Synchronous Optical Fiber Code-Division Multiple-Access Networks with Bipolar Capacity

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Abstract

A non-coherent synchronous optical fiber code-division multiple-access (CDMA) network is proposed. In this network, sequence-inversion keying (SIK) of intensity modulated unipolar balanced Walsh code sequences is employed, whereby a code sequence is transmitted for each data '1' bit while the logical complement of that sequence is transmitted for each data '0' bit. At the receiver the received optical signal is correlated with the bipolar form of the reference sequence. Since the code sequences are balanced and the unipolar-bipolar correlation is implemented the same correlation functions as a bipolar system can be obtained. Hence, in the proposed synchronous optical fiber CDMA network, the cross-correlation of the address sequence and the undesired sequences is zero, that is, the interference is completely eliminated. Therefore, a very large number of users can transmit at the same time and very high throughput can be achieved. The novel design of programmable transmitter and receiver for non-coherent synchronous optical fiber CDMA networks using balanced Walsh codes is also presented. The transmitter and receiver are designed based on the use of electro-optical switches and optical delay-lines.

Keywords*: Optical communications, code-division multiple-access, synchronous optical CDMA networks, sequence-inversion keying, Walsh codes.*

Introduction

Code-division multiple-access (CDMA) techniques have been widely used in satellite and mobile radio communication systems (Dinan and Jabbari 1998). In CDMA systems, in order to accommodate many subscribers and a large number of simultaneous users, long sequences or large spreading factors are required. The available bandwidth in radio channels is normally limited by regulatory authorities and the use of long sequences is not possible. Although copper cables are not subject to this restriction, their bandwidth is generally insufficient for large networks. In contrast, single-mode optical fiber provides enormous bandwidths and the limitations of radio and copper-cable CDMA systems are effectively eliminated. In recent years, many authors have proposed to apply CDMA techniques in future very high-speed optical fiber networks. The optical fiber CDMA network can provide a multiple-access environment without employing wavelength sensitive components, which are required in the wavelength-division multiple-access (WDMA) network, and without using very high-speed electronics processing devices, which are needed in the time-division multiple-access (TDMA) network. Depending on the requirement of time synchronization, there are synchronous (Prucnal *et al.* 1986; Shalaby 1999) or asynchronous optical fiber CDMA systems (O'Farrell and Lochmann 1994; Lam 2000). Compared with asynchronous CDMA network, synchronous CDMA requires network access among all users to be synchronized. It can provide higher throughput (i.e. more successful transmission) and accommodate more subscribers (Kwong *et al.* 1991). It follows that synchronous CDMA is suitable for networks with real time requirements (e.g., voice) and/or high-throughput requirements (e.g., digitized video). On the other hand in applications, where the traffic is busy with no stringent time requirement (e.g., data transmission) asynchronous CDMA is best suited.

In recent years, some non-coherent synchronous optical fiber CDMA schemes have been proposed, e.g., by Prucnal *et al.* (1986), Kostic and Titlebaum (1994), Ohtsuki (1996), Lin and Wu (1998) and Shalaby (1999). Compared to coherent systems non-coherent optical CDMA systems have the advantages of fewer stability requirements for optical encoders and decoders (Marhic 1993). However, because the correlation is based on power summation, they have the limitations of positive systems. It is usually believed that conventional bipolar codes such as Gold codes, Walsh codes (Dinan and Jabbari 1998) cannot be used in non-coherent optical systems. Therefore, new unipolar codes such as prime sequence codes (Prucnal *et al.* 1986), quadratic congruence optical codes (Kostic and Titlebaum 1994) were designed for synchronous optical fiber CDMA networks. However, compared to the conventional bipolar codes of similar length these unipolar codes yield a lower ratio of the auto-correlation peak to the maximum value of the cross-correlation, and are therefore prone to higher multiple-access interference. This leads to a serious degradation in the bit error probability as the number of simultaneous user increases and the degradation cannot be overcome even for arbitrary high optical power. Recently, interference reduction techniques have been proposed by Ohtsuki (1996), Lin and Wu (1998), Shalaby (1999) aiming at improving the performance of synchronous optical fiber CDMA networks. However, multiple-access interference cannot be completely eliminated in those systems.

In this paper we propose a novel non-coherent synchronous optical fiber CDMA network based on balanced Walsh codes, which are derived from unipolar Walsh codes (Dinan E.H. and Jabbari B 1998). In this system, sequence-inversion keying (SIK) (O'Farrell and Lochmann 1994) of intensity modulated unipolar balanced Walsh code sequences is employed at the transmitter, whereby a unipolar code sequence is transmitted for each data '1' bit while the logical complement of that sequence is transmitted for each data '0' bit. At the receiver the received signal is correlated with the bipolar form of the user's address code sequence (or the address sequence). The unipolar-bipolar correlation can be carried out by using two unipolar-unipolar correlators and a balanced detector. The balanced detection subtracts the means or D.C. components of the two signals, so that with the use of balanced Wash code sequences the D.C. component is eliminated and the data can be detected by comparison to zero threshold. Further more, since the unipolar-bipolar correlation is implemented the same correlation functions as a bipolar system can be obtained (O'Farrell and Lochmann 1994). Hence, in the proposed synchronous optical fiber CDMA network, the cross-correlation of the address sequence and the undesired sequences is the cross-correlation of bipolar Walsh code sequences at zero-time shift. Since that cross-correlation is zero, the interference is completely eliminated. Therefore, very high throughput can be achieved. The novel design of programmable transmitter and receiver for non-coherent synchronous optical fiber CDMA networks using balanced Walsh codes is also presented. The transmitter and receiver are designed based on the use of electro-optical switches and optical delay-lines.

Walsh Codes

A Hadamard matrix containing all unipolar Walsh code sequences of length $N = 2^n$ as its rows can be generated by the following recursive algorithm (Dinan and Jabbari 1998):

$$H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \qquad H_{2m} = \begin{bmatrix} H_m & H_m \\ H_m & H^c_m \end{bmatrix}$$

$$H_1 = [0]$$

where $m = 2^j$, $j \geq 1$ and the matrix $H^c{}_m$ is the binary complement of the matrix H_m. A bipolar Walsh code sequence of length $N = 2^n$ can be obtained from its unipolar counterpart by mapping the elements {0,1} onto {1, -1}, respectively. Following are the unipolar Walsh code of length 8 (matrix H_8), its complement (matrix $H^c{}_8$) and the bipolar Walsh code of length 8 (matrix W_8).

$$H_8 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

$$H_8^C = \begin{bmatrix} \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{0} \\ \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} \end{bmatrix}$$

$$W_8 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix}$$

The correlation functions between two bipolar Walsh code sequences x and y can be represented as:

$$q_{x,y}(0) = \begin{cases} N, if \ x = y \\ 0, \ if \ x \neq y \end{cases}$$

That is, the cross-correlation between two bipolar Walsh code sequences at the zero-time shift is zero (Dinan and Jabbari 1998).

Balanced Walsh Codes

Following the construction algorithm described above, any unipolar Walsh code sequence of length $N = 2^n$ ($n \geq 4$) can be broken into $N/8 = 2^{n-3}$ blocks of 8 chips. Furthermore, all unipolar Walsh code sequences of the same length can be grouped in two groups. The first group includes sequences formed by only one type of 8-chip blocks, which is a row of the matrix H_8. The sequences of the second group are formed by two types of 8-chip blocks, which are one row of the matrix H_8 and its complement.

Example: The unipolar Walsh code sequence 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 of length $N = 32$ can be broken into 32/8 = 4 blocks of 8 chips: 01100110; 01100110; 01100110 and 01100110. It can be seen that all 4 blocks are the same as 01100110, which is the 4th row of H_8.

The unipolar Walsh code sequence 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 of length $N = 32$ can be broken into 32/8 = 4 blocks of 8 chips: 01100110; 10011001; 10011001 and 01100110. This code sequence is formed by 2 blocks 01100110, which is the 4th row of H_8 and 2 blocks 10011001, which is the complement of 01100110.

Among the 16 blocks of the matrix H_8 and $H^c{}_8$, except two blocks 00000000 and 111 11111, each of other 14 blocks has four "1" chips. Those blocks can be represented by $X = \{x_1, x_2, x_3, x_4\}$ where 0 £ x_i £ 7 $(i = 1,2,3,4)$ indicates the position of an "1" chip in the block. For each block, the adjacent delays, which are multiples of the duration of the code sequence chip time are defined as $D_1 = x_2 - x_1$, $D_2 = x_3 - x_2$, $D_3 = x_4 - x_3$. Table 1 shows those 14 blocks, its representations and the adjacent delays D_1, D_2, D_3 as well as the number ρ of "0" chips preceded the first "1" chip of each block.

It can be seen from Table 1 that except two blocks 01101001 and 10010110, each of the other 12 blocks have $D_1 = D_3$. Therefore, those are symmetric code sequences of weight w = 4 and they can be generated by a programmable optical lattice based on tunable optical delay lines (Lam 2001). In this paper, those blocks are noted by G_1, G_2,…, G_6 and G^c_1, G^c_2,…,G^c_6 as follow:

G_1 = {01010101}
G_2 = {00110011}
G_3 = {01100110}
G_4 = {00001111}
G_5 = {01011010}
G_6 = {00111100}
G^c_1 = {10101010}
G^c_2 = {11001100}
G^c_3 = {10011001}
G^c_4 = {11110000}
G^c_5 = {10100101}
G^c_6 = {11000011}

The blocks G_1, G_2, …, G_6 are named generator blocks and we call unipolar Walsh code sequences generated by those blocks and their complements *balanced Walsh code sequences* because they are balanced sequences having an equal number of chips "1" and "0". A balanced Walsh code sequence, hence, consists of *N/8* blocks, which can be G_i (*1 £ i £ 6*) or its complements. Therefore, a balanced Walsh code sequence can be represented by its generator block G_i and a control sequence *A* consisting of *N/8* chips $A = \{a_1, a_2, …, a_{N/8}\}$ where a_j = 1 (for *1 £ j £ N/8*) if the corresponding block is G_i and a_j = 0 if the corresponding block is the complement of G_i.

Example: The unipolar Walsh code sequence **0 1 1 0 0 1 1 0** 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 **0 1 1 0 0 1 1 0** of length *N* = 32 is a balanced Walsh code sequence. This sequence is formed by 2 blocks G_3 = {01100110} and 2 blocks G^c_3 = {10011001} and it can be represented by G_3 and a 4-chip control sequence *A* = {1 0 0 1} because the 1st and the last block of the balanced Walsh code sequence are G_3.

It can be seen that the number of balanced Walsh code sequences of length $N = 2^n$ is $N- 2^{n-2} = 2^n - 2^{n-2}$. A bipolar balanced Walsh code sequence of length $N = 2^n$ can be obtained from its unipolar counterpart by mapping the elements {0,1} onto {1, -1}, respectively.

Table 1. Fourteen Walsh code sequences of length 8 and weigh 4

Block	**Representation** X={x_1, x_2, x_3, x_4}	**Adjacent delays**			
		D_1	D_2	D_3	**r**
01010101	1,3,5,7	2	2	2	1
00110011	2,3, 6,7	1	3	1	2
01100110	1,2,5,6	1	3	1	1
00001111	4,5,6,7	1	1	1	4
01011010	1,3,4,6	2	1	2	1
00111100	2,3,4,5	1	1	1	2
01101001	**1,2,4,7**	**1**	**2**	**3**	**1**
10101010	0,2,4,6	2	2	2	0
11001100	0,1,4,5	1	3	1	0
10011001	0,3,4,7	3	1	3	0
11110000	0,1,2,3	1	1	1	0
10100101	0,2,5,7	2	3	2	0
11000011	0,1,6,7	1	5	1	0
10010110	**0,3,5,6**	**3**	**2**	**1**	**0**

Programmable Optical Lattices

Balanced Walsh code sequences can be generated by optical transmitters based on programmable optical lattices. Fig.1 shows a programmable optical lattice for generating generator blocks and their complements. In this lattice 3 tunable optical delay lines (Lam 2001) are used. If an optical pulse of maximum pulse width T_c is received, it is passed through the first 3-stage optical tunable delay line. This delay line provides a delay $\tau_0 = k_0T_c$ (k_0 is an integer, $0 \leq k_0 \leq 4$) preceded the first '1' chip of the generator block. The delayed pulse is then split into two pulses by a passive splitter S_1 and one of the pulse is delayed by a time $\tau_1 = k_1T_c$ (k_1 is an integer, $0 \leq k_1 \leq 3$) provided by the 2-stage tunable optical delay line. The delayed pulse combines with the non-delayed one at the 2x2 coupler S_2. At S_2 these two pulses are split into four pulses and two of them are delayed by a delay $\tau_2 = k_2T_c$ (k_2 is an integer, $2 \leq k_2 \leq 6$) provided by the second 3-stage optical tunable delay line. All the four pulses are then combined at the passive combiner S_3. An 8-chip generator block is obtained at the output of this combiner with the adjacent delays being (τ_1, τ_2-τ_1 , τ_1). By setting 2x2 electro-optical (EO) switches c_n ($0 \leq n \leq 10$) at the bar or cross-state all generator blocks and their complements can be generated by the described programmable optical lattice.

Example: For generating the block G_3 = {01100110} the EO switches c_1, c_3, c_5, c_7, c_9 must be set to the bar state while the EO switches c_0, c_2, c_4, c_6, c_8, c_{10} must be set to the cross state.

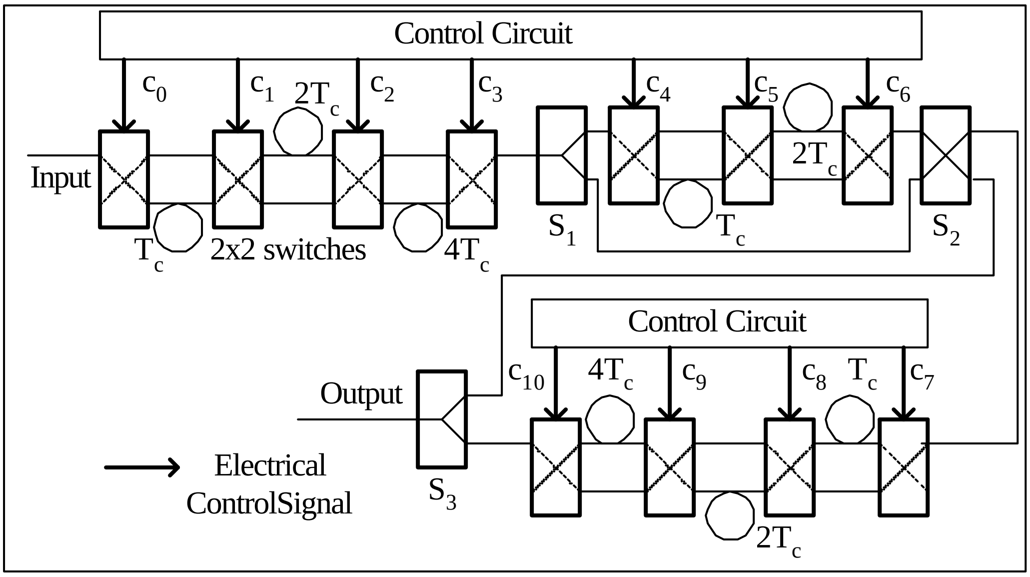

Fig. 1. Optical lattice for generating generator blocks and their complements

Network Architecture

The block diagram of a non-coherent synchronous optical fiber CDMA network using balanced Walsh codes is shown in Figure 2. In this network, in order to ensure that the transmissions of all users of the network are synchronized and each receiver knows exactly the detection time an optical clock distribution scheme is employed. A mode-locked laser used as the master clock emits a train of optical clock pulses of maximum pulse width equal T_c and repetition rate of $1/T$ where $T_c = T/N$, N is the code length and T is the bit time. The optical clock pulses are optically distributed to all users of the network. For ensuring time synchronization the distance from any user to the master clock must be an integral multiple of Tc/n where c/n is the velocity of light in the fiber core and n is the refraction index of the fiber core. The clock is emitted at a wavelength λ_2 different from the optical code sequences wavelength λ_1. At each station of the network a wavelength-division multiplexing (WDM) coupler routes the clock pulses to the synchronization circuit and the data pulses are directed to the correlator receiver. The synchronization circuit provides the clock signal to both transmitter and receiver. At the transmitter the spreading is implemented by sequence inversion keying (SIK). If a user wants to transmit data, it encodes each data bit '1' by an optical waveform consisting of a balanced Walsh code sequence which represents the destination address of that bit, while the complement of this sequence replaces each '0' bit. The starting time for transmitting is determined by the synchronization circuit. At each receiver the data signal is separated from the clock pulses by the WDM coupler and is then split into two parts and directed to two unipolar-unipolar correlators. The upper correlator is configured to correlate the incoming signal to the balanced Walsh code sequence, which is the user address sequence while the lower one correlates to the complement of the address sequence. The optical outputs of these correlators are subtracted in a pair of balanced PIN photodiodes. The resulting signal is then integrated over a chip time T_c and data is recovered by sampling at the auto-correlation peak and zero-threshold detection. The sampling time is determined by a synchronization circuit, which is controlled by the received clock pulses. Since the unipolar-bipolar correlation in an optical fiber SIK CDMA system using balanced codes gives the same correlation functions as a bipolar system (O'Farrell and Lochmann 1994) and the cross-correlation between two bipolar Walsh code sequences at the zero-time shift is zero the multiple-access interference at the destination receiver is eliminated.

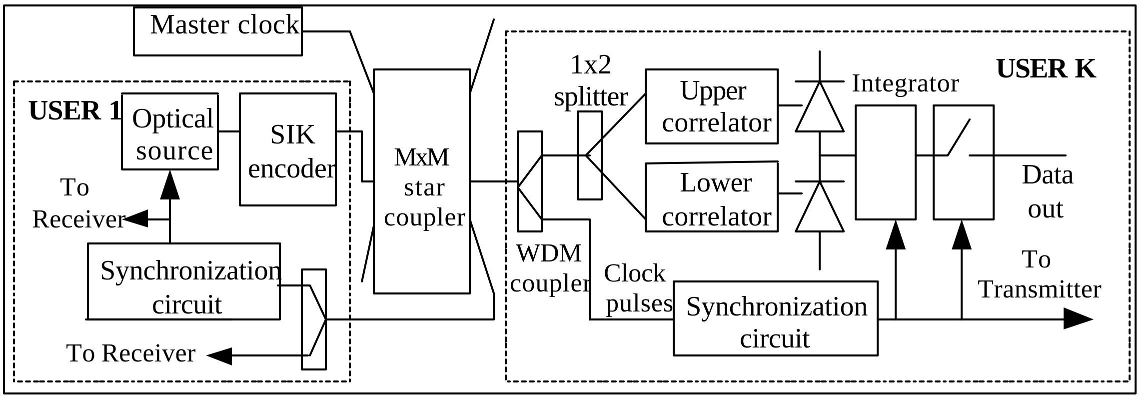

Fig.2. Synchronous optical fiber CDMA network using balanced Walsh codes

Optical Transmitter

A parallel delay line optical transmitter for non-coherent synchronous optical CDMA networks is shown in Figure 3(a). This transmitter is designed based on the principles described in (Lam 2000) and the use of the programmable optical lattice shown in Figure 2. In this transmitter, a mode-locked laser generates a train of optical pulses of maximum pulse width T_c at the rate $1/T$ where $T_c = T/N$ is the chip duration of balanced Walsh code sequences of length N and T is the bit time. The train of optical pulses is fed to a tunable delay before being directed to a parallel encoder. The tunable delay is used to provide an appropriate phase compensation for synchronizing the data frame with the clock signal. The parallel encoder consists of $N/8$ branches providing delays of $0T_c, 8T_c, 16T_c,\ldots, (N-8)\,T_c$ and each branch is connected to a programmable lattice similar to that shown in Figure 2. If data is transmitted to a user each data bit '1' must be encoded by the address code sequence of this user and the complement of the address code sequence is used for encoding bit '0'. When a data bit '1' is transmitted, the control sequence generator will generate a control sequence A

consisting of *N/8* chips and forward *A* to the lattice controller. Based on *A*, the lattice controller will issue appropriate signals for setting lattices L_k $(k = 0,1,2,\dots N/8 - 1)$ so that the lattice L_k can generate the *k*th block of the code sequence. When there is a change from data bit "1" to "0" or "0" to "1" the lattice controller generates signals for resetting each lattice allowing the transmitter to generate the complement of the balanced Walsh code sequence. Thus, the transmitter can be programmable to transmit data bits using SIK modulation of balanced Walsh code sequences.

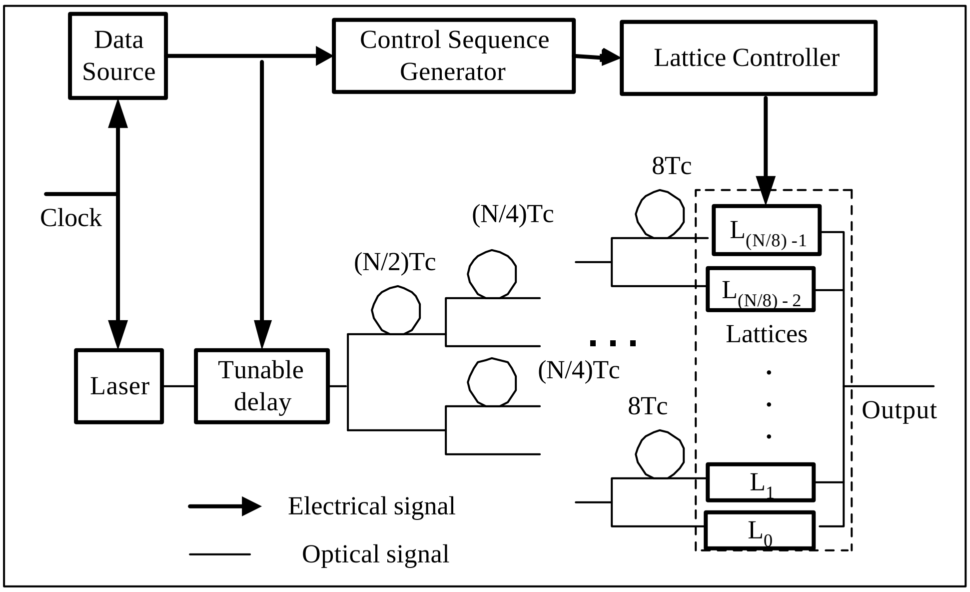

Fig.3 (a). Optical transmitter

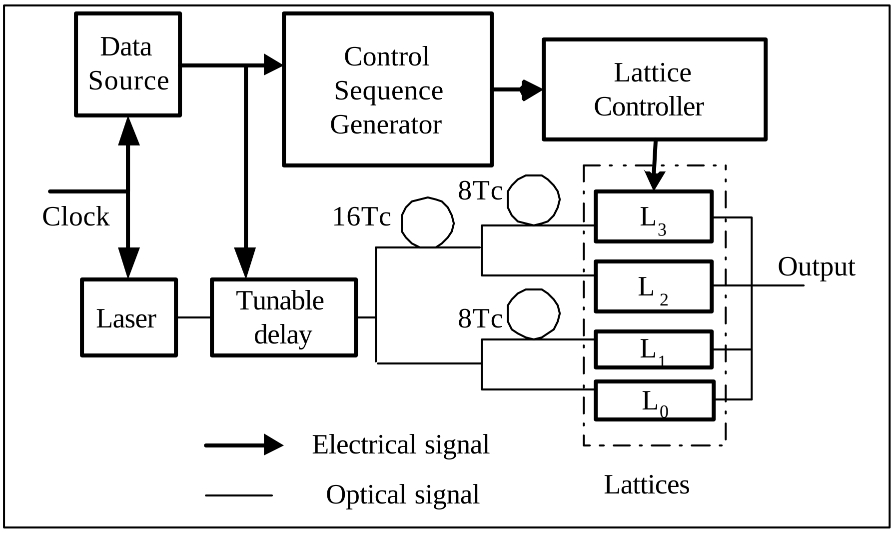

Fig. 3(b). Transmitter for balanced Walsh code sequences of length 32

Example: Balanced Walsh code sequences of length $N = 32$ can be generated by a parallel transmitter consisting of $N/8 = 4$ parallel branches as shown in Fig. 3(b). These branches provide delays of $0T_c$, $8T_c$, $16T_c$, and $24\ T_c$ and each branch is connected to a programmable lattice similar to that shown in Fig. 2. Four lattices L_0, L_1, L_2 and L_3 are used. The mode-locked laser generates a train of optical pulses of maximum pulse width T_c at the rate $1/T$ where $T_c = T/32$ and the pulses is fed to a tunable delay before being directed to four parallel branches. If we want to transmit data to the user its address code sequence is the balanced Walsh code sequence 01100110100110011001100101100110, each data bit ‘1’ must be encoded by this sequence and the complement of this sequence is used for encoding bit ‘0’. Note that this sequence can be represented by the generator block G_3 and a control sequence $A = \{1\ 0\ 0\ 1\}$. When a data bit ‘1’ is transmitted, the control sequence generator will generate the control sequence A and forward this sequence to the lattice controller. Based on sequence A, the lattice controller issues signals for setting lattices L_0, L_3 to generate the generator block G_3 and L_1, L_2 to generate the complement of G_3. Therefore, for each optical pulse received from the laser, the transmitter can optically generate a balanced Walsh code sequence.

Optical Receiver

Figure 4 shows the schematic diagram of a unipolar-bipolar correlator receiver for non-coherent synchronous optical fiber CDMA networks using balanced Walsh codes. In this receiver, the received optical signal is split into two parts and directed to two unipolar-unipolar correlators. The upper correlator is configured to correlate to the balanced Walsh code sequence, which is the user address sequence while the lower one correlates to the complement of that sequence. The optical outputs of these correlators are subtracted in a pair of balanced PIN photodiodes. The resulting signal is then integrated over a chip time T_c and data is recovered by sampling at the auto-correlation peak and zero-threshold detection. The sampling time is set at the last chip slot of a bit frame, and this time is determined by the synchronisation circuit, which is driven by the received clock pulses. Each unipolar-unipolar correlator consists of $N/8$ branches providing delays of $0T_c$, $8T_c$, $16T_c, \ldots, (N/8-1)\,T_c$ and each branch is connected to a programmable lattice similar to that shown in Figure 2. The selection of the address sequence is done via the address selector. A control sequence is issued for setting lattices L_{ka} and L_{kb} $(k = 0,2,\ldots N/8-1)$ so that the lattice can generate the kth block of the address sequence or its complement. Thus, the receiver can be programmable to correlate the received signal to any balanced Walsh code sequences of length N.

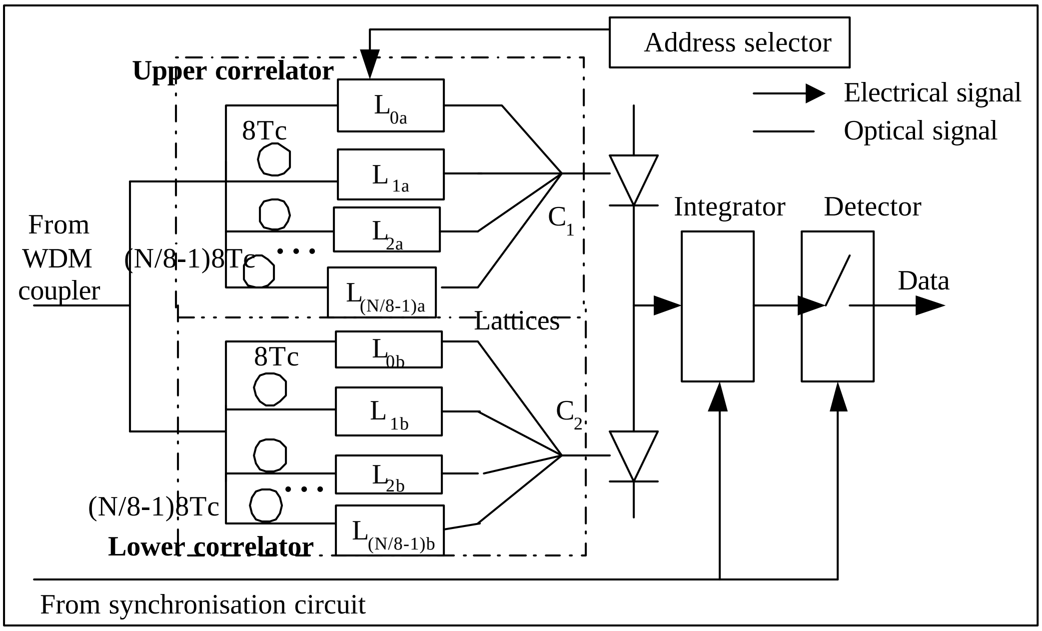

Fig. 4. Optical receiver

Example: The receiver of a non-coherent synchronous optical fiber CDMA network using balanced Walsh code sequences of length N=32 consists of two unipolar-unipolar correlator. Each correlator has four branches with delays being $0T_c$, $8Tc$, $16T_c$, $24T_c$ and lattices L_{0a}, L_{1a}, L_{2a}, L_{3a} are used in the upper correlator while lattices L_{0b}, L_{1b}, L_{2b}, L_{3b} are used in the lower correlator. If the balanced Walsh code sequence is 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 is selected to be the address sequence the upper correlator must be configured to correlate to this sequence and the lower correlator to correlate to its complement. This can be done via the address selector, so that lattices L_{0a}, L_{3a}, L_{1b}, L_{2b} are set to generate the generator block G_3 = {01100110} and lattices L_{0b}, L_{3b}, L_{1a}, L_{2a} are set to generate the complement of G_3. If a data bit "1" is sent to this receiver, the sequence **0** 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 is received at the receiver input (Assume that the 1st received chip is the bold face one). At the output of the optical combiner C_1 we obtain the correlation between the received sequence and the address sequence 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 (Note that the chip power of the signals at the input of the upper correlator and the lower correlator is 50% of the chip power of the received signal due to the use of the 1x2 splitter). The first 32 chips of the signal at the output of C_1 is 0 0 1 2 1 0 2 4 2 2 3 2 3 6 4 0 5 8 4 2 2 6 8 5 4 7 6 6 10 8 2 7 16. At the output of the optical combiner C_2 we obtain the correlation between the received sequence and the sequence 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 which is the complement of the address sequence. The first 32 chips of the signal at the output of C_2 is 0 1 1 0 1 3 2 0 3 3 2 4 4 1 3 8 4 1 5 8 5 3 6 8 5 7 8 4 6 13 10 0. The optical signals obtained at the output of C_1 and C_2 are converted into electrical signals and subtracted by the pair of balanced PIN diodes. Hence, the electrical signal at the output of the integrator is 0 –1 0 2 0 –3 0 4 –1 –1 1 –2 –1 5 1 –8 1 7 –1 –6 1 5 –1 –4 2 –1 –4 6 2 –11 –3 **16**. Since the sampling time is set at the last chip slot of a bit frame (i.e. at the 32th chip time), after sampling we get the value of 16. The detector compares this value to the detection threshold of 0, and detect a data bit '1'.

Assume that the following interference sequence is received at the input of the receiver: **1** 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 (Assume that the 1st received chip is the bold face one). At the output of the optical combiner C_1 we obtain the correlation between a half of the received signal and the address sequence 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 and the first 32 chips of the signal at the output of C_1 is 0 1 2 1 0 1 2 2 2 3 4 3 2 3 4 4 4 4 4 5 6 5 6 6 6 6 6 6 8 8 8 8. At the output of the optical combiner C_2 we obtain the correlation between a half of the received signal and the sequence 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 which is the complement of the address sequence. The first 32 chips of the signal at the output of C_2 is 1 1 0 1 2 1 1 2 3 3 2 3 4 3 3 4 4 4 5 5 5 6 6 6 6 6 7 7 7 8 8 8. The optical signals obtained at the output of C_1 and C_2 are converted into electrical signals and subtracted by the pair of balanced PIN diodes. Hence, the electrical signal at the output of the integrator is –1 0 2 0 –2 0 1 0 –1 0 2 0 –2 0 1 0 0 0 –1 0 1 –1 0 0 0 0 –1 –1 1 0 0 **0.** Since the sampling time is set at the last chip slot of a bit frame (i.e. at the 32th chip time), after sampling we get the value of 0. This result illustrates that the interference is equal zero at the sampling time.

Conclusions

The derivation of balanced Walsh codes sequences from unipolar Walsh code sequences is presented. It is shown that those sequences can be optically generated by using optical lattices, which are cascades of optical delay lines and EO switches. We propose a non-coherent synchronous optical fiber CDMA network using balanced Walsh code sequences, where SIK modulation and balanced detection are implemented. The design of fully programmable transmitter and receiver for the proposed networks is also presented. The design is based on the use of EO switches and optical delay-lines. Both optical transmitter and receiver only require standard electronics for updating the setting of the lattice controller and address selector. That is, the operating speed of networks using these devices can only be limited by the synchronization time. Therefore, very high data bit rates can be achieved. However, the main disadvantage of the transmitter and receiver is the relatively large optical recombination loss factor due to the use of optical splitters and combiners. The optical loss can be compensated by using optical amplifiers, which are now under intensive development.

In the proposed network, unipolar-bipolar correlation is realised and the same correlation functions as a system using bipolar Walsh codes can be obtained. Since, the cross-correlation of bipolar Walsh code sequences at zero-time shift is equal zero, in the non-coherent synchronous optical fiber CDMA network using balanced Walsh code sequences the interference is completely eliminated at the receiver. Therefore, the network is not interference-limited and a large number of users can simultaneously transmit and very high throughput can be achieved. Hence, the proposed scheme is particularly attractive for future high capacity optical fiber networks.

References

Dinan, E.H.; and Jabbari, B. 1998. Spreading codes for direct sequences CDMA and qideband CDMA cellular networks. IEEE Comm. Magazine, Sept. 1998, pp. 48-54.

Kostic, Z.; and Titlebaum E.L. 1994. The design and performance analysis for several new classes of codes for optical synchronous CDMA and for arbitrary-medium time-hopping synchronous CDMA communication systems, IEEE Trans. on Commun. 42: 2608-17.

Kwong, W.C.; Perrier, P.A.; and Prucnal, P.R. 1991. Performance comparision of asynchronous and synchronous code-division multiple-access techniques for fiber-optic local-area networks. IEEE Trans. on Commun. 39: 1625-34.

Lam, P.M. 2000. Incoherent Asynchronous Optical Fiber Code-Division Multiple-Access Networks Using Concatenated Codes. Proc. Asia Pacific Conf. on Communications (APCC ’2000), Seoul, Korea, 30 October - 2 November 2000, pp. 129 - 33.

Lam, P.M. 2001. 2^n prime-sequence codes for incoherent asynchronous optical fiber Code-division multiple-access networks. AU J.T. 4: 164-72.

Lin, C.L.; and Wu, J. 1998. A synchronous fiber-optic CDMA system using adaptive optical hardlimiter. IEEE J. of Lightwave Tech.16: 1393-403.

Marhic, M.E. 1993. Coherent optical CDMA networks. J. Lightwave Technol. 11: 854-63.

O’Farrell, T.; and Lochmann, S.I. 1994. Performance analysis of an optical correlator receiver for SIK DS-CDMA communication systems. Electron. Lett. 30: 63-5.

Ohtsuki, T. 1996. Direct-detection optical synchronous CDMA systems with channel interference canceller using time division reference signal. IEICE Trans. Fundamentals E79-A: 1948-56.

Prucnal, P.R.; Santoro, M.A.; and Sehgal, S.K. 1986. Ultrafast all-optical synchronous multiple access fiber networks. IEEE J. on Selected Areas in Commun. SAC-4: 1484-93.

Shalaby, H.M. 1999. Synchronous fiber-optic CDMA systems with interference estimators. IEEE J. of Lightwave Tech. 17: 2268-75.