

BER Performance of M-ary/ASK-SS System Using Compact Matched Filter Bank for Optical ZCZ Code

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Abstract—The optical ZCZ code, which is a set of pairs of binary and bi-phase sequences with zero correlation zone, can provide code division multiple access (CDMA) communication system without co-channel interference. And M-ary amplitude shift keying spread spectrum (M-ary/ASK-SS) system using this code can detect a desired sequence without interference of undesired sequences. We proposed the compact construction of a bank of matched filters for this code, which is called tree-type bank of matched filters. However, M-ary/ASK-SS system using this filters might go down the bit error rate (BER) performance because input-output characteristics of this filters for zero correlation zone $4n - 2$ is nonlinear characteristics.

In this paper, we clarify that BER performance in ASK-SS and M-ary/ASK-SS system under the additive white Gaussian noise (AWGN) and the frequency nonselective fading environments are not influenced by nonlinear characteristics of this filters by the computer simulation. The BER performance of ASK-SS system using tree-type bank of matched filters under the AWGN and frequency nonselective fading environments go down compared to BER performance of parallel-type filters as expected. But the BER performance of M-ary/ASK-SS system using this compact filters under the AWGN and frequency nonselective fading environment are almost equal compared to BER performance of parallel-type filters. In fact, the BER performance in M-ary/ASK-SS are not influenced by nonlinear characteristics of tree-type bank of matched filters.

Keywords—optical ZCZ code, ASK-SS system, M-ary/ASK-SS system, matched filter bank,

I. INTRODUCTION

The M-ary/ASK-SS system, which is a method to transmit one sequence selected from among M sequences is effective to increase data rate[1], [2], [3]. An M-ary/ASK-SS system using the optical ZCZ code, which is a set of pairs of binary and bi-phase sequences with zero correlation zone can detect a desired sequence without interference of undesired sequences [4], [5]. We proposed the compact construction of a bank of matched filters for this code with zero correlation zone $4n - 2$ [6], which is called tree-type bank of matched filters. However, M-ary/ASK-SS system using this filters might go down the BER performance because input-output characteristics of this filters for zero correlation zone $4n - 2$ is nonlinear characteristics.

In this paper, we analyse the influence on the BER performance in ASK-SS and M-ary/ASK-SS systems under the additive white Gaussian noise (AWGN) and the frequency

nonselective fading environments by nonlinear characteristics of tree-type bank of matched filters for the optical ZCZ code of $Zcz = 4n - 2$.

II. OPTICAL ZCZ CODES

A. Definition of Optical ZCZ Code

Let a_N^j be a bi-phase sequence of length N whose elements take 1 or -1 , written as

$$a_N^j = (a_{N,0}^j, a_{N,1}^j, \dots, a_{N,i}^j, \dots, a_{N,N-1}^j), \quad (1)$$

$$a_{N,i}^j \in \{1, -1\}.$$

Similarly, let $\hat{a}_N^{j,d}$ be a binary sequence of length N whose elements take 1 or 0, written as

$$\hat{a}_N^{j,d} = (\hat{a}_{N,0}^{j,d}, \hat{a}_{N,1}^{j,d}, \dots, \hat{a}_{N,i}^{j,d}, \dots, \hat{a}_{N,N-1}^{j,d}), \quad (2)$$

$$\hat{a}_{N,i}^{j,d} \in \{1, 0\},$$

where i denotes $i \bmod N$. Let A be a set of pairs of bi-phase sequences, a_N^j 's, and binary sequences, $\hat{a}_N^{j,d}$'s, written as

$$A = \{(a_N^1, \hat{a}_N^{1,d}), (a_N^2, \hat{a}_N^{2,d}), \dots, (a_N^j, \hat{a}_N^{j,d}), \dots, (a_N^M, \hat{a}_N^{M,d})\}. \quad (3)$$

A periodic correlation function between sequences a_N^j and $\hat{a}_N^{j',d}$ at shift i' is defined by

$$\rho_{a_N^j, \hat{a}_N^{j',d}, i'} = \sum_{i=0}^{N-1} a_{N,i}^j \hat{a}_{N,(i+i') \bmod N}^{j',d}. \quad (4)$$

In this paper, correlation function $\rho_{a_N^j, \hat{a}_N^{j',d}, i'}$ of $j = j'$ and $j \neq j'$ are called auto- and cross- correlation function, respectively. The set is called an optical ZCZ code[4], [5], if the periodic auto- and cross-correlation functions satisfy

$$\rho_{a_N^j, \hat{a}_N^{j',d}, i'} = \begin{cases} w & ; i' = 0, j = j', d = 0 \\ -w & ; i' = 0, j = j', d = 1 \\ 0 & ; i' = 0, j \neq j' \\ 0 & ; 1 \leq |i'| \leq Zcz \end{cases} \quad (5)$$

with $w = \sum_{i=0}^{N-1} \hat{a}_{N,i}^{j,d} < N$. The optical ZCZ codes are bounded by $M \leq N/(Zcz + 1)$, where M is the number of sequences in a sequence family and is called family size.

B. Construction of Optical ZCZ Codes with $Zcz = 4n - 2$

Let b_{N_1} be a Legendre sequence [7] of length $N_1 = 4n_1 - 1$ with $n_1 \geq 1$ or an M-sequence of length $N_1 = 2^{n_1} - 1$ with $n_1 \geq 2$, whose elements take 1 or -1 , written as

$$b_{N_1} = (b_{N_1,0}, b_{N_1,1}, \dots, b_{N_1,i}, \dots, b_{N_1,N_1-1}), \quad (6)$$

$$b_{N_1,i} \in \{1, -1\},$$

with $\sum_{i=0}^{N_1-1} b_{N_1,i} = 1$. A binary sequence $\hat{b}_{N_1,i} \in \{1, 0\}$ of length N_1 is given by

$$\hat{b}_{N_1,i} = (1 + b_{N_1,i})/2.$$

The periodic correlation function between b_{N_1} and $\hat{b}_{N_1}$ is given by

$$\begin{aligned} \rho_{b_{N_1}, \hat{b}_{N_1}, i'} &= \sum_{i=0}^{N_1-1} b_{N_1,i} \hat{b}_{N_1,(i+i') \bmod N_1} \\ &= \frac{1}{2} (1 + \rho_{b_{N_1}, b_{N_1}, i'}) \\ &= \begin{cases} w_b & ; i' = 0 \\ 0 & ; \text{otherwise} \end{cases} \end{aligned} \quad (7) \quad \text{and}$$

with

$$\begin{aligned} \rho_{b_{N_1}, b_{N_1}, i'} &= \sum_{i=0}^{N_1-1} b_{N_1,i} b_{N_1,(i+i') \bmod N_1} \\ &= \begin{cases} N_1 & ; i' = 0 \\ -1 & ; \text{otherwise} \end{cases} \end{aligned} \quad (8)$$

and

$$w_b = \frac{N_1 + 1}{2}. \quad (9)$$

Let $\mathbf{H}_{N_2}$ be the Sylvester-type Hadamard matrix of size $N_2 \times N_2 = 2^{n_2} \times 2^{n_2}$ with $n_2 \geq 1$, written as

$$\mathbf{H}_{N_2} = [h_{N_2,0}^0, h_{N_2,1}^1, \dots, h_{N_2,i}^j, \dots, h_{N_2,N_2-1}^{N_2-1}]^T, \quad (10)$$

$$\begin{aligned} h_{N_2}^j &= (h_{N_2,0}^j, h_{N_2,1}^j, \dots, h_{N_2,i}^j, \dots, h_{N_2,N_2-1}^j), \quad (11) \\ h_{N_2,i}^j &\in \{1, -1\}, \end{aligned}$$

where the symbol T denotes the matrix transposition, which is defined by

$$\mathbf{H}_{N_2} = \mathbf{H}_{\frac{N_2}{2}} \otimes \mathbf{H}_2 \quad (12)$$

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad (13)$$

where the operation $\otimes$ denotes the Kronecker product. $h_{N_2}^j$ is called a Hadamard sequence. A binary sequence $\hat{h}_{N_2,i}^{j,d} \in \{1, 0\}$ of length N_2 is given by

$$\hat{h}_{N_2,i}^{j,d} = \frac{1 + (-1)^d h_{N_2,i}^j}{2}.$$

The periodic correlation function at $i' = 0$ between $h_{N_2}^j$ and $\hat{h}_{N_2}^{j',d}$ except $j = j' = 0$ is given by

$$\begin{aligned} \rho_{h_{N_2}^j, \hat{h}_{N_2}^{j',d}, 0} &= \frac{1}{2} \sum_{i=0}^{N_2-1} (h_{N_2,i}^j + (-1)^d h_{N_2,i}^j h_{N_2,i}^{j'}) \\ &= (-1)^d \frac{1}{2} \rho_{h_{N_2}^j, h_{N_2}^{j'}, 0} \\ &= \begin{cases} w_h & ; j = j', d = 0 \\ -w_h & ; j = j', d = 1 \\ 0 & ; j \neq j' \end{cases} \end{aligned} \quad (14)$$

with

$$\sum_{i=0}^{N_2-1} h_{N_2,i}^j = 0, \quad (15)$$

$$\begin{aligned} \rho_{h_{N_2}^j, h_{N_2}^{j'}, 0} &= \sum_{i=0}^{N_2-1} h_{N_2,i}^j h_{N_2,i}^{j'} \\ &= \begin{cases} N_2 & ; j = j' \\ 0 & ; j \neq j' \end{cases} \end{aligned} \quad (16)$$

$$w_h = \frac{N_2}{2}. \quad (17)$$

If N_1 and N_2 are relatively prime, i. e., $\gcd(N_1, N_2) = 1$, a bi-phase sequence $a_N^j = (a_{N,0}^j, a_{N,1}^j, \dots, a_{N,i}^j, \dots, a_{N,N-1}^j)$ of length $N = N_1 N_2$ is produced by

$$a_{N,i}^j = b_{N_1,i \bmod N_1} \cdot h_{N_2,i \bmod N_2}^j. \quad (18)$$

Similarly, a binary sequence $\hat{a}_N^{j,d} = (\hat{a}_{N,0}^{j,d}, \hat{a}_{N,1}^{j,d}, \dots, \hat{a}_{N,i}^{j,d}, \dots, \hat{a}_{N,N-1}^{j,d})$ of length $N = N_1 N_2$ is produced by

$$\hat{a}_{N,i}^{j,d} = \hat{b}_{N_1,i \bmod N_1} \cdot \hat{h}_{N_2,i \bmod N_2}^{j,d}. \quad (19)$$

The periodic correlation function between a_N^j and $\hat{a}_N^{j',d}$ except $j = j' = 0$ is given by

$$\begin{aligned} \rho_{a_N^j, \hat{a}_N^{j',d}, i'} &= \sum_{i=0}^{N-1} a_{N,i}^j \hat{a}_{N,(i+i') \bmod N}^{j',d} \\ &= \sum_{i=0}^{N-1} \left\{ b_{N_1,i \bmod N_1} \cdot \hat{b}_{N_1,(i+i') \bmod N_1} \right. \\ &\quad \cdot \left. \left\{ h_{N_2,i \bmod N_2}^j \hat{h}_{N_2,(i+i') \bmod N_2}^{j',d} \right\} \right\} \\ &= \left\{ \sum_{i=0}^{N_1-1} b_{N_1,i \bmod N_1} \cdot \hat{b}_{N_1,(i+i') \bmod N_1} \right\} \\ &\quad \cdot \left\{ \sum_{i=0}^{N_2-1} h_{N_2,i \bmod N_2}^j \hat{h}_{N_2,(i+i') \bmod N_2}^{j',d} \right\} \\ &= \rho_{b_{N_1}, \hat{b}_{N_1}, i'} \rho_{h_{N_2}^j, \hat{h}_{N_2}^{j',d}, i'} \\ &= \begin{cases} w & ; i' = 0, j = j', d = 0 \\ -w & ; i' = 0, j = j', d = 1 \\ 0 & ; i' = 0, j \neq j' \\ 0 & ; 1 \leq |i'| \leq N_1 - 1 \end{cases} \end{aligned} \quad (20)$$

with

$$w = w_b \cdot w_h = \frac{(N_1 + 1)N_2}{4}. \quad (21)$$

Therefore a set of bi-phase sequences, a_N^j 's, and binary sequences, $\hat{a}_N^{j,d}$'s, is an optical ZCZ code with $Zcz = N_1 - 1 = 4n_1 - 2$ and $M = N_2 - 1 = N/(Zcz + 1) - 1$.

III. TREE-TYPE BANK OF MATCHED FILTERS FOR OPTICAL ZCZ CODE

Figure 1 shows an M-ary/ASK-SS system using an optical ZCZ code. A transmitter selects a binary sequence $\hat{a}_N^{j'}$ within

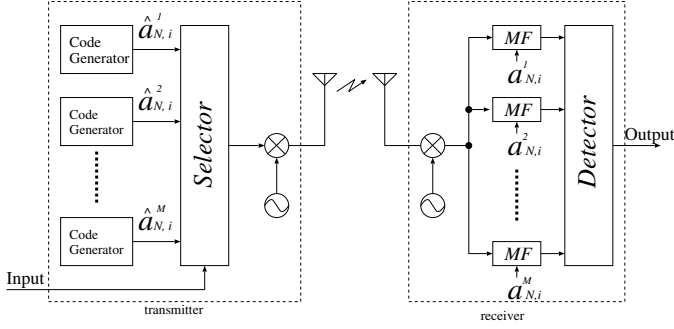


Fig. 1. M-ary/ASK-SS system using an optical ZCZ code.

an optical ZCZ code in according to input data, and it is modulated by on-off keying. A receiver detects the selected sequence from the maximum value of correlations between the received signal and bi-phase sequences, a_N^j 's in bank of matched filters, and recover the data.

In the M-ary/ASK-SS system using an optical ZCZ code, the bank of matched filters yields the M correlation outputs between a received binary sequence $\hat{a}_N^{j'}$ and each of the M bi-phase sequences, a_N^j 's, corresponding to possible transmitted binary sequences, $\hat{a}_N^{j,d}$'s, with $1 \leq j \leq M$. The direct-type matched filter for a sequence of length N , which is constructed by $N - 1$ adders (2-input adders) and $N - 1$ delay circuits is shown in Figure 2. The parallel-type bank of matched filters is constructed by arranging M direct-type matched filters in parallel as shown in Figure 3. Therefore, the number of 2-

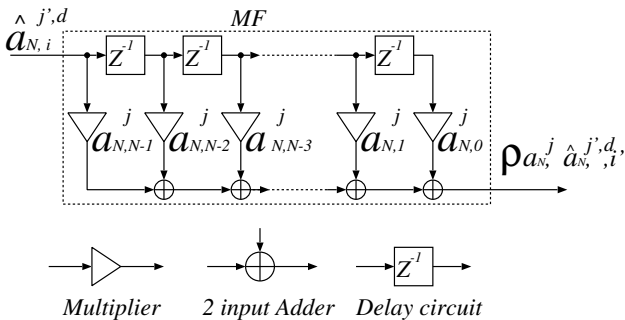


Fig. 2. A direct-type matched filter for a bi-phase sequence a_N^j of length N corresponding to an optical ZCZ code A .

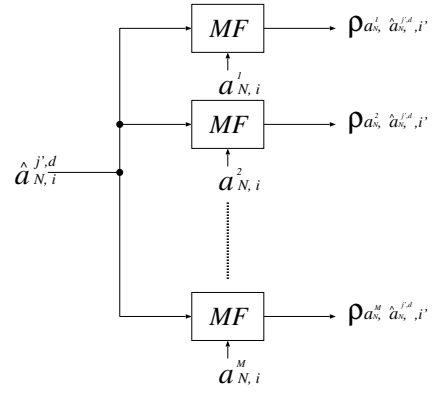


Fig. 3. A parallel-type matched filter bank for a bi-phase sequence a_N^j of family size M corresponding to an optical ZCZ code A .

input adders, N_{add} , and delay circuits, N_{del} , in the parallel-type matched filter bank are written as

$$\begin{aligned} N_{add} &= N_{del} = (N - 1) \cdot M \\ &= \frac{(N - 1)(N - Zcz - 1)}{Zcz + 1}. \end{aligned} \quad (22)$$

It is not easy to realize the filter bank because the 2-input adders and the delay circuits increase as $O(N^2)$.

From Equation (18), the periodic correlation function $\rho_{a_N^j, \hat{a}_N^{j',d}, i'}$ shown in Equation (20) is written as

$$\begin{aligned} \rho_{a_N^j, \hat{a}_N^{j',d}, i'} &= \sum_{i=0}^{N-1} a_{N,i}^j \hat{a}_{N,(i+i') \bmod N}^{j',d} \\ &= \sum_{i=0}^{N-1} \{ b_{N_1,i \bmod N_1} h_{N_2,i \bmod N_2}^j \cdot \hat{a}_{N,(i+i') \bmod N}^{j',d} \} \\ &= \frac{\sum_{i=0}^{N-1} b_{N_1,i \bmod N_1} \hat{a}_{N,(i+i') \bmod N}^{j',d}}{\sum_{i=0}^{N_2-1} \hat{h}_{N_2,i}^{j',d}} \\ &\quad \times \frac{\sum_{i=0}^{N-1} h_{N_2,i \bmod N_2}^j \hat{a}_{N,(i+i') \bmod N}^{j',d}}{\sum_{i=0}^{N_1-1} \hat{b}_{N_1,i}} \\ &= \frac{1}{w} \left\{ \sum_{i_1=0}^{N_1-1} b_{N_1,i_1} \cdot \sum_{k_1=0}^{N_2-1} \hat{a}_{N,(i_1+i'+k_1N_1) \bmod N}^{j',d} \right\} \\ &\quad \left\{ \sum_{i_2=0}^{N_2-1} h_{N_2,i_2}^j \sum_{k_2=0}^{N_1-1} \hat{a}_{N,(i_2+i'+k_2N_2) \bmod N}^{j',d} \right\} \end{aligned} \quad (23)$$

with

$$w = \sum_{i=0}^{N_1-1} \hat{b}_{N_1,i} \sum_{i=0}^{N_2-1} \hat{h}_{N_2,i}^{j'} = \frac{(N_1 + 1)N_2}{4}, \quad (24)$$

which is the same as absolute value of the periodic correlation function $\rho_{a_N^j, \hat{a}_N^{j,d}, 0}$ at shift 0. Equation (23) shows that correlation function $\rho_{a_N^j, \hat{a}_N^{j',d}, i'}$ between a_N^j and $\hat{a}_N^{j',d}$ is expressed by the product of the correlation function between b_{N_1} and $\hat{a}_N^{j',d}$ and the correlation function between $h_{N_2}^j$ and $\hat{a}_N^{j',d}$. Therefore,

we can modify to a bank of matched filters, which consists of matched filters for M-sequence b_{N_1} and Hadamard sequences, $h_{N_2}^j$'s.

Let $e_{N_2}^{jk}$ be a zero-value-inserted sequence of length $n = 2^k + 1$ with $1 \leq k \leq n_2 - 1$, which is obtained by inserting $n - 2 = 2^k - 1$ zero value between the adjacent two values of a Sylvester-type Hadamard sequence h_2^{jk} of length 2, written as

$$\begin{aligned} e_{N_2}^{jk} &= (e_{n,0}^{jk}, e_{n,1}^{jk}, \dots, e_{n,i}^{jk}, \dots, e_{n,n-1}^{jk}) \\ &= (h_{2,0}^{jk}, \underbrace{0, 0, \dots, 0}_{n-2}, h_{2,1}^{jk}) \end{aligned} \quad (25)$$

with $j_k \in \{1, 0\}$. The Hadamard sequence $h_{N_2}^j$ of length $N_2 = 2^{n_2}$ is given by convolving element sequences $h_2^{j_0}, e_3^{j_1}, \dots, e_{2^{n_2-1}+1}^{j_{n_2-1}}$ as follows;

$$h_{N_2,i}^j = h_{2,i}^{j_0} * e_{3,i}^{j_1} * \dots * e_{2^k+1,i}^{j_k} * \dots * e_{2^{n_2-1}+1,i}^{j_{n_2-1}} \quad (26)$$

where operation $*$ denotes discrete convolution as

$$e_{n,i}^{j_k} * e_{n',i'}^{j'_k} = \sum_{i''=0}^{n-1} e_{n,i''}^{j_k} e_{n',i-i''}^{j'_k}. \quad (27)$$

The sequence number j is expressed in a binary notation as follows:

$$j = (j_{n_2-1} j_{n_2-2} \dots j_k \dots j_1 j_0)_2 \quad (28)$$

For example, a Sylvester-type Hadamard sequence $h_4^1 = (1, -1, 1, -1)$ of length 4 is convolved by $h_2^1 = (1, -1)$ and $e_3^0 = (1, 0, 1)$. Similarly, a sequence $h_4^2 = (1, 1, -1, -1)$ is convolved by $h_2^0 = (1, 1)$ and $e_3^1 = (1, 0, -1)$.

For example, Figure 4 shows tree-type bank of matched filters for an optical ZCZ code of length 12, which is constructed by a M-sequence $b_3 = (1, 1, -1)$ of length $N_1 = 3$ and Sylvester-type Hadamard sequences $h_{4,i}^j = h_{2,i}^{j_0} * e_{3,i}^{j_1}$ of length $N_2 = 4$ with $h_2^0 = (1, 1)$, $h_2^1 = (1, -1)$, $e_3^0 = (h_{2,0}^0, 0, h_{2,1}^0) = (1, 0, 1)$, $e_3^1 = (h_{2,0}^1, 0, h_{2,1}^1) = (1, 0, -1)$, where c_i and d_i in Figures 4 are the followings, respectively.

$$c_i = \sum_{k=0}^{N_2-1} \hat{a}_{N,(i+i'+kN_1) \bmod N}^{j',d} \quad (29)$$

$$d_i = \sum_{k=0}^{N_1-1} \hat{a}_{N,(i+i'+kN_2) \bmod N}^{j',d} \quad (30)$$

A filter bank, which is connected in order of $e_3^{j_1}$ and $h_2^{j_0}$, as shown in Figure 4 is constructed by 4 multipliers, 21 adders (2-input adders) and 13 delay circuits. Generally, the number of multipliers, N_{mul} , 2-input adders, N_{add} , and delay circuits, N_{del} , of the tree-type bank of matched filters, which is connected in order of $e_{2^{n_2-1}+1}^{j_{n_2-1}}, \dots, e_{2^k+1}^{j_k}, \dots, e_3^{j_1}$ and

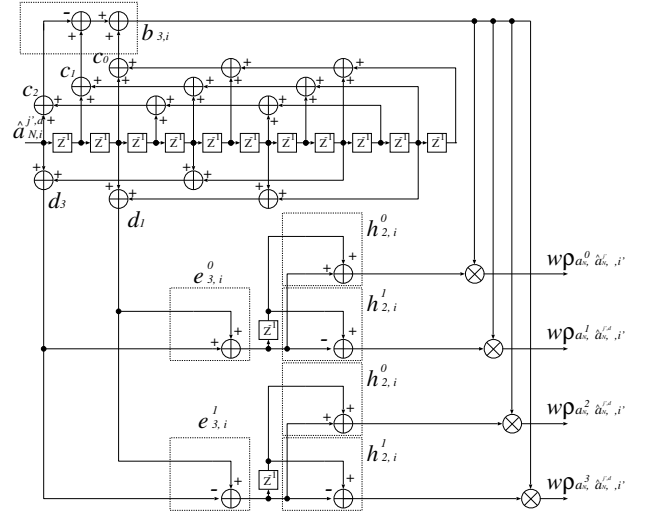


Fig. 4. Tree-type bank of matched filters for an optical ZCZ code of $N = 12$ and $Zcz = 2$ ($e_3^{j_1} \rightarrow h_2^{j_0}$).

$h_2^{j_0}$ are the followings, respectively.

$$N_{mul} = \frac{N}{N_1} = \frac{N}{Zcz + 1} \quad (31)$$

$$\begin{aligned} N_{add} &= \left(\frac{N_1 + 2}{N_1}\right)N + 2N_1 - 5 \\ &= \left(\frac{Zcz + 3}{Zcz + 1}\right)N + 2Zcz - 3 \end{aligned} \quad (32)$$

$$\begin{aligned} N_{del} &= \frac{N}{2N_1} \log_2 \frac{N}{N_1} + \frac{2N_1 - 1}{2N_1} N - 1 \\ &= \frac{N}{2(Zcz + 1)} \log_2 \frac{N}{Zcz + 1} + \frac{2Zcz + 1}{2(Zcz + 1)} N - 1. \end{aligned} \quad (33)$$

The tree-type filter bank can decrease the number of 2-input adders, N_{add} , from $O(N^2)$ to $O(N)$ and delay circuits, N_{del} , from $O(N^2)$ to $O(N \log_2 N)$, respectively, but need $N/(Zcz + 1)$ multipliers. Figure 5 shows the number of multipliers, N_{mul} , 2-input adders, N_{add} and delay circuits, N_{del} of matched filter banks for optical ZCZ codes of length $N = 6, 12, 24, 48, 96$.

The input-output characteristics of bank of matched filters for tree-type bank of matched filters with zero correlation zone $4n - 2$ is nonlinear characteristics, because the transfer function of tree-type filter bank does not transform the transfer function of parallel-type filter bank directly. Figure 6 shows the input-output characteristics of bank of matched filters for the code with $N_1 = 3$ and $N_2 = 4$.

IV. EVALUATION OF BER PERFORMANCE

M-ary/ASK-SS system using tree-type bank of matched filters for optical ZCZ codes of zero correlation zone $4n - 2$ might go down the BER performance because input-output characteristics of this filters for this code is nonlinear characteristics. Therefore, we analyse the influence on the BER

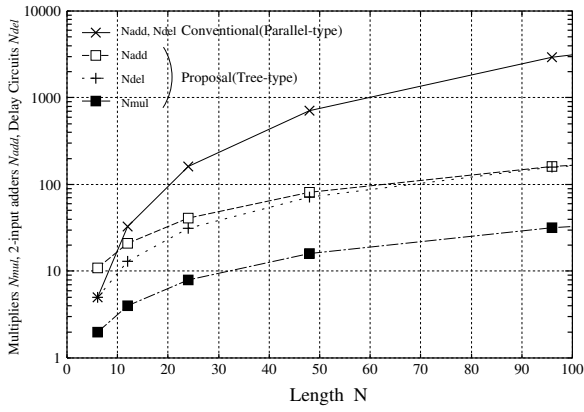


Fig. 5. The number of operation elements N_{mul} , N_{add} and N_{del} of bank of matched filters for an optical ZCZ codes of $Zcz = 2$.

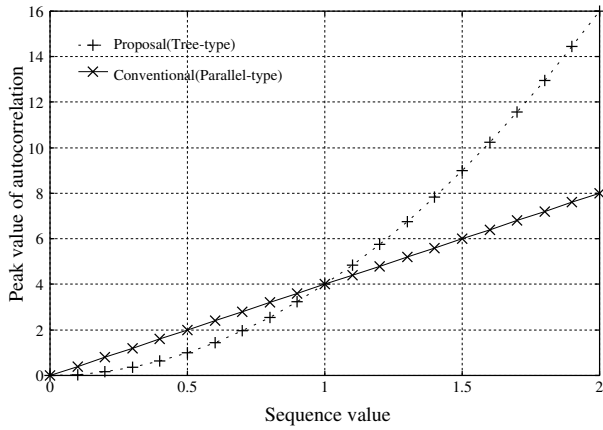


Fig. 6. Input-output characteristics of bank of matched filters ($N_1 = 3$, $N_2 = 4$).

performance by this nonlinear characteristics. Table I shows specifications of computer simulation.

Figure 7 shows BER performance ASK-SS systems under the additive white Gaussian noise (AWGN) environment. The theoretical formula of BER characteristics in ASK-SS system using optical ZCZ code with $Zcz = 4n - 2$ under the AWGN environment is as follows.

$$BER = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{(N_1 + 1)E_b}{4N_1N_0}} \quad (34)$$

, where E_b is the signal energy per bit and N_0 is noise power spectral ratio. The BER performance of ASK-SS system using tree-type bank of matched filters under the AWGN environment go down compared to BER performance of parallel-type filters as expected.

Figure 8 shows BER performance M-ary/ASK-SS systems under the additive white Gaussian noise (AWGN) environment. The BER performance of M-ary/ASK-SS system are improved as sequence length N increases. The BER performance of M-ary/ASK-SS system using tree-type bank of matched filters under the AWGN environment are almost equal

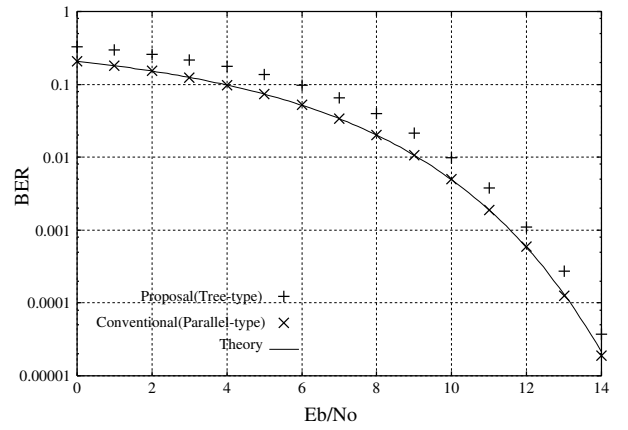


Fig. 7. BER performance of ASK-SS systems under the additive white Gaussian noise (AWGN) environment ($N_1 = 3$).

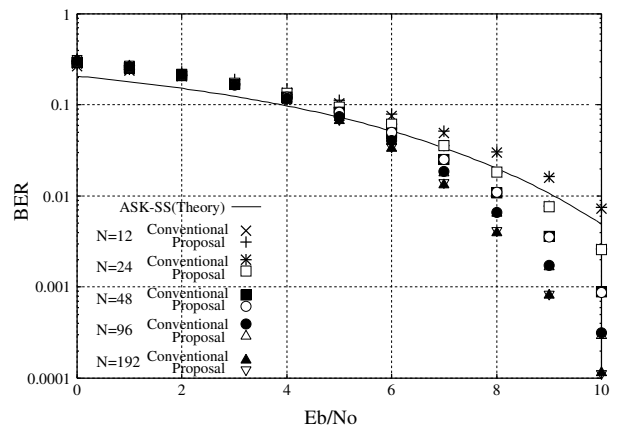


Fig. 8. BER performance of M-ary/ASK-SS systems under the additive white Gaussian noise (AWGN) environment ($N_1 = 3$).

compared to BER performance of parallel-type filters.

Figure 9 shows BER performance ASK-SS systems under the frequency nonselective fading. The theoretical formula of BER characteristics in ASK-SS system using optical ZCZ code with $Zcz = 4n - 2$ under the frequency nonselective fading environment is as follows.

$$BER = \frac{1}{2} \left\{ 1 - \frac{1}{\sqrt{1 + \frac{4N_1N_0}{(N_1+1)E_b}}} \right\} \quad (35)$$

The BER performance of ASK-SS system using tree-type bank of matched filters under the frequency nonselective fading environment go down compared to BER performance of parallel-type filters as expected.

Figure 10 shows BER performance of M-ary/ASK-SS systems under the frequency nonselective fading environment. The BER performance of M-ary/ASK-SS system using tree-type bank of matched filters under the frequency nonselective fading environment are almost equal compared to BER performance of parallel-type filters.

TABLE I
SPECIFICATIONS OF COMPUTER SIMULATION.

Spreading sequence	optical ZCZ code
Sequence length N of optical ZCZ code	6, 12, 24, 48, 96, 192
Family size M	1, 3, 7, 15, 31, 63
Zero correlation zone Z_{cz}	2
Sequence length N_1 of M-sequence	3
Sequence length N_2 of Hadamard code	2, 4, 8, 16, 32, 64
Modulation method	ASK-SS, M-ary/ASK-SS
Bits per symbol	1, 2, 3, 4, 5, 6
Communication environment	AWGN, frequency nonselective fading

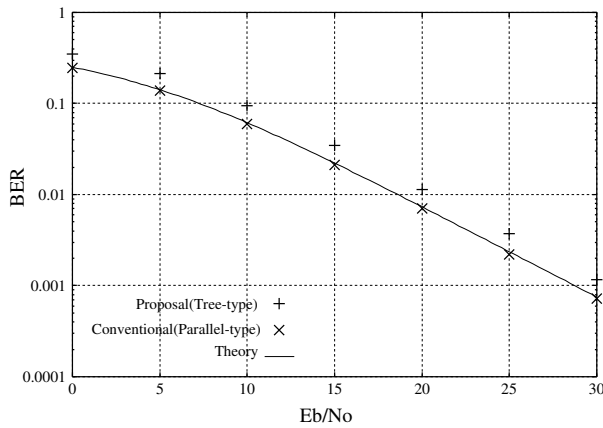


Fig. 9. BER performance of ASK-SS systems under the frequency nonselective fading (AWGN) environment($N_1 = 3$).

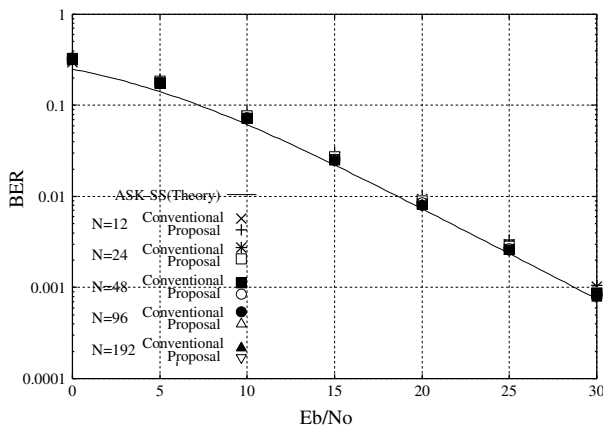


Fig. 10. BER performance of M-ary/ASK-SS systems under the frequency nonselective fading environment($N_1 = 3$).

V. CONCLUSION

In this paper, we analyse the influence on the BER performance in ASK-SS and M-ary/ASK-SS systems under the AWGN and the frequency nonselective fading environments by nonlinear characteristics of tree-type bank of matched filters for the optical ZCZ code of $Z_{cz} = 4n - 2$.

The BER performance of ASK-SS system using tree-type bank of matched filters under the AWGN and frequency

nonselective fading environments go down compared to BER performance of parallel-type filters as expected. But the BER performance of M-ary/ASK-SS system using this compact filters under the AWGN and frequency nonselective fading environment are almost equal compared to BER performance of parallel-type filters. In fact, the BER performance in M-ary/ASK-SS are not influenced by nonlinear characteristics of tree-type bank of matched filters.

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