MMFSK-EOD System Using Binary Hopping Pattern in FH/SS Communications

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Abstract— **In this paper a detailed explanation of our newly proposed frequency hopped spread spectrum system named "MMFSK-EOD System Using Binary Hopping Pattern" (8) is presented. First, to make clear the concept of FH/M-ary Multilevel FSK modulation (abb. FH/ MMFSK or MMFSK), the waveform and the spectrum differences between MFSK and FH/MFSK or FH/MMFSK are reviewed. Next, to understand the error propagation phenomena from the first demodulation stage to the second demodulation stage, system principle of FH/MMFSK using EOD is explained of some length. In an EOD system, a hopping pattern is synthesized from a group A hopping pattern and a group B hopping pattern, which are different properties on even and odd levels. Finally, to prevent the error propagation novel binary hopping pattern method is proposed, and its effectiveness on improving error performance is shown by illustrative computer simulations. Some additional improving method in the design of group A hopping pattern are also shown.**

Index Terms— **MMFSK, hopping pattern, Even-Odd discrimination method (EOD), error performance**

I. INTRODUCTION

Spread spectrum system is an attractive communication system for transmission through inferior medium such as mobile communications and powerline communications. However its poor spectral efficiency prevents wide applications. When its spectral efficiency is considerably improved wide application field will be envisaged. Based on the idea, we have been studied to improve the spectral efficiency of the frequency hopping spread spectrum system by using plural number of hopping patterns instead of single hopping pattern in existing frequency hopping system. We call the novel system as MMFSK (M-ary Multilevel FSK). In MMFSK we transmit $\mathrm{Log}_2 mh$ bits every T second instead of $\log_2 m$ bits in ordinary MFSK, where m is the number of frequencies used and h is the number of hopping patterns used. For simplicity we use the word "level" instead of frequency as later explained in the paper. In MMFSK system the more increase the number of hopping patterns the more the transmission rate can increase, however, the circuit complexity increases and system realizability becomes a problem. To avoid circuit complexity increase, EOD (Even Odd Discrimination method) hopping pattern synthesis method was proposed. In an EOD system, a hopping pattern is synthesized from a group A hopping pattern and a group B hopping pattern, where group A hopping pattern includes both even number levels and odd number levels as EOEEO and group B hopping patterns is composed of even number levels only as EEEEE. When there are m_1 hopping patterns in group A and m_2 hopping patterns in group B, then, $m_1 \times m_2$ hopping patterns can be produced by m_1+m_2 hopping patterns and the circuit can be made greatly simplified.

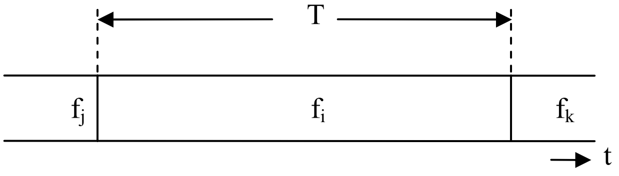
In the EOD demodulation process, first the transmitted A group hopping pattern is discriminated by its EO pattern and subtract it from the input level signal and in the second demodulation stage remaining B group component and the transmitted level are determined through the majority logic. However, in an ordinary EOD system, there was a defect that errors arisen in the first demodulation stage directly affect the second demodulation process and deteriorate the error probability of the system.

In this paper to separate errors from the first demodulation stage and the second demodulation stage, new category of group A hopping pattern named binary hopping pattern is proposed. By using the binary hopping pattern, we can remove the effect of first stage error on the second stage demodulation performance and achieve good error performance.

II. WAVEFORMS AND SPECTRA OF MFSK, FH/MFSK, FH/MMFSK

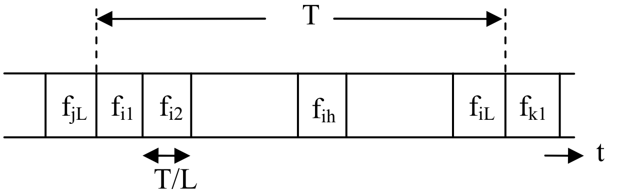
MFSK, FH/MFSK, FH/MMFSK are variations of frequency shift keying modulation schemes. In these the waveform and the spectrum of FH/MFSK and FH/MMFSK are quite the same, so that in this section the difference between MFSK and FH/MFSK or FH/MMFSK is reviewed.

First, MFSK (Multiple Frequency Shift Keying) is a modulation scheme, in which, every T second one of m frequencies is selected and transmitted. The waveform is as shown in Fig.1(a).



$f_i = f_0 + i\Delta f$ (i:0, 1,…,m-1, $\Delta f = 1/T$)

(a) MFSK

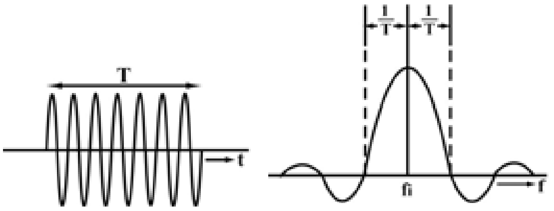


$f_{ih} = f_0 + i_h L\Delta f$ (i_h:0, 1,…,m-1, $\Delta f = 1/T$)

(b) FH/MFSK, FH/MMFSK

Fig.1 Waveform.

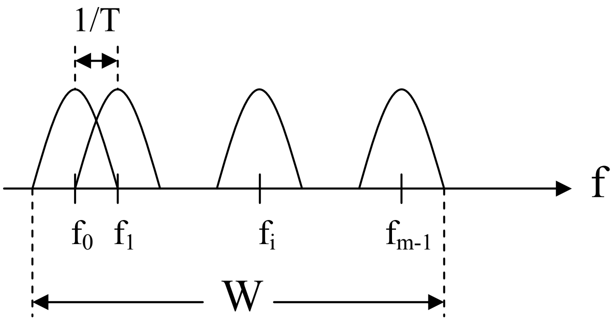
As shown in Fig.1(a) frequencies are keyed every T second from f_j to f_i to f_k and so on. There are m frequencies f_0, f_1, …, f_{m-1} available for each f_i, f_j, f_k and we can transmit $\log_2 m$ bits for every T second. Each keyed duration T frequency segment (tone) shows dumped sinusoidal spectrum as shown in Fig.2.



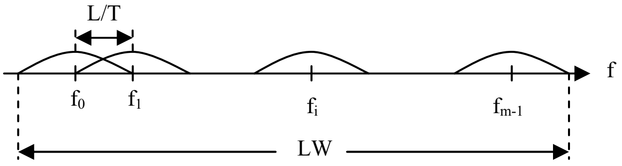
(a): Wave form (b): Spectrum

Fig.2 Tone and its spectrum.

As shown in Fig.1(a) f_i 's are equally spaced as $f_i = f_0 + i\Delta f$ (i:0,1,2,…,m-1) and it is well known that the minimum spacing which satisfies the orthogonally is $\Delta f = 1/T$. Fig.3(a) shows the frequency arrangement of MFSK.



(a) MFSK



(b) FH/MFSK, FH/MMFSK

Fig.3 Spectrum.

In these figures only main lobes are shown for simplicity. Necessary total transmission bandwidth of MFSK which use m tones of duration T is W = (m+1)/T.

Next, consider FH/MFSK and FH/MMFSK. Both FH/MFSK and FH/MMFSK are frequency hopped spread spectrum systems which use frequency hopping pattern as a bandwidth expansion tool. Fig.1(b) shows the waveform. As shown in the figure every signal duration T is subdivided into L chips and frequencies are keyed every T/L second. Similar to MFSK a total of m frequencies are used but their frequency spacing is L times larger than that in MFSK as

$$f_i' = f_0 + iL\Delta f \quad \text{(i:0, 1, 2, …, m-1; } \Delta f = 1/T) \qquad (1)$$

Fig.3(b) shows the frequency arrangement of FH/MFSK and FH/MMFSK. Necessary total transmission bandwidth is W= (m+1)L/T as shown in the figure. Information transmission rate of FH/MFSK is the same as MFSK, that is, R=($\log_2$m)/T [bits/sec]. In this system shorter keying duration does not contribute to increase the information transmission rate, but instead, bandwidth expansion makes the system robust to various disturbances and/or variations of the line as is the characteristic feature common to all spread spectrum systems.

Spectral efficiency of FH/MFSK is given as

$$\frac{R}{W} = \frac{\log_2 m}{(m+1)L} \qquad (2)$$

This is 1/L smaller than that of MFSK.

To improve the spectral efficiency of the system FH/MMFSK was proposed.

In a FH/MFSK system a fixed frequency hopping pattern is used as a bandwidth expansion tool, instead, in a FH/MMFSK system plural number of hopping patterns is used to increase the transmission rate.

This M-aryzation does not affect the transmission bandwidth nor transmission power at all and the spectrum can be given by the same figure as shown in Fig.3(b). Detailed explanation of the system given in later sections.

III. SYSTEM PRINCIPLE OF FH/MMFSK USING EOD

(1) M-aryzation by using plural hopping patterns

In existing frequency hopping systems including FH/MFSK, frequency hopping pattern is used as a key to open the embedded information and single hopping pattern has been used, however in our newly proposed FH/MMFSK many hopping patterns are used to increase the information transmission rate. Hopping patterns are used not only as a key to open the embedded information but also as an information carrier. When we use h hopping patterns we can transmit $\log_2 h$ [bits] per every T second by hopping pattern itself. Then the spectral efficiency of FH/MFSK expressed in equation (2) changes to the following equation (3) for FH/MMFSK.

$$\frac{R}{W} = \frac{\log_2 mh}{(m+1)L} \tag{3}$$

The more increase the number of hopping patterns we can transmit the more information, however, circuit complexity may increase and the system realizability becomes the problem. To avoid the problem EOD hopping pattern synthesis method is invented.

(2) Level and vector notation of the hopping pattern

To simplify the discussion hereafter we will use the word “level” to designate the frequency. Level is the same as number i in equation (1). As shown in Fig.1(b), in FH/MFSK or FH/MMFSK systems frequency changes every T/L second in accordance with the hopping pattern change. Frequency change with time of a hopping pattern is well expressed by the level- chip matrix, ordinate of which indicates levels 0, 1, 2, …, m-1 and abscissa indicates time chips 1, 2, …, L. A hopping pattern in level-time matrix can also be written as $(a_{i1}, a_{i2}, \ldots, a_{iL})$, where a_{ix} indicates the level of chip x. A set $(a_{i1}, a_{i2}, \ldots, a_{iL})$ can be expressed by L dimensional vector $\mathbf{A_i}$, the components of which are $a_{i1}, a_{i2}, \ldots, a_{iL}$.

(3) EOD (Even Odd Discrimination Method) hopping pattern synthesis

In an EOD system a hopping pattern is synthesized from two hopping patterns each belongs to different hopping pattern groups A or B. When there are m_1 hopping patterns in group A and m_2 hopping patterns in group B, then a total of $m_1 \times m_2$ hopping patterns can be produced from m_1+m_2 hopping patterns. To realize the system some discrimination method of distinguishing group A and group B is necessary.

In our proposed EOD system, to give distinctive features to group A and B, group A hopping patterns comprises both even number levels and odd number levels such as EOOEO, while group B hopping patterns are composed of even number levels only such as EEEEE, where E represents an even number level and O represents an odd number level.

(4) MMFSK transmitter using EOD

Fig.4 shows a block diagram of MMFSK transmitter using EOD.

Input K bits dater stream is first divided into K_1 bits and K_2 bits. K_1 bits select a level L_h out of $m=2^{k1}$ levels**.** A level L_h is repeated over L time chips as shown in Fig.5. K_2 bits are further divided into K_{21} bits and K_{22} bits. K_{21} bits select a hopping pattern $\mathbf{A_i}$ out of m_1 hopping pattern generators in group A as shown in the figure. Similarly K_{22} bits select a hopping pattern $\mathbf{B_j}$ out of m_2 hopping pattern generators in group B as shown in the figure. These selected level and hopping patterns are added chip by chip by modulo m base and finally every level is converted to tone and FSK like signal is transmitted. An example of the modulation process of the transmitter is shown in Fig.5.

(5) MMFSK receiver using EOD

Fig.6 shows a corresponding receiver block diagram.

Input frequencies are first converted to levels and the transmitted level signal $\mathbf{L_h}+\mathbf{A}_i+\mathbf{B_j}$ is reproduced. In the first stage of demodulation, input level signal is subtracted by A group hopping patterns in parallel. Output of $\mathbf{A_k}$ subtracted branch is $\mathbf{L_h}+(\mathbf{A_i}-\mathbf{A_k}) +\mathbf{B_j}$ and unless $\mathbf{A_i}=\mathbf{A_k}$ the output contains both even number level E and odd number level O, thus we can determine transmitted $\mathbf{A_i}$ by selecting a branch which exhibit all E or all O. When $\mathbf{A_i}$ is correctly subtracted, the input signal for the second stage becomes $\mathbf{L_h}+\mathbf{B_j}$ and this input signal is subtracted by B group hopping patterns in parallel and only the output of $\mathbf{B_j}$ subtracted branch shows a horizontal straight line $\mathbf{L}_h$ in the receiving matrix, thus we can determine both $\mathbf{B_j}$ and $\mathbf{L_h}$**.**

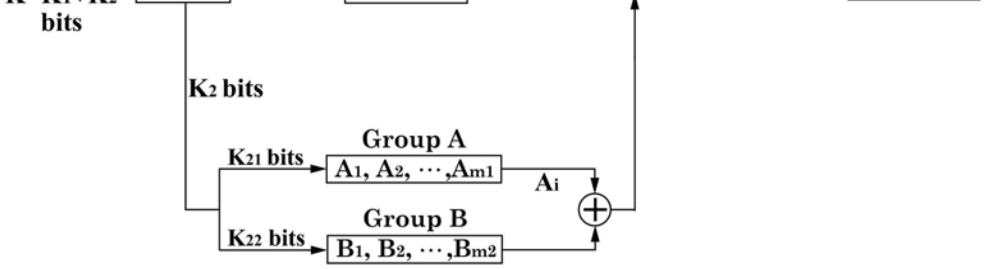


Fig.4 MMFSK transmitter using EOD.

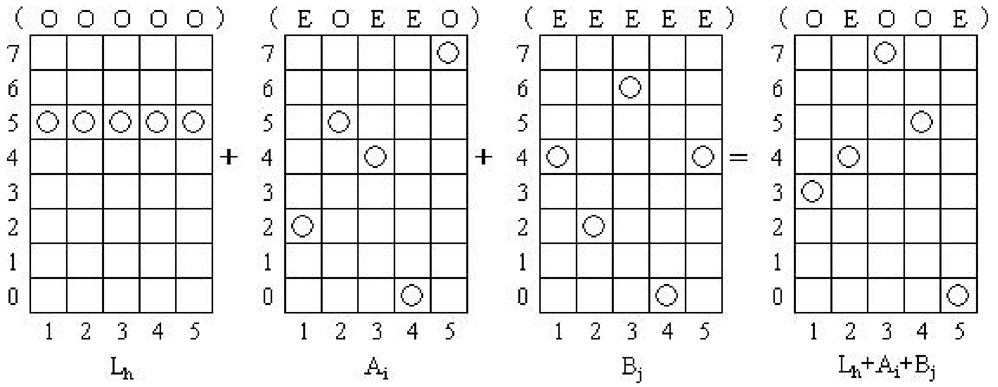


Fig.5 Modulation process.

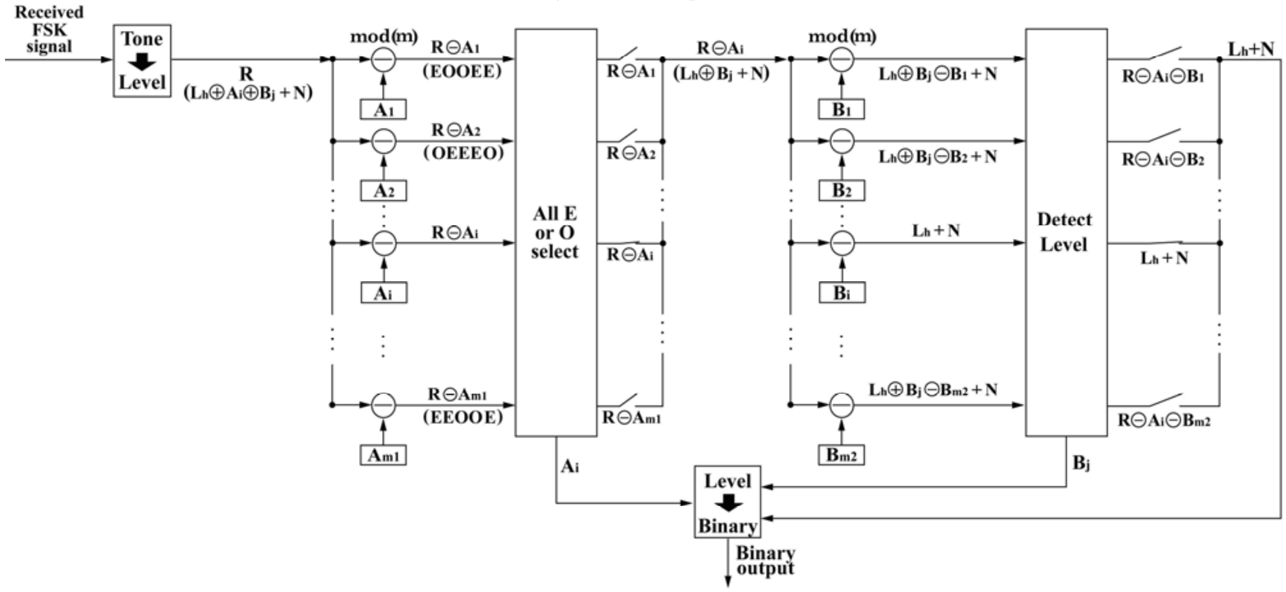


Fig.6 MMFSK Receiver using EOD.

IV. OPERATION OF MAJORITY DECISION LOGIC

There are m_2 group B hopping patterns in the receiver, and, every hopping pattern is subtracted individually from the second stage input signal. When subtract $\mathbf{B_x \cdot B_j}$, the output is as shown in Fig.7.

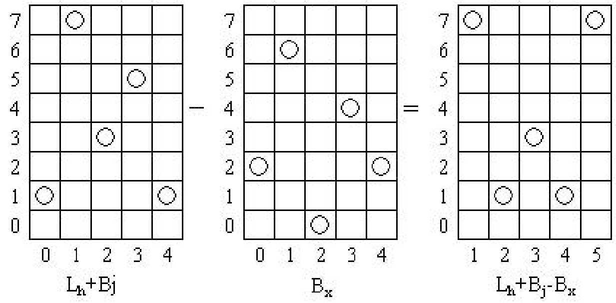


Fig.7 Output of wrong B.

By checking all subtracted outputs through a majority decision logic we can find $\mathbf{B_j}$ and $\mathbf{L_h}$ simultaneously. In the above example no error is postulated in the decision of $\mathbf{A_i}$, however, when a wrong choice of $\mathbf{A_x}$ occurs in the first demodulation stage, second demodulation stage input becomes $\mathbf{L_h}$+($\mathbf{A_i}$-$\mathbf{A_x}$)+$\mathbf{B_j}$ and even correctly subtract $\mathbf{B_j}$, the output becomes $\mathbf{L_h}$+$\mathbf{A_i}$-$\mathbf{A_x}$ as shown in Fig.8.

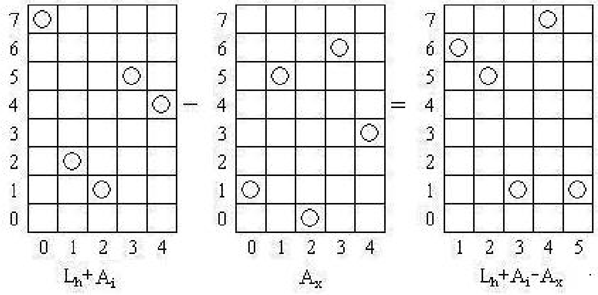


Fig.8 Effect of first stage error.

In such a case it is almost impossible to find correct $\mathbf{L_h}$ and $\mathbf{B_j}$, that is, when we specify EO patterns only for group A hopping patterns, errors arisen in the first demodulation stage influence the second demodulation stage. To prevent error propagation from the first demodulation stage to the second demodulation stage, binary hopping patterns are proposed in the following.

V. BINARY HOPPING PATTERN

Group A hopping patterns are characterized by their EO patterns only. There can be many hopping patterns which exhibit the same EO pattern and this gives some confusion in the design of group A hopping patterns. In this paper a new category of group A hopping pattern named binary hopping pattern is proposed. When we use binary hopping patterns, error propagation from the first demodulation stage to the second demodulation stage can be prevented by the majority decision logic in the second demodulation stage.

Binary hopping patterns are defined as follows. That each level must take a value out of either one of two neighboring values. This makes the components of $\mathbf{A_i}$-$\mathbf{A_k}$ 0 or ± 1.

Table 1 shows a most simple example in which E=0, O=1. (Type 1)

Table 1 Hopping patterns of (0, 1) levels.(Type 1)

$\mathbf{A_1}$	E O E E O	0 1 0 0 1
$\mathbf{A_2}$	O E O E O	1 0 1 0 1
$\mathbf{A_1}$-$\mathbf{A_2}$		-1 1-1 0 0

Table 2 shows another simple example in which E=4, O=5. (Type2)

Table 2 Hopping patterns of (4, 5) levels.(Type 2)

$\mathbf{A_1}$	E O E E O	4 5 4 4 5
$\mathbf{A_2}$	O E O E O	5 4 5 4 5
$\mathbf{A_1}$-$\mathbf{A_2}$		-1 1 -1 0 0

Table 3 shows the other sophisticated but general example in which levels of every chips are made by different neighboring values. (Type 3)

Table 3 Hopping patterns of (2,3)(6,5)(0,1)(4,5)(4,3) levels.(Type 3)

$\mathbf{A_1}$	E O E E O	2 5 0 4 3
$\mathbf{A_2}$	O E O E O	3 6 1 4 3
$\mathbf{A_1}$-$\mathbf{A_2}$		-1 -1 -1 0 0

In this example, for the first chip E=2, O=3 for the second chip E=6, O=5 for the third chip E=0, O=1 for the forth chip E=4, O=5 for the fifth chip E=4, O=3 are assumed. Type 3 is as shown in Fig.9.

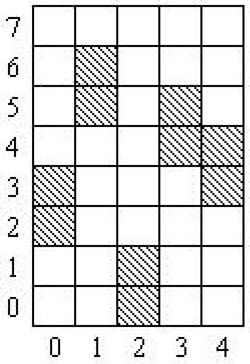


Fig.9 Binary hopping pattern Type 3.

To show the effectiveness of binary hopping patterns an illustrative example is given in Fig.10 and Fig.11.

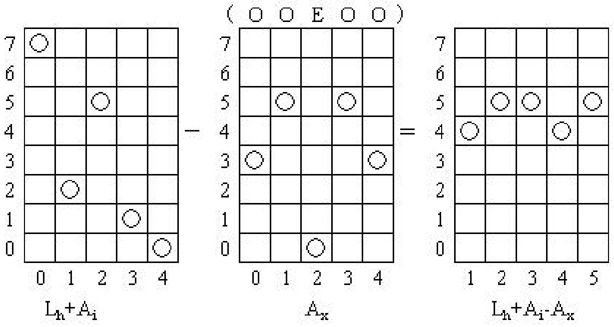


Fig. 11 B_j subtracted output.

Fig.10 shows a transmitting signal in which $\mathbf{A_1}$ in Table 3 is used as $\mathbf{A_i}$. When a wrong choice of $\mathbf{A_x}$ occurs in the receiver, $\mathbf{A_x}$ is also a binary hopping pattern as shown in Fig.11, the result is as shown in the figure. Fig.11 shows the $\mathbf{B_j}$ subtracted output, the other $\mathbf{B_x}$ subtracted output may exhibit a dispersed figure and it may be easy to find $\mathbf{B_j}$ through the majority logic. However, some ambiguity will remain for $\mathbf{L_h}$ as $\mathbf{B_j}$ subtracted output will disperse $\mathbf{L_h}$ ± 1.

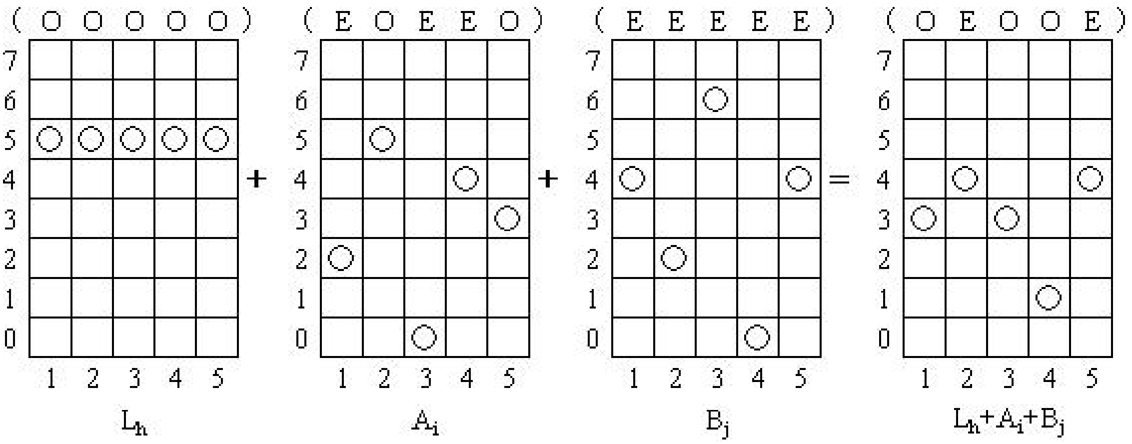


Fig. 10 Modulation by binary hopping pattern. (Type 3)

VI. SOME PROBLEMS IN THE DESIGN OF GROUP A

(1) Minimum Hamming Distance

To make group A hopping pattern itself robust to noise, it is desirable to design EO patterns to have minimum Hamming Distance between codes more than three. When minimum Hamming Distance between codes is set three, effect of one character error can be removed perfectly. Fig.12 shows an example of error probability improvement by Hamming Distances.

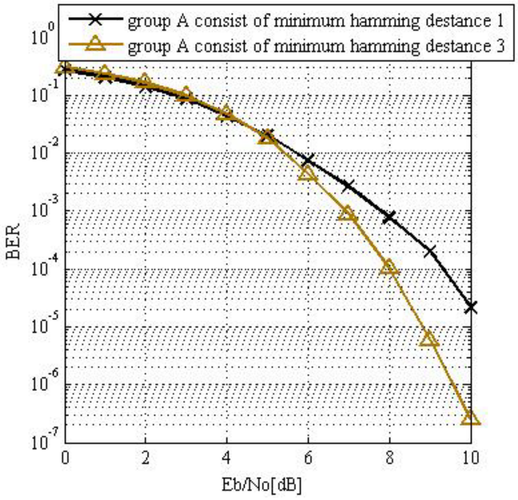


Fig. 12 Comparison of the error performances for minimum distance 3 and 1.

(2) Inversion problem by adding odd level

When an odd level is added to a group A hopping pattern, its EO pattern is reversed. For example a pattern EEEOE will be changed to its reciprocal pattern OOOEO. So that we must discard reciprocal patterns when we use both even levels and odd levels. Instead, if we use even levels only we can use all combinations of EO patterns, and further, ambiguity $\mathbf{L_h} \pm 1$ can be avoided and slight improvement in error probability can be expected.

VII. SIMULATION RESULT

To show the effectiveness of the binary hopping pattern a computer simulation was made. Specification of the simulation is as shown in Table 4. Hopping patterns used in the simulation are shown in Table 5. In Table5, hopping patterns with the same EO pattern are arranged on the same number row.

Fig.13 shows a result of simulation.

Table 4 Simulation model.

Number of frequency level n	16
Number of chips L	7
Number of patterns(group A)	16
Number of patterns(group B)	64
Environment	AWGN
Detection	coherent

Level L_h are even number levels only

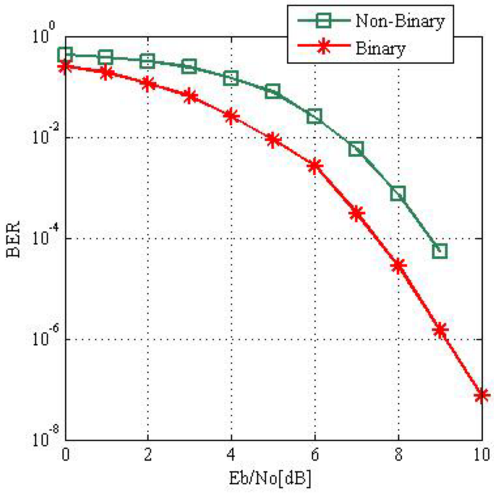
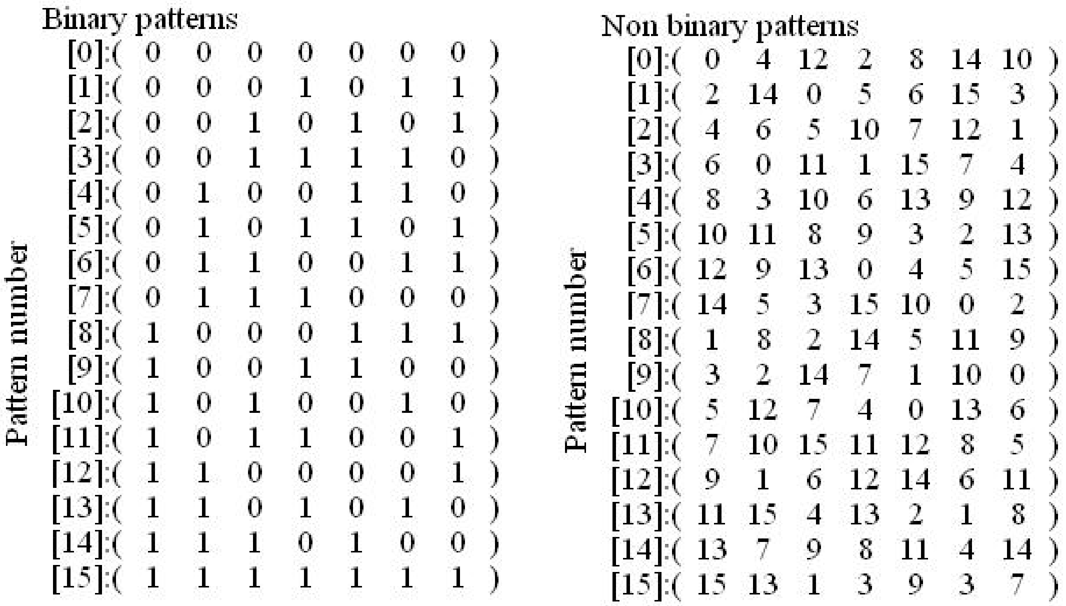


Fig. 13 Comparison of error performances for binary and non-binary.

Table 5 Hopping patterns used.



Binary patterns

Pattern number							
[0]:	0	0	0	0	0	0	0
[1]:	0	0	0	1	0	1	1
[2]:	0	0	1	0	1	0	1
[3]:	0	0	1	1	1	1	0
[4]:	0	1	0	0	1	1	0
[5]:	0	1	0	1	1	0	1
[6]:	0	1	1	0	0	1	1
[7]:	0	1	1	1	0	0	0
[8]:	1	0	0	0	1	1	1
[9]:	1	0	0	1	1	0	0
[10]:	1	0	1	0	0	1	0
[11]:	1	0	1	1	0	0	1
[12]:	1	1	0	0	0	0	1
[13]:	1	1	0	1	0	1	0
[14]:	1	1	1	0	1	0	0
[15]:	1	1	1	1	1	1	1

Non binary patterns

Pattern number							
[0]:	0	4	12	2	8	14	10
[1]:	2	14	0	5	6	15	3
[2]:	4	6	5	10	7	12	1
[3]:	6	0	11	1	15	7	4
[4]:	8	3	10	6	13	9	12
[5]:	10	11	8	9	3	2	13
[6]:	12	9	13	0	4	5	15
[7]:	14	5	3	15	10	0	2
[8]:	1	8	2	14	5	11	9
[9]:	3	2	14	7	1	10	0
[10]:	5	12	7	4	0	13	6
[11]:	7	10	15	11	12	8	5
[12]:	9	1	6	12	14	6	11
[13]:	11	15	4	13	2	1	8
[14]:	13	7	9	8	11	4	14
[15]:	15	13	1	3	9	3	7

VIII. CONCLUSIONS

In this paper as a novel hopping pattern to improve the error probability characteristics of MMFSK-EOD system binary hopping patterns are proposed. By using binary hopping patterns, error propagation from the first demodulation stage to the second demodulation stage can be prevented and the system error performance is improved considerably. Principle of the error performance improvement is explained, and, to show the effectiveness of the binary hopping patterns, a result of computer simulation is given. Further error performance improving methods in the design of group A hopping patterns are also shown.

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