[Volume 1 issue 8 Sep 2013]
Page No.221-232 ISSN :2320-7167

INTERNATIONAL JOURNAL OF MATHEMATICS AND COMPUTER RESEARCH

Improving The Spectral Efficiency And Data Rate Of Fhcdma Scheme For Wireless Communication Channels

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Abstract

In this project, we propose a “two-level” frequencyhopping code-division multiple-access (FH-CDMA) scheme for wireless communication systems. In our two-level FH-CDMA scheme, the available transmission bandwidth is divided into Mh frequency bands with Mm. carrier frequencies in each band. In the first (modulation) level, a number of serial data bits is grouped together and represented by a symbol. Each symbol is, in turn, represented by a modulation code of dimension $Mm \times Lm$. In the second (FH) level, each user is assigned a unique FH pattern of dimension $Mh \times Lh$ and weight (i.e., number of elements) wh, where Mh is the number of frequencies, Lh is the number of time slots (i.e., pattern length). The elements in the modulation codes and FH patterns determine the carrier frequencies of the final FH-CDMA signals. . The new scheme provides flexibility in the selection of modulation codes and FH patterns. Our results show that the partitioned two-level FH-CDMA scheme supports higher data rate and greater SE than Goodman’s frequency-shift-keying FHCDMA scheme

INTRODUCTION

FREQUENCY-HOPPING code-division multiple access (FH-CDMA) provides frequency diversity and helps mitigate multipath fading and diversify interference. Major advantages of FH-CDMA over direct-sequence CDMA include better resistance to multiple access interference (MAI), less stringent power control, and reduced near-far problem and multipath interference. By assigning a unique FH pattern to each user, a FH-CDMA system allows multiple users to share the same transmission channel simultaneously. MAI occurs when more than one simultaneous users utilize the same carrier frequency in the same time slot. “One-hit” FH patterns have been designed in order to minimize MAI.

In addition, Goodman, proposed to add *M*-ary frequency-shift-keying (MFSK) atop FH-CDMA in order to increase data rate by transmitting symbols, instead of data bits. Furthermore, the uses of prime and Reed-Solomon (RS) sequences as modulation codes atop FH-CDMA were proposed in which the symbols were represented by non-orthogonal sequences, rather than orthogonal MFSK. These prime/FH-CDMA and RS/FH-CDMA schemes supported higher data rate than Goodman's MFSK/FH-CDMAscheme at the expense of worsened performance. However, the weights and lengths of the modulation codes and FH patterns needed to be the same in both schemes, restricting the choice of suitable modulation codes and FH patterns to use.

In Section II of this project, we propose a new two-level FH-CDMA scheme, in which both modulation codes and FH patterns do not need to have the same weight or length anymore. The only requirement is that the weight of the FH patterns is at least equal to the length of the modulation codes, which is usually true in modulated FH-CDMA schemes (such as prime/FH-CDMA and RS/FH-CDMA) because each element of the modulation codes needs to be conveyed by an element of the FH patterns. Therefore, our two-level FH-CDMA scheme is more flexible in the selection of the modulation codes and FH patterns (not limited to prime or RS sequences only) in order to meet different system operating requirements. The prime/FH-CDMA and RS/FHCDMA schemes are special cases of the new scheme.

Also in Section II, we propose a partitioning method on the modulation codes, such that modulation codes with lower cross-correlation values are grouped together. Using different groups of modulation codes as an additional level of address signature, the partitioned two-level FH-CDMA scheme allows the assignment of the same FH pattern to multiple users, thus increasing the number of possible users. The performance of our two-level FH-CDMA scheme over additive white Gaussian noise (AWGN), and Rayleigh and Rician fading channels are analyzed algebraically in Section III.

While previous analyses used a constant $\beta 0$ (the actual threshold divided by the root-mean-squared receiver noise) to approximate the false-alarm and deletion probabilities caused by additive noise or fading, we include a more accurate model of $\beta 0$ (as a function of actual signal-to-noise ratio) in the analyses of Section III, better reflecting the actual effects of false alarms and deletions to the scheme performance. In Section IV, we compare the new scheme with Goodman's MFSK/FH-CDMA scheme in terms of performance and, a more meaningful metric, spectral efficiency (SE). Numerical examples show that our two-level FH-CDMA scheme provides a trade-off between performance and data rate. In the comparison of SE, the partitioned two-level FH-CDMA scheme exhibits better system efficiency than Goodman's MFSK/FH-CDMA scheme under some conditions.

NEW TWO-LEVEL FH-CDMA SCHEME DESCRIPTION

A. Two-level FH-CDMA Scheme

In our two-level FH-CDMA scheme, the available transmission bandwidth is divided into Mh frequency bands with Mm. carrier frequencies in each band, giving a total of $MmMh$ carrier frequencies. In the first (modulation) level, a number of serial data bits is grouped together and represented by a symbol. Each symbol is, in turn, represented by a modulation code of dimension $Mm \times Lm$ and weight (i.e., number of elements) wm, where Mm is the number of frequencies, Lm 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 ϕm available modulation codes, each symbol can represent up to $\lfloor \log 2\ \phi m \rfloor$ data bits, where $\lfloor \cdot \rfloor$ is the floor function.

TABLE I

TWENTY-FIVE (4 × 5, 4, 0, 1) PRIME SEQUENCES, WHICH CAN BE ORGANIZED INTO FIVE GROUPS WITH $\lambda'c$, = 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

In the second (FH) level, each user is assigned a unique FH pattern of dimension $Mh \times Lh$ and weight (i.e., number of elements) wh, where Mh is the number of frequencies, Lh is the number of time slots (i.e., pattern length). The elements in the modulation codes and FH patterns determine the carrier frequencies of the final FH-CDMA signals. While an element of a modulation code defines the carrier frequency used in a frequency band in a given time slot, an element of the FH pattern determines which frequency band (out of Mh bands) to use. In our scheme, we can choose any families of ($Mm \times Lm$, wm, $\lambda a,m$, $\lambda c,m$) modulation codes and ($Mh \times Lh$, wh, $\lambda a,h$, $\lambda c,h$) FH patterns as long as $wh \geq Lm$, where $\lambda a,m$ ($\lambda a,h$) and $\lambda c,m$ ($\lambda c,h$) denote the maximum autocorrelation sidelobes and cross-correlation values of the modulation codes (FH patterns), respectively.

To illustrate the main concept of our two-level FH-CDMA scheme, we here use prime sequences as the modulation codes; other codes, such as the RS sequences, quadratic congruence codes (QCCs), and multilevel prime codes (MPCs), can also be used. The prime sequences are constructed in Galois field GF(p) of a prime number p. Each prime sequence of weight $wm = p$ is denoted by $Si1,i2 = (si1,i2,0,\ si1,i2,1,\ .\ .\ .\ ,\ si1,i2,l,\ .\ .\ .\ ,\ si1,i2,p{-}1)$, where the lth element $si1,i2,l = i2 \oplus p\ (i1 \odot p\ l)$ represents the frequency used in the lth position (i.e., time slot) of $Si1,i2$, $\{i1, i2, l\} \in$ GF(p), "$\oplus p$" denotes a modulo-p addition, and "$\odot p$" denotes a modulo-p multiplication.

Since these prime sequences are used as the modulation codes, each element of $Si1,2$ determines which carrier frequency of a frequency band in a given time slot to use. If the number of available carrier frequencies is restricted or the sequence weight needs to be varied in order to achieve certain scheme performance, we can always adjust the sequence weight to be $wm < p$ by dropping the largest $p{-}wm$ elements in $Si1,2$. As a result, the construction algorithm gives $= p2$

$- p + w_m$ prime sequences1 of weight $w_m \leq p$ and length $L_m = p$ with $\lambda_c, = 1$ (i.e., symbol interference).

For example, with $p = 5$ and $w_m = 4$, Table I shows twenty-four $(M_m \times L_m, w_m, \lambda_a,, \lambda_{c,m})$ = (4 × 5, 4, 0, 1) prime sequences, where "x" denotes the drop of the fifth element in order to have a code weight of four. Using these prime sequences as the modulation codes, we can support at most twenty-four symbols and each symbol represents ⌊log2 24⌋ = 4 data bits.

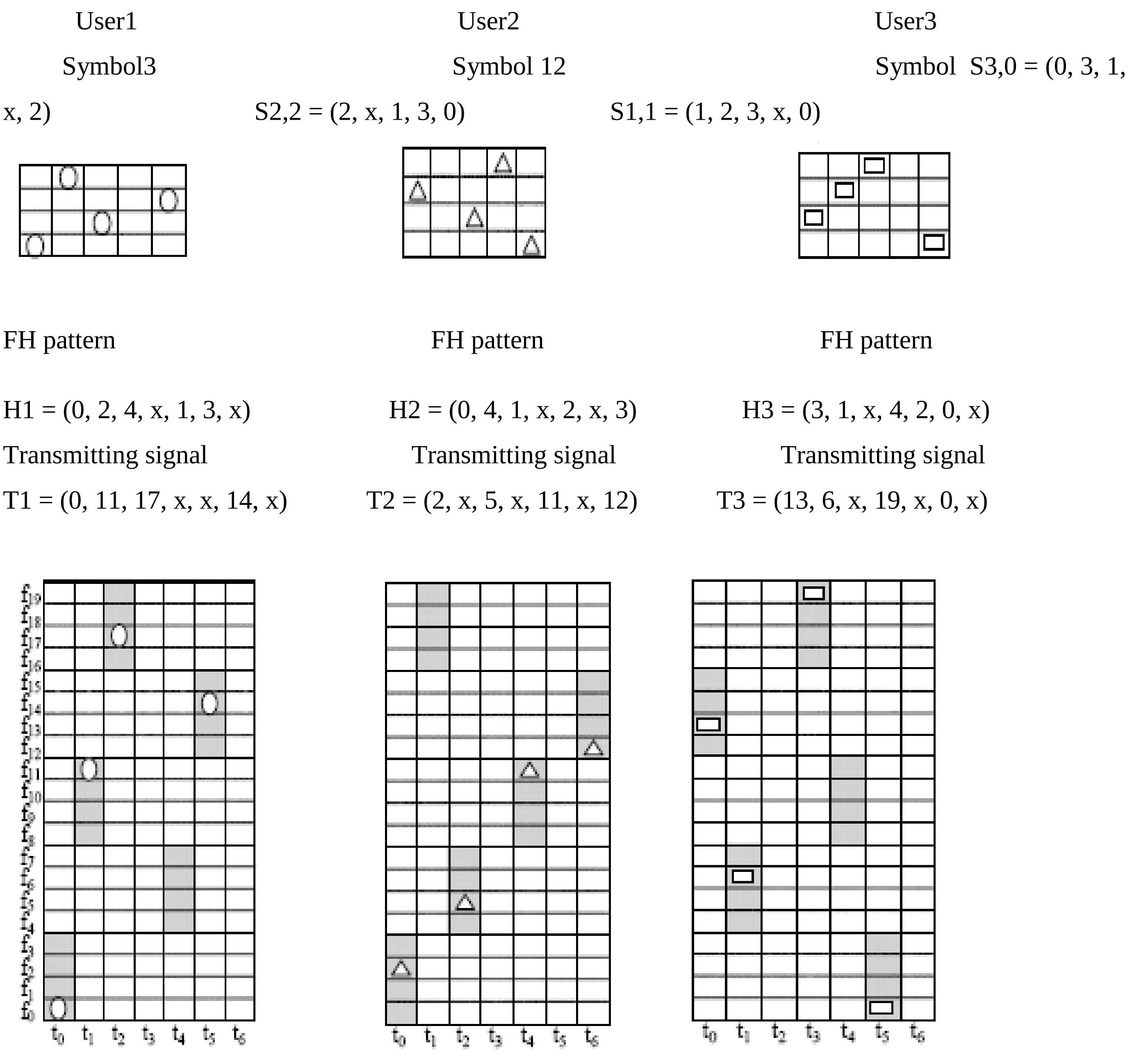

Fig. 1. Example of the encoding process of the two-level FH-CDMA scheme with three simultaneous users. (

The shaded columns in the transmitting signals, T_k, represent the frequency bands specified by the corresponding FH patterns, H_k, for $k = \{1, 2, 3\}$.) As mentioned earlier, we can choose any FH patterns for the second level of our two-level FH-CDMA scheme as long as $w_h \geq L_m$. To illustrate this, we choose the $(M_h \times L_h, w_h, \lambda_{a,h}, \lambda_{c,h}) = (5 \times 7, 5, 0, 1)$ prime sequences as the one-hit FH patterns and the top sixteen $(M_m \times L_m, w_m, \lambda_{a,m}, \lambda_{c,m}) = (4 \times 5, 4, 0, 1)$ prime sequences in Table I as the modulation codes.[3] Fig. 1 shows the encoding process of three simultaneous users. If the data symbols of these three users at one time instant are "3", "12", and "6", then we pick $S_1 = S_{3,0} = (0, 3, 1, x, 2)$, $S_2 = S_{2,2} = (2, x, 1, 3, 0)$, and $S_3 = S_{1,1} = (1, 2, 3, x, 0)$ as the modulation codes, respectively.

Let the 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 final two-level FHCDMA signal, where $k = \{1, 2, 3\}$. The shaded columns in the transmitting signals, T_k, of Fig. 1 represent the frequency bands specified by the corresponding FH patterns, H_k, for $k = \{1, 2, 3\}$. In summary, the two-level FH-CDMA signal can be represented by $T_k = (T_{k,0}, T_{k,1}, \ldots, T_{k,i}, \ldots, T_{k,L_h-1}) = S_k \triangle (M_m H_k)$, where $T_{k,i}$ represents the carrier frequency used in the ith time slot and $\triangle$ denotes the superimpose operation. For example, the two-level FH-CDMA signal of the first user is found to be $T_1 = (0+0 \cdot 4, 3 + 2 \cdot 4, 1 + 4 \cdot 4, x, x, 2 + 3 \cdot 4, x) = (0, 11, 17, x, x, 14, x)$ after superimposition. Similarly, the other two simultaneous users have $T_2 = (2, x, 5, x, 11, x, 12)$ and $T_3 = (13, 6, x, 19, x, 0, x)$.

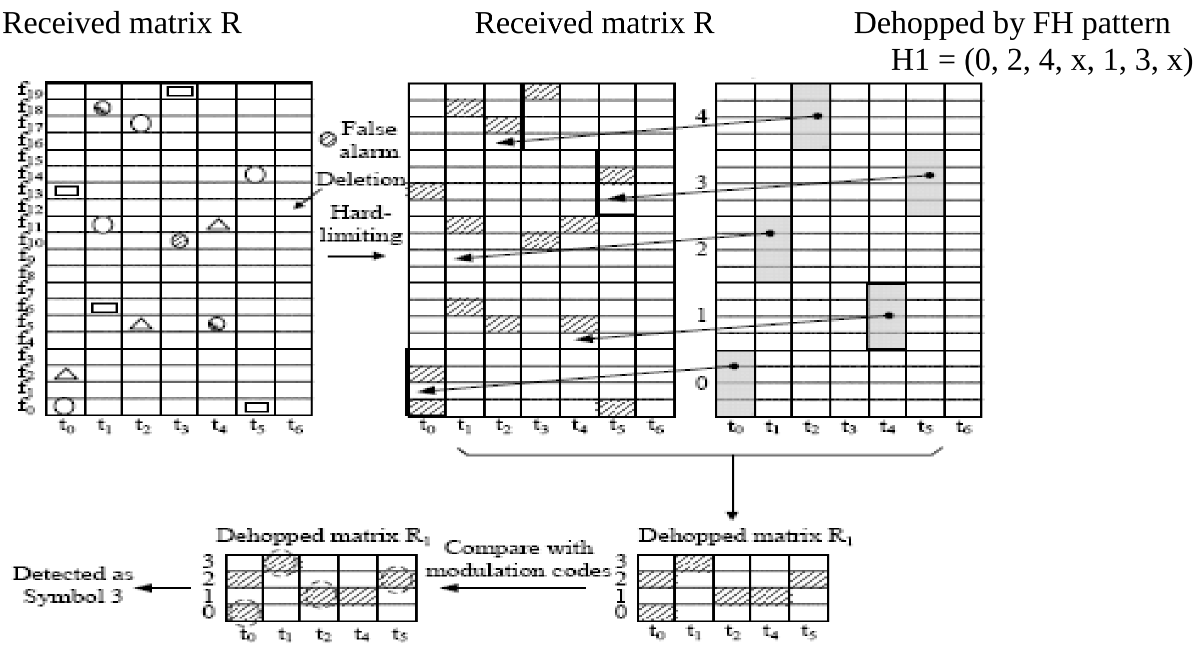

Fig. 2. Example of the decoding and detection process of the two-level FH-CDMA scheme with user 1.

In a receiver, the received two-level FH-CDMA signals of all users and effects of MAI, fading, and noise (i.e., hits, deletions, and false alarms) are hardlimited, dehopped, and finally decoded in order to recover the transmitted data symbols. Fig. 2 illustrates the decoding and detection processes of user 1.The received signal R is first hardlimited and then dehopped by user 1's FH pattern $H1$ to give a dehopped signal $R1$ of dimension 4×5. The role of the dehopping process simply brings the frequency bands in each time slot of R back to the baseband, according to the frequency bands specified by $H1$. The elements of $R1$ are compared with the elements of all modulation codes in use. The modulation code (e.g., $S3,0$, with its elements shown as circles in Fig. 2) with the minimum distance from the shaded slots of $R1$ is chosen as the recovered symbol.

Although the prime sequences can only support up to $\lfloor \log 2(p2 - p + wm) \rfloor$ bit/symbol, it is important to point out that our two-level FH-CDMA scheme allows the use of other codes, such as the RS sequences ,QCCs ,and MPCs ,as the modulation codes. For example, the MPCs have pn+1 sequences of weight $wm = p$ and length $Lm = p$ with $\lambda c, = n$ (i.e., symbol interference), where n is a natural number. If the MPCs are used as the modulation codes, the date rate can be increased because the MPCs can support up to $\lfloor \log 2\ pn{+}1 \rfloor$ bit/symbol at the expense of worsened symbol interference.

B.Partitioned Two-level FH-CDMA Scheme

In general, the number of possible users in a FH-CDMA system is limited by the number of available FH patterns. However, our two-level FH-CDMA scheme can flexibly increase the number of possible users by trading for lower data rate through a reduction of symbol size. It is done by partitioning the modulation codes into several groups and each group contains reduced number of modulation codes with a lower λc,. Each user can now only use one group of modulation codes for symbol representation. In addition to the unique FH pattern assigned to a user, the group of modulation codes that the user can use adds another degree of user address signature.

The same FH pattern can now be reused by multiple users as long as they have different groups of modulation codes. Let say there are ϕh FH patterns and ϕm modulation codes with λc,. If the modulation codes are partitioned into t groups of codes with $\lambda' c$,. (Usually, the partition results in $\lambda' c, = \lambda c, -1$.) We can then assign each user with one FH pattern and one of these t groups of modulation codes, thus supporting a total of $t\phi h$ possible users. The tradeoff is that each group now has at most $\phi m/t$ modulation codes and thus the number of bits per symbol is lowered from $\lfloor \log 2\ \phi m \rfloor$ to $\lfloor \log 2(\phi m/t) \rfloor$.

For example, the twenty-four $\lambda c, = 1$ prime sequences in Table I can be partitioned into five groups of prime sequences of $\lambda' c, = 0$ and assigned to five different users with the same FH pattern. Although 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 ϕh to $5\phi h$. We can also choose the MPCs of length p and λc, = n as the modulation codes. As shown in [12], the MPCs can be partitioned into $pn-n'$ groups and each group has $\lambda' c$, = n' and ϕm = pn'+1, where $n > n'$. The number of possible users is increased to $\phi hpn-n'$, but the number of bits per symbol is reduced to ⌊log2 pn'+1⌋.

PERFORMANCE ANALYSES

In FH-CDMA systems, MAI depends on the crosscorrelation values of FH patterns. For our two-level FHCDMA scheme, the cross-correlation values of the modulation codes impose additional (symbol) interference and need to be considered. Assume that one-hit FH patterns of dimension $Mh \times Lh$ are used and the transmission band is divided into $MmMh$ frequencies, in which Mm frequencies are used to carry the modulation codes of weight wm. The probability that a frequency of an interferer hits with one of the wm frequencies of the desired user is given by

$$q = \frac{w_m^2}{M_m M_h L_h}. \qquad (1)$$

Assume that there are K simultaneous users, the probability that the dehopped signal contains n entries in an undesired row is given by

$$P(n) = \binom{w_m}{n} \sum_{i=0}^{n} (-1)^i \binom{n}{i} \left[1 - q + \frac{(n-i)q}{w_m}\right]^{K-1}. \qquad (2)$$

Over AWGN, and Rayleigh and Rician fading channels, false alarms and deletions may introduce detection errors to the received FH-CDMA signals. A false-alarm probability, , is the probability that a tone is detected in a receiver when none has actually been transmitted. A deletion probability, pd, is the probability that a receiver missed a transmission tone. For these three types of channels, the false-alarm probability is generally given by

$$p_f = \exp\left(-\beta_0^2/2\right). \qquad (3)$$

For an AWGN channel, the deletion probability is given by
where $\beta 0$ denotes the actual threshold divided by the rootmean- squared receiver noise, kb is the number of bits per symbol, Eb/No is the average bit-to-noise density radio, $Q(a, b)$ = ∫ ∞ b x exp[−(a2 +x2)/2]I0(ax)dx is Marcum's Q-function, and I0(·) is the modified Bessel function of the first kind and zeroth order. To minimize the error probability, the optimal $\beta 0$ of an AWGN channel should be a function of the signal-to-noise ratio (SNR), (Eb/No) · (kb/wm) and can be more accurately written as

$$\beta_0 = \sqrt{2 + \frac{(\overline{E_b}/N_o) \cdot (k_b/w_m)}{2}} \qquad (5)$$

rather than an inaccurate constant value (i.e., $\beta 0 = 3$, used). For a Rayleigh fading channel, the deletion probability is given by

$$p_d = 1 - \exp\left\{\frac{-\beta_0^2}{2 + 2(\overline{E_b}/N_o) \cdot (k_b/w_m)}\right\}. \qquad (6)$$

Similarly, the optimal $\beta 0$ of a Rayleigh fading channel can be more accurately written as

$$\beta_0 = \sqrt{2 + \frac{2}{(\overline{E_b}/N_o) \cdot (k_b/w_m)}} \times \sqrt{\log\left[1 + (\overline{E_b}/N_o) \cdot (k_b/w_m)\right]}. \qquad (7)$$

Finally, for a Rician fading channel, the deletion probability is given by

$$p_d = \left[1 - Q\left(\sqrt{\frac{2\rho(\overline{E_b}/N_o) \cdot (k_b/w_m)}{1 + \rho + (\overline{E_b}/N_o) \cdot (k_b/w_m)}}, \beta_1\right)\right] \qquad (8)$$

where the Rician factor ρ is given as the ratio of the power in specular components to the power in multipath components . Similarly, $\beta 0$ and $\beta 1$ can be more accurately written as

$$\beta_0 = \sqrt{2 + \frac{(\overline{E_b}/N_o) \cdot (k_b/w_m)}{2}} \qquad (9)$$

$$\beta_1 = \frac{\beta_0}{\sqrt{1 + (\overline{E_b}/N_o) \cdot (k_b/w_m)/(1+\rho)}}. \qquad (10)$$

Including the noise or fading effect, the probability that the dehopped signal contains n entries in an undesired row is given by

$$
\begin{aligned}
P_s(n) = & \sum_{j=0}^{n} \sum_{r=0}^{\min[n-j, w_m-n]} \Bigg[P(n-j) \binom{n-j}{r} \\
& \times p_d^r (1-p_d)^{n-j-r} \binom{w_m-n+j}{r+j} \\
& \times p_f^{r+j} (1-p_f)^{w_m-n-r} \Bigg] \\
& + \sum_{j=1}^{w_m-n} \sum_{r=j}^{\min[n+j, w_m-n]} \Bigg[P(n+j) \binom{n+j}{r} \\
& \times p_d^r (1-p_d)^{n+j-r} \binom{w_m-n-j}{r-j} \\
& \times p_f^{r-j} (1-p_f)^{w_m-n-r} \Bigg]. \qquad (11)
\end{aligned}
$$

In FH-CDMA systems, an error occurs when interference causes undesired rows in the dehopped signal to have equal or more entries than the desired rows. In addition, an error may still occur in our two-level FH-CDMA scheme even when the undesired rows have less entries than the desired rows. It is because the nonzero cross-correlation values of the modulation codes add extra undesired entries. To account for this, let Azi denote the conditional probability of the number of hits (seen at any one of the incorrect rows) being increased from z to $z+i$, where $i \in [1, \lambda c,]$. To account for the effect of $\lambda c, \neq 0$, we derive a new probability of having a peak of z as

$$
\begin{aligned}
P'_s(z) = & A^z_{\lambda_{c,m}} P_s(z-\lambda_{c,m}) + A^z_{\lambda_{c,m}-1} \\
& \times P_s(z-(\lambda_{c,m}-1)) + \cdots + A^z_1 P_s(z-1) \\
& + \left(1 - \sum_{t=1}^{\lambda_{c,m}} A_t^{z+t}\right) P_s(z) \qquad (12)
\end{aligned}
$$

where $A_t^{z+t} = 0$ when $z + t > wm$. The computation of A_i^z is exampled in Appendix. If there are $2kb - 1$ incorrect rows, the probability that n is the maximum number of entries and that exactly t unwanted rows contain n entries is given by

$$
P_r(n,t) = \binom{2^{k_b}-1}{t} [P'_s(n)]^t \left[\sum_{m=0}^{n-1} P'_s(m)\right]^{2^{k_b}-1-t}. \quad (13)
$$

Over a noisy or fading channel, the probability of having an entry in a desired row is $1-pd$. Therefore, the probability that there exist n entries in a desired row is given by

$$P_c(n) = \binom{w_m}{n} (1-p_d)^n (p_d)^{w_m - n}. \quad (14)$$

The desired symbol is detected wherever the maximum number of entries in the t incorrect rows is less than n. As the receiver decides which symbol (out of $2kb$ symbols) is recovered by searching for the modulation code with thelargest matching entries, the bit error probability (BEP) is finally given by

$$P_b(K) = \frac{2^{k_b}}{2(2^{k_b}-1)} \times \left\{1 - \sum_{n=1}^{w} \left[P_c(n) \sum_{t=0}^{2^{k_b}-1} \frac{1}{t+1} P_r(n,t)\right]\right\}. (15)$$

PERFORMANCE AND SE COMPARISONS

In this section, we compare the performances of the new two-level FH-CDMA and Goodman's MFSK/FH-CDMA schemes under the condition of same transmission parameters: $Mg = MmMh$, $Lg = Lh$, and $wg = wm$, where Mg, Lg, and wg are the number of frequencies, number of time slots, and weight of FH patterns utilized by Goodman's MFSK/FHCDMA scheme, respectively. As illustrated , the prime sequences may give at most two hits in Goodman's MFSK/FHCDMA scheme under a symbol-asynchronous assumption. The main difference is that Goodman's MFSK/FH-CDMA scheme supports Mg modulation symbols (represented by the orthogonal frequencies), while the two-level FH-CDMA scheme supports $p2 - p + wm$ symbols with the symbolinterference level λc, = 1 if the prime sequences in Section II are used as the modulation codes. This symbol interference is accounted for by the probability term $P_s'(z)$.

In Fig. 3, the BEPs of both schemes are plotted against the number of simultaneous users K over a Rayleigh fading channel, based on the condition of same transmission parameters, where $Mg \times Lg$ = 44×47, $wg = wm$ = 4, $Mm \times Lm$ = 4×11, $Mh \times Lh$ = 11×47, and Eb/No = 25 dB. Using p = 11, our two-level FH-CDMA scheme supports kb = 6 bits/symbol, while Goodman's MFSK/FH-CDMA scheme supports kb = 5 bits/symbol. Based on (7) and kb = {5, 6}, we more accurately calculate $\beta 0$ = {3.4633, 3.5148}, respectively, instead of the constant $\beta 0$ = 3. In general, the performance of our scheme is worse than that of Goodman'sscheme because of the additional symbol interference created by the prime sequences.

Also shown in the figure is the computer-simulation result for validating our theoretical analysis. The computer simulation of our two-level FH-CDMA scheme is performed as follows. The FH pattern assigned to each user is arbitrarily selected from all 472 possible (11 × 47, 11, 0, 1) prime sequences constructed from GF(47) and then all 112 possible (4 × 11, 4, 0, 1) prime sequences constructed from GF(11) are used as the modulation codes for each user. For each simulation point in the figure, the total number of data bits involved in the simulation ranges from 104 to 106, depending on the targeted error probability.

In our partitioned two-level FH-CDMA scheme, the modulation codes (e.g., the prime sequences) are partitioned into p groups and the cross-correlation values of each group are zero (i.e. zero symbol interference). We then have Azc = 0 and $P' s(z) = Ps(z)$. In Goodman's MFSK/FH-CDMA scheme, we can also partition Mg frequency bands into p subbands to achieve the same number of possible users as our partitioned two-level FH-CDMA scheme.

However, the number of data bits per symbol in Goodman's scheme is decreased to $kb = \lfloor \log2(Mg/p) \rfloor$. In Fig. 4, the BEPs of both schemes over a Rayleigh fading channel are plotted against the number of simultaneous users K, based on the conditions of same number of possible users and same transmission parameters, where $Mg \times Lg = 44 \times 47$, $wg = wm = 4$, $Mm \times Lm = 4 \times 11$, $Mh \times Lh = 11 \times 47$, and $Eb/No = 25$ dB. Our partitioned scheme supports $kb = 3$ bits/symbol, while Goodman's scheme supports $kb = 2$ bits/symbol.

Based on (7) and $kb = \{2, 3\}$, we more accurately calculate $\beta 0 = \{3.1943, 3.3154\}$, respectively, instead of the constant $\beta 0 = 3$ .The performance of our partitioned scheme is very comparable to that of Goodman's scheme.

In Fig. 5, the BEPs of our two-level FH-CDMA scheme under AWGN, and Rayleigh and Rician fading channels are plotted against the number of simultaneous users K, where $wm = 4$, $Mm \times Lm = 4 \times 11$, $Mh \times Lh = 11 \times 47$, $\rho = 13$, $kb = 6$, and $Eb/No = 25$ dB. Based on (5), (7), (9), and (10), we more accurately calculate $\beta 0$ and $\beta 1$, which are given in Fig. 5. As expected, the AWGN curve always performs the best and the Rayleigh curve performs the worse, while the Rician curve is in between. Also shown in the figure is the computer-simulation result for validating our theoretical analysis.

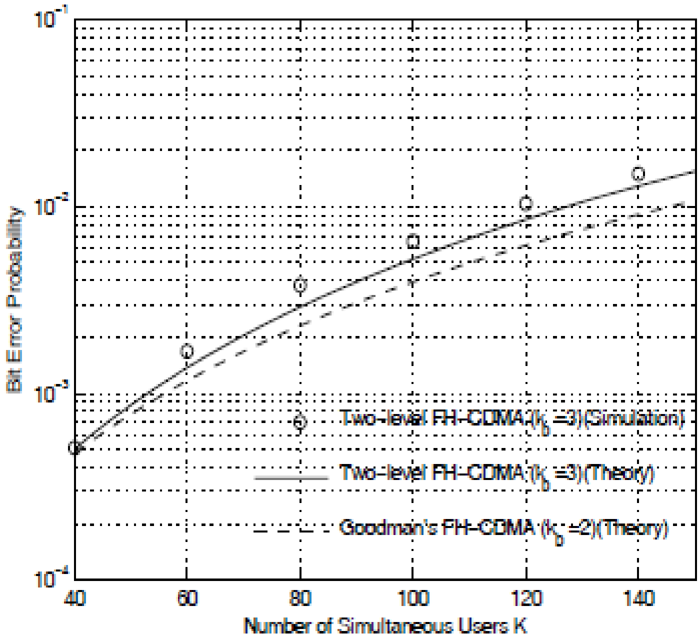

Fig. 4. BEPs of the partitioned two-level FH-CDMA and Goodman's FHCDMA schemes versus the number of simultaneous users K over a Rayleigh fading channel, where $Mg \times Lg$ = 44×47, $wg = wm$ = 4, $Mm \times Lm$ = 4 × 11, $Mh \times Lh$ = 11 × 47, kb = {2, 3}, $\beta 0$ = {3.1943, 3.3154}, and Eb/No = 25 dB.

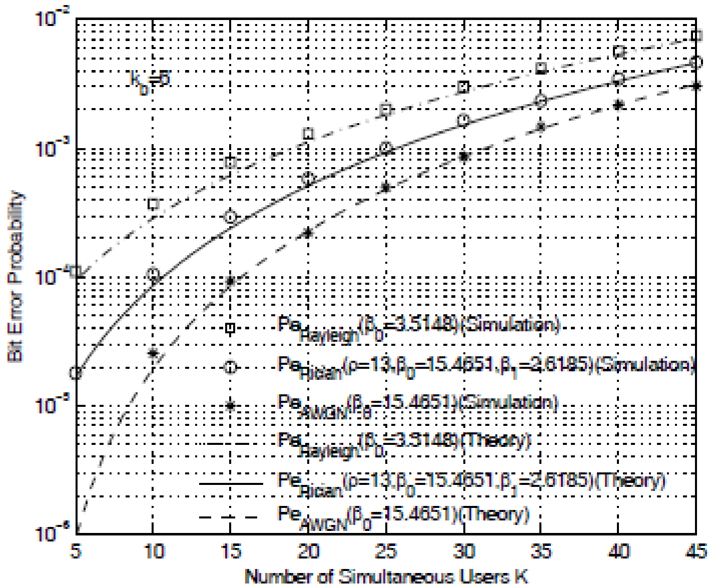

Fig. 5. BEPs of the two-level FH-CDMA scheme versus the number of simultaneous users K over AWGN, and Rayleigh and Rician fading channels, where wm = 4, $Mm \times Lm$ = 4 × 11, $Mh \times Lh$ = 11 × 47, ρ = 13, kb = 6, and Eb/No = 25 dB.

TABLE II

SE COMPARISON OF BOTH SCHEMES WITH $Pe = \{10-2, 10-3\}$, BASED ON THE PARAMETERS FROM FIG. 4.

Bit error probability	P_e=10^{-2}	P_e=10^{-3}
Goodman's FH-CDMA (k_b = 2)	K=144 SE=13.93%	K=56 SE=5.42%
Two-level FH-CDMA (k_b = 3)	K=126 SE=18.29%	K=53 SE=7.69%

To compare our partitioned two-level FH-CDMA and Goodman's MFSK/FH-CDMA schemes,

$$\mathrm{SE} = \frac{k_b K}{ML} \qquad (16)$$

is another figure of merits, which considers the number of bits per symbol kb, number of simultaneous users K, number of carrier frequencies M, and number of time slots L as a whole, for a given performance (i.e., BEP) . Our goal is to get the SE as large as possible for better system efficiency or utilization. Table II compares the SEs of both schemes with fixed Pe = {10−2, 10−3}, based on the parameters from Fig. 4. In our partitioned two-level FH-CDMA scheme, we can always increase the number of possible users by partitioning the modulation codes, thus resulting in a larger kb than Goodman's FH-CDMA scheme for the same bandwidth
expansion (i.e., ML).

While the number of simultaneous users K of our partitioned two-level FH-CDMA scheme is only slightly less than that of Goodman's FH-CDMA scheme in Fig. 4, the larger kb results in a net gain in the SE, as shownin Table II. Combining with higher data rate, greater SE, and flexible selection of modulation codes and FH patterns, our two-level FH-CDMA scheme is a better choice in meeting various system operating criteria.

CONCLUSION

In this project, we proposed a new two-level FH-CDMA scheme. The prime/FH-CDMA and RS/FH-CDMA schemes were special cases of our scheme. The performance analyses showed that the two-level FH-CDMA scheme provided a trade-off between performance and data rate. The partitioned two-level FH-CDMA scheme increased the number of possible users and exhibited higher data rate and greater SE than Goodman's MFSK/FH-CDMA scheme. In summary, the new scheme offered more flexibility in the design of FH-CDMA systems to meet different operating requirements.