Optical CDMA Random Access Protocols With and Without Pretransmission Coordination

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***Abstract*—The link layer of an optical direct-detection code-division multiple-access (CDMA) packet network is considered. Two different protocols that need pretransmission coordination are proposed. A variation of the second protocol that does not need pretransmission coordination is discussed. Both system throughput and average packet delay are derived and investigated for two different receiver models: the correlation and chip-level receivers. Both multiple-access interference and the photodetector's shot noise are taken into account in the analysis. The case where the number of users exceeds the available number of CDMA codes is numerically investigated. Our results reveal that the proposed protocols yield competitive system throughputs when used with the correlation receivers. Further, significant improvement in the throughput is achieved when using chip-level receivers along with the second protocol.**

***Index Terms*—Chip-level receivers, code-division multiple access (CDMA), correlation receivers, direct detection optical channel, on–off keying, optical CDMA, optical link layer, optical networks.**

I. Introduction

OPTICAL fibers offer a large bandwidth in the order of terahertz, making it the best candidate for current and future communication and computer networks. Optical code-division multiple-access (CDMA) systems [1]–[16] have been shown to be competitive candidates in order to mine this terahertz bandwidth when combined with wavelength-division multiplexing (WDM) techniques.

In optical CDMA techniques, a user is normally given a signature code that satisfies *good* auto- and cross-correlation properties [1] to help in its data transmission and identifying itself. Several receiver detection models have been proposed in literature. Some of them are summarized in [14]. The most traditional ones are the correlation receiver [2], correlation receiver with double hardlimiters [8], [9], and chip-level receiver [10]. The main difference between the correlation receivers and chip-level receivers is that in the latter, the bit decision rule depends on the received optical power in each mark chip of the signature code, whereas in the former, it depends on the total optical power in all underlined mark chips. A comparison between chip-level and double-optical-hardlimiters correlation receivers can be found in [16]. It was shown that although chip-level receivers are much simpler and more practical than double-optical-hardlimiters correlation receivers, the bit error probabilities of both of them are almost *similar* to each other, even under ideal conditions for the optical hard limiters. Other powerful, but rather complex, receiver models have also appeared in the literature. These include multiuser detection receiver [6], interference estimation and cancellation [11] receiver, etc.

Basically two types of optical direct-detection CDMA signal formats have been studied in the literature: binary on–off keying (OOK) [2]–[6] and M-ary pulse-position modulation (PPM) schemes [4], [7], [12]. It has been shown that for fixed data rate and chip duration, there is no advantage in using PPM in place of OOK, but PPM becomes superior to OOK if the average power rather than the chip time is the constraining factor.

Although there is a lot of research in the field of optical WDM that has been done at the level of network layer [17]–[23], most of the research in the field of optical CDMA has focused on the physical layer of the network [2]–[16]. There are, however, a few authors [26]–[32] that have examined the network or link layer of optical CDMA communication systems.

In this paper, we propose two different protocols for slotted optical CDMA packet networks. These protocols, called Pro 1 and Pro 2, need pretransmission coordination; and a control packet is sent by a transmitter before launching its data. Of course in order to implement Pro 1 and Pro 2, we need both the transmitter and the receiver be tunable. That is they should be able to tune their signature codes to the one assigned in the control packet. Furthermore, we suggest a variation of Pro 2 that does not need pretransmission coordination. Of course the implementation of this variant protocol does not require any receiver tunability, and is thus simpler.

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 of course 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.

Since under normal situations the network users send their data in a burst mode, i.e., they are not all active at the same time, we will allow the total number of users to exceed the number of available codes.

Two types of performance measures are examined in this paper. The first one is the *average system (or network) throughput* in packets per slot, which tells how many packets on the average are received successfully per time slot. The other one is the *average packet delay* in time slots, which tells after how many slots (from transmission) on the average a packet will be received successfully. Our second aim in this paper is to figure out which of the two proposed protocols leads to a better performance in terms of average throughput (in packets

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per slot) and average delay (in time slots). In our analysis, we will consider only two receiver models: the correlation and chip-level receivers.

The remainder of this paper is organized as follows. Section II is devoted for a basic description of system architecture, where the two protocols are introduced. A mathematical model and theoretical study of the system is presented in Section III, where a derivation of the steady-state system throughput and average packet delay is given. In this analysis, focus is oriented toward multiple-access interference only, where the effect of both receivers' shot and thermal noises are neglected in this section. Section IV is maintained for a study of the effect of photodetector's shot noise on the performance of chip-level receivers with Pro 2. Some numerical results including a comparison between the performances of different receiver models are presented in Section V. The conclusion is given in Section VI.

II. SYSTEM ARCHITECTURE

The basic architecture of an optical CDMA network is shown in Fig. 1. It is composed of a set of N nodes or users, an optical star network, and a set of direct-sequence optical-orthogonal codes (OOCs) $C = \{a_1, a_2, a_3, \ldots, a_{|C|}\}$ with cardinality $|C|$. The type of transmission is a sort of broadcast and select, where a message transmitted by any node is received by all other nodes. Each node selects the appropriate message according to a signature code. We assume that nodes are located uniformly from the star coupler. The near–far effect can thus be neglected and each node can be assumed to receive an equal amount of transmitted power. The cardinality $|C|$ of an OOC depends on the code length L, the code weight w, and the out-of-phase autocorrelation and cross-correlation constraints λ_a, λ_c, respectively. For the case of $\lambda_a = \lambda_c = 1$, we have [1], [2]

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

where $\lfloor x \rfloor$ denotes the largest integer not greater than x. N is allowed to be greater than $|C|$ and codes are assigned to users according to one of two different protocols as given below.

A. First Protocol: Pro 1

In this protocol, we assume that all codes are available in a pool (Fig. 1). When a user wants to transmit a packet to a receiver, it is assigned a code at random. This code is then removed from the pool and is no longer available for further assignment during a slot. It is obvious that 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.

B. Second Protocol: Pro 2

This protocol is similar to the one above but the codes are never removed from the pool. That is, any active user can always find a code to transmit its data. Of course more interference is possible in this case since a code can be used more than once. However, the offered traffic (at a given time slot) might be higher than the previous case. In order to reduce the probability of interference among different users, a code is randomly cyclic shifted around itself once selected.

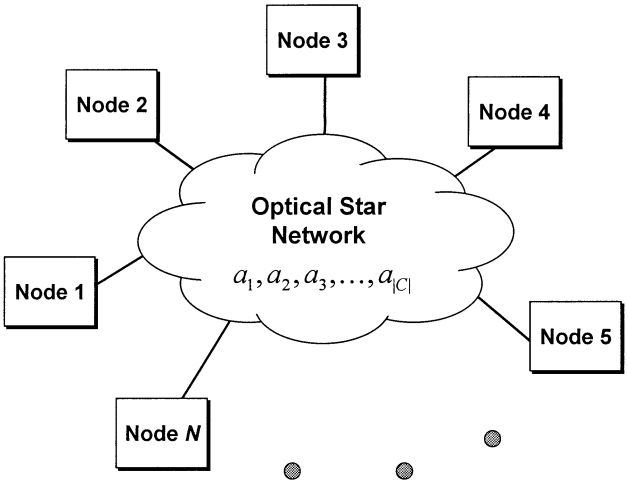

Fig. 1. Optical CDMA network architecture.

The two aforementioned protocols require pretransmission coordination. Indeed the transmitter should first broadcast a control message (or packet) to all receivers informing them about its address, the destination address, and the code to be used for data transmission. The control packet can probably be broadcast using a specific period at the head of each time slot or using another channel with different wavelength. All idle receivers are normally tuned to this control channel, listening to their addresses. The transmitter and receiver of any user should thus be tunable (TT-TR), i.e., be able to tune to any available code.

C. Variation of Pro 2

A variation of Pro 2 that avoids the receiver tunability, and hence does not require any pretransmission coordination, can be achieved by distributing the codes to all receivers a priori (Fig. 2). That is, when a user subscribes to the network, it is given a code (possibly used) randomly. Further, a code is randomly cyclic shifted around itself once assigned.

In the next two sections, we incorporate the above protocols in a complete optical direct-detection system and analyze its performance when considering different receiver models, namely, the correlation [2] and chip-level [10] receivers. In our analysis we assume that the control packet is always successful and neglect any delay that it may cause. Although the variant Pro 2 does not require any pretransmission coordination, its theoretical analysis is similar to that of Pro 2 for successful control packets. Of course, if there is a probability of control packet failure, variant Pro 2 should outperform Pro 2. Further, we will be focusing on performance degradation due to both multiple-access interference and receiver shot noise. The effect of thermal noise will, however, be neglected.

III. SYSTEM MODEL AND THEORETICAL ANALYSIS

Our system model is composed of N users having same average activity A (Fig. 1). As mentioned in the introduction, we focus on slotted data transmission. Thus after a successful control message, a user transmits a packet (with probability A) at the beginning of a time slot to the destination. The length of

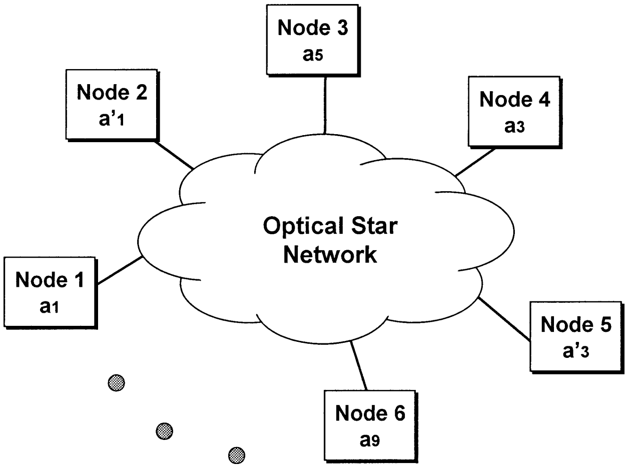

Fig. 2. Optical CDMA network model utilizing Pro 2 without pretransmission coordination.

a packet is K bits and corresponds to a slot duration. An active user (one that is about to transmit a packet) is assigned an optical-orthogonal code according to the rule given in Pro 1 or 2 depending on the protocol used. The intended receiver, once it has received a packet, transmits an acknowledgment to the sending user, indicating whether the packet is received successfully or not. If not, the transmitter enters a backlog mode and retransmits the packet after a random delay time with average d time slots. Assuming that at a given slot the number of backlogged users is n, the offered traffic and system throughput are

$$G(n) = (N-n)A + \frac{n}{d} = NA - n\Big(A - \frac{1}{d}\Big) \qquad (2)$$

and (3) as shown at the bottom of the page, respectively, where the symbol $x \wedge y$ denotes the minimum of the two numbers x and y. The two probabilities

$$\begin{aligned} P_{bl}(i|n) &= \binom{n}{i}\Big(\frac{1}{d}\Big)^{i}\Big(1-\frac{1}{d}\Big)^{n-i} \\ P_{th}(j|n) &= \binom{N-n}{j}A^{j}(1-A)^{N-n-j} \end{aligned} \qquad (4)$$

denote the probabilities of i backlogged and j thinking (transmitting new packets) users, respectively, being active at a given time slot with n backlogged users, and $P_s(r)$ denotes the probability of a packet success given r active users. The packet-success probability $P_s(r)$ depends on the type of the receiver model. As mentioned in the last section, we focus on two different receivers, the correlation [2], and chip-level [10] receivers.

A. Packet-Success Probability for a Correlation Receiver

Let the number of active users in a given slot be r. Since we are using OOCs with correlation constraints equal 1, 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 w chips. Let p_1 and p_w denote the probability of one and w chip-interferences, respectively, between two users. Assuming chip-synchronous interference model among users, we get the equation at the bottom of the page, and

$$p_w = \begin{cases} 0, & \text{for the case of Pro 1} \\ \frac{1}{L}\cdot\frac{1}{|C|} = \frac{1}{L}\cdot\left\lfloor\frac{L-1}{w(w-1)}\right\rfloor^{-1}, & \text{for the case of Pro 2.} \end{cases} \qquad (5)$$

Notice that

$$p_1 + wp_w = \frac{\omega^2}{L}. \qquad (6)$$

Since we have r active users, there are $r-1$ interfering users to the desired one. Out of these $r-1$ users, let m users interfere with the desired user at w chips and ℓ users interfere with it at one chip. Assuming equally likely binary data bits ($\Pr\{0\} = \Pr\{1\} = 1/2$), the conditional bit-correct probability $P_{bc}(m,\ell)$ is calculated as follows. The 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 $\theta = w$ [2]. A data bit 0 is decided otherwise

$$\begin{aligned} &P_{bc}(m,\ell) \\ &= \Pr\{\text{a bit success}|m,\ell\} \\ &= \frac{1}{2}\Pr\{\text{a bit success}|m,\ell,1 \text{ was sent}\} \\ &\quad + \frac{1}{2}\Pr\{\text{a bit success}|m,\ell,0 \text{ was sent}\} \\ &= \frac{1}{2}\Pr\{Z \ge w|m,\ell,1 \text{ was sent}\} + \frac{1}{2}\Pr\{Z < w|m,\ell,0 \text{ was sent}\} \\ &= \frac{1}{2} + \frac{1}{2}\Pr\{\text{all } m \text{ users send 0s and } Z < w|m,\ell,0 \text{ was sent}\} \\ &= \frac{1}{2} + \frac{1}{2}\cdot\frac{1}{2^m}\cdot\frac{1}{2^\ell}\sum_{i=0}^{w-1}\binom{\ell}{i}. \end{aligned} \qquad (7)$$

The conditional success probability for the correlation receiver is thus

$$P_s(r|m,\ell) = \Big[P_{bc}(m,\ell)\Big]^K = \left[\frac{1}{2} + \frac{1}{2^{\ell+m+1}}\sum_{i=0}^{w-1}\binom{\ell}{i}\right]^K.$$

Finally, the success probability given r active users is as shown in (8) at the bottom of the page.

$$\beta(n) = \begin{cases} \displaystyle\sum_{j=0}^{N-n}\sum_{i=0}^{n}\big((i+j)\wedge|C|\big)P_s\big((i+j)\wedge|C|\big)P_{bl}(i|n)P_{th}(j|n); & \text{for Pro 1} \\ \displaystyle\sum_{j=0}^{N-n}\sum_{i=0}^{n}(i+j)P_s(i+j)P_{bl}(i|n)P_{th}(j|n); & \text{for Pro 2} \end{cases} \qquad (3)$$

$$p_1 = \begin{cases} \frac{w^2}{L}, & \text{for the case of Pro 1} \\ \frac{\omega^2}{L}\cdot\frac{|C|-1}{|C|} + \frac{\omega(\omega-1)}{L}\cdot\frac{1}{|C|} = \frac{w^2}{L} - \frac{w}{L}\cdot\left\lfloor\frac{L-1}{w(w-1)}\right\rfloor^{-1}, & \text{for the case of Pro 2} \end{cases}$$

B. Packet-Success Probability for a Chip-Level Receiver

This case differs from that of the correlation receiver in the bit decision rule [10]: a data bit 1 is decided if the number of pulses in every weighted chip $\{Z_1, Z_2, \ldots, Z_w\}$, of a code is nonzero. Otherwise a data bit 0 is decided. Let $\mathcal{X} = \{1, 2, \ldots, w\}$ and ℓ_i, $i \in \mathcal{X}$, denote the number of users (out of ℓ users) that interfere with weighted chip i. Of course $\ell = \sum_{i=1}^{w} \ell_i$. Further, let $\overline{\ell}$ be the vector $(\ell_1, \ell_2, \ldots, \ell_w)$. We evaluate the bit-correct probability as follows:

$$\begin{aligned}
&P_{bc}(m, \overline{\ell})\\
=&\frac{1}{2}\,\mathrm{Pr}\{\text{a bit success}|m, \overline{\ell}, 1 \text{ was sent}\}\\
&+\frac{1}{2}\,\mathrm{Pr}\{\text{a bit success}|m, \overline{\ell}, 0 \text{ was sent}\}\\
=&\frac{1}{2}\,\mathrm{Pr}\{Z_i \geq 1\ \forall i \in \mathcal{X}|m, \overline{\ell}, 1 \text{ was sent}\}\\
&+\frac{1}{2}\,\mathrm{Pr}\{Z_i = 0,\ \text{some } i \in \mathcal{X}|m, \overline{\ell}, 0 \text{ was sent}\}\\
=&\frac{1}{2} + \frac{1}{2}\,\mathrm{Pr}\{\text{all } m \text{ users send 0s and } Z_i = 0\\
&\text{some } i \in \mathcal{X}|m, \overline{\ell}, 0 \text{ was sent}\}\\
=&\frac{1}{2} + \frac{1}{2} \cdot \frac{1}{2^m}\\
&\cdot \left(\sum_{i=1}^{w} \frac{1}{2^{\ell_i}} - \sum_{i=1}^{w-1} \sum_{j=i+1}^{w} \frac{1}{2^{\ell_i + \ell_j}} + \cdots + (-1)^{w-1} \frac{1}{2^{\ell}} \right)
\end{aligned} \tag{9}$$

where we have used the inclusion–exclusion property to justify last equality. The conditional success probability for the correlation receiver is thus $P_s(r|m, \overline{\ell}) = \left[P_{bc}(m, \overline{\ell})\right]^K$ and the success probability given r active users is finally combined as

$$\begin{aligned}
&P_s(r)\\
=&\sum_{\ell=0}^{r-1} \sum_{m=0}^{r-1-\ell} \frac{(r-1)!}{\ell!m!(r-1-m-\ell)!} \cdot p_1^{\ell} p_w^{m} (1 - p_1 - p_w)^{r-1-\ell-m}\\
&\cdot \sum_{\substack{\ell_1, \ell_2, \ldots, \ell_w:\\ \ell_1 + \cdots + \ell_w = \ell}} \frac{\ell!}{\ell_1! \ldots \ell_w!} \cdot \left(\frac{1}{w}\right)^{\ell}\\
&\cdot \left[\frac{1}{2} + \frac{1}{2^{m+1}} \left(\sum_{i=1}^{w} \frac{1}{2^{\ell_i}} - \sum_{i=1}^{w-1} \sum_{j=i+1}^{w} \frac{1}{2^{\ell_i + \ell_j}} + \cdots + (-1)^{w-1} \frac{1}{2^{\ell}} \right)\right]^K.
\end{aligned} \tag{10}$$

C. Steady-State Performance

To obtain the steady-state throughput and average packet delay, the above system can be described by a discrete-time Markov chain [31]. The chain consists of $N+1$ states depending on the number of backlogged users $n \in \{0, 1, \ldots, N\}$. The transition from one state to another occurs on a slot-by-slot basis. We determine the transition probability P_{nm} from state n to state m, where $n, m \in \{0, 1, \ldots, N\}$, of backlogged users as follows. Let k and l denote the number of thinking and backlogged users, respectively, being active at state n.

1) System With Protocol Pro 1 and $k+l-|C|$: It is obvious that there are $n-l$ backlogged users that are still idle and cannot succeed in transmission. For the system to jump to state m, $m-(n-l) = l+m-n$ users have to fail out of $k+l$ transmitting users. The remaining $k-m+n$ users have to succeed.

2) System With Protocol Pro 1 and $k+l-|C|$: Since there are only $|C|$ available codes, it is obvious that $k+l-|C|$ are not assigned any codes and cannot succeed. Further, $n-l$ backlogged users are still idle and cannot succeed as well. For the system to jump to state m, $m-(n-l)-(k+l-|C|) = |C|-k+m-n$ users have to fail out of $|C|$ transmitting users. The remaining $k-m+n$ users have to succeed.

Thus we obtain the transition probability for the system with Pro 1 as shown in (11) at the bottom of the page.

3) System With Protocol Pro 2: This case is similar to that of Pro 1 with $k+l < |C|$, since any transmitting user can always find a code, possibly used. Thus we obtain the transition probability for the system with Pro 2 as shown in (12) at the bottom of the page.

A stationary probability distribution π_n, $n \in \{0, 1, \ldots, N\}$, always exists for the above irreducible Markov chain. It can be obtained from the following set of equations:

$$\sum_{n=0}^{N} \pi_n = 1 \text{ and } (\forall m \in \{0, 1, \ldots, N\}) \quad \sum_{n=0}^{N} \pi_n P_{nm} = \pi_m\,. \tag{13}$$

Finally, the steady-state system throughput β, average offered traffic G, and average packet delay D can be calculated from [24], [25]

$$\begin{aligned}
\beta =& \sum_{n=0}^{N} \beta(n)\pi_n, \quad G = \sum_{n=0}^{N} G(n)\pi_n\\
D =& 1 + \frac{E\{n\}}{\beta} = 1 + \frac{1}{\beta} \sum_{n=0}^{N} n\pi_n
\end{aligned} \tag{14}$$

$$P_s(r) = \sum_{\ell=0}^{r-1} \sum_{m=0}^{r-1-\ell} \frac{(r-1)!}{\ell!m!(r-1-m-\ell)!} p_1^{\ell} p_w^{m} (1 - p_1 - p_w)^{r-1-\ell-m} \left[\frac{1}{2} + \frac{1}{2^{\ell+m+1}} \sum_{i=0}^{w-1} \binom{\ell}{i}\right]^K. \tag{8}$$

$$P_{nm} = \sum_{l=0 \vee (n-m)}^{n} \sum_{k=0 \vee (m-n)}^{(N-n) \wedge (|C|+m-n)} P_{bl}(l|n) P_{th}(k|n) \binom{(k+l) \wedge |C|}{k-m+n} \cdot P_s^{k-m+n}((k+l) \wedge |C|) \Big[1 - P_s((k+l) \wedge |C|)\Big]^{(k+l) \wedge |C| - k + m - n}. \tag{11}$$

$$P_{nm} = \sum_{l=0 \vee (n-m)}^{n} \sum_{k=0 \vee (m-n)}^{N-n} P_{bl}(l|n) P_{th}(k|n) \cdot \binom{k+l}{k-m+n} P_s^{k-m+n}(k+l) \Big[1 - P_s(k+l)\Big]^{l+m-n}. \tag{12}$$

respectively, where $E\{\cdot\}$ denotes the expected value.

IV. EFFECT OF PHOTODETECTOR'S SHOT NOISE ON THE NETWORK THROUGHPUT OF CHIP-LEVEL RECEIVERS

In this section, we study the effect of a photodetector's shot noise on throughput performance of chip-level receivers. The only change in the throughput evaluation as derived in the last section is in the calculation of the conditional bit-correct probability $P_{bc}(m,\overline{\ell})$ of (9). Assuming a Poisson shot noise at the receiver's photodiode, $P_{bc}(m,\overline{\ell})$ is modified as follows. Let the number of photons collected from weighted chip $i \in \mathcal{X}$ be Y_i. Every Y_i is modeled as a Poisson random variable with mean QZ_i, where Q is the average received photons per pulse and Z_i is the number of received pulses in chip i. A suboptimal, but good, decision rule is: decide data bit 1 was transmitted if for every $i \in \mathcal{X}$, $Y_i > 0$; otherwise decide a data bit 0 was transmitted. Defining $\ell, \overline{\ell} = (\ell_1, \ell_2, \ldots, \ell_w)$ as before, we have

$$\begin{aligned}
P_{bc}(m,\overline{\ell}) =& \frac{1}{2}\Pr\{\text{a bit success}|m,\overline{\ell},1 \text{ was sent}\}\\
&+\frac{1}{2}\Pr\{\text{a bit success}|m,\overline{\ell},0 \text{ was sent}\}\\
=&\frac{1}{2}\Pr\{Y_i \geq 1\ \forall i \in \mathcal{X}|m,\overline{\ell},1 \text{ was sent}\}\\
&+\frac{1}{2}\Pr\{Y_i = 0,\ \text{some } i \in \mathcal{X}|m,\overline{\ell},0 \text{ was sent}\}\\
=&\frac{1}{2}-\frac{1}{2}\Pr\{Y_i = 0,\ \text{some } i \in \mathcal{X}|m,\overline{\ell},1 \text{ was sent}\}\\
&+\frac{1}{2}\Pr\{Y_i = 0,\ \text{some } i \in \mathcal{X}|m,\overline{\ell},0 \text{ was sent}\}
\end{aligned}$$

where the last two probabilities can be evaluated as follows. For $b \in \{0,1\}$

$$\begin{aligned}
&\Pr\{Y_i = 0,\ \text{some } i \in \mathcal{X}|m,\overline{\ell},b \text{ was sent}\}\\
&=\sum_{i=1}^{w}\Pr\{Y_i=0|m,\overline{\ell},b\} - \sum_{i=1}^{w-1}\sum_{j=i+1}^{w}\Pr\{Y_i=Y_j=0|m,\overline{\ell},b\}\\
&\quad+\sum_{i=1}^{w-2}\sum_{j=i+1}^{w-1}\sum_{k=j+1}^{w}\Pr\{Y_i=Y_j=Y_k=0|m,\overline{\ell},b\}\\
&\quad+\cdots\\
&\quad+(-1)^{w-1}\Pr\{Y_1=Y_2=\cdots=Y_w=0|m,\overline{\ell},b\}
\end{aligned}$$

and

$$\begin{aligned}
&\Pr\{Y_{i_1}=Y_{i_2}=\cdots=Y_{i_t}=0|m,\overline{\ell},b\}\\
&=e^{-Qbt}\cdot\sum_{u=0}^{m}\binom{m}{u}\left(\frac{1}{2}\right)^{u}\left(\frac{1}{2}\right)^{m-u}e^{-Qut}\\
&\quad\cdot\sum_{v=0}^{\ell_{i_1}}\binom{\ell_{i_1}}{v}\left(\frac{1}{2}\right)^{v}\left(\frac{1}{2}\right)^{\ell_{i_1}-v}e^{-Qv}\\
&\quad\cdots\sum_{y=0}^{\ell_{i_t}}\binom{\ell_{i_t}}{y}\left(\frac{1}{2}\right)^{y}\left(\frac{1}{2}\right)^{\ell_{i_t}-y}e^{-Qy}\\
&=e^{-Qbt}\cdot\left(\frac{1}{2}+\frac{1}{2}e^{-Qt}\right)^{m}\cdot\left(\frac{1}{2}+\frac{1}{2}e^{-Q}\right)^{\ell_{i_1}+\ell_{i_2}+\cdots+\ell_{i_t}}.
\end{aligned}$$

Combining the last three equations, we obtain

$$\begin{aligned}
&P_{bc}(m,\overline{\ell})\\
&=\frac{1}{2}+\left(\frac{1}{2}-\frac{1}{2}e^{-Q}\right)\cdot\left(\frac{1}{2}+\frac{1}{2}e^{-Q}\right)^{m}\cdot\sum_{i=1}^{w}\left(\frac{1}{2}+\frac{1}{2}e^{-Q}\right)^{\ell_i}\\
&\quad-\left(\frac{1}{2}-\frac{1}{2}e^{-2Q}\right)\cdot\left(\frac{1}{2}+\frac{1}{2}e^{-2Q}\right)^{m}\cdot\sum_{i=1}^{w-1}\sum_{j=i+1}^{w}\left(\frac{1}{2}+\frac{1}{2}e^{-Q}\right)^{\ell_i+\ell_j}\\
&\quad+\left(\frac{1}{2}-\frac{1}{2}e^{-3Q}\right)\cdot\left(\frac{1}{2}+\frac{1}{2}e^{-3Q}\right)^{m}\\
&\quad\cdot\sum_{i=1}^{w-2}\sum_{j=i+1}^{w-1}\sum_{k=j+1}^{w}\left(\frac{1}{2}+\frac{1}{2}e^{-Q}\right)^{\ell_i+\ell_j+\ell_k}\\
&\quad+\cdots\\
&\quad+(-1)^{w-1}\left(\frac{1}{2}-\frac{1}{2}e^{-Qw}\right)\cdot\left(\frac{1}{2}+\frac{1}{2}e^{-Qw}\right)^{m}\cdot\left(\frac{1}{2}+\frac{1}{2}e^{-Q}\right)^{\ell}.
\end{aligned}\tag{15}$$

Here Q denotes the average photons per chip pulse, which is related to the average photons/bit μ by

$$Q=\frac{2\mu}{w}.$$

It should be noticed that in the limiting case, as $Q \to \infty$, (15) converges to (9).

V. NUMERICAL RESULTS

The steady-state system throughput and average packet delay derived above have been evaluated for different protocols, receivers, and link parameters. The shot noise effect of the last section is taken into consideration only in the last figure (i.e., Fig. 7). In Figs. 3 and 4, the throughput has been plotted versus the average activity for the two different protocols Pro 1 and 2. The same thinking and backlog activities $1/d = A$ have been assumed in these two figures. The code length and code weight (L, w) are (31, 3) and (121, 3) in Figs. 3 and 4, respectively . The number of users N is 30 and 80 in Figs. 3 and 4, respectively, which is greater than the available number of codes $|C|$ as given in (1). In fact $|C| = 5$ and 20 in Figs. 3 and 4, respectively.

General trends of the curves can be noticed. Indeed when using the first protocol (Pro 1), the throughput increases as A increases until it reaches a saturation value, which is always less than the number of codes, whereas when using the second protocol (Pro 2), the throughput increases as A increases until it reaches a maximum value that is greater than the number of codes and then decreases when increasing A further. In fact, the initial increase of the throughput in both cases is because as A increases above zero, more packets become available with low interference. The saturation in the case of Pro 1 is because when A becomes large enough, the number of active users asking for CDMA codes increases until there are not enough codes and no more users (no more interference as well) can transmit their data. On the other hand, the throughput decay in the case of Pro 2 after reaching a peak value is because in this case an active user can always find a code (probably used) to transmit its data. In such a case, the interference would increase rapidly and packet failures become more probable.

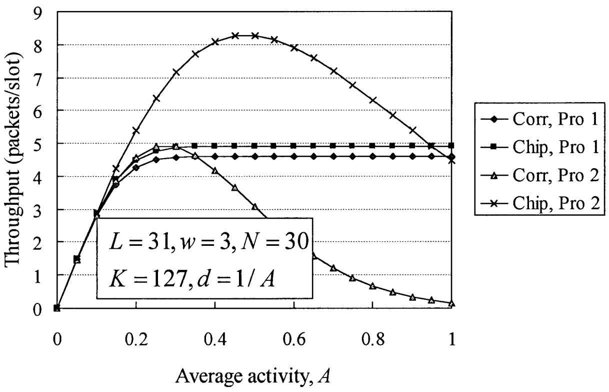

Fig. 3. Network throughput versus average activity A for different protocols and same thinking and backlogged activities $1/d = A$ when $L = 31$ and $N = 30$.

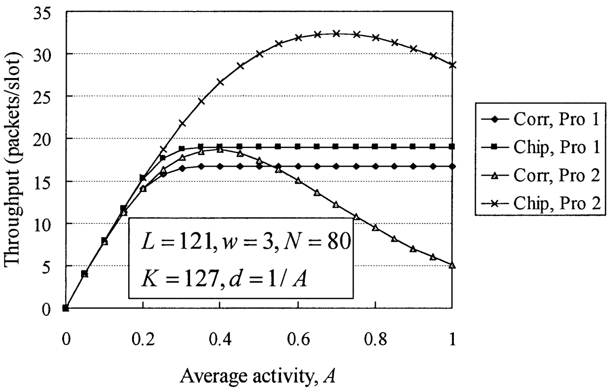

Fig. 4. Network throughput versus average activity A for different protocols and same thinking and backlogged activities $1/d = A$ when $L = 121$ and $N = 80$.

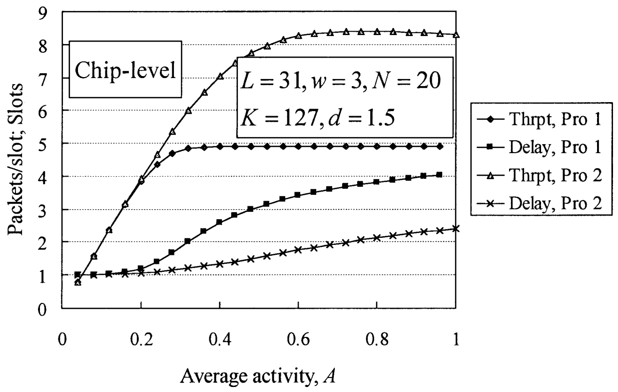

Fig. 5. Network throughput and delay, for chip-level systems, versus average activity A for different protocols when the average backlogged delay $d = 1.5$.

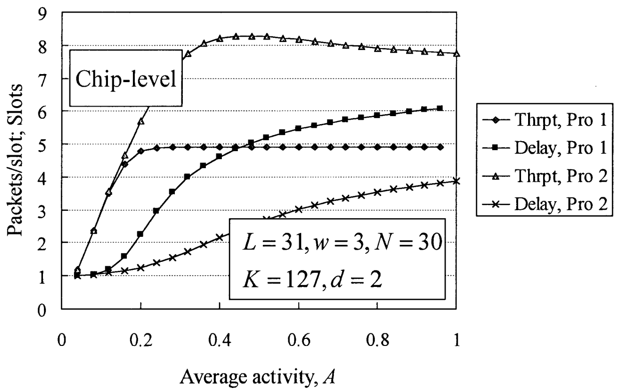

Fig. 6. Network throughput and delay, for chip-level systems, versus average activity A for different protocols when the average backlogged delay $d = 2$.

Furthermore, from these figures we notice that when using correlation receivers, the system throughputs of the two protocols are competitive to each other, although that of Pro 1 is better for most activities. In fact, the interval over which Pro 2 is better is very limited and the improvement is not that significant. It seems that Pro 1 is the choice for correlation receivers.

On the other hand, when using chip-level receivers, the system throughput of Pro 2 outperforms that of Pro 1 for almost all activities. In fact there are significant improvements when using chip-level receivers along with Pro 2 over that of chip-level receivers with Pro 1 and over that of correlation receivers with any of the above protocols. The reason is due to the powerful capability of chip-level receivers in attacking multiple-access interference.

A final observation is that in Fig. 4 the rate of decay of average throughput of Pro 2 as A increases is slower than its correspondent in Fig. 3. This of course is due to the larger code length used in Fig. 4, which reduces the effect of multiple-access interference as well.

In Figs. 5 and 6, we focus on steady-state throughputs and average packet delays for systems of chip-level receivers only and consider the case with different thinking and backlog activities $d \neq 1/A$. Indeed in Fig. 5 we use a fixed backlogged delay $d = 1.5$ and $N = 20$, whereas in Fig. 6 we use a fixed backlogged delay $d = 2$ and $N = 30$. All other parameters are as in Fig. 3. There is a difference in the general trend of the throughputs with Pro 2 in Figs. 5 and 6 over that in Figs. 3 and 4. Indeed here after the throughputs reach their peaks, they do not decay that fast and they become almost constant. This is because here the offered traffic (2) for large activities $A > 1/d$ is less than that for the previous case. This in turn introduces less interference and hence slow-decaying throughputs. It is obvious from the figures as well that the average packet delays for Pro 2 significantly outperform that of Pro 1. It seems that Pro 2 with constant backlogged delay is the choice for chip-level receivers.

Finally, the effect of the photodetector's shot noise is taken into account for the case of chip-level receivers with Pro 2. This is shown in Fig. 7 for several average activities. As was expected [10], the degradation due to shot noise is negligible with respect to multiple-access interference. Indeed, the throughput immediately increases from zero to a maximum value, which is identical to the ideal case, by increasing the average received photons/bit from zero to a very small value ≈15.

VI. CONCLUDING REMARKS

Two different protocols, with and without pretransmission coordination, have been proposed for optical CDMA slotted packet networks. Steady-state system throughput and average packet delay, at the link-layer level, have been derived for both correlation and chip-level receivers. In our analysis, we have

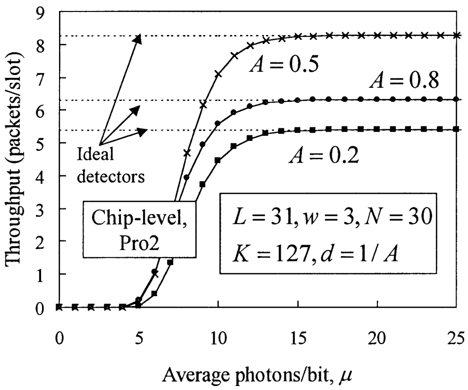

Fig. 7. Effect of photodetector's shot noise on the network throughput of chip-level receivers with second protocol (Pro 2).

focused only on the effect of both multiple-access interference and receiver shot noise, and neglected that of receiver thermal noise. These system measures have been numerically evaluated for different protocols, receivers, and link parameters. The following concluding remarks can be extracted from our results.

1) When using correlation receivers, the system throughputs of the two protocols are competitive to each other, although that of Pro 1 is better for most activities.
2) Significant improvements in the throughputs are obtained when using chip-level receivers along with Pro 2 over that of chip-level receivers with Pro 1 and over that of correlation receivers with any of the proposed protocols.
3) Significant improvements in the average packet delays are obtained when using chip-level receivers with Pro 2 over that with Pro 1.
4) It seems that the first protocol (Pro 1) is the best choice for correlation receivers, whereas the second protocol (Pro 2) is the best choice for chip-level receivers.
5) The effect of the shot-noise of chip-level receiver's photodiode is negligible with respect to that of the multiple-access interference.

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