LETTER *Special Section on Optical Access Technologies*

Beat Noise Cancellation in 2-D Optical Code-Division Multiple-Access Systems Using Optical Hard-Limiter Array

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SUMMARY We analyze the beat noise cancellation in two-dimensional optical code-division multiple-access (2-D OCDMA) systems using an optical hard-limiter (OHL) array. The Gaussian shape of optical pulse is assumed and the impact of pulse propagation is considered. We also take into account the receiver noise and multiple access interference (MAI) in the analysis. The numerical results show that, when OHL array is employed, the system performance is greatly improved compared with the cases without OHL array. Also, parameters needed for practical system design are comprehensively analyzed.

key words: *two-dimensional optical code-division multiple-access (2-D OCDMA), beat noise, optical hard-limiter (OHL)*

1. Introduction

The recent growth of the Internet has been driving the development of new multiple-access techniques for optical broadband access networks. Optical code-division multiple-access (OCDMA) technique with its many advantages, such as asynchronous access for high-speed connection, flexible number of users, and inherent security, is considered a promising candidate for next-generation optical broadband access networks [1]. OCDMA systems using two-dimensional (2-D) coding offer even more advantages, including zero autocorrelation side-lobes, low cross-correlation, and large cardinality [2].

In 2-D OCDMA systems, one of the major issues limiting the system performance is the beat noise, which is caused by the beating between optical signals with identical wavelength, which simultaneously arrive at a photodetector [3], [4]. The impact of the beat noise depends on the number of interfering pulses and thus is governed by the number of users. Due to the beat noise, the number of supportable users in 2-D OCDMA systems is limited. It is shown in [3] that only less than five users can be supported at the bit error rate (BER) $\leq 10^{-9}$ when the code length is 169 and the number of wavelengths are 31.

Several methods have been proposed to improve the performance of OCDMA systems in the presence of the beat noise [5]–[7]. First, forward error coding (FEC) was proposed to improve the system performance. In this method, the beat noise is in fact not reduced but redundant information is added to correct errors. The system throughput is thus decreased. Another method that actually reduces the beat noise is to use pulse position modulation (PPM) [6], [7]. As the use of PPM reduces multiple access interference (MAI), the beat noise can be relaxed. The PPM systems are however more affected by the dispersion because of the reduction of pulse width, especially when the PPM multiplicity is large. Finally, the beat noise can also be mitigated by using a heterodyne detection receiver as in [7]. This method can effectively suppress the beat noise, but it requires a more complex design of the receiver.

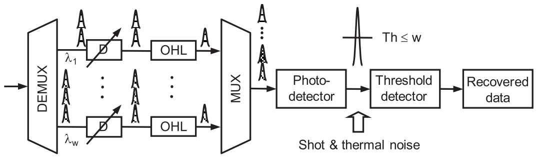

Fig. 1 2-D OCDMA receiver with OHL array.

An optical hard-limiter (OHL), a nonlinear device that is capable of limiting the received power (at a wavelength) to a fixed level when it is higher than or equal to a threshold, is a popular device to reduce MAI in OCDMA systems [8]. The beat noise thus can also be relaxed by using OHL. This phenomenon in 2-D OCDMA systems has been reported in [6] based on the assumption that optical pulse is ideally rectangular. The assumption is however impractical, and the analytical result is thus not helpful for system design.

In this paper, we thus employ the pulse propagation theory and assume that the optical pulse has a Gaussian shape to analyze the beat noise cancellation in 2-D OCDMA systems using OHL. Unlike one-dimensional systems [8], an array of OHLs is required with one OHL for each wavelength, as shown in Fig. 1. The impacts of MAI and receiver noise as well as pulse propagation in optical fiber are taken into account. Our analysis also includes many parameters which are crucial for practical system design, including number of users, transmitted power, and especially transmission length.

2. Performance Analysis

2.1 2-D OCDMA Receiver with OHL Array

The proposed system employs SUM detection and an OHL array for the receiver. The received multi-wavelength signal is first de-multiplexed into w separate wavelengths by the de-multiplexer (DEMUX), where w is the code weight. At

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a specific wavelength λ_i $(1 \le i \le w)$, each chip pulse can be modeled as a Gaussian pulse, whose propagation model is expressed as [9]

$$E_i(t) = \sqrt{P_s}\frac{T_0}{(T_0^2 - j\beta_{2i}L)^{1/2}}\exp\left(-\frac{t^2}{2(T_0^2 - j\beta_{2i}L)}\right) \times \exp[j(\omega_i t + \phi_i)], \quad (1)$$

where T_0 is the half-width of pulse (at 1/e-intensity point). β_{2i} is the dispersion parameter at λ_i, which moderates the width and the peak power of the optical pulse. ω_i and ϕ_i are the optical frequency and the phase of the optical carrier, respectively. To simplify the analysis, optical pulses from all transmitters are assumed to have the same transmitted power, and their peak level is denoted as P_0. P_s can therefore be expressed as $P_s = P_0 \exp(-\alpha L)$, where α is the fiber attenuation coefficient, and L is the transmission length between a transmitter and a receiver, which is assumed to be the same between any transmitter and receiver.

Optical pulses at different wavelengths are then differently delayed by delay components (D) which are tuned so that the desired pulses (from targeted transmitter) at the input of OHLs are aligned in time. It is worth noting that, due to dispersion, the relative temporal shifting (i.e., time skewing) between optical pulses on different wavelengths will happen, which causes the misalignment between desired pulses [10]. Therefore, we apply the post-skewing technique to the tunable-delay components so that the time skewing is compensated [11].

Next, at the OHL of a specific wavelength, only the pulses whose peak power is larger than or equal to threshold power (P_{Th}) can pass through the device. The power-transfer response of an ideal OHL is defined as [8]

$$P_{\text{out}}(P_{\text{in}}) = \begin{cases} 0 & \text{if } 0 < P_{\text{in}} < P_{\text{Th}}, \\ P_{\text{OHL}} & \text{if } P_{\text{in}} \ge P_{\text{Th}}. \end{cases} \quad (2)$$

In the proposed receiver, all OHLs have the same value of P_{Th} and P_{OHL}. Also, P_{OHL} is set to the received peak power of the optical pulse, whose wavelength is the most affected by the dispersion, i.e. $P_{\text{OHL}} = \min\{P_1^{\text{peak}}, ..., P_i^{\text{peak}}, ..., P_w^{\text{peak}}\}$. Here, the peak power of the received optical pulse at the wavelength λ_i can be derived from Eq. (1) as

$$P_i^{\text{peak}} = P_s\left|\frac{T_0}{(T_0^2 - j\beta_{2i}L)^{1/2}}\right|^2. \quad (3)$$

In the 2-D OCDMA systems, only interfering pulses that appear at the same time with the desired one are MAI. And, as at most one pulse can pass through each OHL, all MAI pulses are filtered out by the OHL when bit “1” is transmitted, i.e., only the desired pulse will pass through the OHL. When bit “0” is transmitted, at most one MAI pulse can pass through each OHL. The optical pulses from the output of OHLs are finally combined at the multiplexer (MUX) and converted to photocurrent by the photodetector (PD). At each wavelength, as at most one optical pulse is incident on the PD at a specific time, the beat noise is completely removed. The photocurrent at the output of the PD is then compared with the threshold current, $I_{\text{Th}} = \Re D w P_{\text{OHL}}$, where $\Re$ is the PD responsivity, Th is the threshold ($Th \le w$), and D is the normalized threshold ($D = Th/w$). If the photocurrent is larger than or equal to I_{Th}, bit “1” is detected. In the inverse case, bit “0” will appear at the output of the detector.

2.2 Bit Error Rate

The proposed system’s BER is now calculated based on the assumption that all users have the same probabilities of sending bit “1” and bit “0,” which are equal to 1/2. The 2-D signature code set of the system is constructed from prime codes [2]. In the time domain, the code weight $w = p_s$ and the code length is p_s^2, where p_s is a prime number. Each pulse in a sequence is assigned one of p_h wavelengths according to the wavelength hopping pattern constructed from a prime number p_h ($p_h \ge p_s$). The cross-correlation value is at most one and the cardinality of the 2-D prime signature code set is $p_s(p_h - 1)$.

When the desired user sends bit “1,” the total number of optical pulses appearing at the input of the PD is w regardless of interfering users sending bit “1” or “0.” An error may happen due to the impact of shot and thermal noise since they make the photocurrent be smaller than the threshold current. In this case, the photocurrent is calculated as $I_{s1} = \Re w P_{\text{OHL}}$. The shot and thermal noise currents can be modeled as Gaussian random variables and their variances can be expressed as $i_{sh1}^2 = 2eB_eI_{s1}$ and $i_{th}^2 = 8\pi k_B T_n B_e^2 C$, respectively. Here, e is the electron charge, B_e is the photodetector electrical bandwidth, k_B is Boltzman’s constant, T_n is the receiver noise temperature, and C is the receiver capacitance. The probability of falsely detecting bit “0” when bit “1” is transmitted can be expressed as

$$\text{PE}(0/1) = Q\left(\frac{I_{s1} - I_{\text{Th}}}{\sqrt{i_{sh1}^2 + i_{th}^2}}\right), \quad (4)$$

where $Q(.)$ is the Q function.

When the desired user transmits bit “0,” the MAI pulses from interfering users sending bit “1” may cause the bit error. We assume that i out of $K - 1$ interfering users are sending bit “1.” i can, therefore, be modeled as a binomial random variable with probability 1/2. Among i interfering users sending bit “1,” we assume that, at a specific wavelength, there are k MAI pulses ($0 \le k \le i$). Denote p as the probability that an interfering pulse becomes the MAI one, k hence can be modeled as a binomial random variable with probability p. For 2-D prime signature code set, $p = \mu_\lambda / p_s^3$, where μ_λ is the average number of wavelengths common to any pair of 2-D prime signature codes [3].

A pulse appears at the output of an OHL when there is at least one pulse arriving at its input ($1 \le k \le i$). The probability that there is a pulse at the output of each OHL can hence be expressed as

$$P_c = \sum_{k=1}^{i} \binom{i}{k} p^k (1-p)^{i-k}. \qquad (5)$$

Denote n as the total number of MAI pulses appearing at the input of the PD ($0 \leq n \leq w$), the photocurrent in this case is $I_{s0} = \Re n P_{\mathrm{OHL}}$. The variance of shot noise can be expressed as $i^2_{sh0} = 2eB_e I_{s0}$ while the variance of thermal noise is as the previous case. As n can be modeled as a binomial random variable with probability P_c, the probability of detecting bit "1" when bit "0" is sent can be calculated as

$$\mathrm{PE}(1/0) = \sum_{i=1}^{K-1} \binom{K-1}{i} 2^{-(K-1)} \sum_{n=0}^{w} \binom{w}{n} P_c^n (1-P_c)^{w-n} \times Q\left(\frac{I_{\mathrm{Th}} - I_{s0}}{\sqrt{i^2_{sh0} + i^2_{th}}} \right). \qquad (6)$$

The system's BER is finally given by PE = $1/2\{\mathrm{PE}(0/1) + \mathrm{PE}(1/0)\}$.

3. Numerical Results

We now compare the proposed system performance to that of the conventional ones using SUM and AND detections [4]. We use the 2-D prime signature code set with $p_s = 11$ and $p_h = 31$. p_h wavelengths belong to the window 1550 nm with wavelength spacing of 0.4 nm. Other system parameters are shown in Table 1.

For a fair comparison, the numerical results are considered under a constraint on the average power per chip, denoted as P_{avg}. The relation between P_{avg} and the peak transmitted power per chip P_0 can be expressed as $P_{avg} = \frac{1}{T_c} \int_{-T_c/2}^{T_c/2} |G(t)|^2 dt$, where T_c is the chip duration and $G(t)$ is the amplitude of transmitted Gaussian pulse, and $G(t) = \sqrt{P_0} \exp(-\frac{t^2}{2T_0^2})$.

Figure 2 shows that BER is greatly improved when the OHL array is employed in the two cases of normalized threshold $D = 0.5$ and $D = 0.7$. BER of the proposed system is much reduced in comparison to that of the conventional ones using AND or SUM detection receivers. Higher normalized threshold results in better performance in this figure. More specifically, up to 31 users can be supported at $D = 0.7$ at BER $= 10^{-9}$, which is about 5 times larger than that of the system with $D = 0.5$.

Table 1 System parameters.

Name	Symbol	Value
Receiver capacitance	C	0.02×10^{-12} F
Noise temperature	T_n	300 K
PD responsivity	$\Re$	1 A/W
Bit rate per user	B_e	1 Gbit/s
Chip duration	T_c	8.3 ps
Half-width of pulse	T_0	1.2 ps
Attenuation coefficient	α	0.2 dB/km
Dispersion coefficient	D_{1550}	16 ps/nm×km
Dispersion slope coefficient	S_{1550}	0.08 ps/nm^2×km

Next, BER versus the average transmitted power per chip (P_{avg}) with different D is shown in Fig. 3. The number of simultaneous users is 30 and the transmission length is 20 km. It is seen that, when P_{avg} increases, BER is reduced until it saturates at a floor level. To reduce the floor level, higher D is required, however, higher transmitted power to reach the floor is also needed.

For practical system design, we also analyze BER versus D to identify the optimum threshold. We shows different systems with different settings of K and P_{avg}. It is seen in Fig. 4 that optimum performance is threshold sensitive. The optimum threshold selection depends on parameter settings, especially the average transmitted power per chip P_{avg}.

Finally, we find the maximum transmission length ($L_{\max}$), the length at which BER $\leq 10^{-9}$ can be maintained, corresponding to a specific transmitted power and the number of users. Figure 5 shows that, when $P_{avg} = -12$ dBm and $K = 30$ users, $L_{\max} = 33$ km at $D = 0.73$. When $L < 33$ km, the threshold can be selected with a wider range of values.

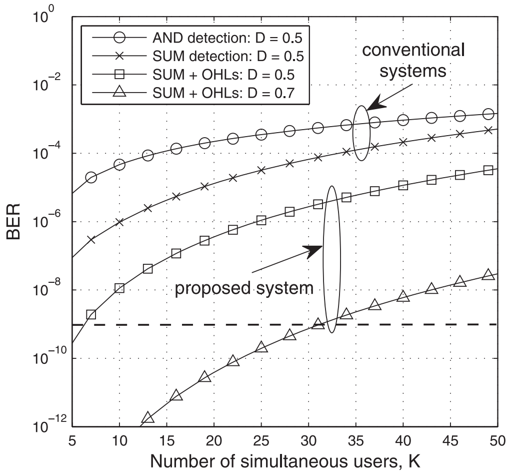

Fig. 2 BER versus the number of simultaneous users K when $P_{avg} = -15$ dBm and $L = 20$ km.

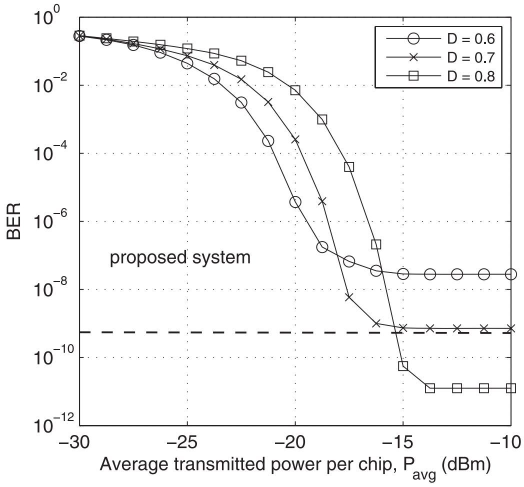

Fig. 3 BER versus the average transmitted power per chip P_{avg} when $K = 30$ users and $L = 20$ km.

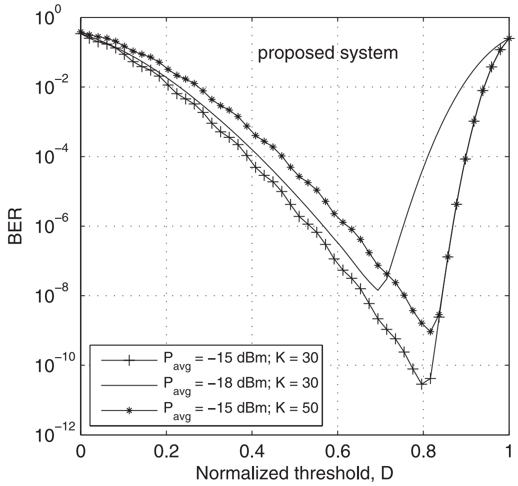

Fig. 4 BER versus normalized threshold D with different numbers of users and transmitted powers. $L = 20$ km.

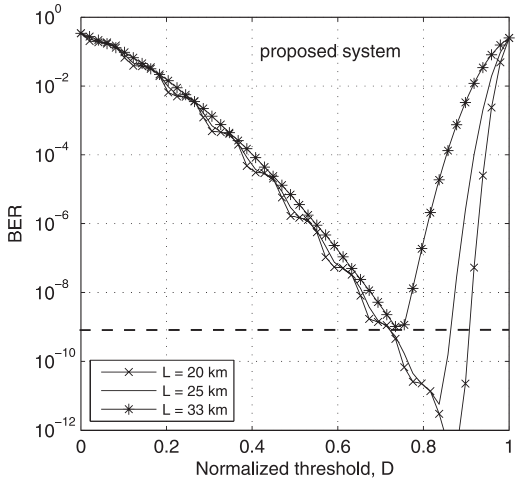

Fig. 5 BER versus normalized threshold D with different transmission lengths. $P_{avg} = -12$ dBm and $K = 30$ users.

For example, the threshold range is from 0.73 to 0.91 when $L = 20$ km.

4. Conclusion

We have comprehensively analyzed the beat noise cancellation in 2-D OCDMA systems using OHL array, considering the real shape of optical pulse, receiver noise, MAI, and pulse propagation. The numerical results reveal that the system performance is greatly improved compared with the cases without OHL array. Many necessary parameters for practical design were also analyzed, including required transmitted power, number of users, transmission length, and the optimum threshold.

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References

[1] A. Stok and E.H. Sargent, “The role of optical CDMA in access networks,” IEEE Commun. Mag., vol.40, no.9, pp.83–87, 2002.

[2] L. Tancevski and I. Andonovic, “Hybrid wavelength hopping/time spreading schemes for use in massive optical networks with increased security,” J. Lightwave Technol., vol.14, no.12, pp.2636–2647, 1996.

[3] L. Tancevski and L.A. Rusch, “Impact of the beat noise on the performance of 2-D optical CDMA systems,” IEEE Commun. Lett., vol.4, no.8, pp.264–266, 2000.

[4] M. Meenakshi and I. Andonovic, “Effect of physical layer impairments on SUM and AND detection strategies for 2-D optical CDMA,” IEEE Photonics Technol. Lett., vol.17, no.5, pp.1112–1114, 2005.

[5] H. Lundqvist and G. Karlsson, “On error-correction coding for PON,” J. Lightwave Technol., vol.23, no.8, pp.2342–2351, 2005.

[6] T.M. Bazan, D. Harle, and I. Andonovic, “Mitigation of beat noise in time-wavelength optical code-division multiple-access systems,” J. Lightwave Technol., vol.24, no.11, pp.4215–4222, 2006.

[7] A.T. Pham and H. Yashima, “Performance enhancement of the 2-D WH/TS synchronous OCDM system using a heterodyne detection receiver and PPM signaling,” OSA J. Opt. Netw., vol.6, no.6, pp.789–800, 2007.

[8] J.A. Salehi, “Code-division multiple access technique in optical fiber networks-part II: Systems performance analysis,” IEEE Trans. Commun., vol.37, no.8, pp.834–842, 1989.

[9] G.P. Agrawal, Nonlinear Fiber Optics, Academic, CA, 2001.

[10] N.T. Dang, A.T. Pham, and Z. Cheng, “Impact of GVD on the performance of 2-D WH/TS OCDMA systems using heterodyne detection receiver,” IEICE Trans. Fundamentals, vol.E92-A, no.4, pp.1182–1191, April 2009.

[11] H. Taima, H. Iwamura, N. Minato, and S. Oshiba, “Experimental study on time-spread/wavelength-hop optical code division multiplexing with group delay compensating en/decoder,” IEEE Photonics Technol. Lett., vol.16, no.1, pp.335–337, 2004.