Analysis of MAC Protocols with Correlation Receiver for OCDMA Networks - Part II

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Abstract—In this paper optical code-division multiple-access (O-CDMA) packet network is considered, which offers inherent security in the access networks. Two types of random access protocols are proposed for packet transmission. In protocol 1, all distinct codes and in protocol 2, distinct codes as well as shifted versions of all these codes are used. O-CDMA network performance using optical orthogonal codes (OOCs) 1-D and two-dimensional (2-D) wavelength/time single-pulse-per-row (W/T SPR) codes are analyzed. The main advantage of using 2-D codes instead of one-dimensional (1-D) codes is to reduce the errors due to multiple access interference among different users. In this paper, correlation receiver is considered in the analysis. Using analytical model, we compute and compare packet-success probability for 1-D and 2-D codes in an O-CDMA network and the analysis shows improved performance with 2-D codes as compared to 1-D codes.

Keywords—Optical code-division multiple-access, optical CDMA correlation receiver, wavelength/time optical CDMA codes

I. INTRODUCTION

OPTICAL code-division multiple-access (O-CDMA) has received considerable attention as a multiple access scheme in high speed local area networks. In this O-CDMA scheme multiple users to transmit information over the same physical channel concurrently. Each user is identified with a unique orthogonal sequence, and the data is encoded using the particular sequence, as a result this scheme is inherently secure. However, the performance and capacity of CDMA systems are limited by multiple user interference [1]. In broadcast network like O-CDMA, multiple access interference (MAI) is dominant compared to receiver noises [2]. It is another technology of multiplexing and multiple-access besides OTDM and WDM and a potentially promising technique for optical networks in the future, and especially, due to its easy access and flexible network structure, it is applicable to the access network. A typical network architecture for O-CDMA [3] is shown in Fig. 1. The O-CDMA technique has several advantages over other multiple access techniques, e.g., asynchronous scheme, simple communication protocols, better utilization of the time-frequency domain by each subscriber, flexibility in network design, and inherent security against interception [4].

In this paper, we propose two random access protocols for slotted O-CDMA packet networks, which use OOCs or W/T

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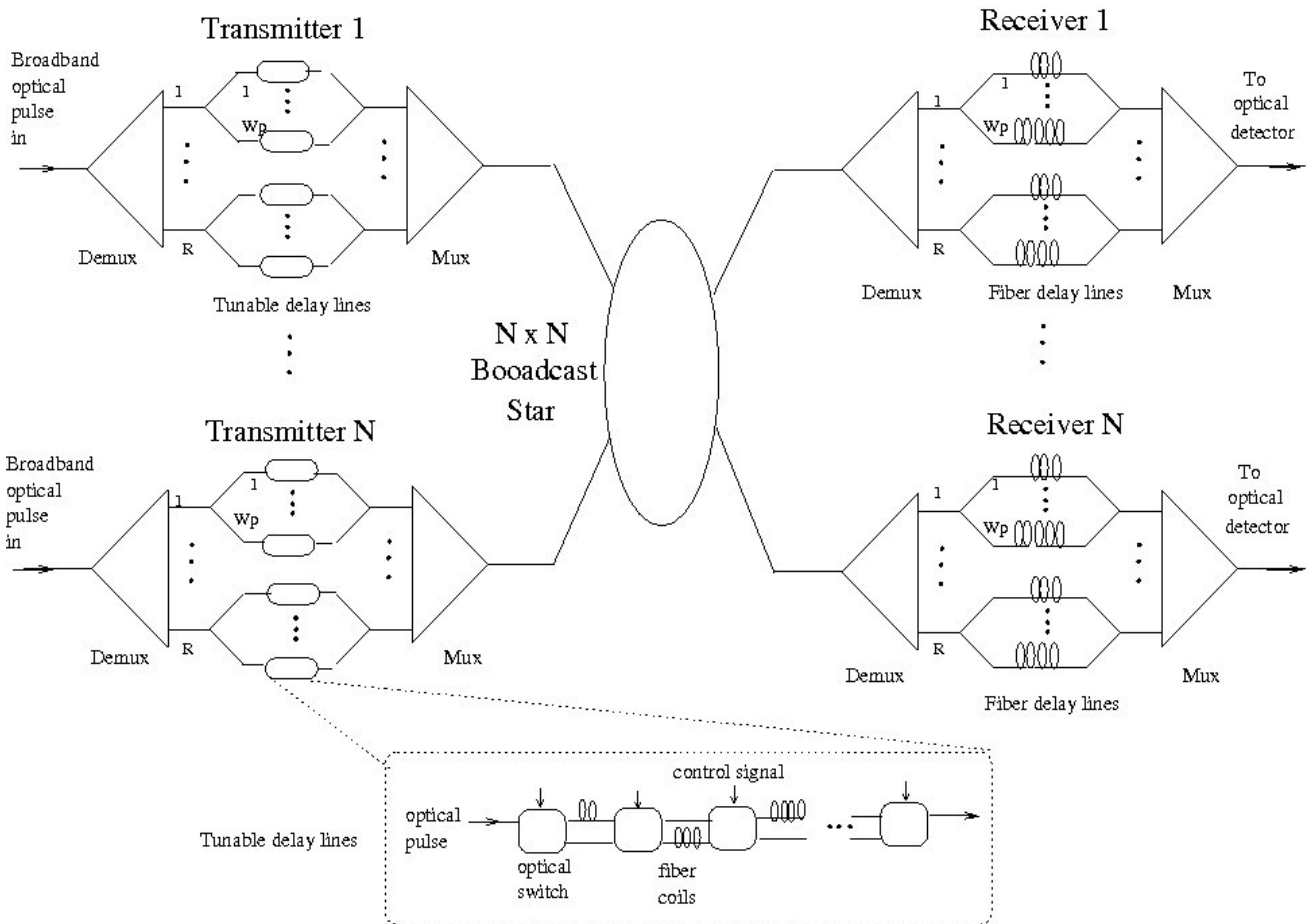
SPR codes [5]. We named our proposed protocols as Protocol-1 and Protocol-2. In [4], [6] and [7] 1-D codes are used in the O-CDMA packet network. Among several 1-D codes OOCs have the lowest out-of-phase auto-correlation and cross-correlation values, equal to 1. But the disadvantage of OOCs is that as the number of users or the weight of the code is increased, the length of the sequence increases rapidly. As a result of this, for a given chip width the bit rate reduces which is not desirable. Hence, aimed at the shortcoming of 1-D codes, 2-D OCDMA codes are used.

With the aid of cyclic redundancy check (CRC) codes, a receiver can determine whether a received packet is correctly detected or not. If not it will ask for retransmission. This would increase the channel traffic and interference. A transmitter asked for data retransmission is not allowed to generate new packets; rather it keeps retransmitting the same packet (after random delay time slots) until it receives a successful acknowledgment from destination [6].

Two types of performance measures are examined in this paper. The first one is the probability of chip (one chip (P_1) and w chip (Pw)) interference. The other one is the packet-success probability, (Ps). The main objective of this paper is to compare the performance (packet-success probability) of the optical CDMA networks using 1-D codes with that of the 2-D codes. In our analysis, we will consider the correlation receiver model.

The organization of the paper is as follows: In section II, the O-CDMA system architecture and the two MAC protocols we are proposed. Analytical modeling of the two protocols for correlation receiver for OOCs and W/T SPR codes is derived, in section III. Further, in section IV, the results obtained from the analytical models are discussed for the two protocols.

II. SYSTEM ARCHITECTURE

The notations used in this section are:
- N # of nodes or users in network
- C Cardinality
- W Weight of 1-D code
- R # of rows = code weight ($R=W$ in 2-D codes)
- L temporal length of code
- λ_a out-of-phase autocorrelation peak
- λ_c cross-correlation peak

The cardinality |C| of 1-D codes depends on L, W, λ_a and λ_c.

In the case of OOCs, $\lambda_a = \lambda_c = 1$, we have

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Fig. 1 Network architecture of 2-D O-CDMA network in star configuration

$$|C| = \left\lfloor \frac{L-1}{W(W-1)} \right\rfloor \qquad (1)$$

The cardinality $|C|$ of 2-D codes depends on L, R, λ_a and λ_c. For the case of W/T SPR codes, $\lambda_a = 0$, $\lambda_c = 1$. We have $C \le P$. $|C| = P$, when $L=P$, P prime number.

Assumptions made in this section are:

- N is allowed to be greater than $|C|$
- Codes are assigned to users depending on Protocol-1 or Protocol-2

A. Protocol-1

- Initially all codes are available in the code-pool
- In order to transmit a packet by user to destination, user is assigned a code from pool in random manner.
- The assigned code is no longer available to other transmitting users in the same slot.
- Also, if N > |C|, there might be some active users that cannot be assigned any code. These users should try to transmit at subsequent time slots.
- Using this protocol only 1-chip interference

P1 will occur between any two transmitting users.

B. Protocol-2

- This protocol is similar to the one above (Protocol-1) but the codes are never removed from the pool. It means all active users can always find a code (original code or shifted version code) to transmit its packet.
- When using this protocol, more interference is possible since a code can be used more than once.
- In order to reduce the probability of interference between different users, a code is randomly cyclic shifted around itself once selected.
- In this case, the offered traffic at a given time slot might be higher than the previous case (in Protocol-1).

Using this protocol, two types (1-chip P_1 and R-chip P_R) of interference can occur between any two transmitting users.

III. ANALATICAL MODELING OF THE SYSTEM

The definitions used in this section are:

- *active user*: one that is about to transmit a packet
- *backlogged mode*: the mode where users retransmit same (faulty) packet

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- *backlogged users*: the users who are in backlogged mode
- *thinking mode*: the mode where users transmit newly generated packets
- *thinking users*: the users who are in thinking mode [8]

The notations used in this section are:

- K = the length of a packet in bits
- n = number of backlogged users out of total N users in network
- r = number of active users in a given slot
- $r-1$ = number of interfering users to the desired user
- s = number of users (out of r-1 users) interfere with desired user at 1-chip
- a = number of users (out of r-1 users) interfere with desired user at w-chips
- Z = total received pulses from all weighted chips
- $P_{bc}(a,s)$ = the conditional bit-correct probability (given a & s)
- $P_s(r/a, s)$= the conditional probability of a packet-success (given a & s)
- $P_s(r)$ = the probability of a packet success given 'r' active users.
- P_1 = the probability of 1-chip interference between two users
- P_R = the probability of R-chip ($R=W$) interference between two users

Let the system model consists of N users having same average activity A. The packets are transmitted in slotted manner. The length of a packet is K bits and corresponds to slot duration. An active user is assigned a code before packet transmission depending on the protocol used (Protocol-1 or Protocol-2). On the other end, the intended receiver transmits an acknowledgment to the sender as soon as packet is received successfully. If packet is not received successfully, the sending user enters a backlog mode and retransmits the packet after a random delay time with average d time slots. In the next section we calculate a packet-success probability $P_s(r)$ for the correlation receiver model [6].

A. Packet Success Probability for a Correlation Receiver

Correlation receiver decides a data bit 1 was transmitted if the total received pulses Z from all weighted chips is greater than or equal to a threshold $\theta = R$. A data bit 0 is decided otherwise [9]. Since we are using codes with correlation constraints equal to 1, that is users of different codes interfere with each other by one chip at most. On the other hand, users of same code interfere with each other by zero, one, or R chips.

Assuming chip-synchronous interference model among users, we derived the probabilities of 1-chip interference (P_1) and probabilities of R-chip interference (P_R), for OOCs and W/T SPR codes are:

$$p_1(ooc) = \begin{cases} \dfrac{W^2}{L}; & protocol-1 \\[2ex] \dfrac{W^2}{L} \cdot \dfrac{|C|-1}{|C|}; & protocol-2 \end{cases} \quad (2a)$$

$$p_1(spr) = \begin{cases} \dfrac{R}{L}; & protocol-1 \\[2ex] \dfrac{R}{L} \cdot \dfrac{|C|-1}{|C|}; & protocol-2 \end{cases} \quad (2b)$$

$$p_R = \begin{cases} 0, & protocol-1 \\[2ex] \dfrac{1}{L} \cdot \dfrac{1}{|C|}; & protocol-2 \end{cases} \quad (3)$$

Assuming there are r active users and r-1 interfering users with the desired user. Out of these r-1 users, let s users interfere, with the desired user, at 1-chip and a users interfere at R-chip. Also by assuming equally likely binary data bits (Pr{0} = Pr {1} = ½), the conditional bit-correct probability $P_{bc}(a,s)$ is calculated:

$$P_{bc}(a,s)$$
$$= \Pr\{\, bit\ success \mid a,s\}$$
$$= \frac{1}{2}\Pr\{\, bit\ success \mid a,s, 1\ was\ sent\}$$
$$+ \frac{1}{2}\Pr\{\, bit\ success \mid a,s, 0\ was\ sent\}$$
$$= \frac{1}{2}\Pr\{Z \geq R/a,s,\ 1\ was\ sent\} + \frac{1}{2}\Pr\{Z \langle R/a,s,\ 0\ was\ sent\}$$
$$= \frac{1}{2} + \frac{1}{2}\Pr\{all\ 'a'users\ send\ 0\ and\ Z\langle R/a,,s\ 0\ was\ sent\}$$
$$= \frac{1}{2} + \frac{1}{2} \cdot \frac{1}{2^a} \cdot \frac{1}{2^s}\sum_{i=0}^{R-1}\binom{l}{i} \quad (4)$$

Thus the conditional success probability for the correlation receiver is

$$P_s(r \mid a,s) = \left[P_{bc}(a,s)\right]^K = \left[\frac{1}{2} + \frac{1}{2} \cdot \frac{1}{2^{s+a+1}}\sum_{i=0}^{R-1}\binom{l}{i}\right]^K \quad (5)$$

Finally, the packet success probability given r active users for protocol-1 and protocol-2 are as shown in equations (6) and (7) respectively at the end of this paper.

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IV. RESULTS AND DISCUSSION

Performance comparison of 1-D and 2-D codes in an O-CDMA network is analyzed in this section for the two protocols discussed in the previous section. The O-CDMA network performance is analyzed by using 1-D and 2-D codes with variation in the number of users and also the spread sequence length.

In Figures 2 and 3, packet success probability is evaluated for protocols-1 and protocol-2 using 1D and 2D codes respectively, as the number of active users are increased, for constants *C=10, L=21 and R=w=2* constant. This result shows that, the packet-success probability, in case of protocol-1 and protocol-2 using 2D codes is higher than using 1D codes. As the number of active users increase the probability of packet success decreases due to increased multiple access interference from other interfering users.

In Figures 4 and 5, probability of packet success is evaluated for protocols 1 and 2, with variation of the spread sequence length, keeping number of active users *r=10* and *r=19* respectively and *C=10* is kept constant. This result shows that, the packet-success probability, in case of protocol-1 and protocol-2, improves as the spread sequence length increases due to reduced interference per chip.

In Figures 6 and 7 the performance of two protocols are compared for 1D and 2D codes respectively. In protocol-1 the maximum number of active users is limited to *C,* since all the users are given distinct codes. In protocol-2 the distinct codes are assigned when C ≤ r, otherwise shifted versions of the codes are assigned randomly. *Ps* is higher for 2D codes than 1D codes as seen from Figures 6 and 7 due to the reduced MAI for given weight of the code, sequence length and number of users.
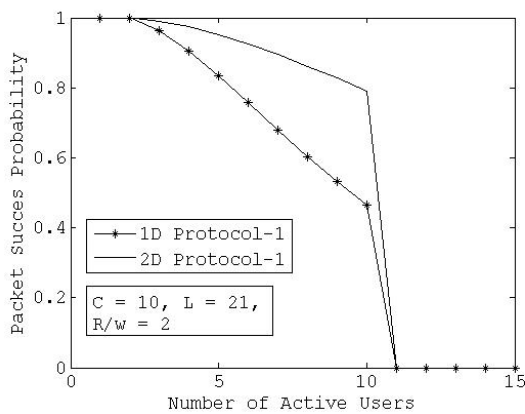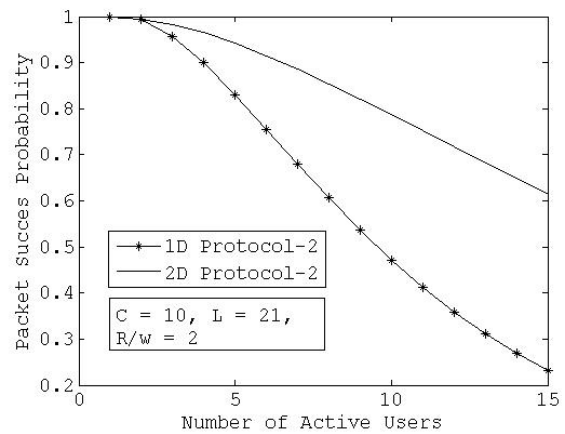
Fig. 3 Deteriorating packet-success probabilities with the increase in active users, in Protocol-2 with 1D and 2D codes

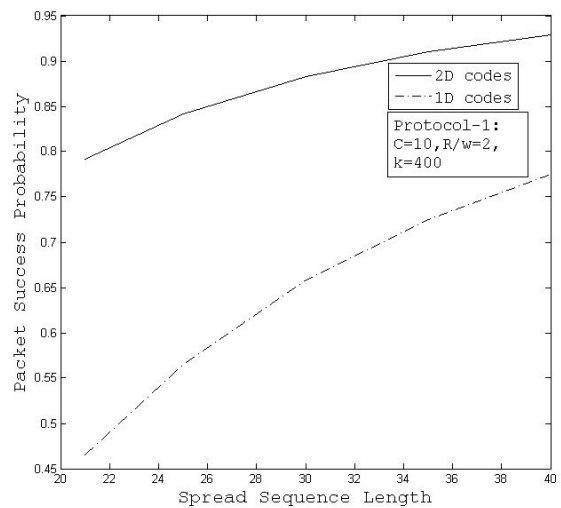Fig. 4 Comparison of packet-success probabilities in Protocol-1 between 1D and 2D codes
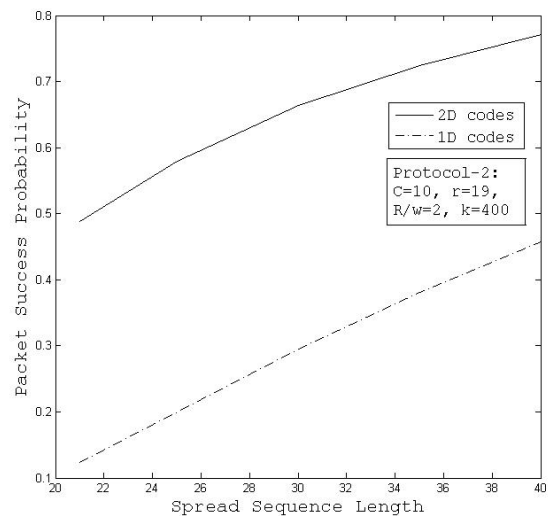
Fig. 2 Deteriorating packet-success probabilities due to inc-rease in MAI from interfering users, in Protocol-1 with 1D and 2D codes

Fig. 5 Comparison of packet-success probabilities in Protocol-2 between 1D and 2D code

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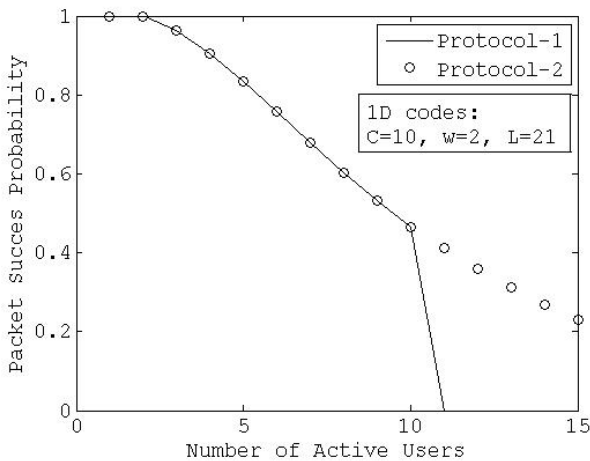Vol:5, No:5, 2011

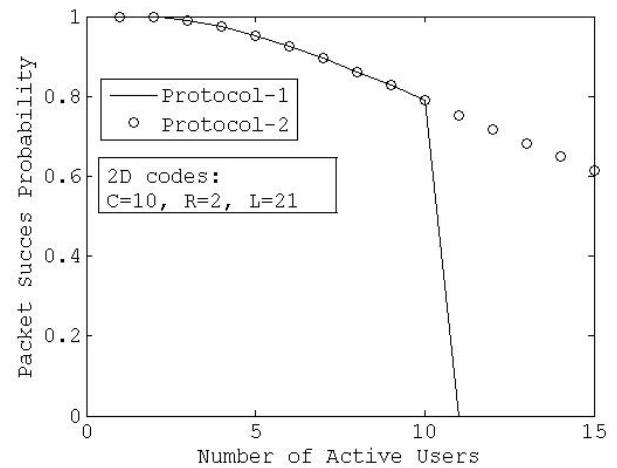Fig. 6 Comparison of performance of the two protocols for 1D codes

Fig. 7 Comparison of performance of the two protocols for 2D codes

V. CONCLUSIONS

Optical CDMA has attracted considerable attention in the recent years for high speed access network applications due to the salient features it has such as inherent security, asynchronous transmission, concurrent access to the channel etc. Two MAC protocols for O-CDMA access networks have been proposed and analyzed, with correlation receiver, for 1-D OOCs and 2-D W/T SPR codes.

From our analysis, we find that 2-D codes perform better over 1-D codes, due to decreased interference between codes, for a given weight of the code, as a result have higher packet success probability. We have observed from the analysis, the performance deteriorates with increase in the MAI as the number of active users increase. On the other hand the performance improves with the increase in the spread sequence length of the codes.

For protocol-1 packet success probability is:

$$P_S(r) = \sum_{s=0}^{r-1} \frac{(r-1)!}{s!(r-1-s)!} p_1^s (1-p_1)^{r-1-s} \left[\frac{1}{2} + \frac{1}{2^{s+1}} \sum_{i=0}^{R-1} \binom{s}{i} \right]^K \tag{6}$$

For protocol-2 packet success probability is:

$$P_s(r) = \sum_{s=0}^{r-1} \sum_{m=0}^{r-1-s} \frac{(r-1)!}{s!a!(r-1-a-s)!} p_1^s p_R^a (1-p_1-p_R)^{r-1-s-a} \left[\frac{1}{2} + \frac{1}{2^{a+s+1}} \sum_{i=0}^{R-1} \binom{s}{i} \right]^K \tag{7}$$

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