# A Fast Wavelength Hopped CDMA System for Secure Optical Communications

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## Abstract

In this paper, we describe a fast wavelength hopped optical code division multiple access (CDMA) scheme employing a balanced detector to enable bipolar signaling and achieve true orthogonality in non-coherent optical systems. The idea can be used to construct secure wavelength hopped CDMA systems. We give the interference analysis for randomly chosen codes.

**Keywords:** optical CDMA, wavelength hopping, bipolar signaling, multiple access interference, security, optical communications

## 1. Introduction

Bipolar signaling was thought to be difficult in non-coherent intensity modulated and direct detection optical communication systems. Using a balanced detection scheme and differentially modulating complementary pairs of wavelengths, it is possible to achieve bipolar signaling optically [1] while avoid using complicated coherent optical systems. Compared to most proposed optical CDMA systems which use sparse sub-optimal and pseudo-orthogonal optical intensity correlation codes [2-4], a bipolar signaled system enables us to make more efficient use of the spectrum by allowing true orthogonal codes in the system. This is important for building future high throughput high security optical networks.

Providing high security transmission at the physical layer becomes an imminent need in real time secure applications with poor tolerance to encryption delays such as voice and motion picture transmission. The recent development in WDM technologies has made multi-wavelength optical CDMA systems a potentially viable technology for future high security applications. In this paper, we propose a fast wavelength hopped optical CDMA system capable of supporting a large number of codes and secure optical communications.

## 2. System Description

Assume we have N wavelengths $\lambda_1, \lambda_2 \ldots \lambda_N$. To achieve bipolar signaling, we arrange the available wavelengths into groups of two $\Lambda_i = (\lambda_{i0}, \lambda_{i1})$ where $1 \le i \le N/2$, so that each group of wavelengths $\Lambda_i$ represents one symbol. The two wavelengths $\lambda_{i0}$, $\lambda_{i1}$

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are used to transmit 0 and 1 values of a symbol in a "frequency shift keying" fashion. A bit of duration $T_b$ consists of a sequence of chips of duration $T_c$ similar to frequency hopped radio CDMA. However, each chip is represented by a wavelength group. The transmitter transmits the bits of information in sequences of chips in a pseudo-random fashion as shown in Figure 1. The receiver hops the wavelength pairs in synchronous with the transmitter in order to recover the signal.

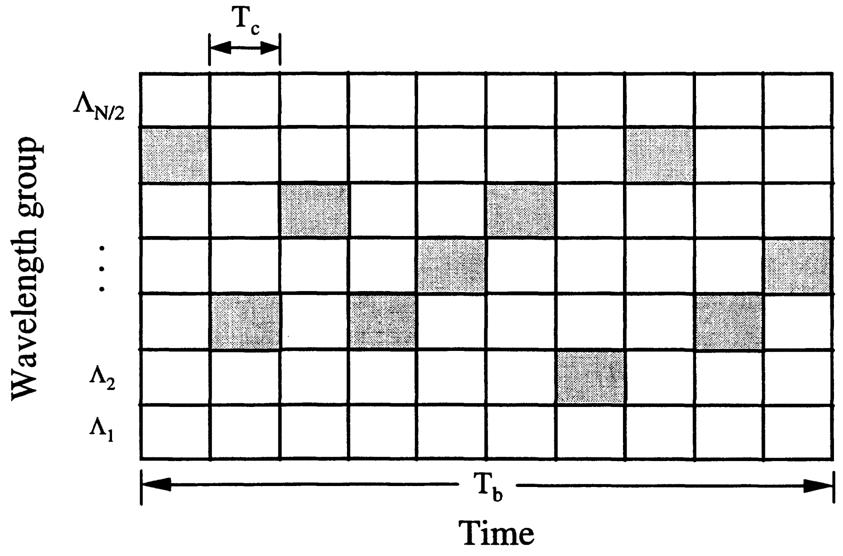

**Figure 1. Pictorial representation of fast wavelength hopped optical CDMA. The shaded squares represent the wavelength groups selected for each chip.**

The simplest transmitter could be a tunable laser diode source which can be tuned to the desired wavelength from chip to chip. Fast widely tunable laser diodes are being developed in research labs [5-7]. Alternatively, we can also use multi-wavelength laser diode array modules. Recently, there have been demonstrations of such sources [8]. Another possible transmitter implementation is shown in Figure 2. In this structure, a broadband light source consisting of all the wavelength components is used. The broadband source could be a super-luminescent light emitting diode (SLD) or an Erbium doped fiber amplifier (EDFA) biased into super luminescent mode. The output from the broadband source is sliced into individual wavelength components using a wavelength demultiplexer [9-10]. Each wavelength is then selectively dropped or transmitted by an array of optical switches as shown in Figure 2. The control signals to the switch array are determined by the code and input data. Only one wavelength group is selected for each chip and the particular wavelength used in the selected pair of wavelengths is determined by the value of the chip symbol which is either 0 or 1. Fast optical switches such as Lithium Niobate or polymeric electro-optic switches [11-12] can be used in the switch array for wavelength hopping. These switches can be modulated at more than 10GHz speed. In fact, the structure shown in Figure 2 has been proposed as a fully configurable optical add-drop multiplexer (ADM) [13].

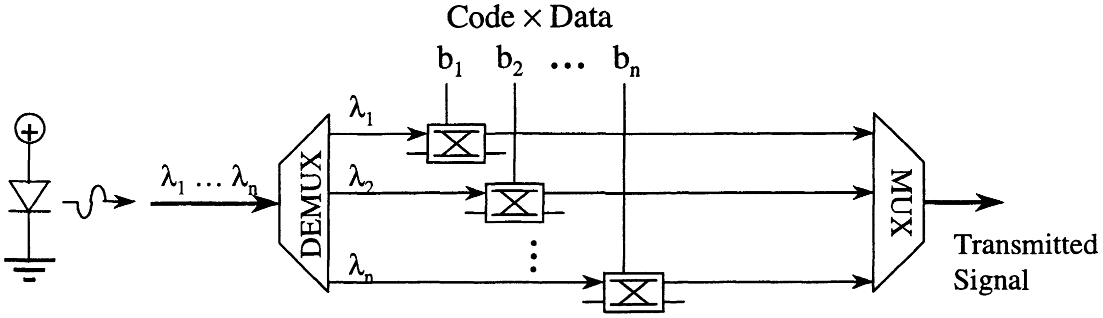

**Figure 2.** **A transmitter structure for wavelength hopped optical CDMA**

The receiver is shown in Figure 3. The received signal is split into two halves using a 3-dB splitter. Each half of the received optical signal is passed through an optical ADM similar to the one in Figure 2. In this setting, both the upper and lower ADM hop in synchronous with the wavelength group hopping sequence of the desired transmitter. For a code symbol 0, the upper ADM in the receiver selects $\lambda_{i0}$ of the wavelength group $\Lambda_i$ and the lower ADM selects $\lambda_{i1}$. The reverse is true for a code symbol 1. So the balanced photodetectors following the two ADMs will detect the difference signal between $\lambda_{i0}$ and $\lambda_{i1}$. Since zeros and ones of the chip symbols are transmitted using either $\lambda_{i0}$ or $\lambda_{i1}$, depending on the transmitted symbols, the balanced detector will detect bipolar signals at (A) in Figure 3. The balanced detector output is integrated over a bit period $T_b$. The result is compared with a threshold value to determine the actual received bit value.

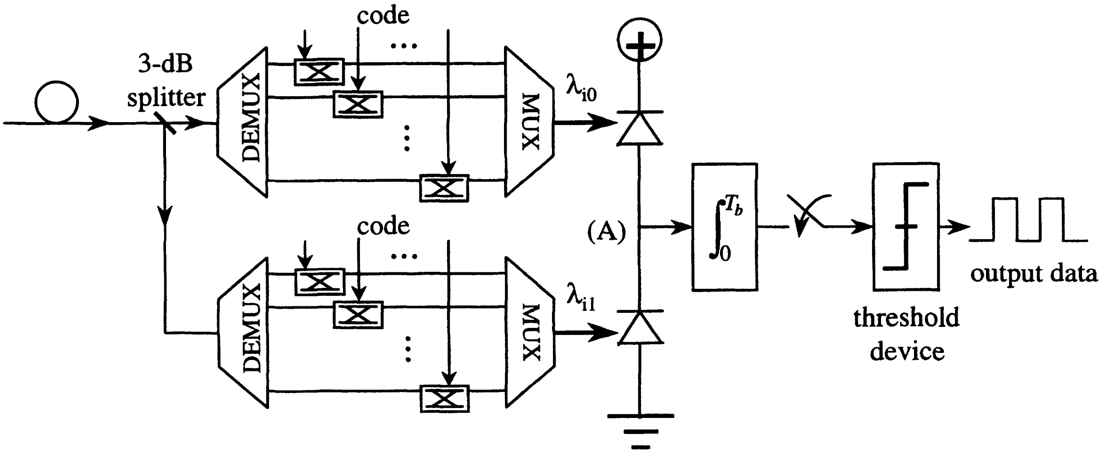

**Figure 3.** **Receiver structure of the fast optical CDMA**

## 3. Performance Analysis

In this section, we give an analysis for the signal to interference ratio. We assume that the optical power used in the transmitter is large enough so that shot noise and thermal noise can be neglected. We also assume the optical power received from each active co-channel user is the same at the receiver. In the following analysis, we normalize the output from the balanced receiver so that each matched chip symbol from the matched transmitter produces either a +1 or –1 at the balanced detector output (A) in Figure 3. An interfering transmitter hopping at an unmatched frequency group produces no output at the receiver because all the optical signal energy is dropped by the receiver ADMs.

To investigate interference among the active users, we assume the case in which there is no co-ordination among the different users. The probability that a user picks a particular wavelength group for a specific chip is assumed to be completely random and evenly distributed among the N/2 wavelength groups. The probability that a user hops to a particular wavelength group during any chip time is therefore 2/N. For K+1 active users where K is the number of interfering users, the average number of interfering users hopped to the same wavelength group $\Lambda_i$ selected by the receiver during a chip period is K×(2/N). Let $p$ and $q = 1-p$ be the probability that a user is transmitting a symbol 0 and a symbol 1 respectively. Assume all users are equal. Without loss of generality, if the balanced receiver is set to receive $\lambda_{i0}$ by the upper detector and $\lambda_{i1}$ by the lower detector during a particular chip, users sending a symbol using $\lambda_{i0}$ will produce a +1 at the balanced detector output (A) and users sending a symbol using $\lambda_{i1}$ will produce a –1 as explained. Therefore, the average value and the variance of the balanced detector output due to interference in each chip are:

$$\overline{u_c} = K\frac{2}{N}(p-q) \tag{1}$$

and

$$\left\langle (u_c - \overline{u_c})^2 \right\rangle = K\frac{2}{N}pq \tag{2}$$

For random and evenly distributed symbols, $p = q = 1/2$ and $\overline{u_c} = 0$. The variance of the interference signal is $\left\langle u_c^2 \right\rangle = \frac{K}{2N}$ which can be regarded as the interference power per chip due to co-channel interfering users.

Each coded bit consists of M = $T_b/T_c$ chips. The signal strength per bit of the matched channel is $s = \pm M$ after being processed by the integrate-and-dump circuit in Figure 3. The received bit value is determined by comparing the output from the integrate-and-dump to a threshold value. For codes which are selected randomly and evenly as assumed here, the M chips will be non-correlated and the average interference power per bit after the integrate-and-dump circuit is:

$$\left\langle u_b^2 \right\rangle = M\left\langle u_c^2 \right\rangle = \frac{KM}{2N} \tag{3}$$

Therefore the signal to interference power ratio is given by

$$SIR = \frac{s^2}{\left\langle u_b^2 \right\rangle} = \frac{2NM}{K} \tag{4}$$

We can see from (4) that for random codes, the signal to interference power ratio is improved by the product of the code length M and the number of optical wavelengths N.

Assume the code length is long enough and the number of interfering users is so large that the received output signal distribution can be approximated by the Gaussian distribution. Ignoring shot noise and thermal noise, the bit error rate for bipolar signaling is given by [14]:

$$BER = \frac{1}{2}[1 - erf(SIR)] \tag{5}$$

where *erf(x)* is the error function.

As an example, if each user transmits at 100Mbps and the wavelength hopping speed is 10Gcps (giga-chips per second), then each code consists of M=100 chips. The bit error rate against the number of co-channel users is plotted for different values of N. The result is shown in Figure 4 for N equal to 50, 80, 100 and 120. It can be seen that for N=50 and M=100, 556 concurrent active users can be supported for a BER of $10^{-9}$. Figure 5 shows the bit error rate plotted against the number of wavelengths N for different numbers of concurrent users.

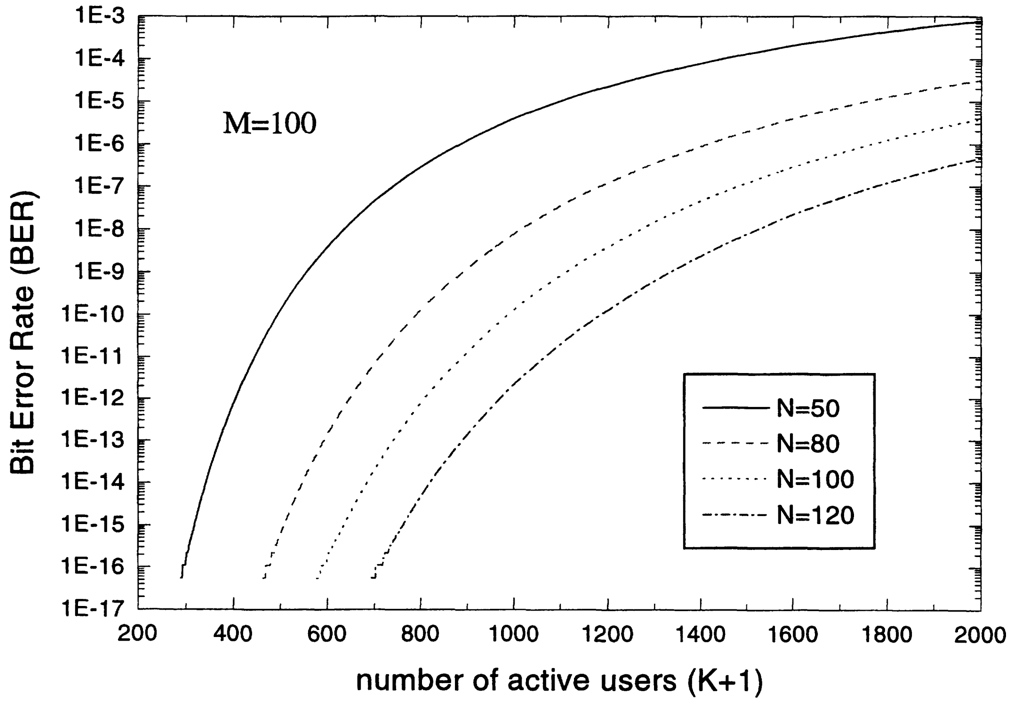

**Figure 4. Bit error rate against the number of co-channel active users. A code length of 100 is assumed.**

The available throughput for a certain bit error rate performance can be evaluated in the following manner. Suppose each user has a bandwidth $B=1/T_b$ in bits per second. The code length M equals $B_H/B$ where $B_H=1/T_c$ is the hopping speed in chips per second. Therefore, (4) becomes:

$$SIR = \frac{2N}{K}\frac{B_H}{B} \tag{6}$$

for K+1 active users. The total throughput is given by:

$$(K+1)B \approx KB = \frac{2NB_H}{SIR} \qquad K >> 1 \tag{7}$$

It is interesting to notice that the total throughput is fully determined by the minimum SIR requirement, the number of available wavelengths and the hopping speed. The latter two are solely determined by the available technology. As mentioned before, electro-optic switches with more than 10GHz speed are available commercially. Wavelength demultiplexers with more than 100 wavelength channels are also commercially available. Given the currently available technologies, fast wavelength hopped optical CDMA systems with several hundred gigabits per second throughput is theoretically possible.

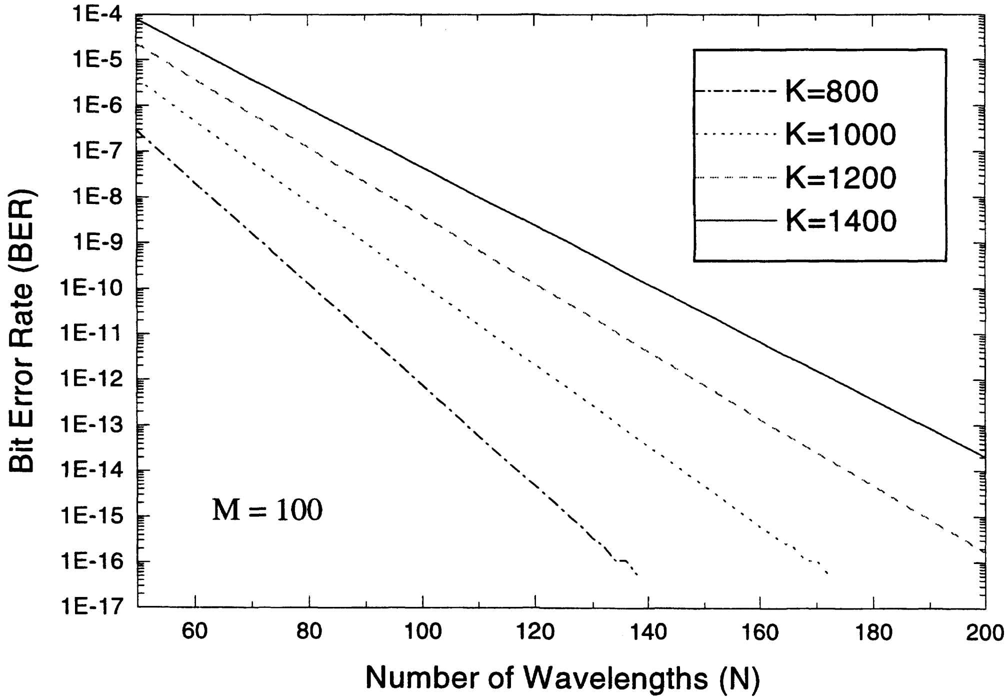

**Figure 5. Bit error rate against the number of wavelengths plotted for different number of concurrently active users. A code length of 100 is assumed.**

It is also worth noticing that the analysis given here is for completely random hopping sequence. The performance can be further enhanced by carefully designing the codes to achieve code orthogonality and decrease the interference from other channels. True orthogonality is theoretically possible because the balanced detector output is bipolar.

## 4. Security

In order to decode the signal, an eavesdropper has to obtain the correct wavelength group pair-up first, and then guess the correct hopping sequence and the particular code used in the system.

The number of ways to pair up N (where N is even) wavelengths into N/2 ordered pairs is given by

$$F(N) = \frac{N!}{(N/2)!} \tag{8}$$

For N = 50, F(N) = $1.96 \times 10^{39}$ which is a very big number. Figure 6 plots F(N) against N.

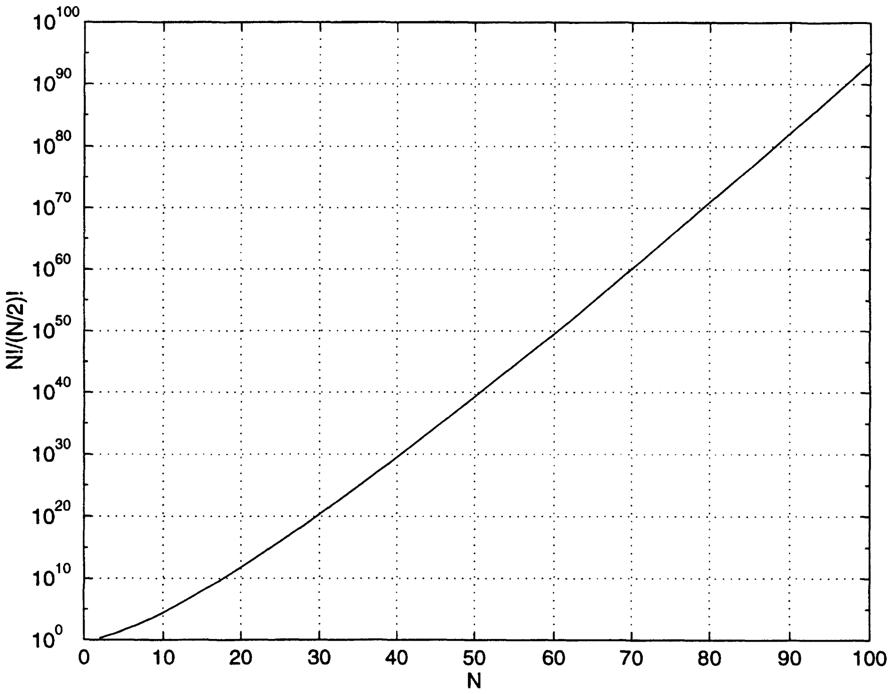

**Figure 6. Plot of N!/(N/2)!, the number of ways of forming bipolar signaling wavelength groups, against N, the number of wavelengths used.**

Given that the eavesdropper knows the wavelength groups to use, for the random wavelength hopped case considered in Section 3, the number of possible hop sequences for a code of M chips is $(N/2)^M$ which increases exponentially with M. For example, when N = 50 and M=100, $(N/2)^M = 6.22 \times 10^{139}$. In order to retrieve the information, this number has to be further multiplied by the complexity of the code chips selected because there are two possible values for each chip. In reality, certain hop patterns and chip combinations may be preferred in order to reduce the crosstalk. But we can see that the probability of guessing a right code is diminished by employing a large number of wavelengths with fast hopping speed, and therefore, a very high security optical CDMA system is presented to the eavesdropper.

## 5. Conclusion

We have presented a fast wavelength hopped optical CDMA system for secure communications. Bipolar signaling is used in this system to increase the efficiency of spectral usage and reduce co-channel interference. A performance analysis is given for random and evenly distributed wavelength hopped codes. The result shows that given enough optical power and the system is interference limited, throughputs of several hundred gigabits per second are available. The system capacity can be further improved by choosing codes which are orthogonal to each other and hence minimize co-channel crosstalk. We have also shown that the system possesses very high security. Further studies on specific code families and their effects on the performance will be pursued in the future research.

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