Multiuser Demodulation and Iterative Decoding for Frequency-Hopped Networks

Naresh Sharma, *Member, IEEE*, Hesham El Gamal, *Member, IEEE*, and Evaggelos Geraniotis, *Senior Member, IEEE*

***Abstract*—Demodulation and decoding for frequency-hopped spread-spectrum multiple-access (FH/SSMA) systems have been traditionally conducted by conventional single-user (noncollaborative) demodulation and errors and erasures correcting decoding techniques. In this paper, we study the demodulation and decoding aspects of collaborative multiuser reception for FH/SSMA and propose methods which increase the number of users the system can support. In particular, we propose and analyze the optimum maximum *a priori* probability demodulation of multiple symbols or type, and the use of iterative multiuser decoding after the demodulation. Since hits from one or two other users are the most likely hit events in FH/SSMA, the joint demodulation of two or of three users is performed based on likelihood ratio tests. M-ary frequency-shift keying modulation with noncoherent demodulation and Reed–Solomon codes with hard-decision minimum distance decoding are used in the FH/SSMA system. Results are derived for both synchronous and asynchronous frequency-hop systems. The performance of the proposed multiuser detector in additive white Gaussian noise and flat Raleigh fading channels is evaluated. Scenarios when all simultaneous users or only a subset of them are collaboratively demodulated and decoded are simulated.**

***Index Terms*—Frequency hopping, iterative decoding, multiuser detection, spread spectrum.**

I. Introduction

MANY properties of the frequency-hopped spread-spectrum multiple access (FH/SSMA) make it a preferred multiple-access communication scheme such as robust performance against frequency-selective fading, security against jamming because of robust anti-jam margins and low probability of intercept/low probability of detection (LPI/LPD), etc. While there has been much work in trying to improve the performance of the system against jamming and making the system robust to channel distortions, there is a considerable scope of improvement in supporting larger number of users at given signal-to-noise ratio (SNR) and probability of error requirements, as we show in this paper.

A common form of receiver is to perform the noncollaborative single-user decoding of all the users or in other words, pretend that other users are not present at all. This is clearly the simplest design and the burden of errors due to single-user demodulation is put entirely on the error correcting code. This approach can be extended to erase the symbol for all the users in the event of two or more users occupying the same frequency slot, also termed as *hit*. This is followed by errors and erasures decoding. Since the error correcting code, like Reed–Solomon (RS) codes, can correct more erasures than errors, this results in a better performance than a simple single-user receiver. However, one needs to know the hopping patterns of all users to follow this approach.

An improvement to the second approach was suggested in [2] which suggests a Bayesian approach to either decode the strongest user signal or to erase all the signals. However, there are a number of issues which are unresolved. It is not clear as to how the decision of a single user is allocated to the respective user and its resulting effect on the performance improvement by this approach in terms of supporting larger number of users, gain in SNR, etc., over the noncollaborative or simple erasures decoding. Further for the Bayesian approach, some assumptions are made about the number of frequency bins and users being very large (infinite), which may not be realistic in certain cases of interest.

The contribution of this paper is the introduction and investigation of a collaborative or joint detection approach coupled with iterative decoding of RS-coded FH/SSMA. More specifically, we do the joint demodulation of the received signal in the event of the *hit*. One can draw parallels between the proposed method and the code-division multiple-access (CDMA) demodulation. However, unlike the CDMA scenario, we do not have the luxury of signature waveforms identifying each user.

In the asynchronous case, an identifying parameter for each user signal is its time (of arrival at the receiver). In this context in the synchronous case, the situation is more complicated as we *cannot* distinguish one user from another. We exploit the notion of *type* (this term is well known in information theory [3]) and revisit the demodulation to identify the type. If in a hit, all but one users are decoded at the receiver, the proposed type demodulation is specialized to obtain an optimum maximum *a priori* probability (MAP) estimate of the remaining user. Since hits from one or two other users are the most likely events in FH/SSMA than hits from more users, the demodulation of two or of three users is performed based on likelihood ratio tests.

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N. Sharma was with the Department of Electrical Engineering and the Institute for Systems Research, University of Maryland, College Park, MD 20742 USA. He is now with Lucent Technologies, Whippany, NJ 07981 USA (e-mail: nareshs@lucent.com).

H. El Gamal was with the Department of Electrical Engineering and the Institute for Systems Research, University of Maryland, College Park, MD 20742 USA. He is now with the Department of Electrical Engineering, Ohio State University, Columbus, OH 43210 USA (e-mail: helgamal@ee.eng.ohio-state.edu).

E. Geraniotis is with the Department of Electrical Engineering and the Institute for Systems Research, University of Maryland, College Park, MD 20742 USA (e-mail: evagelos@eng.umd.edu).

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After the symbol or type demodulation, we propose an iterative decoder that exploits the symbol and type decisions to decode the codeword for each user.

We consider the performance of the method to channels with multiuser interference, additive white Gaussian noise (AWGN), and Rayleigh fading and compare it with the number of supported users by the conventional methods [5]. In this paper, we restrict attention to the hard-decision symbol and type demodulation. M-ary frequency-shift keying (MFSK) modulation with noncoherent demodulation and RS codes with hard-decisions minimum distance decoding are used in the FH/SSMA system. Results are derived for both synchronous and asynchronous frequency-hop systems. Scenarios when 1) all of the simultaneous users or 2) only a subset of them are jointly demodulated and decoded are evaluated.

The multiuser design described in this paper is valid for all FH/SSMA systems that employ frequency hopping that is not fast; that is, when the number of data symbols per hop (N_s) is larger or equal to one. These include the "pure" slow frequency-hopping case ($N_s \gg 1$ is a large integer) and the case when $N_s \geq 1$ is a small integer or equals one (regular frequency hopping). It is not applicable to FH/SSMA systems with "pure" fast hopping where each data symbol is transmitted over several hopping frequencies, although the demodulation principles developed in this paper can be extended easily for such scenarios.

The paper is organized as follows. In Section II, we provide the FH/SSMA system model. In Section III, we present optimal decision tests for the symbol or type demodulation of synchronous and FH/SSMA in both AWGN and Rayleigh fading channels and then for asynchronous FH/SSMA. Following in Section IV is the description of the algorithm for iterative collaborative decoding that uses the results of the joint demodulation schemes of Section III and enhances the multiuser detector performance. In Section V, performance results are shown for the various FH/SSMA systems and multiuser detection scenarios of interest and a discussion of the complexity considerations of the proposed multiuser detection algorithms is provided. Finally, in Section VI, conclusions are drawn from this work.

Notation: We define the notation used throughout the paper.

- AWGN indicates the additive white Gaussian noise.
- MAP indicates maximum *a priori* probability.
- $I_0(x) = 1/\pi \int_0^\pi \exp(x \cos\theta) d\theta$.
- $\|x, y\| = \sqrt{x^2 + y^2}$.

II. System Model and Mathematical Preliminaries

The system under consideration is similar to the one described in [6] and [7]. Frequency-hop spread-spectrum transmission with noncoherent demodulation is considered with an (n, k) RS code for errors and erasures decoding. The modulation scheme considered is MFSK with $M = n + 1$. There are other types of modulation schemes considered in the literature like block binary frequency-shift keying (BFSK). However, the type of modulation is not critical to illustrating the essential features of our method and we restrict our attention to MFSK.

The total number of frequency slots or bins available are q, and there are K users present in the system. All the K users are assumed to be active, i.e., transmitting at all times. The symbols are interleaved at the transmitter. The channel thus has multiple-access interference and adds AWGN. We also consider the case of fading channel in addition to the above interferences. We assume that all the users have the same average power. For the fading channel, the instantaneous power will be different. The assumption of same power for all users is considered for the sake of illustration and is not critical for the proposed method. One can easily extend the demodulation and decoding principles to the case where the users have unequal powers. The receiver is interested in all the K users. Later, we will consider the case when the receiver is interested only in a fraction of users which have the same power and are considered for joint demodulation and decoding, and the rest with lower power and unknown hopping patterns are ignored by the receiver. The power of the ignored users adds on to the noise level of the received signal.

Let $s_i(t)$ denote the transmitted signal by the ith user. For MFSK

$$s_i(t) = \sqrt{\frac{2E_s}{T}} \cos\left(\omega_i(t - \tau_i) + \theta_i\right)$$

where E_s denotes the symbol energy, T is the symbol duration, τ_i is the time lag of each user relative to a fixed time reference, ω_i is the frequency of the ith user, and θ_i is the angle added by the transmitter oscillator which is unknown at the receiver. For the synchronous case, τ_i's are te same for all users. The FSK signal is frequency hopped according to the hopping pattern for that user and the hopped frequencies are chosen from the set of q frequency bins. The time between the hops (or the dwell time) T_h is an integer multiple of T and usually much larger than T for slow frequency hopping. We assume that random hopping patterns are used where the probability of the ith user hitting the jth user (with $i \neq j$) is

$$p_h = \begin{cases} \dfrac{1}{q}\left(1 + \dfrac{1}{N_s}\left(1 - \dfrac{1}{q}\right)\right), & \text{asynchronous} \\ \dfrac{1}{q}, & \text{synchronous} \end{cases}$$

where $N_s = T_h/T$, the number of M-ary symbols per hop [6]. If we assume that N_s is quite large (slow frequency-hopping case) then $p_h \approx 1/q$ for both synchronous and asynchronous.

Notice that if we have $N_s \geq 1$ but not $N_s \gg 1$, the resulting probability of hits is still $p_h \approx 1/q$ for synchronous FH/SSMA, but $p_h \approx 2/q$ for asynchronous FH/SSMA. This latter case is characterized by frequency hopping that is neither slow ($N_s \gg 1$: a good many data symbols per hop) nor fast (in which case more than one frequency hops occur within each data symbol). The performance results included in this paper (Section V) are valid for any $N_s \geq 1$ (any hopping except for fast hopping) for synchronous FH/SSMA but only for $N_s \gg 1$ (slow hopping) for asynchronous FH/SSMA. However, our approach for multiuser detection can be easily applied to any asynchronous FH/SSMA system with $N_s \geq 1$, that is, to all cases except fast FH/SSMA.

We assume that the hopping patterns of all the users are independent, hence the probability of $l - 1$ other users hitting a given user is

$$\binom{K-1}{l-1} p_h^{l-1} (1 - p_h)^{K-l}.$$

The probability of hit decreases substantially as l increases for large q. Consider now the case when l users are present in a particular slot which we call a l-hit. The received signal is given by

$$r(t) = \sum_{i=1}^{l} a_i s_i(t) + n(t) \tag{1}$$

where a_i denotes the fade level for the ith user and $n(t)$ denotes the white Gaussian noise with spectral density $N_0/2$. For the fading channel case, a_i's are random variables modeled by probability distribution such as Rayleigh, Rician, etc. For the purposes of this paper, we consider a_i's to be Rayleigh with unit variance. If there is no fading present, then a_i is equal to unity for all users.

We assume that the receiver that acts as a base station, hub, or command station and thus has knowledge of the hopping patterns assigned to all users as well as interest in demodulating all signals (we also consider later the case where the receiver does not have information of hopping patterns of all users). The hub receiver is also in time synchronism and frequency-hopping pattern lock with all the transmitted signals; it thus knows when hits occur between the received FH signals from various users. The demodulation is accomplished by a bank of matched filters taking the quadrature and in-phase component with respect to M different frequencies. As we show that in the event of a hit, the envelope detector outputs are sufficient statistics for the two-hit synchronous case, but one needs the quadrature and in-phase components separately for the asynchronous case and l-hit asynchronous case with $l > 2$. We consider hard-decision demodulation for the symbol or type which is followed by multiuser decoder based on RS codes.

III. Multiuser Demodulation

Severe degradation of performance in multiple-access frequency-hop communication systems occurs in the event of a hit. One can try to erase the symbols of all the users involved in the hit. However, this inherently limits the number of users supported by the system because as the number of users increases, the probability of hit increases, and one would not like to have more hits so as not to exceed the decoding capability of the RS code. If one wishes to support more users, then the only possible way is to use a stronger error correcting code, which will affect (lower) the transmission data rate. In order to overcome this limitation on throughput, we revisit the usual FSK demodulation. Further in the next section, we develop a multiuser decoder for this demodulator.

A. Synchronous FH/SSMA

Consider an l-hit, i.e., there are l users out a total of K involved in that hit. The first question we ask is as follows: what is the maximum amount of information present in the received signal in the event of a hit? Note that since all the users occupy the same frequency bin and the users having the same average received powers, there is no way of distinguishing between the respective users. However, the "type" of the l-length sequence can, in principle, be determined by the demodulator. The "type" of a sequence is completely specified by the number of times each of the M symbols have occurred in a sequence [3]. For more discussion of types, please see [4]. For example, for two-user BFSK, in the event of a hit, the three sequences with different types are given by $\{1,1\}$, $\{1,2\}$, $\{2,2\}$. For MFSK with l users involved in a hit, the total number of l-length sequences with different types is given by

$$\mathcal{T} = \binom{M+l-1}{l}. \tag{2}$$

The demodulation now becomes a $\mathcal{T}$-ary hypothesis testing problem instead of M-ary one. Since $\mathcal{T}$ is larger than M, there is a potential increase in demodulator complexity (and of probability of decoding incorrectly). Let $i_1, \ldots, i_l$ denote the indices of the l users present at the current hit and let ω_{i_j} be the corresponding frequency (of the MFSK modulation) of each user.

1) Type Demodulation: Hence, the signal received at the time of hit (after removing the FH carrier frequency common to all users and for which the hit occurs) is given by

$$x(t) = \sqrt{\frac{2E_s}{T}} \sum_{j=1}^{l} \cos(\omega_{i_j} t + \theta_{i_j}) + n(t) \tag{3}$$

where E_s and T are defined as before in Section II, $n(t)$ is the AWGN with $E\{n(t)n(t-\tau)\} = N_0/2\delta(t-\tau)$, and θ's are the phase angles of the local oscillator of each user and are modeled as random variables with uniform probability density function in $[0, 2\pi]$. The frequencies ω_{i_j} take values in the M-value set $\{\omega_1, \omega_2, \ldots, \omega_M\}$ of MFSK tones used by all users and thus the frequency of one user ω_{i_j} can be equal to that of another user ω_{i_k} with probability $1/M$, while the phase angles θ_{i_j} are typically different from user to user since they are generated by the individual local oscillators.

Let $p(x(t)|s_k)$ denote the likelihood function when the type of the transmitted signal is s_k, and let π_k denote the *a priori* probabilities of each type. We now present the likelihood function for the two-hit case, i.e., when two interfering users are present in the event of a hit. There are $M(M+1)/2$ types with each type s_k denoted by symbols k_1 and k_2 (or equivalently frequencies ω_{k_1} and ω_{k_2}). Since the types are unchanged by permutation, $\{k_1, k_2\}$ is equivalent to $\{k_2, k_1\}$. Define the envelope detector outputs as

$$y_{i_j} = \sqrt{\frac{\left(\int_0^T x(t)\cos(\omega_{i_j} t)dt\right)^2 + \left(\int_0^T x(t)\sin(\omega_{i_j} t)dt\right)^2}{0.5E_sT}}.$$

The likelihood function for the type s_k after integrating with respect to the nuisance or unknown parameters, which are the unknown phases, is

$$p(x(t)|s_k) = \begin{cases} \dfrac{1}{\pi}\displaystyle\int_0^{\pi} I_0\left(2S\sqrt{y_{k_1}^2 - 2y_{k_1}\cos\theta + 1}\right) \\ \times \exp(2Sy_{k_1}\cos\theta)d\theta, & \text{if } k_1 = k_2 \\ I_0(2Sy_{k_1})I_0(2Sy_{k_2}), & \text{if } k_1 \neq k_2 \end{cases}$$

where $S = E_s/N_0$ denotes the SNR. Note that similar to the single-user receiver, the vector of M envelope detector outputs forms the set of sufficient statistics. Further, we can show that the probability density function of y_{i_j} is either Rayleigh, Rician, or conditionally Rician (due to unknown θ's). Moreover, y_{i_j}'s are mutually independent.

The *a priori* probabilities are given by

$$\pi_k = \begin{cases} \frac{1}{M^2}, & k_1 = k_2 \\ \frac{2}{M^2}, & k_1 \neq k_2. \end{cases}$$

The demodulator then selects the type for which the product $\pi_k\, p(x(t)|s_k)$ is maximum, which is the MAP decision. We give the probability density functions of the M envelope detector outputs y_i matched to frequencies ω_i, respectively. For the case when $k_1 = k_2$, if $i = k_1$

$$p(y_i|s_k) = \frac{2Sy_i}{\pi}\int_0^{\pi} \exp\left(-S(y_i^2 + 2(1+\cos\theta)\right) \times I_0\left(2Sy_i\sqrt{2(1+\cos\theta)}\right) d\theta$$

which is a Rician distribution conditioned on θ, and if $i \neq k_1$, then

$$p(y_i|s_k) = 2Sy_i \exp\left(-Sy_i^2\right)$$

which is a Rayleigh distribution. For the case when $k_1 \neq k_2$, if $i = k_1$ or $i = k_2$, then

$$p(y_i|s_k) = 2Sy_i \exp\left(-S(1+y_i^2)\right) I_0(2Sy_i)$$

which is a Rician distribution, else if $i \neq k_1$ and $i \neq k_2$, then

$$p(y_i|s_k) = 2Sy_i \exp\left(-Sy_i^2\right)$$

which is a Rayleigh distribution.

The results are explained intuitively for two-user BFSK. The three types are given by $s_1 = \{1,1\}$, $s_2 = \{1,2\}$, $s_3 = \{2,2\}$. The decision region for this case is drawn in Fig. 1 for the value of $SNR = 6$ dB. To physically explain this region, take the noise (AWGN) as negligible. In this case when s_2 is transmitted, both the envelope detector outputs must be nearly 1. Since the white noise has flat frequency spectrum with no preference for any particular frequencies, this reflects in the decision region where s_2 is chosen if y_1 and y_2 are close to each other and not too small. When s_1 is transmitted, the exact value of y_1 is not definite because there can be constructive or destructive interference depending on the values of θ_1 and θ_2. However, y_2 must be small with the only contribution coming from noise as the signal part cancels out due to orthogonal frequencies. Hence, if y_1 is larger than y_2 and they are not too close to each other when they are not small, s_1 is chosen. The case for s_3 is similar to this with the roles of y_1 and y_2 reversed. The likelihood functions for the case of three-hit case are given in the Appendix.

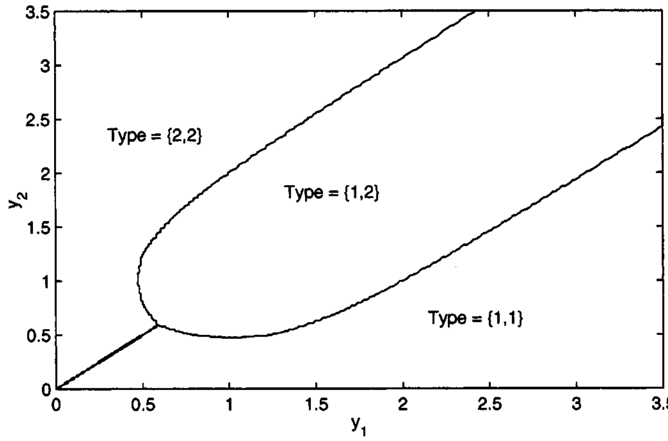

Fig. 1. Typical decision region for two-user BFSK (synchronous).

The two- and three-hit cases turn out to be the most important one as also verified by numerical simulations. It should be noted here that for typical values of M, $\mathcal{T}$ may be much larger than M. For example, for $M = 32$ and $l = 4$, $\mathcal{T} = 52\,360$. The error probabilities of the $\mathcal{T}$-ary hypothesis testing (decision) problem increase due to this and there may not be a gain in performance by using a l-hit demodulator for $l > 3$. Since hits with large value of l occur with small probability (of the order of $1/q^{l-1}$), additional information about such hits is not expected to result in a significant gain in performance. In conclusion, we expect the above multiuser detection region to be useful when few users (2 or 3) are jointly demodulated.

We now consider the case when channel fades the signal in addition to adding noise [see (1)]. In this case, the fade levels are the nuisance or unknown parameters in addition to the phases. The likelihood function is given the equation shown at the bottom of the page, where $P_A(a)$ is the cumulative probability distribution of random variable a. For Rayleigh distribution with characteristic λ, $dP_A(a) = 2a\lambda\exp(-\lambda a^2)da$.

The probability density functions of the M envelope detector outputs y_i matched to frequencies ω_i, respectively, are given for the case when $k_1 = k_2$ and $i = k_1$ as

$$p(y_i|s_k) = \frac{2Sy_i}{\pi}\int_0^{\infty}\int_0^{\infty}\int_0^{\pi} \exp\left(-S\left(y_i^2 + \left(a_1^2 + a_2^2 + 2a_1a_2\cos\theta\right)\right)\right) \times I_0\left(2Sy_i\sqrt{a_1^2 + a_2^2 + 2a_1a_2\cos\theta}\right) d\theta\, dP_{A_1}(a_1)\, dP_{A_2}(a_2)$$

which is a Rician distribution conditioned on θ, a_1, a_2 and if $i \neq k_1$, then

$$p(y_i|s_k) = 2Sy_i \exp\left(-Sy_i^2\right)$$

$$p(x(t)|s_k) = \begin{cases} \frac{1}{\pi}\int_0^{\infty}\int_0^{\infty}\int_0^{\pi} I_0\left(2S\sqrt{a_1^2 y_{k_1}^2 - 2a_1^2 a_2 y_{k_1}\cos\theta + a_1^2 a_2^2}\right) \\ \quad \times \exp\left(S(2a_2 y_{k_1}\cos\theta - a_1^2 - a_2^2)\right) d\theta\, dP_{A_1}(a_1)\, dP_{A_2}(a_2), & \text{if } k_1 = k_2, \\ \int_0^{\infty}\int_0^{\infty} I_0(2Sa_1 y_{k_1}) I_0(2Sa_2 y_{k_2}) \\ \quad \times \exp\left(-S(a_1^2 + a_2^2)\right) dP_{A_1}(a_1)\, dP_{A_2}(a_2), & \text{if } k_1 \neq k_2 \end{cases}$$

which is a Rayleigh distribution. For the case when $k_1 \neq k_2$, if $i = k_1$ or $i = k_2$, then

$$p(y_i|s_k) = 2Sy_i \int_0^\infty \exp\left(-S\left(a^2 + y_i^2\right)\right) I_0(2Say_i) dP_A(a)$$

which is a Rician distribution conditioned on a, else if $i \neq k_1$ and $i \neq k_2$, then

$$p(y_i|s_k) = 2Sy_i \exp\left(-Sy_i^2\right)$$

which is a Rayleigh distribution.

2) Symbol Demodulation: If the receiver has taken decisions, by some means, of all but one symbol involved in a hit, then it can use these decisions to arrive at the optimum symbol decision of the remaining symbol. Let the type for the l-hit case be given by $s_k = \{k_1, \ldots, k_l\}$ and let the symbols $k_2, \ldots, k_l$ be known. Let the likelihood functions for the type demodulation are given by $p(x(t)|s_k)$, then the M likelihood functions for symbol demodulation are given by $p(k_1|x(t), k_2, \ldots, k_l) = p(x(t)|s_k)$ and the receiver chooses that symbol for which $p(k_1|x(t), k_2, \ldots, k_l)$ is maximum.

B. Asynchronous FH/SSMA

We do a similar analysis for the asynchronous system where we assume that the relative time delays are known *a priori*. For the case of two users hitting each other, the symbol of each user is hit partially by two symbols of the other user but for the whole symbol duration (full hit), except at the start and end of dwell time. Note that in an asynchronous system, partial hits can occur, i.e., signal from the various users in the event of a hit do not overlap for the whole symbol interval. However, if $N_s \gg 1$, which implies that there are several MFSK symbols transmitted during each dwell time (slow hopping assumption), partial hits occur with much smaller probability than full hits. For the purpose of the present paper, we neglect such hits and assume all hits are full hits. We describe the likelihood equations for MFSK when two users are present at the time of the hit.

In particular, let the symbol of user of interest occupy the duration $[0, T]$ and let its frequency be denoted by the index k. Let the other user's symbols occupy the durations $[-\tau, T - \tau]$ and $[T - \tau, T + \tau]$ with their frequencies indexed by l_1 and l_2, respectively. For MFSK, $k, l_1, l_2 \in \{1, \ldots, M\}$. Hence, the nuisance parameters for the likelihood equations for the symbol of user of interest are the unknown phases for the three symbols and the two unknown frequencies l_1, l_2 of the symbols of the other user. The sufficient statistics are the in phase and quadrature phase components which are conditionally Gaussian random variables and are defined as

$$L_{i,j}^c = \sqrt{\frac{2}{E_s T}} \int_{S_i} x(t) \cos(\omega_j t) dt$$
$$L_{i,j}^s = \sqrt{\frac{2}{E_s T}} \int_{S_i} x(t) \sin(\omega_j t) dt$$

where $i = 1$ or 2, $S_1 = [0, T - \tau]$, $S_2 = [T - \tau, T]$, and $j \in \{1, \ldots, M\}$. The frequencies are denoted by ω_j. Note that unlike the synchronous case, envelope detector outputs are no longer the sufficient statistics. We define few more quantities as

$$\begin{aligned} &f_1(k, l_1, \theta) \\ &\quad = I_0\left(2S\|L_{1,l_1}^c - \alpha\cos\theta\delta_{k,l_1}, L_{1,l_1}^s + \alpha\sin\theta\delta_{k,l_1}\|\right), \\ &f_2(k, \theta) \\ &\quad = \exp\left(2S\left[\left(L_{1,k}^c + L_{2,k}^c\right)\cos\theta - \left(L_{1,k}^s + L_{2,k}^s\right)\sin\theta\right]\right) \\ &f_3(k, l_2, \theta) \\ &\quad = I_0\left(2S\|L_{2,l_2}^c - (1-\alpha)\cos\theta\delta_{k,l_2}, L_{2,l_2}^s + (1-\alpha)\sin\theta\delta_{k,l_2}\|\right) \end{aligned}$$

where S is the SNR as before

$$\alpha = \frac{(T - \tau)}{T},$$

and $\delta_{i,j} = 1$ if $i = j$ and zero elsewhere. Finally, the decision is taken by choosing that value of $k \in \{1, \ldots, M\}$, which maximizes $p(x(t)|s_k)$, where

$$p(x(t)|s_k) = \sum_{l_1, l_2 = 1}^{M} \int_0^\pi f_1(k, l_1, \theta) f_2(k, \theta) f_3(k, l_2, \theta) d\theta.$$

If l_1 is known *a priori*, then the likelihood functions are given by

$$p(x(t)|s_k) = \sum_{l_2 = 1}^{M} \int_0^\pi f_1(k, l_1, \theta) f_2(k, \theta) f_3(k, l_2, \theta) d\theta.$$

The summation for l_2 is also removed if l_2 is known *a priori*.

Unlike the synchronous case, the sufficient statistic are correlated. If $\text{cov}(x, y)$ denotes the covariance between random variables x and y, then

$$\begin{aligned} \text{cov}\left(L_{1,j}^c L_{1,k}^c\right) &= \text{cov}\left(L_{1,j}^s L_{1,k}^s\right) \\ &= \frac{N_0}{2E_s T} \frac{\sin((\omega_j - \omega_k)(T - \tau))}{\omega_j - \omega_k} \\ \text{cov}\left(L_{2,j}^c L_{2,k}^c\right) &= \text{cov}\left(L_{2,j}^s L_{2,k}^s\right) \\ &= -\frac{N_0}{2E_s T} \frac{\sin((\omega_j - \omega_k)(T - \tau))}{\omega_j - \omega_k} \\ \text{cov}\left(L_{1,j}^c L_{1,k}^s\right) &= \frac{N_0}{2E_s T} \frac{1 - \cos((\omega_j - \omega_k)(T - \tau))}{\omega_j - \omega_k} \\ \text{cov}\left(L_{2,j}^c L_{2,k}^s\right) &= -\frac{N_0}{2E_s T} \frac{1 - \cos((\omega_j - \omega_k)(T - \tau))}{\omega_j - \omega_k} \\ \text{cov}\left(L_{1,j}^c L_{2,k}^c\right) &= \text{cov}\left(L_{1,j}^c L_{2,k}^s\right) = 0 \\ \text{cov}\left(L_{1,j}^s L_{2,k}^c\right) &= \text{cov}\left(L_{1,j}^s L_{2,k}^s\right) = 0. \end{aligned}$$

We assume here that $\omega_j \gg 1, \forall\, j$. Appropriate limits can be taken when $\omega_i = \omega_k$. Note that if the frequencies are placed far apart, i.e., $|\omega_j - \omega_k| \gg 1$ when $j \neq k$, then all the statistics can be taken as uncorrelated.

For the case of fading, fade levels are three additional unknown parameters and have to be integrated. We redefine the previously defined quantities as the equation shown at the bottom of the page. Finally, the decision is taken by choosing that value of $k \in \{1, \ldots, M\}$, which maximizes $p(x(t)|s_k)$, where

$$p(x(t)|s_k) = \sum_{l_1,l_2=1}^{M} \int_0^{\pi} \int_0^{\infty} \exp\left(-Sa_2^2\right) f_1(k,l_1,a_2,\theta) \times f_2(k,a_2,\theta) f_3(k,l_2,a_2\theta) d\theta dP_{A_2}(a_2).$$

The covariances of the random variables remain the same as in the case without fading.

If l_1 is known *a priori*, then the likelihood functions are given by

$$p(x(t)|s_k) = \sum_{l_2=1}^{M} \int_0^{\pi} \int_0^{\infty} \exp\left(-Sa_2^2\right) f_1(k,l_1,a_2,\theta) \times f_2(k,a_2,\theta) f_3(k,l_2,a_2\theta) d\theta dP_{A_2}(a_2).$$

The summation for l_2 is also removed if l_2 is known apriori.

IV. Iterative Multiuser Decoding

After the demodulation process described in the previous sections, the decoder has available to itself the single-user decisions, the type decoded sequences (for the synchronous case) and any of the symbols which the demodulator decided to erase (for example, all the symbols in a hit may be erased if the number of users involved in the hit is large). For the synchronous case, the decoder can feedback its already decoded codewords of users to the demodulator, which can provide the symbol decisions in place of type decisions, at the places of hit, if all but one users in those hits are not decoded. The complete task of the decoder is to extract the code word for each user.

For the asynchronous case, the symbol is directly demodulated for two-hit case and erased for all other hits. The errors and erasures RS decoder of each user attempts decoding. A successfully decoded user's codeword is fed back to the demodulator to use the decoded symbols for better demodulation of other users' symbols. The situation is more complicated in the synchronous case. Due to the type demodulation at the places of hit, ambiguity persists as to which symbol belongs to which user. To resolve this ambiguity, we propose the use of an iterative decoder (see Fig. 2). The idea basically is that successful decoding of one user can provide additional information which can be used for the successful decoding of other user to which it was involved in a hit and this decoding process can be iterative. If the type demodulation at the place of a hit gives a sequence with all symbols as the same, then these symbols can be unambiguously assigned to each user involved in that hit.

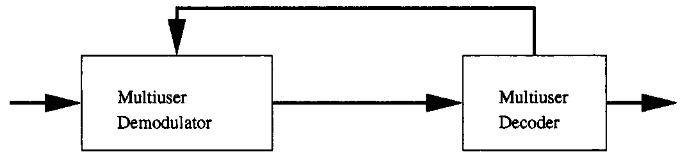

Fig. 2. Multiuser receiver with collaboration between multiuser demodulator and decoder.

All the users are protected by the same (n,k) RS code. One of the many interesting properties of RS codes is its low probability of decoding error. The RS decoder declares its inability to decode when it cannot decode correctly. This property is useful for our method since we attempt to help in decoding the users whose decoding was not successful by the successful decoding of some of the users. The multiuser decoder hence consists of a K parallel single-user RS decoders; a collaborative iterative decoding algorithm is executed. We assume that the demodulator provides us with demodulated types for all hits involving less than l users.

The proposed iterative decoding algorithm is described as follows.

1) In the first iteration, for any hit involving less than $i < l$ users, do type demodulation for synchronous case and symbol demodulation for asynchronous by treating other users as unknown. For the synchronous case, if the decoded i-length sequence has all the symbols as same, then assign the symbol to all the i users, else erase the symbols of all the i users and start decoding each user.
2) For the synchronous case, if at any hit involving i users $(i \leq l)$, the decoding of $i-1$ users is successful, then the symbol for the remaining user is available from the M-ary MAP test as given in Section III-A-II. This feedback information, if correct, provides better demodulation for the asynchronous case (Section III-B).
3) Stop if in any iteration, Step 2) is never successful decoding since there will not be any additional information available for subsequent iterations.

Steps 1) and 2) of the algorithm provide the collaboration among the users, and the type or M-ary MAP demodulation becomes crucial in this respect. Due to the low probability of decoding error for the RS codes, we expect that the information passed on to other users by the successful decoding of a user will be correct. It is well known that an (n,k) RS code can correct e erasures and t errors if $2e+t \leq n-k$. It is probable that not all users suffer from severe multiuser interference. The information passed on by successful decoding of a user may push another user with which the first user hits, into its successful decoding region. This may in turn affect the other users and so on.

$$f_1(k,l_1,a_2,\theta) = \int_0^{\infty} \exp(-S\alpha a_1^2) I_0\left(2a_1 S \| L_{1,l_1}^c - a_2\alpha\cos\theta\delta_{k,l_1}, L_{1,l_1}^s + a_2\alpha\sin\theta\delta_{k,l_1}\|\right) dP_{A_1}(a_1)$$

$$f_2(k,a_2,\theta) = \exp\left(2a_2 S\left[\left(L_{1,k}^c + L_{2,k}^c\right)\cos\theta - \left(L_{1,k}^s + L_{2,k}^s\right)\sin\theta\right]\right),$$

$$f_3(k,l_2,a_2,\theta) = \int_0^{\infty} \exp\left(-S(1-\alpha)a_3^2\right) I_0\big(2a_3 S \| L_{2,l_2}^c - a_2(1-\alpha)\cos\theta\delta_{k,l_2}, L_{2,l_2}^s + a_2(1-\alpha)\sin\theta\delta_{k,l_2}\|\big) dP_{A_3}(a_3)$$

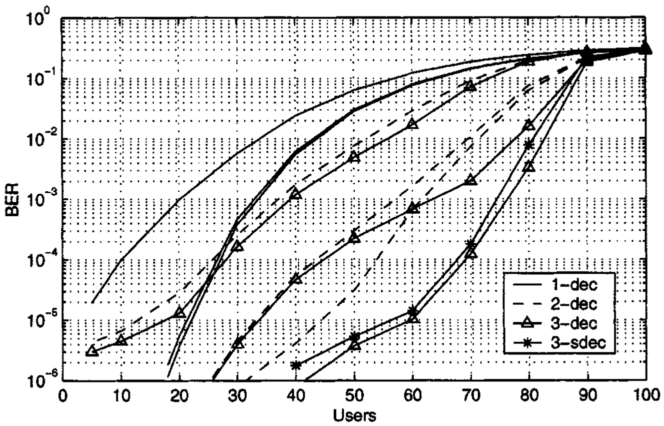

Fig. 3. BER versus number of users for $E_b/N_0 = 6, 8, 10$ dB (synchronous). Lower curves correspond to higher SNR.

Hence, we expect a performance improvement in terms of the number of users which can be supported by the system, as compared to the receiver without joint demodulation and iterative decoding. Since the decoder tries to resolve the type decoded sequence with maximum length l, we call this decoder in short as l-dec. By this terminology, the erase-only decoder is 1-dec. As will be shown by the numerical results in the next section, 2-dec or 3-dec receivers achieve most of the performance improvement at lower SNR, and it may not be necessary to go for more complex receiver than this.

For the synchronous case, it is possible to simply the above decoder by eliminating the type demodulation in Step 1) since it is useful only when all the symbols in a hit are same. For an l-hit case with users having uniform probability distribution of choosing a M-ary symbol, the probability that both symbols are same is $1/M^{l-1}$. We call this simplified decoder l-sdec.

V. Numerical Results

In this section, the numerical results of the proposed method are presented for synchronous and asynchronous case for the AWGN channel with or without fading. We present the results as bit-error rate (BER) against the different values of SNR. This enables one to see the performance improvement over the conventional erase-only method at a given BER. The system parameters are $q = 100$ (frequency bins used for frequency hopping), $M = 32$ (32-FSK modulation with noncoherent demodulation) and each user uses an RS(31,15) code.

A. Performance Results for the Multiuser Detector

For the synchronous case with AWGN channel, Fig. 3 plots the BER versus the number of users supported (defined previously as K) for various values of E_b/N_0 expressed in decibel units where $E_b = E_s/\log_2 M$ is the energy per bit). These curves are plotted for $E_b/N_0 = 6, 8, 10$ dB.

In the figure, the solid curve plots the results for a conventional receiver which erases all hits. The dashed curve corresponds to the performance of 2-dec where the demodulator erases all the hits involving three or more users. The performance of 3-dec is also plotted. As shown in Fig. 3, the performances of 2-dec and 3-dec are very nearly the same at lower SNR and almost all the advantage is obtained by the jointly demodulating only the hits involving two users. To explain this, note first that the probability of three users involved in a hit is substantially smaller than the two-user hits. For the present system configuration and $K = 30$, the probability of a single user hitting a given user is 0.219, where as two users hitting a given user is 0.0096, which is much smaller than the two-hit probability. Also, the probability of error in a MAP decision or the type demodulation increases with l in an l-hit case. For higher SNR, we can see greater performance improvement of 3-dec over 2-dec. It should however be noted that most of the performance improvement over 1-dec is gained by the 2-dec. It is a hence case of diminishing returns to use a l-dec receiver by increasing l.

TABLE I
Performance of 2-dec Decoder in Terms of the Number of Users

	Erase only			Synchronous			Asynchronous		
BER	6dB	8dB	10dB	6dB	8dB	10dB	6dB	8dB	10dB
10^{-2}	34	42	43	56	77	82	50	69	71
10^{-3}	20	32	33	39	63	76	32	55	58
10^{-4}	10	26	26	28	44	69	17	44	48
10^{-5}	-	22	22	-	33	60	-	36	40
10^{-6}	-	16	17	-	26	41	-	29	31

There is a performance improvement by the proposed method. For SNR of 6 dB, 0 users can be supported by the erase-only method at a BER of 10^{-3}, where 37 and 39 users can be supported at the same BER by 2-dec and 3-dec. The performance improvement is more for higher SNR. Note that the performance of erase-only scheme is very nearly the same for E_b/N_0 of 8 and 10 dB implying that the dominant limiting factor is the multiuser interference. However, the performance of proposed method improves substantially with increase in SNR. For example, at a BER of 10^{-5}, the number of users supported by erase-only is 21 and 22 for E_b/N_0 of 8 and 10 dB, but 34 and 60 users can be supported by the proposed method at E_b/N_0 of 8 and 10 dB, respectively. We also plot the performance of 3-sdec decoder at $E_b/N_0 = 10$ dB. This decoder as defined in Section IV does not use the type demodulation in the Step 1) of the iterative multiuser decoder. There is a loss of performance of about two users as compared to the 3-dec decoder at the same E_b/N_0. If the complexity of the demodulator is of importance, then one can use the simplified l-sdec decoder in place of l-dec decoder at a small loss of performance. Table I provides comparative results on number of users supported at a particular BER for the various cases of interest. The plot for the synchronous case with fading is presented in Fig. 4. The E_b/N_0 values for this plot are 9, 12, and 15 dB.

Similarly, Fig. 5 plots the results for the asynchronous case in with E_b/N_0 values as 6, 8, and 10 dB. The plot for the asynchronous case with fading is shown in Fig. 6 with E_b/N_0 values of 9, 12, and 15 dB. Note that in the asynchronous case, we assume that the symbols per hop are large and probability of hit from any other user is $1/q$. We assume that there are no partial hits. Though this is not the case in a practical situation, the probability of error for joint demodulation of a symbol is more

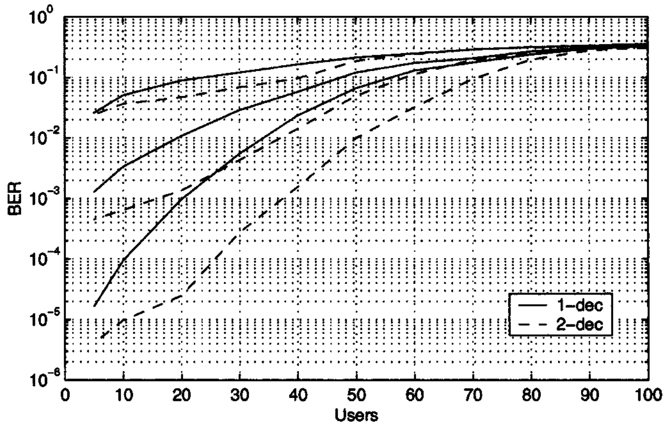

Fig. 4. BER versus number of users for fading channel with $E_b/N_0 = 9, 12, 15$ dB (synchronous with fading).

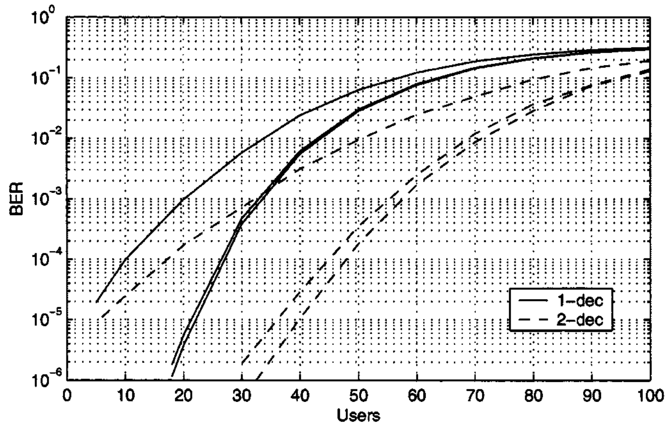

Fig. 5. BER versus number of users with $E_b/N_0 = 6, 8, 10$ dB (asynchronous).

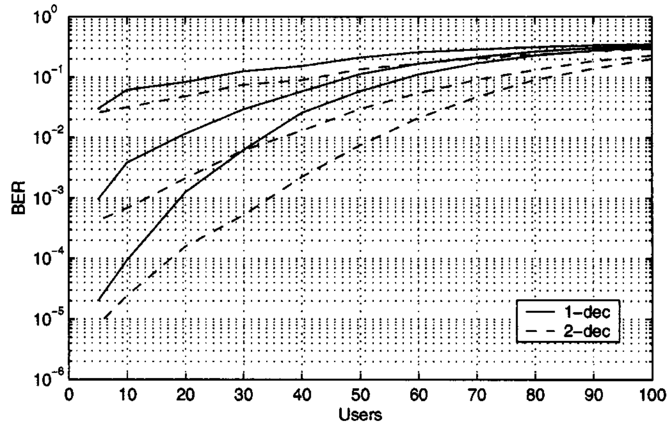

Fig. 6. BER versus number of users with $E_b/N_0 = 9, 12, 15$ dB (asynchronous with fading).

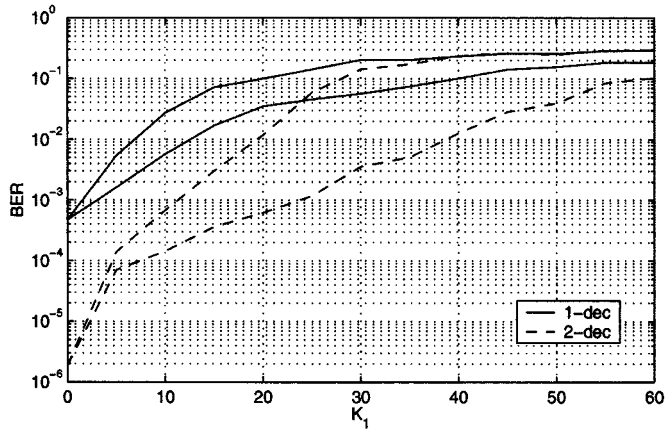

Fig. 7. BER versus K_1, the number of users than are not jointly demodulated; $K = 30$ users are jointly demodulated/decoded, $E_b/N_0 = 8$ dB (synchronous). Received power of K_1 users is eithter 0 or 10 dB higher than the power of the K users.

for a full hit than a partial hit. Hence, by assuming that all hits are full hits, we provide upper bounds of the performance in a realistic case having some partial hits.

Note also that the performance improvement over the erase-only scheme is less when number of users are small because the hit probability decreases when the number of users becomes small. Since in FH/SSMA systems BER depends (up to a first-order approximation) on the ratio of K/q (system multiuser efficiency) and not on the exact values of K and q, we believe that the performance trends and comparisons remain valid when we scale upwards both values of K and q.

The complete performance comparisons (in terms of number of users) is illustrated in Table I for the AWGN channel at E_b/N_0 of 6, 8, and 10 dB for both synchronous and asynchronous cases for the 2-dec decoder.

B. Performance Results for Multiuser Detection of a Subset of Users

As discussed in the introduction a scenario of practical interest is when there are FH/SS users present whose hopping patterns are either unknown to the receiver of interest and thus cannot be jointly demodulated or hardware limitations and complexity considerations do not allow the multiuser detection of all active user signals.

In this section, we first evaluate the performance of the proposed multiuser method when there are K_1 active users with unknown hopping patterns that are neglected by the receiver and there are K active users whose hopping patterns are known by the receiver and multiuser detection is used for these users. The K_1 users act as tone jammers to the receiver. We choose $K = 30, q = 100, E_b/N_0 = 8$ dB, and assume that the received power of K_1 users is the same (0 dB) or is 10 dB higher than the power of the other K users. The results are plotted as BER versus K_1 for both the erase-only and the proposed method in Fig. 7.

In the next scenario, we evaluate the performance of the multiuser detector when only K_2 of the active user signals out of the total K are jointly demodulated and iteratively decoded. In Fig. 8, we plot the results as BER versus K_2, the number of signals that are jointly demodulated, when the total number of active users is $K = 30$, $q = 100$, and $E_b/N_0 = 8$ dB. All received signal powers are assumed equal.

C. Complexity Considerations

An important issue for any decoding scheme is its complexity. A too complex decoding method may not be practically useful

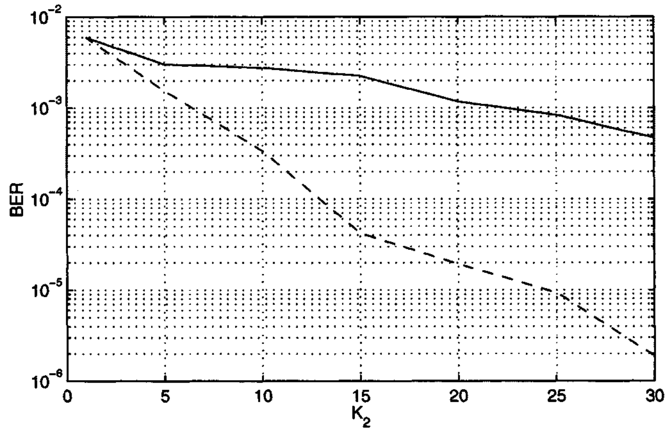

Fig. 8. BER versus K_2, the number of users that are jointly demodulated/decoded out of a total of $K = 30$ active users, $E_b/N_0 = 8$ dB (synchronous). All users have same received power levels.

TABLE II
MULTIUSER DETECTOR COMPLEXITY

	Erase only	Synchronous		Asynchronous
K	1-dec	2-dec	3-dec	2-dec
100	70.63	94.98	94.37	692.14
90	147.04	289.62	373.49	844.44
80	296.11	794.99	1014.31	955.17
70	499.87	984.62	1007.06	992.21
60	724.69	1001.21	1004.77	999.23
50	896.28	1000.98	1002.32	1000.00
40	979.02	1000.25	1001.40	1000.00
30	998.51	1000.02	1000.60	1000.00

even though it may give better performance. We define the complexity in terms of the RS decoding iterations needed per user for 1000 transmitted codewords at a fixed SNR and number of simultaneous users. We show the numerically computed complexity rounded up to the last two decimal places in Table II for synchronous and asynchronous, respectively, for $E_b/N_0 = 8$ dB.

Note that the maximum complexity of the proposed detectors is very close to 1000, i.e., one RS decoding for every transmitted codeword which is the single-user complexity, taken as as the benchmark. When the number of users become small, the complexity of the erase-only schemes and the proposed method becomes almost the same due to small probability of hits.

VI. CONCLUSIONS

In conclusion, we have presented a scheme for joint demodulation that provides the type or the symbol in synchronous or asynchronous FH/SSMA case, respectively. An iterative multiuser decoding scheme was also developed to enhance the reliability of the information provided by the type demodulator. The results show a significant performance improvement in the number of users supported by FH/SSMA systems. Performance comparisons between different systems and operating scenarios were provided and computational complexity issues were discussed. The improvement in the number of users, though significant (greater than 100%) in the synchronous/asnchronous SFH/SSMA case, is lower in the presence of fading because the probability of correct symbol or type demodulation also increases. In the authors' opinion, the performance enhancement of FH/SSMA through multiuser detection (compared to DS/CDMA) is limited by the use of noncoherent demodulation of MSFK and of hard-decisions in the decoding of the RS codes. We are currently extending the work of this paper to the case of soft-decision RS decoding.

APPENDIX
LIKELIHOOD FUNCTIONS FOR JOINT DEMODULATION OF THREE FH/SSMA SIGNALS

In this appendix, we present the likelihood functions for synchronous case when three users are present, i.e., $l = 3$. The type s_k is defined by the three symbols $\{k_1, k_2, k_3\}$ and let π_k be the probability of each type. Define

$$L_{c,i} = \sqrt{\frac{2}{E_s T}} \int_0^T x(t)\cos(\omega_i t)dt$$
$$L_{s,i} = \sqrt{\frac{2}{E_s T}} \int_0^T x(t)\sin(\omega_i t)dt$$
$$y_i = ||L_{c,i}, L_{s,i}||$$
$$f_1(i, \theta_1, \theta_2) = \cos(\theta_1 - \theta_2) - L_{c,i}(\cos\theta_1 + \cos\theta_2) + L_{s,i}(\sin\theta_1 + \sin\theta_2).$$

Then

$$\pi_k = \begin{cases} \frac{6}{(M+1)(M+2)}, & \text{if } k_1 = k_2 = k_3 \\ \frac{3(M-1)}{(M+1)(M+2)} & \text{if } k_1 = k_2 \neq k_3, \\ \frac{M-1}{M+2}, & \text{if } k_1 \neq k_2 \neq k_3 \end{cases}$$

and see the equation at the bottom of the next page, where $s_k = \{k_1, k_2, k_3\}$. That s_k is chosen for which $\pi_k\, p(x(t)|s_k)$ is maximum.

The probability density functions for the M envelope detector outputs are given below. For $k_1 = k_2 = k_3$, if $i = k_1$ then

$$p(y_i|s_k) = \frac{2Sy_i}{4\pi^2} \int_0^{2\pi}\int_0^{2\pi} \exp\big(-S(y_i^2 + 3 + \cos\theta + \cos(\beta+\theta) + \cos\beta)\big) \times I_0\Big(2Sy_i\sqrt{3+\cos\theta + \cos(\beta+\theta) + \cos\beta}\Big)\, d\theta d\beta$$

else if $i \neq k_1$, then

$$p(y_i|s_k) = 2Sy_i \exp\left(-Sy_i^2\right)$$

and for $k_1 = k_2 \neq k_3$, if $i = k_1$ then

$$p(y_i|s_k) = \frac{Sy_i}{\pi} \int_0^{2\pi} \exp\left(-S(y_i^2 + 2(1+\cos\theta))\right) \times I_0\left(2Sy_i\sqrt{2(1+\cos\theta)}\right) d\theta$$

else if $i = k_3$ then

$$p(y_i|s_k) = 2Sy_i \exp\left(-S(y_i^2 + 1)\right) I_0(2Sy_i)$$

$$p(x(t)|s_k) = \begin{cases} \frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi} I_0\left(2S\sqrt{2+y_{k_1}^2+2f_1(k_1,\theta_1,\theta_2)}\right) & \\ \quad \times\exp(-2Sf_1(k_1,\theta_1,\theta_2))d\theta_1 d\theta_2, & \text{if } k_1=k_2=k_3, \\ \frac{I_0(2Sy_{k_3})}{\pi}\int_0^{\pi} I_0\left(2S\sqrt{1+y_{k_1}^2-2y_{k_1}\cos\theta}\right) & \\ \quad \times\exp(2Sy_{k_1}\cos\theta)d\theta, & \text{if } k_1=k_2\neq k_3, \\ I_0(2Sy_{k_1})I_0(2Sy_{k_2})I_0(2Sy_{k_3}) & \text{if } k_1\neq k_2\neq k_3, \end{cases}$$

else

$$p(y_i|s_k) = 2Sy_i\exp\left(-Sy_i^2\right)$$

and for $k_1 \neq k_2 \neq k_3$, if $i = k_1$ or $i = k_2$ or $i = k_3$, then

$$p(y_i|s_k) = 2Sy_i\exp\left(-S(y_i^2+1)\right)I_0(2Sy_i)$$

else

$$p(y_i|s_k) = 2Sy_i\exp\left(-Sy_i^2\right).$$

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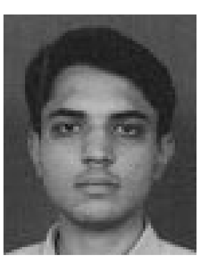

Naresh Sharma (M'98) received the B.Tech. and M.Tech. degrees in electrical engineering from the Indian Institutes of Technology at Kanpur and Bombay, respectively, and the the Ph.D. degree in electrical engineering from the University of Maryland at College Park in April 2001.

Since May 2000, he has been with the Wireless Technology Laboratory, Lucent Technologies, Whippany, NJ, where he is now a Member of Technical Staff. His research interests include communication theory, spread spectrum, multiantenna, and chaotic systems.

Hesham El Gamal (M'99) received the B.S. and M.S. degrees in electrical engineering from Cairo University, Cairo, Egypt, in 1993 and 1996, respectively, and the Ph.D. degree in electrical engineering from the University of Maryland at College Park in 1999.

From 1993 to 1996, he served as a Project Manager in the Middle East Regional Office of Alcatel Telecom. From 1996 to 1999, he was a Research Assistant in the Department of Electrical and Computer Engineering, the University of Maryland at College Park. From February 1999 to January 2001, he was with the Advanced Development Group, Hughes Network Systems, Germantown, MD, as a Senior Member of Technical Staff. In the Fall of 1999, he served as a lecturer at the University of Maryland at College Park. In January 2001, he assumed his new position as an Assistant Professor in the Department of Electrical Engineering at the Ohio State University, Columbus. His research interests include spread-spectrum communication systems design, multiuser detection techniques, coding for fading channels with emphasis on space–time codes, and the design and analysis of codes based on graphical models.

Evaggelos Geraniotis (SM'88) received the Diploma (with highest honors) in electrical engineering from the National Technical University of Athens, Athens, Greece, and the M.S. and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana-Champaign.

Since September 1985 he has been with the University of Maryland, College Park, where he is presently a Professor of Electrical Engineering and a Member of the Institute for Systems Research. He is co-author of the book *CDMA: Access and Switching for Terrestrial and Satellite Networks* (New York: Wiley, February 2001) and over 250 technical papers in journals and conference proceedings. He serves regularly as a consultant for government and industrial clients. His research has been in communication theory, information theory, and their applications with emphasis on wireless communications. His recent work focuses on data modulation, error control coding, multiuser detection and interference cancellation, array processing, retransmission techniques, and multiaccess protocols for wireless spread-spectrum and anti-jam communications. The algorithms are applied to cellular, mobile, PCS, fixed wireless, satellite but also to optical, copper-loop, and cable networks. He has also worked on multimedia and mixed-media integration in radio and optical neworks as well as on interception, feature-detection, and classification of signals, radar detection, and multisensor data fusion.

Dr. Geraniotis has served as Editor for Spread Spectrum of the IEEE TRANSACTIONS ON COMMUNICATIONS from 1989 to 1992.