Symmetric Codes for Synchronous Optical fiber CDMA Networks

by
Ms. Chanikarn Praepanichawat

Submitted in Partial Fulfillment of
The Requirements for the Degree of
Master of Science
in Telecommunications Science
Assumption University

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ABSTRACT

A non-coherent synchronous all-optical code-division multiple-access (CDMA) network is proposed. In this network, symmetric codes derived from prime sequence codes are used. We present the construction of symmetric codes and show that the pseudo-orthogonality of the new codes is the same as that of the original prime-sequence codes while the number of code sequences of the new codes is larger than that of the prime sequence codes and the modified prime codes in the same field GF(p). Therefore, an optical CDMA LAN using symmetric codes can have a larger number of potential subscribers. The new codes allow designing fully programmable serial all-optical transmitter and receiver suitable for low-loss, high-capacity, optical CDMA LANs. It also shows that compared to systems using modified prime codes the proposed system can achieve better BER performance for low received chip optical power.

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CHAPTER 1: INTRODUCTION

Spread spectrum code-division multiple-access (CDMA) has been extensively studied in the area of satellite and mobile radio communication. In recent years, the use of CDMA in local area network (LANs) has also been investigated. CDMA is becoming an increasingly practical multiple-access scheme for fiber optic local area networks (LANs) because it allows multiple user to asynchronously access the same fiber channel with no delay or schedule. In order to exploit the huge bandwidth offered by single mode fiber, the encoding and decoding process should be performed optically. In optical CDMA system using incoherent optical signal processing, only unipolar codes can be used. Therefore, there is a need of new families of unipolar optical orthogonal codes (OOCs) for optical CDMA systems.

The families of OOCs proposed so far are prime sequence [1], optical orthogonal codes [2], quadratic congruence codes [3] which can be generated/correlated by encoder/decoder based on parallel optical delay lines [4]. The main drawback of the parallel delay-line encoder/decoder is that their architecture requires optical summations that involve considerable optical loss. In order to overcome this drawback, schemes have been proposed for incoherent optical CDMA systems based on the use of optical fiber lattices [5],[6] for constructing serial encoders and decoders. Those systems use codes, which are grouped into the class of symmetric codes. The advantage of the symmetric code is that serial encoder/decoder can be constructed using 2x2 opto-electrical switches

and optical delay-lines. Thereby, the recombination loss in each encoder/decoder pair is significantly reduced compared to the loss in parallel delay-line encoder/decoder

However, due to the strong interference caused by unipolar sequences and non scheduled transmission in asynchronous optical CDMA networks, incoherent optical CDMA can allow only a limited number of subscribers and even fewer simultaneous users before a rapid deterioration of the system performance occurs. Therefore, synchronous CDMA (S/CDMA) [7],[8] for fiber optic LANs using all optical signal processing was investigated [9].

In synchronous CDMA networks, a common clock is distributed to all users of the network to control users who want to transmit the data, the user can only transmit data bits at the beginning of each bit time, and at the receiver, the detection time is based on the common clock signal.

S/CDMA fiber optic LANs use codes developed from prime sequence codes, which can be generated/correlated by encoder/decoder based on parallel optical delay-lines. S/CDMA is more attractive multiple-access scheme than asynchronous CDMA because in a synchronous optical CDMA network using code sequence of length $N=p^2$ (p is a prime number) the number of possible subscribers is p^2 compared to a maximum of p possible subscribers for an asynchronous optical CDMA network using code sequence of the same length. Furthermore, error free transmission can be achieved when the number of simultaneous users $K \leq p\text{-}1$. In general, synchronous accessing schemes, with rigorous

transmission schedules, produce higher throughput (i.e more successful transmissions) than asynchronous techniques where network access is random and collision occurs. It follows that in environments with real time and/or high throughput requirements (e.g. digital video), synchronous accessing techniques are most efficient.

Synchronous optical CDMA networks described in [9] use prime-sequences codes, which are non-symmetric codes. The major disadvantage of all-optical CDMA systems using non-symmetric codes is the encoding and decoding of those codes by parallel optical fibre delay-line where transmitters/receivers require optical splitters/combiners that involve considerable recombination loss. These passive optical devices are realised using combinations of $2x2$ couplers, each of which introduces an inherent optical loss of 3 dB. Therefore, both the transmitter and the receiver introduce a loss of N^2 to give a total loss in the desired signal of N^4 with respect to the launched laser pulse. The loss may be excessively high if the sequence is long. This loss, at the receiver, can be reduced to W^2 for a receiver with fixed reference sequence. However, at the transmitter, where the programmability (i.e. the capability of generating any sequence) is absolutely necessary, the optical loss is always N^2.

Recently, a new class of 2^n prime sequence codes for incoherent asynchronous optical fiber code-division multiple-access networks has been proposed [10]. They are symmetric codes which are derived from prime-sequence code but the number of code sequences is larger than that of prime sequence codes [1] or another 2^n prime sequence codes [11]Although asynchronous optical CDMA networks using symmetric codes of length p^2

described in [10] can support $p(p-3)/2$ different subscribers, the low weight limits the maximum number of subscribers of the network. In order to accommodate more subscribers, longer sequences of higher weight are required which in turn increases the complexity of the encoders and decoders and reduces the cost effectiveness of the network.

In this work, the use of the symmetric codes described in [10] for synchronous optical CDMA networks is investigated. The advantage of the symmetric codes is that serial encoder/decoder can be constructed using $2x2$ opto-electrical switches. Thereby, the recombination loss in each encoder/decoder pair is substantially reduced compared to the loss in parallel delay-line encoder/decoder. In addition, the number of optical components (switches, delays) required for constructing the encoder/decoder is less than that of the parallel architecture. The use of symmetric codes in synchronous optical CDMA networks can overcome the disadvantages of synchronous optical CDMA networks using prime-sequences codes (e.g. very high optical loss) and that of asynchronous optical CDMA networks using symmetric codes (e.g. limited number of code sequences)

We have studied the possibility of generating symmetric code sequences for synchronous optical CDMA networks. The codes for synchronous networks are based on symmetric codes for asynchronous optical CDMA networks. Computer program for generating the codes was designed. We designed both transmitter and receiver for synchronous optical CDMA networks. The performance of synchronous optical CDMA network using symmetric codes was evaluated and compared to the performance of synchronous optical CDMA network using prime sequence codes.

The organization of this report is as follow: Chapter I is the introduction of the report. Chapter II is the synchronous optical CDMA LANs, where the advantage and disadvantage of each system is analyzed and we define the objective of our work. Chapter III is the symmetric codes for synchronous optical fiber CDMA networks. Chapter IV is the transmitter and receiver for symmetric codes. The evaluation of the performance of symmetric code for synchronous optical CDMA networks and the comparison of symmetric code with prime code are presented in Chapter V. Finally in Chapter VI we present the thesis conclusion and recommendation.

CHAPTER 2: SYNCHRONOUS OPTICAL CDMA LANs

2.1 Optical CDMA LANs

In an optical fiber CDMA network, the transmitter performs the data bandwidth expansion and then launches the resulting signal into the optical fiber channel. The bandwidth expansion is achieved in the encoder by mapping unipolar digital data bits onto code sequences which have a chip rate that greatly exceeds the data bit rate. Each user in the network is assigned a fixed code sequence which serves as its address (or reference code sequence). This code sequence is approximately orthogonal (i.e has low cross-correlation) with the code sequences of other users. When the receiver-based code is employed, the source user encodes the data to be transmitted with the code sequence assigned to the destination user. The data modulated code sequence is used to control a light source. The emitted light is then coupled into the optical fiber LAN. At the receiver, the incoming signal is correlated with the receiver's reference code sequence for detecting the data bits. Although the receiver receives all of the energy sent by all of the transmitters, after despreading it will see only the desired signal. Provided that the code sequences used at any one time do not interfere with each other beyond a predetermined limit (i.e. their cross-correlation functions are below a given threshold) then a number of users may simultaneously access the network.

For the receiver to be able to correctly distinguish the desired data the code sequences must have the two following features:

- Each code sequence can easily be distinguished from a shifted version of itself. To achieve this the auto-correlation function of each code sequence should be as small as possible at all non-zero shifts.

- Each code sequence can be easily distinguished from a possibly shifted version of every other code sequences in the set. To achieve this the cross-correlation function between pairs of code sequence used in the code set should be as small as possible for all shifts. This helps to minimise the interference of other users during the recovery of the desired signal and allows a multiple access capability.

The choice of the code sequences and the modulation techniques used in optical fiber CDMA systems depends on the processing method available. In traditional radio or copper-bases spread spectrum systems the binary data bits (0,1) are mapped into bipolar (+1,-1) sequences. Several bipolar sequences of good correlation properties, such as m-sequences, Gold-code sequences, Kasami code sequences, etc ... have been used in radio-based CDMA systems. The construction and properties of these code sequences, which are called "Conventional CDMA sequences", are well documented in the literature [12]. In an optical system the channel sequences are limited to unipolar values. However, conventional CDMA sequences have been proposed for use in coherent optical CDMA systems [13],[14],[15]. Conventional CDMA sequences can be used also in non-coherent optical CDMA systems where the received unipolar sequences are correlated with a bipolar reference sequence [16]. In optical fiber CDMA systems where On-Off Keyed (OOK) modulation and optical

processing devices are used, conventional CDMA sequences can not be used [4]. New types

of unipolar sparse code sequences have been developed for use in such systems [4],[2],[17].

Figure 2-1: A fiber optical communication system using optical encoder and decoder

A typical optical CDMA communication system is best represented by an information data

source, followed by a laser when the information is in electrical signal form, and an optical

encoder that map each bit of the output information into a very high rate optical sequences,

that is then coupler into the single-mode fiber channel (Fig. 2-1). At the receiver end of the

optical CDMA, the optical pulse sequence would be compared to a store replica of itself

(correlation process) and to a threshold level at the comparator for the data recovery.

Figure 2-2 shows a schematic block diagram of an optical fiber CDMA LAN based on the

passive star topology which has been indicated as suitable for optical fiber CDMA

networks [18]. In this network each user is connected to an input port and an output port

of the star coupler. This passive star topology allows the optical signals from

simultaneous users to be added linearly at the star coupler and maintaining a power

balance between the output signals.

Figure 2-2: Schematic diagram of an optical code division multiple-access communication system with all-optical encoder and decoder in a star configuration

The set of optical CDMA pulse sequences essentially becomes a set of address codes or signature sequences for the network. To send information from user j to user k, the address code for receiver k is impressed upon the data by the encoder at the jth node. One of the primary goals of optical CDMA is to extract data with the desired optical pulse sequences in the presence of all other users' optical pulse sequence.

Intensity-modulated optical transmission can only be on-off keyed (OOK). In such OOK systems the simplest encoding (spreading) scheme is to encode, say, only binary ones and to transmit zero intensity for binary zeroes. The encoder can be implemented by using optical fiber delay lines for sequence generation and, as necessary at all transmitters, opto-electrical switches for sequence or destination selection. This last requirement of programmable

addressing also means that the number of delay lines must practically be the same as the sequence length (N). Since the outputs of the delay lines are summed in an optical $N{\times}l$ coupler whose recombination loss is proportional to N, serious practical limitations are imposed by the use of long sequences, irrespective of code weight.

The decoder (despreading), as usual, is implemented by using optical fiber delay lines, as at the encoder, or by using optical switches, or a combination of the two. For the first type, the number of delay lines needed is the same as the code weight for a given receiver as long as a fixed address (not programmable) is acceptable. In such a situation it becomes attractive to limit the code structure to low-weight codes that can be used to reduce the recombination loss and to reduce the decoder complexity.

2.2 Synchronous Optical CDMA Network

A synchronous optical CDMA network has a clock, which is called master clock. The clock signal is distributed to all users of the network. This is a reference clock to users who want to send data bits. The user can transmit data bit only at the beginning of a bit time. Each data bit "1" is encoded into a waveform consisting of a sequence of N time slots (or chips) and the sequence represents the destination address (in the case of fixed receiver assignment) of that bit. Data bit "0" is not encoded. At the receiver the received signal is correlated to the destination address sequence and the detection is done by sampling at the last time slot and comparing the sample to a detection threshold. The sampling time is determined by the received clock signal. Figure 2-3 shows a schematic block diagram of a synchronous optical fiber CDMA network based on the passive star coupler.

In general, synchronous accessing schemes, with rigorous transmission schedules, produce higher throughput (i.e., more successful transmissions) than asynchronous techniques where network access is random and collision occurs. It follows that in environments with real time and/or high-throughput requirements (e.g., digitized video), synchronous access techniques are most efficient.

For the purpose of synchronization the distance L_M from the master clock to the star coupler must be adjusted so that the transmission time from the master clock to the coupler is a multiple of the bit time. When installing a new user, we have to calculate the distance L_k

from the user to the star coupler so that the transmission time from the user to the star coupler is a multiple of the bit time (T).

Figure 2-3: Synchronous Optical Fiber CDMA Network

Transmission time from master clock to coupler: $T_M = L_M / C$

Where C is light speed $\approx 300,000$ km/s.

So $T_M = m_M T$, where m_M is integer.

Transmission time from user1 to Coupler $T_1 = L_1 / C$

Transmission time from user2 to Coupler $T_2 = L_2 / C$

we need $\qquad T_1 = m_1 T$

$\qquad\qquad T_2 = m_2 T$

Where m_1 and m_2 are integer.

1 clock pulse going from master clock to user1 needs $T_{M} + T_1 = (m_1 + m_M)T$

1 clock pulse going from master clock to user2 needs $T_{M} + T_1 = (m_2 + m_M)T$

Figure 2-4: Distance(L) of each user in synchronous optical CDMA

Figure 2-5: Transmission time of each user in synchronous optical CDMA

Example: $m_1 = 2$, $m_2 = 3$ $m_M = 4$

$T_M + T_1 = 6T$

$T_M + T_2 = 7T$

Figure 2-6: Clock diagram for synchronous CDMA networks

2.3 Synchronous Optical CDMA Networks Using Prime-Sequence Codes

2.3.1: Prime-Sequence Codes

A prime sequence [1] $S_i = \{s_{i,0}, s_{i,1}, ..., s_{i,j}, ...s_{i,p-1}\}$ is constructed by $s_{i,j} = i.j \ (mod \ p)$ where $i,j \in GF(p)$, the Galois field and p is a prime number. The binary prime sequences are generated by mapping each prime sequence S_i into a binary code sequence $C_i = \{c_{i,0}, c_{i,1}, ..., c_{i,k}, ..., c_{i,N-1}\}$ of length $N=p^2$ according to

$$c_{i,k} = \begin{cases} 1 & for \ k = s_{i,j} + jp \\ 0 & otherwise \end{cases}$$

Note that a binary prime sequence C_i is made up of p subsequences of length p that consists of only one "1" chip and the value of each $s_{i,j}$ in the prime sequence S_i represents the position of the "1" chip in the jth subsequence.

Example: Binary prime-sequence code generated by the prime number p= 5

Prime sequence $S_i = \{s_{i,0}, s_{i,1}, s_{i,2}, s_{i,3}, s_{i,4}\}$ is constructed by multiply every element j of GF(5) by i., also an element of GF(5) modulo 5

$S_{i,j} = i.j \ (mod \ p)$

For i = 0

$S_0 = \{S_{00}, S_{01}, S_{02}, S_{03}, S_{04}\}$

$$S_{00} = 0.0 \Rightarrow 0$$

$$S_{01} = 0.1 \Rightarrow 0$$

$$S_{02} = 0.2 \Rightarrow 0$$

$$S_{03} = 0.3 \Rightarrow 0$$

$$S_{04} = 0.4 \Rightarrow 0$$

For i = 1

$$S_1 = \{S_{10}, S_{11}, S_{12}, S_{13}, S_{14}\}$$

$$S_{10} = 1.0 \Rightarrow 0$$

$$S_{11} = 1.1 \Rightarrow 1$$

$$S_{12} = 1.2 \Rightarrow 2$$

$$S_{13} = 1.3 \Rightarrow 3$$

$$S_{14} = 1.4 \Rightarrow 4$$

For i = 2

$$S_2 = \{S_{20}, S_{21}, S_{22}, S_{23}, S_{24}\}$$

$$S_{20} = 2.0 \Rightarrow 0$$

$$S_{21} = 2.1 \Rightarrow 2$$

$$S_{22} = 2.2 \Rightarrow 4$$

$$S_{23} = 2.3 \Rightarrow 1$$

$$S_{24} = 2.4 \Rightarrow 3$$

For i = 3

$$S_3 = \{S_{30}, S_{31}, S_{32}, S_{33}, S_{34}\}$$

$$S_{30} = 3.0 \Rightarrow 0$$

$$S_{31} = 3.1 \Rightarrow 3$$

$S_{32} = 3.2 \Rightarrow 1$

$S_{33} = 3.3 \Rightarrow 4$

$S_{34} = 3.4 \Rightarrow 2$

For i = 4

$S_4 = \{S_{40}, S_{41}, S_{42}, S_{43}, S_{44}\}$

$S_{40} = 4.0 \Rightarrow 0$

$S_{41} = 4.1 \Rightarrow 4$

$S_{42} = 4.2 \Rightarrow 3$

$S_{43} = 4.3 \Rightarrow 2$

$S_{44} = 4.4 \Rightarrow 1$

In Table 2-1, the prime sequences $(S_{i,j})$ in *GF(5)* are shown. The value of $S_{i,j}$ is the position of the "1" chip in the jth subsequence of binary prime code.

Table 2-1: Prime sequences in GF(5)

i	j				
	0	1	2	3	4
0	0	0	0	0	0
1	0	1	2	3	4
2	0	2	4	1	3
3	0	3	1	4	2
4	0	4	3	2	1

The binary prime sequences are generated by mapping each prime sequence S_i into a binary code sequence.

For i.= 0

$C_0 = \{c_{0,0},\ c_{0,1},\ c_{0,2},\ c_{0,3},\ c_{0,4}\}$

$= \{10000,10000,10000,10000,10000\}$

For i.= 1

$C_1 = \{c_{1,0},\ c_{1,1},\ c_{1,2},\ c_{1,3},\ c_{1,4}\}$

$= \{10000,01000,00100,00010,00001\}$

For i.= 2

$C_2 = \{c_{2,0},\ c_{2,1},\ c_{2,2},\ c_{2,3},\ c_{2,4}\}$

$= \{10000,00100,00001,01000,00010\}$

For i.= 3

$C_3 = \{c_{3,0},\ c_{3,1},\ c_{3,2},\ c_{3,3},\ c_{3,4}\}$

$= \{10000,00010,01000,00001,00100\}$

For i.= 4

$C_4 = \{c_{4,0},\ c_{4,1},\ c_{4,2},\ c_{4,3},\ c_{4,4}\}$

$= \{10000,00001,00010,00100,01000\}$

2.3.2 Prime-Sequence Codes for Synchronous Optical CDMA Networks

A binary prime code sequence is approximately orthogonal (i.e has low cross-correlation) with the code sequences of other users, but the number of code sequences is limited to the prime number p, and therefore so is the number of total subscribers [4],[7]. A scheme was proposed which can accommodate a greater number of subscribers for the same bandwidth-

expansion, at the expense of requiring synchronization. This scheme uses a set of code sequences generated from time-shifted version of binary prime sequence codes [9].

Each of the original p prime sequence S_i is taken as a seed from which a group of new code sequences can be generated. The code sequences of the first group (i.e., i={0}) are obtained by left-rotating the binary prime code sequence C_0. C_0 can be left-rotated $p-1$ times before being recovered, so that $p-1$ new code sequences can be generated from C_0. For other $p-1$ groups (i.e., i={1,...,$p-1$}), the elements of the corresponding prime sequence S_i can be left-rotated $p-1$ times to create new prime sequences $S_{i,t} = (S_{i,t0}, S_{i,t1} ,..., S_{i,t(p-1)})$, where t represent the number of times S_i has been left-rotated. Each prime sequence $S_{i,t}$ is then mapped into a code sequence $C_{i,t}$ (as example in 2.3.1). Therefore, a total of p prime sequences per group are obtained. In table 2-2, each synchronous CDMA (S/CDMA) code sequence $C_{i,0}$ is the same as the original CDMA code sequence C_i Whereas the other S/CDMA code sequence $C_{i,t}$ (with $t \neq 0$) are time-shifted version of C_i. Since the number of possible subscribers is determined by the number of code sequences, in S/CDMA, p^2 subscribers can be supported, a factor of p larger than for CDMA. These p^2 code sequences are still pseudo-orthogonal to each other. The auto-correlation peak for all new code sequences at each decoder output has an amplitude equal to p and is made to occur in the last chip position to which all receivers are synchronized.

Example: Generation of binary prime sequence codes for synchronous CDMA (S/CDMA) in GF(5)

Table 2-2 : Left-rotated prime sequence $S_{i,t}$ and associated S/CDMA code sequence $C_{i,t}$ for GF(5)

Group i	j 01234	Sequence $S_{i,t}$	Binary prime code sequence $C_{i,t}$
0	00000	S_{00}	$C_{00} = 10000,10000,10000,10000,10000$
	44444	S_{01}	$C_{01} = 00001,00001,00001,00001,00001$
	33333	S_{02}	$C_{02} = 00010,00010,00010,00010,00010$
	22222	S_{03}	$C_{03} = 00100,00100,00100,00100,00100$
	11111	S_{04}	$C_{04} = 01000,01000,01000,01000,01000$
1	01234	S_{10}	$C_{10} = 10000,01000,00100,00010,00001$
	12340	S_{11}	$C_{11} = 01000,00100,00010,00001,10000$
	23401	S_{12}	$C_{12} = 00100,00010,00001,10000,01000$
	34012	S_{13}	$C_{13} = 00010,00001,10000,01000,00100$
	40123	S_{14}	$C_{14} = 00001,10000,01000,00100,00010$
2	02413	S_{20}	$C_{20} = 10000,00100,00001,01000,00010$
	24130	S_{21}	$C_{21} = 00100,00001,01000,00010,10000$
	41302	S_{22}	$C_{22} = 00001,01000,00010,10000,00100$
	13024	S_{23}	$C_{23} = 01000,00010,10000,00100,00001$
	30241	S_{24}	$C_{24} = 00010,10000,00100,00001,01000$
3	03142	S_{30}	$C_{30} = 10000,00010,01000,00001,00100$
	31420	S_{31}	$C_{31} = 00010,01000,00001,00100,10000$
	14203	S_{32}	$C_{32} = 01000,00001,00100,10000,00010$
	42031	S_{33}	$C_{33} = 00001,00100,10000,00010,01000$
	20314	S_{34}	$C_{34} = 00100,10000,00010,01000,00001$
4	04321	S_{40}	$C_{40} = 10000,00001,00010,00100,01000$
	43210	S_{41}	$C_{41} = 00001,00010,00100,01000,10000$
	32104	S_{42}	$C_{42} = 00010,00100,01000,10000,00001$
	21043	S_{43}	$C_{43} = 00100,01000,10000,00001,00010$
	10432	S_{44}	$C_{44} = 01000,10000,00001,00010,00100$

2.3.3 Transmitter and Receivers for Synchronous Optical CDMA Networks

In a synchronous optical CDMA networks using binary prime sequence codes the code sequences can be generated and correlated by encoder/decoder based on parallel optical delay lines.

Figure 2-7: Optical transmitter for synchronous optical CDMA networks using binary prime sequence codes

Figure 2-7 and 2-8 show the block diagram of the transmitter and receiver for such a system, where parallel architecture is used for sequence generation, selection and correlation. The transmitter for generating sequences of length N consists of a $1xN$ optical power splitter, a set of N parallel optical fiber delay lines, and a $Nx1$ power combiner. A laser produces high intensity pulse streams at the data rate. The duration of each pulse is less than or equal the chip time $Tc = T/N$, where T is the bit time. The time of emitting the light pulses is

controlled by the received clock, so that a pulse is emitted only at the beginning of each bit time. These pulses are modulated by an optical gate, such as a directional coupler switch, which is driven by the data waveform to generate the optical data signal. At the $1xN$ optical power splitter, the optical pulse is splitted into N pulses which are then delayed in the set of parallel optical fiber delay lines. The sequence selection can be realised by controlling N opto-electrical switches each of which is located in one branch of the transmitter. The switch in a given branch is closed if this branch corresponds to the position of a "1" chip in the selected sequence. This switch is opened if the branch corresponds to the position of a "0" chip. By controlling these switches, only W (the number of "1" chips in a sequence) properly delayed pulses according to the position of "1's" in the intended receiver address sequence are selected and recombined so that the resulting optical sequence is obtained at the output of the optical combiner and is transmitted to star coupler.

Figure 2-8: Optical receiver for synchronous optical CDMA networks using binary prime sequence codes

In the receiver, the decoder receives optical sequences from star coupler. The decoder consists of N optical fiber delay lines connected in parallel using an $1xN$ optical power splitter and a $Nx1$ optical power combiner. In this receiver, the selection of delay lines is such that the delays correspond to the position of "1's" in the time reversed version of the receiver reference sequence. At the input of the correlator receiver the received optical signal is split into N different paths. However, only W properly delayed signals are recombined at the optical combiner. At each decoder output, the auto-correlation peak for all new codes sequences has an amplitude equal to p (prime number) and is made to occur in the last chip position of data bit to which all receivers are synchronized. The synchronized signals are then photo-detected by a photo-detector (PIN or APD). The data are received by threshold-detecting the auto-correlation peaks.

Example: Explain how the encoder is constructed and how it works for generating the code sequence $C_{l,0} = 1000001000001000001000001$ if the data rate = 1 Mb/s and the sequence length is N=25.

D = Data rate   Dc = Chip rate   Tc = Chip time   T = Bit time

Chip rate Dc   = N x D

= 25 x 1Mbit/s

= **25 M chip/s**

Chip time Tc   = 1/Dc

= $1/25(1024)^2$

= **3.8 x $(10)^{-8}$ second**

Bit time T   = 1/D

$$= 1/1024^2$$

$$= 9.5 \times (10)^{-7} \text{ second}$$

So, if the data rate is 1Mbp/s the chip rate of the transmitter is 25 Mchip/s. For sending a data bit (can be bit "1" or "0") the transmitter has to generate 25 chips.

For example, if one user wants to transmit data to another user whose address sequence is $C_{1,0} = 1000001000001000001000001$ all data bit "1" will be encoded with that code sequence. User can only send data bits at the beginning of each bit time (that is, at the 1st chip time slot of each bit time). At that time, the laser produces a high intensity pulse and sends the pulse through the opto-electrical switch to the encoder which consists of *1x25* optical power splitter, a set of *25* parallel optical fiber delay lines and a *25x1* combiner. The opto-electrical switch is closed only if the data bit is "1". Therefore, when a "0" bit is sent, no pulse is passed through the encoder resulting in no code sequence is transmitted or at the output of encoder the sequence "0000000000000000000000000" is obtained. The sequence selection can be realised by controlling *25* opto-electrical switches each of which is located in one branch of the transmitter. The switch in a given branch is closed if this branch corresponds to the position of a "1" chip in the selected sequence. This switch is opened if the branch corresponds to the position of a "0" chip. Only 5 opto-electrical switches in branches, which have delay 0Tc, 6Tc, 12Tc, 18Tc, 24Tc are closed, all the others remain open. If a data bit "1" is transmitted the laser pulse passes through the parallel delay-line encoder and at the output of the 25x1 combiner we get the sequence "1000001000001000001000001".

Figure 2-9: Encoder for synchronous optical CDMA networks set for generating the code

sequence $C_{1,0}=10000010000010000010000001$

Figure 2-10: Decoder for synchronous optical CDMA networks set for correlating with the

code sequence $C_{1,0}=10000010000010000010000001$ used as the address sequence

Output sequence will be sent through star coupler. At the receiver, the decoder receives optical sequence from star coupler.

Example: Assume that the sequence $C_{1,0}=100000100000100000100000100000$ is received at the decoder shown in Figure 2-10, which is set to the address sequence $C_{1,0}=100000100000100000100000100000$. The result of the auto-correlation between the received sequence and the address sequence is shown in Table 2-3. It can be seen that at the decoder output, the auto-correlation peak for the received code sequence has an amplitude equal to 5 at the time $t = 24 \ T_c$.

If the sequence $C_{2,0} = 100000010000001010000000010$ is received at the above decoder, the result of the cross-correlation between the received sequence and the address sequence is shown in Table 2-4. It can be seen that at the decoder output at the time $t = 24 \ T_c$, the cross-correlation has an amplitude equal to 1, which is less than 5.

Table 2-3: The auto correlation of code C10 "1000001000001000001000001"

Time(Tc)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Output generated by pulse 1	1						1						1						1						1																								
Output generated by pulse 2							1						1						1						1						1																		
Output generated by pulse 3													1						1						1						1						1												
Output generated by pulse 4																			1						1						1						1						1						
Output generated by pulse 5																									1						1						1						1						1
Output of 25x1 Combiner	1						2						3						4						5						4						3						2						1

Table 2-4: The cross correlation of code C20 "1000000100000010100000010"

Time (Tc)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Output generated by pulse 1	1						1						1						1						1																								
Output generated by pulse 2								1						1						1						1						1																	
Output generated by pulse 3															1						1						1						1						1										
Output generated by pulse 4																	1						1						1						1						1								
Output generated by pulse 5																														1						1						1							1
Output of 25x1 Combiner	1						1	1					1	1	1		1		1	1	1		1	1	1	1	1		1	1		1	1		1	1			1		1	1							1

2.4 Advantage and Disadvantage of S/CDMA

In S/CDMA, p^2 subscribers can be supported, these subscribers use p^2 code sequences, which are still pseudo-orthogonal to each other. The auto-correlation peak for all new code sequence at each decoder output has an amplitude equal to p and is made to occur in the last chip position to which all receivers are synchronized. But p^2 code sequences of S/CDMA are non-symmetric code sequences. Non-symmetric sequences can be correlated by the noncoherent optical correlator receiver based on parallel optical fiber delay lines. The major disadvantage of all-optical CDMA systems using non-symmetric codes is the encoding and decoding of those code sequences by parallel optical fiber delay-line, where transmitters/receivers require optical splitters/combiners that involve considerable recombination loss. These passive optical devices as illustrated in Figure 2-8 are realised using combinations of $2x2$ couplers, each of which introduces an inherent optical loss of 3 dB. Therefore, both the transmitter and the receiver introduce a loss of N^2 to give a total loss in the desired signal of N^4 with respect to the launched laser pulse. The loss may be excessively high if the sequence is long. This loss, at the receiver, can be reduced to W^2 for a receiver with fixed reference sequence. However, at the transmitter, where the programmability (i.e. the capability of generating any sequence) is absolutely necessary, the optical loss is always N^2.

Figure 2-11: Passive optical splitter/combiner

Example: Data rate = 1 Mb/s, N = 25 calculate the loss due to the use of combiners and splitter at transmitter and receiver.

$N^2 = 25^2$ $W^2 = 5^2$

Loss at transmitter = $10 \log 25^2$

= 27.96 dB

If a programmable receiver is used, the loss at receiver is also 27.96 dB. So, the total loss due to the use of combiners and splitter at transmitter and receiver is 54.92 dB. If a fixed address receiver is used, only W=5 parallel branches are needed, that is only 1xW splitter and Wx1 combiner are required. Hence, the loss at receiver = $10 \log 5^2 = 13.98$ dB. In this case, the total loss due to the use of combiners and splitter at transmitter and receiver is 41.94 dB

2.5 Symmetric Codes for Non-coherent Optical CDMA Networks

In order to overcome the above drawbacks, schemes have been proposed for noncoherent all-optical CDMA systems based on the use of optical fiber lattices for constructing serial encoders and correlator receivers. Those systems use codes which are grouped into the class of symmetric codes [5],[11],[10]. The term "symmetric codes" is due to the fact that originally, only sequences that contain "1's" in a symmetric pattern around the sequence center were generated [19].

2.5.1 Generation of symmetric code from prime-sequence codes

A prime binary sequence C_i is made up of p subsequences of length p that consists of only one "1" chip and the value of each $s_{i,j}$ in the prime sequence S_i represents the position of the "1" chip in the jth subsequence. Hence, Table 2-1 shows the position of the "1" chip in the jth subsequences of binary prime sequences generated by the prime number $p=5$. For $i \in GF(p)$, the adjacent delay between two "1" chips of C_i generated by S_i is defined as

$$t_j^i = \begin{cases} s_{i,j+1} - s_{i,j} + p & for \ j = 0,1,...,p-2 \\ p - s_{i,j} & for \ j = p-1 \end{cases} \tag{1}$$

Example: Calculation of adjacent delays for binary prime sequences in GF(5)

For i=0

$$t^0_0 = (S_{0,0+1} - S_{0,0}) + p$$

$$= (0 - 0) + 5$$

$$= 5$$

$$t^0_1 = (S_{0,1+1} - S_{0,1}) + p$$

$$= (0 - 0) + 5$$

$$= 5$$

$$t^0_2 = (S_{0,2+1} - S_{0,2}) + p$$

$$= (0 - 0) + 5$$

$$= 5$$

$$t^0_3 = (S_{0,3+1} - S_{0,3}) + p$$

$$= (0 - 0) + 5$$

$$= 5$$

For i=1

$$t^1_0 = (S_{1,0+1} - S_{1,0}) + p$$

$$= (1 - 0) + 5$$

$$= 6$$

$$t^1_1 = (S_{1,1+1} - S_{1,1}) + p$$

$$= (2 - 1) + 5$$

$$= 6$$

$$t^1_2 = (S_{1,2+1} - S_{1,2}) + p$$

$$= (3 - 2) + 5$$

$$= 6$$

$$t^1_3 = (S_{1,3+1} - S_{1,3}) + p$$

$$= (4 - 3) + 5$$

$$= 6$$

For i=2

$$t^2_0 = (S_{2,0+1} - S_{2,0}) + p$$

$$= (2 - 0) + 5$$

$$= 7$$

$$t^2_1 = (S_{2,1+1} - S_{2,1}) + p$$

$$= (4 - 2) + 5$$

$$= 7$$

$$t^2_2 = (S_{2,2+1} - S_{2,2}) + p$$

$$= (6 \ mod(5) - 4) + 5$$

$$= 2$$

$$t^2_3 = (S_{2,3+1} - S_{2,3}) + p$$

$$= (8 \ mod(5) - 6 \ mod(5)) + 5$$

$$= 7$$

For i=3

$$t^3_0 = (S_{3,0+1} - S_{3,0}) + p$$

$$= (3 - 0) + 5$$

$$= 8$$

$$t^3_1 = (S_{3,1+1} - S_{3,1}) + p$$

$$= (6 \ mod(5) - 3) + 5$$

$$= 3$$

$$t^3_2 = (S_{3,2+1} - S_{3,2}) + p$$

$$= (9 \ mod(5) - 6 \ mod(5)) + 5$$

$$= 8$$

$$t^3_3 = (S_{3,3+1} - S_{3,3}) + p$$

$$= (12 \bmod(5) - 9 \bmod(5)) + 5$$

$$= 3$$

For i=4

$$t^4_0 = (S_{4,0+1} - S_{4,0}) + p$$

$$= (4 - 0) + 5$$

$$= 9$$

$$t^4_1 = (S_{4,1+1} - S_{4,1}) + p$$

$$= (8 \bmod(5) - 4) + 5$$

$$= 4$$

$$t^4_2 = (S_{4,2+1} - S_{4,2}) + p$$

$$= (12 \bmod(5) - 8 \bmod(5)) + 5$$

$$= 4$$

$$t^4_3 = (S_{4,3+1} - S_{4,3}) + p$$

$$= (16 \bmod(5) - 12 \bmod(5)) + 5$$

$$= 4$$

Table 2-5 shows the adjacent delays for the binary prime sequences in $GF(5)$. It can be seen that, for prime sequences in $GF(p)$, the $(p-2)$ adjacent delays t_1, t_2,..., t_{p-2} of a given binary prime sequence are symmetric with the symmetric center being the delay of the column $j = (p-1)/2$ of the table of adjacent delays. In Table 2-5, the delays of column $j = 1$ are equal to the delays of column $j = 3$.

Table 2-5: Adjacent delays of binary prime sequences in GF(5)

i	j			
	0	1	2	3
0	5	5	5	5
1	6	6	6	6
2	7	7	2	7
3	8	3	8	3
4	9	4	4	4

This observation leads to the following important property of binary prime sequences [10]

For the ith binary prime sequence ($0 \leq i \leq p-1$) in $GF(p)$ the adjacent delays t_1^i, t_2^i, ..., t_{p-2}^i are

related by $t_j^i = t_{p-1-j}^i$ for $0 < j < (p-1)/2$.

Based on the above property of the binary prime sequences, new codes of weight 2^n (that is,

the number of "1" chips in each code sequence is 2^n, for $n = 2,3,...$) can be generated.

The new codes are called 2^n prime-sequence codes.

Construction of Symmetric Codes

A binary sequence of length N and weight 4 can be represented by $X = \{x_1, x_2, x_3, x_4\}$ where

$0 \leq x_i \leq N-1$ $\{i = 1,2,3,4\}$ indicates the position of an "1" chip in the sequence. In this

sequence, the adjacent delays which are multiples of the duration of the sequence chip time

are $\Delta_1 = x_2 - x_1$, $\Delta_2 = x_3 - x_2$, $\Delta_3 = x_4 - x_3$. The construction of 2^n prime sequences of

weight 4 from a binary prime sequence of length p^2 is given in the following:

Step 1: From the ith binary prime sequence $(0 \leq i \leq p-1)$, for each integer m such that $1 \leq m \leq (p-3)/2$, the adjacent delays $\Delta_1^{i,m}$, $\Delta_2^{i,m}$ and $\Delta_3^{i,m}$ of a new 2^n prime-sequence are determined by

$$\Delta_1^{i,m} = t_1^i + t_2^i + \ldots + t_m^i$$

$$\Delta_2^{i,m} = t_{m+1}^i + t_{m+2}^i + \ldots + t_{p-m-2}^i$$

$$\Delta_3^{i,m} = t_{p-m-1}^i + t_{p-m-2}^i + \ldots + t_{p-2}^i$$

where t_r^i $(1 \leq r \leq p-2)$ are the adjacent delays of the ith binary prime sequence.

Step 2: Keep the "1" chips of the binary prime sequence corresponding to $\Delta_1^{i,m}$, $\Delta_2^{i,m}$ and $\Delta_3^{i,m}$ unchanged. All other "1" chips of the binary prime sequence are replaced by "0".

Step 3: Truncate the first p "0" chips of the new formed sequence.

The resulting sequence is of length $p(p-1)$, weight 4 and can be represented by $(t_0^i - p, \Delta_1^{i,m}, \Delta_2^{i,m}, \Delta_3^{i,m})$, where $t_0^i - p$ represents the number of "0" chips preceded the first "1" chip, $\Delta_1^{i,m}, \Delta_2^{i,m}, \Delta_3^{i,m}$ are the adjacent delays. Since $t_j^i = t_{p-1-j}^i$ for $0 < j < (p-1)/2$ we have $\Delta_1^{i,m} = \Delta_3^{i,m}$ for $1 \leq m \leq (p-3)/2$.

Using the described method, from a binary prime sequence we can construct $(p-3)/2$ new sequences of length $p(p-1)$ with weight 4. Hence, for a set of p binary prime sequences, a total of $p(p-3)/2$ new sequences can be constructed. Therefore, compared to 2^n prime-sequence codes of weight 4 constructed by [11], the number of sequences of the new code is $(p-3)/2$ times larger. The generation of the new code is based on removing the $p-4$ unwanted "1" chips from binary prime sequences of weight p. Hence, the cross-correlation constraint

of the new codes is not different from that of prime-sequence codes [1] and $2''$ prime-sequence codes [11].

Example: $2''$ prime-sequence of weight 4 generated from binary prime sequence in GF(5)

For each binary i^{th} ($i \in$ GF(5)) sequence we can construct $m = (p-3)/2 = 1$ new sequence.

For i=0, m =1

$$\Delta_1^{0,1} = t_1^0 = 5$$

$$\Delta_2^{0,1} = t_2^0 = 5$$

$$\Delta_3^{0,1} = t_3^0 = 5$$

$$t_0^0 - p = 5\text{-}5 = 0$$

For i=1, m =1

$$\Delta_1^{1,1} = t_1^1 = 6$$

$$\Delta_2^{1,1} = t_2^1 = 6$$

$$\Delta_3^{1,1} = t_3^1 = 6$$

$$t_0^1 - p = 6\text{-}5 = 1$$

For i=2, m =1

$$\Delta_1^{2,1} = t_1^2 = 7$$

$$\Delta_2^{2,1} = t_2^2 = 2$$

$$\Delta_3^{2,1} = t_3^2 = 7$$

$$t_0^2 - p = 7\text{-}5 = 2$$

For i=3, m =1

$$\Delta_1^{3,1} = t_1^3 = 3$$

$$\Delta_2^{3,1} = t_2^3 = 8$$

$$\Delta_3^{3.1} = t_3^3 = 3$$

$$t_0^3 - p = 8-5 = 3$$

For i=4, m =1

$$\Delta_1^{4,1} = t_1^4 = 4$$

$$\Delta_2^{4.1} = t_2^4 = 4$$

$$\Delta_3^{4,1} = t_3^4 = 4$$

$$t_0^4 - p = 9-5 = 4$$

From 5 binary prime sequences generated by the prime number $p=5$ a total of $p(p-3)/2=5$ new sequences can be constructed and shown in Table 2-6, therefore, if the prime number is larger, the number of new sequences is increased.

Table 2-6 : Symmetric sequences of W=4 in GF(5)

Group	$(t_0^i - p, \Delta_1^{i,m}, \Delta_2^{i,m}, \Delta_3^{i,m})$	Binary prime code sequence
i=0		C_{00} = 10000,10000,10000,10000,10000
m=1	(0,5,5,5)	A_{00} = 10000,10000,10000,10000
i=1		C_{10} = 10000,01000,00100,00010,00001
m=1	(1,6,6,6)	A_{10} = 01000,00100,00010,00001
i=2		C_{20} = 10000,00100,00001,01000,00010
m=1	(2,7,2,7)	A_{20} = 00100,00001,01000,00010
i=3		C_{30} = 10000,00010,01000,00001,00100
m=1	(3,3,8,3)	A_{30} = 00010,01000,00001,00100
i=4		C_{40} = 10000,00001,00010,00100,01000
m=1	(4,4,4,4)	A_{40} = 00001,00010,00100,01000

2.5.2 Codes Properties

Following are some properties of the new 2^n prime-sequence codes of weight 4 [10], which are used for designing encoder and decoder of optical fiber CDMA networks.

Property 1: The first i chips of the sequences generated from the ith binary prime sequence ($0 \leq i \leq p-1$) are "0".

Property 2: The minimum value of the first adjacent delay of the new sequence is min $(\Delta_1^l) = (p+1)/2$ where $1 \leq l \leq p(p-3)/2$.

Property 3: The maximum value of the first adjacent delay of the new sequence is max $(\Delta_1^l) = (p^2-p-6)/2$ where $1 \leq l \leq p(p-3)/2$.

Property 4: The minimum value of the sum of the first two adjacent delays of the new sequence is min $(\Delta_1^l + \Delta_2^l) = (p-1)^2/2$ where $1 \leq l \leq p(p-3)/2$.

Property 5: The maximum value of the sum of the first two adjacent delays of the new sequence is max $(\Delta_1^l + \Delta_2^l) = p^2-2p-3$ where $1 \leq l \leq p(p-3)/2$.

2.5.3 Problem Statements

1. Advantage of Synchronous Optical CDMA Networks

S/CDMA is more attractive multiple-access scheme than CDMA because of its property of error free transmission when the number of simultaneous users $K \leq p\text{-}1$ together with the large increase in the possible number of subscribers and simultaneous user for the same bandwidth expansion. In general, synchronous accessing schemes, with rigorous transmission schedules, produce higher throughput (i.e more successful transmissions) than asynchronous techniques where network access is random and collision occurs. It follows that in environments with real time and/or high throughput requirements (e.g. digital video), synchronous accessing techniques are most efficient.

2. Problems of Synchronous Optical CDMA Networks Using Prime-Sequences Codes

Synchronous optical CDMA networks described in [9] use prime-sequences codes, which are non-symmetric code sequence. The major disadvantage of all-optical CDMA systems using non-symmetric codes is the encoding and decoding of those codes by parallel optical fibre delay-line where transmitters/receivers require optical splitters/combiners that involve considerable recombination loss. These passive optical devices are realised using combinations of *2x2* couplers, each of which introduces an inherent optical loss of 3 dB. Therefore, both the transmitter and the receiver introduce a loss of N^2 to give a total loss in the desired signal of N^4 with respect to the launched laser pulse. The loss may be

excessively high if the sequence is long. This loss, at the receiver, can be reduced to W^2 for a receiver with fixed reference sequence. However, at the transmitter, where the programmability (i.e. the capability of generating any sequence) is absolutely necessary, the optical loss is always N^2.

3. Advantages of Asynchronous Optical CDMA Networks using Symmetric Codes

The advantage of the symmetric codes is that serial encoder/decoder can be constructed using *2x2* opto-electrical switches. Thereby, the recombination loss in each encoder/decoder pair is substantially reduced compared to the loss in parallel delay-line encoder/decoder. In addition, the number of optical components (switches, delays) required for constructing the encoder/decoder is less than that of the parallel architecture. In addition, the number of optical component (switches, delays) required for constructing the encoder/decoder is less than that of the parallel architecture

4. Problems of Asynchronous Optical CDMA Networks using Symmetric Codes

Although asynchronous optical CDMA networks using symmetric codes of length p^2 described in [10] can support *p(p-3)/2* different subscribers the low weight limits the maximum number of subscribers of the network. In order to accommodate more subscribers, longer sequences of higher weight are required which in turn increases the complexity of the encoders and decoders and reduces the cost effectiveness of the network.

5. The Use of Symmetric Codes for Synchronous Optical CDMA Networks

The use of symmetric codes in synchronous optical CDMA networks can overcome the disadvantages of synchronous optical CDMA networks using prime-sequences codes (e.g. very high optical loss) and that of asynchronous optical CDMA networks using symmetric codes (e.g. limited number of code sequences).

CHAPTER 3: SYMMETRIC CODES FOR SYNCHRONOUS OPTICAL FIBER CDMA NETWORKS

3.1 Program for Generating Symmetric Codes

We can generate synchronous symmetric code sequences for synchronous optical fiber CDMA networks by taking different time shift of symmetric code sequences A_i described in Section 2.5.1. Each synchronous symmetric code sequence $A_{i,0}$ is the same as the original symmetric code sequence A_i whereas the other synchronous symmetric code sequences $A_{i,t}$ (with $t \neq 0$) are time-shift versions of A_i. Note that some of the time-shift versions of A_i are not symmetric code sequences, therefore, they can not be used for the synchronous optical CDMA network using symmetric codes and will be excluded. Table 3-1 shows all the code sequences generated from symmetric sequence in GF(5). It can be seen that there are 8 non-symmetric sequences: $A_{1,2}$, $A_{1,4}$, $A_{2,2}$, $A_{2,4}$, $A_{3,2}$, $A_{3,4}$, $A_{3,2}$, $A_{3,4}$, which should be excluded.

The cross correlation of two code sequences at shift $\tau = 0$ can be calculated by

$$C(\tau = 0) = \sum_{m=0}^{p(p-1)} A_1(m) \cdot A_2(m)$$

Where $A_1(m)$ and $A_2(m)$ are 2 different code sequences.

Example: Find the cross correlation of symmetric code sequence A_{10} and A_{20}

$A_{10} = 01000,00100,00010,00001$

$A_{20} = 00100,00001,01000,00010$

The cross correlation of symmetric code sequence A_{10} and A_{20} is

$C(0) = A_1(0) \cdot A_2(0) + A_1(1) \cdot A_2(1) + \ldots + A_1(N-1) \cdot A_2(N-1) = 0$

We design computer program based on MatLab for generating symmetric codes for synchronous optical fiber CDMA networks. The source code (SSC2.m) is shown in Appendix A.

The program consists of the following modules:

- Module for generating prime sequence

- Module for generating the adjacent delay of prime code sequences

- Module for generating the matrix that contains absolute value of symmetric code

- Module for generating code sequences for synchronous networks

- Module for determining symmetric code for synchronous network

- Module for generating binary code sequence for symmetric code for synchronous network

- Module for calculating cross correlation of 2 symmetric sequences

- Module for counting number of cross correlation equal 0,1 or 2

Table 3-1: Synchronous symmetric code sequences in GF(5) for synchronous optical fiber

CDMA networks

Group	Sequence $A_{i,t}$	Symmetric code sequence
I=0	A_{00}	10000,10000,10000,10000
M=1	A_{01}	00001,00001,00001,00001
	A_{02}	00010,00010,00010,00010
	A_{03}	00100,00100,00100,00100
	A_{04}	01000,01000,01000,01000
I=1	A_{10}	01000,00100,00010,00001
M=1	A_{11}	10000,01000,00100,00010
	A_{12}	00001,10000,01000,00100
	A_{13}	00010,00001,10000,01000
	A_{14}	00100,00010,00001,10000
I=2	A_{20}	00100,00001,01000,00010
M=1	A_{21}	01000,00010,10000,00100
	A_{22}	10000,00100,00001,01000
	A_{23}	00001,01000,00010,10000
	A_{24}	00010,10000,00100,00001
I=3	A_{30}	00010,01000,00001,00100
M=1	A_{31}	00100,10000,00010,01000
	A_{32}	01000,00001,00100,10000
	A_{33}	10000,00010,01000,00001
	A_{34}	00001,00100,10000,00010
I=4	A_{40}	00001,00010,00100,01000
M=1	A_{41}	00010,00100,01000,10000
	A_{42}	00100,01000,10000,00001
	A_{43}	01000,10000,00001,00010
	A_{44}	10000,00001,00010,00100

The program can be used for generating symmetric code sequence and calculating the cross-correlation statistics of symmetric codes for any prime number. When running the program we have to input the prime number p, then the program will construct prime sequence matrix first, then it calculates the adjacent delay for generating the symmetric code. After we get the symmetric code the program continue to calculate the cross-correlation. The result shows all symmetric code sequences for synchronous network and cross-correlation statistics.

We have checked the correctness of the program by comparing the results (for p=5) obtained from running the program and the results manually calculated. We have run the program for p=5, 7, 11, ..., 29. Although the program can be used with any prime number p. we have to stop at p=29 because of insufficient capability of our computer to run the program and the complexity of program which contains many modules as we listed in the last paragraph. For running p = 29 it takes 3 days and for p=31 the computer was hang.

3.2 Numerical Results

We run the program for all prime numbers between p=5 and p=29. Table 3-2 shows the resume of the obtained results.

Table 3-2 : Results obtained by running program.

p	No. of symmetric code	Code length p(p-1)	Weight	Cross-correlation		
				0	1	2
5	17	20	4	52	84	0
7	66	42	4	1348	772	25
11	324	110	4	41264	10696	366
13	565	156	4	131468	27012	850
17	1351	272	4	793488	115392	3045
19	1928	342	4	1643808	208752	5068
23	3530	506	4	5644516	572244	11925
29	7293	812	4	24638780	1918660	32838

3.3 Comparison Between Symmetric Code and Prime Sequence Code for Synchronous Optical CDMA Networks

We compare symmetric codes (Table 3-3) and prime codes (Table 3-4) for synchronous CDMA, we found that for the same p the number of code sequences of symmetric code is larger than the number of code sequences of prime code. That means the network using the symmetric code can support more subscribers than that using prime sequence code. Furthermore, symmetric code sequences are shorter than prime code sequence. That means the network using the symmetric code can better utilize bandwidth. Another advantage of symmetric codes is that serial encoder/decoder can be constructed using 2x2 opto-electrical switches and the loss factor of each switch is 2. So, the need of input power at the serial decoder is less than the parallel ones.

Table 3-3: The symmetric codes for prime codes sequences

Prime number (p)	The number of code sequence	Code length p(p-1)
5	17	20
7	66	42
11	324	110
13	565	156
17	1351	272
19	1928	342
23	3530	506
29	7293	812

Table 3-4: Prime code sequence for synchronous optical CDMA networks [7]

Prime number (p)	The number of code sequence (p^2)	Code length (p^2)
5	25	25
7	49	49
11	121	121
13	169	169
17	289	289
19	361	361
23	529	529
29	841	841

3.4 Cross-correlation Statistics

The symmetric codes are generated from prime sequence codes. Since the maximum value of cross-correlation of prime sequence codes is 2 [1] then the maximum value of cross-correlation of symmetric codes is also 2. We have verified this fact as shown in Table3-2. Therefore, when bit "1" is transmitted the cross-correlation can be 0, 1 or 2 but for sending bit "0" the cross-correlation can be 0 only (because of OOK).

Assume that :

$C_1(0)$ is the number of cross-correlation equal 0, when bit "1" is transmit

$C_1(1)$ is the number of cross-correlation equal 1, when bit "1" is transmit

$C_1(2)$ is the number of cross-correlation equal 2, when bit "1" is transmit

$C_0(0)$ is the number of cross-correlation equal 0, when bit "0" is transmit

We have

$$C_0(0) = C_1(0) + C_1(1) + C_1(2) = C^2_{Si\text{-}ss}$$

Where Si-SS is the number of symmetric code sequences for a given number p. and

$$C^2_{Si\_SS} := \frac{Si\_SS!}{(Si\_SS - 2)!\, 2!}$$

These numbers shown in Table3-5 are determined by calculating the cross-correlation of all pairs of 2 sequences of the whole set of symmetric code sequences using MatLab program. For symmetric codes the number of pairs is $C^2_{Si\text{-}ss}$

C(0) : All the number of cross-correlation equal 0 when a user transmits one bit "0" and one bit "1"

$$C(0) = C_1(0) + C_0(0)$$

C(1) : All the number of cross-correlation equal 1 when a user transmits one bit "1" and one bit "0"

$$C(1) = C_1(1)$$

C(2) : All the number of cross-correlation equal 2 when a user transmits one bit "1" and one bit "0"

$$C(2) = C_1(2)$$

Table 3-5: Cross-correlation statistics

p	$C_1(0)$	$C_1(1)$	$C_1(2)$
5	52	84	0
7	1348	772	25
11	41264	10696	366
13	131468	27012	850
17	793488	115392	3045
19	1643808	208752	5068
23	5644516	572244	11925
29	24638780	1918660	32838

3.5 The Mean of Cross-correlation (μ)

The mean of the cross correlation can be calculated by

$$\mu = 0 \cdot p(0) + 1 \cdot p(1) + 2 \cdot p(2)$$

Where

$$p(0) = \frac{C(0)}{C(0) + C(1) + C(2)}$$

$$p(1) = \frac{C(1)}{C(0) + C(1) + C(2)}$$

$$p(2) = \frac{C(2)}{C(0) + C(1) + C(2)}$$

Where p(0) is the probability of cross-correlation equal 0

p(1) is the probability of cross-correlation equal 1

p(2) is the probability of cross-correlation equal 2

Example: Find the Mean (μ) of cross correlation for symmetric codes generated by p=5. First, find the probability of cross correlation equal 0,1 and 2 and the mean of cross correlation

p=5

p(0) = C(0) / (C(0) + C(1) + C(2))

= (52+136) / 2 *72*

= 0.6911765

p(1) = C(1) / (C(0) + C(1) + C(2))

= 84 / 272

= 0.3088235

p(2) = C(2) / (C(0) + C(1) + C(2))

= 0 / 272

= 0

Find Mean μ

μ = 0 x p(0) + 1 x p(1) + 2 x p(2)

= (0 x 0.6900765)+(1 x 0.3088235)+(2 x 0)

= 0.3088235

So μ = 0.3088235, we have calculated the mean μ for all symmetric code generated using p=5 to 29. The results are shown in Table 3-6. Details of calculation are shown in Appendix B

Table 3-6: The Probability, Mean and Variance of Cross-correlation

p	Probability of Cross-correlation			Mean	Variance
	p(0)	p(1)	p(2)		
5	0.6911765	0.3088235	0	0.308824	0.213452
7	0.8142191	0.1799534	0.0058275	0.191608	0.16655
11	0.8942973	0.1022054	0.0034973	0.1092	0.10427
13	0.9125651	0.0847675	0.0026674	0.090102	0.087319
17	0.9350621	0.0632648	0.0016695	0.066607	0.06551
19	0.9424481	0.0561878	0.0013641	0.058916	0.058173
23	0.9531066	0.0459362	0.0009573	0.047851	0.047476
29	0.9633043	0.0360782	0.0006175	0.037313	0.037156

3.6 The Variance of Cross-correlation (σ^2)

The variance is calculated by

$$\sigma^2 = E(x^2) - [E(x)]^2$$

$$= E(x^2) - \mu^2$$

Where

$$E(x^2) = 0^2 \cdot p(0) + 1^2 \cdot p(1) + 2^2 \cdot p(2)$$

so,

$$\sigma^2 = p(1) + 4 \cdot p(2) - \mu^2$$

Example : Find the variance (σ^2) of cross correlation for symmetric codes generated by p=5.

p=5

$$\sigma^2 = [p(1) + 4 x p(2)] - \mu^2$$

$$= (1x0.3088235 + 4x0) - 0.095372$$

$$= 0.2134515$$

So, $\sigma^2 = 0.2134515$, we have calculated the variance σ^2 for all symmetric codes generated using p=5 to 29. The results are shown in Table 3-6. Details of calculation are shown in Appendix C.

CHAPTER 4: TRANSMITTER AND RECEIVER FOR SYMMETRIC CODES

4.1 Principle of Serial Encoder/Decoder

For On-Off Keying (OOK) systems, when transmitting an "1" bit the optical source generates an optical pulse of maximum pulse width T_c where $T_c = T/N$ is the sequence chip time, T is the bit time, N is the sequence length and no pulse is emitted for a "0" bit. At the input of the encoder, the optical pulse is split into two pulses by a passive splitter and one of the pulse is delayed by a delay of τ_1. The delayed pulse combines with the non-delayed one at the 2x2 passive star coupler. The two pulses then split into four pulses with two pulses will be delayed by a delay of τ_2 and all four pulses are combined at the passive combiner. An optical sequence of weight 4 is obtained at the output of the combiner with the adjacent delays being $(\tau_1, \tau_2, \tau_1 + \tau_2)$. For the lth $2''$ sequence of weight 4 ($1 \leq l \leq p(p-3)/2$) we have $\tau_1 = \Delta_1^l$ and $\tau_2 = \Delta_1^l + \Delta_2^l$ This encoder can also be used as the decoder if the optical source is removed. The advantage of the serial encoder is that it can be constructed using passive optical couplers. Thereby, the recombination loss in each encoder/decoder pair is substantially reduced compared to the loss in parallel delay-line encoder/decoder [12]. However, this encoder can only generate one specific $2''$ sequence of a fixed combination of the adjacent delays. That is, the usual programmable addressing requirement for CDMA encoders can not be realised. In order to be able to generate all new $2''$ prime sequences, the delays τ_1 and τ_2 must be tunable (or programmable).

4.2 Programmable Lattice

The encoder and decoder for optical fiber CDMA networks using 2^n prime-sequence codes of weight 4 were designed [10] based on the use of programmable optical lattices [11],[4] shown in Figure 4-1. A programmable optical lattice of K stages consists of $K+1$ 2x2 electro-optic switches and K $(K\geq 1)$ optical delay lines. The kth delay line $(0 \leq k \leq K)$ causes a delay equal $2^{k-1}T_c$, where T_c is the duration of the sequence chip time. Each 2x2 electro-optic switch can be configured into two possible states (i.e. cross-state or bar-state) according to its DC bias voltage controlled by the electronic control circuit. The total amount of delay that an optical pulse experiences when passing through the lattice can be varied from $0T_c$ to $(2^{K-1}-1)T_c$ and the delay depends on the states of all the 2x2 electro-optic switches.
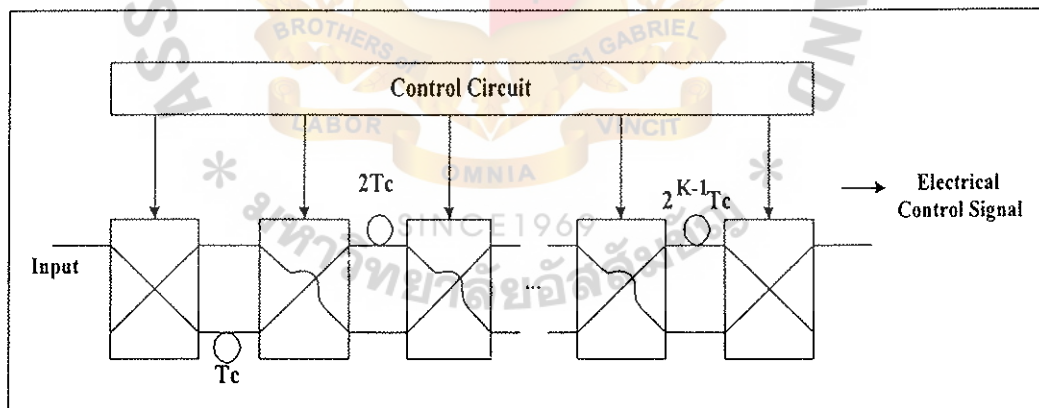

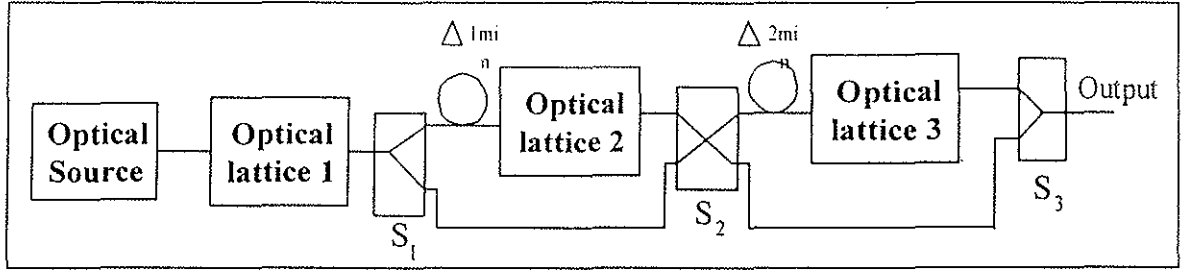Figure 4-1: Programmable optical lattice of K stages

Figure 4-2: Programmable optical encoder for 2^n prime-sequence codes using 3 optical

lattices

4.3 Design of Transmitter/Receiver

The schematic diagram of a programmable optical encoder for 2^n prime-sequence codes of

weight 4 is shown in Figure 4-2. In this design three programmable optical lattices are

used. At the encoder, when transmitting an "1" bit the optical source generates an optical

pulse of maximum pulse width T_c where $T_c = T/(p^2-p)$ is the sequence chip time and T is

the bit time and no pulse is emitted for a "0" bit. The pulse is passed through the optical

lattice 1 of $K = \lfloor log_2 p \rfloor + 1$ stages, where $\lfloor x \rfloor$ is the integer part of x. This lattice provides the

delay preceded the first "1" chip of the sequence and the delay can be any integer value

between $0T_c$ and $(p-1)T_c$. The delayed optical pulse is then split into two pulses by a passive

splitter S_1 and one of the pulse is delayed by a time of τ_1. For a set of $p(p-3)/2$ new sequences

of weight 4, the delay τ_1 for the lth sequence $(1 \leq l \leq p(p-3)/2)$ is equal $\Delta_1{}^l$. This delay is

provided by the programmable optical lattice 2 of $K_2 = \lfloor log_2 \Delta \tau_1 \rfloor + 1$ stages connected in

series with an optical delay of Δ_{1min}, where $\Delta \tau_1 = \Delta_{1max} - \Delta_{1min}$, $\Delta_{1max} = max (\Delta_1{}^l)$, $\Delta_{1min} = min$

$(\Delta_1{}^l)$. The delayed pulse combines with the non-delayed one at the 2x2 coupler S_2. These two

pulses then split into four pulses and two of them are delayed by a delay of τ_2. The delay τ_2 for the lth sequence ($1 \leq l \leq p(p-3)/2$) is equal $\Delta_1{}^l + \Delta_2{}^l$. This delay is provided by the programmable optical lattice 3 of $K_3 = \lfloor log_2 \Delta \tau_2 \rfloor + 1$ stages connected in series with an optical delay of Δ_{2min}, where $\Delta \tau_2 = \Delta_{2max} - \Delta_{2min}$, $\Delta_{2max} = \max (\Delta_1{}^l + \Delta_2{}^l)$, $\Delta_{2min} = \min (\Delta_1{}^l + \Delta_2{}^l)$. All the four pulses are then combined at the passive combiner S_3. Optical 2^n prime-sequence codes of weight 4 are obtained at the output of this combiner with the adjacent delays being (τ_1, τ_2, $\tau_1 + \tau_2$). By controlling the control circuit of the lattices 1, 2 and 3 for setting 2x2 switches at the bar or cross-state all $p(p-3)/2$ sequences can be generated by the encoder. If the laser of the encoder is removed the encoder can be used as a decoder for the described codes

Example: Encoder and Decoder for symmetric code W=4 and N=20

Lattice 1: The number of stages is $K_1 = \lfloor log_2 p \rfloor + 1$ stages

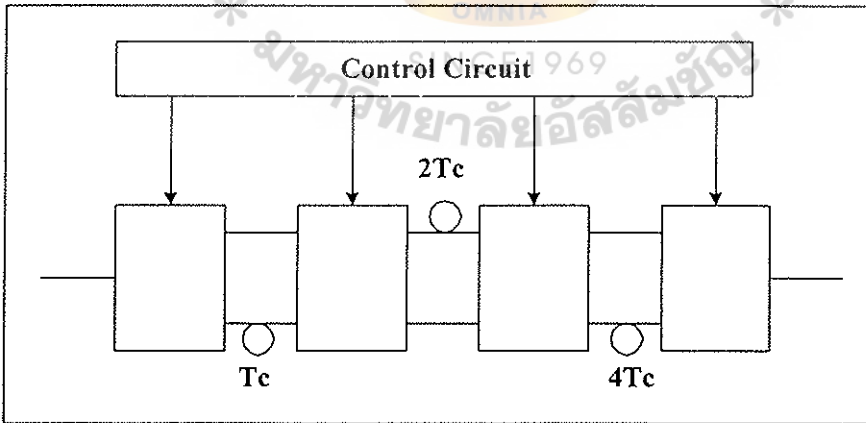$\qquad K_1 = \lfloor log_2 5 \rfloor + 1$ stages $\quad = 3$ stages

Figure 4-3: Lattice for serial transmitter/receiver using symmetric codes based on GF(5)

Lattice2 : The number of stages is $K_2 = \lfloor \log_2 \Delta\tau_1 \rfloor + 1$ stages   (1)

Where $\Delta\tau_1 = \Delta_{1max} - \Delta_{1min}$ and $\Delta_{1min} = \min(\Delta_1^l)$, $\Delta_{1max} = \max(\Delta_1^l)$.

From Property 2 : $\min(\Delta_1^l) = (p+1)/2$ where $1 \le l \le p(p-3)/2$

$$\min(\Delta_1^l) = (5+1)/2 = 3$$

From Property 3 : $\max(\Delta_1^l) = (p^2-p-6)/2$ where $1 \le l \le p(p-3)/2$

$$\max(\Delta_1^l) = (5^2-5-6)/2 = 7$$

From property 2 and property 3, we can find the value of $\Delta_{1max} = 7$, $\Delta_{1min} = 3$ after that we can find the value of $\Delta\tau_1 = 4$, put the value of $\Delta\tau_1$ in equation (1) to find K_2 as following

Find $K_2 = \lfloor \log_2 4 \rfloor + 1$ stages $= 2 + 1 = 3$ stages

Note : The figure is the same as lattice1

Lattice3 : The number of stages is $K_3 = \lfloor \log_2 \Delta\tau_2 \rfloor + 1$ stages   (2)

where $\Delta\tau_2 = \Delta_{2max} - \Delta_{2min}$, and $\Delta_{2max} = \max(\Delta_1^l + \Delta_2^l)$, $\Delta_{2min} = \min(\Delta_1^l + \Delta_2^l)$

From Property 4: $\min(\Delta_1^l + \Delta_2^l) = (p-1)^2/2$ where $1 \le l \le p(p-3)/2$

$$= (5-1)^2/2 = 8$$

From Property 5: $\max(\Delta_1^l + \Delta_2^l) = p^2-2p-3$ where $1 \le l \le p(p-3)/2$

$$= 5^2-2(5)-3 = 12$$

From property 4 and property 5, we can find the value of $\Delta_{2max} = 8$, $\Delta_{2min} = 12$ after that we

can find the value of $\Delta\tau_2 = 4$, put the value of $\Delta\tau_2$ in equation (2) to find K_3 as following

Find $K_3 = \lfloor \log_2 \Delta\tau_2 \rfloor + 1$ stages $= \lfloor \log_2 4 \rfloor + 1$ stages $= 2 + 1$ stages $= 3$ stages
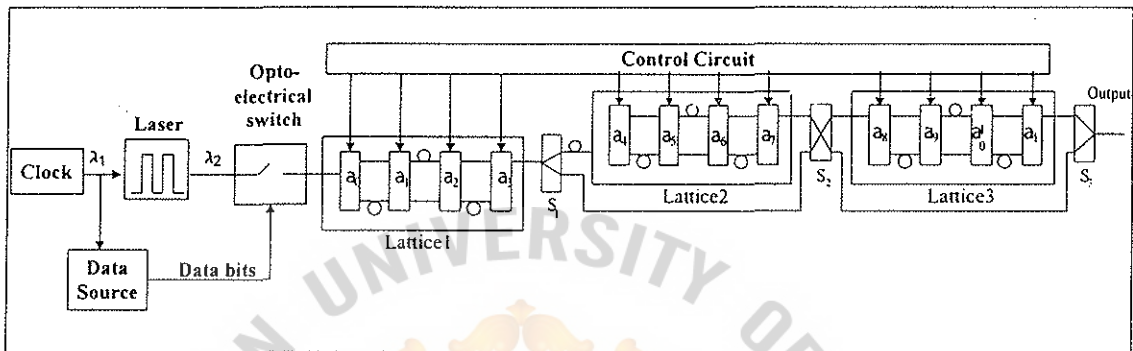
Note : The figure is the same as lattice1

Figure 4-4: Encoder for synchronous optical CDMA networks using symmetric codes of

W=4 and N=20

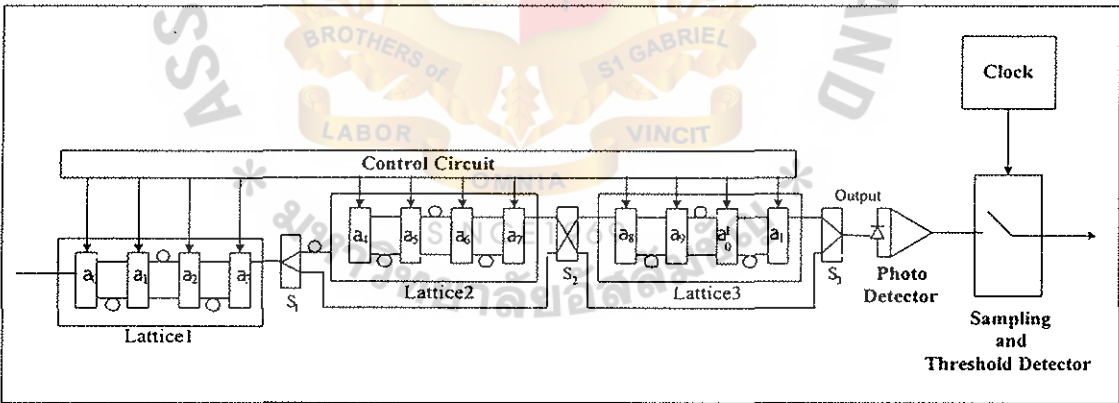
Figure 4-5: Decoder for synchronous optical CDMA networks using symmetric codes of

W=4 and N=20

4.4 Advantage of Serial Transmitter/Receiver

The loss factor of the serial transmitter is equal to the loss factor of the receiver, the loss factor of each coupler S1, S2 and S3 is 2. So, the loss factor at transmitter is 8 (that is, loss (in dB) = 10 log 8 = 9 dB) and the loss factor at receiver is also 8. The total loss due to both transmitter and receiver is 18 dB which is lower than the loss of the system using parallel encoder/decoder for almost the same code length[8]. In Section 2.4, it has been found that the system using parallel encoder/decoder for binary prime sequences of length N, the loss due to transmitter is $10 \log N^2$(dB) and the loss due to programmable receiver is also $10 \log N^2$. If fixed address receiver is used, the loss at receiver is $10 \log W^2$. So total loss for system using programmable receiver (both transmitter and receiver) is $20 \log N^2$, total loss for system using fixed address receiver (both transmitter and receiver) is $10 \log N^2 + 10 \log W^2$. Therefore, for system using binary prime sequences, the total loss increases if the sequences are longer. For example, if N=25, the total loss is 54.92 dB or 41.94 dB (if fixed address receivers are used). If N=49 the total loss is 67.60 dB or 50.70 dB (for fixed address receiver system) while for the system using symmetric code the total loss does not depend on the sequence length and always equals 18 dB.

Example: Data rate = 1 Mb/s, p=5, laser power 0 dBm calculate the input power at receiver for symmetric code sequence and prime code sequence for synchronous CDMA networks

Note that in this calculation we do not count the loss due to fiber, nor loss due to the star coupler because we use the same system for two codes

---

a) Prime codes sequence

Loss at transmitter $= 10 \log 25^2 = 27.96$ dB

so, the input power at the receiver will be 0 - 27.96 dB = -27.96 dB
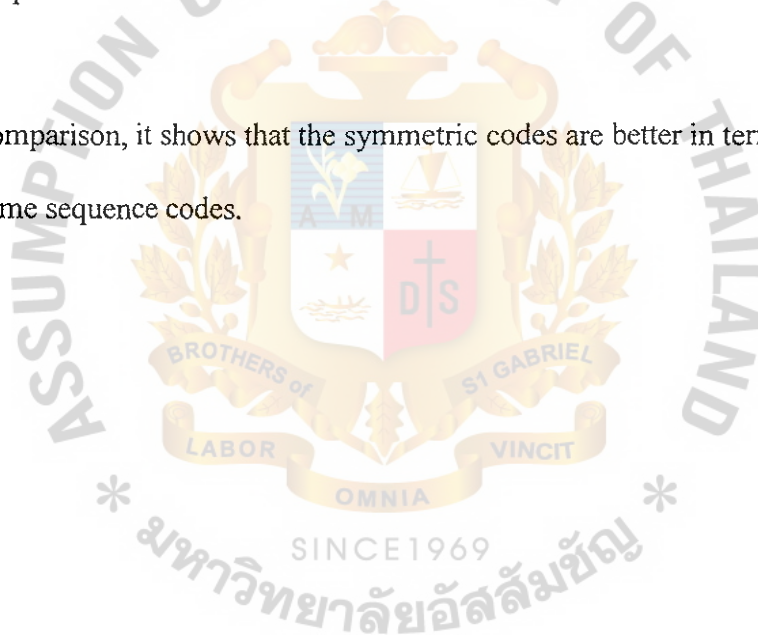
b) Symmetric codes sequence

From Figure 4-4, the transmitter composes of 3 electro-optic switch (S1,S2 and S3), the loss

factor of each S1, S2 and S3 is 2.

Loss at transmitter $= 10 \log 8 = 9$ dB

So, the input power at the receiver will be 0 - 9 dB = -9 dB

From this comparison, it shows that the symmetric codes are better in term of loss compared

to binary prime sequence codes.

CHAPTER 5: PERFORMANCE OF SYMMETRIC CODE FOR SYNCHRONOUS OPTICAL CDMA NETWORKS

5.1 BER Calculation

We can evaluate the BER performance of synchronous optical CDMA network using symmetric codes by [20]

$$BER = \frac{1}{2} \cdot erfc \left[\frac{i0 - i1}{(\sigma1 + \sigma0) \cdot \sqrt{2}} \right]$$

Where i_0, i_1 denote the average currents at the input of the detector for bits "0" and "1" respectively and σ_0 and σ_1 are the corresponding standard deviations of their gaussian distributions. For networks using symmetric code for synchronous optical CDMA network i_0, i_1, σ_0 and σ_1 are given in paragraphs 5.1.1, 5.1.2, 5.1.3 and 5.1.4 respectively.

The following interpretation of i0, i1, σ_0, σ_1 is based on [21]

5.1.1. The current "i_0" is the mean current at the input of the detector when a "0" bit is transmitted to Rx1(the receiver of user 1). The current i_0 composes of only the interference signal $(K-1)I_{k,1}$ because nothing is transmitted for a "0" bit. Where K is number of simultaneous users

$$i0 = (K-1)I_{k,1}$$

5.1.2. The current "i_1" is the mean current at the input of the detector when a "1" bit is transmitted to Rx1(the receiver of user 1). The current i_1 composes of the interference signal $(K-1)I_{k,1}$ and the desired signal I.

$$i1 = (K-1)I_{k,1} + I$$

The desired signal (I) is the current due to the in-phase auto-correlation

$$I = \frac{R \cdot Ps \cdot W}{Sp}$$

Where R : is the photo diode responsivity measured in amperes per watt (A/W).

Ps : is the power of chip pulse

Sp : is the loss factor of receiver

W : is the weight of the code

The term interference $I_{k,1}$ is the mean of interference generates by the kth user at Rx1

$$I_{k,1} = \frac{R \cdot Ps}{Sp} \cdot \mu$$

Where μ is the mean of cross-correlation calculated in Chapter 3.

5.1.3. σ_0 is the standard deviations of the gaussian distribution when bit "0" is transmitted

$$\sigma 0 = \sqrt{\sigma^2_{Mai} + \sigma^2_{N0}}$$

Where σ^2_{Mai} is the variance of the total interference.

σ^2_{N0} is the noise when received bit "0".

5.1.4. σ_1 is the standard deviation of the gaussian distributions when bit "1" is transmitted

$$\sigma 1 = \sqrt{\sigma^2_{Mai} + \sigma^2_{N1}}$$

Where σ^2_{N1} is the noise when received bit "1".

5.2 Noise

Whenever the received bit is "1" or "0" noise can be generated. It includes shot noise, dark current noise and thermal noise.

1. Noise when received bit "0" (σ^2_{N0})

$$\sigma^2_{N0} = \sigma^2_{S0} + \sigma^2_d + \sigma^2_T$$

Where σ^2_{S0} : Shot noise when received bit "0"

σ^2_d : Dark current noise

σ^2_T : Thermal noise

Shot noise (σ^2_{S0}) is only generated by interference current $I_{k,1}$, the power of shot noise is

$$\sigma^2_{S0} = 2qBI_{k,1}(K-1)$$

Dark current noise (σ^2_d) :

$$\sigma^2_d = 2qBI_d$$

Thermal noise (σ^2_T) :

$$\sigma^2_T = \frac{4k_BT_TB}{R_L}$$

Where q : Electron charge

B : Receiver bandwidth

$I_{k,1}$: Interference current

I_d : Dark current

K_B : Bolzmamn's constant = $1.38*10^{-23}$ J/K

T_T : Receiver noise temperature

R_L : Receiver load resistor

2. Noise when received bit "1" (σ^2_{N1})

$$\sigma^2_{N1} = \sigma^2_{S1} + \sigma^2_d + \sigma^2_T$$

Where σ^2_{S1} : Shot noise when receive bit "1"

σ^2_d : Dark current noise

σ^2_T : Thermal noise

Note that the formula of thermal noise and dark current noise are the same as those when received bit "0".

The shot noise (σ^2_{S1}) is generated by interference current $I_{k,1}$ and the desire signal :

$$\sigma^2_{S1} = 2qB[(K-1)I_{k,1}+I]$$

5.3 Power of Interference

The power of the interference due to (K-1) interferer is calculated by

$$\sigma^2_{MAI} = (K-1)\, \sigma^2_{k,1}$$

Where MAI stands for Multiple Access Interference and

$$\left(\sigma^2\right)_{k,1} = \sigma^2 \cdot \left(\frac{R \cdot Ps}{Sp}\right)^2$$

Where $\sigma^2_{k,1}$ is the power of interference generated by k^{th} user at Rx1.

σ^2 is the variance of cross correlation, calculated in Chapter 3.

5.4 Numerical Results

We use the program in MATHCAD (See Appendix D)for calculating the BER of system using symmetric codes generated from a prime number p with different number of simultaneous users K. The mean and variance of cross-correlation shown in Chapter 3 are used for each code generated from a given p. We use the program to find Kmax. Kmax is the value of K that we get BER $\leq 10^{-9}$ or if we can not have BER $\leq 10^{-9}$, the value of Kmax is the value of K that get the smallest BER. Figure 5-1 and Figure 5-2 show the BER performance of S/CDMA system using symmetric codes for p=5 and p=29.
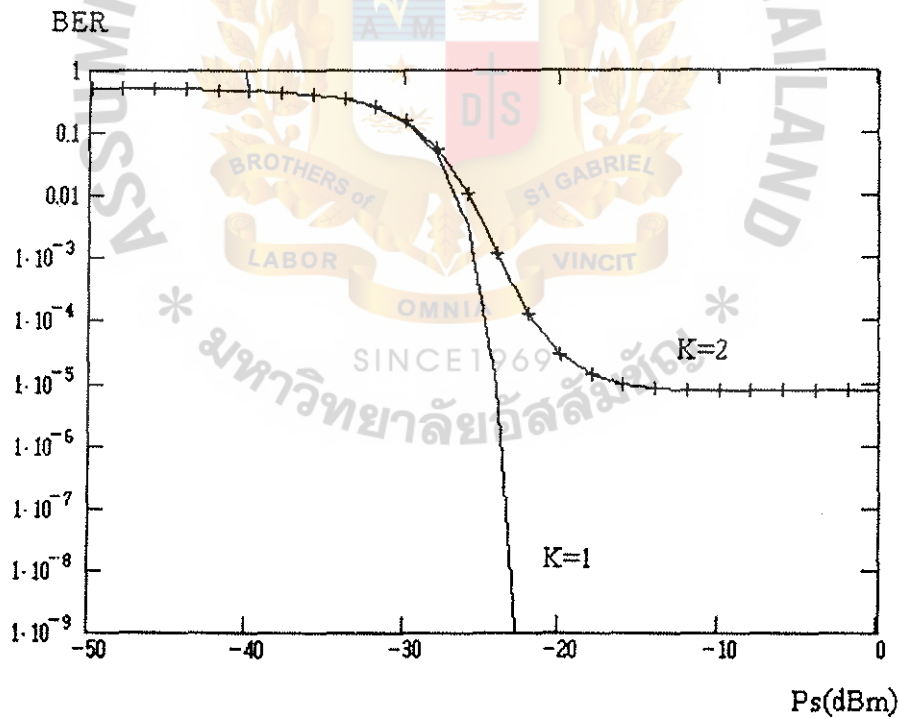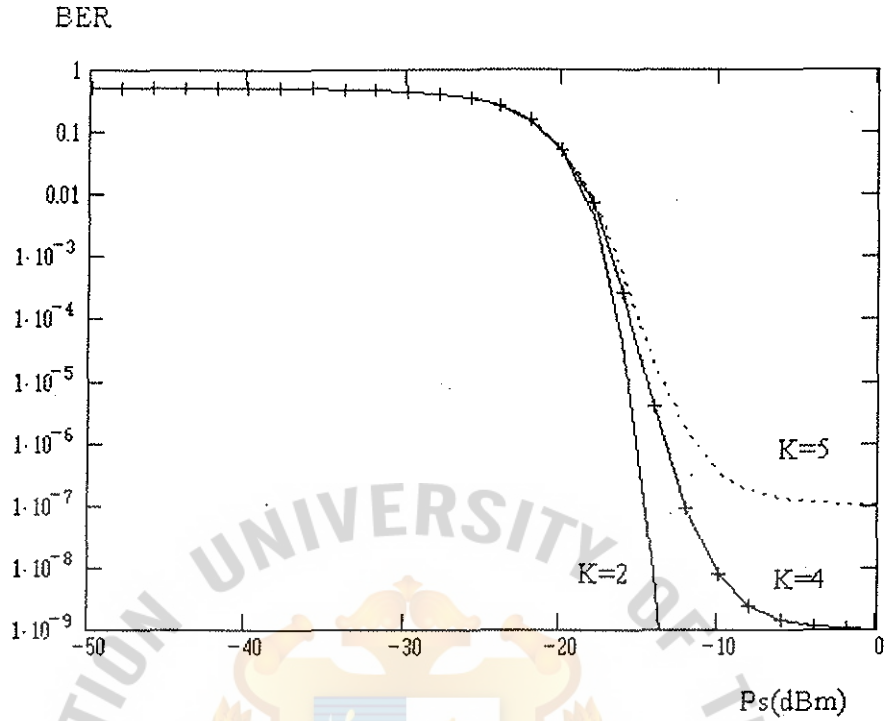

Figure 5-1: BER for p=5

Figure 5-2: BER for p=29

The graphs showing the performance of synchronous optical CDMA system using symmetric codes for p=7 to 23 are included in Appendix E. The BER for p=5,7,…,29 and K=1,2,…,6 are presented in Table 5-1.

Table 5-1: BER for p=5,7,…,29

P	BER					
	K=1	K=2	K=3	K=4	K=5	K=6
5	$4.641*10^{-12}$	$7.339*10^{-6}$	$1.091*10^{-3}$	$6.176*10^{-3}$	$1.5*10^{-2}$	$2.6*10^{-2}$
7	$4.553*10^{-14}$	$4.585*10^{-7}$	$2.593*10^{-4}$	$2.298*10^{-3}$	$7.056*10^{-3}$	$1.4*10^{-2}$
11	$< 10^{-14}$	$2.804*10^{-10}$	$5.798*10^{-6}$	$1.715*10^{-4}$	$9.651*10^{-4}$	$2.773*10^{-3}$
13	$< 10^{-14}$	$6.034*10^{-12}$	$8.167*10^{-7}$	$4.528*10^{-5}$	$3.493*10^{-4}$	$1.214*10^{-3}$
17	$< 10^{-14}$	$< 10^{-14}$	$1.463*10^{-8}$	$2.971*10^{-6}$	$4.393*10^{-5}$	$2.258*10^{-4}$
19	$< 10^{-14}$	$< 10^{-14}$	$2.173*10^{-9}$	$8.188*10^{-7}$	$1.651*10^{-5}$	$1.022*10^{-4}$
23	$< 10^{-14}$	$< 10^{-14}$	$3.523*10^{-11}$	$5.068*10^{-8}$	$2*10^{-6}$	$1.856*10^{-5}$
29	$< 10^{-14}$	$< 10^{-14}$	$1.037*10^{-13}$	$9.958*10^{-10}$	$1.019*10^{-7}$	$7*10^{-6}$

From Table 5-1 for BER $<= 10^{-9}$ the maximum number of simultaneous users for each symmetric codes are shown in Table 5-2.

Table 5-2: The maximum number of simultaneous users (Kmax)

p	Kmax
5	1
7	1
11	2
13	2
17	2
19	2
23	3
29	4

As we can see from Table 5-1 the BER will degrade if the number of simultaneous users increase. For small p (p=5, p=7), if BER=10^{-9} is required only 1 user can be allowed to transmit. The reason is that the ratio W/p(p-1) is small (W=4). For moderate p (p=11,13,17,19), for BER=10^{-9} 2 simultaneous can be allowed. Therefore, it is recommended that the codes generated by p=11 is used. Because this code requires the minimum bandwidth (proportional to sequence length p(p-1)) for the same Kmax=2. For large p (p=23,29) Kmax=3 (p=23) and Kmax=4 for p=29. Hence, if we need a larger Kmax we have to use longer code sequences.

The number of simultaneous users K can be higher (for all codes) if the required BER is higher than 10^{-9}

Example: If BER=10^{-5} is required we have the results shown in Table 5-3.

Table 5-3: The number of simultaneous users if BER=10^{-5} is required

p	K
5	2
7	2
11	3
13	3
17	4
19	4
23	5
29	6

5.5 Comparison to System Using Prime Code Sequence

We compare the performance of the proposed system with that of the non-coherent synchronous optical CDMA system using modified prime codes [7]. The BER performance for both systems is calculated as a function of the received chip optical power P with the number of simultaneous users K as parameter. The effects of interference, shot noise and thermal noise on the BER are considered and Gaussian approximation is used for calculating the BER [21]. The following parameters are used: Data bit rate D =10 Mb/s, PIN diode of responsivity R=0.8 A/W, dark current noise I_d=10 nA, the power spectral density of the thermal noise N_{Th} = 10^{-24} A^2/Hz, received chip optical power $P_s \in$ (-30 dB, 30 dB).

Figure 5-3 shows the BER for the proposed system with synchronous symmetric sequences of length N = 506 (p=23) and that for systems using modfied prime sequences of N = 529 (Both fixed address and programmable receivers). The number of simultaneous is K =3.

It can be seen that for BER = 10^{-9} the system using synchronous symmetric code requires the lowest received chip optical power (only P_s = -12 dBm while the system using modified prime codes needs P_s = -5 dBm for fixed address receiver and P_s = 23 dBm for programmable receiver, respectively).
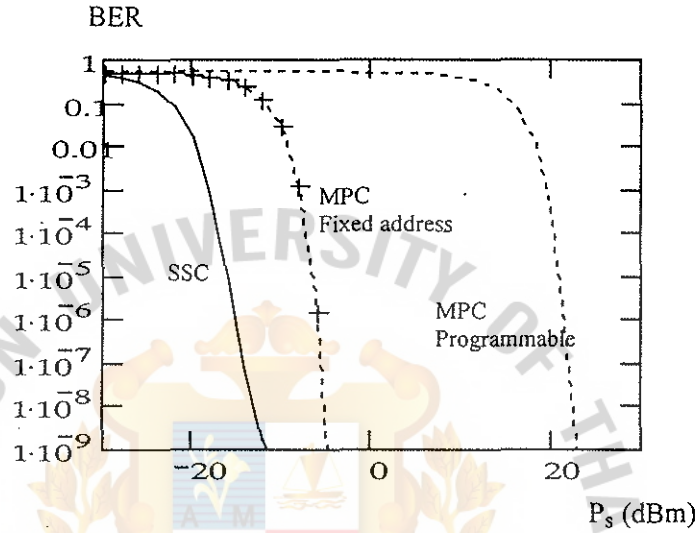

Figure 5-3: BER for K=3

However, due to the lower weight (W=4) when the number of simultaneous users increases, the BER of the system using synchronous symmetric codes degrades rapidly. This is illustrated in Figure 5-4, where the BER of the two systems for K=10 is presented. It should be noted that the system using modified prime codes can only achieve BER = 10^{-9} for very high received power (P_s = -3 dBm for fixed address receiver and P_s = 24 dBm for programmable receiver, respectively). For low received power, the BER of systems using modified prime codes is worse than that of the system using synchronous symmetric codes.
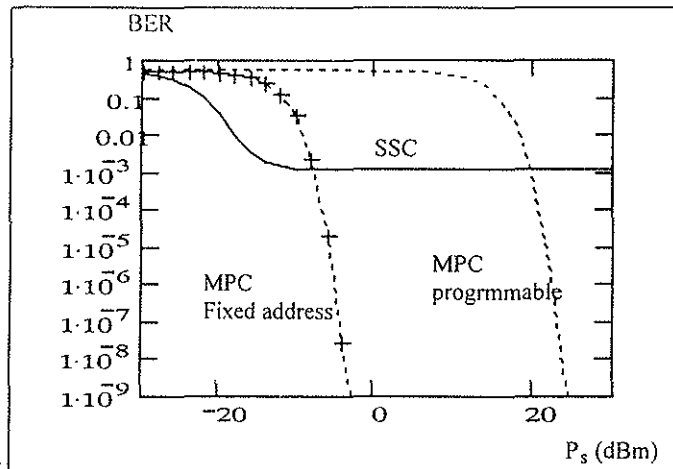
Figure 5-4: BER for K=10

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

In this work we propose a non-coherent synchronous all-optical CDMA LAN using new symmetric codes. The construction of the new codes based on the well-known prime sequence codes is presented. It shows that the size of a new code is larger than that of the original prime sequence code [1] and the modified prime-code [7] in the same field GF(p). This implies that optical CDMA networks using the new codes can have a larger number of potential subscribers. We also show that the pseudo-orthogonality of the new codes is the same as that of the prime sequence codes. The design of fully programmable transmitter and receiver for all-optical CDMA LANs using the new codes is presented. This configuration is particularly attractive for the future ultra-fast optical CDMA networks because of its low-loss and programmable features. Finally, the BER of the proposed system is compared to that of systems using modified prime codes. It shows that the proposed system can achieve better performance for low received chip optical power.

In order to improve the BER performance of synchronous network using symmetric code, the following should be done:

- We can improve the correlation characteristic of symmetric codes by making the code sequence longer. That is to make the code length equal p^2 instead of $p(p-1)$ by not removing the first p "0" of the original prime code sequences.

- We can increase the code weight from 4 to 8 or 16. By doing that, we increase the ratio $W/p(p-1)$ or W/p^2.

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APPENDIX A: MATLAB PROGRAMS

```
%#######################################################################
% GENERATION OF SYMMETRIC CODE FOR SYNCHRONOUS NETWORK
FROM PRIME CODE SEQUENCE
%#######################################################################


%INPUT: THE PRIME NUMBER p
%OUTPUT: THE SYMMETRIC CODE SEQUENCES FOR SYNCHRONOUS
NETWORK


clear;

pack;


p=input ('Please input the prime number p = ') ;


%------------------------------------------------
%GENERATE THE MATRIX OF PRIME CODE SEQUENCES
%------------------------------------------------


Z=[];

N = p * p;

for i=0: p - 1
```

```matlab
B=[];

for j = 0: p - 1

    b= rem (i * j,p);

    B=[B b];

end

Z=[Z;B];

end

disp ('The prime code sequences');

disp (Z);
```

```matlab
%--------------------------------------------------------------
%GENERATE THE MATRIX OF ADJACENT DELAY OF PRIME CODE
SEQUENCES
%--------------------------------------------------------------

Y=[];

N = p * p;

for i=0: p - 1

    X=[];

    for j = 0: p - 2

        x= rem (i*(j+1),p)- rem (i*j,p)+ p;

        X=[X x];

    end
```

```
        Y=[Y;X];

end

disp ('The adjacent delay of prime code sequences');

disp (Y);



%------------------------------------------------------------------------

% GENERATE THE MATRIX THAT CONTAINS ABSOLUTE VALUE OF

SYMMETRIC CODE

%------------------------------------------------------------------------



m = (p-3)/2;

for j=0:p-1

    for i = 1:m



        %Find DELTA1

        tmp = 0;

        for k = 1:i

            tmp = tmp + Y(j+1,k+1);

        end

        D1(j+1,i) = tmp;



        %Find DELTA2

        tmp = 0;
```

```
for k = i+1:p-i-2

    tmp = tmp + Y(j+1,k+1);

end

D2(j+1,i) = tmp;


%Find DELTA3

tmp = 0;

for k = p-i-1:p-2

    tmp = tmp + Y(j+1,k+1);

end

D3(j+1,i) = tmp;


    end

end


% CONSTRUCT MATRIX OF ABSOLUTE VALUE OF THE SYMMETRIC CODE

MATRIX WITH WEIGHT 4

W = 4;

S1 = [];

S2 = [];

S3 = [];

S4 = [];

for i = 1:p
```

```matlab
for k = 1 : m;

  for j = 2;


    % THE VALUE OF COLUMN 1 IS TAKEN FROM COLUMN 2 OF MATRIX Z

    col1 = Z(i,j);

    S1 = [S1;col1];


    % THE VALUE OF COLUMN 2 IS COLUMN1 + D1

    col2 = col1 + D1(i,k);

    S2 = [S2;col2];


    % THE VALUE OF COLUMN 3 IS COLUMN1 + D2

    col3 = col2 + D2(i,k);

    S3 = [S3;col3];


    % THE VALUE OF COLUMN 4 IS COLUMN1 + D3

    col4 = col3 + D3(i,k);

    S4 = [S4;col4];


    % ABSOLUTE POSITIONS OF "1" CHIP

    SYM = [S1 S2 S3 S4];

  end

end
```

end

disp ('The Absolute positions of "1" chip');

disp (SYM);

%disp ('The total number of symmetric code sequences are');

NUM = m*p;

%disp (NUM);

%--

%GENERATE CODE SEQUENCES FOR SYNCHRONOUS NETWORKS

%--

%FIND THE ABSOLUTE VALUE OF SYMMETRIC CODE FOR SYNCHRONOUS

NETWORK

%Matrix of new absolute position of "1" for sequence for synchronous network

npos=[];

for i=1:NUM

  orpos=[];

  for k = 1:p-1

    lipos = [];

    for j = 1:4

      xx=SYM(i,j);

      if k == 1

        orpos = [orpos xx];

```
end

%Determine the no.of sub sequence g in code sequence

%and the value of h determine the position of "1" in the sub-seq

g = floor(xx/p);

h = rem(xx,p);


%Calculate the new position of "1" in the sub-seq by shift position of "1"

z = mod(h-1+p,p);


%Calculate the new absolute position of "1" in the new-seq

pos = g*p+z;

lipos = [lipos pos];

end

SYM(i,:) = lipos;

npos = [npos;lipos];

end

npos = [npos;orpos];

end

disp ('The Absolute positions of "1" chip for synchronous network (some not

symmetric)');

disp (npos);

Si_SYM = size (npos,1);
```

```
%-----------------------------------------------------------------

%DETERMINE SYMMETRIC CODE FOR SYNCHRONOUS NETWORK AND MAP

ABSOLUTE VALUE INTO CODE SEQUENCE

%-----------------------------------------------------------------


sspos = [];


for i = 1:Si_SYM

    val1 = npos(i,2) - npos(i,1);

    val2 = npos(i,4) - npos(i,3);

    if val1 == val2

        temp = [];

        for j = 1:4

            temp = [temp npos(i,j)];

        end

        sspos = [sspos;temp];

    end

end

disp('The Absolute positions of "1" chip of symmetric code for synchronous network')

disp(sspos);


disp ('The total of symmetric code for synchronous network');

Si_SS = size(sspos,1);
```

```
disp (Si_SS);
```

```
%-----------------------------------------------------------------------

%GENERATE BINARY CODE SEQUENCE FOR SYMMETRIC CODE FOR

SYNCHRONOUS NETWORK

%-----------------------------------------------------------------------
```

```
%AT FIRST, FORM A MATRIX OF ALL "0" (MATRIX SSC)

SSC = [];

for i = 1:Si_SS

   for j = 1: p*(p-1)

    X = [];

    x = 0;

      X = [X x];

   end

   SSC = [SSC;X];

end
```

```
%REPLACING CHIP "0" OF Sq BY CHIPS "1" TO FORM SYMMETRIC CODE

SEQUENCES

for i = 1:Si_SS
```

```
for j = 1 : 4

    k = sspos(i,j)+1;

    SSC(i,k)=1;

  end

end


disp ('The symmetric code sequences for synchronous network');

disp (SSC);


%disp ('The total of symmetric code sequences for synchronous network');

%Si_SSC = size(SSC,1);

%disp (Si_SSC);


%----------------------------------------------------------------

%FIND CROSS CORRELATION OF SYMMETRIC CODE AT SHIFT(S) = 0

%----------------------------------------------------------------


C0 = 0;

C1 = 0;

C2 = 0;

count =0;

for i = 1:Si_SS-1

  code1 = [];
```

```
for j = 1:p*(p-1)

    code1 = [code1 SSC(i,j)];

end

for m = i+1 : Si_SS

    cos = 0;

    code2 = [];

    for n = 1:p*(p-1);

        code2 = [code2 SSC(m,n)];

        A = code1(n)*code2(n);

        cos = cos+A;


    end


    if cos == 0

        C0 = C0+1;


    elseif cos == 1

        C1 = C1+1;



    else C2 = C2+1;



    end

end
```

```
end

disp ('The number of Cross-Correlation = 0');

disp (C0);

disp ('The number of Cross-Correlation = 1');

disp (C1);

disp ('The number of Cross-Correlation = 2');

disp (C2);
```

APPENDIX B: CALCULATION OF MEAN OF

CROSS-CORRELATION FOR p=7 to p=29

p=7

$P(0) = C(0) / (C(0) + C(1) + C(2))$

    $= (1348+2145) / 4290$

    $= 0.8142191$

$P(1) = C(1) / 2 \, x \, (C(0) + C(1) + C(2))$

    $= 772 / 4290$

    $= 0.1799534$

$P(2) = C(2) / 2 \, x \, (C(0) + C(1) + C(2))$

    $= 25 / 4290$

    $= 0.0058275$

$\mu = 0 x p(0) + 1 x p(1) + 2 x p(2)$

    $= (0 x 0.8142191)+(1 x 0.1799534)+(2 x 0.0058275)$

    $= 0.1916084$

p=11

$P(0) = C(0) / 2 \, x \, (C(0) + C(1) + C(2))$

    $= (41264+52326) / 104652$

    $= 0.8942973$

$P(1) = C(1) / 2 \, x \, (C(0) + C(1) + C(2))$

$= 10696 / 104652$

$= 0.1022054$

$P(2) = C(2) / 2 x (C(0) + C(1) + C(2))$

$= 366 / 104652$

$= 0.0034973$

$\mu = 0xp(0) + 1xp(1) + 2xp(2)$

$= (0x0.8942973)+(1x0.1022054)+(2x0.0034973)$

$= 0.1092$

P=13

$P(0) = C(0) / 2 x (C(0) + C(1) + C(2))$

$= (131468+159330) / 318660$

$= 0.9125651$

$P(1) = C(1) / 2 x (C(0) + C(1) + C(2))$

$= 27012 / 318660$

$= 0.0847675$

$P(2) = C(2) / 2 x (C(0) + C(1) + C(2))$

$= 850 / 318660$

$= 0.0026674$

$\mu = 0xp(0) + 1xp(1) + 2xp(2)$

$= (0x0.9125651)+(1x0.0847675)+(2x0.0026674)$

$= 0.0901023$

$P=17$

$p(0) = C(0) / 2\ x\ (C(0) + C(1) + C(2))$

$= (793488+911925) / 1823850$

$= 0.9350621$

$p(1) = C(1) / 2\ x\ (C(0) + C(1) + C(2))$

$= 115392 / 1823850$

$= 0.0632684$

$p(2) = C(2) / 2\ x\ (C(0) + C(1) + C(2))$

$= 3045 / 1823850$

$= 0.0016695$

$\mu\ = 0xp(0) + 1xp(1) + 2xp(2)$

$= (0x0.9350621)+(1x0.0632684)+(2x0.0016695)$

$= 0.0666074$

$P=19$

$p(0) = C(0) / 2\ x\ (C(0) + C(1) + C(2))$

$= (1643808+1857628) / 3715256$

$= 0.9424481$

$p(1) = C(1) / 2\ x\ (C(0) + C(1) + C(2))$

$= 208752 / 3715256$

$= 0.0561878$

$p(2) = C(2) / 2\ x\ (C(0) + C(1) + C(2))$

$= 5068 / 3715256$

$= 0.0013641$

$\mu = 0xp(0) + 1xp(1) + 2xp(2)$

$= (0x0.9424481)+(1x0.0561878)+(2x0.0013641)$

$= 0.058916$

P=23

$p(0) = C(0) / 2 \, x \, (C(0) + C(1) + C(2))$

$= (5644516+6228685) / 12457370$

$= 0.9531066 \, \%$

$p(1) = C(1) / 2 \, x \, (C(0) + C(1) + C(2))$

$= 572244 / 12457370$

$= 0.0459362$

$p(2) = C(2) / 2 \, x \, (C(0) + C(1) + C(2))$

$= 11925 / 12457370$

$= 0.0009573$

$\mu = 0xp(0) + 1xp(1) + 2xp(2)$

$= (0x0.9531066)+(1x0.0459362)+(2x0.0009573)$

$= 0.0478508$

P=29

$p(0) = C(0) / 2 \, x \, (C(0) + C(1) + C(2))$

$= (24638780+26590278) / 53180556$

$= 0.9633043$

p(1) = C(1) / 2 x (C(0) + C(1) + C(2))

    = 1918660 / 53180556

    = 0.0360782

p(2) = C(2) / 2 x (C(0) + C(1) + C(2))

    = 366 / 53180556

    = 0.0006175

μ = 0xp(0) + 1xp(1) + 2xp(2)

    = (0x0.9633043)+(1x0.0360782)+(2x0.0006175)

    = 0.0373132

APPENDIX C: CALCULATION OF VARIANCE OF CROSS-CORRELATION FOR p=7 to p=29

p=7

$$\sigma^2 = [p(1) + 4 \times p(2)] - \mu^2$$

$$= (1x0.1799534 + 4x0.0058275) - 0.0367138$$

$$= 0.1665496$$

p=11

$$\sigma^2 = [p(1) + 4 \times p(2)] - \mu^2$$

$$= (1x0.1022054 + 4x0.0034973) - 0.0119246$$

$$= 0.10427$$

p=13

$$\sigma^2 = [p(1) + 4 \times p(2)] - \mu^2$$

$$= (1x0.0847675 + 4x0.0026674) - 0.0081184$$

$$= 0.0873187$$

p=17

$$\sigma^2 = [p(1) + 4 \times p(2)] - \mu^2$$

$$= (1x0.0632684 + 4x0.0016695) - 0.0044365$$

$$= 0.0655099$$

p=19

$$\sigma^2 = [p(1) + 4 \, x \, p(2)] - \mu^2$$

$$= (1x0.0561878 + 4x0.0013641) - 0.0034711$$

$$= 0.0581731$$

p=23

$$\sigma^2 = [p(1) + 4 \, x \, p(2)] - \mu^2$$

$$= (1x0.3088235 + 4x0) - 0.095372$$

$$= 0.2134515$$

p=29

$$\sigma^2 = [p(1) + 4 \, x \, p(2)] - \mu^2$$

$$= (1x0.0.360782 + 4x0.0006175) - 0.0013923$$

$$= 0.0371559$$

APPENDIX D: MATHCAD PROGRAMS

Performance of Synchronous optical CDMA (ALL NOISES included) using Synchronous Symmetric codes of W=4) and PIN

$p := 5$ $N := p \cdot (p-1)$ Sequence length $W := 4$ Code weigh

$K := 1$ Number of simultaneous users

$PdBm := -50, -48 .. 0$ Variable is the received chip optical power in dBm

$D := 10 \cdot 10^6$ Data bit rate (bits/second) $Sp := 8$ Loss factor

$T := \dfrac{1}{D}$ Bit time (in seccond) $Tc := \dfrac{T}{N}$ Chip time (in second)

$B := \dfrac{1}{2 \cdot Tc}$ Bandwidth $q := 1.6 \cdot 10^{-19}$ Electric Charge (in Cb)

$id := 10 \cdot 10^{-9}$ dark current $R := 0.787$ PIN Responsivity (in A/W)

$kB := 1.38 \cdot 10^{-23}$ Bolzman constant (in J/oK) $Tt := 300$ Receiver Noise Temperature (oK)

$RL := 50$ Receiver Load Resistance (in Ohm)

$va := 0.213$ Variance of Interference

$mea := 0.308$ Mean of interference

$P(PdBm) := 10^{-3} \cdot 10^{\left(\frac{PdBm}{10}\right)}$ P (PdBm) in W, 1dBm corresponds to 1mW

$I(PdBm) := \dfrac{R \cdot P(PdBm) \cdot W}{Sp}$ Desired Current for bit "1"

$$Iki(PdBm) := \frac{R \cdot P(PdBm) \cdot mea}{Sp} \qquad \text{Current of 1 interferer}$$

$$sn0(PdBm) := 2 \cdot q \cdot B \cdot (K - 1) \cdot Iki(PdBm) \qquad \text{Shot noise for "0" bit}$$

$$sn1(PdBm) := 2 \cdot q \cdot B \cdot [(K - 1) \cdot Iki(PdBm) + I(PdBm)] \qquad \text{Shot noise for "1" bit}$$

$$dn := 2 \cdot q \cdot B \cdot id \qquad \text{dark current noise}$$

$$tn := \frac{4 \cdot kB \cdot Tt \cdot B}{RL} \qquad \text{Thermal noise}$$

$$pofI(PdBm) := (K - 1) \cdot \left(\frac{R \cdot P(PdBm)}{Sp} \right)^2 \cdot va \qquad \text{Variance of MAI}$$

$$N0(PdBm) := sn0(PdBm) + dn + tn \qquad \text{Noise for "0" bit}$$

$$N1(PdBm) := sn1(PdBm) + dn + tn \qquad \text{Noise for "1" bit}$$
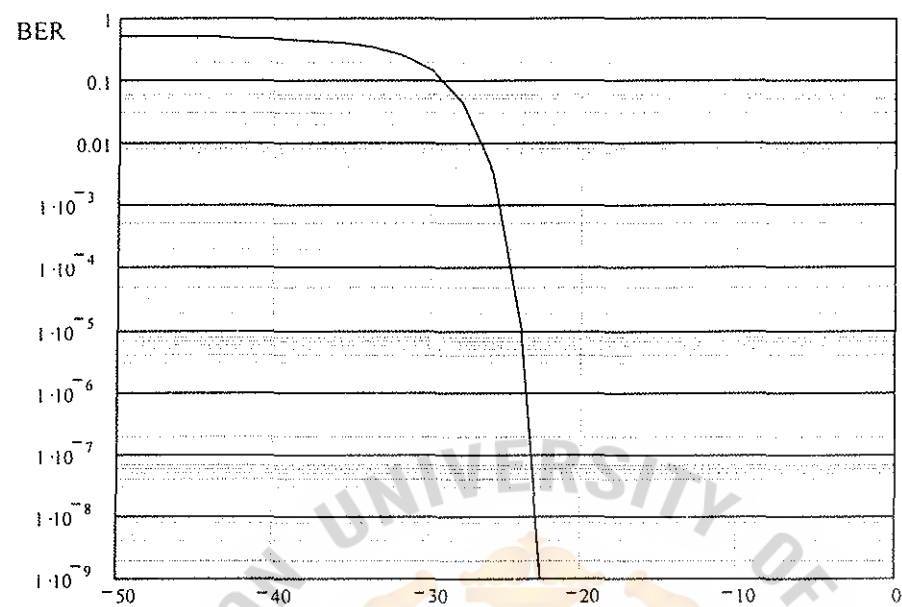
$$v0(PdBm) := \sqrt{pofI(PdBm) + N0(PdBm)}$$

$$v1(PdBm) := \sqrt{pofI(PdBm) + N1(PdBm)}$$

$$i0(PdBm) := (K - 1) \cdot Iki(PdBm)$$

$$i1(PdBm) := (K - 1) \cdot Iki(PdBm) + I(PdBm)$$

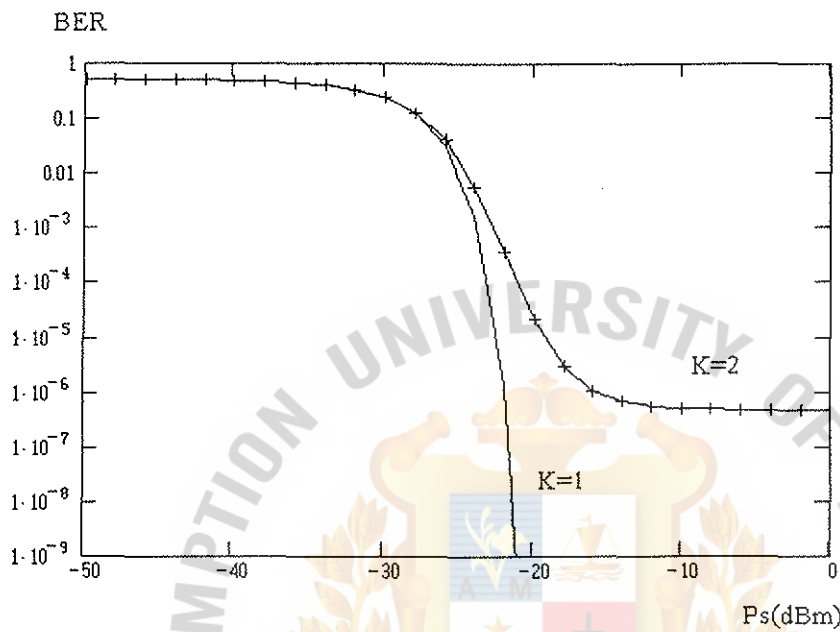$$BER(PdBm) := \frac{1}{2} \cdot erfc\left[\frac{i1(PdBm) - i0(PdBm)}{\sqrt{2} \cdot (v1(PdBm) + v0(PdBm))} \right]$$
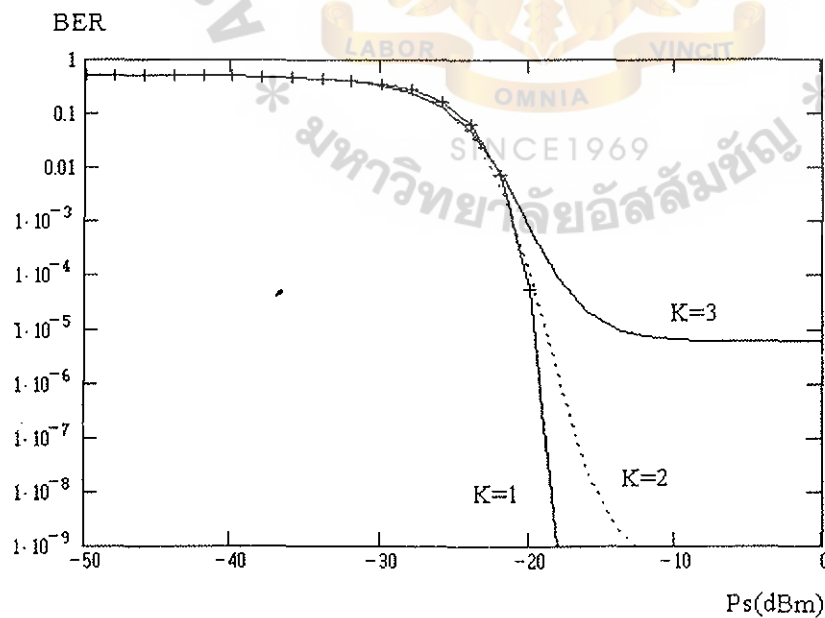
WRITE("S_cdma_sym_5_1.dat") := BER(PdBm)

APPENDIX E: GRAPHS FOR Kmax

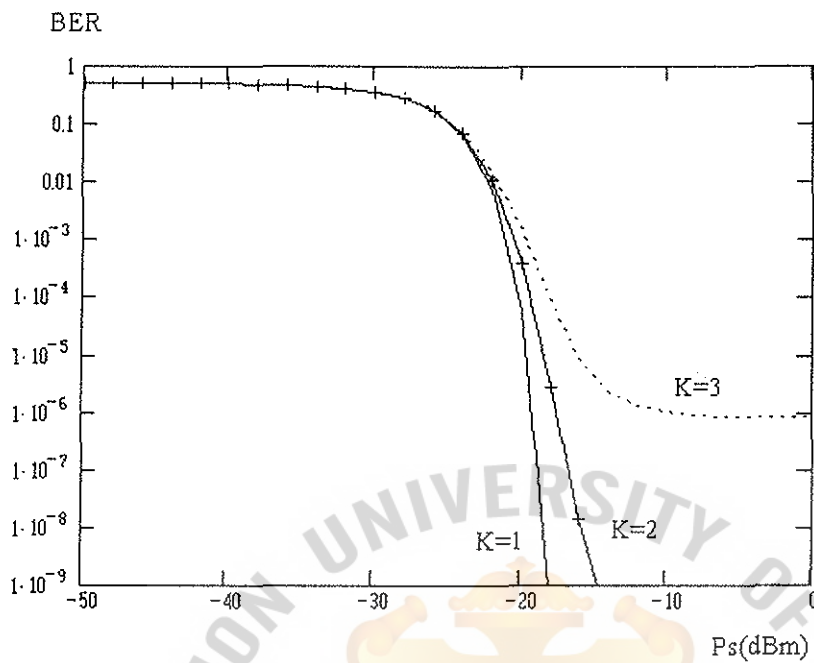**p=7, Kmax=1**

p=11, Kmax = 2

p=13, Kmax=2

BER

p=17, Kmax=2

BER

p=19, Kmax=2

BER

p=23, Kmax=3

BER

APPENDIX F: PUBLISHED PAPER

Parts of this work are presented in the paper entitled " All-optical Synchronous CDMA Networks with Symmetric codes". The paper has been accepted to present at the 2002 International Technical Conference on Circuits/Systems, Computers and Communications July 16-19, 2002 at Phuket Arcadia Hotel & Resort, Phuket, Thailand. The full paper is included in this Appendix.

Synchronous All-Optical Code-Division Multiple-Access Local-Area Networks with Symmetric Codes

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Abstract: A non-coherent synchronous all-optical code-division multiple-access (CDMA) network is proposed. In this network, symmetric codes derived from prime sequence codes are used. We present the construction of symmetric codes and show that the pseudo-orthogonality of the new codes is the same as that of the original prime-sequence codes while the cardinality of the new codes is larger than that of the prime sequence codes and the modified prime codes in the same field GF(p). Therefore, an optical CDMA LAN using symmetric codes can have a larger number of potential subscribers. The new codes allow designing fully programmable serial all-optical transmitter and receiver suitable for low-loss, high-capacity, optical CDMA LANs. It is also shown that compared to systems using modified prime codes the proposed system can achieve better BER performance for low received chip optical power.

1. Introduction

Code-division multiple-access (CDMA) techniques have been widely used in satellite and mobile radio communication systems. In recent years, many authors have proposed to apply CDMA techniques in future very high-speed optical fiber networks. Depending on the requirement of time synchronization, there are asynchronous or synchronous optical fiber CDMA systems. Comparing with asynchronous CDMA (A/CDMA) network, synchronous CDMA (S/CDMA) that requires network access among all users be synchronized can provide higher throughput (i.e. more successful transmission) and accommodate more subscribers.

In recent years, some non-coherent optical S/CDMA schemes have been proposed. Among the families of codes proposed so far for optical S/CDMA are modified prime codes, quadratic congruence codes, which can be generated/correlated by all-optical transmitter/receiver based on parallel optical delay lines [1]. The main disadvantage of the parallel delay-line transmitter/receiver is the very high optical loss due to the use of optical splitter and combiner. In order to overcome this drawback, serial transmitter and receiver based on optical fiber lattices have been proposed for non-coherent optical S/CDMA networks using modified prime codes [2]. However, the system described in [2] is not an all-optical system but an electro-optical one, where the processing speed is limited by the speed of the controlling electronics used for changing the state of

electro-optical switches. Therefore, the huge bandwidth of optical fiber is not efficiently exploited.

In this paper we propose a non-coherent all-optical S/CDMA LAN based on a new class of symmetric codes. The construction of the new codes is presented. Those codes are derived from the symmetric codes for non-coherent all-optical A/CDMA networks [3], which in turn are generated based on prime sequence codes [4]. In order to differentiate the new codes from the original symmetric codes we called them *synchronous symmetric codes (SSC)*. We shown that the pseudo-orthogonality of synchronous symmetric codes is not different from that of prime sequence codes while the cardinality (that is, the number of code sequences) of the new codes is larger than that of prime sequence codes and modified prime codes. The architecture of all-optical fully programmable transmitter and receiver, which cause significantly lower optical loss as compared to the transmitter and receiver based on parallel optical delay lines is also proposed. Finally, the BER of the proposed system is compared to that of systems using modified prime codes described in [5].

2. Symmetric Codes for S/CDMA

A prime sequence [4] $S_i = \{s_{i,0}, s_{i,1}, ..., s_{i,j}, ...s_{i,p-1}\}$ is constructed by $s_{i,j} = i.j \pmod{p}$ where $i,j \in GF(p)$, the Galois field with prime number p. A binary prime sequence (BPS) is generated by mapping a prime sequence S_i into a binary sequence $C_i = \{c_{i,0}, c_{i,1}, ..., c_{i,k}, ..., c_{i,N-1}\}$ of length p^2 according to

$$c_{i,k} = \begin{cases} 1 & for\ k = s_{ij} + jp \\ 0 & otherwise \end{cases}$$

A prime sequence code (PSC) consists of p BPS C_i, which is made up of p subsequences of length p. Each subsequence has only one "1" chip and the value of each $s_{i,j}$ in the prime sequence S_i represents the position of the "1" chip in the jth subsequence. For $i \in GF(p)$, the adjacent delay between two "1" chips of C_i generated by S_i is defined as [3]

$t_j = s_{i,j+1} \pmod{p} - s_{i,j} \pmod{p} + p$ for $j \in [0,p-2]$.

It has been shown in [3] that the adjacent delays t_1^i, $t_2^i,..., t_{p-2}^i$ of the ith binary prime sequence ($0 \le i \le p-1$) in $GF(p)$ are related by $t_j^i = t_{p-1-j}^i$ for $0 < j < (p-1)/2$. Based on this characteristic, synchronous symmetric code sequences of weight equal $2^n < p$ (that is, the number of "1" chips in each code sequence is 2^n, for $n = 2,3,...$) can be constructed from binary prime sequences of weight p [3]. However, in this paper only the construction of

symmetric code sequences of weight 4 is presented. The construction of symmetric codes of higher weight will be reported in other literature.

Starting from a binary prime sequence C_i of weight p and length p^2 symmetric code sequences of weight 4 and length $p(p-1)$ for S/CDMA can be constructed by the following algorithm.

Step 1: From the ith binary prime sequence C_i of weight p $(0 \le i \le p-1)$, for each integer m such that $1 \le m \le (p-3)/2$, the adjacent delays $\Delta_1^{i,m}$, $\Delta_2^{i,m}$ and $\Delta_3^{i,m}$ of a new symmetric code sequence are determined by

$\Delta_1^{i,m} = t_1^i + t_2^i + ... + t_m^i$
$\Delta_2^{i,m} = t_{m+1}^i + t_{m+2}^i + ... + t_{p-m-2}^i$
$\Delta_3^{i,m} = t_{p-m-1}^i + t_{p-m-2}^i + ... + t_{p-2}^i$

where t_r^i, $(1 \le r \le p-2)$ are the adjacent delays of the ith binary prime sequence.

Step 2: Keep the "1" chips of the binary prime sequence C_i corresponding to $\Delta_1^{i,m}$, $\Delta_2^{i,m}$ and $\Delta_3^{i,m}$ unchanged. All other "1" chips of the binary prime sequence are replaced by "0".

Step 3: Truncate the first p "0" chips of the obtained sequence. The resulting sequence A_{im} is of length $N=p(p-1)$, weight 4 and can be represented by a quadruple $SA_{im} = (t_0^i - p, \Delta_1^{i,m}, \Delta_2^{i,m}, \Delta_3^{i,m})$, where $t_0^i - p$ is the number of "0" chips preceded the first "1" chip, $\Delta_1^{i,m}$, $\Delta_2^{i,m}$, $\Delta_3^{i,m}$ are the adjacent delays. From a binary prime sequence C_i $(p-3)/2$ symmetric code sequences A_{im} can be constructed [3].

Step 4: Each of $p(p-3)/2$ symmetric code sequence A_{im} is taken as a seed from which a group of new sequences can be generated. Left-rotate W chips "1" of sequence A_{im} $p-1$ times to create $(p-1)$ new sequences A_{imt} where t $(0<t<p)$ represents the number of times A_{im} has been left-rotated.

Step 5: Exclude any of the sequences A_{imt}, which are not symmetric, we obtain a new set of synchronous symmetric code sequences for S/CDMA networks.

Table 1 shows all the sequences A_{imt} of weight 4 and length 20 generated in GF(5). Note that each synchronous symmetric code sequence $A_{i,m0}$ is the same as the original symmetric code sequence A_{im} whereas the other synchronous symmetric code sequences $A_{i,mt}$ (with $t \ne 0$) are time-shift versions of A_{im}. It can be seen that there are 8 non-symmetric sequences: A_{112}, A_{114}, A_{212}, A_{214}, A_{312}, A_{314}, A_{412}, A_{414}, which must be excluded. The remaining 17 sequences are symmetric.

We find that the number V of synchronous symmetric code sequences generated in GF(p) can be calculated by the following formula

If $p=4k+1$ (k is positive integer)

$$V = (2k-1)(8k^2 + 8k + 1) - 8\sum_{i=0}^{k-1} i(i - 2k + 1)$$

If $p=4k+3$

$$V = 2k(8k^2 + 18k + 7 - 8\sum_{i=0}^{k-1} i(i - 2k)$$

Table 2 shows the sequence length N, the cardinality V of synchronous symmetric codes (SSC), prime sequence codes (PSC) [4] and modified prime codes (MPC) [5]. It can be seen that compared to the other two codes the

number of the synchronous symmetric code sequences is larger while the sequence is shorter (for the same $p>5$).

Table 1. Synchronous Symmetric Sequences in GF(5) for S/CDMA

i	$A_{i,mt}$	Synchronous symmetric code sequences for S/CDMA
0	A_{010}	10000,10000,10000,10000
	A_{011}	00001,00001,00001,00001
	A_{012}	00010,00010,00010,00010
	A_{013}	00100,00100,00100,00100
	A_{014}	01000,01000,01000,01000
1	A_{110}	01000,00100,00010,00001
	A_{111}	10000,01000,00100,00010
	A_{112}	**00001,10000,01000,00100**
	A_{113}	00010,00001,10000,01000
	A_{114}	**00100,00010,00001,10000**
2	A_{210}	00100,00001,01000,00010
	A_{211}	01000,00010,10000,00100
	A_{212}	**10000,00100,00001,01000**
	A_{213}	00001,01000,00010,10000
	A_{214}	**00010,10000,00100,00001**
3	A_{310}	00010,01000,00001,00100
	A_{311}	00100,10000,00010,01000
	A_{312}	**01000,00001,00100,10000**
	A_{313}	10000,00010,01000,00001
	A_{314}	**00001,00100,10000,00010**
4	A_{410}	00001,00010,00100,01000
	A_{411}	00010,00100,01000,10000
	A_{412}	**00100,01000,10000,00001**
	A_{413}	01000,10000,00001,00010
	A_{414}	**10000,00001,00010,00100**

Table 2. N and V of SSC, PSC and MPC

p	SSC		PSC		MPC	
	N	V	N	V	N	V
5	20	17	25	5	25	25
7	42	66	49	7	49	49
11	110	324	121	11	121	121
13	156	565	169	13	169	169
17	272	1351	289	17	289	289
19	342	1928	361	19	361	361
23	506	3530	529	23	529	529

The generation of synchronous symmetric sequences is based on removing the p-4 unwanted "1" chips from binary prime sequences of weight p. Hence, the cross-correlation constraint of the new codes is not different from that of prime sequence codes. That is, the maximum cross-correlation of two synchronous symmetric code sequences is equal 2.

3. Optical Transmitter and Receiver

The optical transmitter and receiver for synchronous all-optical CDMA LANs using synchronous symmetric codes of weight 4 are designed based on programmable optical lattices [6]. A programmable optical lattice of L stages consists of a cascade of $L+1$ 2x2 electro-optic switches and L $(L \geq 1)$ optical delay lines. The lth delay line $(0 \leq l \leq L)$ causes a delay equal $2^{l-1}T_c$, where T_c is the duration of the sequence chip time. Each 2x2 electro-optic switch can be configured into two possible states (i.e. cross-state or bar-state) according to its DC bias voltage controlled by the electronic control circuit. The total amount of delay that an optical pulse experiences when passing through the lattice can be varied from $0T_c$ to $(2^{L-1}-1)T_c$ and the delay depends on the states of all the 2x2 electro-optic switches.

The schematic diagram of a fully programmable optical transmitter is shown in Figure 1. In this transmitter three programmable optical lattices are used. When transmitting an "1" bit the optical source generates an optical pulse of maximum pulse width T_c where $T_c = T/(p^2-p)$ is the sequence chip time and T is the bit time and no pulse is emitted for a "0" bit. The pulse is passed through the optical

lattice 1 of $L_1 = \lfloor log_2p \rfloor + 1$ stages, where $\lfloor x \rfloor$ is the integer part of x. This lattice provides the delay preceded the first "1" chip of the sequence and the delay can be any integer value between $0T_c$ and $(p-1)T_c$. The delayed optical pulse is then split into two pulses by a passive splitter S_1 and one of the pulse is delayed by a time of τ_1. For a set of V new sequences of weight 4, the delay τ_1 for the jth sequence $(1 \leq j \leq V)$ is equal Δ_1^j. This delay is provided by the programmable optical lattice 2 of $L_2 = \lfloor log_2\Delta\tau_1 \rfloor + 1$ stages connected in series with an optical delay of Δ_{1min}, where $\Delta\tau_1 = \Delta_{1max} - \Delta_{1min}$, $\Delta_{1max} = \max (D_1^j)$, $\Delta_{1min} = \min (D_1^j)$, where D_1^j is the first adjacent delay of the jth sequence. The delayed pulse combines with the non-delayed one at the 2x2 coupler S_2. These two pulses then split into four pulses and two of them are delayed by a delay of τ_2. The delay τ_2 for the jth sequence is equal $\Delta_1^j + \Delta_2^j$. This delay is provided by the programmable optical lattice 3 of $L_3 = \lfloor log_2\Delta\tau_2 \rfloor + 1$ stages connected in series with an optical delay of Δ_{2min}, where $\Delta\tau_2 = \Delta_{2max} - \Delta_{2min}$, $\Delta_{2max} = \max (D_1^j + D_2^j)$, $\Delta_{2min} = \min (D_1^j + D_2^j)$, where D_2^j is the second adjacent delay of the jth sequence. All the four pulses are then combined at the passive combiner S_3. Optical symmetric code sequences of weight 4 are obtained at the output of this combiner with the adjacent delays being $(\tau_1, \tau_2, \tau_1 + \tau_2)$. By controlling the control circuit of the lattices 1, 2 and 3 for setting 2x2 switches at the bar or cross-state all V sequences can be generated. If the laser and the optical gate are removed the transmitter can be used as decoder in the receiver. Note that the delays will be set so that they are inversely matched to the pulse spacings in the receiver address sequence.
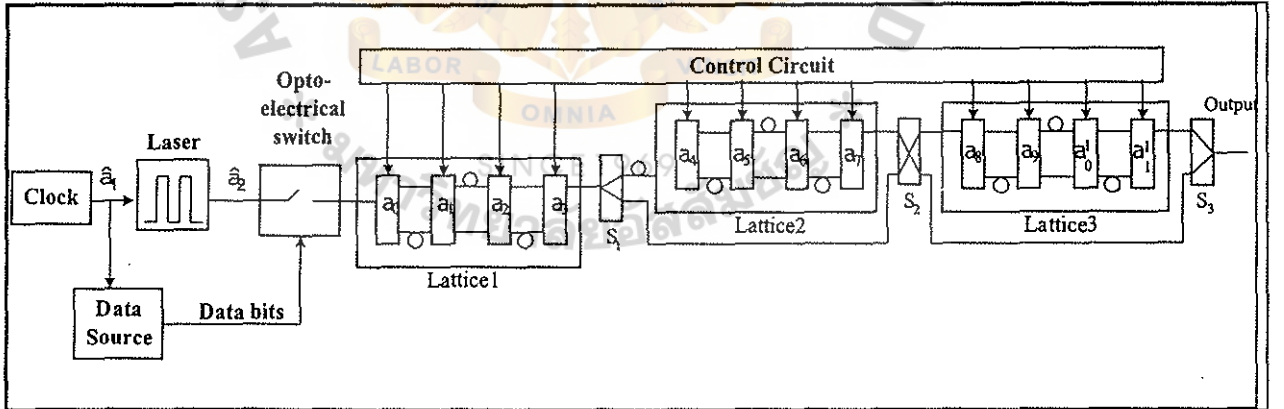

Figure 1 Optical Transmitter

4. BER Performance

We compare the performance of the proposed system with that of the non-coherent synchronous optical CDMA system using modified prime codes [5]. The BER performance for both systems is calculated as a function of the received chip optical power P_s with the number of simultaneous users K as parameter. The effects of interference, shot noise and thermal noise on the BER

are considered and the Gaussian approximation presented in [7] is used for calculating the BER performance of two systems. The following parameters are used: Data bit rate $D = 10$ Mb/s, PIN diode of responsivity $R=0.8$ A/W, dark current noise $I_d=10$ nA, the power spectral density of the thermal noise $N_{Th} = 10^{-24}$ A²/Hz, the received chip optical power P_s is varied from -30 dB to 30 dB.
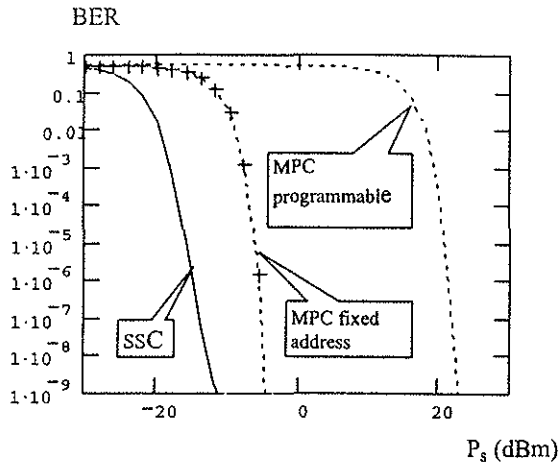
BER

Figure 2. BER for K=3

Figure 2 shows the BER for the proposed system with synchronous symmetric sequences of length $N = 506$ and that for systems using modified prime sequences of $N = 529$ (Both fixed address and programmable receivers). The number of simultaneous is $K =3$. It can be seen that for BER $= 10^{-9}$ the system using synchronous symmetric code requires the lowest received chip optical power (only $P_s =-12$ dBm) while the system using modified prime codes needs $P_s = -5$ dBm for (fixed address receiver) and $P_s = 23$ dBm (for programmable receiver).
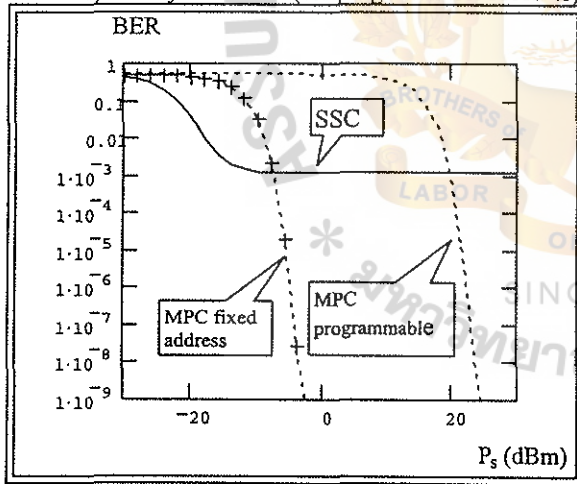

Figure 3. BER for K=10

However, due to the lower weight (W=4) when the number of simultaneous users increases, the BER of the system using synchronous symmetric codes degrades rapidly. This is illustrated in Figure 3, where the BER of the two systems for K=10 is presented. It should be noted that the system using modified prime codes can only achieve BER $= 10^{-9}$ for very high received power ($P_s = -3$ dBm for fixed address receiver and $P_s = 24$ dBm for programmable receiver, respectively). For low received power, the BER of systems using modified

prime codes is worse than that of the system using synchronous symmetric codes. In order to improve the performance of the proposed system, SSC of higher weight (e.g. W=8 or W=16) are needed. The performance of such systems will be reported in other literature.

5. Conclusions

In this paper we propose a non-coherent synchronous all-optical CDMA LAN using new symmetric codes. The construction of the new codes based on the well-known prime sequence codes is presented. It is shown that the size of a new code is larger than that of the original prime sequence code [4] and the modified prime-code [5] in the same field GF(p). This implies that optical CDMA networks using the new codes can have a larger number of potential subscribers. We also show that the pseudo-orthogonality of the new codes is the same as that of prime sequence codes. The design of fully programmable transmitter and receiver for all-optical CDMA LANs using the new codes is presented. This configuration is particularly attractive for the future ultra-fast optical CDMA networks because of its low-loss and programmable features. Finally, the BER of the proposed system is compared to that of systems using modified prime codes. It is shown that the proposed system can achieve better performance for low received chip optical power.

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