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A Novel FH-CDMA Scheme for Greater SpectralEfficiency and Higher Data Rate

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***Abstract*—In this paper, we propose a novel FH-CDMA scheme for communication systems. By proper selection of FH patterns for the modulation codes, our scheme supports more possible users. The performance and spectral efficiency of the scheme are analyzed. Our results show that the proposed scheme supports higher data rate and spectral efficiency than Goodman's FSK FH-CDMA scheme with some conditions.**

***Index Terms*—Frequency hopping, CDMA, code division mul- tiple access, higher data rate, spectral efficiency.**

I. INTRODUCTION

In an FH-CDMA system, each user is assigned a distinct FH code sequence(or matrices). Because an FH matrix con- trols the hopping sequence of the carrying frequencies, the transmitted FH-CDMA signal appears as a data modulated carrier, which is hopping from one frequency to the others. By assigning a distinct FH matrix to every user, FH-CDMA systems allow many users to share the same bandwidth simul- taneously because of spectrum spreading [1]. FH-CDMA is an effective scheme in combating multi-path fading in wireless systems because of its inherent frequency diversity [2], [3]. Advantages of FH-CDMA over DS-CDMA includes smaller total interference, lessening of the reverse link and near-far problems, better external jamming, and improved frequency agility [4]–[6]. Multiple-access interference is frequently seen in FH-CDMA, occurs when more than one user occupies the same carrier frequency at the same time slot simultaneously. To minimize the effects due to MAI, one hit FH patterns with cross correlation values no greater than one can be used [7]–[9]. In addition, a well known modulation technique, M- ary frequency shift keying(MFSK), was proposed to add on top of CDMA to increase data rate by transmitting symbols, instead of data bits [10]. These prime/FH-CDMA [11] and RS/FH-CDMA [12] schemes supported higher data rate than Goodman's MFSK/FH-CDMA [10] at the cost of worsened performance. However, the weights and lengths of the modu- lation codes and FH patterns needed to be the same in both schemes, stopping the choice of suitable modulation codes andFH patterns to use.

In section II of this paper, we propose a novel FH-CDMA scheme in which both modulation codes and FH patterns do not need to have the same weight or length anymore. The onlyrequirement is that the weight of the FH patterns is at least equal to the length of the modulation codes such that each element of modulation codes can be conveyed by an element of the FH patterns. Therefore, our novel FH-CDMA scheme is more flexible in the selection of the modulation codes and FH patterns. This new scheme is a special case of the [11]– [13], which is clearly explained in section II. The behavior of our novel FH-CDMA scheme over AWGN, and Rayleigh and Rician fading channels are analyzed algebraically in section III. In section IV we compare the new scheme with Goodman's MFSK/FH-CDMA scheme in terms of performance and, a more meaningful metric normalized spectral efficiency(NSE). Numerical examples show that our novel FH-CDMA scheme provides performance in commutation with data rate and show off better system efficiency than Goodman's MFSK/FH-CDMA scheme under some conditions.

II. Novel FH-CDMA Description

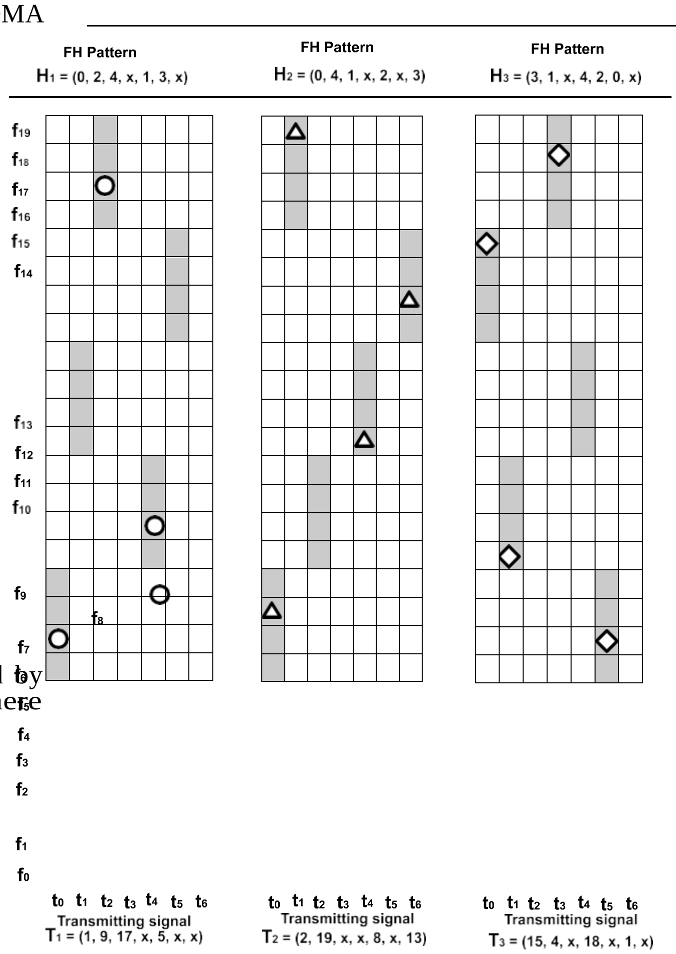
In our novel FH-CDMA scheme, the available transmission bandwidth is divided into F_h frequency bands which contains F_m carrier frequencies in each band, giving a total of $F_m.F_h$ carrier frequencies. The total system is described in two levels, in the first level, a number of serial data bits are grouped together and represented by a symbol. Each symbol is in turn represented by a modulation code of dimension F_m x L_m and weight w_m(i.e., number of elements), where F_m is the number of frequencies, L_m is the number of time slots (i.e., code length). The number of data bits that can be represented by a symbol depends on the number of available modulation codes. If there are ψ_m modulation codes, each symbol can represent up to $\lfloor \log_2 \psi_m \rfloor$, where $\lfloor . \rfloor$ is the floor function. $_{c,m}(\lambda_{c,h})$ denote the maximum autocorrelation side lobes and cross correlation values of the modulation codes(FH patterns) respectively.

To demonstrate the main concept of our novel FH-CDMA scheme we here use prime sequences as modulation codes and FH patterns [9]. Other codes can also be used depending on the symbol interference level permission in the system. The original prime code is constructed through the use of finite field arithmetic. Finite fields are also called Galois fields [14], [15]. For any prime number p, there exists a finite field of p elements, which is denoted by GF(p)=$0, 1, ...p-1$. In GF(p), additions and multiplications are done under modulo-p. The construction of original prime code begins with the Galois field GF(p) of a prime number p. A prime sequence $S_i = (S_{i,0}, S_{i,1}...S_{i,j}...S_{i,p-1})$ is constructed by the element.

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

where $S_{i,j}$, i, and j are all in GF(p).

Each prime sequence of weight $w_m = p$ is denoted by $S_{i_1,i_2} = (S_{i_1,i_2,0}, S_{i_1,i_2,1}, ..., S_{i_1,i_2,l}, ..., S_{i_1,i_2,p-1})$ where the l th element $S_{i_1,i_2,l} = i_2 \oplus_p (i_1 \otimes_p l)$ represents the frequency used in the l th position (i.e., time slot), $\oplus_p$ denotes modulo-p addition and $\otimes_p$ denotes a modulo-p multiplication. Table I shows prime sequences for $i_2 = 0$ and $i_1 = 0, 1, 2, 3, 4$. Since these prime sequences are used as modulation codes, each element of S_{i_1,i_2} determines which carrier frequency of a frequency band in a given time slot to use. If the number of available carrier frequencies are confined or the sequence



weight needs to be varied in order to get destined scheme performance. We can always adjust the sequence weight to be $w_m < p$ by excluding the largest $p \quad w_m$ elements in S_{i_1,i_2}. As
a result, the construction algorithm gives $\psi_m = p^2 \quad p + w_m$
prime sequences of weight $w_m \quad p$ and length $L_m = p$
with $\lambda_{c,m} = 1$ (i.e., symbol interference). For example, with $p = 5$ and $w_m = 4$, Table II shows twenty four $(F_m\ L_m,\ w_m,\ \lambda_{a,m},\ \lambda_{c,m}) = (4\ 5,\ 4,\ 0,\ 1)$ prime sequences, where x denotes the drop of the
x fifth element in order to have code weight of four. Using these prime sequences as the modulation codes, we can support at most 24 symbols
and each symbol represents $\log_2 24 = 4$ data bits. In our scheme the modulation codes are divided into several groups
and each group contains lessened number of modulation codes with a $\lambda'_{c,m} = 0$. Each user uses the modulation codes only from one group this avoids the symbol interference created by the prime sequences. So now the same FH pattern can now is reused by multiple users as long as they have varied groups of modulation codes.

For example, the twenty four $\lambda_{c,m} = 1$ prime sequences in table II can be made into five groups of prime sequences of $\lambda'_{c,m} = 1\ \lambda_{c,m} = 0$ [13] and can be assigned to five different users with the same FH pattern. The number of
bits represented by each symbol decreases from $\lfloor \log_2 24 \rfloor$ to
$\lfloor \log_2 5 \rfloor$, the number of possible users is now increased from

Fig. 1. Example of the encoding process of the novel FH-CDMA with three simultaneous users.(The shaded columns in the transmitting signals, T_k represent the frequency bands specified by the corresponding FH patterns, H_k, for k = {1, 2, 3}).

TABLE I

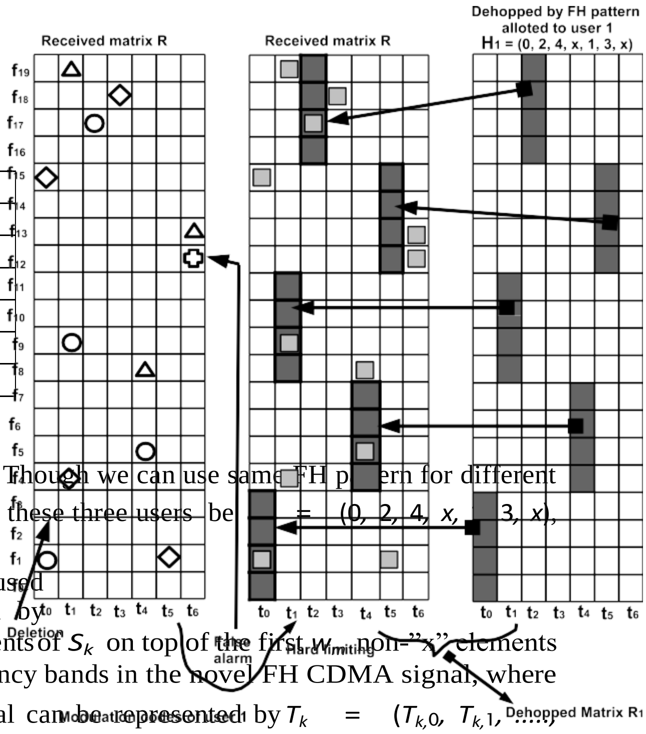
i_2	i_1	$S_{i2,i1,0}$	$S_{i2,i1,1}$	$S_{i2,i1,2}$	$S_{i2,i1,3}$	$S_{i2,i1,4}$
0	0	0	0	0	0	0
0	1	0	1	2	3	4
0	2	0	2	4	1	3
0	3	0	3	1	4	2
0	4	0	4	3	2	1

ψ_h to $5\psi_h$.

As mentioned earlier, the FH pattern must be selected so as to satisfy the condition $w_h \geq L_m$. For example we have selected the $(F_h \times L_h, w_h, \lambda_{a,h}, \lambda_{c,h}) = (5 \times 7, 5, 0, 1)$ prime sequences as the one hit FH patterns and the modulation codesof different groups for different users are as shown in table II. Figure 1 shows the encoding process of three simultaneous users. If the data symbols of these three users at one time instant are ”1” of user 1, ”2” of user 2, and ”3” of user 3, then we picked $S_1 = (1, 1, 1, 1, x)$, $S_2 = (2, 3, x, 0, 1)$ and

TABLE II
TWENTY-FIVE $(4 \times 5, 4, 0, 1)$ PRIME SEQUENCES, WHICH CAN BE ORGANIZED INTO FIVE GROUPS WITH $\lambda'_{c,m} = 0$ WITHIN EACH GROUP

	Group 0	**Group 1**	**Group 2**	**Group 3**	**Group 4**
i_2	$i_1 = 0$	$i_1 = 1$	$i_1 = 2$	$i_1 = 3$	$i_1 = 4$
0	0000x	0123x	02x13	031x2	0x321
1	1111x	123x0	1302x	1x203	10x32
2	2222x	23x01	2x130	203x1	210x3
3	3333x	3x012	302x1	31x20	3210x
4	xxxxx	x0123	x1302	x2031	x3210



$S_3 = (3, 0, 2, x, 1)$ as the modulation codes, respectively. Though we can use same FH pattern for different groups, for convenience we took one-hit FH-patterns of these three users be $H_1 = (0, 2, 4, x, 1, 3, x)$, $H_2 = (0, 4, 1, x, 2, x, 3)$, and $H_3 = (3, 1, x, 4, 2, 0, x)$. The carrier frequency used in each frequency band in a time slot is determined by superimposing(element by element) all $w_m = 4$ elements of S_k on top of the first w_m non-”x” elements of H_k, and the ”x”-elements of S_i produce empty frequency bands in the novel FH CDMA signal, where k = 1, 2, 3 .In sum- mary, the novel FH-CDMA signal can be represented by $T_k = (T_{k,0}, T_{k,1}, ..., T_{k,i}, ..., T_{k,L_h-1}) = S_k \triangle (F_m \cdot H_k)$ where $T_{k,i}$ represents the carrier frequency used in the ith time slot and $\triangle$ denotes the superimpose operation. For example, the novel FH-CDMA signal of first user is found to be $T_1 = (1 + 0.4, 1 + 2.4, 1 + 4.4, x, 1 + 1.4, x, x) = (1, 9, 17, x, 5, x, x)$ after simplified operation. Similarly, the other two simultaneous users will have $T_2 = (2 + 0.4, 3 + 4.4, x, x, 0 + 2.4, x, 1 + 3.4) = (2, 19, x, x, 8, x, 13)$ and $T_3 = (3+3.4, 0+1.4, x, 2+2.4, x, 1+0.4, x) = (15, 4, x, 18, x, 1, x)$ after superimposition.

During transmission, the signal might undergo interference, noise and fading. In the receiver, the received FH-CDMAsignals are hardlimited, dehopped, and finally decoded in order

[1] vol. 12, no. 4, pp. 593–604,1994.