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Optical CDMA Systems

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ABBREVIATIONS

CDMA	Code Division Multiple Access
S-CDMA	Synchronous Code Division Multiple Access
TDMA	Time Division Multiple Access
WDMA	Wavelength Division Multiple Access
FDMA	Frequency Division Multiple Access
SDMA	Space Division Multiple Access
IM	Intensity Modulation
DD	Direct Detection
MAI	Multiple Access Interference
OOC	Optical Orthogonal Code
ASK	Amplitude Shift Keying
OOK	On-Off-Keying
PPM	Pulse Position Modulation
BPSK	Binary Phase Shift Keying
OFA	Optical Fiber Amplifier
STM	Synchronous Transfer Mode

ABSTRACT

This report gives an overview of the implementation methods and applications of code division multiple access using an optical carrier in both the fiber optic and the wireless optical channel. The differences of synchronous and asynchronous systems and coherent and noncoherent systems are described. Optical CDMA is also compared with other multiple access methods TDMA and WDMA.

1. INTRODUCTION

During the last 15 years the number of optical communication systems has rapidly increased. Using optical fiber together with semiconductor laser transmitter has made it possible to transmit high bit rate signals with low attenuation. CDMA has become very popular during the last years in cellular radio networks. This has given the reason to study if the advantages of CDMA could also be utilized in optical communication links.

In a CDMA system all the users are transmitting simultaneously on the same carrier frequency. To distinguish the signals of the different users each information bit is coded by a signature sequence which has pseudonoise character and the same temporal length as the information bit. Each user has a different 0,1 -code pair which is known by the transmitter and the receiver. The receiver identifies the information bits of the user by correlating the received signal with the user's 0- and 1- sequences. The signature sequence consists of chips having the value 0 or 1.

The optical CDMA communication system can be all-optical or partly optical. In a partly optical CDMA system at least the communication channel is optical. It may be optical fiber or wireless channel. The information bits may be originally optical or electrical. The all-optical CDMA system is usually a fiber optic noncoherent system. It usually has no separate modulation operation. The signature coding is performed by an optical waveguide structure. The 1-chips are given a certain intensity level in the signature coding. In the fiber optic coherent system signature coding is performed electrically and after that the optical carrier of the laser transmitter is modulated coherently. In the wireless systems the signature coding and subcarrier modulation are performed electrically and then this signal is used to modulate the laser or LED transmitter. At the receiving side the operations are performed in the reversed order. The optical CDMA system may be asynchronous or synchronous (S-CDMA). In a synchronous system the bits and chips are synchronized. In the asynchronous system the bits are not synchronized but the chips may be transmitted synchronously.

Optical CDMA-system :

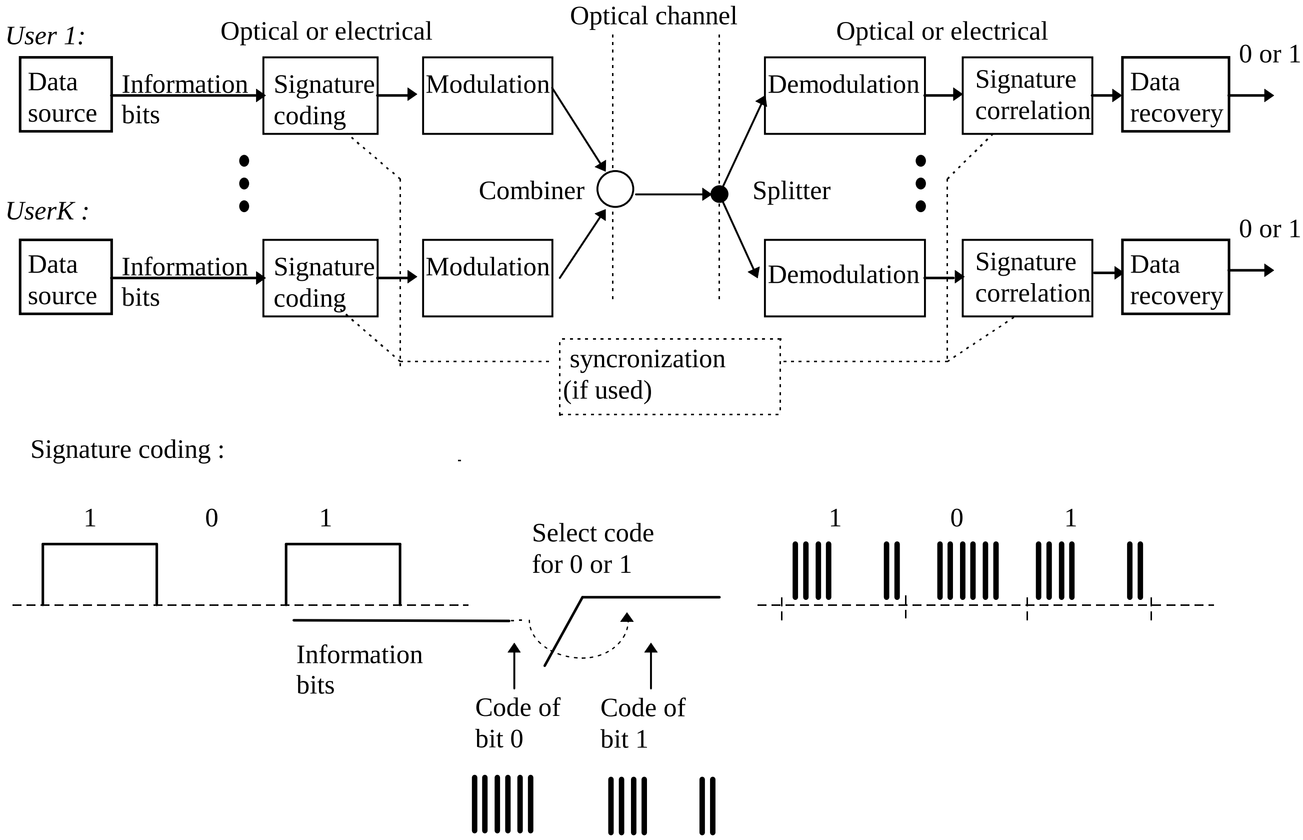


Figure 1-1: Optical CDMA system

2. NONCOHERENT OPTICAL CDMA SYSTEMS

2.1 Intensity modulation and direct detection

The noncoherent communication systems use direct detection receivers. In direct detection (DD) the photodetector gives the output current I_D which is proportional to the average power of the received optical (modulated) signal. Because only the power level is detected the laser or LED transmitter is intensity modulated (IM). Amplitude-shift keying (ASK) is performed on all the optical carrier frequencies at the same time by changing the drive current of the transmitter so that the wanted optical power level is obtained.

Each receiver correlates its own signature sequence $s_i(t)$ with the combined received signal $r(t)=\sum_{m=0}^{M} s_m(t)$ of all the users. The correlation function $c(t)$ is obtained as the output of a filter matched to the user's own signature sequence $s_0(t)$. The output is sampled at the end of the bit interval T_b and compared to the threshold value of logical 0 and 1. The optical correlation is shown in the *Figure 2-1*.

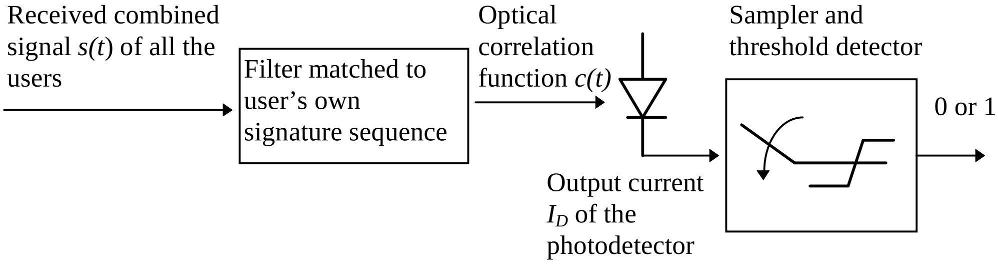


Figure 2-1: Direct detection using optical correlator

If the signature correlation is performed electrically the operation principle is the same. Then only the photodetector is located before the matched filter.

2.2 Signature codes for noncoherent optical CDMA systems

Because the noncoherent detection is based on the received optical power the chip of logical 0 has zero power level and the chip of logical 1 has a real positive power level. To avoid interference from other users the signature sequences should be as orthogonal as possible. However because the chip values are always non-negative orthogonality can be achieved only so that when the chip has the value 1 at some chip position the chips values of other signature sequences at the same chip position must be 0.

Because of this the optical codes are sparse in 1s, which means that to get a certain energy per bit, either the peak power level or the number of chips per bit (or both) must be larger than for the traditional electronic CDMA systems that use waveforms in which every chip contains energy. Thus, while optical codes can be designed that have few coincidences of 1 between the desired signal and the many interfering signals, the link budget suffers drastically. If there were no system noise in the system this could be tolerated, but in a real network with losses in the star couplers and with propagation over useful distances, this sparseness constraint on the signaling waveforms is a significant problem in optical CDMA with non-coherent detection [5].

To get a good discrimination of the 0- and 1-levels and because the number of signature codes are limited usually the zero power level is used for the signature sequence of the bit 0.

When the received bit is 1 the interference from other users does not disturb the level detection but when the received bit is 0 the interference may cause a wrong decision. The sensitivity of the noncoherent system to overlapping 1´s is demonstrated in the following simplified example. There are 4 synchronized users and the length of the bit is 16 chips.

$s_1(t)$, $s_2(t)$, $s_3(t)$, $s_4(t)$ = Signature codes of users 1, 2, 3 and 4 . 1-bit is transmitted to the users 1, 2 and 3. Bit 0 is transmitted to the user 4. The receiver of the user 4 makes a wrong decision when it correlates its own signature sequence $s_4(t)$ with the received signal $s_1(t)+s_2(t)+ s_3(t)+ s_4(t)$.

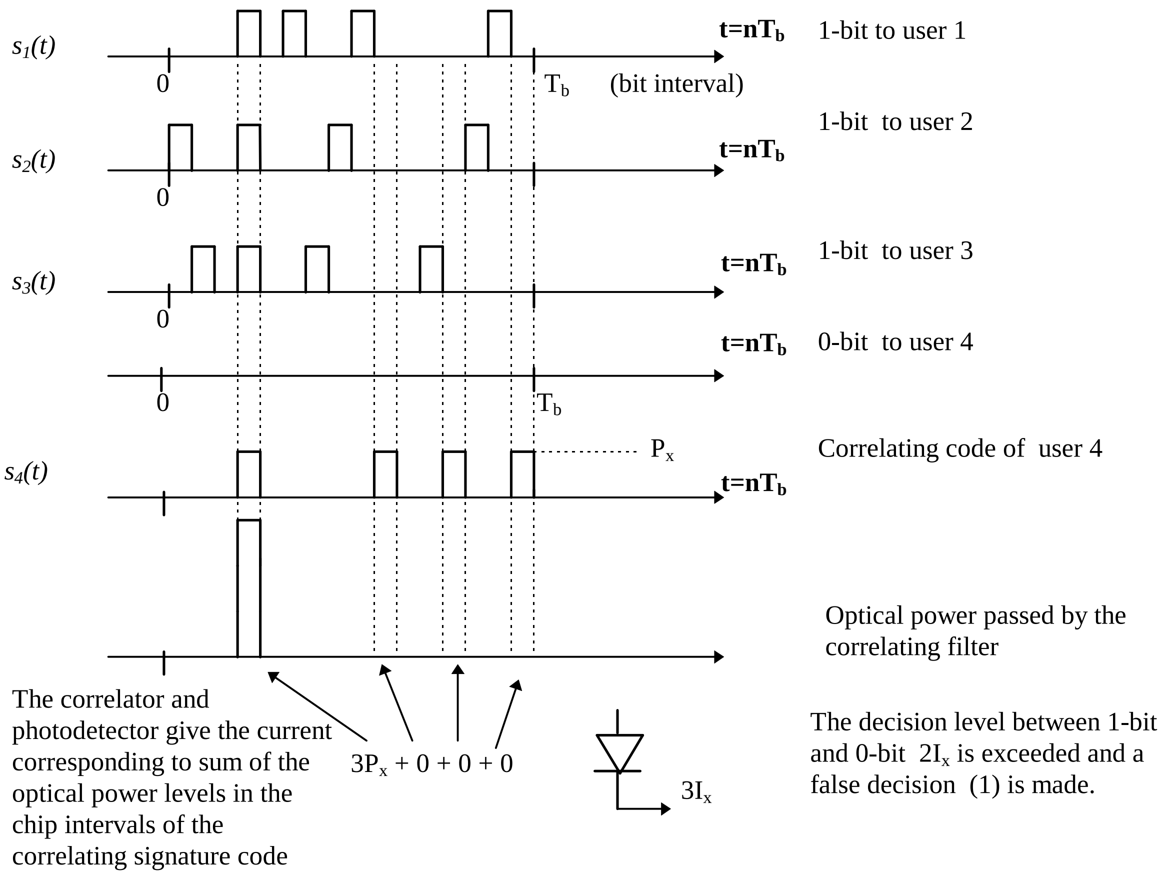
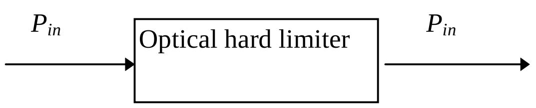


Figure 2-2: Wrong decision caused by overlapping 1's in signature codes

One way to reduce the interference power is to use an optical hard-limiter. It is a nonlinear device which clips the power to the normal chip power level during every chip interval



$$P_{out} = \begin{cases} 0 & \text{if } P_{in} < P_x \\ P_x & \text{if } P_{in} \geq P_x \end{cases}$$

Figure 2-3: Operation of an optical hard-limiter

In the previous example the power level would be clipped to P_x and a correct decision would be made.

The achievable bit error rate and maximum number of users for a certain link length and bit rate depend on the multiple access interference (MAI), channel noise and photodetector noise. In a noncoherent fiber optic CDMA system the MAI level is the dominant factor. The signature code of each user should be distinguished from a shifted version of itself and from the shifted versions of the codes of other users. When x_n and y_n are signature codes of two users the code design problem reduces to constructing codes that satisfy the following two conditions of periodic correlation [6]:

$$\left|\sum_{n=0}^{F-1} x_n x_{n+L}\right| = \begin{cases} K & \text{for } L = 0 \\ \lambda_a & \text{for } 1 \le L \le F\text{-}1 \end{cases} \quad , F = \text{the length of the code} \qquad (1)$$

$$\left|\sum_{n=0}^{F-1} x_n y_{n+L}\right| = \lambda_c \quad \text{for } 1 \le L \le F\text{-}1 \qquad (2)$$

The in-phase autocorrelation K is the number 1's in x_n. It is called the weight of the code. L is the amount of shifting between the code sequences and F is the length of code sequence.

The out-of-phase autocorrelatioin λ_a and the cross-correlation between the codes λ_c should minimum. However, a small out-of-phase autocorrelation is important for acquiring and maintaining the code synchronization.

Because in noncoherent CDMA systems x_n , y_n are unipolar (0,1) all the terms in the correlation sums are non-negative and the codes designed to be used in radio CDMA systems in which both positive and negative values are available do not give λ_a and λ_c values small enough. For this reason so called optical orthogonal codes (OOC) with $\lambda_a = \lambda_c = 1$ have been developed. They are generated by starting from orthogonal codes of short length and extending the number of codes and the code length step by step. [6] Their drawback is that the number of different code words, i.e. the number of users in the system is limited to $M \le \left\lfloor \frac{F-1}{K(K-1)} \right\rfloor$ *(3)*

,where $\lfloor x \rfloor$ denotes the integer portion of the real value of x. When the optical orthogonal codes are used the error probability will increase if the number of 1´s (K) is decreased. The error probability for the code length F = 1000 and for different number of users in an optical fiber CDMA systems shown in the *Figure 2-4.* [1]

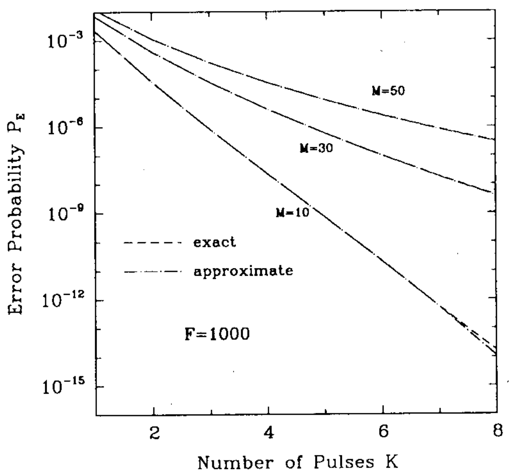


*Figure 2-4: **[1]** , page 1167*

Bit error probability with OOCs versus number of 1´s (K) for the code length F=1000 and for M users, M=10, 30, 50 in an optical fiber CDMA system.

Because the number of simultaneous users is upper bounded by $M \le \left\lfloor \frac{F-1}{K(K-1)} \right\rfloor$ and because the error probability increases when the K decreases there is a tradeoff between the number of users and the error performance. For typical parameters of F = 1000 and K = 4 we have at most 83 users with OOCs. When the bit error probability less than 10^{-9} is wanted the number of simultaneous users can be about 10 [2].

The number of simultaneous users can be increased without losing in the error performance by using the prime sequence codes. They allow the cross correlation λ_c = 2 and the out-of-phase autocorrelation λ_a even higher than 2.

The prime sequence codes are a set of codes having the code length $F = p^2$ derived from prime sequences of length p, where p is a prime number. Starting with the Galois field GF(p) = $\{0,1,...,j,...,p\text{-}1\}$, each element $s_{x,j}$ of a prime sequence $S_x = (s_{x,0}, s_{x,1}, \ldots, s_{x,j}, \ldots, s_{x,(p-1)})$ is constructed by multiplying every element from GF(p) by x, and then reducing the product by modulo p. Each prime sequence is then mapped into a binary code sequence $C_x = (c_{x,0}, c_{x,1}, \ldots, c_{x,i}, \ldots, c_{x,(p^2-1)})$ according to

$$c_{x,i} = \begin{cases} 1, & \text{for } i = s_{x,j} + jp, \quad j = 0,1,\ldots,p-1 \\ 0, & \text{otherwise} \end{cases} \qquad (4)$$

There are p binary code prime sequences with length p^2 generated by the above rule. The mapping of the prime sequence S_x into the code sequence C_x with p = 5 is shown in *Table 2-I.* Each code has p binary 1's. [3]

Table 2-1: ***[3]*** *, page 1880*

PRIME SEQUENCES S_x AND PRIME SEQUENCE CODES C_x FOR GF(5)

x	i 01234	Sequence	Code Sequences				
0	00000	S_0	C_0=10000	10000	10000	10000	10000
1	01234	S_1	C_1=10000	01000	00100	00010	00001
2	02413	S_2	C_2=10000	00100	00001	01000	00010
3	03142	S_3	C_3=10000	00010	01000	00001	00100
4	04321	S_4	C_4=10000	00001	00010	00100	01000

In the *Figure 2-5a* is shown the autocorrelation of the code sequence C_3 for the bit stream 1110010100. In the *Figure 2- 5b* is shown the cross-correlation of the code sequence C_3 with the code sequence C_2 for the same bit stream.

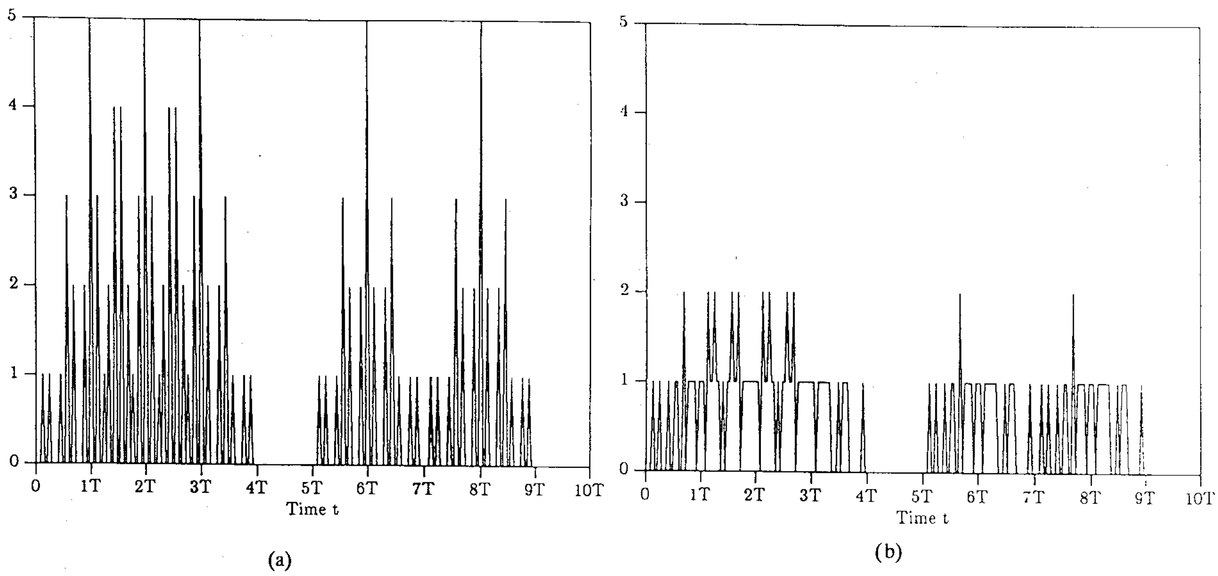


Figure 2-5 ***[2]*** *, page 1626*
a) autocorrelation of the code sequence C_3 for the bit stream 1110010100
b) cross-correlation of the code sequence C_3 with the code sequence C_2 for the same bit stream

The probability of error in an optical fiber CDMA system is plotted in the *Figure 2-6* for various prime numbers *p*. As an example, for *p*=31 (code length *F*=961) 23 simultaneous users are allowed with a probability of errors less than 10^{-9}.

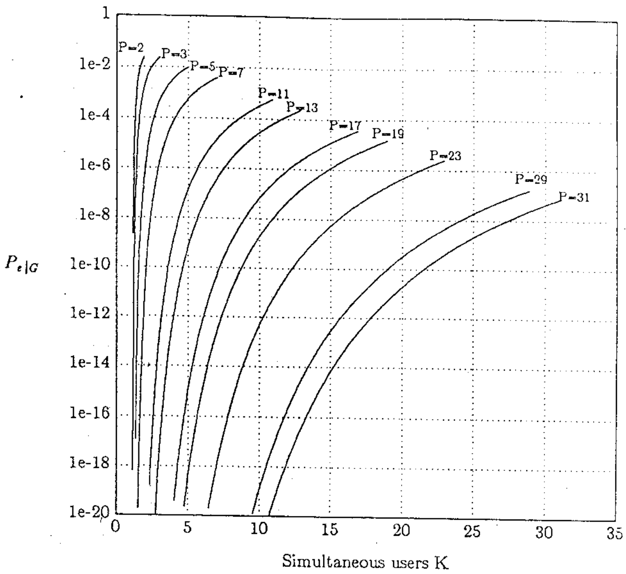


Figure 2-6: ***[2]*** *,. page 1627*

*Bit error probability versus the number of simultaneous users K as a function of p in an optical fiber system. (In the Figure 2-4 M was used for the number of simultaneous users because it is from **[1]**. There K was the number of 1´s.)*

2.3 **Synchronous and asynchronous noncoherent optical CDMA systems**

For prime sequence codes of length p^2 , the number of code sequences is limited to p, and therefore so is the number of total users. In order to generate more code sequences for the same length, modified prime sequence codes can be used. However, synchronization among the users is required. Modified prime sequence codes are time-shifted versions of prime sequence codes. With these code sequences, the cross-correlation peak between two time-shifted versions of a code sequence can be as high as the autocorrelation peak, but always occurs delayed from the autocorrelation peak. By synchronizing the receiver to the expected position of the autocorrelation peak, it can be distinguished from adjacent cross-correlation peaks. [2]

Each of the original p prime sequences S_x is taken as a seed from which a group of new code sequences can be generated. The code sequences of the first group (x=0) are obtained by left-rotating the prime sequence code C_0 . C_0 can be left-rotated $p-1$ times before the original C_0 is recovered, so that $p-1$ new sequence codes can be generated from C_0 . For the other $p-1$ groups (x = {1, ... , $p-1$}), the elements of the corresponding prime sequence S_x can be left-rotated $p-1$ times in a similar way to create new prime sequences $S_{x,r} = (s_{x,r,0}\ , s_{x,r,1}\ , \ldots , s_{x,r,(p-1)})$ where r represents the number of times S_x has been left-rotated. Therefore, p prime sequences per group are obtained.[3] Each prime sequence $S_{x,r}$ is then mapped into a binary code sequence $C_{x,r} = (c_{x,r,0}\ , c_{x,r,1}\ , \ldots , cs_{x,r,(p^2\ 1)})$ according to

$$c_{x,r,i} = \begin{cases} 1, & \text{for } i = s_{x,r,j} + jp, \quad \text{j} = 0,1,\ldots, p-1 \\ 0, & \text{otherwise} \end{cases} \quad [3] \qquad (5)$$

The set of new prime sequences $S_{x,r}$ and their associated code sequences $C_{x,r}$ for GF(5) are shown in the *Table 2- 2.*

Table 2-2: ***[3]*** *, page 1881*

LEFT–ROTATED PRIME SEQUENCES $S_{x,r}$ AND MODIFIED PRIME SEQUENCE CODES $C_{x,r}$ FOR GF(5)

Group x	i 01234	Sequence	Code Sequences				
0	00000	$S_{0,0}$	$C_{0,0}$=10000	10000	10000	10000	10000
	44444	$S_{0,1}$	$C_{0,1}$=00001	00001	00001	00001	00001
	33333	$S_{0,2}$	$C_{0,2}$=00010	00010	00010	00010	00010
	22222	$S_{0,3}$	$C_{0,3}$=00100	00100	00100	00100	00100
	11111	$S_{0,4}$	$C_{0,4}$=01000	01000	01000	01000	01000
1	01234	$S_{1,0}$	$C_{1,0}$=10000	01000	00100	00010	00001
	12340	$S_{1,1}$	$C_{1,1}$=01000	00100	00010	00001	10000
	23401	$S_{1,2}$	$C_{1,2}$=00100	00010	00001	10000	01000
	34012	$S_{1,3}$	$C_{1,3}$=00010	00001	10000	01000	00100
	40123	$S_{1,4}$	$C_{1,4}$=00001	10000	01000	00100	00010
2	02413	$S_{2,0}$	$C_{2,0}$=10000	00100	00001	01000	00010
	24130	$S_{2,1}$	$C_{2,1}$=00100	00001	01000	00010	10000
	41302	$S_{2,2}$	$C_{2,2}$=00001	01000	00010	10000	00100
	13024	$S_{2,3}$	$C_{2,3}$=01000	00010	10000	00100	00001
	30241	$S_{2,4}$	$C_{2,4}$=00010	10000	00100	00001	01000
3	03142	$S_{3,0}$	$C_{3,0}$=10000	00010	01000	00001	00100
	31420	$S_{3,1}$	$C_{3,1}$=00010	01000	00001	00100	10000
	14203	$S_{3,2}$	$C_{3,2}$=01000	00001	00100	10000	00010
	42031	$S_{3,3}$	$C_{3,3}$=00001	00100	10000	00010	01000
	20314	$S_{3,4}$	$C_{3,4}$=00100	10000	00010	01000	00001
4	04321	$S_{4,0}$	$C_{4,0}$=10000	00001	00010	00100	01000
	43210	$S_{4,1}$	$C_{4,1}$=00001	00010	00100	01000	10000
	32104	$S_{4,2}$	$C_{4,2}$=00010	00100	01000	10000	00001
	21043	$S_{4,3}$	$C_{4,3}$=00100	01000	10000	00001	00010
	10432	$S_{4,4}$	$C_{4,4}$=01000	10000	00001	00010	00100

Each code sequence has p binary 1's. Considering all groups, the total number of modified prime sequence codes is p^2 . For a synchronous system, the cross-correlation between the modified prime sequence codes of the *xth* and the *yth* users can be written as

$$\Gamma_{x,i} = \begin{cases} p, & \text{when } x = y \\ 0, & \text{when } x \text{ and } y \text{ are in the same group} \\ 1, & \text{when } x \text{ and } y \text{ are in the different groups} \end{cases} \qquad [3]$$

Figure 2-7a shows the autocorrelation of S-CDMA code sequence $C_{1,1}$ for the bit stream 1110010100. The arrows indicate instants at which the synchronization is applied. The cross-correlation between S-CDMA code sequences $C_{1,0}$ and $C_{1,1}$ (same group), and the cross-correlation between S-CDMA code sequences $C_{2,2}$ and $C_{1,1}$ (different groups) for the same data stream are shown in the *Figure 2-7b* and *Figure 2-7c* respectively.

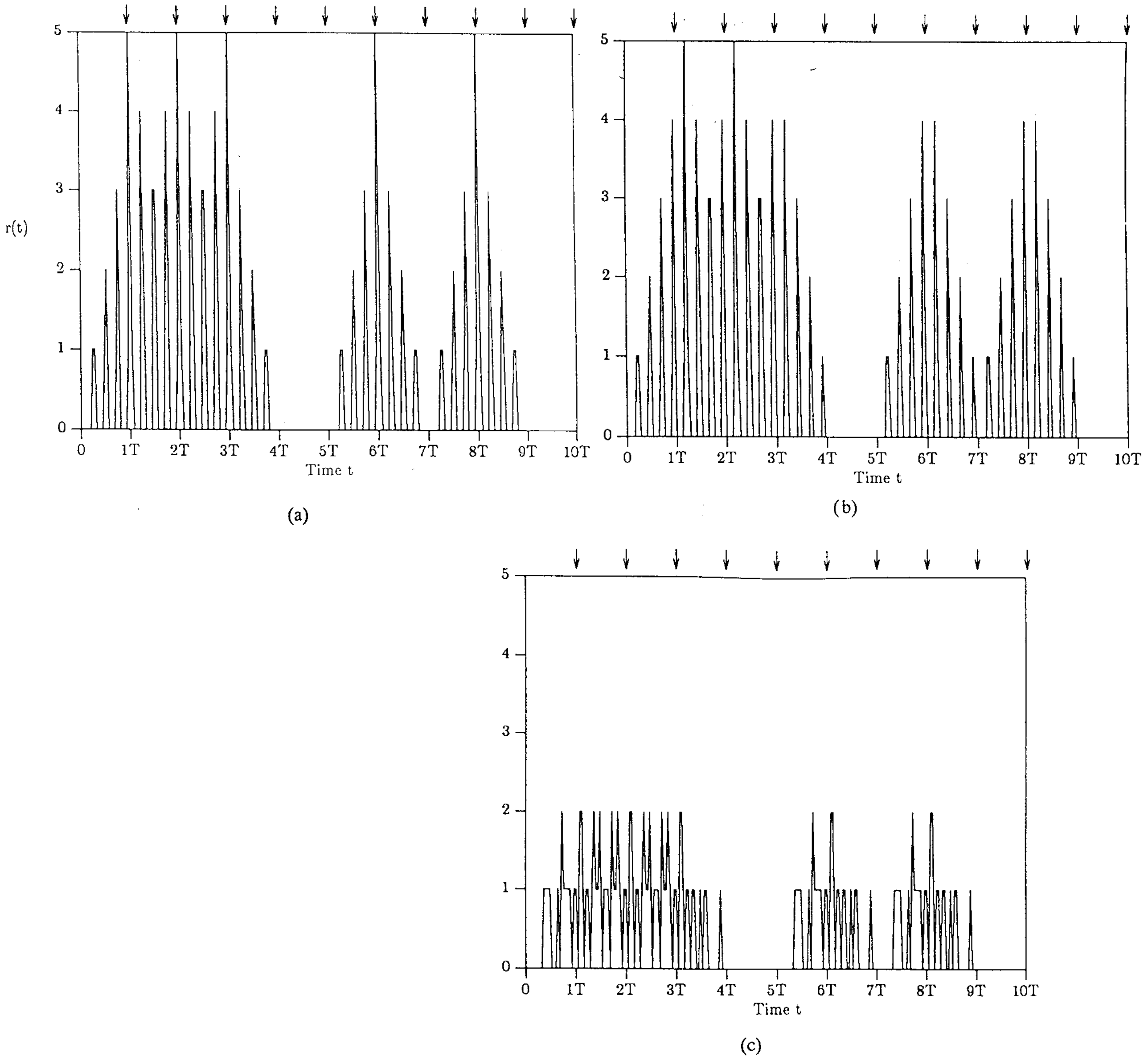


*Figure 2-7: **[2]** , Pages 1628 and 1629*
a) Autocorrelation of S-CDMA code sequence $C_{1,1}$ for the bit stream 1110010100
b) Cross-correlation of S-CDMA code sequences $C_{1,0}$ and $C_{1,1}$ for the same bit stream
c) Cross-correlation of S-CDMA codes sequences $C_{2,2}$ and $C_{1,1}$ for the same bit stream

The probability of error versus the number of simultaneous users as a function of *p* in an optical fiber transmission system is shown in the *Figure 2-8*. S-CDMA always provides a lower probability of error than the asynchronous CDMA for the same value of *p*.

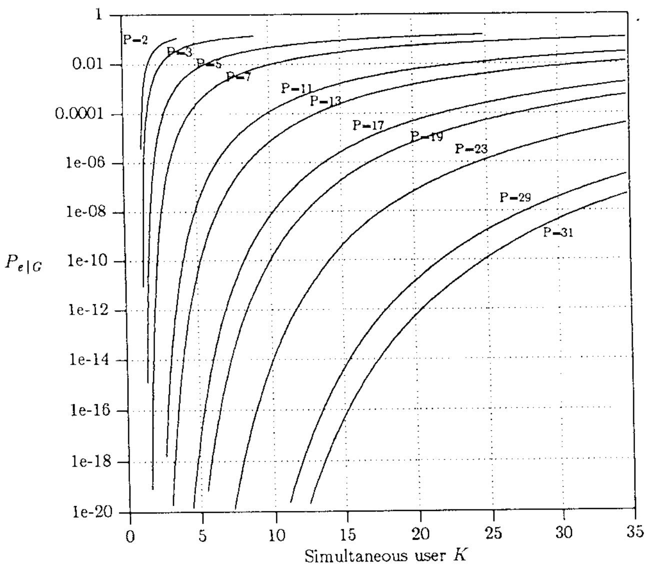


*Figure 2-8: **[2]** , Page 1629*
Bit error probability of S-CDMA versus the number of simultaneous users K (=M) as a function of p in an optical fiber system

Because two overlapping chips can add the value 1 to the cross-correlation of the code sequences, while the peak of autocorrelation function is *p*, S-CDMA can accommodate at least K= *p*-1 simultaneous users without errors. With *p*-1 simultaneous users, the receiver can still discriminate the autocorrelation peak from the cross-correlation peak, of amplitude at most equal to *p*-1 However, when the number of simultaneous users exceeds *p* (i.e. K ≥ *p*), errors in the detection process may result.

When the allowed bit error rate is $\leq 10^{-9}$ S-CDMA can support 31 simultaneous users for *p*=31 which is 8 more than by using the basic prime codes and 21 more than by using the OOCs in an asynchronous optical CDMA system. For a certain bit error probability a S-CDMA system can always accommodate a greater number of simultaneous users than the asynchronous CDMA system. [2]

The number of simultaneous users K versus *p* with the probability of error $\leq 10^{-9}$ for both the asynchronous CDMA and S-CDMA are shown in the *Figure 2-9.*

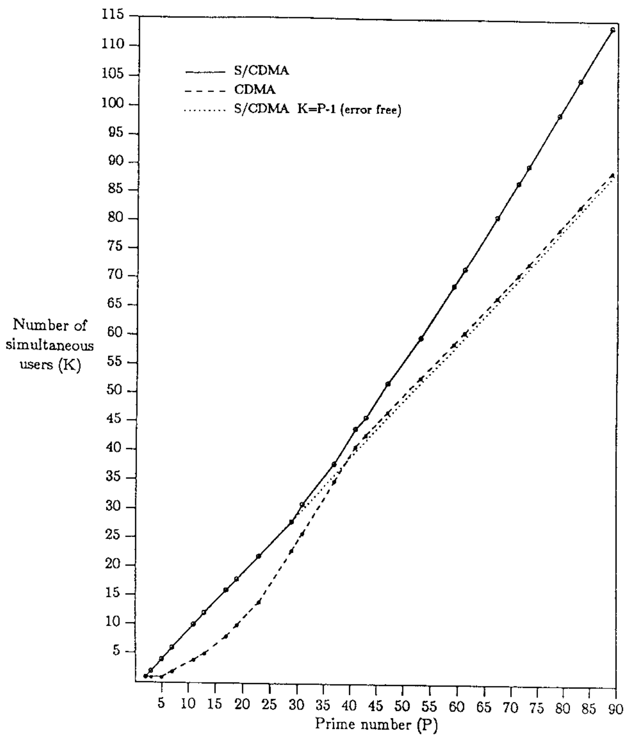


Figure 2-9: ***[2]*** *, Page 1630*

Number of simultanous users K (=M) versus p both for asynchronous CDMA and S-CDMA with the maximum bit error probability 10^{-9} in an optical fiber system.

S-CDMA systems using optical hard-limiter have been shown to have better performance than S-CDMA systems without the hard-limiter when the number of simultaneous users is not large. When their number is large the performance of the S-CDMA system is better without the optical hard-limiter.

In asynchronous CDMA systems the optical hard-limiter improves the performance for any number of simultaneous users. In asynchronous CDMA systems the performance in the chip synchronous case is worse than in the chip asynchronous case. [3]

3. COHERENT OPTICAL CDMA SYSTEMS

In a coherent optical communication system a locally generated signal from an optical local oscillator (LO) is mixed at the receiver with the information-bearing signal. When the mixed light falls on the photodetector it produces a detector current with the frequency equal to the difference between the optical frequencies of the received signal $f_C + f_S$ and the local oscillator f_{LO} , where f_C is the frequency of the optical carrier and f_S the frequency of baseband signal. There are two types of coherent receivers. In the heterodyne receiver the output signal of the photodetector is on an intermediate carrier frequency (IF) $f_C - f_{LO}$ and must be demodulated electrically to get the baseband signal. In the homodyne receiver $f_{LO} = f_C$ and the baseband signal is obtained directly as the output of the photodetector.

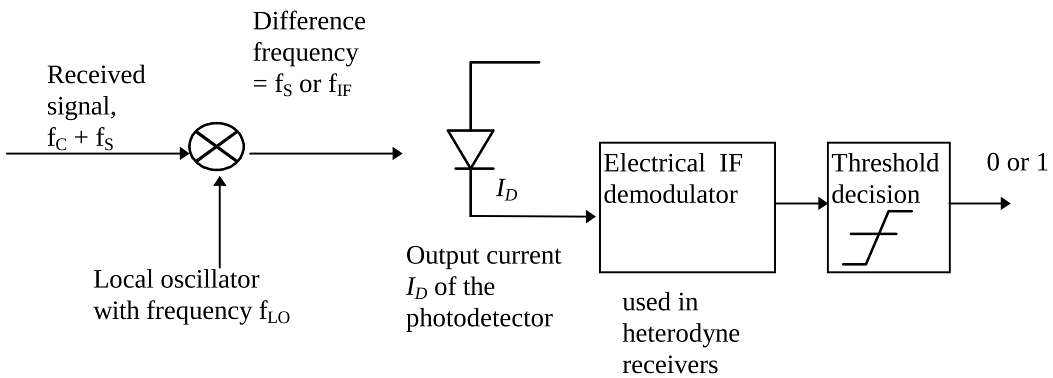


Figure 3-1: Coherent optical CDMA receiver

In general the coherent optical system offers two advantages when compared to the incoherent system. Remarkably better receiver sensitivity and frequency selectivity can be achieved by the coherent system. Because of the high frequency selectivity great capacity can be achieved by using different carrier frequencies close to each other.

An imprortant advantage of the coherent CDMA systems is that different kinds of modulation methods (e.g. ASK, FSK, PSK, QAM) can be used. So the chip values are not restricted to the non-negative 0 and 1 levels of the power based incoherent systems. So the signature codes and multiuser detection methods developed for the radio based systems are available. Because of this greater number of simultaneous users can be achieved. Both synchronous and asynchronous operation is possible.

However, there are many serious problems that make it difficult to implement a coherent optical system. The frequency of the transmitted optical carrier and local oscillator must have the accuracy of the order $0.01 \ldots 0.1 \cdot 10^{-6}$ (0.01 ... 0.1ppm) which about is 2 ... 50 Mhz depending on the used wavelength region. To achieve this temperature stabilization is needed. Only FSK modulation can be implemented by directly changing the control current of the laser transmitter. Other types of modulation require special lasers with separate sections for the continuous wave (CW) generation and modulation or using an external optical modulator after the laser transmitter. In fiber optic systems the fiber changes the polarization of the signal making it difficult to adjust the phase of local oscillator signal to have the same phase as the incoming optical carrier

4. FIBER OPTIC CDMA SYSTEMS

4.1 **Noncoherent Fiber Optic CDMA Systems**

The chip sequence can be generated electronically and after that it can be used to control the laser to give the optical CDMA chip sequence.

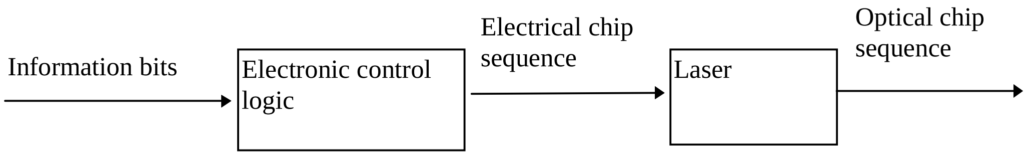


Figure 4-1: Electrical generation of the code sequence

However, in this implementation the achievable chip rate is limited by the speed of the control logic electronics. To get a higher chip rate the optical chip sequence $S_0(t)$ is generated without the electronic control logic so that the laser generates a high power pulse of the chip duration T_{ic}. This laser pulse is then used as an input to a group of parallel delay lines. The outputs of the delay lines are combined by an optical coupler which gives out the optical chip sequence. The greatest possible number of optical delays in one delay line is K, $K \cdot T_c = T_b$, where T_b = bit period. The number of 1's are defined by the number of the delay lines and the positions of 1's by the numbers of delays. For example when there are 8 chips in a bit and three 1's :

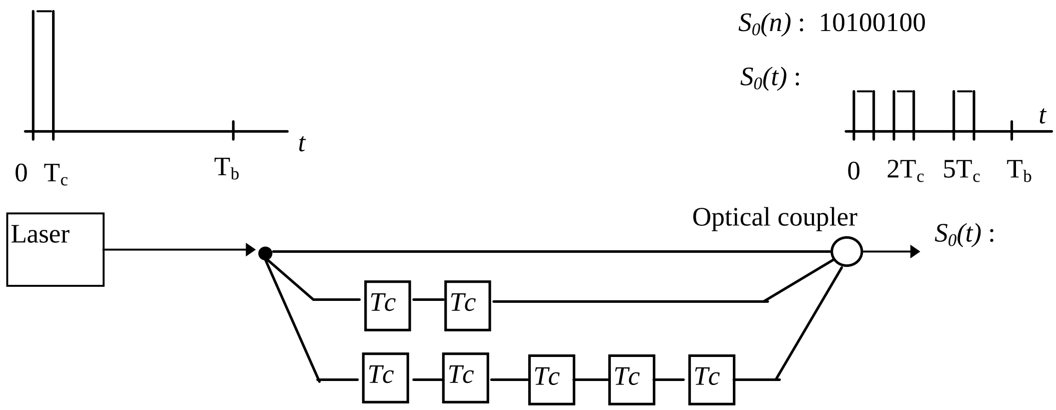


Figure 4-2: Example of the optical generation of the code sequence

The delay line can be implemented by optical fiber when the chip rate is high (about 100 MHz ... 10 GHz). The fiber length is selected to give the total delay of the delay line. Another implementation which can be used also at low chip rates is to use a $LiNbO_3$ based optical waveguide as a delay element. The light passing through the component is delayed by changing the refractive index of the material. This can be done by a changing electric field.

At the receiver the optical correlator used to recognize the desired signature code is a set of optical delay lines inversely matched to the pulse spaces. It is a time reversed version of the set of delay lines used in the transmitter. When the desired optical sequence passes through the correlator, the output light power traces out the correlation function of the sequence. [9] At the last chip position, the sum of the received optical power located in the same positions as the positions of 1 in the desired code is obtained. The receiver corresponding the transmitter of the *Figure 4-2* is the following :

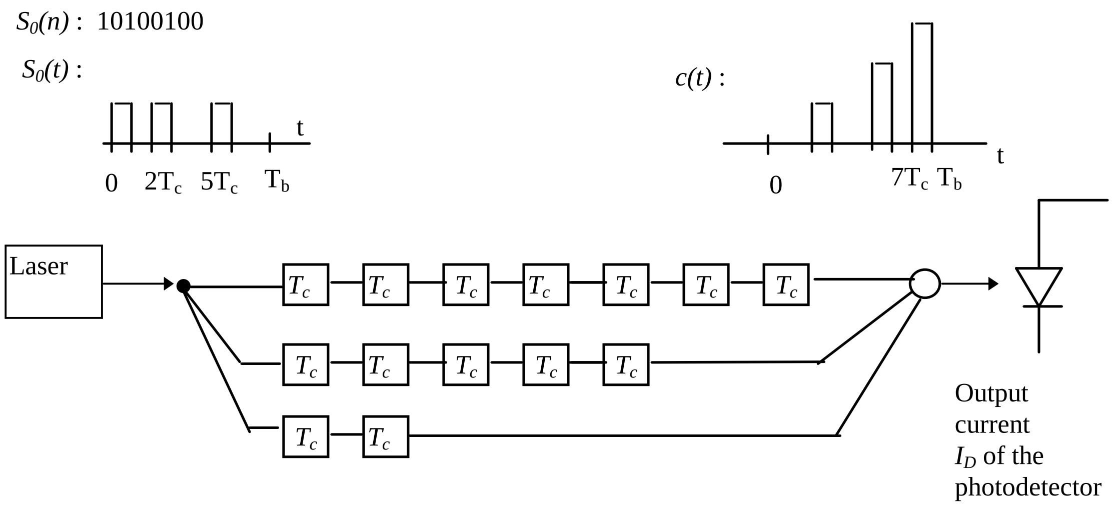


Figure 4-3: Example of the optical correlation

$$c(n \cdot T_c) = \sum_{k=1}^{K} s_0(k) r((k-n) \cdot T_c) \quad \text{, where} \qquad (6)$$

$c(t)$ is the correlation funtion

$s_0(n)$ is the signature code of the receiver

$r(t)$ is the received signal containing the code sequences of different users

T_c , T_b are the chip and bit periods

K is the number of chips in a bit

The output of the correlator is converted to an electrical signal by a photodetector and integrated over the chip periods. This signal value is sampled at the last chip position and compared to the decision threshold of the bit values 0 and 1.

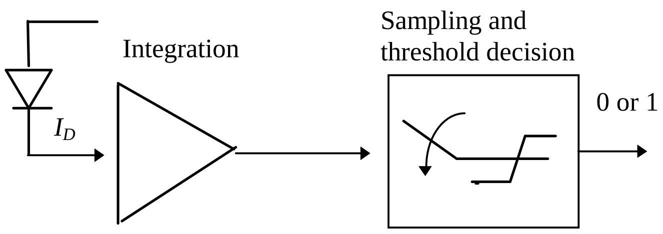


Figure 4-4: Calculation of correlation sample for threshold decision

4.2 **Coherent fiber optic CDMA systems**

The coherent fiber optic CDMA system may be partly optical or all-optical. In the partly optical system the chip sequence is generated electronically and the chip values are used to modulate the optical carrier (e.g. PSK modulation). The optical receiver gives out the electrical chip sequence which is recognized electronically.

4.3 **Other fiber optic CDMA systems**

In addition to the traditional noncoherent and coherent systems a new type of fiber optic CDMA systems has been proposed. It is an intermediate form of them. The final detection is based on the received optical power level as in the noncoherent systems but not on the power of the separate chips. An extra separate modulation level for the chip sequence is used, but only in the transmission channel. When the signal is received from the channel it is transformed back to intensity modulated (IM) signal. So different modulation methods can be used in the transmission channel. The chip values are not restricted to the non-negative 0 and 1, but the final detection is based on the power of the signal and the difficult implementation of the coherent detection can be avoided.

An example of this method is the pulse spreading fiber optic CDMA system. A narrow (about 10^{-12} s) optical pulse is directed to an optical signature encoder consisting of a pair of diffraction gratings and a phase mask. The intensity of the pulse is spread by the first grating and phase modulated when it passes through the mask. Each transmitter has a distinct phase mask. A receiver consists of a decoder and an optical threshold device. The decoder is similar to the optical encoder except that its phase mask is the conjugate of the coding mask. So the original pulse is reconstructed and detected using a power based threshold device. [4]

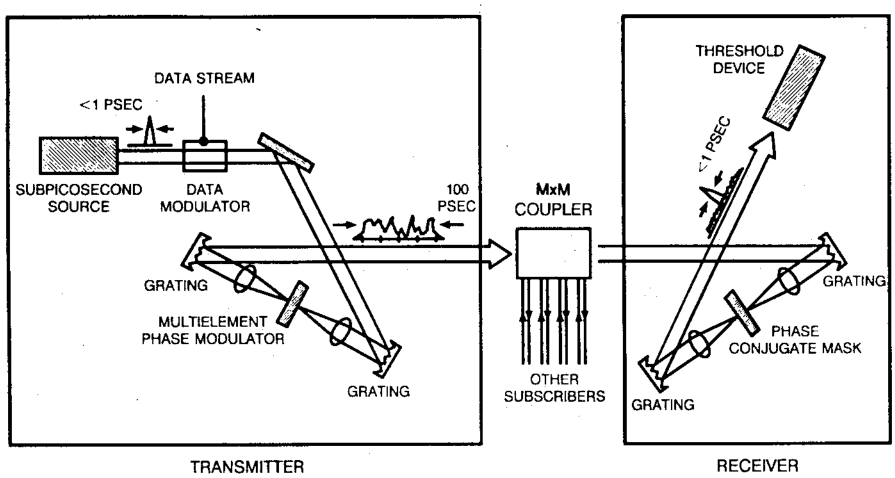


*Figure 4-5: **[4]** , Page 479*

All optical pulse spreading CDMA system

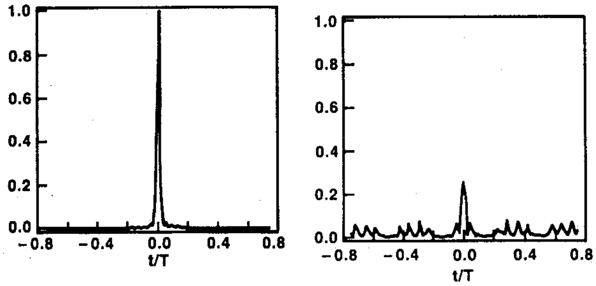


Figure 4-6: ***[4]*** *, Page 482*
The intensity profiles of the signal versus time before and after signature coding N_0 is the number of the chips, T is the bit period

4.4 **Comparison of CDMA with TDMA and WDMA in Fiber Optic Systems**

4.4.1 **CDMA compared with TDMA**

In a CDMA system the signal bandwidth is increased considerably because of the signature coding. The CDMA system requires a greater channel bandwidth than the TDMA system for a certain bit rate. Optical fiber has a great bandwidth. This is why the optical channel seems to be ideal for CDMA. However, the usefulness of CDMA in optical communication is limited by the high bitrate already used in the fiber systems.

In the optical fibers the signals usually are high bit rate TDMA-signals which often already use great part of the fiber bandwidth. For example when 16 signals each of them having the bit rate 155 Mbit/s are multiplexed the capacity of 2.48 Gbit/s is obtained. If the 155 Mbit/s signals are CDMA multiplexed the spreading factor needed is about 100 ...1000. High bit rate optical communication links are usually dispersion limited. The optical pulses become wider in time causing intersymbol interference because the different wavelength components have different velocities. So the amount of dispersion in a CDMA system having the capacity of 16 155Mbit/s signals is about the same as in a TDMA system having the capacity of over 100 155Mbit/s signals. Using the present technology the dispersion in these systems (e.g. STM-256) limits the link length to short distances.

The advantages given by the CDMA in radio systems are related to the tolerance of the multipath fading, soft hand-over in cellular systems and immunity to the channel noise. In the fiber optic CDMA noise immunity is the only one of these factors giving benefit compared to TDMA. However it does not have the same importance as in the radio systems because the channel noise is not a significant factor in optical fiber systems. The number of simultaneous users in TDMA systems for the same signal bandwidth is much greater than in noncoherent CDMA systems.

The important advantage of the optical CDMA is that the users can transmit completely independently. No coordination with other users is required. Also new connections can be added causing only the steady increase of multiple access interference (MAI) until the maximum number of users is reached. Because CDMA provides the user independent access to the network and because the dispersion limits the distance at high bit rates CDMA suits best to local area networks (LANs).

4.4.2 **CDMA compared with WDMA**

When the signals are code (CDMA) or time (TDMA) division multiplexed the signal bandwidth is increased causing dispersion problems at high bit rates. In Wavelength Division Multiple Access (WDMA) each user is transmitting on its own wavelength which eliminates the dispersion problems. Because of this at least now WDMA is the only practical way to increase the capacity in very high bit rate (2.5 -10 Gbit/s) systems. International Telecommunications Union (ITU) has standardized 45 wavelengths to be used in the region 1530nm - 1560 nm. WDMA also gives the same kind of independent access to the network as CDMA.

Earlier using WDMA was limited by the need to do the opto-electric conversion separately on each wavelength in the repeaters of the communication link. This problem was solved by the optical fiber amplifiers (OFAs) which amplify all the wavelengths simultaneous in the optical domain. The development of the OFAs and optical couplers for cross-connecting different wavelengths has caused a rapid growth in WDMA applications.

5. WIRELESS OPTICAL CDMA SYSTEMS

5.1 **Structure of the wireless optical CDMA system [8]**

Implementing a coherent fiber optic system is difficult. It is even more difficult to implement a coherent optical wireless system because the phase of the local oscillator light should be adjusted to the phase of the free space signal. Because of this practical systems are noncoherent (Intensity Modulated / Direct Detection IM/DD) systems.
Implementing lens and optical waveguide structures for optical signature coding and for correlating the received signal with the desired signature code are also difficult. So they are usually performed electrically. The signature code can be used directly to modulate the intensity the laser or LED transmitter (On-Off-Keying, OOK) or subcarrier modulation may be used. Pulse position modulation (PPM) or Binary Phase Shift Keying (PSK) are often used as the modulation method. In the subcarrier modulation the intensity of the transmitter is varied on a radio frequency. This subcarrier is modulated by the chip values.

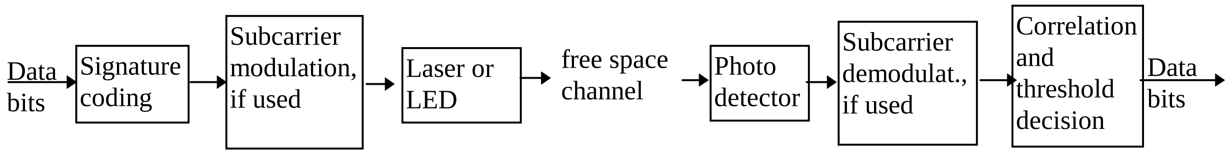


Figure 5-1 : Wireless optical CDMA system

Because the wireless system does not suffer from the material dispersion the channel bandwidth is not limited. So a high spreading factor can be used and high bit rates can be achieved. Unlike in a fiber optic system the relation between optical output power *X(t)* from the laser or LED and the output current *Y(t)* of the photodetector is linear in the wireless optical system. So a linear baseband model can be used :

$$Y(t) = R \cdot X(t) * h(t) + N(t) \text{ , where} \qquad (7)$$

R is the detector responsitivity (A / W)

$h(t)$ is the impulse response of the channel

$N(t)$ is the noise caused by the background light and reflections

By using this model the following signal to noise ration is obtained :

$$SNR = \frac{R^2 \cdot P^2}{R_b \cdot N_0} \text{ , where} \qquad (8)$$

$R_b =$ bit rate and

$P =$ average received optical power

When P decreases SNR decreases relative to P^2. This limits the achievable distance d and sets a requirement to the average power efficiency of the used multiple access method.

The AWGN channel model can be used because there is no fast fading in the wireless optical systems. The minimums of the received signal locate about a wavelength apart from each other but they do not affect the received power because typical detector areas are millions of square wavelengths. The multipath distortion causes intersymbol interference but *N(t)* can be assumed to be dominated by a white Gaussian component having double-sided power spectral density N_0.

5.2 Comparison of the CDMA with other multiple access methods in optical wireless systems [8]

TDMA has a high power efficiency. The power efficiency achieved by CDMA varies depending on the selection of the signature code and the possibly used modulation method. When the subcarrier modulation is used different users can transmit simultaneously at different subcarrier frequencies. The power efficiency of this frequency division multiple access (FDMA) method is poor. Differences of the wireless optical multiple access methods are summarized in the *Table 5-1*

*Table 5-1: **[8]** , Page 293*

Comparison of multiple access methods in wireless optical system

Technique	Nature	Necessary Loss of Per-User Capacity	Optical Average Power Efficiency	Permits Simultaneous Transmission
Wavelength Division	Optical	**No**	**High**	**Yes**
Space Division Multiplexing with Angle Diversity Receiver	Optical	**No**	**High**	**Yes**
Time Division	Electrical	Yes	**High**	No
Code Division	Electrical	Yes	Moderate	**Yes**
Subcarrier Frequency Division	Electrical	Yes	Low	**Yes**

Figure 5-2 presents a comparison of the power efficiency in a wireless cellular LAN for TDMA with 4-PPM, 2-PPM modulation and with OOK. The power efficiency of FDMA is shown with BPSK modulation. The power efficiency of CDMA is shown with 2 signature codes : m-sequence and an optical orthogonal code without modulation.

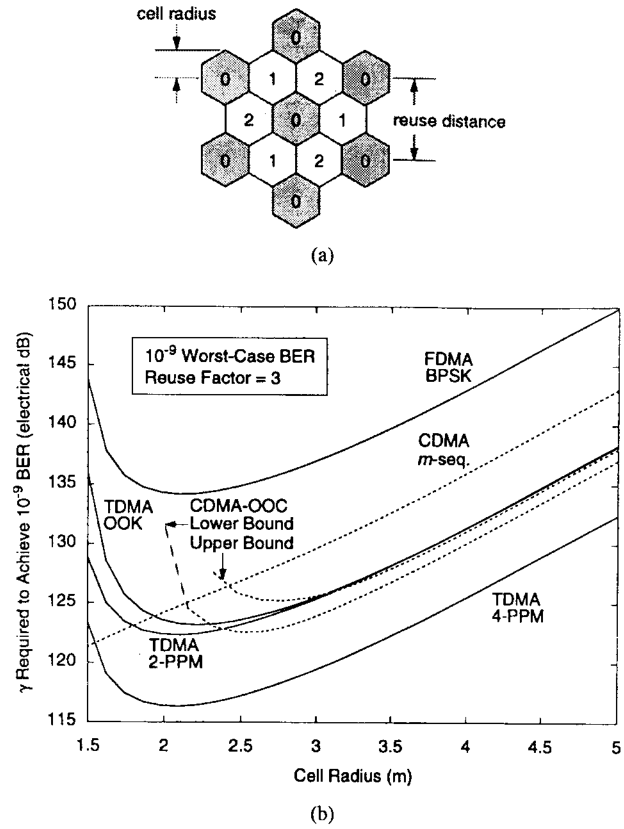


*Figure 5-2: **[8]** , Page 294*
a) Fixed assignment of channels in a optical system having a reuse factor of three.
b) Performance comparison of six methods, assuming hexagonal cells and a reuse factor of three. The throughput in each cell is 10 Mbit/s. BER of 10^{-9} is achieved when the receiver is placed at the worst case location within the cell (the cell corner). The factor γ is equal to the SNR for unit optical path gain and is proportional to the square of the transmitted optical power.

The required power level to achieve BER 10^{-9} increases when very small cells are used because of the co-channel interference. When the radius of the cell is > 3 m the performance does not depend on the co-channel interference. Then only the background light and multipath distortion noise are affecting. The best performance is achieved by TDMA 4-PPM.

Achieving high power efficiency is so important that all the current infrared multiple access LANs are using some form of TDMA although CDMA has a better tolerance for noise on the same received power level. WDMA is technically a competitive method but the laser transmitters and large-area, tunable bandpass filters are at this moment too expensive for commercial products. Space division multiple access (SDMA) involves the use of an angle-diversity receiver to separate signals that are received form different directions. An angle-diversity receiver can reduce the impact of co-channel interference and multipath distortion. The advantages depend on how the signals received in the different elements of the receiver are processed and detected. However, as the number of mobile users increase the spot overlap becomes more probable and SDMA needs to be combined with some other multiple access method to achieve reliable operation.

6. CONCLUSIONS

CDMA gives uncoordinated access to the network and the number of potential subscribers is greater than the number of simultaneous users. On the other hand long transmission distances can not be achieved at high bit rates. Because of these factors CDMA using optical fiber channel is best suitable to local area networks. Because of the inefficient use of signal bandwidth the optical CDMA is not suitable to high capacity circuit switched network.

The efficiency of the fiber optic CDMA can be improved in the coherent systems of the future. Using code division multiplexed optical carriers very close to each other in frequency high capacity and flexible access can be achieved at the same time. So when the technical problems of the coherent systems have been solved also other than LAN applications will be possible.

In wireless optical systems CDMA suits well for high bit rate systems where good security is needed and the mobility is not important.

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APPENDIX

Comparison of radio and optical wireless LANs :

Radio is favored in applications where user mobility must be maximized or transmission through the walls or over long ranges is required and may be favored when transmitter power consumption must be minimized. Infrared is favored for short-range applications in which per-link bit rate and aggregate system capacity must be maximized, cost must be minimized or receiver signal-processing complexity must be minimized.

***[8]** , Page 266 :*

Property of Medium	Radio	IM/DD Infrared	Implication for IR
Bandwidth Regulated?	Yes	No	Approval not required. Worldwide compatibility.
Passes Through Walls?	Yes	No	Less coverage. More easily secured. Independent links in different rooms.
Multipath Fading?	Yes	No	Simple link design.
Multipath Distortion?	Yes	Yes	
Path Loss	High	High	
Dominant Noise	Other Users	Background Light	Limited range.
Input $X(t)$ Represents	Amplitude	Power	Difficult to operate outdoors.
SNR Proportional to	$\int \lvert X(t)\rvert^2 dt$	$\int \lvert X(t)\rvert^2 dt$	Hight transmitter power requirement.
Average Power Proportional to	$\int \lvert X(t)\rvert^2 dt$	$\int X(t) dt$	Choose waveform $X(t)$ with high peak-to-average ratio.