Precise Analysis of Optical OFDM System In Direct and Diffused Optical Wireless Environment

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***Abstract*— In this paper, the precise analysis of an all optical orthogonal frequency division multiplexing (OFDM) is carried out. All optical OFDM is used to achieve high bit rate and to eliminate intersymbol interference (ISI) in optical wireless communications. The overall architecture is enlightened and analytical evaluation of the system in terms of the probability of error is carried out in a line of sight and in a diffused wireless optical environment. As a conclusion, the proposed system shows promising results for a high speed optical wireless channel.**

***Index Terms*—Intersymbol interference, optical orthogonal frequency division multiplexing, wireless optical communications, modified Rayleigh, lognormal distribution.**

I. Introduction

The push for higher data rates in wireless communications such as wireless video and wireless multimedia applications has motivated recent interest in indoor wireless optical communications as the medium for short-range wireless communications [1]. The use of modulated light as a carrier, instead of radio waves, offers the potential for such alternative. The main advantages are the unlimited bandwidth, cheap transmitters and receivers, and free light radiations of any health concerns. Another advantage is that light waves do not penetrate opaque objects and therefore cannot be eavesdropped. As a result, it is very difficult for an intruder to (covertly) pick up the signal from outside the room.

The optical medium can be viewed as complementary to the radio medium rather than competitive. Electromagnetic waves at optical frequencies exhibit markedly different propagation behavior than those at radio or microwave frequencies. At optical frequencies, most building surfaces are opaque, which generally limits the propagation of light to the transmitter room. Furthermore, for most surfaces, the reflected light wave is diffusely reflected (as from a matte surface) rather than specularly reflected (as from a mirrored surface). Diffraction is also an important feature of radio propagation, but it is not of a significant effect at infrared frequencies as the dimensions of most building objects are typically many orders of magnitude larger than the wavelength. These differences, as well as fundamental differences in the transmitting and receiving devices, have led researchers to develop channel models and communication concepts for wireless infrared optical systems.

Infrared has some drawbacks as well. Although multipath propagation obviates the need for a strict line-of-sight (LOS) path between the transmitter and receiver, an IR link is still susceptible to severe shadowing; an IR receiver cannot be carried in a shirt pocket, for example. Also, IR links have a limited range, because the noise from ambient light is high and also because the square-law nature of a direct detection receiver doubles the effective path loss (in decibels) when compared with a linear detector [1].

Nondirected IR links, which do not require alignment between transmitter and receiver, can be categorized as either LOS or diffuse as shown in Fig. 1. An LOS link requires an unobstructed LOS path for reliable communication, whereas a diffuse link relies instead on reflections from the ceiling or other reflectors. LOS links require less power than diffuse links, but diffuse links are more robust to shadowing.

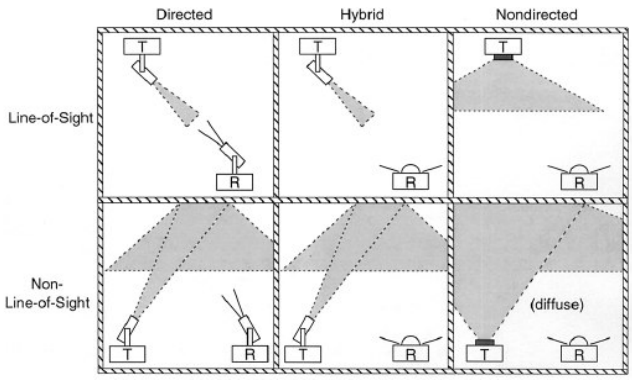

Fig. 1 Classification of simple infrared LOS and non-LOS links [2].

The dominant impairment in a nondirected link is background light, which is typically a combination of fluorescent light, sunlight, and incandescent light. These light sources emit power over a broad range of wavelengths with a significant fraction of this power falling within the wavelength band of sensitivity of silicon photodiodes. There is a way to mitigate the background light effects by using a narrow linewidth optical source, such as a single- or nearly single-frequency laser diode, in combination with a narrow-band optical filter to reject out-of-band ambient light.

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Directed link design maximizes power efficiency, since it minimizes path loss and multipath distortion. On the other hand, non-directed links increase link robustness and ease of use, allowing the link to operate even when barriers, such as people or cubicle partitions, stand between the transmitter and receiver. However, these links increase multipath distortion that causes intersymbol interference (ISI) problems. The robustness and ease of use are achieved by the non-directed-non-LOS link design, which is referred to as a diffuse link.

This paper is organized as follows. In Section II, the concept of optical OFDM is introduced as well as current research carried out in this area. The proposed all optical OFDM system is described in Section III. Analysis of the proposed optical OFDM system in LOS and diffused optical wireless environments is presented in section IV and conclusions are given in section V.

II. Optical OFDM

The ISI due to the multipath propagation is a major concern in indoor wireless optical transmission. This interference greatly degrades the quality of transmission, and its effects become more severe in case of diffuse links. This is a serious problem, especially in the case of ultra high speed optical wireless LAN such as 1 Gbit/s or more. To combat the ISI effect, a parallel transmission technique is one of the possible solutions [3]. This parallel transmission lowers the data rate per channel, which consequently diminishes the ISI effects. OFDM has been extensively studied to combat radio frequency and microwave multipath fading [4]. Optical orthogonal frequency division multiplexing (OOFDM) is proposed to reduce the effects of ISI. This strategy can improve the quality of transmission to a great extent [5].

In an OFDM system, a high data rate serial data stream is split up into a set of low data rate substreams. The parallel data transmission offers possibility for alleviating many of the problems encountered with serial transmission systems such as ISI. The total channel bandwidth is divided into a number of orthogonal frequency sub channels. Each low data rate substream is modulated on a separate sub channel. The orthogonality is achieved by selecting a special equidistant set of discrete carrier frequencies. It can be shown that, this operation is conveniently performed by the Inverse Fast Fourier Transforms (IFFT). At the receiver, the Fast Fourier Transform (FFT) is used to demultiplex the parallel data streams [3].

In current research, optical orthogonal frequency division multiplexing is proposed to combat dispersion in optical fiber media [6]. The authors in [6, 7] presented the theoretical basis for coherent optical OFDM systems in direct up/down conversion architecture. In [8], the authors showed that Optical Orthogonal Frequency Division Multiplexing outperformed RZ-OOK transmission in high-speed optical communication systems in terms of transmission distance and spectral efficiency. In the above mentioned research, the optical OFDM was accomplished by first performing the OFDM electronically then converting to optical signals. In our paper, we propose all optical OFDM system in diffuse wireless optical channel. The proposed system will be explained and analytically evaluated in coming sections.

III. All Optical OFDM System

Figure 2 shows the complete system architecture of an all optical OFDM. The system starts with the serial high data rate input which then passes to a serial to parallel (S/P) block similar to the conventional OFDM system. The all optical OFDM system differs from the conventional OFDM system in the conversion of the low data rate parallel substream into optical signals and performing the Inverse Discrete Fourier Transform (IDFT) techniques optically rather than electrically.

Recent progress of digital signal processing circuit has made it possible to implement the IFFT in wireless communication systems. However, this scheme cannot be applied to the optical communications as the data bit rate is beyond the digital signal processing speed capabilities.

The low rate parallel substream is converted to an optical signal using electrical to optical conversion. This is followed by modulating each optical substream using any type of an optical modulation as discussed in Reference [9] having the same optical wavelength and using the same DFB lasers as light sources. The optical conversion and modulation is called baseband optical modulator. The baseband optical modulator is followed by an optical IDFT. The optical IDFT consists of variable phase shifters and couplers. The phase shifters implement the different subcarriers that are orthogonal and thus will be similar to IFFT done by DSP kits as shown in equation (1).

$$s(t) = \sum_{n=0}^{N-1} d_n(t) e^{j2\pi(f_o + n\Delta f)t}, \qquad (1)$$

where s(t) represents the multiplexed signals, n and $d_n(t)$ denote the channel number and the data sequence of the n^{th} channel, respectively. In (1), $t = K\,\Delta t$, where $\Delta t = (T/N)$ is the sampling interval, f_o is the frequency of the light source and Δf is the frequency spacing.

In conventional OFDM, the output of the IDFT is added together. This is implemented optically using the optical coupler to add the optical signals and correlated with each other. A cyclic prefix (CP) should be added to overcome the ISI and intercarrier interference (ICI) [3]. The CP is a crucial feature of OFDM introduced by the multi-path channel through which the signal is propagated. The basic idea is to replicate a part of the OFDM time-domain waveform from back of the OFDM symbol to front to create a guard period. The duration of the guard period should be greater than the worst case delay spread of the target multi-path environment [10]. This is a challenging technique in optical signals as it is difficult to optically copy and paste. This is overcome using optical gates and what we called optical cyclic prefix.

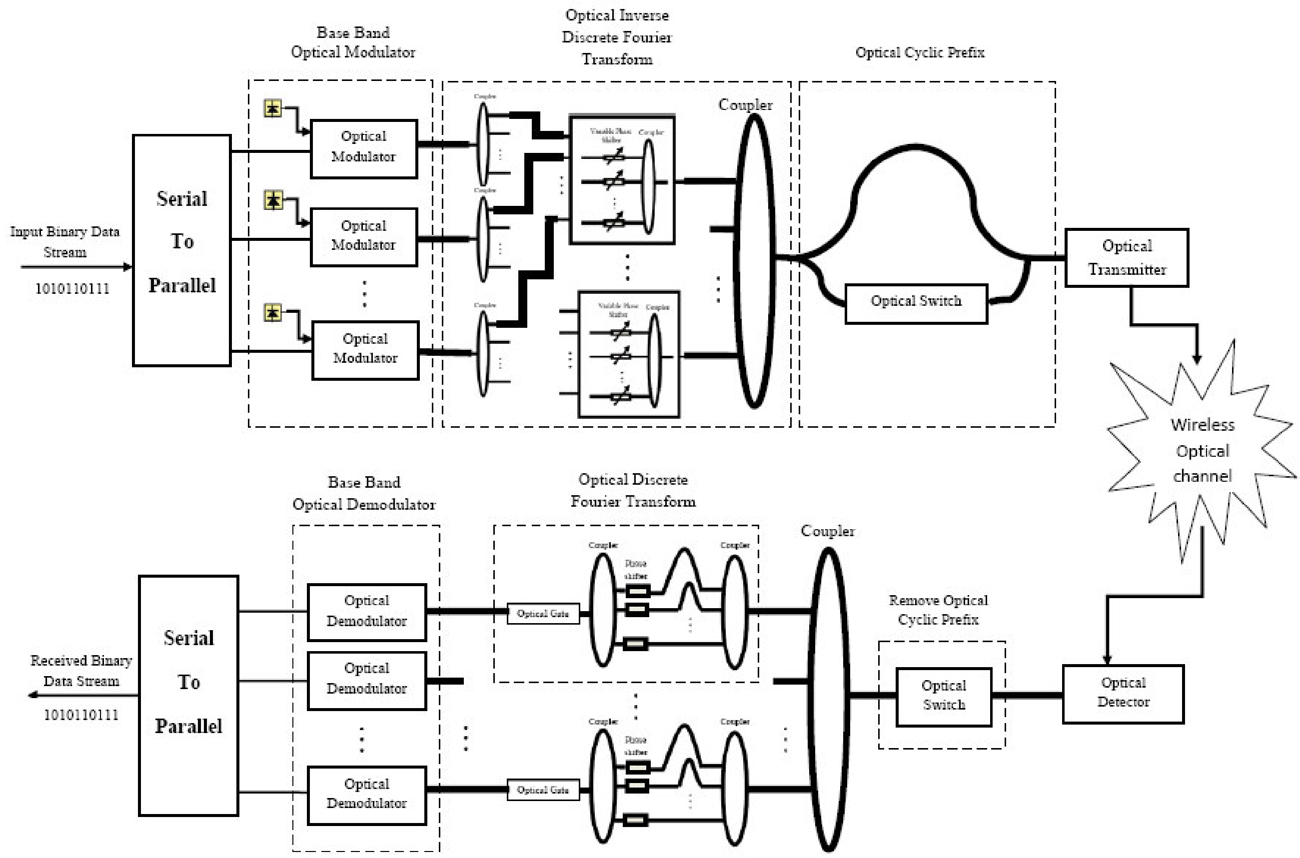

Fig. 2 Complete system architecture of all optical OFDM .

The optical cyclic prefix is divided into two branches by an optical coupler; the first is the fiber delay line and the second is the optical switch. The optical switch is used to cut the last guard time of the active ray period and sum it to the front of the optical ray by an optical coupler after it is delayed by the symbol period. Optical transmitter is used to propagate light to the wireless optical channel. At the receiver side, optical OFDM signal is detected by an optical receiver and then the optical cyclic prefix is removed. The DFT and optical demodulator are performed to get the corresponding transmitted bit streams.

The DFT consists of fiber delay lines and phase shifters. The delay lines realize orthogonality by having different lengths. The phase shifters implement the different subcarriers that are orthogonal [11]. Another approach for performing the CP is by using the optical cavity as optical delay lines. The optical cavity can be used as multipath optical delay lines, folding a light beam so that a long path-length may be achieved in a small space. A plane-parallel cavity with the flat mirrors produces a flat zigzag light path ref [12].

IV. ANALYTICAL EVALUATION OF OPTICAL OFDM

Characterization for optical wireless channels has been done by a variety of methods at different levels [13]. Carruthers and Carroll investigated statistical modelling for the indoor optical wireless channel through the examination of the characteristics of a large set of channel impulse responses [14]. The channel responses are generated using an estimation method based on geometrical modelling of indoor environments together with an iterative technique for calculating multiple reflections. They used x^2-goodness test to evaluate statistical model of the rooms for different values of the distance, D, between transmitter and receiver. They showed that the distribution of the channel gain in dB for the LOS component follows a modified gamma distribution, while the channel gain in dB for LOS channels including all reflections follows a modified Rayleigh distribution for most transmitter–receiver distances. The modified Rayleigh distribution parameters, variance and mean, depends on medium environment. Following the described model in Ref. [14], we obtained the modified Rayleigh distribution, displayed in Fig. 3, of the channel gain in dB for LOS channels with different variance σ^2.

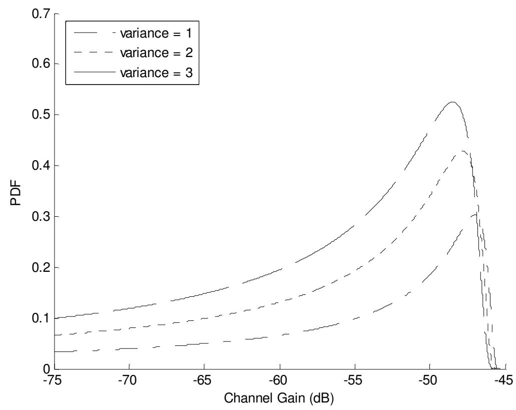

Fig. 3 Channel gain in dB for LOS channels

Following a similar methodology to that used in for the LOS channel, the shifted lognormal distribution is the best fit for the observed distributions of diffuse channel gains [14]. The obtained results at different values of σ^2 are shown in Fig. 4.

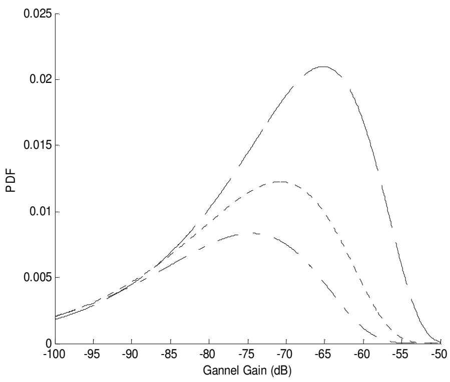

Fig. 4 Channel gain in dB for diffuse channels

In the following, the probability of error (P_e) of an LOS with reflection paths channels is derived using a modified Rayleigh distribution. Consider an LOS link with one transmitter and one receiver apertures. The signal X(t) is the received optical OFDM signal plus noise. Removing cyclic prefix, X(t) will be composed of s(t) plus noise as (1). Performing inverse fast Fourier transform (IFFT), the output will be

$$X(k) = \sum_{n=0}^{N-1} (s(n) + N)\, e^{-j2\pi n k / N} \quad k = 0,1,..., N-1 \tag{2}$$

The received signal after the optical demodulator is

$$r(k) = d(k)\, \eta\, I + v , \tag{3}$$

where d(k) is logic 0 or 1 in each branch, η is the optical-to-electrical conversion coefficient, and v is an additive white Gaussian noise with zero mean and variance of $\sigma_v^2 = N_o/2$. The fading channel coefficient, I, which models the channel gain from the transmit aperture to the receive aperture is given by

$$I = I_o (k_{mr} - R), \tag{4}$$

where I_o is the signal light intensity without turbulence and R is a random variable in a Rayleigh distribution, f(R), with variance σ^2 defined as [14]

$$f(R) = \frac{R}{\sigma^2} e^{-R^2/2\sigma^2}, R \geq 0. \tag{5}$$

Using a linear transformation, the intensity, I, through (4) and (5) follows the modified Rayleigh distribution

$$f(I) = \frac{1}{I_o} \frac{\left(k_{mr} - I/I_o\right)}{\sigma^2} \exp\left(- \frac{\left(k_{mr} - I/I_o\right)^2}{2\sigma^2} \right), for I \leq k_{mr} I_o \tag{6}$$

The parameter k_{mr} in (6) is given by [14]

$$k_{mr} = 10 \log\left(\frac{A_r}{\pi D^2} \right), \tag{7}$$

where A_r is the total optical collection area and D is the distance separating the transmitter and receiver.

Assuming two level intensity modulations L_1 and L_2 and perfect channel state information available at the receiver side, the P_e is calculated as [15]

$$P_e = P(L_1)\, P(e/L_1) + P(L_2)\, P(e/L_2) , \tag{8}$$

where $p(L_1)$ and $p(L_2)$ are the probabilities of transmitting "1" and "0" bits, respectively. $P(e/L_1)$ and $p(e/L_2)$ denote the conditional bit error probabilities when the transmitted bit is "1" or "0". Conditioned on the fading coefficient I^3, one has

$$P(e/L_1) = P(e/L_2) = Q = \left(\frac{\eta I}{\sqrt{2N_0}} \right). \tag{9}$$

Averaging over the fading coefficient, one obtains

$$P(e/L_1) = P(e/L_2) = \int_0^{\infty} f_I(I)\, Q\left(\frac{\eta I}{\sqrt{2N_0}} \right) dI , \tag{10}$$

where Q(.) is the Gaussian-Q function defined as

$$Q(y) = \left(\frac{1}{\sqrt{2\pi}} \right) \int_y^{\infty} \exp\left(\frac{-t^2}{2} \right) dt . \tag{11}$$

Considering the symmetry of the problem, i.e, $p(L_1) = p(L_2) = 1/2$ and $p(e/L_1) = p(e/L_2)$, P_e is obtained as

$$P_e = \int_0^{\infty} f_I(I)\, Q\left(\frac{\eta I}{\sqrt{2N_0}} \right) dI , \tag{12}$$

$$P_e = \frac{1}{I_o} \int_{-\infty}^{k_{mr} I_o} \frac{k_{mr} - \frac{I}{I_o}}{\sigma^2} \exp\left(- \frac{\left(k_{mr} - \frac{I}{I_o} \right)^2}{2\sigma^2} \right) Q\left(\frac{\eta I}{\sqrt{2N_o}} \right) dI \cdot \tag{13}$$

Replacing I in terms of x, P_e can is

$$P_e = \int_0^{\infty} e^{-x} Q\left[\frac{\eta I_o}{\sqrt{2N_o}} \left(k_{mr} - \sqrt{2x}\sigma \right) \right] dx . \tag{14}$$

Using the Gauss-Laguerre formula [16] for the integration, the probability of error is obtained as

$$P_e \approx \sum_{i=1}^{n} w_i Q\left[\frac{\eta I_o}{\sqrt{2N_o}} \left(k_{mr} - \sqrt{2x_i}\sigma \right) \right], \tag{15}$$

where n is the order of approximation x_i, i=1,…, n are the zeros of the $n^{\underline{th}}$-order Gauss-Laguerre and w_i, i=1,…, n are weight factors for the $n^{\underline{th}}$-order approximation. Figure 5 shows the probability of error of optical OFDM system versus the electrical SNR ($=I_0^2/N_0$). The figure is evaluated at $\sigma_x = 3.37$ and at different order of approximation, n.

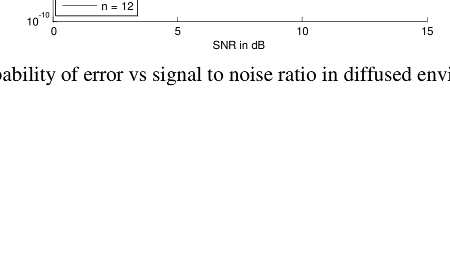

Fig. 5 Probability of error vs signal to noise ratio in diffused environment.

As shown in Fig. 5, increasing the order of approximation, gives a better evaluation of the probability of error. However, we found that if the n^{th} order of approximation is increased to values above 12, the values of P_e at these different orders will be negligible. Therefore, there is no need for further iterations after n = 12.

The probability of error, P_e, of a diffuse channel can be derived using a shifted lognormal probability density function following Ref. [15]. The same considerations in case of LOS and the received signal are used for diffused link. The fading channel coefficient, I, which models the channel from the transmit aperture to the receive aperture in case of diffused link is given by

$$I = I_o \exp(2X), \qquad (16)$$

where I_o is the signal light intensity without turbulence and X is normal random variables with mean μ_x and variance σ_x^2. Therefore, I follows a shifted lognormal distribution.

$$f(I) = \frac{1}{2I}\frac{1}{\sqrt{2\pi\sigma_x^2}}\exp\left(-\frac{(\ln(I/I_o)-2\mu_x)^2}{8\sigma_x^2}\right). \qquad (17)$$

Replacing I in terms of x, P_e is

$$P_e = \int_0^\infty f_I(I)Q\left(\frac{\eta I}{\sqrt{2N_o}}\right)dI, \qquad (18)$$

$$= \int_{-\infty}^\infty \Omega(x, -\sigma_x^2, \sigma_x^2)Q\left(\frac{\eta I_0 e^{2x}}{\sqrt{2N_0}}\right)dx, \qquad (19)$$

where $\Omega(u,v,w)$ is defined by

$$\Omega(u,v,w) = \left[\frac{1}{\sqrt{2\pi w}}\exp\left(\frac{-(u-v)^2}{2w}\right)\right]. \qquad (20)$$

The integration in (19) can be efficiently computed by Gauss-Hermite quadrature formula [15, 17] resulting in

$$P_e \approx \frac{1}{\sqrt{\pi}}\sum_{i=1}^{n} w_i Q\left(\frac{\eta I_0 e^{-2\sigma_x^2 + z_i\sqrt{8\sigma_x^2}}}{\sqrt{2N_0}}\right), \qquad (21)$$

where n is the order of approximation z_i, i=1,…, n are the zeros of the n^{th}-order Hermite polynomial and w_i, i=1,…, n are weight factors for the n^{th}-order approximation.

Figure 6 shows the probability of error of optical OFDM system versus the electrical SNR (= I_0^2/N_0) at $\sigma_x = 0.3$ and at different orders of n. It is clear that, as n increases, P_e converges to a single curve with a negligible difference from which one can use n up to 12 to have a good approximation.

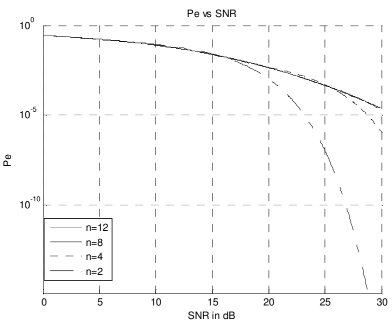

Fig. 6 Probability of error vs signal to noise ratio in LOS environment.

In case of diffused link, the SNR has to be increased to achieve the desired P_e that ensures smooth operation of the system. This becomes clear when Figs. 5 and 6 are compared. In Fig. 5, $P_e = 10^{-5}$ at SNR = 10 dB while in Fig. 6, at the same SNR, P_e = 0.1 for diffused environments which is unacceptable. The comparison is logic because LOS link is free from the non-LOS disadvantage such as multipath fading that causes ISI.

V. Conclusion

In this paper, a novel optical OFDM technique is proposed. The theory of system is explained with design considerations in LOS and diffused links. The formula of probability of error is driven in diffused channel. The proposed optical OFDM system could yield promising results to overcome multipath effects and ISI for optical wireless channels.

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