

Significance in Adding a Queuing Subsystem to the R^3T Random Access OCDMA Protocol

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Abstract—A queuing subsystem is proposed to the round robin receiver/transmitter (R^3T) optical code-division multiple-access (OCDMA) protocol. The corresponding state diagram and its mathematical model are outlined. We prove that significant improvement in terms of system throughput and blocking probability can be achieved by only adding a single buffer at each user node. Furthermore, the modified R^3T protocol can support higher traffic loads with acceptable delay and good efficiency.

Index Terms—Chip-level receivers, OCDMA networks, OCDMA protocols, on-off keying, queuing.

I. 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]–[11]. Most of the research in the field of OCDMA has focused on physical layer issues such as encoding/decoding schemes, spreading codes, receiver structures, etc. [1]–[5]. However, a few authors have examined the data link layer of OCDMA networks [6]–[11]. In [6] and [7] Hsu and Li have studied the performance of slotted and unslotted optical CDMA systems, respectively. Shalaby has proposed two media access control (MAC) protocols with and without pre-transmission coordination for slotted OCDMA networks in [8]. The effect of multi-packet messages, connection establishment and retransmission of corrupted packets was not considered. In [9] Shalaby answered to these questions by introducing the round robin receiver/transmitter (R^3T) protocol, which was based on a go-back n automatic repeat request (ARQ). In his model, Shalaby 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 high dropping probability or in other words a blocking probability, which was not examined in [9]. Selective reject and stop-and-wait ARQs were studied in [10] and [11], respectively as variations to the R^3T protocol. However, the former is very

complex and the latter does not perform as good as the R^3T protocol at lower traffic loads.

In this letter we aim at enhancing the performance of the R^3T model in [9] by introducing a queuing subsystem, namely increasing the number of available buffers. Although we are expecting to increase the system throughput, the average packet delay is also expected to increase. Our goal here is to add only one additional buffer to each user node to preserve simplicity in our model, and to maintain the same complexity and cost of the system. At the same time we are interested in measuring the performance of the modified R^3T protocol to decide how far it is the important to add a queuing subsystem to the simple R^3T model. Our second aim is to calculate the blocking probabilities for R^3T with and without (w/o) queuing buffers and to compare their performances.

The rest of this letter is organized as follows; Section II is devoted to a general description of the network architecture, and the optical CDMA protocol. The mathematical model is then presented in Section III, where we adopted the equilibrium point analysis (EPA) to analyze the state diagram. In our analysis, focus is oriented towards multiple access interference (MAI) only, where the effect of the receiver's noise is neglected. Section IV is maintained for the numerical results of both R^3T models (with and without (w/o) queuing buffers). Finally our conclusions are given in Section V.

II. SYSTEM ARCHITECTURE

A. Optical CDMA Network

In order to support a large number of users denoted by N in a passive OCDMA broadcast network without any switch, we use a simple star configuration as in [9]. Each node is equipped with a queuing system prior to transmission followed by a fixed CDMA encoder. At the physical layer, messages are stored in electrical buffers before transmission. A laser diode is then used to convert the signal to the optical domain, and is followed by a time domain CDMA encoder that is composed of couplers and different lengths delay lines as in [2]. A tunable CDMA decoder made from passive components and followed by a pin photodetector are placed at the receiver side. Transmitters generate optical ON-OFF keying CDMA signals according to their signature sequences representing their data. Users are assigned these codes randomly from a set of 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- and cross-correlation constraints, respectively [3]. A code may be given to more than one user at the same time.

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Furthermore, a code is randomly cyclic shifted around itself upon assignment to control the effect of MAI.

Chip-level receivers are considered because of their high ability to overcome the effect of MAI [4]. 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 $r' \in \{1, 2, \dots, N\}$ active users can be found in [8].

B. Optical CDMA Protocol

In the R^3T protocol many assumptions were imposed [9]. Briefly, time is slotted with a slot size T_s . Each node has a single buffer to store only the message being served, connection requests and acknowledgements are exchanged between stations, finally the ARQ used is a go-back n protocol that depends on the two-way propagation time which is equal to t time slots. The drawback of R^3T is that messages are 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 these extra assumptions in our model for OCDMA 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 if it's timed-out or when it is idle.
- A priority is given for the reception mode than the transmission mode; that is if at the same time slot there's a message arrival and a connection request is found, the user will first respond to the connection request. The message to be transmitted will be stored in the queue if it is free otherwise it will be blocked.

III. MATHEMATICAL MODEL AND ANALYSIS

The complete state diagram of the R^3T protocol with a single buffer in the queue is illustrated in Fig. 1 (see top of next page). Each state is labeled by its number of users. States marked with a '0' indicate that the additional buffer is empty while a '1' indicates that this buffer is full. Transitions between states occur on a slot basis. Users move from states marked with '0' to states marked with '1' if there is a message arrival. Messages are blocked if the users have their queues full and there is a message arrival except after successful transmission/reception, or after request if timed-out. 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.

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 as in [9]. Each mode will be divided into two sets of states: states marked with '0' indicating that the buffer is empty and states marked with '1' indicating that the buffer is full. By writing down the flow equations for all the states, we can derive the steady state system throughput, the protocol efficiency, the average packet delay, and the blocking probability. The same notations as in [9] are used for all the states.

Starting with the transmission mode (Fig. 1) involving states $\{r_1, r_2, \dots, r_t, Tx_{t+1}, Tx_{t+2}, \dots, Tx_t\}$ we have the following flow equations for $n \in \{1, 2, \dots, t\}$:

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

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

$$\begin{aligned} Y_0 &= \sum_i Y_{1,0}, Y_1 = \sum_i Y_{i,1}, Y \\ &= \sum_i Y_{1,0} + Y_{i,1} = Y_0 + Y_1 \end{aligned}$$

Performing the above summations for the states in the transmission mode, we obtain the number of users in the transmission mode $[r_0, r_1, r]$. The same analysis is used for the remaining states in the transmission mode and all the other modes.

A. Steady State Throughput

The steady state system throughput $\beta(N, A, t, \tau, \ell)$ is defined as the average number of successfully received packets per slot, and is simply related to the total number of users in the reception states $\{s_{1,0}, s_{1,1}, s_{2,0}, s_{2,1}, \dots, s_{t,0}, s_{t,1}\}$; we have used the same notations as in [9]. Therefore, the throughput can be expressed as follows:

$$\begin{aligned} \beta(N, A, t, \tau, \ell) &= \sum_{i=1}^t (s_{1,0} + s_{i,1}) \cdot P_s \\ &= P_s(r'), \ell, (r_{1,0} + r_{1,1}). \end{aligned} \quad (2)$$

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

$$\begin{aligned} r' &= r + e \\ &= [\ell + (1 - P_s)(t - 1)(\ell - t/2)] \cdot (r_{1,0} + r_{1,1}). \end{aligned} \quad (3)$$

To calculate r' as a function of the total number of users in the network N , we assume that the total number of users is equal to the number of users in all the states as in [9] and

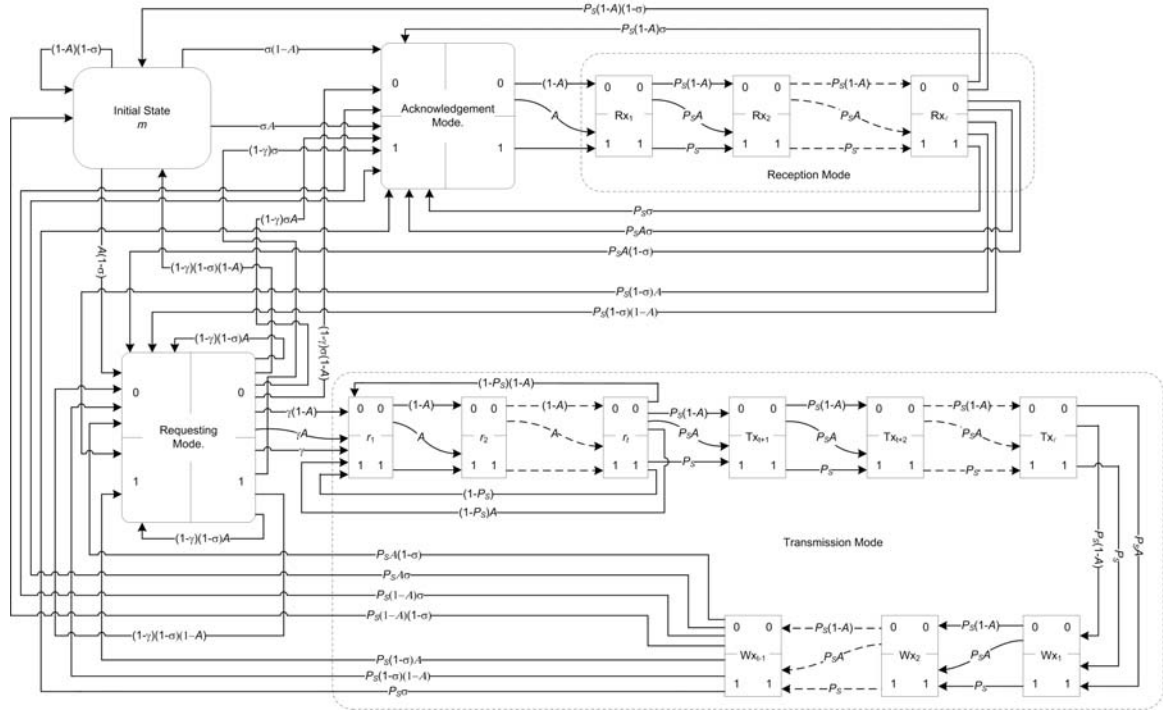


Fig. 1. Complete state diagram of the R^3T optical CDMA protocol with a queuing subsystem.

[11]. Substituting back in (2), the throughput can be expressed as follows:

$$\beta(N, A, t, \tau, \ell) = \frac{P_s(r'), \ell, r'}{[\ell + (1 - P_s)(t - 1)(\ell - t/2)]} \text{packets/slot.} \quad (4)$$

B. 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.

1) The R^3T Protocol without a Queue [9]:

In this case the blocking probability is equal to the probability that the station is not in the initial state m and there is a message arrival A or the station is in the initial state m but there is a request for connection and at the same time there is a message arrival A . Thus, we can write

$$\begin{aligned} P_s &= \frac{m}{N} \cdot \sigma \cdot A + \left(1 - \frac{m}{N}\right) \cdot A \\ &= \left[1 - \frac{1}{2N\ell} \left(\sqrt{\beta^2 + 4\frac{N\ell}{A\tau}\beta} - \beta\right)\right] \cdot A \quad (5) \end{aligned}$$

2) The R^3T Protocol with a Queue:

In this case the blocking probability is equal to the probability that the station is not in the initial state m , there is a message arrival A and the queue is full in addition to:

i. After successful transmission/reception: If there is a connection request and there is a message arrival, blocking will occur.

ii. 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.

C. Protocol Efficiency and Average Delay

The protocol efficiency η is defined as the ratio between the number of successfully received packets and the number of packets available for transmission:

$$\eta = \frac{\beta(N, A, t, \tau, \ell)}{r'} \quad (6)$$

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

$$D = \frac{NA \cdot (1 - P_B)}{\beta(N, A, t, \tau, \ell)} \text{ slots.} \quad (7)$$

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

IV. THEORETICAL RESULTS

In our calculations we have used a set of OOCs denoted by $\phi(31, 3, 1, 1)$ as the user signature codes. To insure minimal interference between users, we have restricted the auto- and cross-correlation constraints to one. The reason why we used short length codes that experience high bit error rate (BER) values was mainly to reduce the average packet delay. Packets that are received incorrectly can then be retransmitted following a go-back n ARQ. The small number of available codes (in our case only 5 codes), are assigned to users according to protocols in [8]. A chip rate of 4 Gchips/s for each user is held constant in our calculations and a packet size of $K = 127$ bits is considered. It is assumed that a packet should fit in a time slot. We have used the EPA in order to compute the

steady state system throughput, the average packet delay, the protocol efficiency, and the blocking probability for both R^3T protocols; with and without transmission queue. The near-far effect has been neglected since all nodes are equally 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, especially when the number of active users is large. Our results are plotted in Figs. 2-4. A message length of $l = 15$, and a timeout duration of $\tau = 1$ slot is imposed in all figures. Note that including a single buffer to the system is expected to improve the protocol performance, but maintains the same trends of the curves in [9].

In Fig. 2, we have plotted the throughput versus the number of users N for both R^3T protocols with and without queuing system for different propagation delays i.e. 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 and thus the throughput increases till it reaches its peak. For the R^3T protocol without queuing system, the throughput falls down rapidly as the number of users is further increased, because the effect of MAI becomes more severe. On the other hand, the system with buffer can still maintain its high throughput. Actually, adding a single buffer to the system has almost doubled the number of states as seen from Fig. 1. The probability of being at the requesting mode or the acknowledgement mode has also increased (users can directly move to these modes after successful transmission/reception and no need to move to the idle mode and to wait for a connection request or message arrivals as in [9]), therefore the number of active users has decreased compared to the case of simple R^3T protocol. We have demonstrated this argument through our evaluations. This smaller number of active users (smaller effect of MAI) is the main reason for the higher throughput or its slower decay for the proposed R^3T protocol. It can also be inferred from these curves that the throughput is decreased for longer propagation delays, which is completely obvious and follows the results presented in [9].

The blocking probability has been plotted versus the user activity and the throughput for both systems in Fig. 3. It can be seen that the blocking probability increases when increasing the user activity as there are more arrivals, also the throughput increases till it reaches saturation. The results also show that including a single buffer to the system has dramatically decreased the blocking probability.

Finally in Fig. 4, we have plotted the blocking probability against the average packet delay for the results in Fig. 3 (i.e. varying the 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 (7). The results show also that for longer distances, the delay is larger as expected. Also when considering a buffer, a queuing delay is added to the total delay in the network, from the curves it can be seen that this queuing delay is always smaller than 3.5

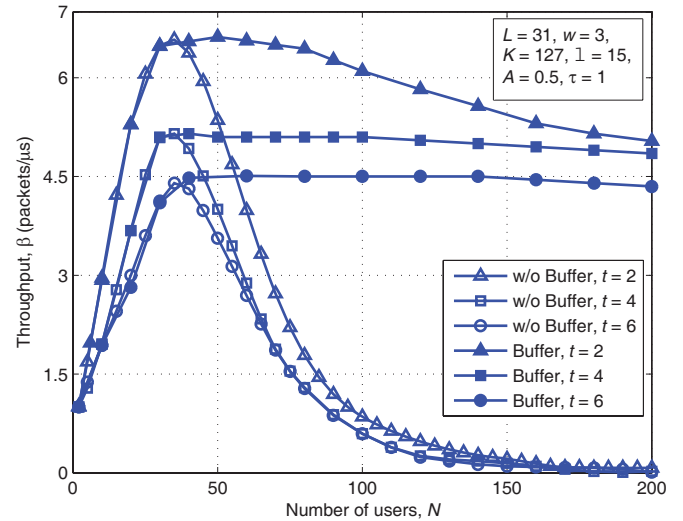


Fig. 2. System throughput versus number of users for different propagation delays (Unfilled markers for the system without a queuing subsystem; filled markers for the system with a single buffer).

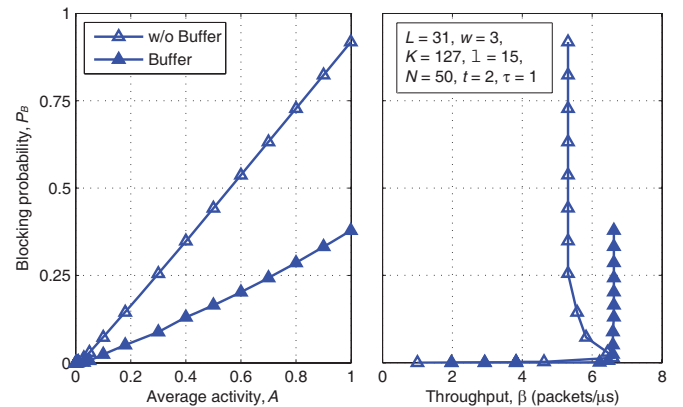


Fig. 3. Blocking probability versus average activity and system throughput for both R^3T protocols (Unfilled markers for the system without a queuing subsystem; filled markers for the system with a single buffer).

μs for the same blocking probability. A tradeoff exists between the steady state system throughput, the average packet delay and the blocking probability. The average packet delay versus the system throughput can simply be viewed when combining Fig. 3 to Fig. 4 for a two-way propagation delay time of 2 slots.

The relation between the protocol efficiency and the number of users in the network has also been evaluated for low and high activity levels, $A \in \{0.1, 0.9\}$ using equation (6). The following result was obtained: 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, which can also be explained from Fig. 2.

V. CONCLUSIONS AND FUTURE WORK

In this letter, 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. For convenience and sake of comparison, only the effect of MAI was considered. Expressions for throughput, blocking probability, av-

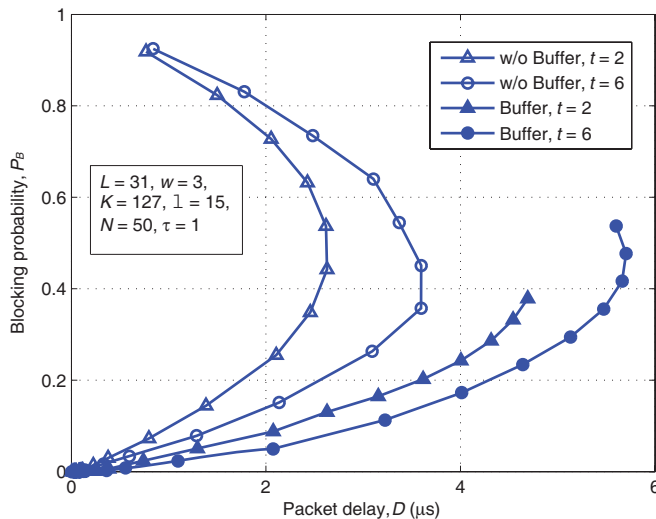


Fig. 4. Blocking probability versus average packet delay for different propagation delays (Unfilled markers for the system without a queuing subsystem; filled markers for the system with a single buffer).

erage packet delay, and system efficiency have been derived, evaluated and compared with that of the R^3T protocol without queuing. The following concluding remarks can be extracted from our results:

- 1) The proposed modifications to the R^3T model exhibits better performance for high population networks and under high traffic loads.
- 2) The blocking probability is significantly reduced by a factor of 50%.
- 3) The queuing delay (maximum of $3.5 \mu\text{s}$ under the evaluation parameters we used) added to the total latency of the network is still acceptable.
- 4) The enhanced R^3T protocol provides a better efficiency over a wider dynamic range.
- 5) Of course the price to be paid for the improvement is the increased system complexity when adding a queuing subsystem.
- 6) Adding more buffers to the system will not any more increase the performance in terms of throughput, on the other hand the average packet delay is expected to increase dramatically.

To sum up the proposed R^3T protocol is a good choice for future and for current local area networks (LANs). More

than 50 users can be served asynchronously at 127 Mb/s over several hundreds of meters. The protocol stack is simple and can be easily downloaded on application specific integrated circuits (ASICs) or on a single field programmable gate array (FPGA) for non-centralized or centralized implementations, respectively. The proposed protocol is transparent to the physical layer, and therefore can be used with different optical CDMA encoding/decoding techniques. It can also be extended to suit for access networks applications, with suitable modifications to the MAC layer; for example scheduling algorithms may be preferred than random access schemes to manage upstream traffic. We would like to add that it would be interesting in the near future to validate our theoretical results and the ones in [9] using a simulation software such as OPNET or ns-2.

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