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Throughput/Delay Analysis of Spectrally Phase-Encoded Optical CDMA over WDM Networks

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***Abstract*-This paper presents a performance analysis of spectrally phase-encoded optical CDMA over WDM networks. Random access protocol is adopted to assign wavelengths. The discrete time Markov chain model is used to build analytical model of multi-channel random access protocol. We measure several performance characteristics, namely, steady-state throughput and average packet delay time. Additionally, the efficiencies of the system, which are based on both the processing gain and the number of WDM wavelengths, are considered. Exponential retransmission is used for solving packet collision problems. In our numerical results, system performance is given in terms of both average throughput and delay time.**

Keywords: Optical CDMA, WDM, Exponential retransmission, Spectrally phase-encoded optical CDMA (SPE-OCDMA)

I. INTRODUCTION

In the middle of 80's, OCDMA (Optical code division multiple access) has been widely developed as high-rate optical communication network systems, where encoding and decoding are all performed in optical domain [1-2]. The advantageous function of the optical CDMA is the fact that it lets each user access the network asynchronously and simultaneously without strict wavelength control and timing synchronization. In addition, optical CDMA local area networks allow shared access to a broadcast medium. However, multiple access interference (MAI) in OCDMA increases as the number of users increases.

Additionally, Optical CDMA can be operated on Ethernet passive optical networks (EPON) which architecture is the key function in local area networks (LANs) in future. Moreover, it can also be upgradeable to either Gigabit or 10 Gigabit Ethernets. In fact when using OCDMA in EPON, both capacity and bandwidth will highly increase [1-2,6]. This can only be achieved by mixing two techniques together, e.g., hybrid optical CDMA/ WDM technique [1].

In this paper, we propose a spectrally phase-encoded optical CDMA (SPE-OCDMA) over WDM network via random access protocol. SPE-OCDMA or coherent ultra-short light pulse techniques seems to be a good technique, since it offers high bit rates [8].

SPE-OCDMA technique is used to encode/decode data with the OCDMA code sets. Each simultaneous user or node is assigned a different unique code. The encoded data is then sent to wavelength division multiplexing (WDM) channels. Multi-channel slotted Aloha is used to contend free WDM wavelengths for each OCDMA code (each node contends the available wavelengths for sending packets out). We assume that the number of channels is equal to the number of wavelengths. Packet collision occurs if more than two active users choose the same wavelength and same CDMA code at the same time. Therefore, to resolve this problem, exponential retransmission is used.

We measure our system performance using both average system steady-state throughput and average system packet delay time. Both are based on discrete time Markov chain model.

The rest of this paper is organized as follows. In section A, the system model description is presented. The mathematical analysis is illustrated in section II, where we give more details about discrete time Markov chain. In section III, the numerical results are shown in terms of both system throughput and delay time versus the number of active users. Finally the conclusions are presented in section IV.

A. Model Description

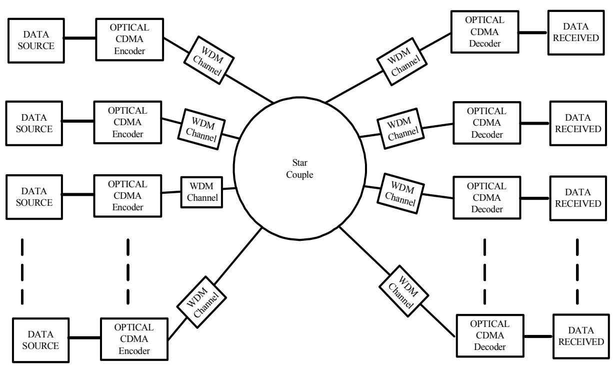

Figure 1. System model description of optical CDMA over WDM networks

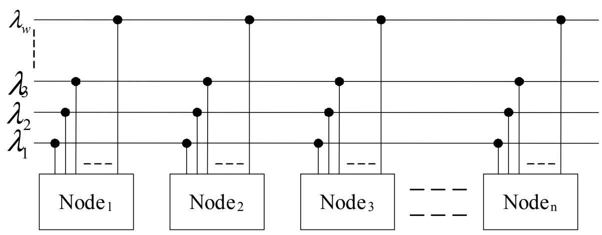

Figure 2. Architecture of optical CDMA code over WDM channel

Figure 1 shows the system model. It composes of a set of transmitters (data sources and tunable lasers, optical CDMA encoders), WDM star couplers and a set of receivers (optical CDMA decoders). The data is encoded/decoded with the set of spectrally phase-encoded optical CDMA (SPE-CDMA) technique [8]. Each encoded data is assigned a WDM wavelength by using multi-channel random access MAC protocol. That is, on each WDM wavelength, N users can be accommodated by individually assigning each user with a different optical CDMA code. Therefore, the same code sequence can be reused on all WDM channels. We use Multi-channel slotted Aloha random access protocol to assign WDM wavelengths $\lambda_i, i = 1,2,3,...w$ [5-6], as shown in Fig. 2. We assume that the packet is received successfully if no collision has occurred (no terminals or nodes have chosen the same wavelength and same code at the same time to transmits packets out). In reality, this problem is unavoidable, therefore, in this paper, the exponential backoff retransmission with probability of retransmission $p = r^n$ is used to solve this problem, $n = 0,1,2,...,k$ is level of retransmission.

II. Mathematical Analysis

A. Packet error rate of SPE-O CDMA

We assume that if the data bit to be transmitted is "0", then no spectral-phase encoder energy is transmitted. On the other hand, if the data bit is "1", an ultrashort pulse is sent out to the spectral-phase encoder [8]. The receiver declares a "1" was sent if the decoded intensity exceed the threshold and declares a "0" otherwise. Therefore, the probability of error P_e for SPE optical CDMA is given by [8-9],

$$P_e = \left(\frac{1}{2}\right)\cdot\left[\sum_{l=1}^{N-1}\binom{N-l}{l}\left(\frac{1}{2K}\right)^{l}\left(1-\frac{1}{2K}\right)^{N-1-l} \cdot\left(1-\left(\gamma(l)-\rho(l)\right)\right)\right] \tag{1}$$

Where $K = T_b / T$ is the processing gain, T_b is period of the data source, T is the encoded pulse duration,

$$\gamma(l) = 1-\exp\left(-I_{th}N_0 / lP_0\right) \tag{2}$$

and

$$\rho(l) = 1-Q\left(\sqrt{\frac{2N_0}{l}},\sqrt{\frac{2N_0 I_{th}}{lP_0}}\right) \tag{3}$$

Here $Q(a,b)$ is the Marcum's Q function, expressed as:

$$Q(a,b) = \int_b^{\infty} x\cdot\exp\left(-\frac{a^2+b^2}{2}\right)I_0(ax)dx \tag{4}$$

P_0 is the peak power of the ultrashort pulse, N_0 is the number of chips in the coded sequence, and I_{th} is the intensity threshold of the receiver comparator for detecting 0 and 1. Therefore, from the probability of packet error in (1), the success probability of L bits length can be given in (5),

$$P_s(N) = \left(1-\frac{1}{2K}\right)^{N-1} + \left[\sum_{l=1}^{N-1}\binom{N-1}{l}\left(\frac{1}{2K}\right)^{l}\left(1-\frac{1}{2K}\right)^{N-1-l} \cdot\left(1-\frac{1}{2}\left(1-\left(\gamma(l)-\rho(l)\right)\right)^{L}\right)\right] \tag{5}$$

B. System Performance Analysis

In this section, we analyze the performance of our system using discrete Markov chain model [9,11]. We assume that the number of channels equal to the number of wavelengths. Packet collision occurs if more than one active user chooses the same wavelength and the same code at the same time. Therefore, to resolve this problem, the exponential retransmission is used. However, if more that one active user select only same wavelength (but different codes) at the same time, there will be multiple access interference (MAI), no collision.

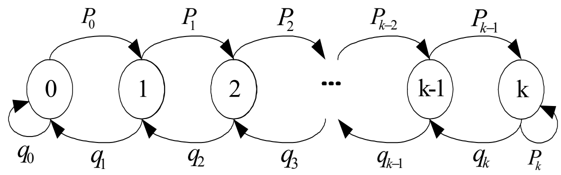

Figure 3. State transitions of Markov chain model of exponential retransmission level

The discrete time Markov chain is shown in Fig. 3. Let $p(t)$ be the retransmission probability in the t-th slot (equal period of a packet length). $p(t)$ is updated according to acknowledgment feedback. There are idle and busy statuses, in the busy statuses correspond to both success and collision of the current time slot, it could be expressed as

$p(t+1) = \min(p_{\max}, p(t)/r)$, if number of idle wavelengths $\geq \lfloor x \cdot M \rfloor$

and $p(t+1) = \max(p_{\min}, p(t)\cdot r)$, if number of wavelengths $< \lfloor x \cdot M \rfloor$

Where $\lfloor x \rfloor$ denotes the largest integer not greater than x. $0 < x < 1$ be the factor of wavelengths remain in system, $0 < r < 1$ be the probability of retransmission when collision occurred, $0 < p_{\max} \leq 1$, and $p_{\min} = r^k$ and k be the maximum value of retransmission level.

Noted that, increasing the k level guarantees system stability but with large system delay time. The system state transition probability from state n to j, $P_{(n,j)}$ is present in [11]

$$P_{(n,j)} = \begin{cases} q_0 & ,n = j = 0 \\ p_k & ,n = j = k \\ p_n & ,j = n+1\, and\, 0 \leq n \leq k-1 \\ q_n & ,j = n-1\, and\, 0 < n \leq k \end{cases} \tag{6}$$

$when\ n = 0,1,2,...k$

Here, by applying binomial distribution, we get the probability that number of idle WDM wavelengths $< \lfloor M \cdot x \rfloor$ p_n when system state n is

$$p_n = \sum_{j=0}^{\lfloor M \cdot x \rfloor - 1} \binom{M}{j} \left\{ \left(1 - \frac{r^n}{M}\right)^N \right\}^j \cdot \left\{ 1 - \left(1 - \frac{r^n}{M}\right)^N \right\}^{M-j} \tag{7}$$

Where N, is the number of stations or nodes

M, is the number of wavelengths

and q_n is the probability that number of idle wavelengths is $> \lfloor M \cdot x \rfloor$

$$q_n = 1 - p_n \tag{8}$$

Let π and P be the limiting probability vector and the transition probability matrix, respectively. Therefore, the limiting probability can be satisfied the steady-state probability from,

$$\pi = \pi P \text{, and } \sum_{i=0}^{k} \pi_i = 1 \tag{9}$$

the overall system throughput $S_{oa}(N)$ given by,

$$S_{oa}(N) = \sum_{j=0}^{N} \left\{ \binom{N}{j} \left(r^n\right)^j \left(1 - r^n\right)^{N-j} \cdot j \left(1 - \frac{1}{M}\right)^{j-1} \right\} \cdot P_s(N) \tag{10}$$

And throughput per wavelength $S_{pc}(N)$,

$$S_{pc}(N) = \frac{1}{M} \cdot S_{oa}(N) \tag{11}$$

the steady-state system throughput with spectrally phase-encoded optical CDMA is given in (12) [3-5,10] and P_s was given in A of Section II,

$$S = \sum_{n=0}^{k} \pi_n s(N) \tag{12}$$

Here,

$$s(N) = \begin{cases} S_{pc}(N), \\ \text{for throughput per wavelengh} \\ S_{oa}(N), \\ \text{for overall throughput} \end{cases} \tag{13}$$

Finally the system packet delay is,

$$D = 1 + \frac{1}{S} \sum_{n=0}^{k} n \pi_k \tag{14}$$

III. NUMERICAL RESULTS

In this section, we present some numerical results in terms of system throughput and system delay time for the spectrally phase-encoded optical CDMA over WDM networks via random access protocol. In all of our calculations of system performance, we select same parameters as given in [3-5,8-9], namely, packet length $L = 128$ bits, $N_0 = 32$, $I_{th} / P_o \approx 1/4$, $x = 0.1$ and $r = 0.9$.

In Fig. 4, we have plotted the system throughput per wavelength versus the number of active users. We vary the number of wavelengths from 18, 20 to 22. The throughput increases up to a maximum value at a number of active users about 15 to 17. Additionally, we found that if the number of wavelengths increased, from 18 to 22, the maximum throughput of 18 wavelengths is still higher than 20 and 22. This is because the utilization of 18 wavelengths is more than the wavelengths of 20 and 22. However, the overall system performance of 22 wavelengths show better performance than 18 wavelengths, illustrated in Fig. 8 and 9.

Figure 5 the system packet delay time per wavelength has been shown versus the number of active users. We also vary the number of wavelengths from 18 to 22 wavelengths. It can be seen that, the delay time decreases when the number of wavelengths are increased. Therefore, if the number of wavelengths increased, from 18 to 22 wavelengths, the maximum delay time is decreased when we compare the results at the same number of active users as well as the system throughput.

In Fig. 6 and 7, we have compared the system throughput and system packet delay time while varying the processing gain K from 2 to 4, respectively, and holding the wavelengths fixed at 22 wavelengths.

From Fig. 6 we see that, the throughput of processing gain with $K = 4$ is more than that of $K = 2$ by 2.5 times. In this case, the maximum throughput is about 2.8, but for $K = 2$ the maximum throughput is about 1.2. It means that, the processing gain (K) strongly affects the system.

Figure 7 shows that the system packet delay time with $K = 4$ is less than $K = 2$, corresponding to system throughput in Fig. 6. Therefore, we see that, when the processing gain is increased the system delay time decreases, and the system throughput increases as well.

In Fig. 8 and 9, we have been compared the over all system throughput and system packet delay time while varying the number of wavelengths of 18, 20 and 22 by using (10). We again observe both the maximum throughput in Fig 8 and minimum delay time in Fig 9, respectively. From Fig 8 and 9, the over all system performance increased when the number of wavelengths increased. It is clear that, the processing gain (K) and the number of wavelengths strongly affect the overall system performance when the SPE-OCDMA is used.

In Fig. 10 and 11, we plot the system throughput and system packet delay time per wavelength while varying the probability of retransmission r. It could be seen that when the number of r increased, the system throughput decreases but system delay time increases cause traffic on network is increased.

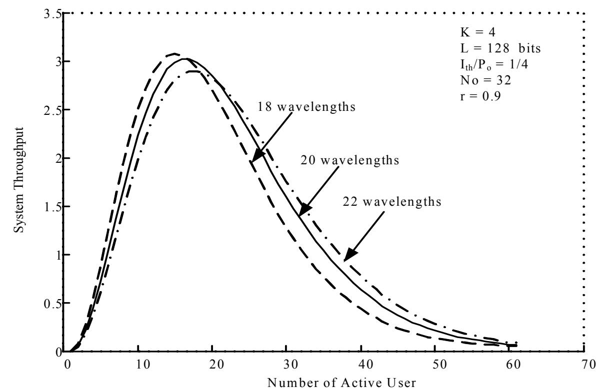

Figure 4. System throughput per wavelength versus number of active users with various wavelengths

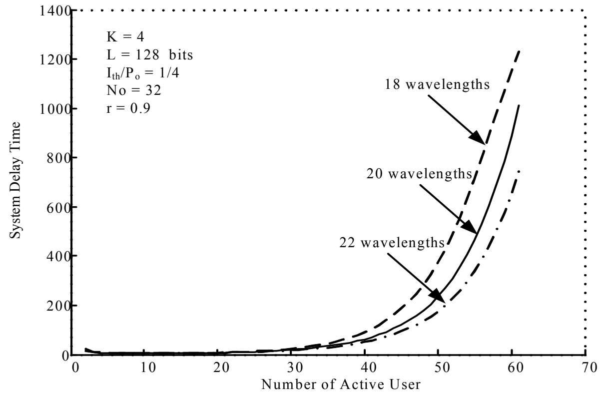

Figure 5. System packet delay time versus number of active users with various wavelengths

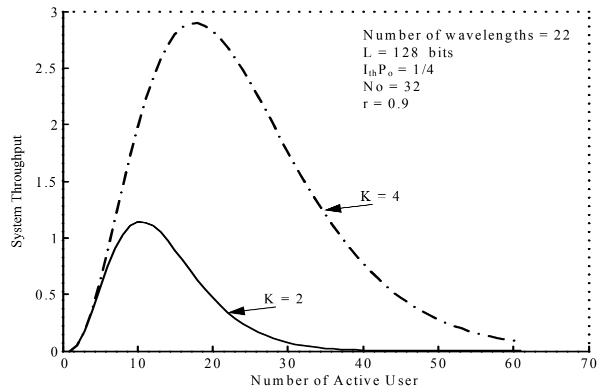

Figure 6. System throughput per wavelength versus number of active user with various K (Processing gain)

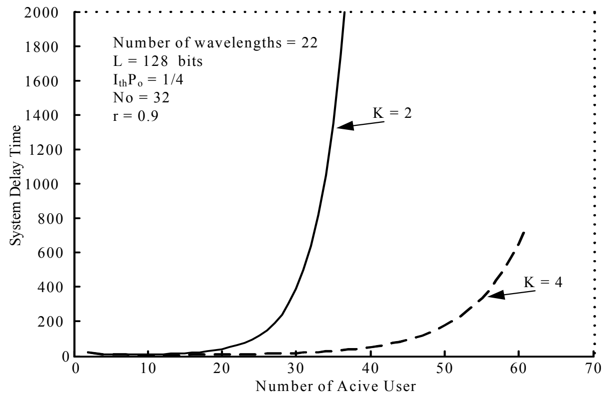

Figure 7. System packet delay time versus number of active user with various K (Processing gain)

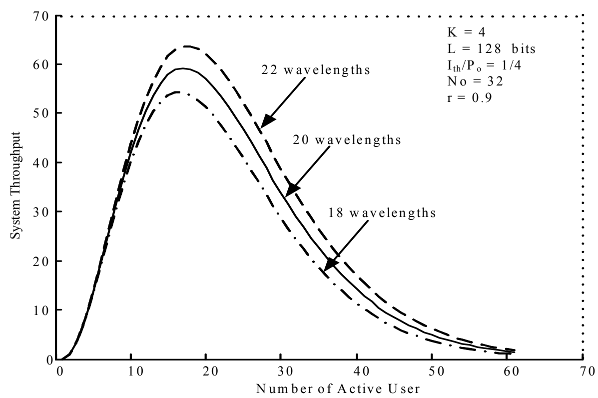

Figure 8. System throughput versus number of active users with various wavelengths

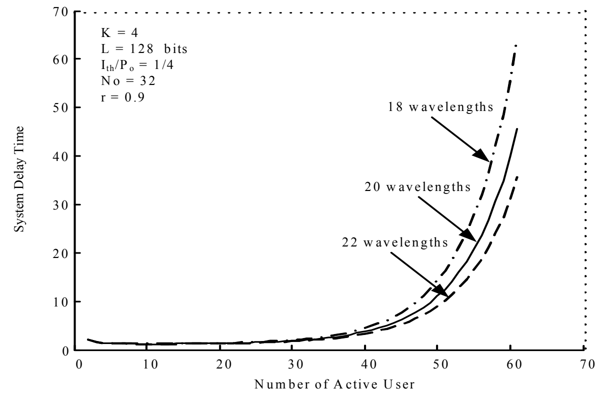

Figure 9. System packet delay time versus number of active users with various wavelengths

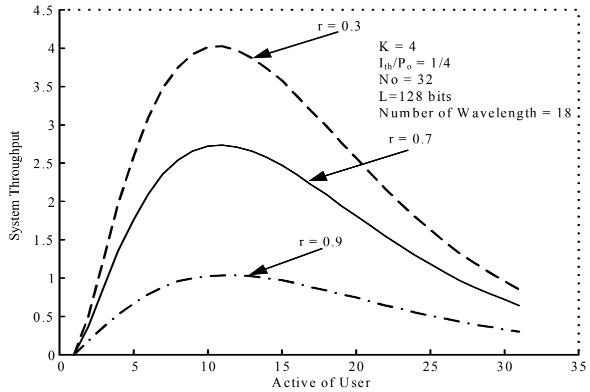

Figure 10. System throughput versus number of active users with various probability of retransmission

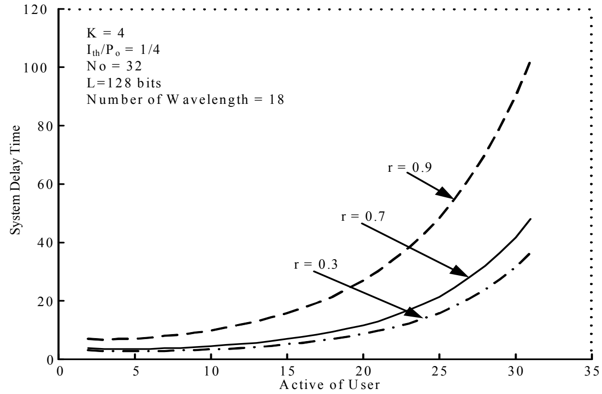

Figure 11. System packet delay time versus number of active users with various probability of retransmission

IV. CONCLUSIONS

We propose a performance analysis of spectrally phase-encoded optical CDMA over WDM networks via random access protocol. The SPE-OCDMA technique is used to encode/decode data with the OCDMA code sets. Each simultaneous user or node is assigned a different unique code. Additionally, multi-channel Slotted Aloha is used to contend the available WDM wavelengths. The two characteristics of system performance are considered. One is system steady-state throughput and another is average system packet delay time. The results show that, the processing gain, probability of retransmission and the number of wavelengths have more effects in system. Therefore, when we use SE-OCDMA technique for optical fiber communication, these factors and effects should be considered.

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