Optical Orthogonal Frequency Division Multiplexing For High Speed Wireless Optical Communications

Mohamed E. Khedr, Member IEEE, Moustafa H. Aly, Member OSA and Mohamed E. Tamazin

Collage of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
Khedr@vt.edu, drmosaly@gmail.com, tamazin@gmail.com

Abstract— **In this paper, an all optical orthogonal frequency division multiplexing is proposed for achieving high bit rate and eliminating inter-symbol interference in optical wireless communications. The overall architecture is explained along with the design considerations that should be followed for parameters calculation. Analytical evaluation of the system in terms of probability of error is carried out in a diffused wireless optical channel. As a conclusion, the proposed system shows promising results for a high speed optical wireless channel.**

Index Terms— **Inter-symbol interference, optical orthogonal frequency division multiplexing, wireless optical communications.**

I. Introduction

In the 21st century, wireless high speed data transmission will play an important role in our daily life. This is due to the fact that multimedia information is envisaged to be available at any place and at any time. However, bandwidth at radio frequency ranges which allow reasonable spatial coverage is a limiting factor. For this reason, many researches are looking towards light as a way to provide the required bandwidth for the expansion of communications. The use of modulated light as a carrier, instead of radio waves offers the potential of having 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 they cannot be eavesdropped. As a result, it is very difficult for an intruder to (covertly) pick up the signal from outside the proximity of the transmitter and receiver.

The optical medium can be viewed as complementary to the radio medium rather than competitive. Electromagnetic waves at optical frequencies exhibit 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 proximity. 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 [1]. 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.

The characteristics of radio and infrared indoor wireless links are summarized in Table 1.

Property of Medium	Radio Channel	Optical Channel
Bandwidth Regulated	Yes	No
Passes Through Walls	Yes	No
Multipath Fading	Yes	No
Multipath Distortion	Yes	Yes
Path Loss	High	High
Dominant Noise	Other Users	Background Light
Input X(t) Represents	Amplitude	Power
SNR Proportional to	$\int \lvert x(t) \rvert^2 dt$	$\int \lvert x(t) \rvert^2 dt$
Average power Proportional to	$\int \lvert x(t) \rvert^2 dt$	$\int \lvert x(t) \rvert dt$

Table 1 Comparison between radio and optical systems for indoor wireless communications [1].

Infrared links may employ various designs. It is convenient to classify infrared links into two most common configurations. The first design is a line-of-sight (LOS) link in which the transmitter (TX) and receiver (RX) must be pointed at each other to establish a link and the path between TX and RX must be clear of obstructions. The second is non-line-of-sight (non-LOS) in which the TX and RX are non-directed. The link is always maintained between the transmitter and any receivers in the same vicinity by reflecting or bouncing the transmitted information-bearing light off reflecting surfaces such as ceiling, walls and furniture. The transmitter employs a wide transmit beam and the receiver has a wide field of view as shown in Figure 1.

Directed link 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 inter-symbol interference (ISI) problems. The robustness and ease of use are achieved by the non-directed-non-LOS link, which is referred to as a diffuse link.

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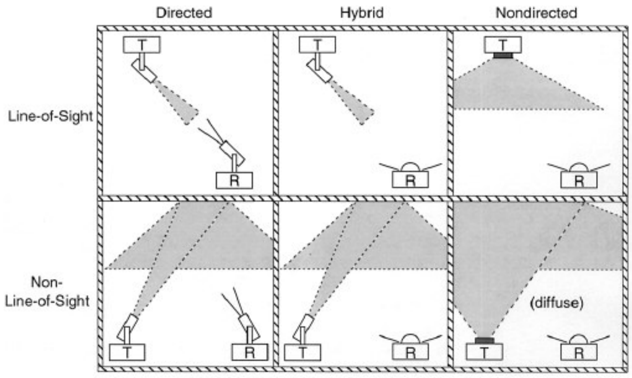

Fig. 1 Classification of infrared LOS and non-LOS links [1].

This paper is organized as follows. In Section II, the concept of optical OFDM is introduced as well as the current research carried out in optical OFDM (OOFDM). The proposed all optical OFDM system is described in Section III. Section IV presents the design considerations that should be followed to calculate the system's parameters. Analysis of the proposed optical OFDM system is presented in section V and conclusions are given in section VI.

II. OPTICAL OFDM

The ISI due to the multipath propagation is a major concern in indoor wireless optical communications. 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 Gbps or more. To combat the ISI effect, parallel transmission technique is one of the possible solutions [2].

Parallel transmission lowers the data rate per channel, which consequently diminishes the ISI effects. Optical orthogonal frequency division multiplexing is proposed to reduce the effects of ISI in optical communications and thus improve the quality of transmission [3].

In an OFDM system, a serial high data rate data stream is split up into a set of low data rate sub-streams. The total channel bandwidth is divided into a number of orthogonal frequency sub-channels and each of these low data rate sub-streams 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 de-multiplex the parallel data streams [2].

In current research, optical orthogonal frequency division multiplexing is proposed to combat dispersion in optical fiber media [4]. The authors in [4, 5] presented the theoretical basis for coherent optical OFDM systems in direct up/down conversion architecture. In [6], 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 researches, optical OFDM was accomplished by first performing the OFDM electronically using DSP kits then converting to optical signals. In our paper, we propose all optical OFDM system in diffuse wireless optical channels. The proposed system will be explained with design considerations and analytical evaluations 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 IFFT 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 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 optical modulation techniques as discussed in [7]. All the optical modulators in Figure 2 have the same optical wavelength and are 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 IFFT [8], which consists of fiber delay lines and phase shifters. The number of fiber delay lines is equal to the parallel sub-streams which also correspond to number of sub-carriers in the conventional OFDM. The delay lines realize orthogonality by having different lengths. The phase shifters implement the different sub-carriers that are orthogonal to each other and thus will be similar to IFFT done by DSP kits.

In conventional OFDM, the output of the IFFT is added together. This is implemented optically using the optical coupler.

A cyclic prefix (CP) should be added to overcome the ISI and inter-carrier interference (ICI) [2]. The CP is a crucial feature of OFDM introduced to overcome the multi-path channel effects through which the signal is propagated. The basic idea is to replicate a part of the OFDM time-domain waveform from back to front to create a guard period. The duration of the guard period should be greater than the worst case delay spread of the multi-path environment [9].

This is a challenging technique in optical signals as it is difficult to optically copy and paste. This can be overcome using optical gates and what we called optical cyclic prefix.

The optical cyclic prefix is divided into two branches using an optical coupler; the first branch is a fiber delay line and the second branch is an optical switch. The optical switch is used to copy the last part of the active ray period and paste it to the front of the optical ray by an optical coupler after it is delayed by a symbol period. The delay is done using the first branch after the coupler. Optical transmitter is used to modulate the OOFDM signal to be suitable for transmission in 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 IFFT and optical demodulator are performed to get the corresponding transmitted bit streams

the value of τ of non-directed indoor infrared channels ranges from 5 to 20 ns.

Since $T_g \geq \tau$, as a rule of thumb, to avoid ISI the guard time must be at least 2-4 times the delay spread of the multipath channel, one can choose $T_g = 4\ \tau$.

The symbol duration T_s, must be set much larger than the guard time. A practical design choice for the symbol time is to be at least five the guard time [11].

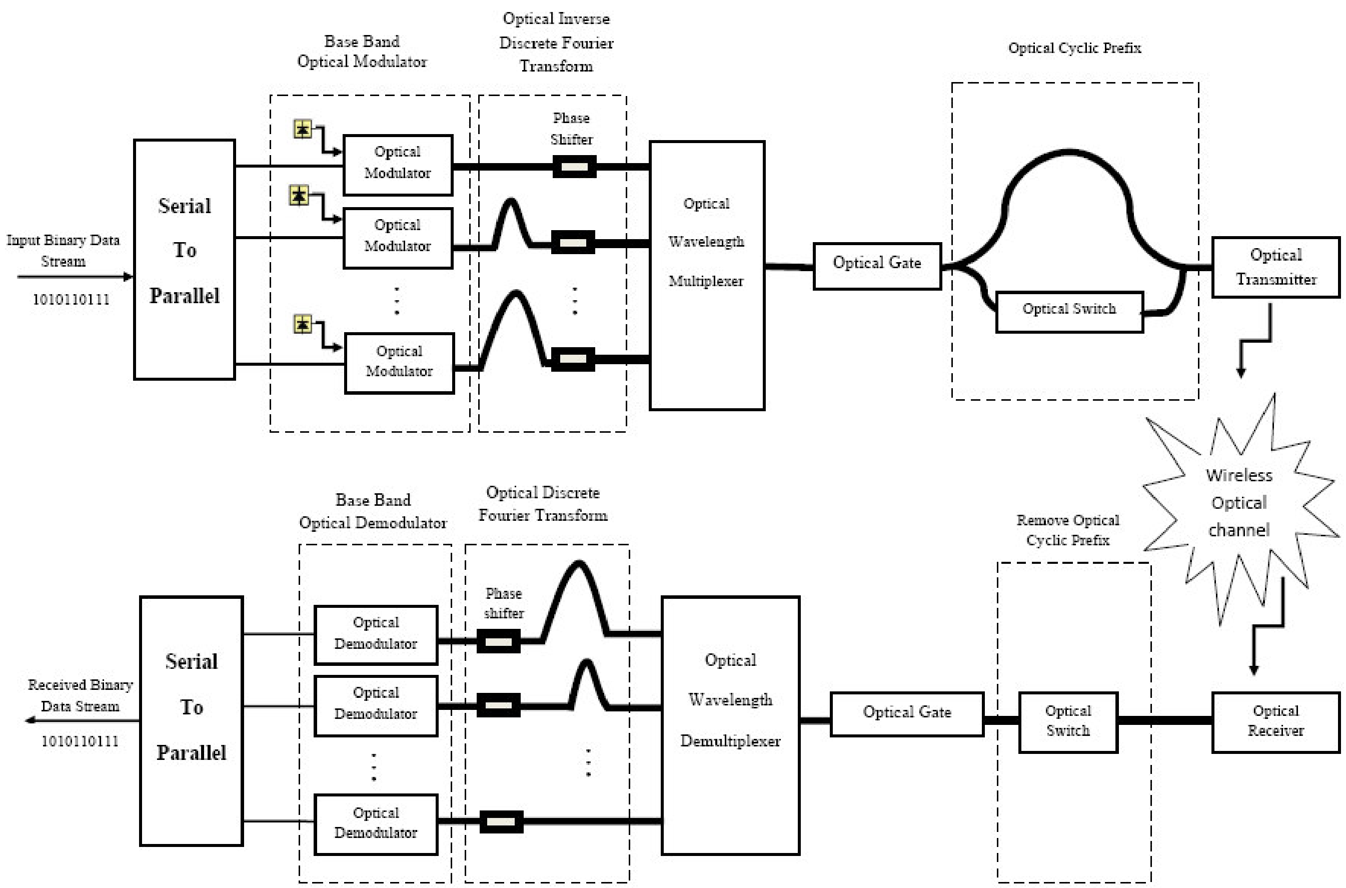

Fig. 2 Complete system architecture of an all optical OFDM .

IV. DESIGN CONSIDERATION

OFDM system design, as in any other system design, involves a lot of trade off's and conflicting requirements. The most important design parameters of the OFDM system are the bit rate required for the system, available band width and the rms delay spread of the channel in order to calculate the guard time, T_g, the OFDM symbol duration, T_{OFDM}, and the number of sub-carriers, N.

The guard time of an OFDM system usually results in a signal to noise ratio (SNR) loss since it carries no new information. The choice of the guard time is straight forward once the multipath delay spread, τ, is known. Based on [10],

The OFDM symbol duration consists of the symbol time and guard time. This duration should be at least six times the guard time. To calculate the numbers of sub-carriers, N, one has two methods; the first is [9]

$$\text{Bandwidth (BW)} = N \times \Delta f\ , \tag{1}$$

where Δf is the frequency spacing. The frequency spacing is equal to the OFDM symbol rate R_s, which is the inverse of T_{OFDM}. Using the previous discussion, the number of sub-carriers can be calculated as

$$N = 2^{\lceil \log_2 24 \times BW \times \tau \rceil}. \tag{2}$$

The second method through the data rate, R_b, and the type of modulation gives the number of sub-carriers as follows

$$\text{Number of bits per symbol} = \frac{R_b}{R_s}, \quad (3)$$

$$N = \frac{\text{Number of bits per symbol}}{\text{Number of bits per subcarrier}}, \quad (4)$$

where the number of bits per sub-carrier is equal to the number of bits per symbol in binary modulation, and is equal to half number of bits per symbol incase of QPSK modulation. Whereas the number of sub-carriers is equal to the number of low rate parallel data substream.

The baseband optical modulator follows the parallel substream, which transfers the low rate substream information to light using the same optical source as light carrier. The two baseband types of optical modulators are intensity or phase modulation [7]. The on–off keying (OOK) intensity modulation is excluded because all carriers should be imposed in our system.

The baseband optical modulator is followed by an optical IFFT. The output of the IFFT [8] is

$$s(t) = \sum_{n=0}^{N-1} d_n(t) e^{j2\pi(f_o + n\Delta f)t}, \quad (5)$$

where s(t) represents the multiplexed signals, n and $d_n(t)$ denote the channel number and the data sequence of the $n^{\underline{th}}$ channel, respectively. In (5), t = K Δt, where $\Delta t = (T/N)$ is the sampling interval, f_o is the frequency of the light source and Δf is the frequency spacing.

Performing IFFT optically, the optical parallel sub-streams are passed into N optical delay lines which have the relative delay time (K Δt). One can calculate the relative fiber delay lines length, L, as follows

L = Relative delay time × Velocity inside the fiber (v), (6)

where v=c/n, c is the velocity of light in air and n is refractive index of the fiber.

The exponential function in (5) represents the phase shift of the signal. This is implemented by an optical phase shifter, with a phase shift of $2\pi nK/N$. The optical coupler implements the optical multiplexer.

An optical gate follows the optical multiplexer. The reason for this gate is to maintain orthogonality between sub-carriers in an OOFDM symbol and the electroabsorption modulator can be used as the optical gate.

The optical cyclic prefix consists of two branches. The first is an optical fiber delay line which is used to delay optical rays by T_s. So, fiber delay line has a length, L, given by

L = c Ts/n. (7)

The second branch is the optical switch, which opens during the symbol time T_s & closes during the period interval $T_s - T_g$.

V. Analytical Evaluation of Optical OFDM

Before going through the analytical evaluation of the proposed system in wireless optical channels, a round figure for the number of sub-carriers needed in the system is calculated.

From (2), the values of N are calculated as a function of the delay bandwidth product BW×τ as shown in Table 2 and plotted in Figure 3.

Range	**BW × τ (GHz.ns)**	**N**
R_1	6 - 10	128
R_2	11 - 21	512
R_3	22 – 42	1024
R_4	43 – 85	2048
R_5	86 - 170	4096

Table 2 Calculated values of sub-carriers.

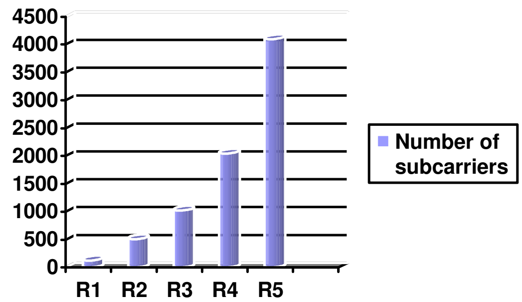

Fig. 3 Values of delay BW product and N

Characterization for optical wireless channels has been done by variety of methods at different levels [10]. Carruthers and Carroll described models for characterizing the properties of transmitters, receivers and reflecting surfaces within the indoor environment [12]. The distribution of channel gain in dB for LOS channels including all reflection follows a modified Rayleigh distribution and the channel gain in dB of diffuse channel follows shifted lognormal distribution.

Using this model in [12], the probability of error (P_e) of a diffuse channel can be derived using a shifted lognormal probability density function as follows [13]. Consider a link with one transmitter and one receiver. X(t) is the received optical OFDM signal plus noise. After removing cyclic prefix, X(t) will be composed of s(t) as in (5) plus noise.

Performing the IFFT, the output will be

$$X(k) = \sum_{n=0}^{N-1} (s(n) + N)\, e^{-j2\pi nk/N} \quad k = 0,1,\ldots,N-1 \quad (8)$$

The received signal after the optical demodulator is

r(k) = d(k)×η×I + v , (9)

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 from the transmit aperture to the receive aperture is given by

$I = I_o \exp(2X)$, (10)

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.

$$f(I) = \frac{1}{2\mathrm{I}} \frac{1}{\sqrt{2\pi\sigma_x^2}} \exp\left(-\frac{(\ln(I/I_o) - 2\mu_x)^2}{8\sigma_x^2}\right) \tag{12}$$

Assuming two level intensity modulations L_1 and L_2 and perfect channel state information (CSI) available at the receiver side, the P_e is calculated as in [13].

$$P_e = P(L_1)\,P(e/L_1) + P(L_2)\,P(e/L_2)\,, \tag{13}$$

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

$$P(e/L_1) = P(e/L_2) = Q = \left(\frac{\eta I}{\sqrt{2N_0}}\right) \tag{14}$$

Averaging over the fading coefficient, one obtains

$$P(e/L_1) = P(e/L_2) = \int_0^\infty f_I(I) Q\left(\frac{\eta I}{\sqrt{2N_0}} dI\right., \tag{15}$$

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

$$Q(y) = \left(1/\sqrt{2\pi}\right)\int_y^\infty \exp(-t^2/2)\,dt\,. \tag{15}$$

Consider the symmetry of the problem, i.e, $p(L_1) = p(L_2) = 1/2$ and $p(e/L_1) = p(e/L_2)$ and replacing I in terms of x, P_e can be obtained as

$$P_e = \int_0^\infty f_I(I) Q\left(\frac{\eta I}{\sqrt{2N_0}} dI\right., \tag{17}$$

$$= \int_{-\infty}^\infty \Omega(x, -\sigma_x^2, \sigma_x^2) Q\left(\frac{\eta I_0 e^{2x}}{\sqrt{2N_0}}\right) dx\,, \tag{18}$$

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

$$\Omega(u,v,w) = \left(\frac{1}{\sqrt{2\pi w}} \exp\left(\frac{-(u-v)^2}{2w}\right)\right). \tag{19}$$

The integration in (18) can be efficiently computed by Gauss-Hermite quadrature formula [13]

$$P_e \approx \frac{1}{\sqrt{\pi}} \sum_{i=1}^n w_i Q\left(\frac{\eta I_0 e^{-2\sigma_x^2 + z_i\sqrt{8\sigma_x^2}}}{\sqrt{2N_0}}\right), \tag{20}$$

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 4 shows the optical OFDM system versus the SNR. The SNR is the electrical SNR defined as I_0^2/N_0. The figure is evaluated at $\sigma_x = 0.3$ and at different order of approximation (n), as shown in Figure. 4, as n increases the P_e converges to a single curve with a negligible difference from which one can use n = 12 to have a good approximation.

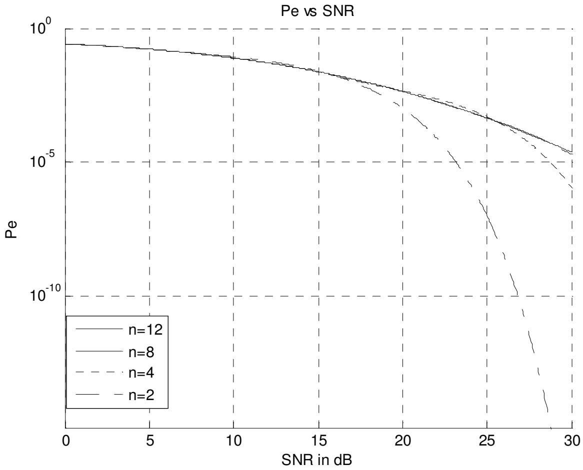

Fig. 4 Probability of error vs signal to noise ratio.

VI. Conclusion

In this paper, a novel optical orthogonal frequency division multiplexing technique is proposed. The theory of the system is explained with design considerations. The 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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