The R^3T Optical Random Access CDMA Protocol with Queuing Subsystem

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ABSTRACT

We introduce a queuing subsystem to an optical random access CDMA protocol, namely, the *round robin receiver/transmitter* (R^3T) protocol. A detailed state diagram is outlined and a mathematical model based on the equilibrium point analysis (EPA) is presented. In addition, the steady state system throughput, the average packet delay, and the blocking probability are derived and evaluated under several network parameters. We prove by numerical analysis that significant improvement in the protocol's performance can be achieved by only adding a single buffer to the system. The blocking probability is significantly reduced by a factor of 50 %. Our results also reveal that the modified R^3T protocol can support higher traffic loads. Further, queuing delays that added to the total network latency are acceptable.

Keywords: Chip-level receivers, code division multiple access, on-off keying, optical CDMA protocols, optical networks, queuing, random access protocols.

1. INTRODUCTION

Optical code division multiple access (CDMA) networks are now receiving more attention because they combine the large bandwidth of the fiber medium with the flexibility of the CDMA technique to achieve high-speed connectivity [1]-[7]. Most of the research in optical CDMA has focused on the physical layer [1], and [2]. However, a few authors have examined the data link layer of optical CDMA networks [3]-[6]. In [3] and [4] Hsu and Li have studied slotted and unslotted optical CDMA systems. Shalaby has proposed two protocols with and without pretransmission coordination for slotted optical CDMA packet networks in [5]. The effect of multi-packet messages, connection establishment and corrupted packets haven't been taken into account. In [6] Shalaby answered these questions by introducing the round robin receiver/transmitter (R^3T) protocol, which was based on a go-back n automatic repeat request (ARQ). He assumed that each node is equipped with a single buffer to store only a single message (the message that is being served); any arrival to a nonempty buffer was discarded. This of course gives rise to a blocking probability, which was not examined in [6].

In this paper we aim at enhancing the performance of the R^3T model by introducing a queuing system, namely increasing the number of available buffers. Our second aim is to investigate the blocking probabilities for R^3T with and without (w/o) queuing buffers and compare the performance of both systems.

The rest of this paper is organized as follows; Section 2 is devoted to a general description of our network architecture, and the optical CDMA protocol. The mathematical model is then presented in Section 3 using a detailed state diagram. In Section 4 we introduce the theoretical analysis based on the equilibrium point analysis (EPA). In our analysis, focus is oriented towards multiple access interference (MAI) only, where the effect of both receiver's shot and thermal noises are neglected. Section 5 is maintained for the simulation results. Finally our conclusions are given in Section 6.

2. SYSYTEM ARCHITECTURE

Optical CDMA Network

In a typical optical CDMA broadcast and select star network there would be N transmitter and receiver pairs (nodes or users). Each node is equipped with a queuing system followed by a fixed CDMA encoder and a tunable CDMA decoder. The transmitter generates an optical ON-OFF keying CDMA (OOK-CDMA) signal (according to its signature sequence) that represents its data. Users are assigned these signature codes randomly from a set of direct-sequence optical orthogonal codes (OOCs); denoted by $\phi(L, w, \lambda_a, \lambda_c)$, where L is the code length, w is the code weight, and λ_a and λ_c are the auto-correlation and cross correlation constraints, respectively. A code may be given to more than one user. Further a code is randomly cyclic shifted around itself upon assignment in order to reduce the effect of MAI. Chip-level receivers [2] are implemented at the physical layer. Considering a message that is composed of $\ell > 0$ packets, each having $K > 0$ bits and taking only the effect of MAI into account, the packet success probability $P_S(r')$ given $r' \in \{1, 2, \ldots, N\}$ active users can be found in [6].

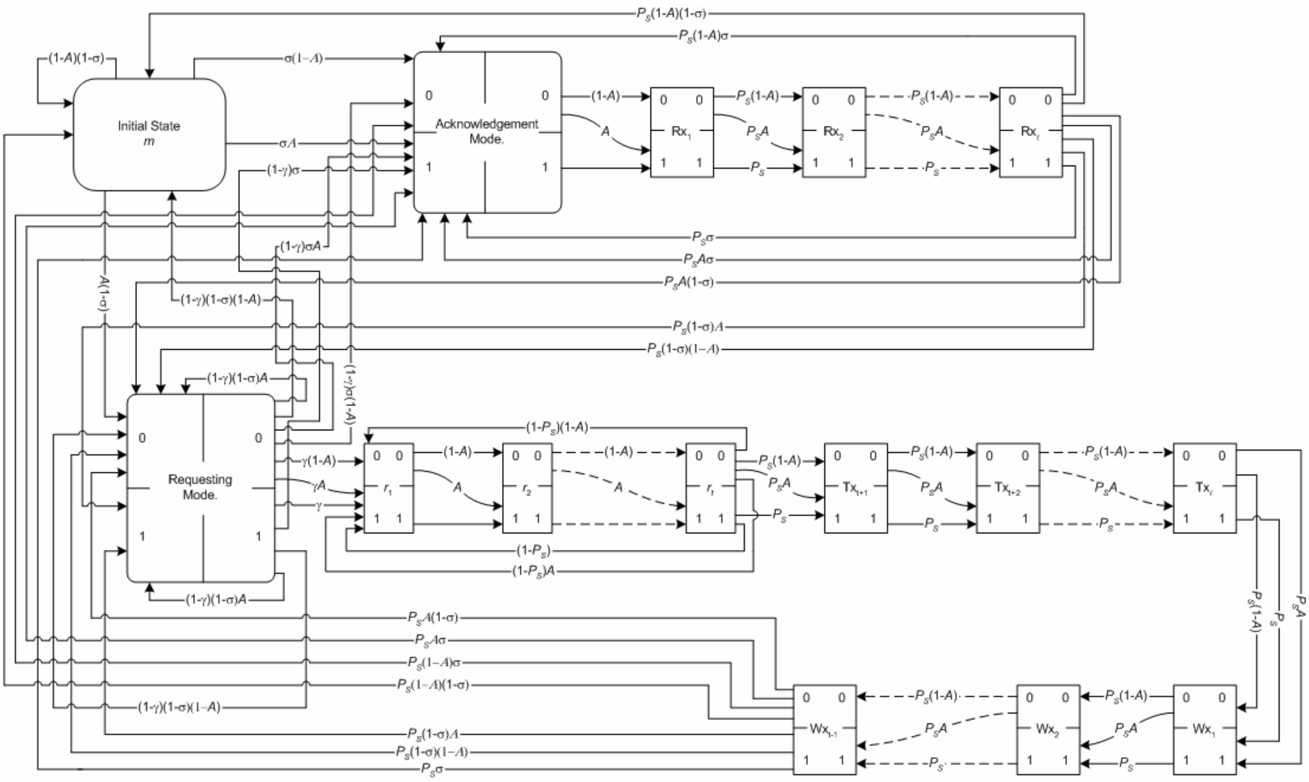

Fig. 1. Complete state diagram of the R^3T optical CDMA protocol with a single buffer in the queue.

Optical CDMA Protocol

In the R^3T protocol many assumptions were imposed [6]. The drawback of the R^3T is that any message that arrives will be dropped unless the buffer is empty. This gives rise to a high blocking probability. In this paper we introduce a queuing subsystem that is able to store one more message (message waiting to be served) if the main buffer is busy. We impose the following assumptions in our model for optical CDMA protocol:

- A maximum of 1 message can arrive at each time slot to a station with probability A (also called user activity) and is stored in the queue if the server is busy.
- Any arrival to a non empty queue is blocked.
- The queue is freed once the stored message is moved to the server for being transmitted.
- A station scans for connection requests only after a successful transmission or reception or when it is idle.
- A priority is given for the reception mode than for the transmission mode.

3. MATHEMATICAL MODEL

The detailed state diagram of the R^3T protocol with a single buffer in the queue is illustrated in Figs. 1, 2, and 3. States marked with a '0' indicate that the buffer is empty while a '1' indicates that the buffer is full. Transition between states is on a slot basis. Users move from states marked with '0' to states marked with '1' if there is a message arrival. Messages will be blocked if users have their queues full and there is a message arrival except for these cases; after successful transmission or reception and after request. In these cases users will move to the requesting mode marked with a '1'. A user in the initial state scans across codes for connection requests. If a request is found (event with probability σ), the user proceeds to send an acknowledgement and enters the reception mode. If no requests are found and there is a message arrival, the station moves to the requesting mode. Users move to the transmission mode only if a positive acknowledgement is received (event with probability γ), otherwise the user is timed-out (after τ time slots). After successful transmission, reception, and if timed-out a user will enter either the initial state or the acknowledgement mode or the requesting mode, depending on the user activity and the connection requests found at that time.

4. THEORETICAL ANALYSIS

Because of the complexity of the mathematical model described above, our analysis will be based on the equilibrium point analysis (EPA) to measure the performance of this random access protocol. By writing down the flow equations for all the states, we can derive the steady state system throughput, the average packet delay, and the blocking probability.

Transmission Mode

This mode involves states $\{r_1, r_2, \ldots, r_t, Tx_{t+1}, Tx_{t+2}, \ldots, Tx_\ell\}$. From Figs. 1 and 3b, we have the following flow

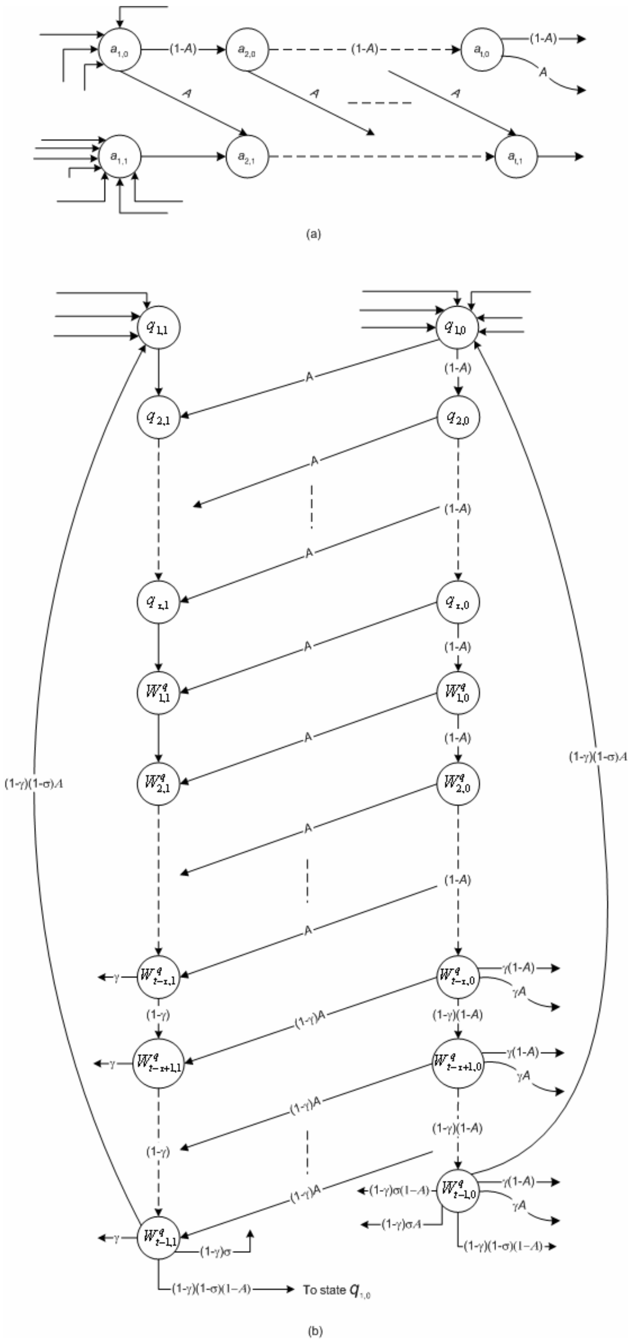

Fig.2 (a) Acknowledgement mode; (b) Requesting mode.

equations for

$n \in \{1, 2, \dots, t\}$:

$$r_{n,0} = (1-A)^{n-1}\cdot r_{1,0} \quad , \quad r_{n,1} = r_{1,1} + \left[1-(1-A)^{n-1}\right]\cdot r_{1,0}. \qquad (1)$$

From Fig. 3c, we can write the flow equations for each state in Tx_{t+i}, $i \in \{1, 2, \dots, \ell - t\}$:

$$\begin{matrix} r_{t+i,0} = \chi^i \cdot r_{t,0} \\ r_{t+i,1} = r_{t,1} + \left(1-\chi^i\right)\cdot r_{t,0} \end{matrix} \text{, where } \chi = \frac{P_S(1-A)}{1-(1-P_S)(1-A)^t}. \qquad (2)$$

Whereas for the retransmission states and for $j \in \{1,2,\dots,t-1\}$:

$$\begin{matrix} e^i_{i+j,0} = (1-P_S)\cdot\chi^i(1-A)^j \cdot r_{t,0} \\ e^i_{i+j,1} = (1-P_S)\cdot r_{t,1} + (1-P_S)\cdot\left[1-\chi^i(1-A)^j\right]\cdot r_{t,0} \end{matrix}.$$

Similarly, for the waiting states $W_{X\,i}$, $i \in \{1, 2, \dots, t-1\}$ shown in Fig. 3d:

$$W^r_{i,0} = \chi^i \cdot r_{\ell,0} \quad , \quad W^r_{i,1} = r_{\ell,1} + \left(1-\chi^i\right)\cdot r_{\ell,0}, \qquad (3)$$

$$\begin{matrix} e^{\ell-t+i}_{\ell-t+i+j,0} = (1-P_S)\chi^i(1-A)^j\cdot r_{\ell,0} \\ e^{\ell-t+i}_{\ell-t+i+j,1} = (1-P_S)\cdot r_{\ell,1} + (1-P_S)\left[1-\chi^i(1-A)^j\right]\cdot r_{\ell,0} \end{matrix},$$

$j \in \{1,2,\dots,t-i\}$

$$\begin{matrix} W^{ei}_{k,0} = \chi^i(1-P_S)(1-A)^{t-i+k}\cdot r_{\ell,0} \\ W^{ei}_{k,1} = (1-P_S)\cdot r_{\ell,1} + (1-P_S)\left[1-\chi^i(1-A)^{t-i+k}\right]\cdot r_{\ell,0} \end{matrix},$$

$k \in \{1,2,\dots,i-1\}$.

Let the set of variables $[Y_0, Y_1, Y]$ denotes the total number of users in state Y with either empty buffer, or full buffer or regardless of the state of the buffer, respectively. We define the following variables:

$$\left[r_0 = \sum_{i=1}^{\ell} r_{i,0} \quad , \quad r_1 = \sum_{i=1}^{\ell} r_{i,1} \quad , \quad r = r_0 + r_1\right]$$

$$\left[W^r_0 = \sum_{i=1}^{t-1} W^r_{i,0} \quad , \quad W^r_1 = \sum_{i=1}^{t-1} W^r_{i,1} \quad , \quad W^r = W^r_0 + W^r_1\right]$$

$$\left[e_0 = \sum_{i=1}^{\ell-t}\sum_{j=1}^{t-1} e^i_{i+j,0} + \sum_{i=1}^{t-1}\sum_{j=1}^{t-i} e^{\ell-t+i}_{\ell-t+i+j,0}, \quad e_1 = \sum_{i=1}^{\ell-t}\sum_{j=1}^{t-1} e^i_{i+j,1} + \sum_{i=1}^{t-1}\sum_{j=1}^{t-i} e^{\ell-t+i}_{\ell-t+i+j,1}, \quad e = e_0 + e_1\right]$$

$$\left[W^e_0 = \sum_{i=1}^{t-1}\sum_{j=1}^{i-1} W^{ei}_{j,0} \quad , \quad W^e_1 = \sum_{i=1}^{t-1}\sum_{j=1}^{i-1} W^{ei}_{j,1} \quad , \quad W^e = W^e_0 + W^e_1\right]$$

Performing the above summations (only for Y_0 and Y), which involve mathematical series, we obtain:

$$r_0 = \left[\frac{1-(1-A)^t}{A}\right]\cdot r_{1,0} + \left(\frac{\chi}{1-\chi}\right)\left(1-\chi^{\ell-t}\right)\cdot r_{t,0}, \qquad r = \ell\left(r_{1,0} + r_{1,1}\right),$$

$$W^r_0 = \left(\frac{\chi}{1-\chi}\right)\left(1-\chi^{\ell-t}\right)\cdot r_{\ell,0} \quad , \qquad W^r = (t-1)\left(r_{1,0}+r_{1,1}\right),$$

$$e_0 = (1-P_S)\left(\frac{1-A}{A}\right)\left(\frac{\chi}{1-\chi}\right)\left[1-(1-A)^{t-1}\right]\left(1-\chi^{\ell-t}\right)\cdot r_{t,0}$$

$$+ (1-P_S)\left(\frac{1-A}{A}\right)\left[\left(\frac{\chi}{1-\chi}\right)\left(1-\chi^{t-1}\right) + (1-A)^t\left(\frac{\chi}{\chi-(1-A)}\right)\left(1-\left(\frac{\chi}{1-A}\right)^{t-1}\right)\right]\cdot r_{\ell,0}$$

$$, \; e = (1-P_S)(t-1)(\ell - t/2)\left(r_{1,0}+r_{1,1}\right),$$

$$W^e_0 = (1-P_S)\left[\frac{(1-A)^{t+1}}{A}\right]\left[\left(\frac{\chi}{\chi-(1-A)}\right)\left(\left(\frac{\chi}{1-A}\right)^{t-1} - 1\right) - \frac{\chi\cdot\left(1-\chi^{t-1}\right)}{(1-\chi)(1-A)}\right]\cdot r_{\ell,0}$$

$$, \; W^e = (1-P_S)(t-1)(t/2-1)\left(r_{1,0}+r_{1,1}\right). \qquad (4)$$

Reception Mode

From Figs. 1 and 3a, we can write the flow equations for states $\{s_{i,0}, s_{i,1}\}$, for $i \in \{1, 2, \dots, \ell\}$ as follows:

$$s_{i,0} = \frac{\chi^i}{P_S}\cdot a_{t,0} \quad , \quad s_{i,1} = \frac{1}{P_S}\cdot a_{t,1} + \frac{1}{P_S}(1-\chi^i)\cdot a_{t,0}. \qquad (5)$$

From the above equations, it is obvious that $s_{i,0} + s_{i,1} = \frac{1}{P_S}\left(a_{t,0} + a_{t,1}\right)$.

Relating the reception mode to the transmission mode, we assume that the number of users transmitting the first packet must be equal to the number of users receiving the same packet, yielding

$$r_{1,0} + r_{1,1} = s_{1,0} + s_{1,1} \quad \Rightarrow \quad r_{1,0} + r_{1,1} = \frac{1}{P_S}\left(a_{t,0} + a_{t,1}\right). \qquad (6)$$

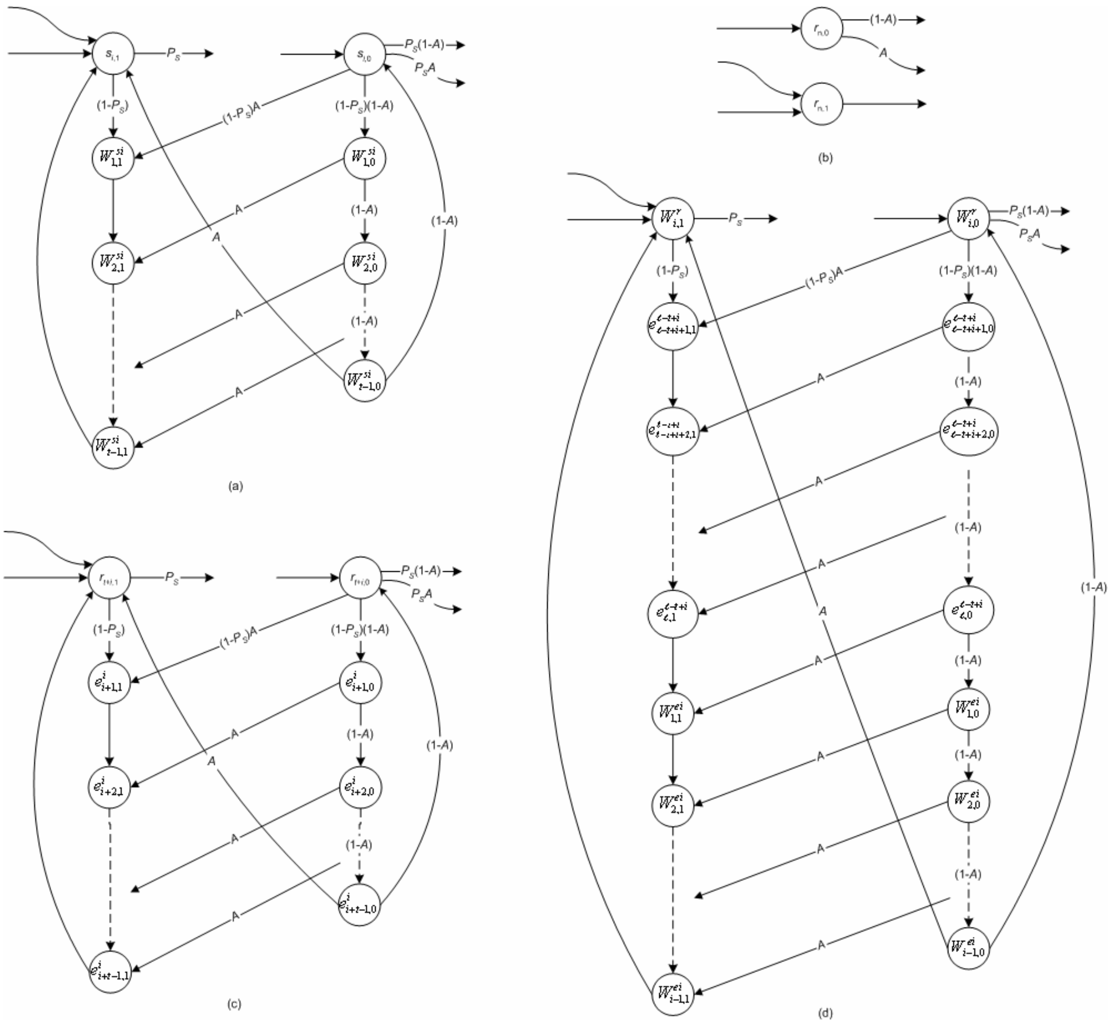

Fig. 3. (a) State $R_{X\,i}$; (b) State r_n ; (c) State Tx_{t+i} ; (d) State W_{Xi}.

Next we write the flow equations for the waiting states for $j \in \{1, 2, \ldots, t-1\}$ as follows:

$$W_{j,0}^{S_i} = \left(\frac{1-P_S}{P_S}\right)\cdot \chi^i (1-A)^j \cdot a_{t,0},$$

$$W_{j,1}^{S_i} = \left(\frac{1-P_S}{P_S}\right)\cdot a_{t,1} + \left(\frac{1-P_S}{P_S}\right)\left(1-\chi^i(1-A)^j\right)\cdot a_{t,0}.$$

Similarly we define the following variables:

$$s_0 = \frac{1}{P_S}\left(\frac{\chi(\chi^{\ell}-1)}{\chi-1}\right)\cdot a_{t,0} \qquad , \qquad s = \ell(r_{1,0}+r_{1,1})$$

$$W_0^{s} = \left(\frac{1-P_S}{P_S}\right)\left[\frac{\chi(\chi^{\ell}-1)}{\chi-1}\cdot\frac{(1-A)\left(1-(1-A)^{t-1}\right)}{A}\right]\cdot a_{t,0}$$

$$W^{S} = \ell(t-1)(1-P_S)(r_{1,0}+r_{1,1}) \tag{7}$$

Acknowledgement Mode

Again by writing the flow equations for the states in this mode, described in Fig. 2a, we can rewrite equation (6) as follows:

$$r_{1,0}+r_{1,1} = s_{1,0}+s_{1,1} = \frac{1}{P_S}(a_{1,0}+a_{1,1}). \tag{8}$$

Then solving for a_0 and a, we get:

$$a_0 = \left(\frac{1-(1-A)^t}{A}\right)\cdot a_{1,0} \quad , \qquad a = tP_S\cdot(r_{1,0}+r_{1,1}). \tag{9}$$

Requesting Mode

Figure 2b illustrates the requesting states and waiting states in the requesting mode. We write down the flow equations for these states as follows:

$$q_{j,0} = (1-A)^{j-1}\cdot q_{1,0} \qquad , \quad j\in\{1,2,\ldots,\tau\} \tag{10}$$
$$q_{j,1} = q_{1,1} + \left(1-(1-A)^{j-1}\right)\cdot q_{1,0}$$

Considering the waiting states for which $k\in\{1,2,\ldots,t-\tau\}$ and $i\in\{1,2,\ldots,\tau-1\}$ we have:

$$\mathrm{W}_{k,0}^{q} = (1-A)^{\tau+k-1}\cdot q_{1,0} \quad , \quad \mathrm{W}_{k,1}^{q} = q_{1,1} + \left(1-(1-A)^{\tau+k-1}\right)\cdot q_{1,0}$$
$$\mathrm{W}_{t-\tau+i,0}^{q} = (1-A)^{t-1}\left((1-A)(1-\gamma)\right)^i\cdot q_{1,0} \tag{11}$$
$$W_{t-\tau+i,1}^{q} = (1-\gamma)^i\cdot q_{1,1} + (1-\gamma)^i\left(1-(1-A)^{t-1+i}\right)\cdot q_{1,0}$$

To relate the requesting mode to the transmission mode, we write the flow equations into state r_1 as follows:

$$r_{1,0} = \gamma\cdot(1-A)\cdot\left[W_{t-\tau,0}^{q}+W_{t-\tau+1,0}^{q}+\cdots+W_{t-1,0}^{q}\right]+(1-P_S)(1-A)\cdot r_{t,0}$$
$$r_{1,1} = \gamma\cdot A\cdot\left[W_{t-\tau,0}^{q}+W_{t-\tau+1,0}^{q}+\cdots+W_{t-1,0}^{q}\right]+(1-P_S)\cdot A\cdot r_{t,0} \tag{12}$$
$$+\left[W_{t-\tau,1}^{q}+W_{t-\tau+1,1}^{q}+\cdots+W_{t-1,1}^{q}\right]\cdot\gamma+(1-P_S)\cdot r_{t,1}$$

Substituting from equations (1) and (11) in (12) we get:

$$q_{1,0} = \frac{P_S}{\gamma\cdot\chi\cdot(1-A)^{t-1}}\cdot\left[\frac{1-(1-A)(1-\gamma)}{1-\left[(1-A)(1-\gamma)\right]^{\tau}}\right]\cdot r_{1,0}$$

$$\left(r_{1,0}+r_{1,1}\right)=\frac{1}{P_S}\left[1-(1-\gamma)^{\tau}\right]\cdot\left(q_{1,0}+q_{1,1}\right). \quad (13)$$

Thus, we can define the following variables:

$$q=q_0+q_1=\tau\cdot\frac{P_S}{\left[1-(1-\gamma)^{\tau}\right]}\cdot\left(r_{1,0}+r_{1,1}\right),$$

$$W^q=W_0^q+W_1^q=\left[t-\tau-1+\frac{1}{\gamma}\left(1-(1-\gamma)^{\tau}\right)\right]\cdot\frac{P_S}{\left[1-(1-\gamma)^{\tau}\right]}\cdot\left(r_{1,0}+r_{1,1}\right). \quad (14)$$

From Fig. 1 we can also write the flow equations into states $\{a_{1,0}, a_{1,1}\}$, as follows:

$$a_{1,0}=\sigma(1-A)\cdot m+P_S\sigma(1-A)\cdot\left(s_{\ell,0}+W_{t-1,0}^r\right)+(1-\gamma)\sigma(1-A)\cdot W_{t-1,0}^q$$

$$a_{1,1}=\sigma A\cdot m+P_S\sigma A\cdot\left(s_{\ell,0}+W_{t-1,0}^r\right)+P_S\sigma\cdot\left(s_{\ell,1}+W_{t-1,1}^r\right)+(1-\gamma)\sigma A\cdot W_{t-1,0}^q+(1-\gamma)\sigma\cdot W_{t-1,1}^q. \quad (15)$$

Solving the above two equations simultaneously, the initial state can be written as:

$$m=\frac{P_S}{\sigma}\left[1-2\sigma-\sigma\left(\frac{(1-\gamma)^{\tau}}{1-(1-\gamma)^{\tau}}\right)\right]\cdot\left(r_{1,0}+r_{1,1}\right)=\left[\frac{1-\sigma}{\sigma}\right]\cdot a_{1,0} \quad (16)$$

The probability that a request is found by a scanning user is equal to the probability that another user is in the requesting mode, yielding

$$\sigma=\frac{1}{N}\sum_{i=1}^{\tau}q_{i,0}+q_{i,1}=\frac{\tau\cdot P_S}{N\left[1-(1-\gamma^{\tau})\right]}\cdot\left(r_{1,0}+r_{1,1}\right). \quad (17)$$

To evaluate σ and γ we need another equation relating them to be solved with equation (17). This relation is obtained by solving the following two equations:

$$q_{1,0}=A(1-\sigma)\cdot m+P_S A(1-\sigma)\cdot\left(s_{\ell,0}+W_{t-1,0}^r\right)+P_S(1-A)(1-\sigma)\cdot\left(s_{\ell,1}+W_{t-1,1}^r\right)+A(1-\sigma)(1-\gamma)\cdot W_{t-1,0}^q+(1-A)(1-\sigma)(1-\gamma)\cdot W_{t-1,1}^q$$

$$q_{1,1}=P_S A(1-\sigma)\cdot\left(s_{\ell,1}+W_{t-1,1}^r\right)+A(1-\sigma)(1-\gamma)\cdot W_{t-1,1}^q.$$

Steady State Throughput

The steady state system throughput $\beta(N,A,t,\tau,\ell)$ is defined as the average number of successful received packets per slot. It can be calculated as follows:

$$\beta(N,A,t,\tau,\ell)=\sum_{i=1}^{\ell}\left(s_{i,0}+s_{i,1}\right)\cdot P_S=\frac{P_S(r').\ell.r'}{\left[\ell+(1-P_S)(t-1)(\ell-t/2)\right]} \quad (18)$$

Here r' denotes the number of users either in transmission states or retransmission states and is given by:

$$r'=r+e=\left[\ell+(1-P_S)(t-1)(\ell-t/2)\right]\cdot\left(r_{1,0}+r_{1,1}\right). \quad (19)$$

It is clear that the number of users in the network must be equal to the total number of users in all the states. Using equations (4), (7), (9), (14), (16), and from (19) we get:

$$N\left[\ell+(1-P_S)(t-1)(\ell-t/2)\right]=r'\left[2\ell+(t-1)+tP_S+(1-P_S)(t-1)(2\ell-1)+\frac{P_S}{\sigma}-2P_S+\left\{t-1-(1-\gamma)^{\tau}+\frac{1}{\gamma}\left(1-(1-\gamma)^{\tau}\right)\right\}\cdot\frac{P_S}{1-(1-\gamma)^{\tau}}\right]. \quad (20)$$

That is r' is the solution of the above equation.

Blocking Probability

The blocking probability is defined as the probability of an arrival being blocked. For convenience and sake of comparison we derive in this subsection the blocking probability for both R^3T optical random access protocols; with and without transmission queue.

The R^3T without a Queue [6]: In this case the blocking probability is equal to the probability that the station is not in the initial state and there is a message arrival, or the station is in the initial state but there is a request for connection and at the same time there is a message arrival. Thus, we can write

$$P_B=\frac{m}{N}\cdot\sigma\cdot A+\left(1-\frac{m}{N}\right)\cdot A=\left[1-\frac{1}{2N\ell}\left(\sqrt{\beta^2+4\frac{N\ell}{A\tau}\beta}-\beta\right)\right]\cdot A. \quad (21)$$

The R^3T with a Queue (Buffer): Here the blocking probability is equal to the probability that the station is not in the initial state, there is a message arrival and the queue is full in addition to:

- After successful transmission / reception: If there is a connection request and there is a message arrival, blocking will occur.
- After request: A message is blocked, if the station is timed-out, there is a message arrival and a connection request is found, or if the station got a positive acknowledgement and there is a message arrival.

Therefore, the blocking probability can be given by

$$P_B=\frac{A}{N}\left[r_1+e_1+W_1^e+W_1^s+a_1+q_1+W_1^r+s_1+W_1^q-(1-P_S\sigma)\left(W_{t-1,1}^r+s_{\ell,1}\right)-(1-\gamma)(1-\sigma)\cdot W_{t-1,1}^q\right]. \quad (22)$$

Average Packet Delay

The average packet delay D can be calculated from Little's theorem:

$$D=\frac{NA\cdot(1-P_B)}{\beta(N,A,t,\tau,\ell)}\ \text{slots}, \quad (23)$$

where $NA\cdot(1-P_B)$ denotes the average total offered traffic in the network.

5. SIMULATION RESULTS

Our results are plotted in Figs. 4-6. A set of OOCs denoted by $\phi(31,3,1,1)$ is used as the user signature codes. A chip rate of 4 Mchips/s for each user is held constant in our simulations. The near-far effect has been neglected since all nodes are uniformly located from the star coupler. We have also neglected the effect of the receiver's shot and thermal noises. Only, the effect of MAI has been taken into account, as it represents the major limitation in CDMA systems. A packet is assumed to fit in a time slot.

Figure 4 shows the relation between throughput and the number of users for both R^3T protocols with and without queuing system for different propagation delays (different interstation distances). General trends of the curves can be noticed. As the number of users in the network increases, more packets are available for transmission with low interference and thus the throughput increases till it reaches its peak. At a higher number of users and for the R^3T protocol with queuing system (buffer), some users may have additional packets stored in their buffer

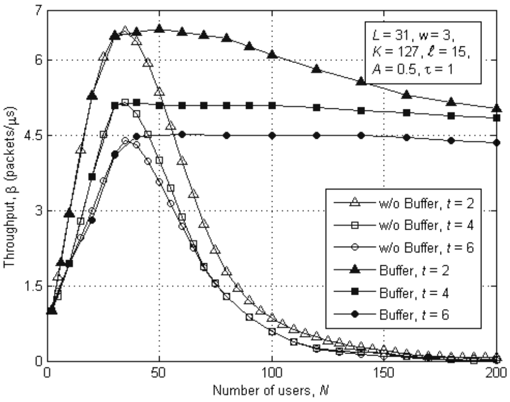

Fig. 4. Throughput vs. number of users.

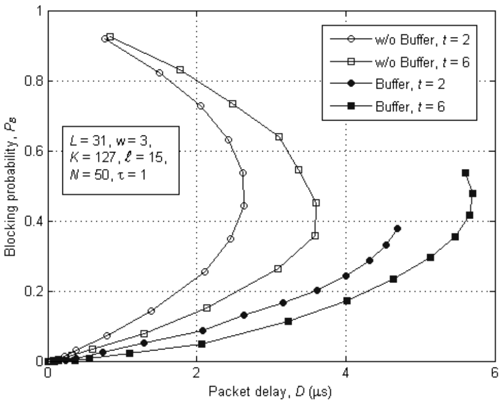

Fig. 5. Blocking probability vs. packet delay.

(to be transmitted later on), yielding a slower decay in the throughput. It can be inferred that the throughput is lower for longer propagation delays, which is obvious.

In Fig. 5, we have plotted the blocking probability against the average packet by varying the average user activity. To investigate the effect of the propagation delay on the performance, we also considered the case where $t = 6$. As the user activity increases, both the average packet delay and the blocking probability increase till the delay reaches its maximum value. From that instant the effect of the blocking probability will dominate and thus the delay starts to decrease according to equation (23). The results show that for longer interstation distances, the delay is larger. Also when considering a buffer a queuing delay is added to the total delay in the network. A tradeoff exists between the steady state system throughput, the average packet delay and the blocking probability.

The protocol efficiency η defined as the ratio between the number of successfully received packets and the number of packets available for transmission is also simulated in Fig. 6 for different values of activities, $A \in \{0.1, 0.9\}$. It can be seen that both R^3T protocols with and without buffer behave similarly for low population networks, while for larger population networks the system with buffer significantly outperforms the ideal R^3T protocol.

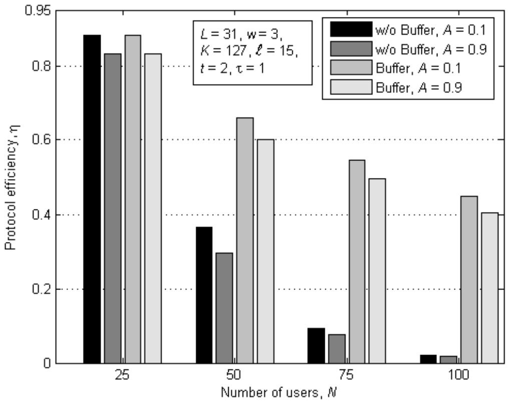

Fig. 6. Protocol efficiency vs. message length.

6. CONCLUSIONS

In this paper, we have proposed a queuing model to improve the performance of the previously proposed R^3T protocol. A single buffer was added to each node. Only the effect of MAI was considered. Expressions for throughput, blocking probability, and average packet delay have been derived, simulated and compared with that of the R^3T protocol without queuing. The following concluding remarks can be extracted from our results:

- The proposed modifications to the R^3T model exhibits better performance for high population networks and under high traffic loads.
- The blocking probability is significantly reduced by a factor of 50 %.
- The queuing delay is added to the total latency of the network, but it is still acceptable.
- The enhanced R^3T protocol provides a better efficiency over a wider dynamic range.
- Of course the price to be paid for the improvement is the increased system complexity when adding a queuing subsystem.

7. REFERENCES

[1] J. A. Salehi and C. A Brackett, "Code division multiple-access techniques in optical fiber networks. Part II: systems performances analysis", **IEEE Trans. Commun**, Vol. COM-37, 1989, pp. 834-842.

[2] H. M. H. Shalaby, "Chip-level detection in optical code-division multiple-access", **IEEE/OSA J. Lightwave Technol.**, Vol. LT-16, 1998, pp. 1077-1087.

[3] C.-S. Hsu and V. O. K. Li, "Performance analysis of slotted fiber-optic code-division multiple-access (CDMA) packet networks", **IEEE Trans. Commun.**, Vol. COM-45, 1997, pp. 819-828.

[4] C.-S. Hsu and V. O. K. Li, "Performance analysis of unslotted fiber-optic code-division multiple-access (CDMA) packet networks", **IEEE Trans. Commun.**, Vol. COM-45, 1997, pp. 978-987.

[5] H. M. H. Shalaby, "Optical CDMA random access protocols with and without pretransmission coordination", **IEEE/OSA J. Lightwave Technol.**, Vol. LT-21, 2003, pp. 2455-2462.

[6] H. M. H. Shalaby, "Performance analysis of an optical CDMA random access protocol", **IEEE/OSA J. Lightwave Technol.**, Vol. LT-22, 2004, pp. 1233-1241.

[7] M. J. Karol, "Performance of the PAC optical packet network", **IEEE/OSA J. Lightwave Technol.**, Vol 11. No. 8, 1993, pp. 1394-1399.