Variable-Size Sliding Window Optical CDMA MAC Protocol

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Abstract *- We analyze an optical code-division multiple-access (CDMA) packet network with variable length data traffic. We focus on sliding window protocol with variable window size, where we propose a media access control (MAC) protocol. A model for interference level fluctuation and an accurate analysis for channel usage is presented. The system performance is evaluated using the traditional average system throughput and average delay. Finally, we apply error control codes (ECCs) in order to enhance the overall performance. Results indicate that the performance can be enhanced to reach its peak using ECC with optimum number of correctable errors.*

Keywords: Code-division multiple access, unslotted ALOHA, Optical network, Optical CDMA, Correlation receiver.

I. INTRODUCTION

In optical CDMA technique a spreading sequence (such as optical orthogonal codes (OOC) [1], [2].) is assigned to each user. This sequence is used for self addressing of packets; thus, the receiver can distinguish between the time overlapped packets received from different users. Multiple access interference (MAI) due to non-perfect orthogonality among the assigned code is the main source of signal degradation. MAI is the only source of noise to be studied in this paper.

Most researches have focused on the physical layer of the optical network. However, few studies have considered the media access control (MAC) sub-layer protocols [4]-[9] which is the main objective of this paper.

Our aim of this paper is to analyze an unslotted optical CDMA packet network and measure its performance. Each terminal in the network sends its message in continuously transmitting packets of constant length. The message length is variable. Two main indicators of the system performance have been focused upon. The first is the network throughput in packets per slot (packet duration), which tells the average number of successfully transmitted packets per slot. The second indicator is the network delay, which tells, on the average, after how many slots the packet is successfully received. Upon successful receiving of packets the receiver sends positive acknowledgment to the transmitter; packet failure is detected due to lack of positive acknowledgement.

In WDMA networks, the available bandwidth is divided into wavelengths. The main problem is to assign a wavelength to only one user. Any overlapping between two or more packets at the same wavelength will destroy all of them. Many researches are proposed to study and improve WDM network protocols [8]-[10]. However, in CDMA networks [3]-[7] the collided packets will not be totally destroyed; the signal degradation will depend on the interference level and its duration. In our analysis perfect packet capture is assumed [7]; this means that the receiver can distinguish between all received packets and capture all of them but not all of them are received successfully.

The rest of the paper is arranged as follows. In Section II network architecture is presented. The mathematical model of the system is illustrated in Section III. In Section IV the packet success probability and system throughput and delay are evaluated. Numerical results are shown in Section V. Finally the paper is concluded in Section VI.

II. NETWORK ARCHITECTURE

The proposed network consists of a large number of users that can be considered as infinite population network. The network topology is a centralized network (star topology) i.e. a hubstation is connected to all terminals. Spread spectrum multiple access (SSMA) technique is applied with a common spreading sequence and the receiver can distinguish between time overlapped packets if there is a time offset that is greater than the width of the auto-correlation function of the used spreading sequence. In unslotted systems we can assume that the receiver can distinguish between all received packets. An optical correlation receiver is adopted at the receiver side of the network.

The traffic offered to the system is assumed to be Poisson with average rate of λ messages/sec. Each packet consists of a fixed number of bits (L bits/packet) and the message length B (packets/message) is geometrically distributed with average length of B_{av} and a maximum length of $B_{\max}$; then the message length is $B \times L$. An error control code is applied and can correct up to errors / packet. The near–far effect is eliminated and all packets arrive to the receiver with equal power.

The system uses ON–OFF Keying (OOK) modulation scheme and applies a spreading sequence from optical orthogonal code (OOC) family of (N , W , λ_a , λ_c), where N is the code length, W is the code weight, and λ_a and λ_c are the maximum values of the auto- and cross-correlation functions, respectively. Both λ_a and λ_c are bounded to one, therefore, any interferer can not interfere with more than one chip pulse. Thus the probability of bit error is given by [3]:

$$P_b(k) = \frac{1}{2}\cdot\sum_{i=W}^{k}\binom{k}{i}\cdot\left(\frac{W^2}{2N}\right)^i\cdot\left(1-\frac{W^2}{2N}\right)^{k-i} \qquad (1),$$

where k is the number of interferers.

III. System Analysis and Mathematical Model

In this section it is aimed to illustrate the mathematical model used in the system analysis in order to evaluate the system performance in terms of the system throughput and delay versus the system offered traffic. First we will evaluate the traffic offered to the system, then the transition of the interference level, and finally the packet success probability.

A. Offered traffic (G)

The system offered traffic is defined as the number of the generated packets per packet duration and is calculated as follows:

$$G = \lambda \cdot T_p \cdot B_{av} \qquad (2)$$

where T_p is the packet duration.

The length of a message is assumed to be geometrically distributed; the probability of a message to be of length x is expressed in (3).The message length is limited to $B_{\max}$;this truncation will be numerically considered.

$$P_x(x) = p\cdot(1-p)^{x-1} \qquad (3)$$

where: $p = 1/B_{av}$ (4)

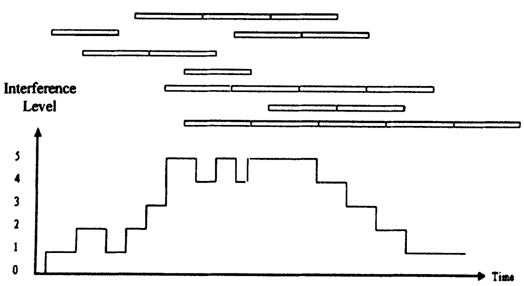

Fig.1 Interference level fluctuation

B. Modeling of the interference level and transition

We evaluate the probability of transition of the number of the interfering messages as follows. Two sources of transition should be considered; the first is the generation of new messages, which is assumed to follow the Poisson distribution with arrival rate (λ messages/sec). The second is the termination of transmitted messages.

Consider the first source, the probability of generating k messages during t sec is given by:

$$P_o(k,t) = \frac{(\lambda\cdot t)^k}{k!}\cdot e^{-\lambda t} \qquad (5)$$

The termination processes is also considered to be a Poisson processes and will be discussed later.

Next we evaluate the interference level during the tagged packet. We assume Markovian model in our analysis, Fig. 2.

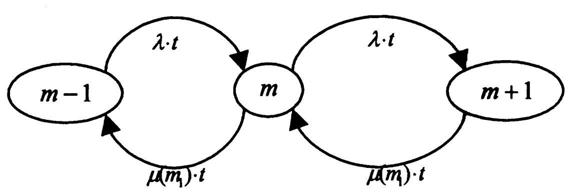

Fig. 2 Transition of the interference level

Since the interference level can be changed by a value of 1 during a bit, and assuming that the level is m at a certain bit, the level of the next bit may be $m+1$, $m-1$, or m.

Thus, the transition probability can be calculated as follows:

$$q(m_j \mid m_{j-1}) = \begin{cases} \lambda\cdot T_b & m_j = m_{i-1}+1 \\ \mu(m_1)\cdot T_b & m_j = m_{i-1}-1 \\ 1-\lambda\cdot T_b-\mu(m_1)\cdot T_b & m_j = m_{i-1} \\ 0 & otherwise \end{cases} \qquad (6)$$

where $\mu(m_1)$ is the death rate, which is the rate of message's termination. Now, it is required to express the average death rate, this is to be discussed in the following steps.

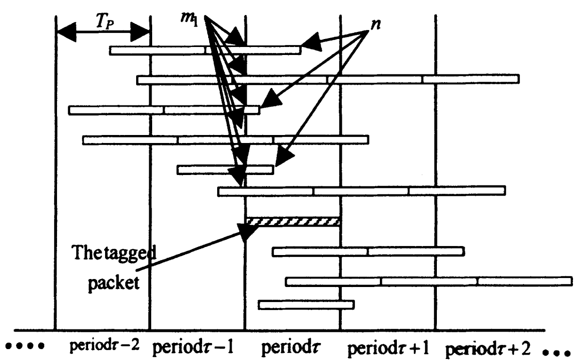

Fig 3. The tagged packet analysis.

As shown in Fig. 3, the tagged packet method is used to analyze the system. The time axis is divided into periods each of length T_P, the tagged packet occupies the period number τ, and previous/next periods are τ-1, τ-2....../ τ+1, τ+2...... . Let τ_j denote the j^{th} bit in the period τ. In the tagged packet, m_j is the interference level at j^{th} bit. The interference level during the tagged packet is changed continuously; for simplicity it will be considered constant during each bit and changes occur at the bit boundaries. In order to study the interference level during the tagged packet we should consider both the generation and termination (death) rate. The generation rate is assumed to be a Poisson process. In this model the level of initial interference m_1 is of great importance, where the death rate depends on how many interferers among m_1 will depart during the tagged packet.

It is now required to calculate $P_I(m_1)$, the probability of initial interference level to be m_1. Define:

a_y: number of interferers existing at τ_1 that have been generated in the period τ-y; $1 \leq y \leq B_{max}$

$A = \{a_1, a_2, ..., a_y, ...\}$: set of all interferers generated in the previous B_{max} periods and exists at τ_1.

To evaluate the probability of a_y, the probability of generating a_y packets in the period τ - y of length greater than or equal to y, consider that k packets are generated in this period and only a_y among k, have the suitable length as expressed by the following equation:

$$\Pr(a_y) = \sum_{k=a_y}^{\infty} \binom{k}{a_y} \cdot (P_x(B \geq y))^{a_y} \cdot (1 - P_x(B \geq y))^{k-a_y} \cdot P_O(k, T_P) \quad (7),$$

where. $$Px(B \geq y) = \sum_{x=y}^{B_{max}} P_x(x) \quad (8),$$

Then the probability to have a set of interferences A : $\{a_1, a_2, ...a_y...\}$ can be obtained by multiplying the probabilities of a_y's as given by:

$$\Pr(A) = \prod_{y=1}^{B\max} \Pr(a_y) \quad (9).$$

Now, it is easy to calculate the probability of having m initial interferences; it is the sum of the probabilities of all A's whose summation is m as expressed by (13)

$$P_I(m) = \sum_u \Pr(A) \quad (10)$$

where $$u = \{A : \forall ay \in A; \sum_{y=1}^{B_{max}} ay = m\} \quad (11),$$

In this model it is assumed that the packet termination is a Poisson process with average rate of $\mu(m)$ packets/sec. In order to evaluate the average death rate $\mu(m)$, suppose that the number of initial interferers in the tagged packet is equal to m, and that n messages among m will depart during the tagged packet. A message will depart during the tagged packet if it was initiated in the period $\tau - y$ and its length is equal to y. Define the probability $P_{d1}(m)$ as follows: the probability of one message to be of length y and generated in the period $\tau - y$.

$$P_{d1}(m_1) = \sum_{y=1}^{B_{max}} \sum_{a_y=1}^{m_1} \Pr(a_y) \cdot a_y \cdot P_x(y) \cdot (1 - P_x(y))^{a_y - 1} \quad (12)$$

Therefore, for a given value of initial interference m_1, the probability of n messages to be terminated in the tagged period follows the binomial distribution as shown:

$$\Pr(n \mid m_1) = \binom{m_1}{n} \cdot (P_{d1}(m_1))^n \cdot (1 - P_{d1}(m_1))^{m-n}. \quad (13)$$

The average value of n, for a given value of m, is given by:

$$n_{av}(m_1) = \sum_{n=1}^{m_1} n \cdot \Pr(n \mid m_1), \quad (14)$$

Finally we can express the average death rate, for a given value of initial interference m_1, as follows:

$$\mu(m_1) = \frac{n_{av}(m_1)}{T_P}. \quad (15)$$

IV. SYSTEM PERFORMANCE

In this section it is required to evaluate recursively the number of errors in the packet. The packet will be successfully transmitted if the number of errors is less than or equal to t, the number of correctable bits by ECC. Define an error counter, $f_j(e, m_j, m_1)$, as follows:

- In the tagged packet the first $j-1$ bits are transmitted with e errors.
- The number of interferers at the j^{th} bit is equal to m_j
- The number of initial interferers is equal to m_1.

This function is being used to calculate recursively the number of errors, error count, in the tagged packet.

At $j = 1$, the first bit of the tagged packet, $m_j = m_1$ and the error count should equal to zero. This fact is used as an initial condition for the recursive calculations as follows:

$$f_1(e = 0, m_1, m_1) = P_I(m_1) \quad (16)$$

$$f_1(e > 0, m_1, m_1) = 0 \quad (17)$$

Now it is required to evaluate the error count at the j^{th} bit of the tagged packet, using the f_j function. The function at the j^{th} bit depends on its value at the previous bit, $j-1^{th}$ bit. At the j^{th} bit, the error count is equal to e; this can occur in two cases:

1. The error count from the first bit till the $j-1^{th}$ bit is equal to $e-1$ and an error occurred in the $j-1^{th}$ bit.
2. The error count from the first bit till the $j-1^{th}$ bit is equal to e and the $j-1^{th}$ bit is free of errors.

Considering the Markovian property of the interference level transition, the f_j function can be expressed as follows:

$$f_j(e,m_j,m_1)=\sum_{m_{j-1}=m_j-1}^{m_j+1} f_{j-1}(e-1,m_j,m_1)\cdot q(m_j\,|\,m_{j-1}) \cdot P_b(m_{j-1})+\sum_{m_{j-1}=m_j-1}^{m_j+1} f_{j-1}(e,m_j,m_1)\cdot q(m_j\,|\,m_{j-1})\cdot(1-P_b(m_{j-1})) \quad (18)$$

Finally, the packet success probability is the probability that the number of errors does not exceed t, the maximum correctable errors by RS coding, at the last bit of the tagged packet using the f_j function till $j=L$ and averaging over all possible values of m_L and m_1. The packet success probability $Q_s(t)$ is expressed as follows:

$$Qs(t)=\sum_{m_L=0}^{\infty}\sum_{m_1=0}^{\infty} f_L(t,m_L,m_1)\cdot(1-P_b(m_L)) + \sum_{e=0}^{t-1} f_L(e,m_L,m_1) \quad (19)$$

The packet success probability (Qs) is given by (19) and the system throughput is as:

$$S=G\cdot Qs(t)\cdot\frac{s}{r}=G\cdot Qs(t)\cdot\left(1-\frac{2\cdot t}{L}\right) \quad (20)$$

The last factor in (20) considers the effect of bandwidth expansion by the RS coding; where s is the number of data bits/code word of length r and the number of correctable bits is given by $t=(r-s)/2$. In this system the packet is considered as one code word i.e $r=L$.

Finally, it is required to evaluate the average delay D which can be expressed as the ratio between the system's offered traffic to the throughput. This can be expressed as follows:

$$D_t=\frac{G}{S_t} \quad (21)$$

V. Numerical Examples

In this section we will present some numerical results. The results measure the performance of the network in terms of system throughput and average delay. The parameters used in analysis are: bit rate of 256 Kbps, average message length of 2 packets per message, and maximum message length of 3 packets per message. The used OOC is of length 127 and of weight 3.

Figures 4 and 5 show the system throughput and delay versus the offered traffic for different values of L (without ECC). We can see from Fig.4 that as the packet length increases the throughput is reduced. But another factor should be considered when choosing the packet length that is reducing the packet length requires more packets to send the message. Thus the packet length should be optimized in order to obtain maximum system performance.

Figures 6 illustrates the enhancement in the average system performance in both throughput and delay due to the use of ECC with different values of t. The use of ECC is expected to enhance the system performance. In fact two factors should be considered when we study the effects of using ECC. The first is the enhancement obtained in the packet success probability; this enhancement is proportional to the number of correctable bits. The second is the bandwidth expansion due to the addition of parity bits. Thus, the effective packet length (number of data bits per packet) is reduced, i.e. more packets are required to send the same message. As shown in Figs. 6 and 7 we can see that the optimum value of t is 3. This means that increasing t from 0 to 3 the performance is enhanced; moreover when t exceeds the optimum value the performance is reduced. This can be shown clearly in Fig. 7 where we plotted the system throughput versus t at $G=0.5$. From this figure we can find that the throughput is enhanced and reach its maximum value at $t=3$; then the curve will decay and the throughput is reduced.

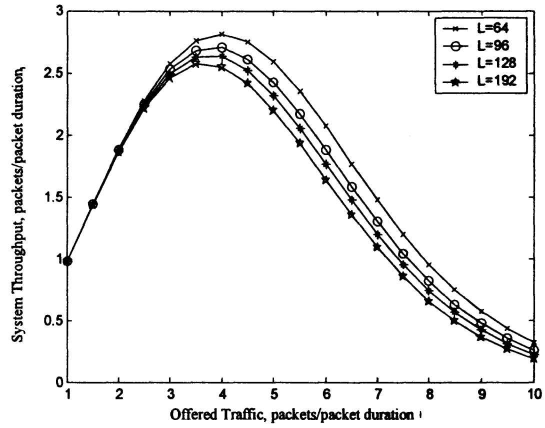

Fig. 4. System Throughput versus Offered Traffic for different values of packet length without ECC

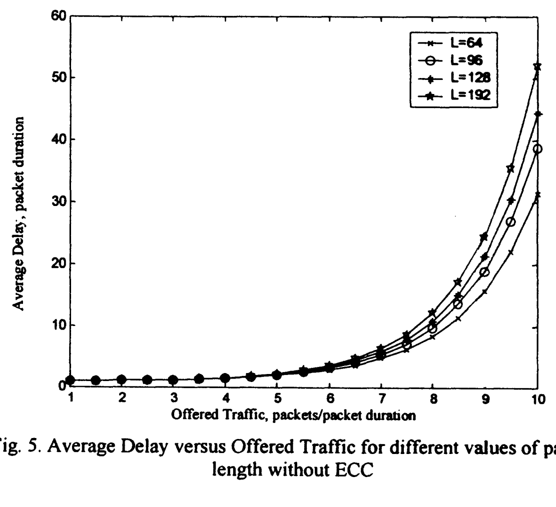

Fig. 5. Average Delay versus Offered Traffic for different values of packet length without ECC

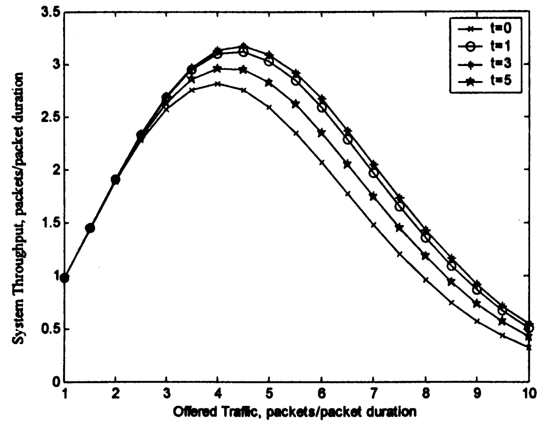

Fig. 6. System Throughput versus Offered Traffic for different values of t

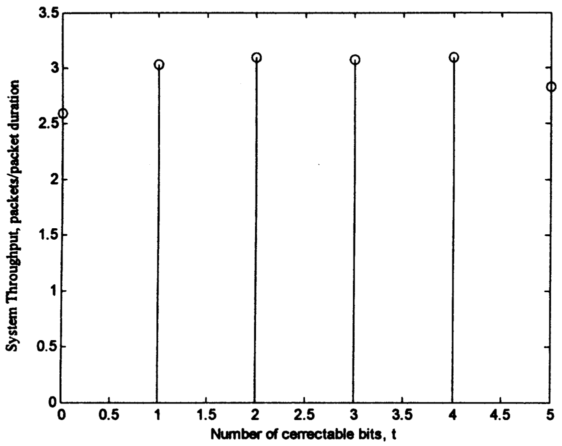

Fig. 7. System Throughput versus number of correctable bits t

VI. CONCLUSION

An accurate analysis of MAC protocol used in optical CDMA networks is presented. Sliding window protocol with variable size is considered. The system throughput and average delay are evaluated and an accurate description of the system state and channel usage are provided. Furthermore, the achieved enhancement by error control codes (ECCs) is examined.

Results show the average system throughput versus the offered traffic, as well as the effect of using ECC. Results indicate that the system performance is enhanced with the increment of number of correctable bits t reaching a maximum value. Moreover, as t increases the throughput decreases.

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