Optical CDMA Protocol with Selective Retransmission

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Abstract

New protocol for optical code-division multiple access (CDMA) networks is proposed. Our proposed protocol is based on selective retransmission technique. A mathematical model is presented using a detailed state diagram. The protocol is analyzed using equilibrium point analysis (EPA), and its performance is examined using traditional throughput and average delay for several network parameters. We also compare the performance of the proposed protocol to the R^3T protocol based on go-back-*n* technique. Results show that a higher performance is achieved by the proposed protocol at the expense of system complexity.

I. Introduction

Optical networks have been of great importance in the last decade due to its extremely high bandwidth that covers the high data rates offered by modern networks and communication systems. Optical code-division multiple access (CDMA) [1]-[11] appears as the best technique that can mine this huge bandwidth. Many researches were presented to propose or study optical CDMA network protocols. In [8] and [9] Hsu and Li have studied the slotted and unslotted optical CDMA systems. In [10] we have studied media access control (MAC) protocol and discussed the problem of multiple packet messages in unslotted optical CDMA systems. Where as, in [11] Shalaby has introduced new protocols for optical CDMA networks to discuss the problem of assigning codes for different users. However, there are other important problems haven't been studied in the previous papers such as:

1. The establishment and release of a connections.
2. The problem of multiple packet messages.
3. How the protocol deals with the lost packets.

In [12] Shalaby has presented a so called round-robin-receiver transmitter (R^3T) protocol to solve these problems. R^3T protocol is based on the go-back-*n* technique; in this technique when a packet is corrupted, the transmitter retransmits the corrupted and all successive packets, on the other hand the receiver accepts only success packets that come in the proper order. Results indicate that the performance of the 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 based on the selective retransmission technique, where only corrupted packets will be retransmitted. In our system chip-level receiver [7] is implemented in all network nodes.

The rest of the paper is arranged as follows: in section 2, first we present the network architecture, then the chip-level receiver, and finally our proposed protocol is presented. The system analysis is presented in section 3, where we present a detailed state diagram for the proposed protocol and calculate the system throughput and average delay. In section 4 we present some numerical results and compare the performance of the proposed protocol to the performance of the R^3T protocol. Finally, the paper is concluded in section 5.

2. The proposed protocol

2.1. Network architecture

The network is composed of N stations or nodes, connected in a star topology. A set of optical orthogonal codes (OCC) $\{a_1, a_2, \ldots\ldots, a_C\}$, where C depends on the code length L and code weight w. Both out-of-phase autocorrelation and cross correlation 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 that x. In our network each user is assigned an optical orthogonal code as its own signature, when the number of

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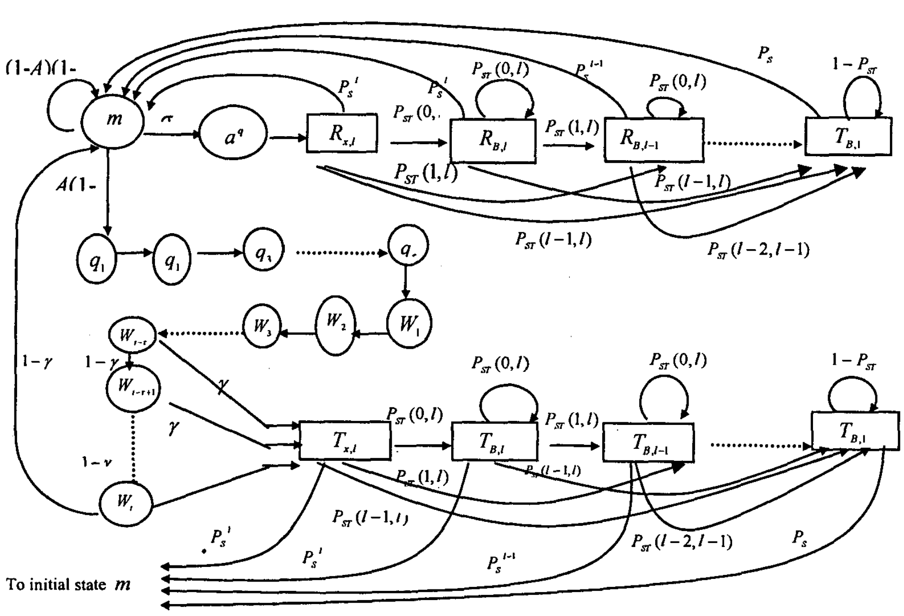

Fig.1. State diagram of the proposed protocol.

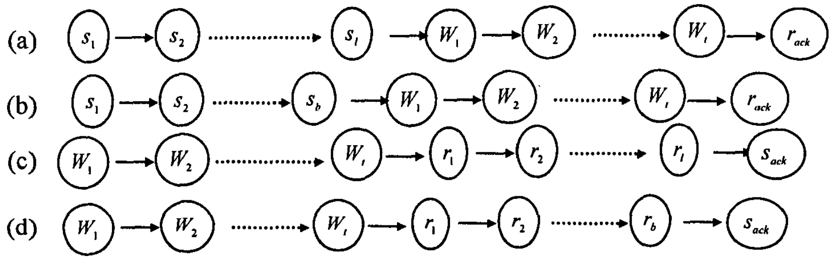

Fig. 2. (a) State $T_{x,l}$; (b) State $T_{B,b}$; (c) State $R_{x,l}$; (d) State $R_{x,b}$.

users exceeds the number of codes, a used code is cyclic shifted around it self and assigned to another user. Each user has a fixed transmitter and 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 codes.

2.2. Chip-level receiver

In our network chip-level receiver in used in all network nodes. The decision rule of the chip-level receiver is: data bit 1 is declared if the number of pulses in all mark positions of the signature code are non zero, otherwise data bit 0 is declared. According to Shalaby [7], packet success probability for a packet with K bits is:

$$Ps(r) = \frac{(r-1)!}{k!m!(r-1-m-k)!} \cdot p_1^k p_w^m (1-p_1-p_w) \cdot \sum_{\substack{k_1,k_2,\ldots,k_w: \\ k_1+k_2+\ldots+k_w=k}} \frac{k!}{k_1!k_2!\ldots.k_w!} \cdot$$

$$\left(\frac{1}{w}\right)^k \cdot \left[\frac{1}{2} + \frac{1}{2^{m+1}}\left(\sum_{i=1}^{w}\frac{1}{2^{k_i}} - \sum_{i=1}^{w-1}\sum_{j=i+1}^{w}\frac{1}{2^{k_i+k_j}} + \ldots\ldots + (-w)^{w-1}\frac{1}{2^k}\right)\right]^K$$

where: $p_w = \frac{1}{L} \cdot \left[\frac{L-1}{w(w-1)}\right]^{-1}$, $\quad p_1 = \frac{w^2}{L} - wp_w$

2.3. The proposed protocol

Time is slotted with a slot size of $T_s = K \cdot L \cdot T_C$, where K is the packet length (bits/packet), T_C is the chip duration and L is the code length. A Packet transmission is permitted to start at the beginning of a time slot. The message contains l packets. Message arrives to a station with a probability A, also called user activity. Each packet has a header contains CRC code and the packet serial number (packet order in the message).

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 acknowledgement. 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 acknowledgement and tunes its receiver to the code of the transmitter. Also it creates the transmission table; a table contains list of the packets to be transmitted; 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 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 acknowledgement 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; where b is the number of packets to be retransmitted. Instantaneously it starts sending these packets. This scenario is repeated till all packets are success.

3. System analysis

3.1. Idle state m

Stations in the idle state are scanning over all codes for a connection requests. If it receives a connection request it responds by an acknowledgement. If it did not found 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 in order to establish a connection with the desired user. This is achieved by sending τ requests $\{q_1, q_2, \ldots\ldots, q_\tau\}$. Then the station waits for request acceptance, it enters a waiting mode contains t states ($W_1, W_2, W_3, \ldots\ldots, W_t$), each state is one time slots length. Whenever a waiting user gets an acceptance for connection it starts sending its message and enters transmission mode $T_{x,l}$.

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 receives an acceptance for connection. By writing the flow equations we get

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

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

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

Define: q : Number of users in the requesting mode

W^q : Number of users in the mode of waiting mode.

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

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

Where σ is the probability that a request is captured by a user, as shown below:

$$\sigma = \frac{1}{N} q = \frac{1}{1 + N/_{m \cdot A \cdot \tau}}$$

3.3. Acknowledge mode a^q

In acknowledge mode idle stations respond to a connection request sent by an active station.

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

3.4. Transmission mode

Transmission mode involves transmitting packets receive acknowledgements. This mode is composed of two types of states, Figs. 2a, 2b; first is for stations that send new message called thinking state $T_{X,l}$, this state has a duration of $l+t+1$ time slots. Second is called backlogged state $T_{B,b}$ in which a backlogged user retransmits corrupted packets, where $b=1,2,...,l$ 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 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. 2a, 2b. The transmission state $T_{X,l}$ is composed of $l+t+1$ states. In this state station sends the message in l sending states $\{s_1, s_2, ..., s_l\}$, then it enters t waiting states $\{W_1, W_2, ..., W_t\}$. These waiting states are required to enable the transmitter to receive acknowledgement from the receiver. Finally, it receivers the acknowledgement in state $\{r_{ack}\}$. 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 $\{s_1, s_2, ..., s_b\}$ followed by t waiting states $\{W_1, W_2, ..., W_t\}$ and finally $\{r_{ack}\}$.

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

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

But: $T_{X,l} = R_{X,l} = \sigma \cdot m$,

thus, $\sigma = A \cdot (1-\sigma) \cdot \left[1-(1-\gamma)^{\tau+1}\right]$

From the last equation we can write γ as a function of σ, A and τ as shown below:

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

Define:

The number of active stations T as the number of stations that send data packets.

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

TX : as the total number of stations in the transmitting mode involving sending, waiting and receiving acknowledgement stations

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

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

$$T_{B,b} = \begin{cases} \dfrac{P_{ST}(0,l)}{1-P_{ST}(0,l)} \cdot T_{x,l} & \text{if } b=l \\ \dfrac{1}{1-P_{ST}(0,b)} \cdot & \\ \left\{\dfrac{1}{1-P_{ST}(0,l)} \cdot T_{x,l} \cdot P_{ST}(l-b,l) + \sum\limits_{\beta=l-1}^{b+1} T_{B,\beta} \cdot P_{ST}(\beta-b,\beta)\right\} & \text{if } 1<b\leq l-1 \end{cases}$$

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:

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

Similarly TX is given by:

$$TX = \frac{1}{1-P_{ST}(0,l)} \cdot T_{x,l} \cdot (l+t+1) \tag{7}$$

$$+ \sum_{b=l-1}^{1} \frac{b+t+1}{1-P_{ST}(0,b)} \cdot \left\{\frac{1}{1-P_{ST}(0,l)} \cdot T_{x,l} \cdot P_{ST}(l-b,l) + \sum_{\beta=l-1}^{b+1} T_{B,\beta} \cdot P_{ST}(\beta-b,\beta)\right\}$$

where the probability $P_{ST}(x,y)$ 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 $P_{ST}(x,y)$ gives the probability of success transmission of x packets. This probability follows the binomial distribution as shown below:

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

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 form a thinking station or receives retransmitted packets from a backlogged station. Figures 2c and 2d 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 $\{W_1, W_2, \ldots\ldots, W_t\}$ followed by l receiving states $\{r_1, r_2, \ldots\ldots, r_l\}$, and finally it sends an acknowledgement in state $\{s_{ack}\}$.

Similarly, the state $R_{B,b}$ is composed of $b+t+1$ states. The start is t waiting states $\{W_1, W_2, \ldots\ldots, W_t\}$, then b receiving states $\{r_1, r_2, \ldots\ldots, r_b\}$ and finally sending the acknowledgement in $\{s_{ack}\}$. It is noticed that the receiving state starts with t waiting states. These states appear as a result to 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 sate $T_{X,l}$. After receiving the new message and up on the number of success packets the receiver sends an acknowledgement 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 in the number of failed packets.

It is noticed 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 as it is established at the transmitter side when it receives the acceptance after one way propagation delay.

Define: R : Number of stations in all receiving states that receive packets.

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

RX : The total number of stations in the transmitting mode involving sending, waiting and receiving acknowledgement stations

$$RX = R_{X,l} \cdot (l+t+1) + \sum_{b=1}^{l-1} R_{B,b} \cdot (b+t+1) = TX \qquad (5)$$

Steady state system throughput S

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

$S(N, A, t, \tau, l) = T \cdot P_S(T)$

The summation of the number of users in all states should equals to the number of all network nodes N, can be written as:

$$N = 2 \cdot TX + m \cdot \left\{ 1 + \sigma \cdot m + A \cdot (1-\sigma) \cdot \left(t + \frac{1-\gamma-(1-\gamma)^{\tau+1}}{\gamma} \right) \right\} (8)$$

Average delay:

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

$$D = \frac{N \cdot A}{S} \text{ slots.}$$

4. Numerical results

In this section we present some numerical results for the system throughput for the proposed protocol. And compare the performance of the proposed protocol to that of the R^3T protocol. Simulation parameters are: packet size $K = 127$ bits/packet, code weight $w = 3$, code length $N = 31$, and time out duration $\tau = 2$.

In Fig. 3, the throughput is plotted versus the average activity for different propagation delays $t = 2,4,6,8$, N=30, for the proposed protocol and R^3T protocol. For the proposed protocol it is noticed that for low propagation delay the curve reaches its maximum at $A = 1$, for higher propagation delays the curve reach its maximum at lower activity and then starts decaying. The value of activity with maximum throughput decreases as the propagation delay increases. For R^3T protocol all curves reaches the maximum throughput at the same average activity. Also, the achieved throughput in R^3T protocol is lower than the throughput of the proposed protocol. However, R^3T protocol gives slightly better performance for very low propagation delay e.g t=2. As the propagation delay increase as the advantage of the proposed protocol appears.

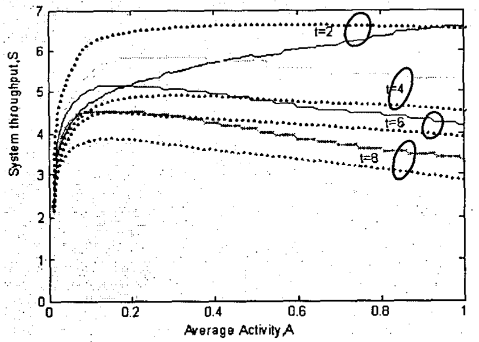

Fig. 3. Throughput vs. average activity for different propagation delays for the proposed protocol "solid lines" and R^3T protocol "dotted lines"

Figure 4 shows the performance of both protocols versus network population. For the proposed protocol it is noticed that: for low network population the performance of the proposed protocol is better with low value of propagation delay, as the network population increases the better performance is achieved with higher propagation delays. As for low population networks propagation delay is expected to be low, while the network population increase the distance between users increases and the propagation delay also increases, and hence the protocol performance is automatically enhanced. 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, another factor should be considered that is not all users in the transmitting mode are permitted to send data; some users send data and others wait for acknowledgement. The number of waiting users is proportional to the propagation delay. As the network population increases the propagation delay increases and the number of waiting users also increases and hence the offered traffic is reduced leading to higher performance. Thus we can say that our proposed protocol is characterized by adaptive offered traffic and as a result the proposed protocol remains efficient for large population networks.

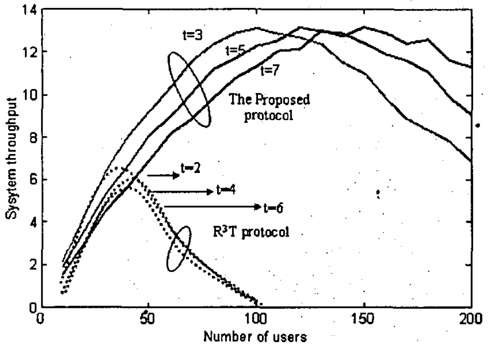

Fig. 4. Throughput vs. number of users for different propagation delays for the proposed protocol "solid lines" and R^3T protocol "dotted lines".

For R^3T protocol [12], it is noticed the performance is accepted for low population networks, while it gives poor performance for higher network population (greater than 50 nodes). This poor performance of R^3T protocol in large population networks is caused by the inefficient utilization of channel; that is approximately all active users transmit data packets, furthermore a small number of the transmitted packets are to be received depends on the status of previous packets. This problem is called flooding and it is responsible for the weakness of network protocols based on go-back-*n* protocol.

5. Conclusions

A new optical CDMA network protocol based on selective retransmission technique has been introduced. Mathematical model is presented using a detailed state diagram. The performance of the proposed protocol is examined using the equilibrium point analysis. 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 R^3T protocol. As for the effect of propagation delay, networks with small population give higher performance with small delays, while as the population increases the 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 R^3T protocol. Also, it requires more buffer capacity at both receiver and transmitter sides.

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