The effect of pointing errors has been modeled and studied in [1,9,10]. Pointing errors are a serious problem in urban areas where FSO equipment are installed on high buildings. To improve the performance of FSO communications, many solutions have been suggested such as error control coding, spatial or cooperative diversity using Multiple Input Multiple Output (MIMO) systems or relaying techniques [11–14]. Hybrid RF/FSO links have also been suggested where one hop uses traditional RF communications and the second hop uses FSO [15–17]. Hybrid RF/FSO can be used in the uplink where multiple RF users are multiplexed in a single high speed FSO link. We can also have RF and FSO communications in parallel. Different relaying techniques have been considered for FSO communications or hybrid RF/FSO such as Amplify and Forward (AF) or Decode and Forward (DF) relaying. Non blind relays using an adaptive amplification gain and blind relays with a constant amplification factor were studied. Most research studies focused on symbol error or outage probabilities of FSO communications in the presence of atmospheric and pointing errors. There are some studies at the packet level [1–5,18–26]. In all previous studies, packet length was fixed and not adapted to propagation conditions [1–5,18–26]. In [1,18–26], only the MCS is adapted to propagation conditions.

In this contribution, we propose an enhanced adaptive link layer protocol for FSO communications using an optimal packet length that is adapted to propagation conditions. We propose a new adaptive link layer protocol that adapts both packet length and MCS to propagation conditions. The instantaneous SNR is estimated at the receiver and sent back to the transmitter in order to adapt packet length and the MCS. We use an optimal packet length obtained by maximizing the throughput. When the SNR is high, we increase packet length and use high modulation such as 16 or 32 PAM (Pulse Amplitude Modulation). When the SNR is low,

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the packet length is reduced and we use a robust modulation such as OOK and a low rate channel code. To the best of our knowledge, adapting both packet length and MCS to channel conditions has not been yet proposed. In conventional optical systems, only the MCS is adapted to the SNR. Our approach will lead to significant throughput enhancement.

The contributions of the paper are:

– Adapt both packet length and the MCS to propagation conditions. The results will be compared to conventional systems where packet length is fixed and only the MCS is adapted.

– Propose an SNR quantization on feedback channel where only few bits are sent back to adapt the MCS and packet length.

– Study the throughput in the presence of atmospheric turbulence as well as pointing errors.

The paper is organized as follows: The system model is provided in next section. Section 3 describes the proposed protocol where both packet length and MCS are adapted to propagation conditions. Section 4 provides some theoretical and simulation results. Some conclusions are drawn in Section 5.

2. Signal model

The baseband model of the electrical signal at the output of the photo-detector is written as

$$y_l = \sqrt{\overline{\Gamma}} g I_p x_l + n_l \tag{1}$$

where x_l and y_l are respectively the transmitted and received signals, $l = 1, \ldots$,L indicates the channel use in each block , g is the atmospheric fading coefficient, I_p is the effect of pointing errors, n_l is a normalized complex Gaussian noise with unit variance and $\overline{\Gamma}$ is the photo-detected electrical average SNR (Signal to Noise Ratio).

The channel is assumed to be constant over each packet. The coherence time of FSO systems is between 0.1 to 10 ms [27]. Since data rates are equal to 10 Mbps to several Gbps, the channel remains constant over thousands to millions of consecutive symbols corresponding to one or several packets. The instantaneous photo detected SNR over a given transmitted packet is equal to

$$\gamma = \overline{\Gamma} g^2 I_p^2 \tag{2}$$

In the following, we denote by

$$h = g^2 \tag{3}$$

the atmospheric turbulence.

It has been shown in [28] that the atmospheric turbulence follows a Gamma Gamma distribution

$$f_h(x) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}} x^{\frac{\alpha+\beta}{2}-1}}{\Gamma(\alpha)\Gamma(\beta)} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta x}\right) U(x) \tag{4}$$

where $U(x)$ is the Heaviside function, $\Gamma(.)$ is the Gamma function and $K_\upsilon(x)$ is the υth order modified Bessel function of second order. Small values of α and β correspond to severe atmospheric turbulence [29,30]. Typical values are $\alpha = 2.064$ and $\beta = 1.342$ for strong turbulence, $\alpha = 2.296$ and $\beta = 1.822$ for moderate turbulence, $\alpha = 2.902$ and $\beta = 2.51$ for weak turbulence [29,30].

When there is no pointing errors, the SNR Probability Density Function (PDF) can be easily deduced using $\Gamma = \overline{\Gamma} h$.

The Gamma distribution is a good approximation of Gamma Gamma distribution [31] using moment matching approach [31]. The PDF of Gamma distribution is equal to

$$f_h(x) = \frac{x^{k-1} e^{\frac{-x}{\theta}}}{\theta^k \Gamma(k)} \tag{5}$$

with $E(h) = \theta k = 1$. θ and k are chosen so that the first two moments of Gamma and Gamma Gamma distribution are equal [31]:

$$k = \frac{\alpha\beta}{\alpha+\beta+1} \tag{6}$$

and $\theta = 1/k$.

In the presence of pointing errors, the distribution of SNR is equal to [32]

$$p(\gamma) = \frac{\zeta^2}{\gamma \Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{3,0}\left[\alpha\beta \frac{\gamma}{\overline{\Gamma}} \Big|_{\zeta,\alpha,\beta}^{\zeta^2+1}\right] \tag{7}$$

where G is the Meijer's function defined in [33] Eq. (9.301), ζ is the ratio between the equivalent beam radius at receiver and pointing error displacement standard deviation. For negligible pointing errors, i.e., $\zeta \to +\infty$, the above distribution converges to non pointing error case [32].

2.1. Shot noise

Another possible model of the additive noise contains the contribution of both thermal noise $n_{th}(t)$ and shot noise $n_{sh}(t)$. The thermal noise can be approximated by a Gaussian noise with variance N_0. The shot noise is a signal dependent noise that be approximated by a Gaussian noise [34]. The variance of shot noise depends on the symbol energy of transmitted signal E_s and atmospheric turbulence h [34]:

$$\sigma_{sh}^2 = \varepsilon E_s h \tag{8}$$

where constant ε depends on receiver characteristics [34].

In the presence of both thermal and shot noises, the SNR can be expressed as [34]

$$\gamma = \frac{E_s h I_p^2}{N_0 + \varepsilon E_s h} \tag{9}$$

If we let $\varepsilon = 0$, we obtain the model studied at the beginning of this section containing only thermal noise. The proposed adaptive link layer protocols can also be implemented when there are both thermal and shot noises. In which, the estimation of the SNR should take into account these two noises. In the rest of the paper, we derive the throughput only when there is thermal noise.

3. Proposed adaptive link layer protocol

The spectral efficiency of M-PPM (Pulse Position modulation) is $\log_2(M)/M$ [35,36]. However, that of M-PAM is $\log_2(M)$. For example, the spectral efficiency of 32-PPM is 0.1563 bit/s/Hz whereas that of 32-PAM which is studied in our paper is 5 bit/s/Hz. Since M-PPM modulations have low spectral efficiency, we consider in this paper only PAM modulations to reach higher throughput.

3.1. Adaptive packet length for M-PAM modulation

In this section, we explain how we can adapt packet length for M-PAM modulations to achieve higher throughput. OOK modulation corresponds to M-PAM with $M = 2$. When M-PAM modulation is used, each packet contains $N + n_d$ bits which are converted in $(N + n_d)/\log_2(M)$ symbols. n_d is the number of parity bits used for error detection. The throughput is equal to [37]

$$\begin{aligned} Thr &= \frac{N\log_2(M)}{N+n_d}(1 - Pbloc(\gamma)) \\ &= \frac{N\log_2(M)}{N+n_d}(1 - Pes_{M-PAM}(\gamma))^{\frac{N+n_d}{\log_2(M)}} \end{aligned} \tag{10}$$