Optical code-division multiple-access protocol with selective retransmission

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Abstract. An optical code-division multiple-access (OCDMA) protocol based on selective retransmission technique is proposed. The protocol is modeled using a detailed state diagram and is analyzed using equilibrium point analysis (EPA). Both traditional throughput and average delay are used to examine its performance for several network parameters. In addition, the performance of the proposed protocol is compared to that of the R^3T protocol, which is based on a go-back-n technique. Our results show that a higher performance is achieved by the proposed protocol at the expense of system complexity. [DOI: 10.1117/1.2205193]

Subject terms: optical code-division multiple-access protocol; selective retransmission technique; modified R^3T protocol.

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1 Introduction

Optical networks have been of great importance in the last decade due to their extremely high bandwidth, which covers the high data rates required by modern networks and communication systems. The optical code-division multiple-access (CDMA) technique[1–12] appears as a promising method that can mine this huge bandwidth. A number of papers have studied or proposed optical CDMA network protocols. In Refs. 8 and 9 Hsu and Li[9] studied the slotted and unslotted optical CDMA systems. In Ref. 10, we have studied media access control (MAC) protocol and discussed the problem of multiple packet messages in unslotted optical CDMA systems. In Ref. 11, Shalaby has introduced new protocols for optical CDMA networks to discuss the problem of assigning codes for different users. In Ref. 12, Shalaby has presented the so called round-robin-receiver transmitter (R^3T) protocol (from now on we call it Shalaby (R^3T) protocol) to solve other issues, namely, the establishment and release of a connections, the problem of multiple packet messages, and how the protocol deals with the lost packets.

The Shalaby R^3T protocol[12] is based on the go-back-n technique. In this technique, whenever a packet is corrupted, the transmitter retransmits the corrupted and all successive packets, since the receiver accepts only success packets that come in the proper order. Results have indicated that the performance of the Shalaby R^3T protocol is good for low-population networks, while it gives lower performance in large population (>50 users) networks.

In this paper, we propose a new optical CDMA protocol that deals with the previous problems and gives better performance for both large and small networks. Our proposed protocol is a modified version of Shalaby R^3T protocol, and it is based on the selective retransmission technique, where only corrupted packets will be retransmitted. In our system architecture, chip-level receivers[7] are implemented in all network nodes.

The rest of the paper is arranged as follows. Section 2, presents the network architecture, then the chip-level receiver and our proposed protocol. The system analysis is studied in Sec. 3, where we present a detailed state diagram for the proposed protocol and calculate the system throughput and average delay. Section 4, gives some numerical results and compares the performance of the proposed protocol to the performance of the Shalaby R^3T protocol. Finally, the paper is concluded in Sec. 5.

2 Proposed Protocol

2.1 *Network Architecture*

The network is composed of N stations or nodes, connected in a star topology and a set of optical orthogonal codes (OOCs) with cardinality $C, \{a_1, a_2, \ldots, a_C\}$, where C depends on the code length L and code weight w. We assume that both out-of-phase autocorrelation and cross-correlation of the code are limited to one, $\lambda_a = \lambda_c = 1$, this gives[1]

$$C = \left\lfloor \frac{L-1}{w(w-1)} \right\rfloor,$$

where $\lfloor x \rfloor$ denotes the largest integer not greater than x. In our network, each user is assigned an optical orthogonal code as its own signature; when the number of users exceeds the number of codes, a used code is cyclically shifted around itself and assigned to another user. Each user has a fixed transmitter and a tunable receiver (FT-TR). The transmitter of each user is adjusted to its signature code, while the receiver can be tuned to any other signature code.

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2.2 *Chip-Level Receiver*

In our network, a chip-level receiver is used at all its nodes. The decision rule of the chip-level receiver is that data bit 1 is declared if the number of pulses in all mark positions of the signature code are nonzero, otherwise data bit 0 is declared. According to Shalaby,[11] the packet success probability for a packet with K bits, given r active users is

$$Ps(r) = \sum_{k=0}^{r-1} \sum_{m=0}^{r-1-k} \frac{(r-1)!}{k!\,m!\,(r-1-m-k)!} p_1^k p_w^m (1-p_1-p_w) \sum_{\substack{k_1,k_2,\ldots,k_w: \\ k_1+k_2+\cdots+k_w=k}} \frac{k!}{k_1!\,k_2,\ldots,k_w!\,w} \frac{1}{w}^{k} \left\{ \frac{1}{2} + \frac{1}{2^{m+1}} \left[\sum_{i=1}^{w} \frac{1}{2^{k_i}} - \sum_{i=1}^{w-1} \sum_{j=i+1}^{w} \frac{1}{2^{k_i+k_j}} + \cdots + (-w)^{w-1} \frac{1}{2^k} \right] \right\}^k$$

where

$$p_w = \frac{1}{L} \left\lfloor \frac{L-1}{w(w-1)} \right\rfloor^{-1} \quad \text{and} \quad p_1 = \frac{w^2}{L} - w p_w .$$

2.3 *Proposed Protocol*

Assume that messages arrive to a station with a probability A, called user activity. Each message contains $l > 0$ packets. Each packet, of length K, has a header that contains a CRC (cyclic redundancy check) code and a packet serial number (packet order in the message). Furthermore, assume that time is slotted with a slot size $T_s = KLT_c$, where T_c is the chip duration, and L is the code length. A packet transmission is permitted at the beginning of a time slot.

When a message arrives to a station, it tries to establish a connection with the desired receiver. First it sends a connection request to the destination node. This connection request should meet an idle station that replies with a connection acknowledgment. Idle stations scan over all codes for connection requests. The connection request contains the source ID, destination ID, and the message length "number of packets per message." Also it includes the serial numbers of packets to be transmitted. A connection request is a series of τ requesting packets, where τ is the time out duration in time slots. After sending the last request the station enters a waiting mode of length t time slots, where t is the two way propagation delay.

When an idle station receives a connection request it replies with a request acknowledgment and tunes its receiver to the code of the transmitter. Also it creates a transmission table—a table that contains list of the packets to be transmitted—and each packet is labeled by its serial number. Finally, it enters the reception mode.

When a connection is established the transmitter enters the transmitting mode and starts sending its message. After $t/2$ time slots "one-way propagation delay," the receiver enters the reception mode and starts receiving the message. A station in the reception mode receives the messages' packets and use the CRC code to check the received packets for errors. Successfully received packets are removed from the transmission tables.

After the transmitter sends all packets, it enters a waiting state of fixed length equal to t time slots. At the same time the receiver scans its transmission table; if the transmission table is empty, this means that all packets have been successfully received; in this case, the receiver sends a positive acknowledgment to the transmitter informing it with the end of transmission. Both stations will return to the initial state and the connection is released.

If the transmission table contains some packets, this means that these packets have not been successfully received and should be retransmitted. Thus, the receiver sends an ask-for-retransmission request to the transmitter informing it with the packets to be retransmitted. If the transmitter receives an ask-for-retransmission, it enters a backlogged mode of length b time slots, where b is the number of packets to be retransmitted. Instantaneously, it starts sending these packets. This scenario is repeated until all packets are received successfully.

3 System Analysis

The state diagram of our system, as just described, is shown in Fig. 1. In this section we give a detailed discussion of these system states.

3.1 *Idle State m*

Stations in the idle state are scanning over all codes for a connection requests. If a station receives a connection request it responds by an acknowledgment. If it did not find a connection request and there is a message arrival, the station enters the requesting mode. Otherwise it remains in the idle state.

3.2 *Requesting Mode*

An idle station with a message to send should enter requesting mode to establish a connection with the desired user. This is achieved by sending τ requests $\{q_1, q_2, \ldots, q_\tau\}$. Then the station waits for a request acceptance [it enters a waiting mode containing t states $(W_1, W_2, W_3, \ldots, W_t)$], each state is one time slot length. Whenever a waiting user gets an acceptance for connection, it starts sending its message and enters transmission mode $T_{X,l}$.

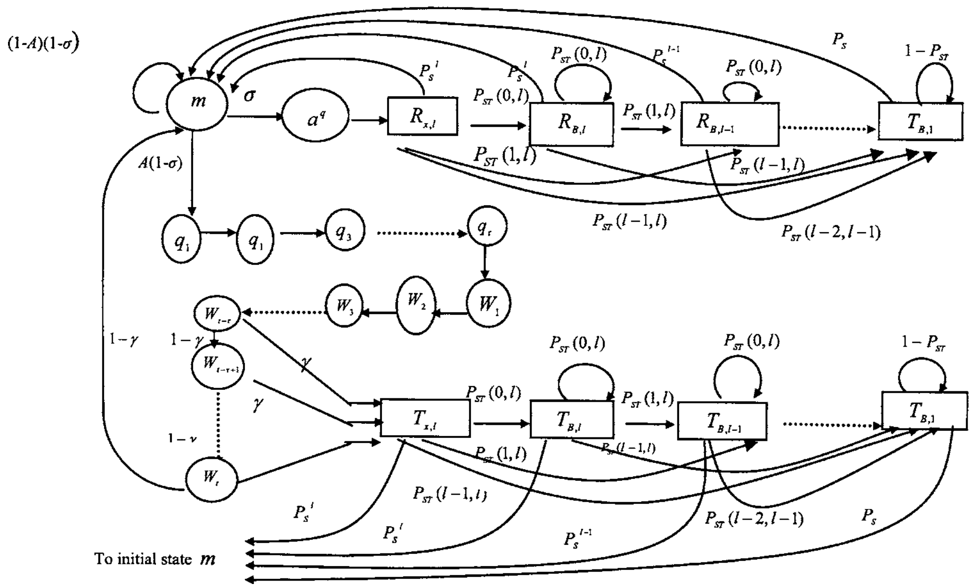

Fig. 1 State diagram of the proposed protocol.

Due to the propagation delay, a waiting user will not receive an acceptance in the first $(t-\tau-1)$ waiting states. We define γ as the probability that a waiting user receives an acceptance for connection. By writing the flow equations we get

$$q_1 = q_2 = \cdots = q_\tau = A(1-\sigma)m,$$

$$W_1 = W_2 = \cdots = W_{t-\tau} = q_1 = A(1-\sigma)m,$$

$$W_{t-\tau+i} = (1-\gamma)^i W_{t-\tau} = (1-\gamma)^i A(1-\sigma)m.$$

Let q denote the umber of users in the requesting mode, and let W^q denote the number of users in the mode of waiting mode:

$$q = \tau q_1 = A\tau(1-\sigma)m, \tag{1}$$

$$W^q = Am(1-\sigma)\left\{t-\tau+\frac{1}{\gamma}[1-\gamma-(1-\gamma)^\tau]\right\}, \tag{2}$$

where σ is the probability that a request is found by a user, as shown next:

$$\sigma = \frac{1}{N}q = \frac{1}{1+N/mA\tau}.$$

3.3 *Acknowledgment Mode a^q*

In acknowledgment mode, idle stations respond to a connection request sent by an active station:

$$a^q = \sigma m. \tag{3}$$

3.4 *Transmission Mode*

Transmission mode involves transmitting packets and then receives acknowledgments. This mode is composed of two types of states, Figs. 2(a) and 2(b). First is for stations that send new message and is called thinking state $T_{X,l}$; this state has a duration of $l+t+1$ time slots. Second is called the backlogged state $T_{B,b}$ in which a backlogged user retransmits corrupted packets, where $b=1,2,\ldots,l$ is the number of packets to be retransmitted. Thus, the backlogged mode involves l different states each of different duration equal to $b+t+1$.

A station enters transmission mode should enter the thinking state for $l+t+1$ time slots in which it sends its

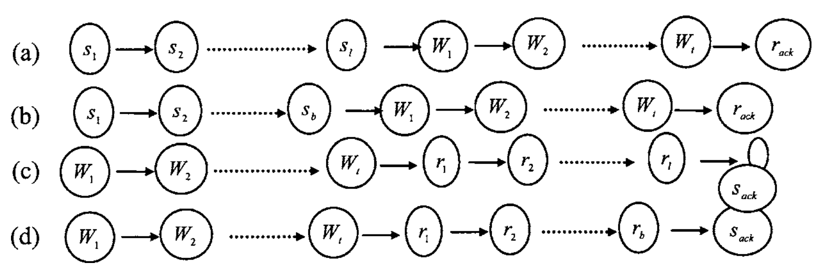

Fig. 2 (a) State $T_{x,l}$, (b) state $T_{B,b}$, (c) state $R_{x,l}$, and (d) state $R_{x,b}$.

message. According to the number of success packets in the thinking mode, the station enters a backlogged state of length b equal to the number of failed packets or returns to initial state if all packets have been successfully received.

Both thinking and backlogged states are compound states [Figs. 2(a) and 2(b)]. The transmission state $T_{X,l}$ is composed of $l+t+1$ states. In this state, a station sends the message in l sending states $\{s_1, s_2, \ldots, s_l\}$, then it enters t waiting states $\{W_1, W_2, \ldots, W_t\}$. These waiting states are required to enable the transmitter to receive an acknowledgment from the receiver. Finally, the acknowledgment is being received in the state $\{r_{\text{ack}}\}$. If all messages' packets have been successfully transmitted, the station returns to the initial state, otherwise if b packets are corrupted the station receives ask-for-retransmission from the receiver and enters a backlogged state $T_{B,b}$. The backlogged state is composed of $b+t+1$ states; starting with b sending states $\{s_1, s_2, \ldots, s_b\}$ followed by t waiting states $\{W_1, W_2, \ldots, W_t\}$ and finally $\{r_{\text{ack}}\}$.

The number of users entering the thinking state is equal to the number of stations waiting for request acknowledgment that got an acceptance:

$$T_{X,l} = \gamma \cdot \sum_{i=0}^{\tau} W_{t-\tau+i} = A(1-\sigma)m[1-(1-\gamma)^{\tau}],$$

but $T_{X,l}=\sigma m$, thus, $\sigma=A(1-\sigma)[1-(1-\gamma)^{\tau}]$.

Using the previous equation we can write γ as a function of σ, A and τ as

$$\gamma = 1 - \left[1 - \frac{\sigma}{A(1-\sigma)}\right]^{1/\tau}.$$

We define the number of active stations T as the number of stations that send data packets:

$$T = T_{X,l} l + \sum_{b=1}^{l} T_{B,b} b.$$

In addition, we define TX as the total number of stations in the transmitting mode involving sending, waiting, and receiving acknowledgment stations:

$$TX = T_{X,l}(l+t+1) + \sum_{b=1}^{l} T_{B,b}(b+t+1). \tag{4}$$

One can prove that the number of users in a backlogged stare $T_{B,b}$ can be written in a recursive relation as follows:

$$T_{B,b} = \begin{cases} \dfrac{P_{\text{ST}}(0,l)}{1-P_{\text{ST}}(0,l)} T_{x,l} & \text{if } b=1 \\ \dfrac{1}{1-P_{\text{ST}}(0,b)} \left[\dfrac{1}{1-P_{\text{ST}}(0,l)} T_{x,l} P_{\text{ST}}(l-b,\, l) + \displaystyle\sum_{\beta=l-1}^{b+1} T_{B,\beta} P_{\text{ST}}(\beta-b,\, \beta) \right] & \text{if } 1 < b \leq l-1. \end{cases} \tag{5}$$

The previous recursive relation can be used to calculate the number of active users T in each backlogged state. Finally, the total number of active users can be written as follows:

$$T = \frac{1}{1-P_{\text{ST}}(0,l)} T_{x,l} l + \sum_{b=l-1}^{1} \frac{b}{1-P_{\text{ST}}(0,b)} \left[\frac{1}{1-P_{\text{ST}}(0,l)} T_{x,l} P_{\text{ST}}(l-b,\, l) + \sum_{\beta=l-1}^{b+1} T_{B,\beta} P_{\text{ST}}(\beta-b,\, \beta) \right]. \tag{6}$$

Similarly, TX is given by

$$TX = \frac{1}{1-P_{\text{ST}}(0,l)} T_{x,l}(l+t+1) + \sum_{b=l-1}^{1} \frac{b+t+1}{1-P_{\text{ST}}(0,b)} \left[\frac{1}{1-P_{\text{ST}}(0,l)} T_{x,l} P_{\text{ST}}(l-b,\, l) + \sum_{\beta=l-1}^{b+1} T_{B,\beta} P_{\text{ST}}(\beta-b,\, \beta) \right], \tag{7}$$

where the probability $P_{\text{ST}}(x,y)$ is the probability of success transmission of x packets out of y packets. This means that a user in a state that involves y packets to be transmitted $P_{\text{ST}}(x,y)$ gives the probability of success transmission of x packets. This probability follows the binomial distribution as

$$P_{\text{ST}}(x,y) = \binom{x}{y} P_S(T)^x [1-P_S(T)]^{y-x},$$

where $P_S(T)$ is the packet success probability given T active users.

3.5 *Reception Mode*

A user in the reception mode receives either a new message from a thinking station or receives retransmitted packets from a backlogged station. Figures 2(c) and 2(d) describe the structure of both types of receiving states. State $R_{x,l}$ has a duration of $l+t+1$ time slots; it starts with t waiting states $\{W_1, W_2, \ldots, W_t\}$ followed by l receiving states $\{r_1, r_2, \ldots, r_l\}$, and finally it sends an acknowledgment in state $\{s_{\text{ack}}\}$.

Similarly, the state $R_{B,b}$ is composed of $b+t+1$ states. The start is t waiting states $\{W_1, W_2, \ldots, W_t\}$, then b receiving states $\{r_1, r_2, \ldots, r_b\}$ and finally sending the acknowledgment in $\{s_{\text{ack}}\}$. Notice that the receiving state starts with t waiting states. These states appear as a result of the propagation delay for the acceptance or ask-for-retransmission packet from the receiver to the transmitter and back to the receiver.

When a station enters the reception mode; first it enters the state $R_{X,l}$ in which it receives a new message from a transmitting station in state $T_{X,l}$. After receiving the new message and based on the number of success packets, the receiver sends an acknowledgment to the transmitter and returns to the idle state m if the message was received successfully; otherwise it enters a state $R_{B,b}$, where b is the number of failed packets.

Notice that there is a time shift between the transmitter and the receiver equal to one way propagation delay "$t/2$ time slots." This is a result for the fact that the connection is established at the receiver side when it accepts the connection while it is established at the transmitter side when it receives the acceptance after one-way propagation delay.

We define R as the number of stations in all receiving states that receive packets and RX as the total number of stations in the transmitting mode involving sending, waiting, and receiving acknowledgment stations:

$$R = R_{X,l}l + \sum_{b=1}^{l} R_{B,b}b = T,$$

$$RX = R_{X,l}(l + t + 1) + \sum_{b=1}^{l} R_{B,b}(b + t + 1) = TX. \quad (8)$$

Finally, note that the summation of the number of users in all states should be equal to the number of all network nodes N, can be written as

$$N = 2TX + m\left\{1 + \sigma + A(1 - \sigma)\left[t + \frac{1 - \gamma - (1 - \gamma)^{\tau}}{\gamma}\right]\right\}. \quad (9)$$

3.6 *Steady State System Throughput S*

Now it is required to evaluate the system performance in terms of the system throughput and average delay

$$S(N,A,t,\tau,l) = TP_S(T).$$

3.7 *Average Delay*

From the Little's theorem, the average packet delay D can be calculated from

$$D = \frac{NA}{S}\text{slots}.$$

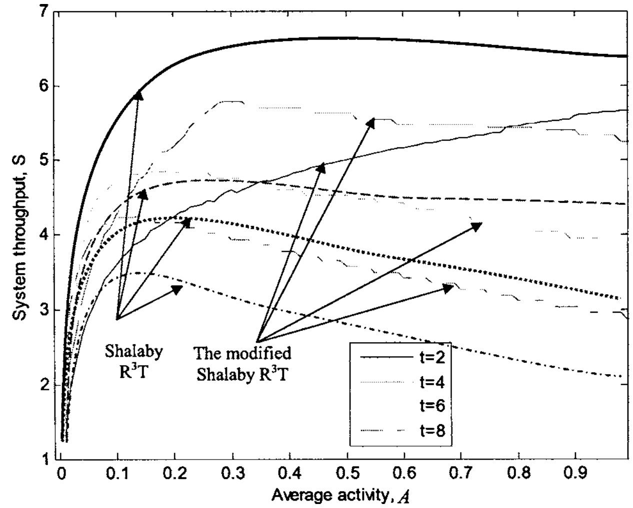

Fig. 3 Throughput versus average activity for different propagation delays for the proposed protocol (solid lines) and the Shalaby R^3T protocol (dotted lines) at N=30.

4 Numerical Results

In this section, we present some numerical results for the system throughput for the proposed protocol, which will carry the name of modified Shalaby R^3T protocol, and then compare its performance to that of the original protocol. The system performance is examined under the influence of changing the following parameters: average activity, propagation delay, network population, and message length. Simulation parameters are packet size K=127 bits/packet, code weight w=3, code length L=31, and time out duration τ=2, except in Fig. 3, where τ=1.

In Fig. 3, the throughput of both original and modified R^3T protocols is plotted versus the average activity for different propagation delays t=2, 4, 6,8 and network population N=30. For the proposed protocol, it is noticed that for a low propagation delay, the curve reaches its maximum at A=1, while for higher propagation delays the curve reach its maximum at lower activity and then begins to

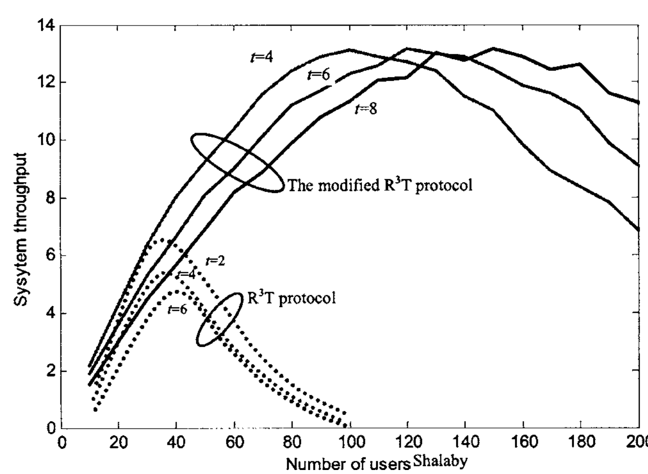

Fig. 4 Throughput versus number of users for different propagation delays of the proposed protocol (solid lines) and the Shalaby R^3T protocol (dotted lines).

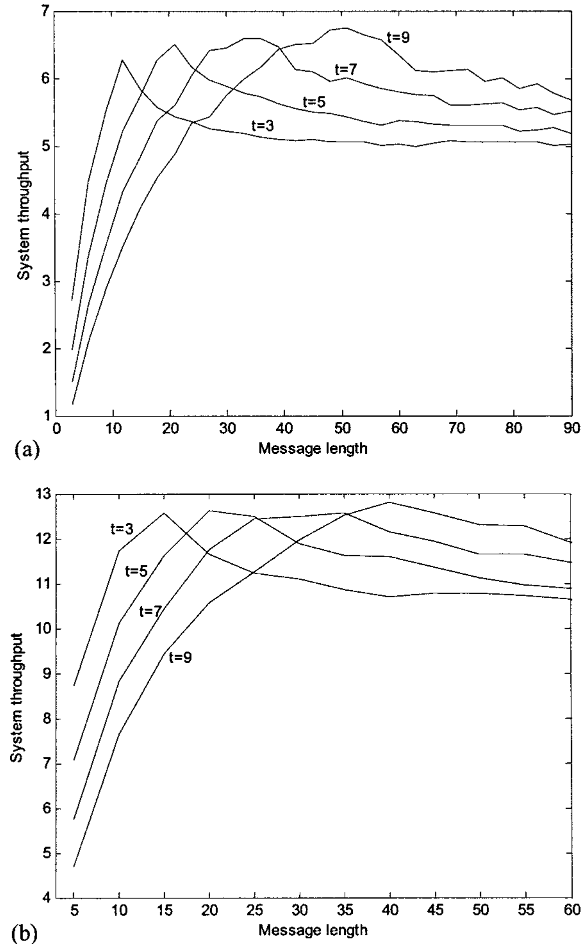

Fig. 5 Throughput versus message length for different propagation delays of the modified Shalaby R^3T protocol at (a) $N=30$ and $A=0.5$ and (b) $N=80$ and $A=0.5$.

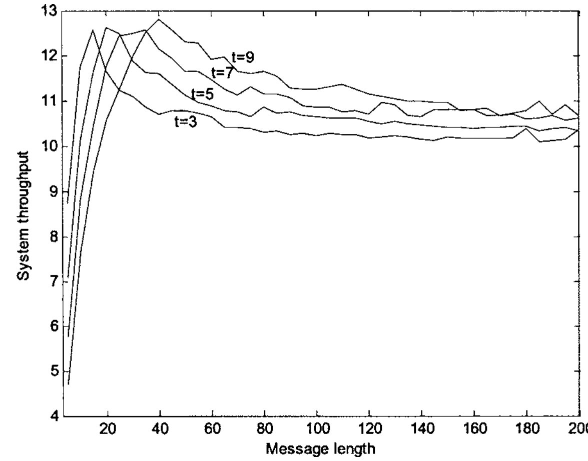

Fig. 6 Effect of dramatic increase of the message length on the system throughput at $N=80$ and $A=0.5$.

decay. The value of activity with maximum throughput decreases as the propagation delay increases. For the Shalaby R^3T protocol, all curves reach the maximum throughput at the same average activity. From Fig. 3 it is found that the Shalaby R^3T protocol gives slightly higher performance compared to the proposed protocol at a low value of propagation delay (e.g., $t=2$). However, the proposed protocol gives higher performance at higher values of propagation delays.

Figure 4 shows the performance of both protocols versus network population. First, we can say that the proposed protocol gives much higher performance than the original one for all values of network population. Furthermore, as the number of users increases the throughput of the Shalaby R^3T protocol decreases dramatically, while, the proposed protocol gives good performance for a high range of network population. Second, as for the effect of propagation delay on the proposed protocol, it is noticed that at low network population, the low values of propagation delay give higher performance, while as the network population increases, a better performance is achieved at higher propagation delays. It is expected that the propagation delay is proportional to the number of users, and hence as the number of users increase, the propagation delay also increases, thus enhancing the system performance. This phenomenon can be explained as follows. As the network population increases, the number of users in transmitting mode also increases, thus the offered traffic is expected to increase. On the other hand, not all users in the transmitting mode are permitted to send data; some users send data and others wait for acknowledgment. The number of waiting users is proportional to the propagation delay. Thus, as the propagation delay increases, the number of waiting users also increases and hence the offered traffic is reduced, leading to higher performance. Hence, we can say that the proposed protocol is characterized by adaptive offered traffic and as a result the proposed protocol remains efficient for large population networks.

For the Shalaby R^3T protocol,[12] it is noticed that the performance is accepted for low population networks, while it gives a poor performance at higher network population (greater than 50 nodes). This poor performance of the R^3T protocol in large population networks is caused by the inefficient utilization of channels; that is, approximately all active users transmit data packets. Furthermore, the receiver cannot receive all successfully transmitted packets; it receives only successful packets that arrive in the proper order.

Now, we consider the effect of the message length on the system throughout. In Figs. 5 and 6, we plot the system throughput versus the message length for different values of propagation delay at network populations of 30 and 80 users. It is found that increasing the message length raises the system throughput to reach its peak at an optimum message length. Then, increasing the message length above this optimum value results in a reduction in the system throughput. Also, optimum message length depends on both the network population and the propagation delay. From Fig. 5, it is found that the optimum message length is proportional to the propagation delay and inversely proportional to the network population. It is also noticed that, before a certain point, a lower propagation delay gives higher performance, while after this point, the higher propagation delays give higher performance. We call this point an inversion limit, that is, increasing the message length to reach this point represents a high number of packets being transmitted, i.e., higher data traffic that requires more idle states in the transmission state to reduce (compensate for) this high traffic to keep the performance at high level. Furthermore, when the message length increases dramatically, the system throughput reaches a saturation level and the effect of the propagation delay is reduced (Fig. 6).

5 Conclusions

A new optical CDMA network protocol based on selective retransmission technique was introduced. A mathematical model was presented using a detailed state diagram. The performance of the proposed protocol was examined using the equilibrium point analysis. Our results show that the proposed protocol gives a good performance for a wide range of network population. Furthermore, its performance is better than that of the original Shalaby R^3T protocol. As for the effect of propagation delay, networks with a small population give higher performance with small delays, while as the population increases, better performance is achieved at higher delays. Practically, as the population increases, the propagation delay also increases, and hence the performance is automatically enhanced. As for the protocol complexity, the proposed protocol has a more complicated transmission algorithm than the R^3T protocol. Also, it requires more buffer capacity at both the receiver and transmitter sides. This gives us the conclusion that the Shalaby R^3T protocol is more suitable for small population, while the modified one is the choice for large population.

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