A Unified Framework of the Performance Evaluation of Optical Time-Wavelength Code-Division Multiple-Access Systems

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Abstract. In this paper, we provide an analysis to the performance of optical time-wavelength code-division multiple-access (OTW-CDMA) network when the system is working above the nominal transmission rate limit imposed by the passive encoding-decoding operation. We address the problem of overlapping in such a system and how it can directly affect the bit error rate (BER). A unified mathematical framework is presented under the assumption of one coincidence sequences with non-repeating wavelengths. A closed form expression of the multiple access interference limited BER is provided as a function of different system parameters. Results show that the performance of OTW-CDMA system may be critically affected when working above the nominal limit; an event that may happen when the network operates at high transmission rate. In addition, the impact of the derived error probability on the performance of two newly proposed MAC protocols, the S-ALOHA and the R3T, is also investigated. It is shown that for low transmission rates, the S-ALOHA is better than the R3T; while the R3T is better at very high transmission rates. However, in general it is postulated that the R3T protocol suffers a higher delay mainly because of the presence of additional modes.

Keywords: Optical time-wavelength CDMA, multirate, overlapping coefficient, one coincidence sequences, S-ALOHA, R3T.

1 Introduction

Lately, optical time-wavelength code division multiple access (OTW-CDMA) has received considerable attention as a multiple access scheme for optical local area networks due to its flexibility and diversity [1][4]-[3]. In addition, multi- services supporting multirate transmission using OTW-CDMA, are now feasible due to the rapid evolution of fiber optic technology that offers ultra-wide optical bandwidth capable of handling fast transmission rates. Toward this target, the bit-error-rate (BER) analysis of such a system is a crucial task [4].

OTW-CDMA has been proposed and discussed in numerous works like [2],[9]. In addition, the BER has been derived and studied in detail in [3]. In [2], we have proposed a multirate OTW-CDMA system using fiber Bragg grating and variable PG.

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The idea was to respect the total round trip time for light from a data bit to go through the encoder. One of the key issues that has been emphasized in [2] is the difference between passive optical CDMA and its electrical active counterpart. In fact, it has been argued that in active CDMA systems there is a one-to-one correspondence between the transmitted symbol duration and the processing gain (PG). On the other hand, this one-to-one relation does not exist in passive optical CDMA systems. For instance, decreasing the bit duration will not affect the symbol duration at the output of the optical encoder. Therefore, for a fixed PG, increasing the link transmission rate beyond a given value, known as the nominal rate, leads to bits overlap at the output of the encoder. In [2], the general problem we have considered is by how much we can increase the transmission rates of different classes of traffic beyond the nominal permitted rates so as to optimize performance to meet the quality of service (QoS) requirements. The QoS requirement has been taken to be the signal-to-interference ratio (SIR).

Although the SIR is considered to be a good QoS index, some network managers prefer the BER as a more reliable and exact QoS measure. In [3] and [9], the BER for the OTW-CDMA system has been presented in detail when the system works below the nominal limit. This means that sequences with ideal cross-correlation function of maximum one were assumed. The probability of having one hit between two code sequences was obtained and the BER is derived using the binomial distribution. On the other hand in [1], although the performance analysis of code sequences with arbitrary cross-correlation values is considered, the explicit equation of the probability of having more than one hit between two code sequences was not presented. Only the probability of having one and two hits was shown in [6] where a special family of non-ideal optical orthogonal codes was analyzed.

In this work, we will try to analyze the performance of the OTW-CDMA system when the network is working above the nominal rate limit imposed by the passive encoding-decoding operation. A unified mathematical framework is presented in a way that the probability of having any number of hits between sequences can be obtained. We will focus on the problem of overlapping in such a system and how it can mathematically affect the expression of the BER. Using this expression, the performance of the OTW-CDMA system is investigated in packetized optical networks using two newly proposed MAC protocols, the R^3T [8] and the S-ALOHA [7].

Following the introduction, the paper is structured as follows. Section 2 introduces the system model. The effect of overlapping on frequency hits is discussed in Section 3. Section 4 discusses the hit quantification due to sequence overlap. Section 5 presents the BER analysis assuming multiple access interference (MAI) limited noise effect. Numerical results are covered in Section 6. Finally, the conclusion is presented in Section 7.

2 System Model

Consider an OTW-CDMA system that supports M users, sharing the same optical medium in a star architecture [9]. We will consider that all users are transmitting their data at the same transmission rate and have the same processing gain (PG) G. The encoding-decoding is achieved passively using a sequence of fiber Bragg grating

(FBG). The gratings spectrally and temporary slice the incoming broadband pulse into several components, equally spaced at chip interval T_c. The chip duration and the number of grating G determine the nominal bit duration to be $T_n = GT_c$. The corresponding nominal transmission rate is $R_n = 1/T_n$. Increasing the transmission rate beyond the nominal rate R_n without decreasing G introduces an overlapping coefficient ε_j among the transmitted bits during the same period T_n, as revealed in Fig. 1.

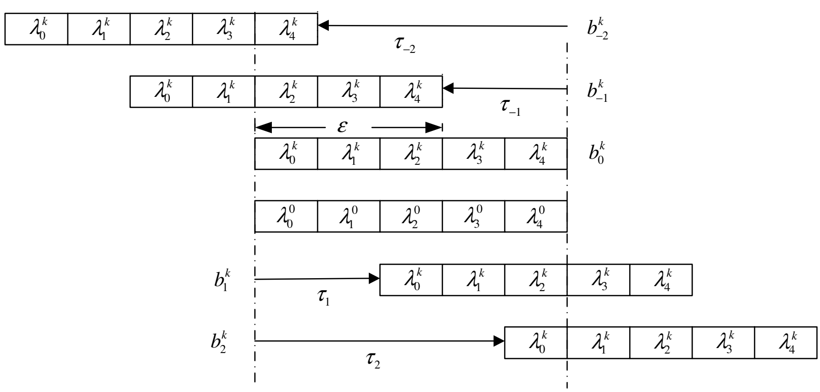

Fig. 1. The concept of overlapping among the bits, showing the effect of the overlapping coefficient ε_j on their transmission rate

In this case, the concept of overlapping is illustrated among six bits of $G = 5$ and the overlapping coefficient is $\varepsilon_j = 3$, which means that there are three chips in each OCDMA-coded bit that overlap with three chips of the other bits in the same class. This, in turn, augments the overall transmission rate of the users involved in this class from three bits after $3T_n$ to six bits. In general, the overlapping coefficient represents the number of overlapped chips among consecutive bits. Accordingly, the new transmission rate of is given by

$$R_j = \frac{G}{G - \varepsilon_j} R_n \tag{1}$$

where $0 \le \varepsilon_j \le G - 1$. This implies that $R^{(\ell)} \le R_j \le R^{(u)}$ where $R^{(\ell)} = R_n$ and $R^{(u)} = GR_n$ are the lower and the upper data rate common to all users, respectively. Also, we assume that the system is chip-synchronous and of discrete rate variation. Furthermore, all users transmit with the equal power and have the same overlapping coefficient.

From Fig. 1, the optical bit stream can be seen as being serial-to-parallel converted to v optical pulses. Assuming that the desired user is using the *class-s*, which is characterized by a PG = G and an overlapping coefficient ε_s. We define v and τ_v as the index of the overlapping bit and its associated time delay, respectively. The bit $b_X^k \in \{0,1\}$ from the v-bits is delayed by $\tau_X = X(G-\varepsilon_s)$. Accordingly, the average cross-correlation function between two one-coincidence sequences [10]-[12] has been obtained in [2] and it is given by

$$\bar{R}(G,\varepsilon_s)=\frac{1}{2F}\left[G+(G+\varepsilon_s)X-(G-\varepsilon_s)X^2\right] \tag{2}$$

where

$$X=\left\lceil \frac{\varepsilon_s}{G-\varepsilon_s} \right\rceil \tag{3}$$

Although we have been able to study the performance of the multirate OTW-CDMA in [2], the work was based on the average of the cross-correlation function assuming one-coincidence sequences. In this work, we attempt to evaluate the performance of this system probabilistically in a way to obtain a closed form solution of the exact BER analysis of this system.

3 Overlapped Interference Sequences Identification

As it has been shown in [2], increasing the transmission rate will increase the overlapping coefficient, and therefore will induce more interference. Throughout this section we will try to study and quantify the effect of overlapping for one coincidence sequences with non repeating frequencies [11].

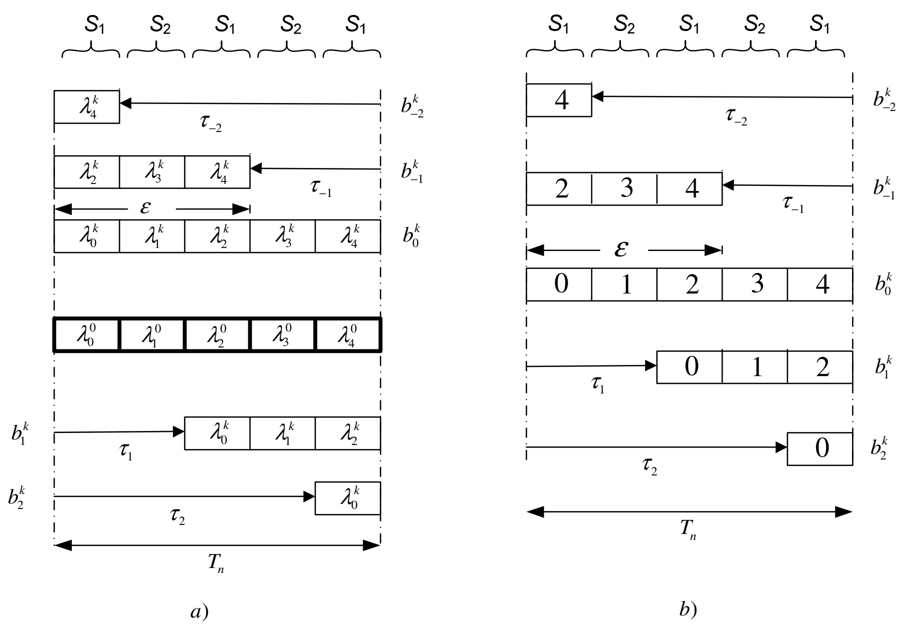

Fig. 2. a) Code interference pattern, b) the corresponding indices of the interference sequences

Consider an interferer user *k* with (G,ε_j) as the one presented in Fig. 1. During the auto-correlation process, we look only to the nominal period T_n. Therefore, the interfering sequence as seen by the desired user's receiver is shown in Fig. 2. In this figure, we can notice many important aspects. The first one is that at every chip position, there is an interfering pattern that forms a sequence with different elements like $S_1=\{\lambda_0^k,\lambda_2^k,\lambda_4^k\}$. The second observation is that each interfering sequence is repeated multiple times at different chip positions.

Lemma 1. *In an overlapped optical CDMA system, let an interferer with* (G,ε_j). *At the desired correlation receiver end, and during the nominal observation time period* T_n, *the observed interfering sequences are subdivided into two groups. In the first group there are* m_1 *sequences of length*

$$N_1=\left\lceil \frac{G}{G-\varepsilon} \right\rceil \tag{4}$$

with

$$m_1=G-(G-\varepsilon)\left\lceil \frac{\varepsilon}{G-\varepsilon} \right\rceil \tag{5}$$

The remaining

$$m_2=(G-\varepsilon)\left\lceil \frac{\varepsilon}{G-\varepsilon} \right\rceil-\varepsilon \tag{6}$$

sequences form the second group in which each sequence is of length

$$N_2=\left\lceil \frac{\varepsilon}{G-\varepsilon} \right\rceil \tag{7}$$

■

Lemma 1 is very important in the sense that it enables us to quantify the effect of overlapping on the interference patterns at a given receiver.

4 Hits Quantification due to Overlap

By observing Fig. 2, we can notice clearly that there are two different kinds of interfering sequences, $S_1=\{\lambda_0^k,\lambda_2^k,\lambda_4^k\}$ and $S_2=\{\lambda_1^k,\lambda_3^k\}$. In addition, S_1 is repeated three times and S_2 is repeated 2 times. Thus, to study the contribution of S_1 on the MAI, we need to compare it with the desired user wavelengths where it is present. Therefore, we need to compare $S_1=\{\lambda_0^k,\lambda_2^k,\lambda_4^k\}$ with $d_1=\{\lambda_0^0,\lambda_2^0,\lambda_4^0\}$. The same argument can be applied to the sequence S_2 where we need to compare $S_2 = \{\lambda_1^k, \lambda_3^k\}$ to $d_2 = \{\lambda_1^0, \lambda_3^0\}$.

Let's take for example S_1 and d_1. It's clear that there are up to three possible matching events between elements in S_1 and elements in d_1. Thus one element in S_1 can be in d_1, two elements in S_1 can be in d_1, or three elements in S_1 can match with three elements in d_1. Each of those events represents the number of hits the interfering sequence S_1 induces at the desired user's receiver. The probabilities of those events are critical in deriving the BER of this system.

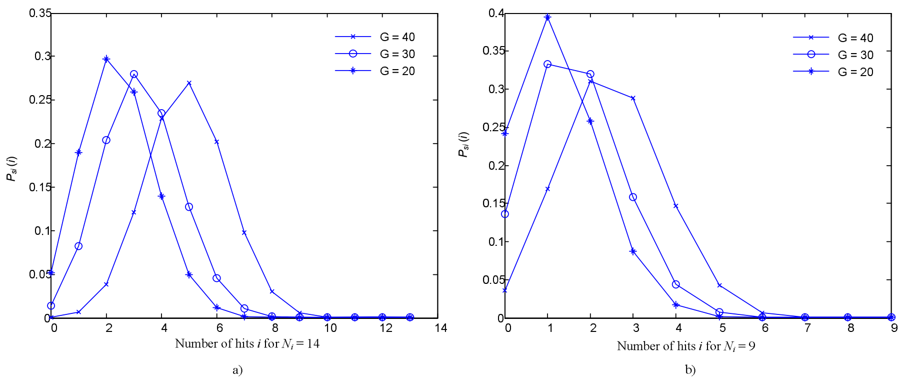

Fig. 3. The probability that the sequence S_i causes i hits in the cross-correlation function

In general, consider an interfering sequence S_i and the desired sequence d_i, both of them with length N_i where N_i can be obtained using Lemma 1. The probability that S_i causes i hits in the cross-correlation function is the probability that exactly i terms in S_i match with i terms in d_i. If we are selecting N_i wavelengths at a time from a set of F possible wavelengths, then the probability of having exactly i wavelengths matching with the sequence d_i of length N_i and $N_i - i$ not matching can be written as

$$P_{S_i}(i) = \frac{\binom{N_i}{i}\binom{F-N_i}{N_i-i}}{\binom{F}{N_i}} \quad \forall\, 0 \le i \le N_i < F \tag{8}$$

where $\binom{x}{i}$ is the binomial coefficient. All the permutations of a given combination s_i will result i hits if assuming that there are exactly i wavelengths in s_i that match with i wavelengths in d_i.

An illustration of (8) is shown in Fig. 3 where we plot the probability that the interfering sequence S_i causes *i* hits versus i for a) $N_i = 14$ and b) $N_i = 9$ and for different values of *G*. In addition, we assume that $F = 2G$. Notice that as the PG increases, although the probability of having smaller number of hits decreases, the probability of higher number of hits increases. This result is not like we expect as in the case of un-overlapped systems where the length of the interfering sequence is always one and increasing the PG will leads to a decrease in the probability of hits.

5 MAI Limited BER Analysis

Obviously, it is clear that due to the overlapping process, the assumption of one coincidence sequences will not guaranty the upper bound on the number of hits to be one as in the classical non overlapped systems. In fact, the number of hits between two overlapped code sequences is related to the number of interference sequences and the size of each of those sequences. For example, if we return to the case studied and shown in Fig. 2, both interference sequences $S_1 = \left\{\lambda_0^k, \lambda_2^k, \lambda_4^k\right\}$ and $S_2 = \left\{\lambda_1^k, \lambda_3^k\right\}$ may cause up to five hits with different probability of occurrence. The importance of our work is to highlight those differences and to emphasize their effect on the performance evaluation of the system.

In order to evaluate the performance of the overlapped system, we need to find the probability that two overlapped codes have one, two, or *p* hits in their cross-correlation function such that $p \le G$. We will proceed by showing the case presented in Fig. 2. The interference pattern of this example can be simplified to two sequences of interference or hits $\left[H_1, H_2\right]$ which represent the number of possible hits caused by interference sequences S_1 and S_2, respectively. In our example, H_1 can take four possible values $H_1 = \{0, 1, 2, 3\}$, and H_2 can take three possible values $H_2 = \{0, 1, 2\}$ with different probabilities as revealed in Fig. 4.

H_1	H_2	H_1	H_2	H_1	H_2	H_1	H_2
0	0	1	0	2	0	3	0
0	1	1	1	2	1	3	1
0	2	1	2	2	2	3	2

Fig. 4. Different possible hit configurations

Different possibilities of hits caused by both sequences are presented in Fig. 4. According to Fig. 4, in order to compute the probability of having *j* hits from a given interferer, we have to find the probability of having $H_1 + H_2 = s$. For example, the probability of having three hits is obtained as follows;

$$q_3 = \Pr\left\{\begin{array}{l}(H_1 = 3 \cap H_2 = 0) \cup (H_1 = 2 \cap H_2 = 1) \\ \cup (H_1 = 1 \cap H_2 = 2)\end{array}\right\}$$
$$= \frac{1}{(N_1+1)(N_2+1)}\left\{\begin{array}{l}P_{S_1}(3)\cdot P_{S_2}(0) + P_{S_1}(2)\cdot P_{S_2}(1) \\ +P_{S_1}(1)\cdot P_{S_2}(2)\end{array}\right\} \tag{9}$$
$$= \frac{1}{(N_1+1)(N_2+1)}\sum_i \left\{P_{S_1}(j)\cdot P_{S_2}(k)\right\}$$

where $N_1 = 3$ and $N_2 = 2$ are the lengths of the sequences S_1 and S_2, respectively. In addition, the parameters j and k are chosen such that $j + k = 3$, $\forall$ $j = \{0, 1, 2, 3\}$ and $k = \{0, 1, 2\}$. The parameter i represents the number of cases satisfying $j + k = 3$.

Lemma 2: *Consider two positive integer numbers* $i = \{0, 1,..., N_1\}$ *and* $j = \{0, 1,..., N_2\}$ *with* $N_1 < N_2$. *The number of possible couples* (i, j), Λ, *satisfying* $i+j = s$, $\forall\ s = \{0, 1,..., N_1 + N_2\}$, *is given by*

$$\Lambda = \begin{cases} s+1, & \text{if } 0 \le s \le N_1 \\ N_1 + 1, & \text{if } N_1 < s \le N_2 \\ N_1 + N_2 - s + 1, & \text{if } N_2 < s \le N_1 + N_2 \end{cases} \tag{10}$$

■

Using Lemma 2 we can generalize (9) to the case of any number of hits. Therefore, the probability of having s hits is given by

$$q_s = \frac{1}{(N_1+1)(N_2+1)}\sum_{i=a}^{b} P_{S_1}(s-i)\cdot P_{S_2}(i) \tag{11}$$

where

$$(a,b) = \begin{cases} (0,s), & \text{for } 0 \le s \le N_1 \\ (0,N_1), & \text{for } N_1 < s \le N_2 \\ (s-N_1, N_2), & \text{for } N_2 < s \le N_1 + N_2 \end{cases} \tag{12}$$

In addition, using Lemma 2, we can generalize the probability of having s hits given in (11) and (12) to any number of interfering sequences. For example, assume that the number of interfering sequences is four. Thus, let $i = \{0, 1,..., N_1\}$, $j = \{0, 1,..., N_2\}$, $k = \{0, 1,..., N_3\}$, and $t = \{0, 1,..., N_4\}$ with $N_1 \le N_2 \le N_3 \le N_4$. The distribution of the number of hits is the probability of having s hits, and it is given by

$$q_s = \frac{1}{\prod_{i=1}^{4}(N_i+1)}\sum_{t=0}^{N_4}\sum_{k=0}^{N_3}\sum_{i=a}^{b} P_{S_1}(s-k-t-i)\cdot P_{S_2}(i)\cdot P_{S_3}(k)\cdot P_{S_4}(t) \tag{13}$$

where

$$(a,b)=\begin{cases}(0,s-k-t), & \text{for } 0\le s-k-t\le N_1\\(0,N_1), & \text{for } N_1<s-k-t\le N_2\\(s-k-t-N_1,N_2), & \text{for } N_2<s-k-t\le N_1+N_2\end{cases} \tag{14}$$

Fig. 5 shows the distribution of the number of hits when $G=15$, $F=18$, and for different values of ε. It is clear that when the system works above the nominal limit, it may induce more then one hit even if the codes used are one coincidence codes. This in turn, will drastically influence the probability of error of the system. Notice that, as we further increase the transmission rate, the probability of having larger number of hits becomes higher, thus increasing the MAI.

Having obtained in (13) the probability of *s* hits in the cross-correlation function, we can now compute the MAI-limited BER when the system is working above the nominal limit. Let *Z*, *TH*, and *M* denote the cross-correlation value seen by the desired receiver, the decision threshold, and the total number of simultaneous users in the system, respectively. Obviously, an error occurs whenever the transmitted data bit is zero, but the interference at the desired receiver results in $Z > TH$. Thus, the probability of error is given by

$$\begin{aligned}P_e &= \Pr(\text{error} / M \text{ simultaneous users})\\ &=\frac{1}{2}\Pr(Z\ge TH / M \text{ users and the desired user sent } 0)\end{aligned} \tag{15}$$

where we have assumed that the data bits zeros and ones are equiprobable.

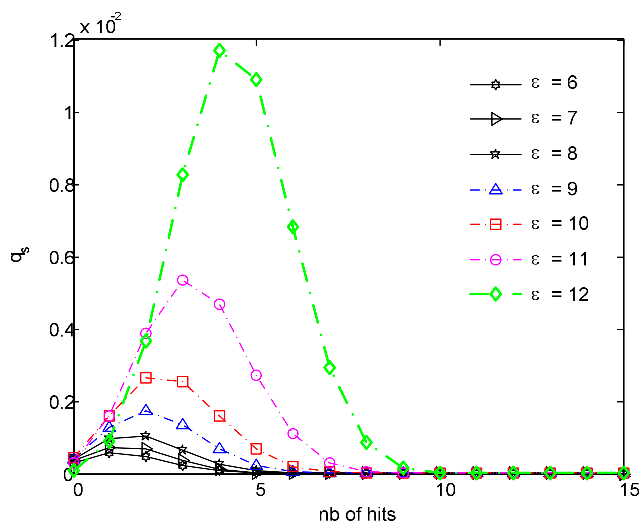

Fig. 5. The Probability mass function of the number of hits for different values of the overlapping coefficient ε

Assuming that S is the total number of interfering pulses in the cross-correlation function and that each interfering user may contribute up to S pulses in it. Let l_j to be the number of interfering users that has a cross-correlation value j. Then, the probability of having $\{l_1, l_2, ..., l_S\}$ interfering users follows a multinomial probability density function [5] and it is given by

$$\Pr(l_1, l_2, ..., l_S) = \frac{(M-1)!}{\left(\prod_{j=1}^{S} l_j!\right)\left(M-1-\sum_{j=1}^{S} l_j\right)!}\left(\prod_{j=1}^{S} q_j^{l_j}\right)\left(1-\sum_{j=1}^{S} q_j\right)^{\left(M-1-\sum_{j=1}^{S} l_j\right)} \tag{16}$$

where q_j is given in (13) and (14). Using (16) in (15) we obtain

$$P_e = \frac{1}{2} - \frac{1}{2}\sum_{l_1=0}^{TH-1} \sum_{l_2=0}^{\left\lfloor \frac{TH-1-l_1}{2} \right\rfloor} \cdots \sum_{l_S=0}^{\left\lfloor \left(TH-1-\sum_{j=1}^{S-1} j l_j\right)/S \right\rfloor} \Pr(l_1, l_2, ..., l_S) \tag{17}$$

6 Numerical Results and Discussion

Throughout this section, we will try to study and discuss the above derived equations using numerical evaluation. In addition, the impact of the exact BER analysis on the performance of two newly proposed MAC protocols, the S-ALOHA and the R3T protocols, is also investigated. For a complete and detailed discussion of both protocols, the reader is invited to refer to [7] and [8]. Throughout this section, we assume that the total number of stations is M = 15, and the processing gain is G = 15.

In Fig. 6, we show the error probability as a function of the number of users M and for different values of the overlapping coefficient ε when (a) the number of available wavelength is double the code length [11] and when (b) the number of available wavelength is equal to the code length [10]. The error probability increases when increasing M, as expected. In addition, the error probability increases when increasing the transmission rate, therefore; increasing ε. This is due to the increase in the probability of hits. Notice the importance of the number of available frequencies F on the performance of OTW-CDMA by observing that the probability of error shown in Fig. 6(a) for $F = 2G$ is much lower than that presented in Fig. 6(b) where $F = G$. This means that code families that provide a flexibility of choosing F like the one in [11], can offer better performance than that in which $F = G$ [10].

In the following simulation, we assume that the packet length under S-ALOHA protocol is L = 100 bits/time slot and the message is one packet. While equivalently, under the R3T protocol the packet length is one bit/time slot and L =100 designates the message length in packets. Note that there is a correspondence between A and P_r. In S-ALOHA, when a terminal enters the backlogged mode, it cannot generate new packets until all the accumulated ones in the system's buffer are retransmitted. Consequently, the offered traffic varies according to the retransmission probability, P_r. Meanwhile, in R3T, the terminal in case of transmission failure retransmits the

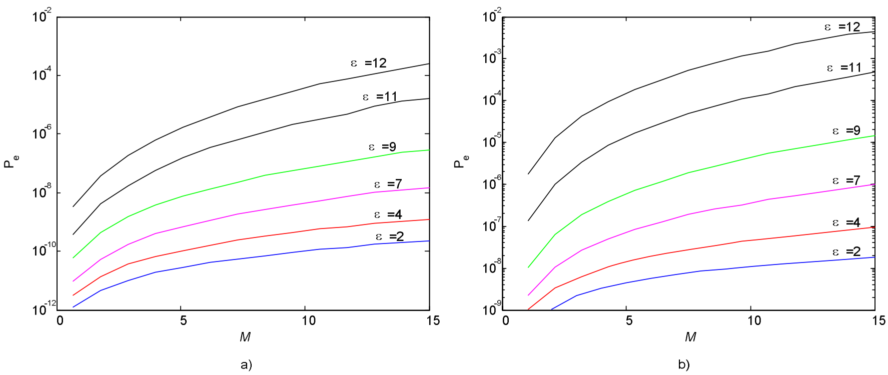

Fig. 6. BER versus the number of users M for different value of ε and when: a) $F = 2G$, b) $F = G$

last unsuccessful t packets with the same transmission probability (user's activity) A whereby which varies the offered traffic. For S-ALOHA, we assume P_r = 0.6, whereas for R3T, we assume A = 0.6, the time out duration τ_o = 1 time slot and the two-way propagation delay is t = 2 time slots.

The throughput of both systems is presented in Fig. 7. In Fig. 7(a) we present the throughput versus the offered traffic using a detection threshold $TH = G/2$, while Fig. 7(b) shows the throughput when using the optimal detection threshold. The impact of the detection threshold is very obvious in the sense that there is a noticeable increase in the network throughput when using the optimal detection threshold.

It is clear that, for high overlapping coefficient, the R3T protocol exhibits higher throughput than the S-ALOHA protocol. While, the throughputs of the S-ALOHA protocol is higher than that of the R3T when ε is relatively small. For the S-ALOHA protocol, when using the optimal detection threshold, the system reaches its maximum throughput of 8 packets per time slot for $\varepsilon < 10$. On the other hand, the R3T protocol reaches its maximum throughput of 7 packets per time slot for $\varepsilon < 10$ as revealed by Fig. 7(b).

As the transmission rate increases, the throughput of the S-ALOHA decreases compared to that of the R3T. This means that the R3T protocol can manage higher-rate users better than the S-ALOHA due to its efficient administration of erroneous packets using the *Round Robin* and the *Go-back-n* protocols.

In Fig. 8 we present the average packet delay versus the system throughput, operating under the two mentioned protocols using the optimal detection threshold as in Fig. 8(b), and a non-optimal detection threshold as in Fig. 8(a), respectively. Here again we remark that the R3T protocol exhibits higher delay at low throughput for relatively small values of ε. On the other hand, the S-ALOHA protocol exhibits higher delay at low throughput for higher values of ε. Notice that when using the optimal detection threshold, the S-ALOHA achieves it maximum throughput with

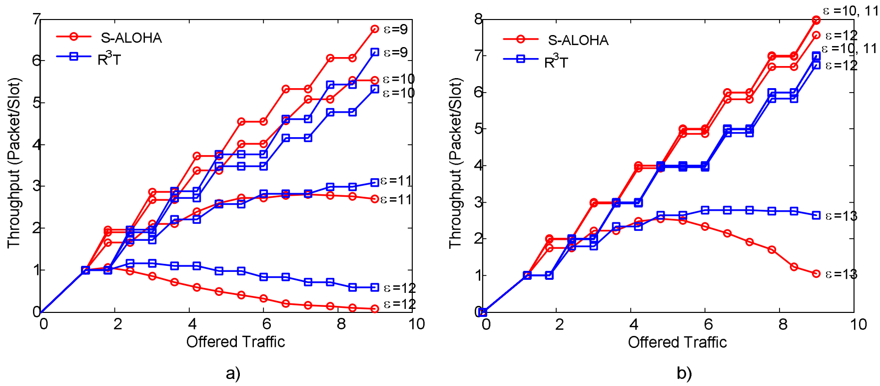

Fig. 7. Throughput versus the offered traffic of the OTW-CDMA system under the two MAC protocols: S-ALOHA and R^3T and using (a) non-optimal detection threshold, (b) optimal detection threshold

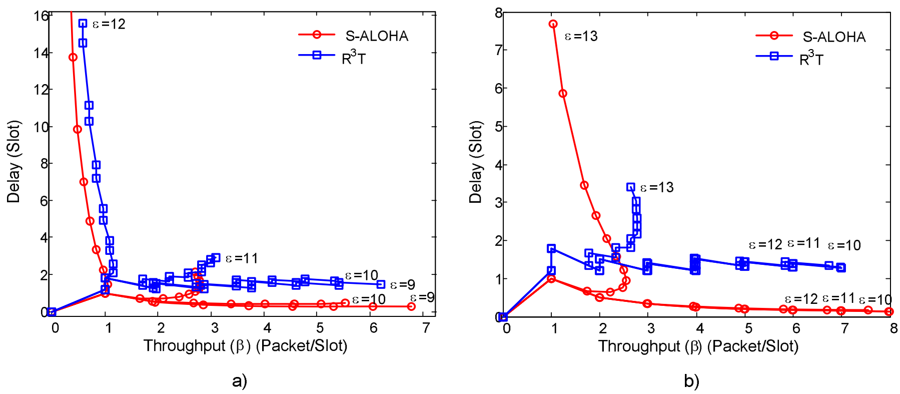

Fig. 8. Average packet delay versus the throughput of the OTW-CDMA system under the two MAC protocols: S-ALOHA and R^3T and using (a) non-optimal detection threshold, (b) optimal detection threshold

virtually not delay when $\varepsilon < 10$, while the R^3T protocol takes around one time slot to achieve its maximum throughput. This is due to the use of the *Go-back-n* protocol.

By comparing the performance of the OTW-CDMA system under both protocols, we notice that for low transmission rates, the S-ALOHA is better than the R3T; while the R3T is better at very high transmission rates.

7 Conclusion

An analysis of the performance of OTW-CDMA network when the system is working above the nominal transmission rate limit has been provided. A unified mathematical framework is presented under the assumption of one coincidence sequences with non-repeating wavelengths. A closed form expression of the BER has been derived. Results show that the performance of OTW-CDMA system may be critically affected when working above the nominal limit. In addition, the impact of the derived error probability on the performance of two newly proposed MAC protocols, the S-ALOHA and the R3T, is also investigated. It is shown that for low transmission rates, the S-ALOHA is better than the R3T; while the R3T is better at very high transmission rates. However, in general, the R3T protocol suffers a higher delay because of the presence of additional modes.

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