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Optical S-ALOHA/CDMA System for Multirate Applications: System Architecture and Performance Evaluation

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***Abstract*–In this paper we propose a new multirate optical network based on a hybrid S-ALOHA/Overlapped-CDMA system as an effective way of integrating multi-class traffic. The key issue in this proposal is to exploit the potential of the optical overlapped CDMA using fiber Bragg grating when jointly used with the S-ALOHA protocol in a link layer. The newly proposed system is modeled using general Markov chain from which both the system throughput and the average packet delay are derived. Our system is then compared to the classical S-ALOHA/variable processing gain (VPG) CDMA system. Numerical results show that our system outperforms the latter especially at high transmission rates.**

Keywords–Slotted ALOHA, overlapped CDMA, VPG CDMA, fiber Bragg grating, optical link layer, variable bit rate, multirate.

I. INTRODUCTION

Owing to the rapid progress in fiber-optic technology, optical CDMA utilizing fiber-Bragg grating (FBG) is gaining more interest in the creation of all-optical communication systems for integrating heterogeneous traffic sharing a single broadband optical channel with multiplicity of quality of services (QoS) and traffic requirements [4][10][11]. In addition, the bursty characteristics of high speed data traffic in optical LANs should yield benefits for CDMA technologies that are capable of allocating a high number of simultaneous resources in a decentralized way while increasing the system throughput and decreasing the average packet delay. Slotted-ALOHA (S-ALOHA) techniques could fulfill these requirements when integrated with the newly proposed optical overlapped fast frequency hopping CDMA (O-FFH-CDMA) system [5].

Most of the previous work in the field of optical CDMA has focused on the physical layer [1]-[3][5][11]. This fact also applies to the works that have been conducted in the area of multirate optical CDMA [1]-[4]. Lately, we have considered the overlapped CDMA (O-CDMA) system [5].

Many researches have been conducted on S-ALOHA and random access CDMA [6][9][12]. Nevertheless, jointly used with O-CDMA, random access packet-switching becomes a challenging issue [7][8][10] to cope with the increasing packet-type demand with large population, shorter message-delay delivery and minimum packet-rejection probability.

In this work, we propose a new hybrid system that combines a variable-transmission-rate optical O-FFH-CDMA system [5] with the S-ALOHA protocol (S-ALOHA/O-FFH-CDMA) as a novel and simple scheme of achieving multi-user and multirate capability in a decentralized optical CDMA packet networks. In particular, variable transmission rate is achieved by increasing the bit rate beyond the nominal limits while keeping the processing gain (PG) and the time slot duration unchanged. This yields overlapping among bits in a single time slot. Thus varying the amount of overlapping bits can vary the transmission rate.

Following the introduction, the paper is structured as follows. Section II introduces the system model, which employs the discrete time Markov chain describing the system states. The signal-to-interference ratio (SIR) is derived in Section III. Section IV presents the performance evaluation of the system. Numerical results are covered in Section V. Finally, concluding remarks end the paper in Section VI.

II. SYSTEM MODEL

We consider an optical FFH-CDMA communication network that supports K terminals, which share the same optical medium in a star architecture [11]. The encoding and decoding are achieved passively using a sequence of fiber Bragg gratings. The gratings will spectrally and temporally slice an incoming broadband pulse into several components equally spaced at chip intervals T_c [11]. The chip duration, and the number of gratings will establish the nominal bit rate of the system, *i.e.* the round trip time of light, from a given transmitted bit, to be totally reflected from the encoder. This nominal bit duration in a structure of G gratings is given by T_n, where G is the PG. The corresponding nominal rate is $R_n = 1/T_n = 1/GT_c$.

Using the above mentioned passive network, we propose a hybrid S-ALOHA/FFH-CDMA optical packet network in which each user is assigned a unique code, which is characterized by zero auto-correlation property using frequency shifted version (FSV) proposed in [11], and a cross-correlation between any two different codewords of at most one. Subsequently, up to K users can transmit simultaneously K

packets in a given time slot. Each of the K terminals can be in one of the three operational modes at a time, origination mode, transmission mode, or backlog mode. The user in the origination mode generates and transmits a new packet at the beginning of the next time slot with a probability P_o. The user enters the backlog mode when an attempt to transmit a new packet fails. The retransmissions of backlogged packet occur in any given time slot with a probability P_r. In a backlogged mode, the blocked terminal can not generate new packets until the backlogged packet is received correctly. In general arrival model, $P_r > P_o$. When $P_r = P_o = p$, the arrivals are binomially distributed. Fig. 1 represents the model of the proposed optical S-ALOHA/FFH-CDMA system. The streams of composite arrivals of this system consist of ξ_o newly generated packets plus ξ_r retransmitted packets. The statistical behavior of the terminals can be described using a general discrete Markov chain [6]. The system state represents the number of backlogged terminals n.

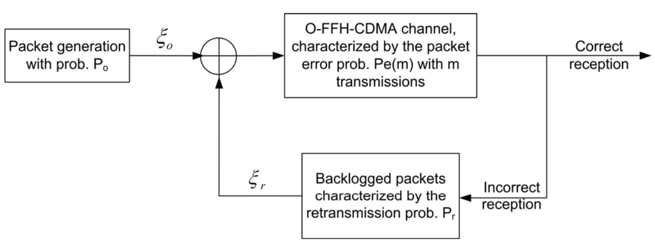

Fig. 1: Optical S-ALOHA/FFH-CDMA system model

Before continuing the analysis, let us impose some restrictions which help simplifying the mathematical evaluations and improving the clarity of the problem under consideration. We assume 1) a synchronous system and discrete rate variation, 2) a single class system, and 3) unit transmission power for all the users.

In this paper the transmission rate of the terminals R_s is allowed to be greater than R_n according to two different methods as explained below.

A. S-ALOHA/VPG-FFH-CDMA System:

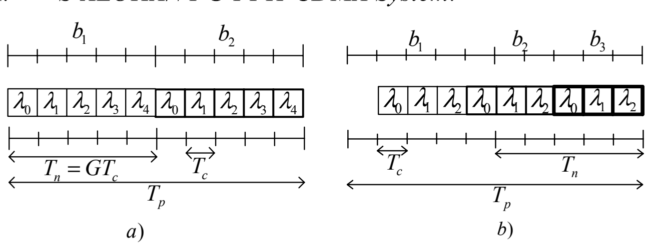

Fig. 2: Optical S-ALOHA/VPG-FFH-CDMA packet model of a single user in a given packet time slot

Assume a fixed packet time duration of $T_p = LT_n = LGT_c$ where L is the nominal packet length. In this system, the variable transmission rate is accomplished by varying the processing gain G_V in such a way that increasing the transmission rate by a factor of $\alpha \geq 1$ allows the reduction of spreading factor by the same amount $G_V = G/\alpha$ [4]. The bit rate in this case is given by

$$R_s = \alpha R_n \ (bits/\sec) \tag{1}$$

In a packet network, $X_b^{(V)} = \lfloor \alpha L \rfloor$ bits are allocated in a time slot instead of L as shown in Fig. 2, where $\lfloor x \rfloor$ is the highest integer less than x. Then, the new transmission rate becomes

$$R_s = \frac{X_b^{(V)}}{L} R_n \ (bits/\sec) \tag{2}$$

In Fig. 2 a), we present a case study where $G = 5$ and $L = 2$ which means the nominal rate is two bits per packet. On the other hand, in Fig. 2 b), we have decreased the PG to $G_V = 3$ (which means $\alpha = 5/3$) in order to increase the transmission rate to three bits per packet.

B. S-ALOHA/O-FFH-CDMA System:

In [5], we have shown that due to the linearity of the encoder-decoder set, multi-bits will be coded and transmitted when the data rate increases beyond R_n as shown in Fig. 3. At the receiver end, the decoder observes practically multicode, which are delayed according to the transmission rate of the source.

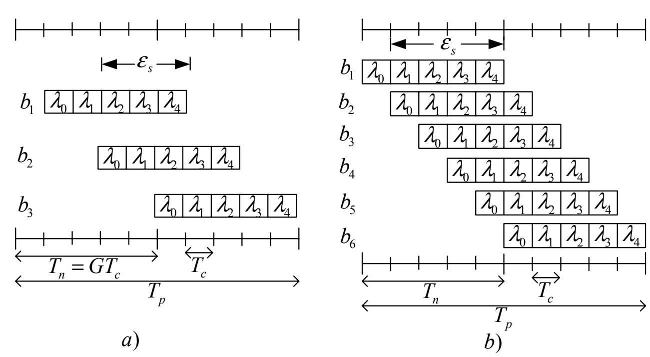

Fig. 3: Optical S-ALOHA/O-FFH-CDMA packet model of a single user in a given time slot

Accordingly, in the S-ALOHA/O-FFH-CDMA, to increase the number of bits per packet of fixed length L, we increase the source transmission rate above the nominal rate without decreasing the PG as in the previous system. When a terminal transmits using a rate $R_s > R_n$, it introduces a bit overlap coefficient ε_s, which represents the number of overlapping chips between two consecutive bits [5]. Accordingly the new bit rate is related to R_n throughout the following equation

$$R_s = \frac{G}{G - \varepsilon_s} R_n \tag{3}$$

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Let ε_s be the overlapping coefficient, and $X_b^{(O)}$ to be the total number of overlapped bits in a packet time slot. For an overlapped packet to be complete for transmission, the following inequality must be satisfied:

$$\varepsilon_s + \underbrace{(G-\varepsilon_s)+\ldots+(G-\varepsilon_s)}_{X_b^{(O)} times} \le LG \tag{4}$$

$$X_b^{(O)} \le \frac{LG-\varepsilon_s}{G-\varepsilon_s} \tag{5}$$

Thus,

$$X_b^{(O)} = \left\lfloor \frac{LG-\varepsilon_s}{G-\varepsilon_s} \right\rfloor \tag{6}$$

Consequently the rate in a packet network will be

$$R_s = \frac{X_b^{(O)}}{L} R_n \ (bits/\sec) \tag{7}$$

Fig. 3 illustrates an example of the overlapping process in a packet time slot. In this example, the packet length is $L=2$, and the PG is $G=5$. If the transmission rate is the nominal rate, the packet format is as shown in Fig. 2 a), which means $\varepsilon_s = 0$ and the transmission rate is two bits per packet. When the overlapped coefficient is increased to $\varepsilon_s = 3$ as shown in Fig. 3 a), the transmission rate is increased to three bits per packet. On the other hand, Fig. 3 b) shows the case where $\varepsilon_s = 4$. Accordingly, the transmission rate is six bits per packet.

The relation between the reduction factor α of the S-ALOHA/VPG-FFH-CDMA system and the overlapping coefficient ε_s of the S-ALOHA/O-FFH-CDMA system can be easily obtained by equating (2) and (7) to obtain

$$\alpha = \frac{G-\frac{\varepsilon_s}{L}}{G-\varepsilon_s} \tag{8}$$

III. SIGNAL-TO-INTERFERENCE RATIO

In this section, we derive the SIR for both systems. In general, we can write the SIR as follows

$$\mathrm{SIR} = \frac{G^2}{\sum_{k=1}^{K-1}\sigma_{I_k}^2 + \sigma_n^2} \tag{9}$$

where $\sigma_{I_k}^2$ is the interference power from the k^{th} terminal and σ_n^2 is the additive white Gaussian noise (AWGN) power. The SIR for both systems differ in $\sigma_{I_k}^2$.

A. S-ALOHA/VPG-FFH-CDMA System:

Assume a class-s users with a transmission rate R_s and an equivalent PG G_V. Also assuming equally probable data, we can write the interference power as follows

$$\sigma_{I_k}^2 = \sum_{q=0}^{G_V-1}\left[H_k^2(0,q)+H_k^2(q,G_V)\right] \tag{10}$$

where

$$H_k(a,b) = \sum_{j=a}^{b} h\left(a_{j-a}^k, a_j^0\right) \tag{11}$$

is the discrete-time partial-period Hamming cross-correlation function of the k^{th} interferer [4]. In addition, $h(.)$ [1] is the hamming function [4]. The sequences a_{j-q}^k and a_j^0 are numbers representing frequencies of the k^{th} interferer and the desired user, respectively. Notice that the interference power is equal for every bit in the packet time slot. Thus, we can write

$$\mathrm{SIR}^{(i)} = \frac{G^2/\alpha^2}{\sum_{k=1}^{K-1}\sigma_{I_k}^2 + \sigma_n^2} \quad \forall\, 1 \le i \le X_b^{(V)} \tag{12}$$

B. S-ALOHA/O-OFFH-CDMA System:

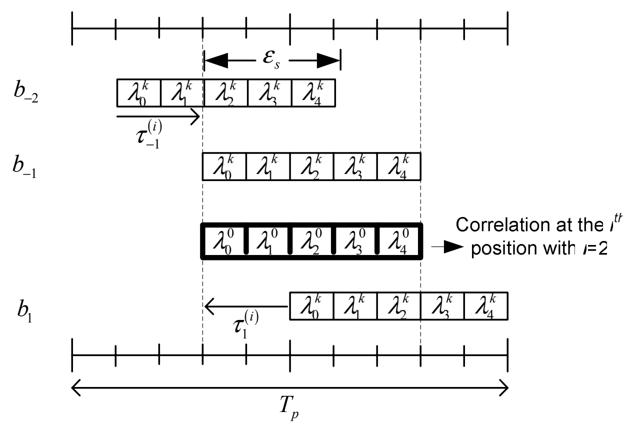

Fig. 4 Interference from user K on the desired user due to overlapping

In the S-ALOHA/O-OFFH-CDMA system, the problem is much more complex due to the fact that not every bit in the packet time slot will have the same SIR. Therefore, the SIR at the i^{th} time slot position is given by

$$\mathrm{SIR}^{(i)} = \frac{G^2}{\sum_{k=1}^{K-1}\sigma_{I_k}^2(i) + \sigma_n^2} \quad \forall\, 1 \le i \le X_b^{(O)} \tag{13}$$

where $X_b^{(O)}$ is given by (6) and $\sigma_{I_k}^2(i)$ can be computed as follows. Let $X_r = \left\lceil \varepsilon_s/(G-\varepsilon_s)\right\rceil$ where $\lceil x \rceil$ is the smallest

1 $h(a,b) = \begin{cases} 0, & a \ne b \\ 1, & a = b \end{cases}$

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integer greater than x, we can notice that the problem can be divided into two parts:

1) $X_b^{(O)} - 2X_r \leq 0$:

$$\sigma_{I_k}^2(i) = \begin{cases} \sum_{\nu=-i}^{-1} H_\nu^2\left(0, q_\nu^{(i)}\right) + \sum_{\nu=0}^{X_r} H_\nu^2\left(q_\nu^{(i)}, G\right), & 0 \leq i \leq X_b^{(O)} - X_r - 1 \\ \sum_{\nu=-i}^{-1} H_\nu^2\left(0, q_\nu^{(i)}\right) + \sum_{\nu=0}^{X_b^{(O)}-i-1} H_\nu^2\left(q_\nu^{(i)}, G\right), & X_b^{(O)} - X_r \leq i \leq X_r - 1 \\ \sum_{\nu=-X_r}^{-1} H_\nu^2\left(0, q_\nu^{(i)}\right) + \sum_{\nu=0}^{X_b^{(O)}-i-1} H_\nu^2\left(q_\nu^{(i)}, G\right), & X_r \leq i \leq X_b^{(O)} - 1 \end{cases} \tag{14}$$

where $q_\nu^{(i)} = \tau_\nu^{(i)} / T_c$ and $\tau_\nu^{(i)}$ is the time delay with respect to the i^{th} bit in the packet. $\left(j - q_\nu^{(i)}\right)$ is evaluated modulo G

2) $X_b^{(O)} - 2X_r > 0$:

$$\sigma_{I_k}^2(i) = \begin{cases} \sum_{\nu=-i}^{-1} H_\nu^2\left(0, q_\nu^{(i)}\right) + \sum_{\nu=0}^{X_r} H_\nu^2\left(q_\nu^{(i)}, G\right), & 0 \leq i \leq X_r - 1 \\ \sum_{\nu=-X_r}^{-1} H_\nu^2\left(0, q_\nu^{(i)}\right) + \sum_{\nu=0}^{X_r} H_\nu^2\left(q_\nu^{(i)}, G\right), & X_r \leq i \leq X_b^{(O)} - X_r - 1 \\ \sum_{\nu=-X_r}^{-1} H_\nu^2\left(0, q_\nu^{(i)}\right) + \sum_{\nu=0}^{X_b-i-1} H_\nu^2\left(q_\nu^{(i)}, G\right), & X_b^{(O)} - X_r \leq i \leq X_b^{(O)} - 1 \end{cases} \tag{15}$$

IV. Performance Evaluation

A. *Packet Error Probalbility:*

If a Gaussian hypothesis is used to model the interference, the probability of bit error in a time slot when there are K simultaneous active terminals using a simple On-Off Keying (OOK) modulation is related to the system's signal-to-interference ratio (SIR) using the following equation

$$P_b(i) = Q\left(\frac{1}{2}\sqrt{SIR^{(i)}}\right) \tag{16}$$

1) *S-ALOHA/VPG-FFH-CDMA System*

Due to the fact that the bit error probability is equal for every bit in the packet, the probability of successfully receiving a packet is

$$P_c(K) = \left[1 - P_b(i)\right]^{X_b^{(V)}} \tag{17}$$

2) *S-ALOHA/O-FFH-CDMA System*

On the other hand, for the TS/O-FFH-CDMA system, bit error probability is not equal for every bit in the packet. It depends on the bit position "*i*" as reveals in (14) and (15). Thus we can write,

$$P_c(K) = \prod_{i=0}^{X_b^{(O)}-1} \left[1 - P_b(i)\right] \tag{18}$$

B. *System Throughput and Average Packet Delay:*

Let $P = \left[P_{nm}\right]$ be the transition matrix, where P_{ij} is the one step transition probability from state i to state j. Consider that P_{nm} is the probability that m backlogged users will be present in the next state given that n are present in the current state. It is given by

$$P_{nm} = \Pr\left\{x(t+1) = m \mid x(t) = n\right\} \tag{19}$$

For random access CDMA, transition can take place in a number of ways since there can be more than one successful transmission per time slot. The transition from state *n* to state *m* is determined by the difference between the number of unsuccessful new transmission $UNTX$ and successful retransmission $SRTX$, i.e. when $SRTX$ exceeds $UNTX$ by $(n-m)$ for $n \geq m$ or $UNTX$ exceeds $SRTX$ by $(m-n)$ for $m \geq n$. Let $NTX = \xi_o$ be the number of new transmissions and $RTX = \xi_r$ be the number of retransmissions. Let $b(\psi, \beta, p)$, denotes the binomial distribution. It characterizes the total number of all possible ψ successes in any order given β attempts; with p is the probability of success. Then the joint probability distribution of $SRTX$ and $UNTX$ given n users in the backlogged mode can be written as

$$\begin{aligned} &\Pr\left\{SRTX = k, UNTX = l \mid x(t) = n\right\} \\ &= \sum_{\substack{\xi_o = l \\ 0 \leq l \leq K-n \\ 0 \leq k \leq n}}^{K-n} \sum_{\xi_r = k}^{n} \left[\begin{array}{l} b\left[l, \xi_o, P_E\left(\xi_o + \xi_r\right)\right] \cdot b\left[\xi_o, K-n, P_o\right] \\ \cdot\, b\left[k, \xi_r, P_C\left(\xi_o + \xi_r\right)\right] \cdot b\left[\xi_r, n, P_r\right] \end{array}\right] \end{aligned} \tag{20}$$

Where $b(\psi, \beta, p)$ is given by

$$b(\psi, \beta, p) = \binom{\psi}{\beta} p^\beta (1-p)^{\psi-\beta} \tag{21}$$

and $P_C(\cdot)$ is the correct packet probability and given by (18) and (29). In addition, $P_E(\cdot) = 1 - P_C(\cdot)$, which represents the packet error probability.

Hence the steady-state transition probability is calculated as follows

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$$P_{nm} = \begin{cases} \sum_{j=0}^{\min(n,K-m)} \Pr\begin{Bmatrix} SRTX = j, \\ UNTX = m-n+j \mid x(t)=n \end{Bmatrix}, & m \ge n \\ \sum_{j=0}^{\min(m,K-n)} \Pr\begin{Bmatrix} SRTX = n-m+j, \\ UNTX = j \mid x(t)=n \end{Bmatrix}, & m \le n \end{cases} \quad (22)$$

The long-term state occupancy probability $\mu(n)$ is given by the solution of:

$$\mu^T = \mu^T P,\ \ \mu^T = [\mu(0),\ldots,\mu(n)],\ \ \sum_{n=0}^{K}\mu(n) = 1 \quad (23)$$

The method to solve (23) is to find the eigenvalues of P^T and their corresponding eigenvectors. By sorting the $(K+1)$ eigenvalues in the ascending order, the desired eigenvector is the one which index is the index of the highest eigenvalue. Then, the long-term state probability vector will correspond to the desired eigenvector divided by the sum of their entries.

Thus, the probability of success can be seen as a binomial distribution by which S packets are received successfully given M attempted transmissions in a given time slot. This leads to the following:

$$\Pr(S = s \mid M = m) = b[s, m, P_c(m)] \quad (24)$$

The steady state composite arrival distribution given that there are n backlogged users in the system and m backlogged users in the next time slot is given by

$$f_M(m \mid x = n) = \sum_{j=\max(m-n,0)}^{\min(m,K-n)} b(j, K-n, P_o) \times b(m-j, n, P_r) \quad (25)$$

The throughput in packet per time slot, β, is defined as the expected number of successful transmission per time slot

$$\beta = E\{S\} = \sum_{m=1}^{K} m P_C(m) \left[\sum_{n=0}^{K} f_M(m \mid n)\mu(n)\right] \quad (26)$$

The offered traffic can be estimated by

$$R = (K - \overline{n}) P_o + \overline{n} P_r \quad (27)$$

Where, $\overline{n}$ is the expected backlog or the average system state, and given by

$$\overline{n} = \sum_{n=0}^{K} n\mu(n) \quad (28)$$

The steady state delay according to Little's theorem can be written as

$$D = \overline{n} / \beta \quad (29)$$

V. NUMERICAL RESULTS

Throughout this part, we present simulation results using our derived system model and using Extended Hyperbolic Congruential (EHC) family of codes [12] in a multirate environment. In addition, a comparison between our newly proposed S-ALOHA/O-FFH-CDMA system and the classical S-ALOHA/VPG-FFH-CDMA system is also studied. In this simulation we have taken the number of active terminals $K = 6$, the packet length $L = 300$ bits per time slot, and the PG $G = 29$. In addition, the transmission rate, R_s, is normalized in the sense that it represents the number of bits per time slot T_p.

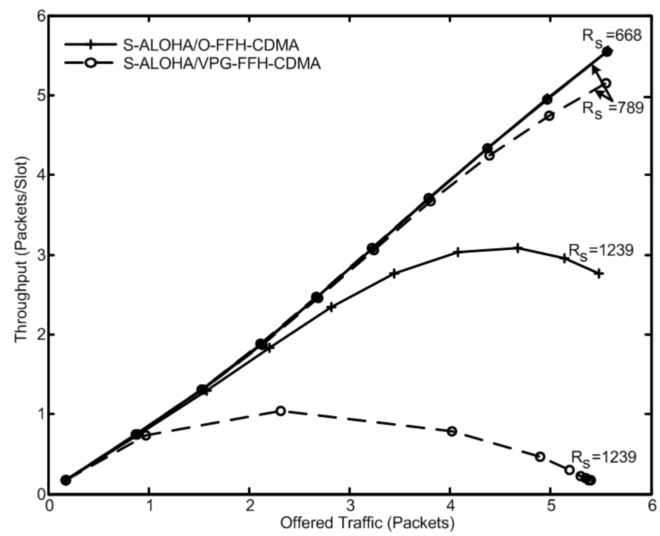

Fig. 5: Throughput vs offered traffic for $P_r = 0.9$

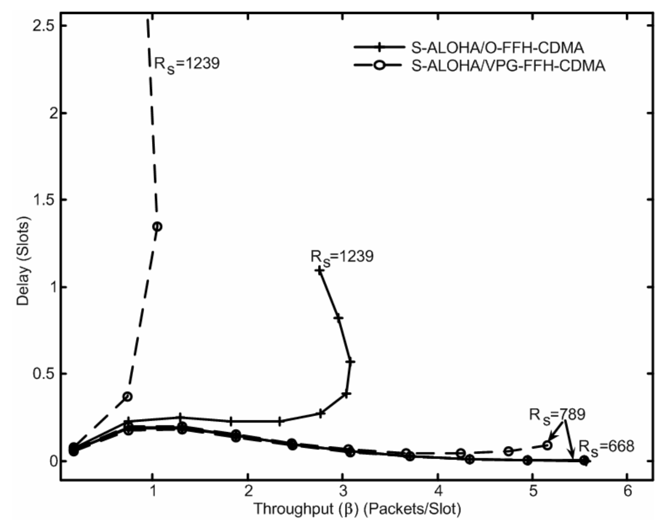

Fig. 6: Average delay vs throughput for $P_r = 0.9$

First, assume that the probability of retransmission is taken to be $P_r = 0.9$. In Fig. 5 we plot the throughput versus the offered traffic for different values of R_s. On the other hand, Fig. 6 shows the average delay versus the throughput. It is clear that for both performance measures, the S-ALOHA/O-FFH-CDMA system always outperform the S-ALOHA/VPG-FFH-CDMA system and for different R_s. Notice that as the transmission rate increases, the S-ALOHA/O-FFH-CDMA becomes much better than the S-ALOHA/VPG-FFH-CDMA in the sense that its throughput becomes much higher and its delay becomes much smaller. This result is expected because when the transmission rate becomes very high, the PG becomes very small for the S-ALOHA/VPG-FFH-CDMA system. This in turn drastically decreases the packet correct probability. On the other hand, for the S-ALOHA/O-FFH-CDMA system the PG is fixed and the overlapping coefficient is increased. Although the MAI is higher, the signal power remains the same, which makes the SIR high enough to achieve an acceptable packet correct probability.

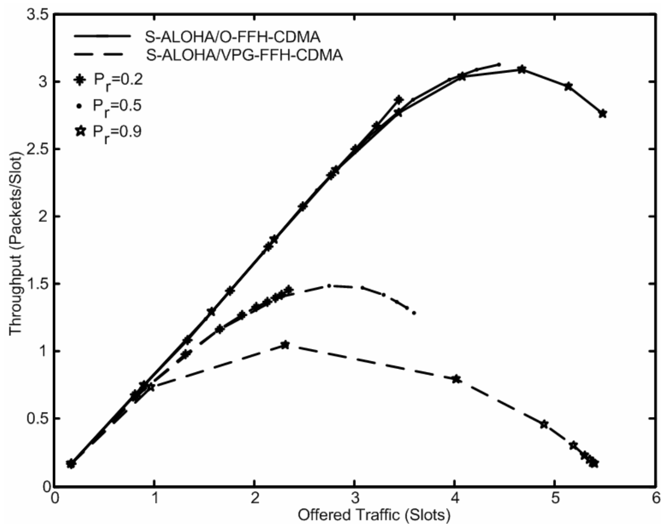

Fig. 7: Throughput vs offered traffic for R_s = 1239 bits/slot

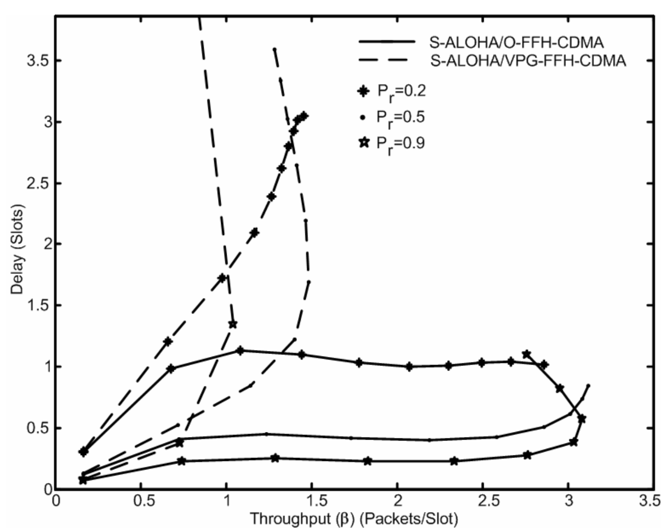

Fig. 8: Average delay vs throughput for R_s = 1239 bits/slot

The effect of the retransmission probability is studied in Fig. 7 and Fig. 8 by varying P_r and fixing R_s to 1239 bit/slot. In Fig. 7 we plot the throughput versus the offered traffic and Fig. 8 shows the average delay versus the throughput. We can notice clearly that the S-ALOHA/O-FFH-CDMA system still outperforms the S-ALOHA/VPG-FFH-CDMA system. In addition, it is clear that as P_r decreases, the throughput decreases and the delay increases which what we should expect.

VI. CONCLUSION

In this paper, a variable bit rate system based on hybrid S-ALOHA/O-FFH-CDMA system was proposed for optical CDMA time slotted packet networks. Two different systems were introduced and compared; the novel S-ALOHA/O-FFH-CDMA system and the classical S-ALOHA/VPG-FFH-CDMA system. The SIR for the new system was obtained. In addition, the time slotted system model has been derived using the general Markov chain from which the steady-state throughput and average packet delay have been evaluated. Simulation results showed that the newly proposed S-ALOHA/O-FFH-CDMA system outperforms the S-ALOHA/VPG-FFH-CDMA system, especially at higher transmission rate.

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