Design of a Hybrid OCDMA/WDMA System by Using Multi-slot OCDMA Scheme

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ABSTRACT

The data rate of the coherent ultrashort light pulse code-division multiple access (CDMA) communication systems proposed by J. A. Salehi, et al. [5] is limited by the low repetition rate of the ultrashort pulse laser source. In this paper, we propose a Multi-slot OCDMA system to resolve the issue of low data rate and use the scheme in the hybrid OCDMA/WDMA system. Data rate and total throughput can be really increased with the increased number of slots with the proposed system. For example, if 512 chips are used for OCDMA system, the system can simultaneously accommodate more than 10 6-slot OCDMA and 30 WDMA users, achieving a total throughput of around 660Gbps at a BER of 10^{-9}.

1: INTRODUCTION

Optical fiber communication is the most popular type of computer communication network. Fiber is the best waveguide in light applications. It has lots of advantages such as low loss, high bandwidth, high security, etc. Conventional communication cable is short of these advantages. Optical communication has various ways for transmission. Because of the high frequency of light, if we could control and use light as the carrier of communication, capacity would be larger than conventional communication.

For optical communication networks, the Wavelength Division Multiple Access (WDMA) system has been developed at first and maturely commercialized. Today's WDMA networks achieve total throughputs of at most ten Gbps, primarily because the use of incoherent optical techniques limits their total throughput to the speeds that can be handled by electronics technology. This bottleneck can be eliminated by the use of optical switching, narrowlinewidth tunable lasers, and coherent detection. But its disadvantage is low efficiency in utilizing bandwidth for the high bandwidth optical communication system due to the guardbands between the adjacent channels.

Thus, the Optical Code Division Multiple Access (OCDMA) is developed because it does not need the stable, tunable lasers with accurate wavelength control that WDMA needs. This technology is limited to Local Area Networks (LANs) since the same broad bandwidth that makes OCDMA desirable leads to severe problems of dispersion. At the scale of LAN, though, these problems can be easily alleviated with Dispersion Compensated Fiber (DCF) [1], but the disadvantage of the OCDMA system is the low bit rates caused by the low repetition rates of ultrashort pulse laser source [2] [3].

In this paper, we design a Multi-slot OCDMA system based on Optical Time Division Multiple Access (OTDMA) technology [4]. Before, the ultrashort light pulse is spread at the encoder and occupies only one slot in the bit duration of each OCDMA user. Now, we try to utilize the remaining unused slots and by so doing, data rate of each user can be increased with the increased number of slots. After we insert WDMA users, the advantages of these two technologies will be combined and it can provide a more flexible LANs and high-speed access WANs.

The performance of OCDMA and hybrid OCDMA/WDMA system has been discussed in [5][6]. Salehi, et al, have obtained the bit error rate (BER) of an ultrashort pulse pure ST-CDMA system in which there were no WDMA users and the codes were modeled as independent, identically distributed random variable [5]. Chang has argued that the hybrid scheme offers large throughputs and flexible connectivity for a large number of users [6].

The remainder of the paper is organized as follows. In Section 2, we describe the hybrid OCDMA/WDMA system model. In Section 3, we propose a structure called Multi-slot OCDMA system. The performance analysis is outlined in Section 4. Finally, we provide a conclusion in Section 5.

2: HYBRID OCDMA/WDMA SYSTEMS DESCRIPTION

The hybrid system scheme is sketched in Fig. 1, in which OCDMA is overlaid with WDMA in the same spectral region, and the hybrid system model is shown in Fig. 2.

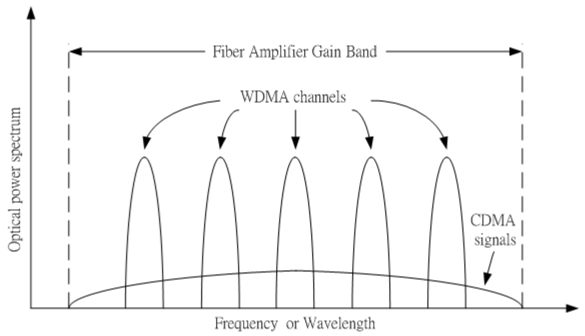

Fig. 1 Hybrid OCDMA/WDMA scheme in which OCDMA and WDMA channels are overlaid in the same spectral region. With proper code and system designs, crosstalk between the two types of channels should be minimal. Such an overlay may increase network capacity above that possible with WDMA alone.

It is of interest to evaluate the performance of hybrid OCDMA/WDMA assuming a channel transfer function $H(f)$, which is the same between all pairs of M OCDMA users and those of L WDMA users, and a rate of R bits/s for each user. It is assumed that the transmitted signal for OCDMA user m is of the form

$$S_m(t) = \sum_j d_j^{(m)} p_m(t - jT_b^{(c)}) \quad (1)$$

and that for WDMA user l is of the form

$$s_l(t) = \sum_i a_i^{(l)} p_l(t - iT_b^{(w)}) \quad (2)$$

where $\{d_j^{(m)}\}$ and $\{a_i^{(l)}\}$ are the sequences of information bits for OCDMA user m and the WDMA user l, respectively, $T_b^{(w)}$ is the bit duration of each WDMA user, and $T_b^{(c)}$ is the bit duration of each OCDMA user. $p_m(t)$ and $p_l(t)$ are the baseband pulses assigned to those users, and $1/T_b^{(c)}$ is the symbol rate.

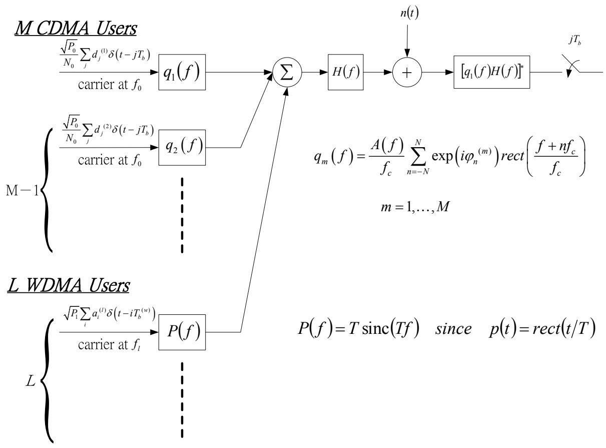

Fig. 2 OCDMA/WDMA hybrid system model.

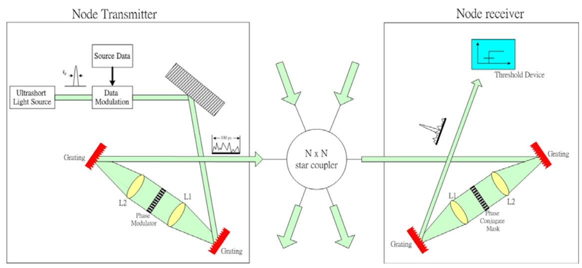

Fig. 3 Proposed scheme for optical CDMA based on spectral encoding and decoding of ultrashort light pulses. Only one transmitter station and one receiver station are shown. [5]

Fig. 3 shows the proposed scheme for the OCDMA system [5]. An encoder and decoder for ST-CDMA are shown in Fig. 4 [7]. The input to the encoder, $A(f)$, is the square root of the transmitted spectrum, $|A(f)|^2$. It is modulated in the frequency domain by the spectral phase code sequence PN_m. The decoder consists of a Fourier transformer, which computes the Fourier transform of the windowed data signal, a conjugate modulator, and an integrator, which is equivalent to a filter matched to the transmitted pulse. The code assigned to a particular transmitter is a complex-valued PN-sequence, with each sequence element chosen from a set of uniformly spaced point on the unit circle. Given that the intended receiver is properly synchronized, the demodulation by the "conjugate" code, in which each PN-sequence element is replaced by its conjugate, enables detection of the transmitted data sequence. If, however, the decoder is matched to a different PN-sequence, the output signal remains additive low-intensity interference, called multi-access interference (MAI).

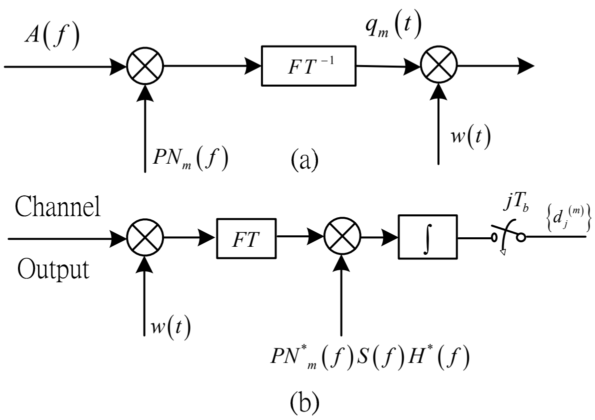

Fig. 4 (a) ST encoder. (b) ST decoder. [7]

Let us assume the Fourier transform of the ST pulse $q_k(t)$ to be

$$q_m(f) = A(f)\sum_{n=-N}^{N} a_n^{(m)} rect\left(\frac{f+nf_c}{f_c}\right) \quad (3)$$

where $|A(f)|^2$ is the desired transmitted spectrum, f_c is the chip width in the frequency domain, $N_0 = 2N+1$ is the processing gain (that is, number of frequency chips), $\{a_n^{(m)}\}$ is the complex PN-sequence, $rect(f/f_c)$ is the rectangle function

$$rect(f/f_c) = \begin{cases} 1, & |f| < f_c/2, \\ 0, & otherwise. \end{cases} \quad (4)$$

Note the transmitted spectrum in ST-CDMA is selected a priori. Assume that for ST the transmitted spectrum is matched to the ideal bandlimited channel; i.e., $A(f) = |H(f)|$. Then the pulse $q_m(t)$ that results from taking the inverse Fourier transform of $q_m(f)$ in equation (3) is of infinite duration and must be windowed by some function $w(t)$. In analogy with the ideal bandlimited channel $H(f)$, we can choose the ideal time-limited windows $w(t)=1$ for $|t| < T/2$, and $w(t)=0$ elsewhere. Then the Fourier transform of the encoder output $y(t)$ is

$$y(f) = H(f)A(f) \times\left(\sum_{n=-N}^{N} a_n^{(m)}\left[w(f) * rect\left(\frac{f-f_c}{f_c}\right)\right]\right) \quad (4)$$

where $w(f) = T\,\mathrm{sinc}(Tf)$ is the Fourier transform of the ideal time-limited window $w(t)$. The intensity of the ST modulated pulse varies as $f_c\,\mathrm{sinc}(f_c t)$ and consequently, most (approximately 90%) of the energy in is contained in the interval $[-T/2, T/2]$.

3: MULTI-SLOT OCDMA SYSTEM

As mentioned before, the OCDMA is mainly used in the transmission of the LANs. Its data rate is limited by the low repetition rate of the ultrashort pulse laser source. Hence, we design a new structure which is called the Multi-slot OCDMA system, and it can utilize other timeslots efficiently as shown in Fig. 5. Here, s slots are used among K slots, and as a result, data rate can be improved. The system structure is shown in Fig. 6.

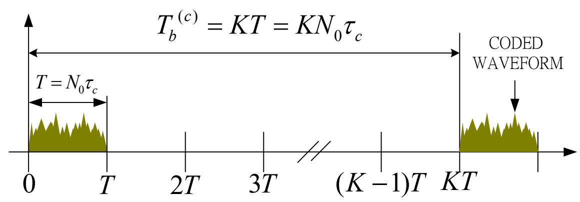

Fig. 5 Train of encoded ultrashort pulses.

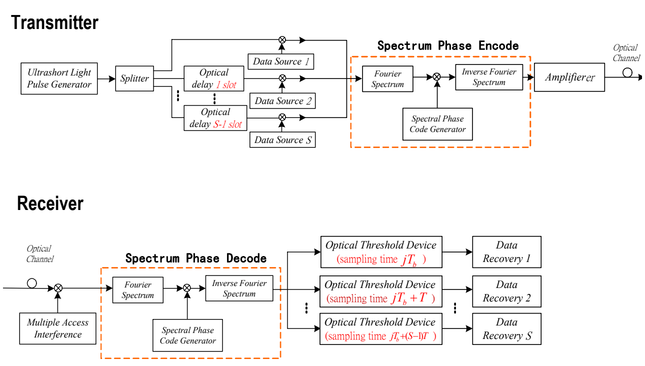

Fig. 6 A typical representation of an ultrashort pulse multi-slot OCDMA system.

At first, in the transmitter, ultrashort laser pulse is divided into s pulses via $1\times s$ splitter and sent onto s paths. The pulse on the first path performs E/O conversion on bit one, the pulse on the second path delays a timeslot T via optical delay line and E/O conversion on bit two, and so on. After E/O conversion, all bits turn into optical signals and are coupled with the combiner. The pulse duration of this combined signal is spread to sT after the spectral phase encoding. Because the instantaneous peak power reduces to $1/s$ via splitter, we need a compensator which can amplify s times. We transmit signals via star coupler on the optical fiber with other users inserted.

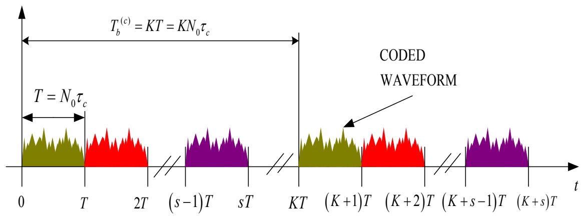

Fig. 7 s-slot OCDMA Timing Diagram

For a unique user, the bits on different slots will not interfere with each other even though the same codeword is used throughout the bit stream it sends. Therefore, these bits can be detected and decoded correctly within accurate slots. Furthermore, MAI is an interference produced by other users. Hence, detection device must determine the threshold within corresponding slots so that a minimum bit error rate can be achieved.

4: PERFORMANCE ANALYSIS

In our system performance evaluation, we assume that all M Multi-slot OCDMA users have identical bit rates and signal formats, all L WDMA users have identical bit rates and signal formats and they are sufficiently separated so that any adjacent-channel interference (caused by overlap of the adjacent WDMA channels) can be ignored, and the effects of quantum and thermal noise are neglected. Without loss of generality, we assume that Multi-slot OCDMA user j is the desired signal and all other $(M\text{-}j)$ Multi-slot OCDMA users will produce MAI. The L WDMA users can be viewed, from Multi-slot OCDMA user j's standpoint, as narrow-band interference (NBI).

At receiver, the received signal can be represented as

$$r(t) = s(t) + i_{MA}(t) + i_{NB}(t)\,. \quad (5)$$

Where

$$\begin{aligned} s(t) &= d_0^{(j)}\,\mathrm{sinc}(f_c t) V_j(t) \\ &= d_0^{(j)}\,\mathrm{sinc}(f_c t)\frac{\sqrt{P_0}}{N_0}\sum_{n=-N}^{N}\exp\left[-i\left(n\Omega t + \varphi_n^{(j)}\right)\right], \end{aligned} \quad (6)$$

$$\begin{aligned} i_{MA}(t) &= \sum_{\substack{m=1\\ m\neq j}}^{M} d_0^{(m)}\sin c(f_c t) V_m(t) \\ &= \sum_{\substack{m=1\\ m\neq j}}^{M} d_0^{(m)}\sin c(f_c t)\frac{\sqrt{P_0}}{N_0}\sum_{n=-N}^{N}\exp\left[-i\left(n\Omega t + \varphi_n^{(m)}\right)\right], \end{aligned} \quad (7)$$

$$i_{NB}(t) = \sum_{l=1}^{L} i_{NB}^{(l)}(t) = \sum_{l=1}^{L}\sqrt{P_1}\,a_0^{(l)} rect\left(\frac{t - T_b^{(w)}/2}{T_b^{(w)}}\right), \quad (8)$$

and $d_0^{(m)} \in \{0,1\}$.

Here p_0 is the peak power of the incident ultrashort pulse, $\varphi_n^{(m)}$ is the n'th spectral code element of the mth OCDMA user's address code, $N_0 = 2N+1$ is the total number of code elements, P_1 is the peak power of each WDMA user, $T_b^{(w)}$ is the bit duration of each WDMA user, and $T_b^{(c)}$ is the bit duration of each OCDMA user.

The ensemble average of signal $V_m(t)$ in the Equation (8) defines as

$$\begin{aligned} \langle V_m(t)\rangle &= \frac{\sqrt{P_0}}{N_0}\sum_{n=-N}^{N}\exp\{-in\Omega t\}\left\langle \exp\left(-i\varphi_n^{(m)}\right)\right\rangle \\ &= (p-q)V_p(t) \end{aligned}, \quad (9)$$

where $V_p(t) = \frac{\sqrt{P_0}}{N_0}\sum_{n=-N}^{N}\exp\{-in\Omega t\}$. We calculate the ensemble average intensity

$$\begin{aligned} &\langle I(t)\rangle \\ &= \frac{P_0}{N_0^{\,2}}\left(N_0 + (p-q)^2\sum_{n=-N}^{N}\sum_{m\neq n=-N}^{N}\exp\{-i(n-m)\Omega t\}\right. \end{aligned}. \quad (10)$$

By using the method described in [8] or central limit theorem, the encoded pulses are modeled to obey Gaussian statistics as follows:

$$\begin{aligned} &P_{\alpha_x,\alpha_y}(\alpha_x,\alpha_y,t) \\ &= \frac{1}{2\pi\Phi'\Psi'}\exp\left\{-\frac{(\alpha_x - \Upsilon')^2}{2\Phi'^2} - \frac{\alpha_y^2}{2\Psi'^2}\right\}, \end{aligned} \quad (11)$$

where Υ', Φ'^2 and Ψ'^2 are defined as

$$\Upsilon' = (p-q)V_p(t) \tag{12}$$

$$\Phi'^2 = \left(1-(p-q)^2\right)\frac{P_0}{2N_0}\left(1+\frac{V_p(2t)}{\sqrt{P_0}}\right) \tag{13}$$

$$\Psi'^2 = \left(1-(p-q)^2\right)\frac{P_0}{2N_0}\left(1-\frac{V_p(2t)}{\sqrt{P_0}}\right) \tag{14}$$

α_x and α_y are the real and imaginary parts of complex amplitude $V(t-t')$ are defined as

$$\alpha_x(t-t') = \frac{\sqrt{P_0}}{N_0}\sum_{n=-N}^{N}\cos\left(n\Omega(t-t')+\eta\right) \tag{15}$$

and

$$\alpha_y(t-t') = \frac{\sqrt{P_0}}{N_0}\sum_{n=-N}^{N}\sin\left(n\Omega(t-t')+\eta\right). \tag{16}$$

The total variance of $i_{NB}(t)$ of WDMA users has been provided in [6] and can be written as

$$\sigma_1^2 = \sum_{r=1}^{L}\frac{P_1 D(4K-D)}{16K^2} \tag{17}$$

where $D = T_b^{(c)}/T_b^{(w)}$, P_1 is the peak power for WDMA users , $P_1 = P_0/d$, and parameter *d* is set *100*.

The numbers of Multi-slot OCDMA and WDMA users which send '1' in the first bit are denoted as l_s and *n*, respectively. Here l_s and *n* are both random variables with binomial distributions

$$P(l_s) = \binom{M_s-1}{l_s}\zeta_s^{\,l}\left(1-\zeta_s\right)^{M_s-1-l_s}, \tag{18}$$

and

$$P(n) = \binom{L}{n}(\xi)^n\left(1-\xi\right)^{L-n}, \tag{19}$$

where $\xi = 1/2D$ and $\zeta_s = s/2K$.

In order to calculate the conditional probability distribution function $P(I,t\,|\,d_0^{(1)},l_s,n)$, it is sufficient to find the conditional joint distribution function $P(r_x,r_y,t\,|\,d_0^{(1)},l_s,n)$, where r_x and r_y are the real and imaginary parts of the received signal $r(t)$. The real and imaginary parts of the received signal are modeled as joint Gaussian and the conditional joint distribution function can be represented as

$$P_{r_x r_y}\left(r_x,r_y,t/d_0^{(m)},l_s,n\right) = \frac{1}{2\pi z}\exp\left\{-\frac{\left(r_x-d_0^{(m)}V_p(t)\right)^2+r_y^{\,2}}{2z}\right\} \tag{20}$$

where

$$z = l_s\frac{P_0}{2N_0} + n\frac{P_1 D(4K-D)}{16K^2}. \tag{21}$$

When bit *"0"* or *"1"* was sent, we get

$$P(I\,|\,d_0^{(1)}=0,l_s,n) = \frac{1}{2z}\exp(-\frac{I}{2z}) \tag{22}$$

or

$$P(I\,|\,d_0^{(1)}=1,l_s,n) = \frac{1}{2z}\exp(-\frac{(I+P_0)}{2z})I_0\left(\frac{\sqrt{IP_0}}{z}\right), \tag{23}$$

To determine the bit error rate, we first determine the bit error rate conditioned on l_s, and *n* as

$$\begin{aligned} &BER(l_s,n) \\ &= P_r(I \ge I_{th}\,|\,d_0^{(1)}=0,l_s,n)P_r\left(d_0^{(1)}=0\right) \\ &\quad + P_r(I < I_{th}\,|\,d_0^{(1)}=1,l_s,n)P_r\left(d_0^{(1)}=1\right) \\ &= \frac{1}{2}\left(P_{FA}(l_s,n)+P_{MD}(l_s,n)\right), \end{aligned} \tag{24}$$

where

$$P_{FA}(l_s,n) = \exp(-\frac{I_{th}}{2z}) \tag{25}$$

and

$$P_{MD}(l_s,n) = 1-Q(\sqrt{\frac{P_0}{z}},\sqrt{\frac{I_{th}}{z}}) \tag{26}$$

Finally, we calculate the BER as the system performance which can be shown as

$$BER = \frac{1}{2}\sum_{l_s=1}^{M_s-1}\sum_{n=0}^{L}P(l_s)P(n)\left(P_{FA}(l_s,n)+P_{MD}(l_s,n)\right), \tag{27}$$

where $P_{FA}(l_s,n)$, $P_{MD}(l_s,n)$, $P(l_s)$, $P(n)$ are given in Equations (26),(27), (19) and (20), respectively.

The user number and the throughputs of the system versus BER are shown in Figs.8 through 10, and we find that they can really be increased with the increased number of slots.

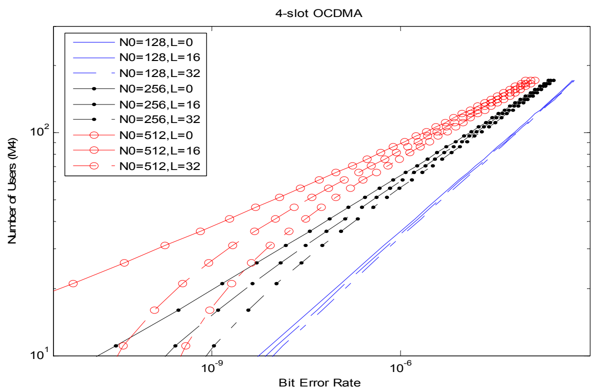

Fig. 8 The number of 4-slot OCDMA users (*M1*) versus the minimal BER for different values of WDMA users (L) and N0.

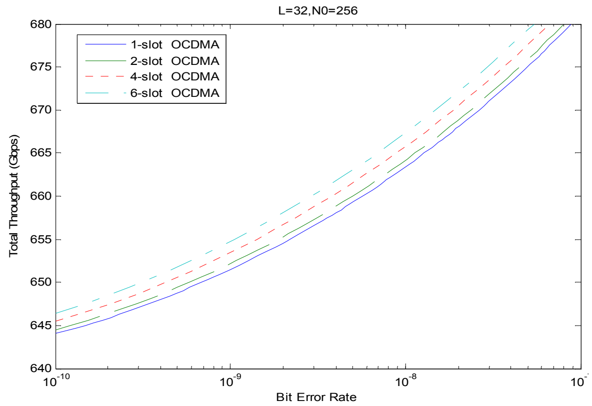

Fig. 9 The total throughput for 1-slot OCDMA, 2-slot OCDMA, 4-slot OCDMA, and 6-slot OCDMA, for code length N0=256 versus the minimal BER, number of WDMA users *L=32*.

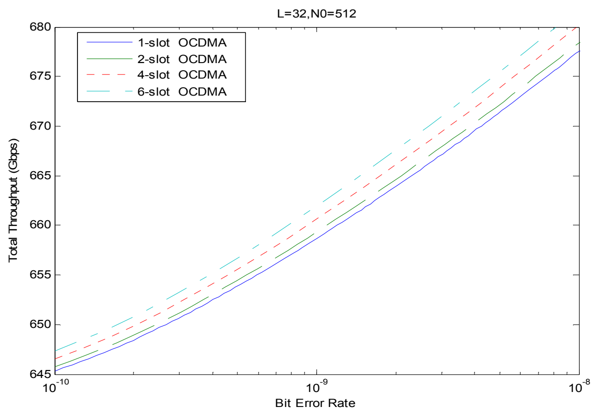

Fig. 10 The total throughput for 1-slot OCDMA, 2-slot OCDMA, 4-slot OCDMA, and 6-slot OCDMA, for code length N0=512 versus the minimal BER, number of WDMA users *L=32*.

5: CONCLUSION

In this paper, we utilize multi-slots to improve each OCDMA user's data rate effectively, but the throughput can not be unconditionally improved. Although data rate can really be increased with the increased number of slots, number of users will be reduced. We must establish a standard number which, when the number of users in the system exceeds, can motivate the use of Multi-slot OCDMA system.

Furthermore, in the Multi-slot OCDMA system, we insert WDMA users and calculate the number of users, data rate, normalized threshold, and total throughput. We obtain a conclusion that the Multi-slot OCDMA users will be more interfered with the increase of WDMA users, and it results in the decrease of total throughput

If we want to increase the range of the data rate of the Multi-slot OCDMA system, it will be constrained by today's technology. Therefore, we expect the advent of a high density LCM product in the future so that it can be applied on the Multi-slot OCDMA system to increase data rate and throughput efficiently.

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