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New optical random access code-division multiple-access protocol with stop-and-wait automatic repeat request

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Abstract. A random access protocol that adopts stop-and-wait automatic repeat request (ARQ) is proposed for optical code-division multiple-access (CDMA) communication systems. A detailed state diagram and a mathematical model based on the equilibrium point analysis (EPA) technique are presented. Several performance measures are evaluated under different network parameters. In addition, the performance of the proposed protocol is compared to that of the round-robin receiver/transmitter (R^3T) protocol, which is based on a go-back-n-technique. The ALOHA CDMA protocol is also considered. Finally, our protocol is analyzed when a queuing subsystem is added. Our numerical analysis shows that the proposed protocol is less complex and significantly outperforms the R^3T protocol. We show that adding a single buffer to the system does not improve the performance much. [DOI: 10.1117/1.2748746]

Subject terms: code-division multiple-access protocol; optical random access; automatic repeat request; stop and wait.

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1 Introduction

The success of modern communication systems has shifted focus toward optical fiber networks. Optical code-division multiple-access (CDMA) systems particularly have been shown to be competitive candidates to support large number of simultaneous users.[1–11] Most research in optical CDMA networks has concentrated on the physical layer.[1–4] There are, however, a few authors that examined the network and/or link layer of optical CDMA communication systems.[5–10] Raychaudhuri introduced a simple but general random access CDMA protocol based on ALOHA.[5] In Refs. 6 and 7, Hsu and Li have studied slotted and unslotted optical CDMA networks, respectively. In Ref. 8, Shalaby has proposed two media access control (MAC) protocols for optical CDMA networks. However, the effect of multipacket messages, connection establishment, and retransmission of corrupted packets have not been taken into account. Recently, Shalaby developed a new protocol called the round-robin receiver/transmitter (R^3T) protocol that has solved some of these problems.[9] The R^3T protocol is based on a go-back-n automatic repeat request (ARQ), i.e., when a packet gets corrupted, the transmitter retransmits it and all subsequent packets. This scenario gives good performance in low population networks, while the performance is still low in larger population networks. Considering only retransmission of corrupted packets, a selective reject ARQ has been applied in Ref. 10, which yields better results in cases of high population networks. On the other hand, more complexity was added to the system.

Our goal in this work is to develop a new optical random access CDMA protocol based on a stop-and-wait ARQ to reduce the complexity of previously proposed protocols. At the same time, we aim at improving the system performance compared to the R^3T protocol. More precisely, we wish to support a larger number of users with a higher system throughput and an acceptable packet delay. For convenience, our protocol is compared to ALOHA CDMA and R^3T protocols.[5,9] Moreover, the proposed protocol is examined for the case of both chip-level and correlation receivers. In addition, the performance is studied when introducing a queuing subsystem, namely increasing the number of available buffers, as in Ref. 11.

The rest of this work is organized as follows. In Sec. 2 we discuss the system and hardware architecture of our optical CDMA network. Section 3 is devoted to a description of the proposed protocol. The optical link layer is described and a complete state diagram of this protocol is presented. Section 4 is maintained for the mathematical model, where derivations of the steady-state system throughput, the average packet delay, and the blocking probability are given. In our analysis, focus is oriented toward multiple access interference (MAI) only, where the effect of the receiver's noise is neglected. In Sec. 5 the proposed protocol is examined with the addition of a queuing subsystem; the same performance metrics are considered. In Sec. 6 we present some of the numerical results obtained. A comparison between the proposed protocol and the R^3T protocol[9] is also considered. Finally, we give our conclusions in Sec. 7.

2 System and Hardware Architecture

The network is composed of N stations or nodes, connected in a passive star topology. Optical orthogonal codes

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(OOCs) are used because they have both unity peak cross-correlation and shifted autocorrelation. The choice of code weight w and code length L for OOCs is arbitrary because they determine the cardinality of the code family.[1] Due to the bursty nature of the traffic, we allow the number of users to exceed the number of available codes.

In our model, we assume that all codes are always available in a pool. To avoid receiver tunability, codes are assigned to users *a priori*. That is, when a user subscribes to the network, he is given a code (possibly used) randomly. Further, a code is randomly cyclic shifted around itself once assigned, for security purposes and to control the MAI. In this way there is no need for pretransmission coordination. It has been shown that for fixed data rate and chip duration, there is no advantage in using pulse position modulation (PPM) in place of on-off keying (OOK). That is why each user is able to generate an optical OOK-CDMA signal according to its signature code that represents its data. Considering a message that is composed of ℓ packets, each having K bits and taking only the effect of MAI into account, we can write the packet success probability $P_S(r_o)$ given $r_o \in \{1,2,\ldots,N\}$ active users, for both chip-level and correlation receivers, as in Ref. 8.

3 Mathematical Model

Because of its simplicity over other ARQs, stop-and-wait is implemented at the data link layer of our optical CDMA network. After a packet is sent, a user enters a waiting mode to receive a feedback of that packet. If a positive acknowledgement is received, the user will send the next packet, otherwise he will retransmit another version of the corrupted packet. We impose the following assumptions in our model for optical CDMA protocol.

- Time is slotted with slot size T_s, a two-way propagation delay time is assumed to be equal to t time slots, and a timeout duration of τ time slots is selected such that $1 \leq \tau \leq t$.
- A message is composed of $\ell > t$ packets each having $K > 0$ bits. One packet should fit in a time slot $T_s = K\ell T_c$, where T_c is the chip duration.
- A maximum of one message per time slot can arrive at each time slot to a station with probability A (also called user activity). This message is stored in a buffer until its successful transmission. Any arrival to a nonempty buffer will be blocked.
- For connection initialization and establishment, connection requests and acknowledgements are exchanged between stations. Transmission times for requests and acknowledgements are neglected.
- A priority is given for the reception mode other than for the transmission mode.
- Receivers use a cyclic redundancy check (CRC) to determine whether a received packet is correctly detected or not.

The complete state diagram of the proposed optical CDMA random access protocol with stop-and-wait ARQ is illustrated in Fig. 1. Each state is labeled by its number of users. Transition between states is, on a slot basis, that is, the duration of each state equals one time slot. At any time slot, any user in the network will be in one of the following states or modes.

- Initial state $\{m\}$. Users in the initial state scan across all codes in a round-robin manner. If a connection request (event with probability σ) is found, a station will proceed to the acknowledgment mode. If there is a message arrival and there is no connection request, it will go to the requesting mode. If there is neither message arrival nor connection request, the station will remain in the initial state.
- Requesting mode $\{q_1,q_2,\ldots,q_\tau\}$. Stations in this mode send repeated requests $\{q_1,q_2,\ldots,q_\tau\}$ for τ time slots. Then the station should wait for feedback and thus enters a waiting mode $\{W_1^q,W_2^q,\ldots,W_{t-1}^q\}$, for $t-1$ time slots, as depicted in Fig. 1. Whenever a waiting station gets a positive acknowledgement (event with probability γ) from the destination, it starts sending its message and enters the transmission mode, otherwise it remains in the waiting mode. In the last waiting state, if an acknowledgment is not received, the station is timed out and returns to the initial state.
- Acknowledgment state $\{a\}$. In this state, the station sends an acknowledgment to a requesting station and then enters a waiting mode $\{W_1^{s1},W_2^{s1},\ldots,W_{t-1}^{s1}\}$ for t time slots until the reception of the first packet.
- Reception mode $\{Rx_1,Rx_2,\ldots,Rx_\ell\}$. A user in the reception mode receives either new packets or retransmitted ones. Figure 1 illustrates the structure of the states, $R_{X,i}$, $i \in \{1,2,\ldots,\ell\}$. In states s_i, a user receives packet i. If it is successfully received, the user will move to states $\{W_1^{si+1},W_2^{si+1},\ldots,W_{t-1}^{si+1}\}$ waiting for the next packet, otherwise he will ask for retransmission and enters a waiting mode $\{W_1^{si},W_2^{si},\ldots,W_{t-1}^{si}\}$. If the station receives the last packet successfully, it goes back to the initial state.
- Transmission mode $\{Tx_1,Tx_2,\ldots,Tx_\ell\}$. This mode involves transmission states r_i, $i \in \{1,2,\ldots,\ell\}$, and waiting states W_j^{ri}, $j \in \{1,2,\ldots,t-1\}$, as in Fig. 1. A user in state r_i is transmitting packet i, then he enters a waiting mode $\{W_1^{ri},W_2^{ri},\ldots,W_{t-1}^{ri}\}$ to get the acknowledgment of that packet. If a positive feedback is received, the user will proceed to state r_{i+1}, otherwise he will return to state r_i for retransmission. After successful transmission of the last packet, the user will return to the initial state.

4 Performance Analysis

Because of the complexity of the prior model and the prohibitively large number of states, the problem will be analytically intractable if we try to calculate the transition probabilities between states and the stationary probabilities using Markov chains.[12] Fortunately, the equilibrium point analysis (EPA) technique significantly simplifies the problem. In this technique, the system is always assumed to be operating at an equilibrium point[13]; that is, the number of users entering a state is equal to the number of users de-

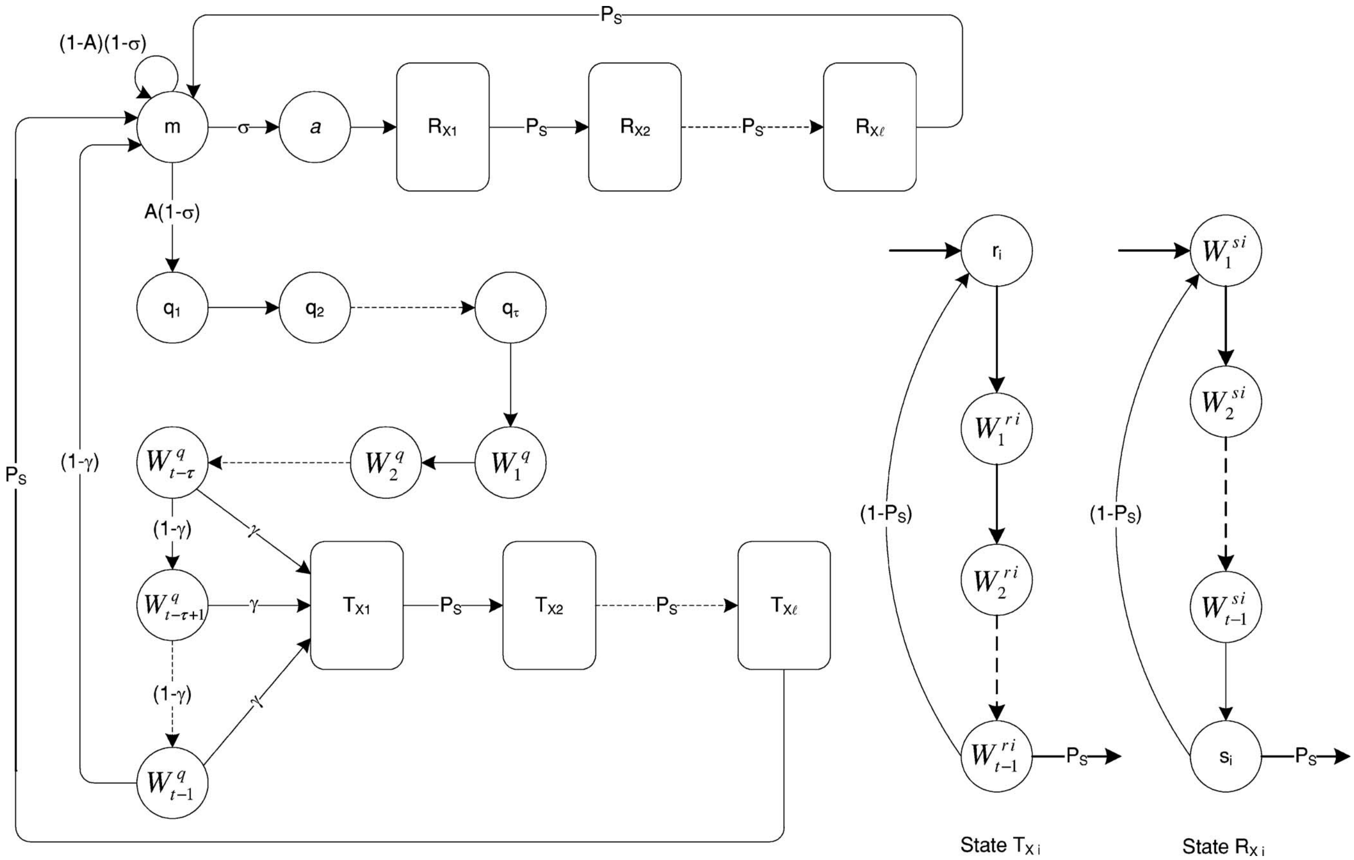

Fig. 1 Complete state diagram of the proposed stop-and-wait optical CDMA protocol.

parting from the same state. By writing down the flow equations for each state, the performance of the proposed optical CDMA protocol can be evaluated.

4.1 *Transmission Mode*

This mode involves states r_i and states W_j^{ri}, where $i \in \{1,2,\ldots,\ell\}$ and $j \in \{1,2,\ldots,t-1\}$. From Fig. 1, we have the following flow equations.

$$r_1 = r_2 = \ldots = r_\ell \quad \text{and} \quad W_j^{ri} = r_1.$$

Let r_o denotes the number of transmitting users in a given slot, such that

$$r_o = \sum_{i=1}^{\ell} r_i = \ell\, r_1. \tag{1}$$

We define W^r as the number of users waiting after transmission

$$W^r = \sum_{i=1}^{\ell} \sum_{j=1}^{t-1} W_j^{ri} = \ell\,(t-1)\cdot r_1. \tag{2}$$

4.2 *Reception Mode*

Assuming that the number of users transmitting packet i is equal to that receiving the same packet, for $i=1$ we can directly write $r_1 = s_1$. From Fig. 1, we can write the flow equations for states s_i and W_j^{si}, for $i \in \{1,2,\ldots,\ell\}$ and $j \in \{1,2,\ldots,t-1\}$ as follows:

$$W_1^{s1} = a + (1-P_S)\cdot s_1,$$

$$s_1 = s_2 = \ldots = s_\ell = r_1 \quad \text{and} \quad W_j^{si} = r_1. \tag{3}$$

We define the following variables

$$s = \sum_{i=1}^{\ell} s_i = \ell\, r_1$$

$$W^s = \sum_{i=1}^{\ell} \sum_{j=1}^{t-1} W_j^{si} = \ell\,(t-1)\cdot r_1. \tag{4}$$

4.3 *Acknowledgment Mode*

Again, by writing the flow equations for the states in this mode described in Fig. 1 and using Eq. (3) we get:

$$a = \sigma m = P_S r_1. \tag{5}$$

Therefore,

$$m = \frac{P_S}{\sigma} r_1 . \tag{6}$$

4.4 *Requesting Mode*

Figure 1 illustrates the requesting states and waiting states in the requesting mode. By writing down the flow equations as in Ref. 9, we define:

$$q + W^q = \sum_{i=1}^{\tau} q_i + \sum_{i=1}^{t-1} W_i^q = \left\{ t - 1 + \frac{1}{\gamma}[1 - (1 - \gamma)^{\tau}] \right\} A \frac{1-\sigma}{\sigma} P_S r_1 . \tag{7}$$

The probability that a request is found by a scanning user σ and the probability that a station gets an acknowledgment γ can be computed as follows[9]:

$$\sigma = \frac{1}{2}\left\{ \left[\left(A P_S \tau \frac{r_1}{N} \right)^2 + 4 \left(A P_S \tau \frac{r_1}{N} \right) \right]^{1/2} - A P_S \tau \frac{r_1}{N} \right\}$$

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

4.5 *Steady-State System Throughput*

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

$$\beta(N, A, t, \tau, \ell) = \sum_{i=1}^{\ell} s_i \cdot P_S = P_S(r_o)\, \ell\, r_1 .$$

Substituting with Eq. (1), we get

$$\beta(N, A, t, \tau, \ell) = r_o P_S(r_o) . \tag{8}$$

To compute r_o, we assume that the total number of users in all states is equal to N, yielding

$$N = m + r + W^r + s + W^s + a + q + W^q = \frac{r_o}{\ell}\left(\frac{P_S}{\sigma} + 2\,\ell\, t + P_S + \left\{ t - 1 + \frac{1}{\gamma}[1 - (1-\gamma)^{\tau}] \right\} A \frac{1-\sigma}{\sigma} P_S \right), \tag{9}$$

where we have used Eqs. (1)–(7).

4.6 *Blocking Probability*

The blocking probability is defined as the probability of an arrival being blocked. 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

$$P_B = \frac{m}{N} \cdot \sigma \cdot A + \left(1 - \frac{m}{N} \right) \cdot A .$$

Substituting with Eqs. (1) and (6), we get

$$P_B = A \left[1 - \frac{P_S}{\ell N} \left(\frac{1-\sigma}{\sigma} \right) r_o \right] . \tag{10}$$

4.7 *Average Packet Delay*

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

$$D = \frac{NA \cdot (1 - P_B)}{\beta(N, A, t, \tau, \ell)} \quad \text{slots}, \tag{11}$$

where $NA \cdot (1 - P_B)$ denotes the total traffic in the network. Note that Eqs. (10) and (11) are valid for both optical random access CDMA protocols: stop-and-wait ARQ and go-back-n ARQ.[9]

5 Proposed Protocol with Queuing Model

In an attempt to decrease the blocking probability of the previous model, we equipped each node with a single buffer. This queuing subsystem is able to store one more message (message waiting to be served) if the main buffer is busy. Any arrival to a nonempty queue is blocked. The queue is ready to receive a new message once the stored message is moved to the server for transmission. The state diagram of the proposed optical CDMA protocol with queuing subsystem is illustrated in Fig. 2. Each mode is 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. Transitions between states are on a slot basis. Users move from states marked with 0 to states marked with 1 if there is a message arrival. The transmission and reception modes are illustrated in detail in Fig. 2(b). For further explanation about the other modes, we refer the reader to Ref. 11.

We apply the EPA technique to measure the performance of the model described earlier. A similar mathematical model has been previously presented in Ref. 11. By writing down the flow equations for all the states, we can derive the steady-state system throughput, average packet delay using Eqs. (8) and (11), respectively. When 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 the following.

1. After successful transmission/reception: if there is a connection request and there is a message arrival, blocking will occur.
2. After request: a message is blocked if the station is timed out, if 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.

$$P_B = \frac{A}{N}[r_1 + W_1^s + a_1 + q_1 + W_1^r + s_1 + W_1^q - (1 - P_S\sigma) \times (W_{t-1,1}^r + s_{\ell,1}) - (1-\gamma)(1-\sigma) \cdot W_{t-1,1}^q] . \tag{12}$$

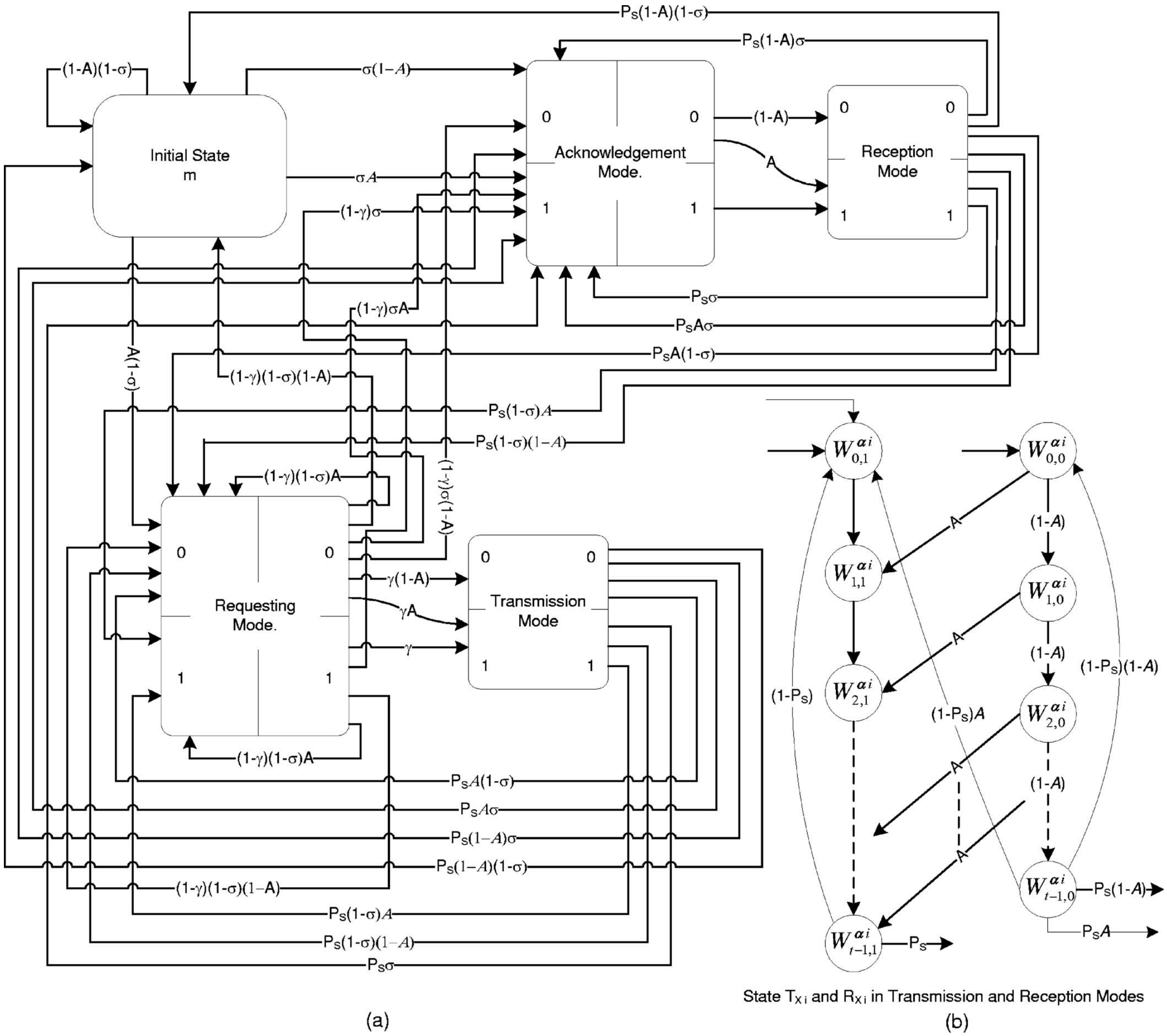

Fig. 2 State diagram of the proposed optical CDMA protocol with a single buffer in the queue.

6 Numerical Results and Discussion

In this section, we discuss some numerical results for the proposed optical random access CDMA protocol. The steady-state system throughput, the blocking probability, and the average packet delay derived before have been evaluated and compared to the results in Ref. 9. Our results are plotted in Figs. 3–7. In our simulations, a user bit rate of $R_b = 127$ Mbps is held constant. Optical orthogonal codes with length $L = 31$, code weight $w = 3$, and unity correlation constraints are used. A message length of $\ell = 15$ packets each having $K = 127$ bits is selected. A two-way propagation delay time $t \in \{2, 4, 6\}$ slots (or interstation distances of $z = vT_s t/2 \in \{200, 400, 600\}$ m, where $v \approx 2 \times 10^8$ m/s is the speed of light inside a fiber) and a timeout duration $\tau = 1$ slot are imposed in our simulations. The performance of the proposed protocol using both chip-level receivers and correlation receivers is also presented. Correlation receivers are only considered in Fig. 3.

In Fig. 3 we have plotted the throughput versus the number of users for both chip-level receivers and correlation receivers. General trends of the curves can be noticed. As the number of users in the network increases, more packets become available for transmission with low interference. Thus the throughput increases until it reaches its peak. As the number of users is further increased, the effect of MAI becomes significant and the throughput starts to decay. It is noticed that the R^3T outperforms the proposed protocol at low population networks. This is due to the fact that the channels are efficiently utilized in smaller networks; that is, approximately all active users can transmit their packets without errors. In cases of high population networks, stop-

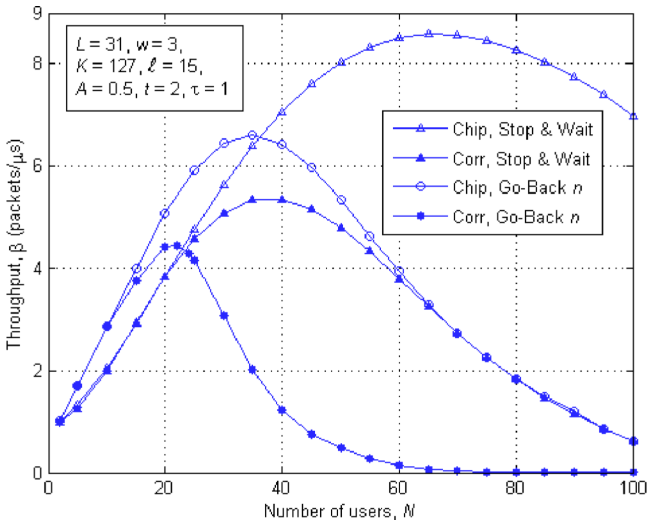

Fig. 3 Throughput versus number of users for different receivers.

and-wait ARQ significantly surpasses the R^3T. This is because in stop-and-wait, the channel is not busy all the time, as users enter a waiting mode after sending each packet. On the other hand, for a protocol depending on a go-back-n ARQ, users continuously send their packets, which contribute to higher traffic loads, yielding lower packet success probability and in turn lower throughput values. It can be inferred that the performance of both protocols is reduced when using correlation receivers and that the performance of the stop-and-wait with correlation receivers is nearly close to that of the R^3T protocol with chip-level receivers.

In Fig. 4 we have plotted the system throughput and the average packet delay versus the average activity for different number of users $N \in \{30, 70\}$. It can be noticed that the R^3T protocol exhibits higher throughput values and lower delays at N=30, whereas the proposed protocol outperforms the R^3T protocol at N=70, as argued in Fig. 3. For short interstation distances, as the user activity increases the throughput also increases until it reaches saturation, whereas for longer distances the throughput falls after reaching its peak. In fact, the initial increase of throughput is because as A increases above zero, more packets become available with low interference. The throughput decays in the case of long propagation delays after reaching its peak, because the number of active users increases while other users already in the transmission mode are still busy transmitting their messages over long distances. The interference would thus increase rapidly and packet failures would become more probable. Finally, it is noticed that for longer interstation distances and an increase in user activity, the average packet delay increases.

Figure 5 depicts the relationship between the system throughput and the carried load for our protocol, the R^3T, and the ALOHA CDMA protocols. In the case of stop-and-wait and R^3T protocols, we have defined the carried load as the number of available packets per time slot that is identical to the number of active users. By varying the total

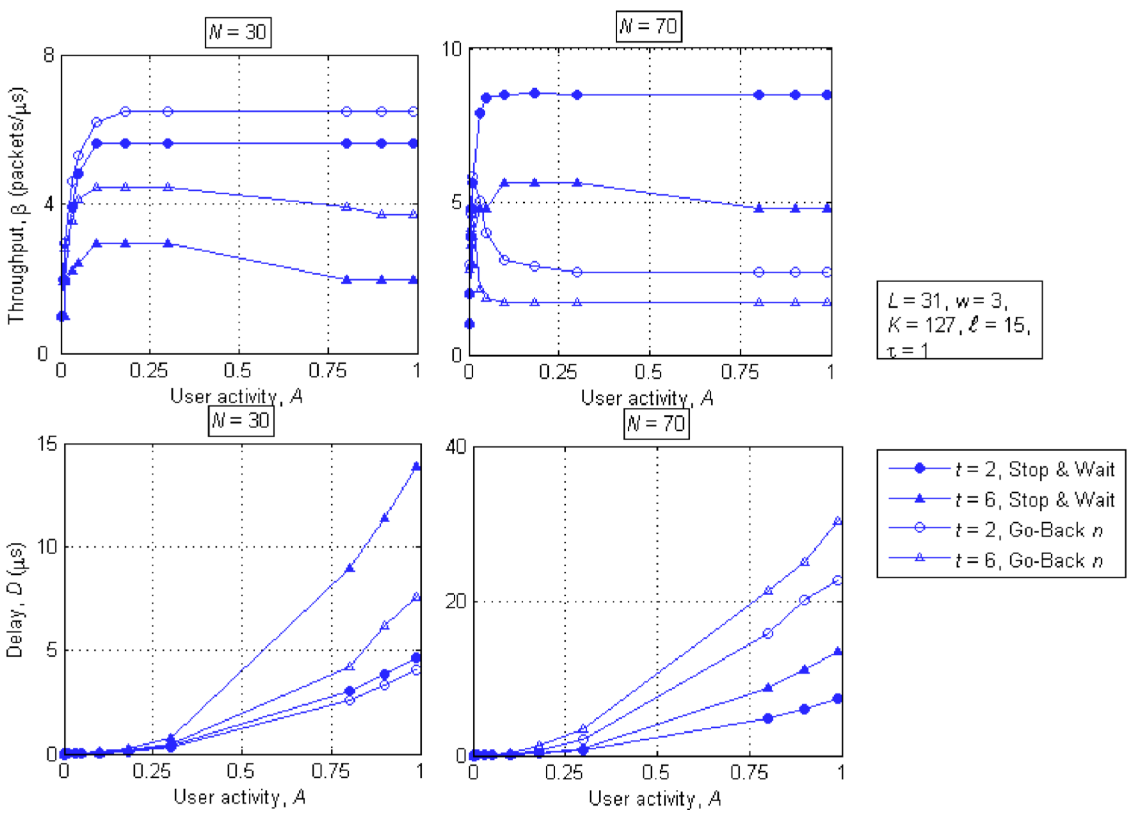

Fig. 4 Throughput and delay versus activity for different numbers of users and different interstation distances.

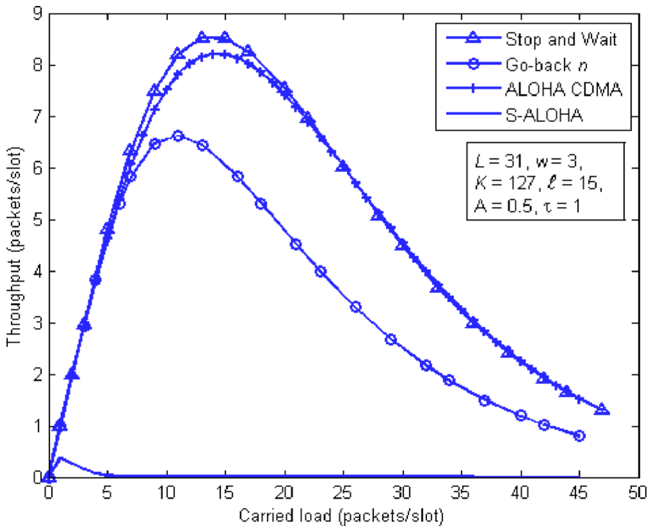

Fig. 5 Throughput versus carried load.

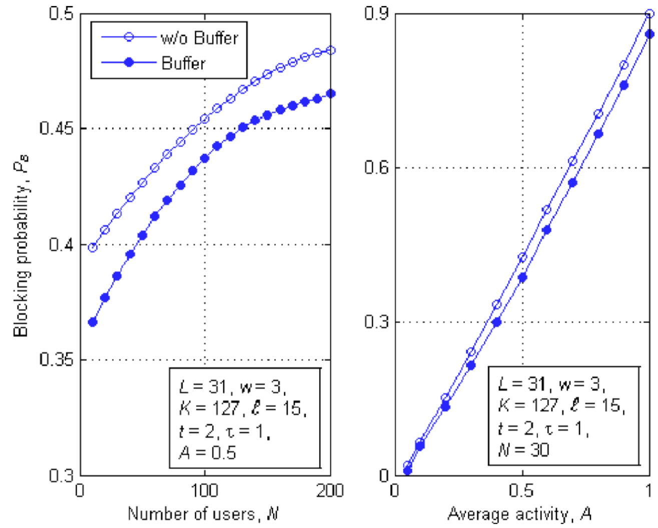

Fig. 7 Blocking probability versus number of users and average activity.

number of users N in the network and for a 50% average user activity, we were able to obtain the same carried load as the ALOHA CDMA protocol. Since the effect of MAI is negligible at lower loads, the three protocols behave similarly. However, at moderate loads, our protocol outperforms the R^3T protocol and ALOHA CDMA protocol. The latter is because our protocol includes coordination between users through connection requests and acknowledgments, compared to ALOHA CDMA. It is evident that for a fully loaded channel, all the protocols will behave the same way. The traditional S-ALOHA was also plotted for convenience.

In Fig. 6 we have plotted the relation between the throughput and the average packet delay when varying the average user activity and for different numbers of users in the network. General trends of the curves can be noticed. As the user activity increases, both the throughput and the average packet delay increase until the throughput reaches its saturation value. It can be shown that this value depends on both the code length and the interstation distance.[9] It is immediately noticed that for larger numbers of users and higher activity levels, the queuing delay adds to the total latency of the network.

Finally, the blocking probability has been plotted against both the number of users and the average activity in Fig. 7. It can be noticed that by including only a single buffer to the system, the blocking probability can be reduced.

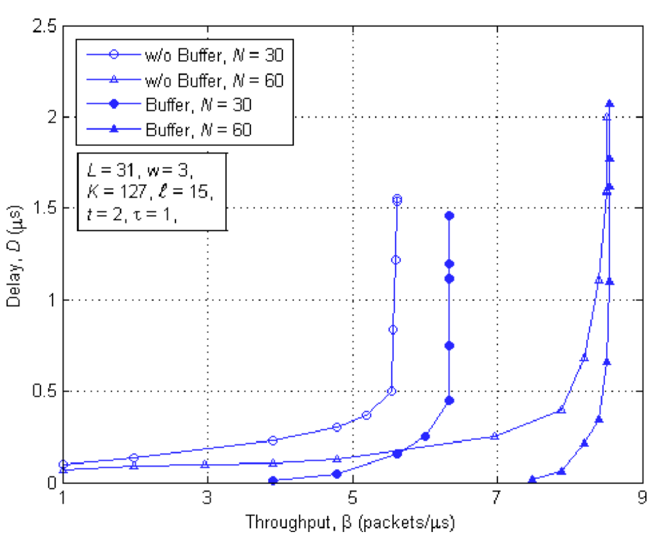

Fig. 6 Average packet delay versus throughput for different numbers of users.

7 Conclusions

In this work, an optical random access CDMA protocol based on a stop-and-wait ARQ is proposed. A mathematical description of this protocol is presented using a detailed state diagram. Mathematical expressions for the steady-state system throughput, the blocking probability, and the average packet delay are derived and simulated. In our numerical calculations, we focus only on the effect of MAI. Both correlation and chip-level receivers are also examined. The following concluding remarks can be extracted from our results.

1. The performance of the proposed CDMA protocol using correlation receivers is almost the same as that of the R^3T protocol with chip-level receivers.
2. The proposed protocol outperforms the R^3T protocol (in terms of the system throughput and average packet delay) in high population networks, whereas for smaller size networks the R^3T protocol slightly outperforms the proposed one.
3. Our protocol slightly outperforms the ALOHA CDMA protocol at moderate traffic loads.
4. Both protocols exhibit satisfactory blocking probability only for small traffic loads. Furthermore, the average packet delay is acceptable under different network parameters.
5. For larger interstation distances, the proposed protocol accommodates a higher number of users. Also,

the quality of service (QOS) requirements can be achieved in a larger dynamic range (wider range of users).

6. The complexity of the proposed protocol is significantly reduced compared to the R^3T protocol. Also, the cost is reduced when using correlation receivers.
7. The proposed protocol with queuing subsystem shows a slight improvement in the performance for low propagation delays and small population networks. Also, the blocking probability is reduced and the queuing delay is negligible.

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