An Effective Cancellation Technique of Cochannel Interference Based on Multiuser Detection Scheme for MFSK/FH-SSMA Systems

JYH-HORNG WEN[1], CHUAN-WANG CHANG[2,3,*] and SHENG-FONG LIN[2]
[1]Department of Electrical Engineering, Tunghai University
[2]Department of Electrical Engineering, National Chung Cheng University
[3]Department of Electrical Engineering, Chien Kuo Technology University
No. 1, Chieh Shou N. Rd., Changhua City, Taiwan, R.O.C.
TEL:+886-4-7111111 Ext.3234
Email: calvin@ctu.edu.tw
*Correspondence address

Abstract: - The performance of a multilevel frequency shift keying/frequency hopping-spread spectrum multiple access (MFSK/FH-SSMA) system over a cochannel interference scenario is dependent on multiuser detection schemes. Many investigations have demonstrated huge potential capacity and performance improvement by using multiuser detection schemes. However, their schemes are extremely complex while the total number of users is increased because the multiuser interference becomes larger. In this paper, we propose a novel multiuser detection scheme to reduce the complexity of decoding process. The performance of the system with the proposed scheme over a nonfading channel is simulated and compared with that of conventional and other multiuser interference cancellers. Simulation results show that the proposed scheme reduces the system complexity and improves the bit error rate (BER).

Key-Words: - Multilevel Frequency Shift Keying (MFSK), Frequency Hopping-Spread Spectrum Multiple Access (FH-SSMA)

1. Introduction

The spread spectrum techniques in communication systems, such as DS-SSMA [1]-[3] and FH-SSMA[4],[5], permit many simultaneous users to share a single transmission medium through the assignment of unique codeword or hopping pattern to each user, respectively. Nevertheless, unlike in DS-SSMA where the data bandwidth is spread by direct modulation with a wideband spreading code, the spreading code in FH-SSMA is used to control the sequence of carrier frequencies. Frequency diversity is achieved by applying an FH pattern onto a data pattern and is obtained to mitigate multipath and diversity of the interferences as seen by any given user [6], [7]. However, the user capacity in FH-SSMA systems is hampered by multiuser cochannel interference (CCI). The term “CCI”, or named “hit”, occurs when more than one users’ tones occupy a specific frequency slot at the same time. An MFSK/FH-SSMA system was proposed by Goodman [7] to reduce the effect of hits. In addition, by properly designing frequency-hopping patterns, CCI can also be minimized as few as possible. Various kinds of address code sets have been studied [8].

For MFSK/FH-SSMA systems, Mabuchi *et al*. proposed a multiuser detection scheme based on canceling CCI [9]-[14]. In the scheme, the receiver decodes all users' candidate data symbols jointly and then these symbols are utilized to produce the estimates of the received data matrix. By using the maximum likelihood decision rule, the matrix that has the most number of coincident entries with the received data matrix is selected. A modified Mabuchi scheme was proposed by Lin *et al*. [15], which further improved the system performance. However, these two schemes are unacceptable in many applications because of their huge amount of computational complexity especially when the total number of users increases in the system. Therefore, another scheme based on modification of Mabuchi's scheme was proposed by us to improve the system complexity [16]-[19]. Furthermore, an effective interference cancellation algorithm that we proposed will get outstanding performance especially in nonfading environments.

The rest of this paper is organized as follows. In Section 2, a novel multiuser detection scheme used in MFSK/FH-SSMA systems is proposed to cope with the increasing complexity resulting from the augmentative number of active users. The algorithm here gives a new method in choosing the candidate rows that will dramatically reduce the complexity of the system. In Section 3, the numerical analysis of the complexity of this system is carried out. In Section 4, computer simulations for various kind of schemes in the MFSK/FH-SSMA system will be carried out and the results of them will also be discussed. Finally, in Section 5, the main results of this paper are summarized.

2. System Description

In an MFSK/FH-SSMA system, there are M pairs of transmitters and receivers. Fig. 1 shows the block diagram of one transmitter. In the transmitter, every k bits of the input binary data are stored in a k-bit buffer. The k-bit message is then mapped into a symbol selected from one integer of the set $\{0,\ 1,\ 2,\cdots,K-1\}$ and denoted by x_m for the mth user, where K=2^k . The symbol x_m with symbol duration of T_s is subdivided into L chips and then the vector $\boldsymbol{X}_m$ = ($X_{m,0}, X_{m,1},\ldots, X_{m,L-1}$) is produced, where $\boldsymbol{X}_{m,i} = x_m$ for i = 0, 1,…, L-1. Fig. 2 shows an instance of the encoding procedure, where the data vector $\mathbf{X}_1$ = (3, 3, 3, 3, 3) is showed in the matrix representation for K = 8 (k = 3) and L = 5. Each element of the resulting vector $\mathbf{X}_m$ is then translated in frequency by an amount that is determined by the corresponding element of hopping sequence $\mathbf{R}_m$, where $\mathbf{R}_m$ is generated by different address element γ_m(m=1,2,…, M) selected from $\boldsymbol{GF}(K)$. The symbol $\boldsymbol{GF}(K)$ denotes the finite field (Galois field) of K elements. Let the address (hopping) pattern of user m be denoted by a vector

$$\mathbf{R}_m = (R_{m,0},\ \ R_{m,1},\ \ \cdots\ \ ,R_{m,L-1}) \tag{1}$$

where $R_{m,i} \in \boldsymbol{GF}(K)$ represents the frequency channel occupied by the address at time slot i. With the addition operator denoted by "⊕", we will derive the encoded data pattern $\mathbf{Y}_m$ by imposing the hopping pattern R_m upon the data pattern $\mathbf{X}_m$. That is, the vector $\mathbf{Y}_m = (Y_{m,0}, Y_{m,1}, \ldots , Y_{m,L-1})$ transmitted by user m can be derived from $\mathbf{Y}_m$=$\mathbf{X}_m$+$\mathbf{R}_m$, where $Y_{m,l}$, $X_{m,l}$, and $R_{m,l} \in \{0, 1, 2, \ldots, K\text{-}1\}$. The addition rule denoted by "⊕" here is exclusive-OR (XOR) addition (the addition is operated after $\mathbf{R}_m$ and $\mathbf{X}_m$ are transformed into binary digits). As a result, the center frequencies of the data pattern elements are changed (hopped) by the elements of the hopping pattern. The matrix representation of $\mathbf{Y}_1$ in Fig. 2

shows an example of the output of the frequency synthesizer derived from the hopping pattern $\mathbf{R}_1$ = (4, 3, 6, 7, 5) and the data symbol pattern $\mathbf{X}_1$ = (3, 3, 3, 3, 3).

Without loss of generality, it is assumed that user 1 is the desired user and the others are the undesired ones to CCI. Moreover, it is assumed that the FH patterns of all users are known and are distinct to each other.

2.1. Address Code Assignment

In this section, we briefly review the method of hopping pattern assignment and invoke some propositions to show the properties of the transmission patterns. In order to make the detection precisely, the address pattern sets having good cross-correlation properties must be found. From the results presented in [8], it has been shown that the code set constructed by Einarsson is the optimal one for the MFSK/FH-SSMA system [6].

Let the address pattern of user *m* be denoted by the vector $\mathbf{R}_m$. Einarsson [6] proposes the following equation to generate a set of *K* addresses.

$$\mathbf{R}_m = (\gamma_m,\ \gamma_m\beta,\ \gamma_m\beta^2,\ \cdots\ ,\ \gamma_m\beta^{L-1}) , \qquad (2)$$

where γ_m is an element of $GF(K)$ assignment to user *m* and β is a fixed primitive element of $\boldsymbol{GF}(K)$. To see what transmitted signals $\mathbf{Y}_m(m=1,2,\ldots,M)$ can interfere with each other, properties of the pair of transmitted sequences are enumerated as follows. Let $\mathbf{Y}_1$ and $\mathbf{Y}_2$ denote two sequences generated by two different hopping sequences $\mathbf{R}_1$ and $\mathbf{R}_2$, respectively. It is noted that the properties showed next are all based on the word synchronous system.

Proposition 1: With appropriate choice of β, two transmitted vectors with different address will coincide in at most one chip [6].

Proposition 2: In the decoded matrix, any two frequency tones selected arbitrarily from L tones of the same undesired user are different. The proof of this proposition will be presented in Appendix.

There is an important concept concealed in proposition 2, where it exhibits each tone in an incorrect row must comes from different users in the decoded matrix. That is, all the undesired users will at most contributes one of its tones to a specific incorrect row. The concept showed above will provide an important idea of “PO row”.

2.2. A Novel Multiuser Detection Algorithm Based on Mabuchi’s Scheme for MFSK/FH-SSMA System

In this section, a novel decoding algorithm for multiuser detection scheme is proposed to improve the complexity of the MFSK/FH-SSMA system. Fig. 3 shows the receiver structure of the proposed scheme. As we know, two previous works on multiuser detection schemes proposed by [9] and [14] will generate great amounts of candidate matrices as the number of the active users increases. For the reason, the algorithm we proposed will focus on the reduction of the number of candidate matrices. In our scheme, the majority rows would be selected as the candidate rows of the desired user, while on the other side, the row named “PO row” (Pseudo-Optimal row) would be respectively chosen for the other users in their decoded matrices. The algorithm of the proposed multiuser detection scheme for the MFSK/FH-SSMA system is summarized as follows:

2.2.1. Firstly, the receiver detects the energy in each time-frequency cell of the received matrix. The energy in each cell is the summation of transmitted tones from all active users. Fig. 4 shows an example where K = 8, L = 3 and M = 5.

2.2.2. The receiver decodes every user's data symbols by the FH patterns $\mathbf{R}_m$ (m= 1, 2, …, 5) and then choose the candidate of the data symbols of each user in Fig. 4 (d). In the desired user's (user 1) decoded matrix D_1, the majority rows are considered as candidates of the correct data symbol in the desired user's decoded matrix. While in the other users' decoded matrix, the "PO row" is selected as candidates of the correct data symbol. The reason for the choice of majority row instead of "PO row" in the desired user's decoded matrix is to enlarge the probability of selecting the correct row. Fig. 4 (d) shows the decoded matrices of users derived from the hopping patterns $\mathbf{R}_m$ (m= 1, 2, …, 5) and the received matrix in Fig. 4 (c).

2.2.3. Definition of PO row: A row which satisfies the following two conditions is named as the "PO row", the first condition is that the row is a complete row (majority row) and the second is that this complete row must be the row having the largest energy among the K rows. The name "PO row" is denominated by us and is of the full name "Pseudo Optimal row". This is because in most of the situations, the row belonging to the "PO row" is generally the correct data row.

2.2.4. The reason for choosing the PO row: From proposition 2, one interference user will at most contribute one tone out of its L tones to a specific row. Moreover, owing to the matched dehopping pattern for the desired user, all the L tones of the user for decoding will appears in the correct row in nonfading environments. From the two property described above, the correct row is the one that has the most chances to become the "PO row" among the K rows. Nevertheless, when the number of interference user increases, it is not necessarily that the correct row is always the "PO row", the name "Pseudo" is thus applied.

2.2.5. Let J_m ($1 \le J_m \le K$) denote the number of the candidate rows decoded by the hopping pattern $\mathbf{R}_m$. Therefore, when in the receiver of user 1, J_1 means the number of majority rows and J_m ($m \neq 1$) means the PO rows in the mth decoded matrix, respectively. Each candidate of the desired user's data symbols is re-encoded and added with the candidate of the other users' data symbols using the "energy SUM" operation. Since each time we select one candidate row from each user, there are total $\prod_{m=1}^{M} J_m$ candidate matrices generated from this procedure. The example in Fig. 4 (d) shows that there are two candidates for the data symbols of users 1 and one candidate for the data symbols of the other three users. Therefore, there are total two candidate matrices, "t2" and "t4", derived from the "sum" operation of each re-encoded matrix generated from the combination of candidate rows. Nevertheless, there are four candidate matrices in the Mabuchi's scheme.

2.2.6. Among these $\prod_{m=1}^{M} J_m$ candidate matrices, we choose the one that has the most number of coincident cells with the original received matrix. In other words, the energy of each cell in the candidate matrix is the same with that in the original received matrix, and the number of the cells is the maximum. Finally, the correct data symbol of the desired user would be extracted. In Fig. 4 (e), the fourth candidate matrix named "t4", which consists of data symbols (7, 5, 3, 2, 2) extracted from each decoded matrix, is the one that has the most number of coincident cells with cells of the received matrix in Fig. 4 (c). Consequently, we can decode the correct data symbol "7" of the desired user (user 1) from the selected candidate matrix "t4". On the contrary, there are four candidate matrices generated in the Mabuchi's scheme and random choice between the matrices "t2" and "t4" would be applied. Finally, a decoding error in the Mabuchi's scheme happens.

In this example, we have shown that the proposed scheme can decode the correct data symbol even when the errors will occur in the Mabuchi's scheme.

3. Performance Analysis of System Complexity

3.1. The Number of Candidate Matrices in Mabuchi's Scheme

In this subsection, the number of candidate matrices generated in the decoding process of Mabuchi's and Lin's scheme is analyzed (it is the same in both schemes). The analysis here assumes time and frequency synchronization of the FH pattern generator in the transmitter and receiver. Hop synchronous is also assumed. The situation where there is no noise or fading in the system is considered.

Since J_m ($1\leq J_m \leq K$) denote the number of the candidate rows (complete rows) decoded by the hopping pattern $\mathbf{R}_m$. In both of the multiuser detection schemes in [9] and [14], there are $\prod_{m=1}^{M} J_m$ ($1\leq J_m \leq K$) candidate matrices of received matrix in each scheme. The symbol N_{candi} is defined as the number of the candidate matrices normalized by the number of symbols per user [9] and is used to measure the system complexity.

$$N_{candi} = \frac{Number\ \ of\ \ total\ \ candidate\ \ matrices}{Number\ \ of\ \ total\ \ symbols\ \ per\ \ user}. \quad (2)$$

In the following, theoretical analysis will be established. Firstly, the independence between all the decoded matrices is assumed. A tight bound proposed by [6] derives the probability that an incorrect row to be evolved into a complete row. Thus, in each of the decoded matrix, the probability for an incorrect row to become a complete row is

$$P_{cmp} = \prod_{i=0}^{L-1} \left[1-(1-\frac{1}{K-i})^{M-1-i} \right]. \quad (3)$$

Over the K-1 incorrect rows, the probability that exactly q unwanted rows belong to the complete rows is

$$P(q) = \binom{K-1}{q} \left[P_{cmp}\right]^{q} \left[1-P_{cmp}\right]^{K-1-q}. \quad (4)$$

The mean value concerning the average number of incorrect complete rows in a decoded matrix is defined and expressed as

$$\overline{J_m} = \sum_{q=0}^{K-1} q \cdot \left\{ \binom{K-1}{q} \left[P_{cmp}\right]^{q} \left[1-P_{cmp}\right]^{K-1-q} \right\}. \quad (5)$$

Finally, through the multiplication of all the number of candidate matrices in each decoded matrices, the averaged number of candidate matrix is derived as

$$\overline{N_{candi}} = \left(1 + \overline{J_m} \right)^M . \quad (6)$$

It is noted that the number "1" in equation (6) represents the correct complete row which occurs inevitably in interference only channel.

3.2. Reduction Efficiency of System Complexity

In this subsection, a parameter η is defined to measure the degree of complexity reduction. The reduction efficiency of the system complexity is defined as

$$\eta = \frac{(N)_{Mabuchi} - (N)_{Proposed}}{(N)_{Mabuchi}}, \quad (7)$$

where N is the average candidates (candidate rows or matrices per symbol, per user) in the process of decoding.

4. Numerical and Simulation Results

In this section, the presented numerical results are evaluated for various values of system parameters K, M and L. To better illustrate, the results will be presented into two parts: "analysis of bit error rate" and "analysis of system complexity".

4.1. Analysis of Bit Error Rate

In this section, the performance of the system using the proposed CCI canceller is compared with those systems using the conventional, the Mabuchi's and the Lin's CCI canceller. Fig. 5 shows the bit error probability versus the number of active users for the four schemes K=16 and L=5 without fading. As expected, the proposed scheme performs better than the conventional scheme, the Mabuchi's scheme and the Lin's scheme in a non-fading channel. For instance, given nine users, $P_b(M) = 3.11\times10^{-6}$ for the proposed canceller, while $P_b(M) = 4.06\times10^{-2}$ for the conventional receiver, $P_b(M) = 5.7\times10^{-3}$ for the Mabuchi's canceller, and $P_b(M) = 2.8\times10^{-5}$ for the Lin's canceller. Noted that, as the number of active users M increases, the bit error rates (BER) of the Mabuchi's scheme, the Lin's scheme and the proposed scheme approach the bit error rate of the conventional scheme. This is because there are too many ambiguous candidates in the decoded matrix, which dramatically decreases the probability of correct decisions in all schemes. Fig. 5 reveals that when the BER is fixed at 10^{-3}, there are 6 users supported by the conventional scheme, 8 users in the Mabuchi's scheme and 12 users in both the Lin's and the proposed schemes. The result shows that high traffic load is admitted in the proposed scheme under a fixed value of BER.

4.2. Analysis of System Complexity

In this subsection, the system complexity of the system using the proposed CCI canceller is compared with the Mabuchi's CCI canceller. The analysis in this subsection is concentrated on the number of candidate rows and matrices. Moreover, in the conventional scheme, none of the candidate matrices will be generated. Fig. 6 shows the number of candidate matrices N_{candi} versus the number of active users M in log scales for the two schemes: the Mabuchi's canceller in [9], and the proposed receiver. The number of the candidate matrices was with K=16 and the hopping pattern length L=5. As expected, the value N_{candi} in the Mabuchi's receiver increases nonlinearly as M increases. On the contrary, the value N_{candi} increases almost linearly in the proposed receiver as M increases. Besides, the numerical and simulated results of N_{candi} in the Mabuchi's scheme will also be compared. From this figure, it is shown that these two curves are most of the time coincidence in values. Table. 1 shows the detail values of the number of candidate matrices for the Mabuchi's scheme and the proposed scheme, and the reduction efficiency of these two schemes is also calculated. As shown in Table 1, when the number of active users M is greater than 11, the reduction efficiency η will attain more than the percentage of ninety. Moreover, the reduction efficiency increases as the number of active users increases.

Finally, Fig. 7 shows the complexity reduction efficiency η versus the number active users M for the candidate matrices and candidate rows in a non-fading channel. From the results in this figure, it can be observed that in spite of the reduction efficiency of candidate rows is not large, the efficiency is almost reaches to the percentage of 100 as the number of active users M approaching to K.

5. Conclusions

This paper developed a novel algorithm for the multiuser detection schemes to decrease system complexity in MFSK/FH-SSMA systems. The performance of the system has been analyzed and compared with those of conventional the Mabuchi's and the Lin's CCI canceller. Simulation results show that the proposed scheme has much lower system complexity than the two multiuser detection schemes proposed by Mabuchi and Lin. Moreover, the bit error probability of the proposed scheme also outperforms the other detection schemes in nonfading channels.

Appendix:

In this section, the proof of the proposition 2 in section 2 will be presented. Without loss of generality, we assume that user 1 is the desired user. For the mth user($m\neq 1$), we have $\mathbf{Y}_m=\mathbf{R}_m+\mathbf{X}_m\cdot 1$. After decoding by the hopping pattern of the desired user, the frequency position at the ith chip of the mth user is

$$Y_{m,i} - R_{1,i} = (\gamma_m - \gamma_1)\beta^{i-1} + x_m \,. \tag{8}$$

Now consider the next symbol $Y_{m,j}$-$R_{1,j}$ at chip position j, where $j\neq i$. We have

$$Y_{m,j} - R_{1,j} = (\gamma_m - \gamma_1)\beta^{j-1} + x_m \,. \tag{9}$$

If we assume equation (8) is equal to equation (9), then we will derive

$$\beta^{i-1} = \beta^{j-1} \,. \tag{10}$$

The result derived in equation (10) conflicts with the finite field rule described in [20], where the conditions to the orders i, j of β meets $i, j \leq L$ and $L \leq K$-1. That is, any two frequency tones selected from L tones of the same undesired user are different in the decoded matrix.

Acknowledgment. This work was supported by the National Science Council (Taiwan) under grant NSC 98-2218-E-029 -004 -.

References:

[1] C. Pateros, "Novel direct sequence spread spectrum multiple access technique," *IEEE 21st Century Military Communications Conference Proceedings*, vol. 1, pp. 564-568, Oct. 2000.

[2] Y.K. Jeong, J.H.Cho, and J.S. Lehnert, "An asymptotic analysis of band-limited DS/SSMA systems," *IEEE International Symposium on Information Theory*, pp. 434, July. 2004.

[3] Yeon Kyoon Jeong, Joon Ho Cho, and J.S. Lehnert,

"Performance bounds on chip-matched-filter receivers for bandlimited DS/SSMA communications," *IEEE Trans. Commun*., vol. 53. , no. 1, pp.131 –141, Jan. 2005.

[4] J.F. Weng, G.Q. Xue, Tho Le-Ngoc, and S. Tahar, "Analysis of multilevel-quantized soft-limiting detector for an FH-SSMA system," *IEEE International Conference on Communications*, vol. 3, pp. 1380-1384, Jun. 2000.

[5] Daeyoung Park, G.L. Byeong, "Iterative decoding in convolutionally and turbo coded MFSK/FH-SSMA systems," *IEEE International Conference on Communications*, vol. 9, pp. 2784-2788, Jun. 2001.

[6] G. Einarsson, "Address assignment for a time-frequency-coded, spread-spectrum system," *Bell Syst. Tech. J*., vol. 59, no. 7, pp. 1241-1255, Sep. 1980.

[7] D.J. Goodman, P.S. Henry, and V. K. Prabhu, "Frequency-hopping multilevel FSK for mobile radio," *Bell Syst. Tech. J*., vol. 59, no. 7, pp. 1257-1275, Sep. 1980.

[8] B.G. Haskell, "Computer simulation results on frequency hopped MFSK mobile radio-noiseless case," *IEEE Trans. Commun*., vol. com-29, no. 2, pp.125 –132, Feb. 1981.

[9] T. Mabuchi, R. Kohno and H. Imai, "Multiuser detection scheme based on canceling cochannel interference for MFSK/FH-SSMA system," *IEEE J. Select. Areas Commun*., vol. 12, no. 4, pp. 593-604, May 1994.

[10] R. Kohno, H. Imai, and M. Hatori, "Cancellation technique of cochannel interference in asynchronous spread spectrum multiple access system," *Trans. On The Institute of Electronics, Information and Communication Engineerings Japan*, vol. J65-A, no. 5, pp.416-423, May 1983.

[11] S. Verdu, "Optimum multiuser asymptotic efficiency," *IEEE Trans. Commun*., vol. COM-34, pp. 890-897, Sept. 1986.

[12] R. Kohno, H. Imai, and M. Hatori, and S. Pasupathy, "Combination of an adaptive array antenna and a canceller of interference for direct-sequence spread-spectrum multiple-access system," *IEEE J. Select. Areas Commun*. , vol. SAC-8, pp. 675-682, May 1990.

[13] R. Kohno, H. Imai, and M. Hatori, and S. Pasupathy, "An adaptive canceller of cochannel interference for spread-spectrum multiple-access communication networks in a power line," *IEEE J. Select. Areas Commun*. , vol. SAC-8, pp. 691-699, May 1990.

[14] Y. Zaihe, Y.Q. Shi, and S. Wei, "A practical classification algorithm for M-ary frequency shift keying signals," *IEEE 21st Century Military Communications Conference Proceedings*, vol. 2, pp. 1123-1128, oct. 2004.

[15] S.-Y. Lin, G.-C. Yang, S.-C. Tseng, and C.F. Hong, "Improved cochannel interference cancellation for MFSK/SSMA systems," *IEEE J. Select. Areas Commun*., vol. 17, no. 11, pp. 1940-1952, Nov. 1999.

[16] H. Zhang, H. Yang, R. Luo, H. Wang, "Improved multiuser detector for fast FH/MFSK systems with soft-limiter,"*IEEE 2005 Int. Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Commun*., Vol 2, pp. 1464 – 1467, Aug. 2005.

[17] Z. Yu, C.C. Chai, T.T. Tjhung, "Multiuser detection algorithm based on iterative interference cancellation for MC-MFSK systems," *Personal, Indoor and Moible Radio Communications*, *IEEE 2004* PIMRC, vol. 4, pp. 2915 – 2919, Sep. 2004.

[18] Z. Yu, T.T. Tjhung, C.C. Chai, "Performance of MC-MFSK systems with IIC-based multiuser detection over Rayleigh fading channels," *IEEE Global Telecommunications Conference*, vol. 2, pp. 893-897, Dec. 2004.

[19] S. Ahmed, L.L. Yang, L. Hanzo, "Successive Interference Cancellation in Clipped and Product Combining aided FFH Multi-User Systems," *IEEE Vehicular Technology Conference*, vol. 5, pp. 2188-2192, Spring 2006.

[20] B. W. Stephen, *Error Control System for Digital Communication and Storage*, NJ: Prentice Hall, 1995.

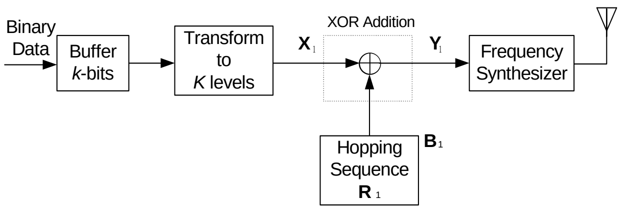

Fig. 1 Block diagram of an MFSK/FH-SSMA transmitter

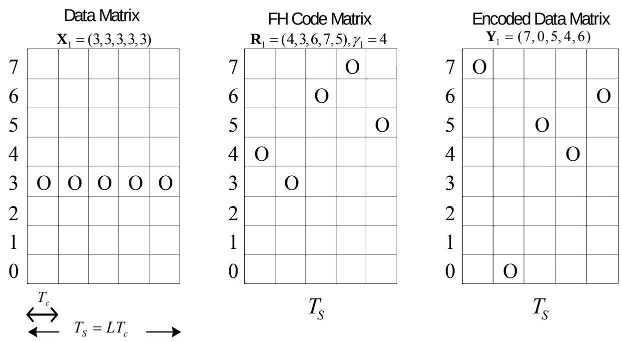

Fig. 2 An example of the encoding procedure for an MFSK/FH-SSMA transmitter

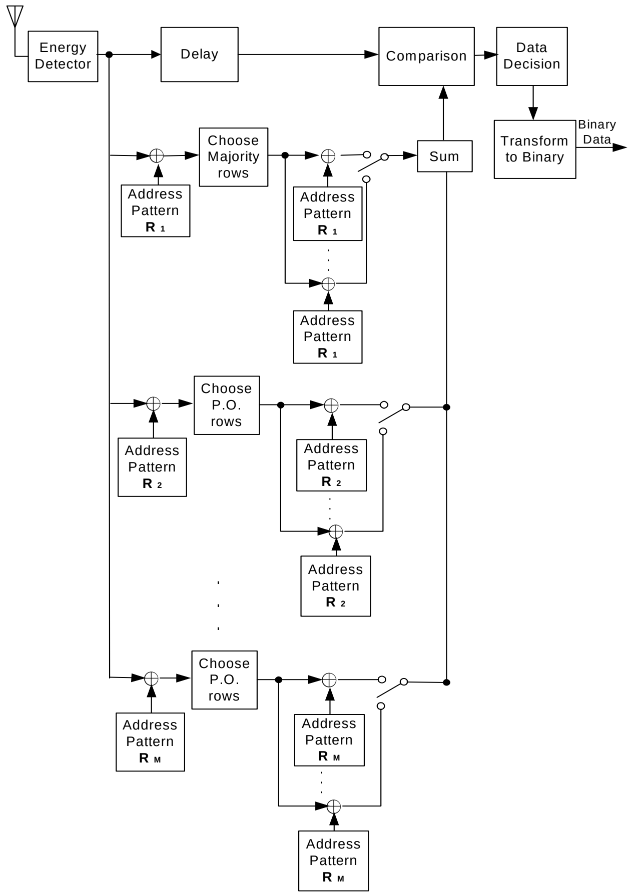

Fig. 3 The receiver structure of the proposed scheme for the MFSK/FH-SSMA system

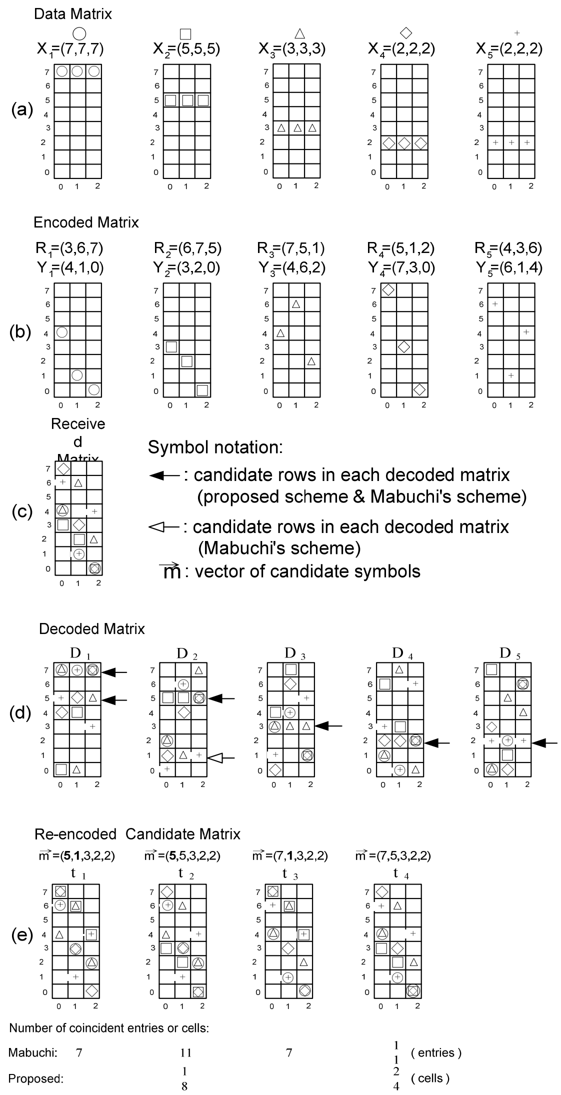

Fig. 4 An example of decoding procedures proposed by us

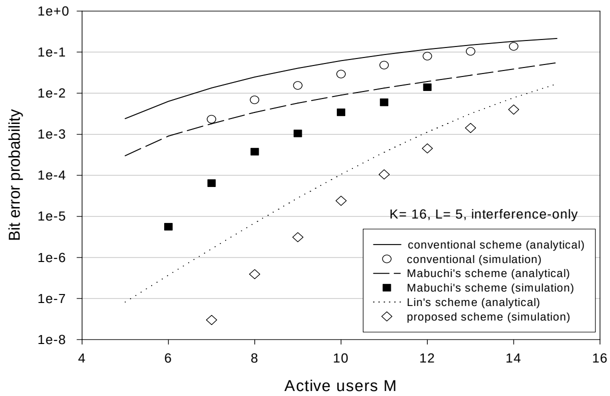

Fig. 5 BER versus the number of active users M using the conventional canceller, the Mabuchi's canceller, the Lin's canceller, and the proposed canceller in a non-fading channel

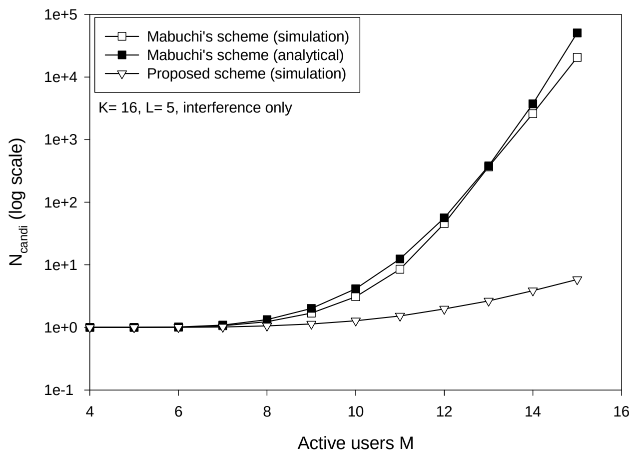

Fig. 6 The number of candidate matrix N_{candi} (per symbol, per user) versus the number of active users M using the Mabuchi's canceller and the proposed canceller in a non-fading channel

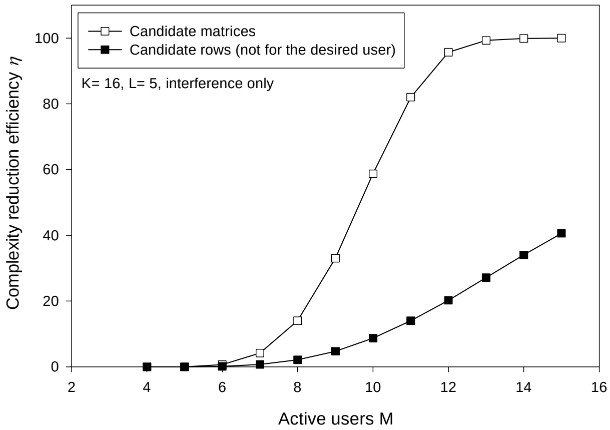

Fig. 7 The complexity reduction efficiency η versus the number active users M in a non-fading channel, where the efficiency η is defined in equation (7)

Active users M	Mabuchi's Scheme	Proposed Scheme	Reduction Efficiency η
5	1	1	0
6	1.011	1.004	0.673
7	1.06	1.018	4.16
8	1.23	1.056	14.05
9	1.69	1.135	33.01
10	3.10	1.278	58.71
11	8.50	1.529	82.01
12	45.75	1.969	99.69
13	367.7	2.657	99.28
14	2604.5	3.86	99.85
15	20584.8	5.849	99.97

Table. 1 The number of the compared candidate matrices and the reduction efficiency (K = 16, L = 5,non-fading channel)