Analysis of MAC Protocols with Correlation Receiver for Optical CDMA Networks – Part I

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ABSTRACT
In this paper optical code-division multiple-access (O-CDMA) packet network is considered. 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.

General Terms
MAC protocols, Optical CDMA networks.

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

1. 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 transmit information over the same physical channel concurrently. However, the performance and capacity of CDMA systems are limited by multiple user interference (MAI) [1]. In broadcast network like O-CDMA, multiple access interference is dominant compared to receiver noises [2]. O-CDMA is another multiplexing technology and 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, for the access networks. A typical network architecture for O-CDMA [3] in broadcast star 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 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 networks. 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 O-CDMA are used.

With the aid of cyclic redundancy check (CRC) codes, a receiver can determine whether a received packet is correctly detected. 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 one chip (P_1) and w chip ($Pw= P_R$) interferences. The other one is the packet-success probability, (Ps). The main objective of this paper is to compare the performance (P_S) of the O-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 proposing are discussed. 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.

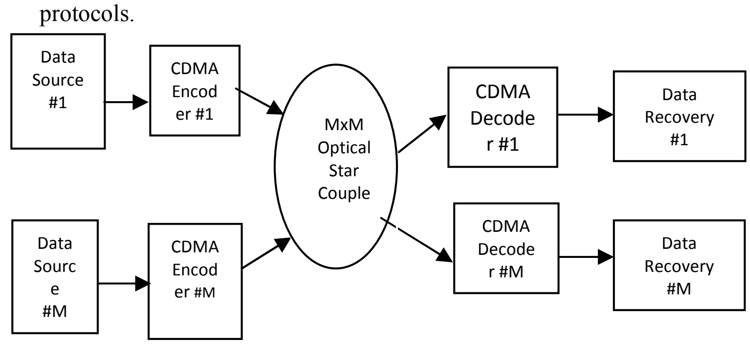

Fig 1. Schematic diagram of an O-CDMA system

2. SYSTEM ARCHITECTURE

The notations used in this section are as follows:

- 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 basic architecture of an O-CDMA network with N nodes is shown in Fig. 2 in a broadcast star configuration. 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 cardinality as,

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

The cardinality $|C|$ of 2-D codes depends on L, R, λ_a and λ_c. For the case of W/T SPR codes, λ_a=0, λ_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 according to two different proposed protocols (Protocol-1 or Protocol-2)

2.1 Protocol-1

- Initially all codes are available in the code-pool
- In order to transmit a packet by an user to destination, first the 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 P_1 will occur between any two transmitting users.

2.2 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. As a result the number of active users allowed to transmit packets is higher than in protocol-1.
- 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, both types (P_1 and P_R) of interference can occur between any two transmitting users.

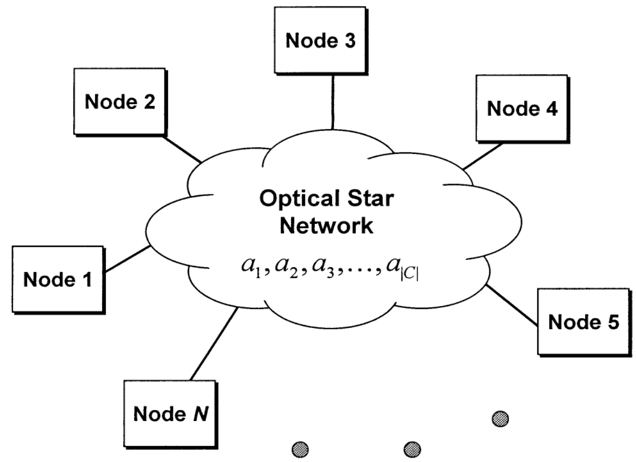

Fig 2. Optical CDMA network architecture

3. ANALYTICAL MODELING OF THE SYSTEM

The definitions used in this section are as follows:

- *backlogged mode*: the mode where users retransmit same (faulty) packet
- *thinking mode*: the mode where users transmit newly generated packets
- *backlogged users*: the users who are in backlogged mode
- *thinking users*: the users who are in thinking mode [8]
- *active user*: one that is about to transmit a packet

The notations used in this section are as follows:

- 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 with the desired user
- l number of users (out of r-1 users) interfere with desired user at 1-chip
- m number of users (out of r-1 users) interfere with desired user at w-chips
- Z total received pulses from all weighted chips
- $P_{bc}(m,l)$ the conditional bit-correct probability (given m & l)
- $P_s(r|m, l)$ the conditional probability of a packet-success (given m & l)
- $P_s(r)$ the probability of a packet success given 'r' active users.
- P_1 the probability of 1-chip interference between two users
- P_W the probability of W-chip ($W=R$ *in case of SPR codes*) interference between two users

The relationship between r-1, l and m is given by, $r-1=l+m$.

Let the system model consists of *N* users having same average activity *A* (Fig. 2). 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. 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].

3.1 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 threshold $\theta = W$, *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 in one chip at most. On the other hand, users of same code interfere with each other by zero, one, or *W* chips.

Assuming chip-synchronous interference model among users, we derive the probabilities of P_1 and P_R, for OOCs and W/T SPR codes as follows:

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

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

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

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

$$\begin{aligned} &P_{bc}(m,l) \\ &= \Pr\{a\ bit\ success \mid m,l\} \\ &= \frac{1}{2}\Pr\{a\ bit\ success \mid m,l,1\ was\ sent\} \\ &\quad + \frac{1}{2}\Pr\{a\ bit\ success \mid m,l,0\ was\ sent\} \\ &= \frac{1}{2}\Pr\{Z \ge R \mid m,l, 1\ was\ sent\} + \frac{1}{2}\Pr\{Z \langle R \mid m,l, 0\ was\ sent\} \\ &= \frac{1}{2} + \frac{1}{2}\Pr\{all\ m\ users\ send\ 0\ and\ Z \langle R \mid m,l, 0\ was\ sent\} \\ &= \frac{1}{2} + \frac{1}{2}\cdot\frac{1}{2^m}\cdot\frac{1}{2^l}\sum_{i=0}^{R-1}\binom{l}{i} \end{aligned} \tag{4}$$

Thus the conditional success probability for the correlation receiver is

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

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

4. 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 has improved performance by using 2-D codes in transferring the packets in the network.

In Figures 3 and 4, the dependence of P_1 on *L* is shown, for weight of the code=2, 3 and 4 for the protocol-1 and protocol-2 respectively. The parameter C is kept constant. The result shows that, the probability of single-chip interference is less using 2-D codes than using 1-D codes. It also shows that, as *R* increases, P_1 in both cases (using 1-D and 2-D codes) increases due to the crowding of the network with more number of pulses. Also, as *L* increases the P_1 decreases in both cases (using 1D and 2D codes) due to the decreased interference per chip.

P_s is evaluated for protocols 1 and 2 for constant *C=5* with variation of *L*, in Figures 5 and 6 number of active users *r=5* and *r=10* respectively. This result shows that, the packet-success probability, in case of protocol-1 and protocol-2, is higher using 2D codes than 1D codes.

5. CONCLUSIONS

Optical CDMA has attracted considerable attention in the recent years for high speed access network applications. Two MAC protocols for O-CDMA access networks have been proposed and analyzed, with correlation receiver, for

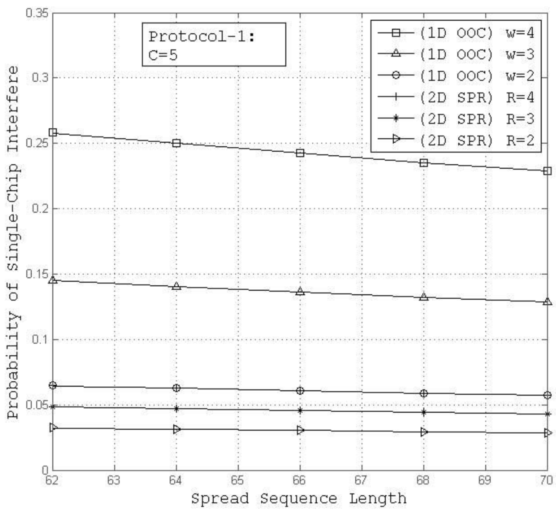

Fig 3. Comparison of single-chip interference in case of protocol-1 for 1D and 2D codes

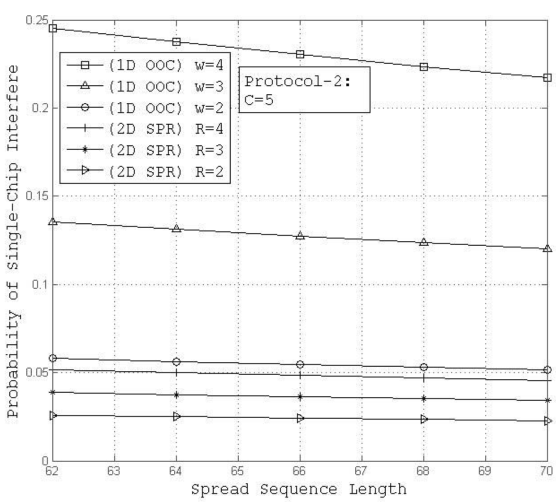

Fig 4. Comparison of single-chip interference in case of protocol-2 for 1D and 2D codes

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
For protocol-1 packet success probability is:

interference between codes, for a given weight of the code, as a result have higher packet success probability.

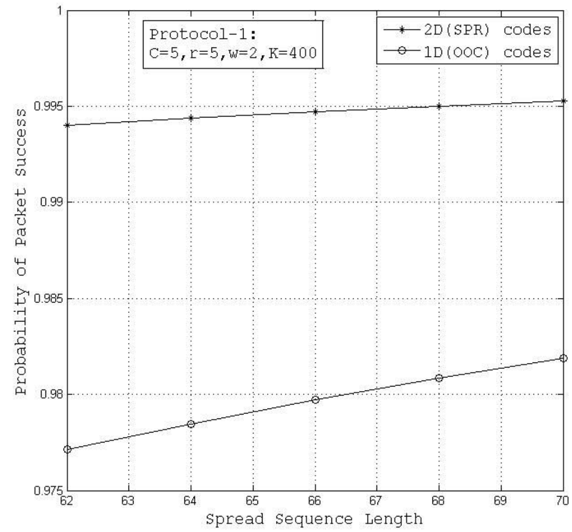

Fig 5. Comparison of packet-success probabilities in protocol-1 between 1D and 2D codes

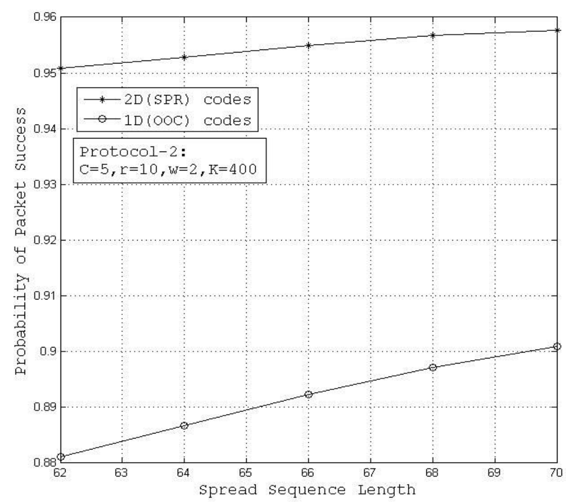

Fig 6. Comparison of packet-success probabilities in protocol-2 between 1D and 2D codes

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

For protocol-2 packet success probability is:

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

6. ACKNOWLEDGMENTS

This work has been funded by IISc-DRDO Mathematical Program. We are thankful for their financial assistance.

7. REFERENCES

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