On the Performance of Multi-Stage Multi-User Detection Assisted Fast-FH/MFSK

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Abstract- ***A multi-stage Multi-User Detection (MUD) scheme designed for a fast Frequency-Hopping/Multilevel Frequency-Shift-Keying (fast-FH/MFSK) system is proposed, which exploits the explicit knowledge of the hopping addresses assigned to users. The received signal level is attenuated by a constant scaling factor, when it is deemed to be overwhelmed by multi-user interference. For the sake of preventing erroneous detection events, when communicating over frequency-selective fading channels, the scheme advocated invokes a variable detection threshold parameter. In the investigated scenario the achievable Bit Error Rate (BER) of the proposed scheme was reduced by as much as an order of magnitude in comparison to that of a Single-User Detection (SUD) scheme when transmitting over an AWGN channel. For transmission over a channel exhibiting uncorrelated frequency-domain fading, a variable - rather than fixed - threshold was used for the sake of achieving a reduced BER.***

I. Introduction

Eliminating multi-user interference is of vital importance in wireless communication systems for the sake of improving the achievable transmission quality and system capacity within a limited bandwidth. In particular, Multi-User Detection (MUD) schemes [1]-[4] employed in fast Frequency-Hopping (FH) Multilevel Frequency-Shift-Keying (MFSK) systems [5] are attracting considerable attention owing to their attractive performance and low computational complexity. In this paper, we consider an efficient MUD scheme designed for synchronous FH/MFSK multi-user systems.

An efficient MUD scheme has been proposed in [2] for improving the achievable Bit Error Rate (BER) performance of MFSK/FH-SSMA based wireless communication systems. In this scheme, all legitimate transmitted signals are generated by the receiver and then compared to the received signal. This Maximum-Likelihood (ML) detection approach results in a high interference rejection capability, which is achieved at the cost of a potentially excessive computational complexity, particularly when the number of users is high. An efficient Multi-Stage (MS) MUD scheme has been developed [3] for reducing the complexity imposed in such cases. This scheme successively eliminates the interfering signals by exploiting the explicit knowledge of the users' MUD addresses. Recently, a further improved MS-MUD scheme was proposed in [4], where the contribution of the estimated interfering signal is cancelled from the received composite signal by exploiting both the knowledge of all users' MUD addresses as well as that of their received signal powers. In other words, the MS-MUD of [4] is capable of successfully mitigating the effects of interference, as long as all users' received signal powers are known. In practice, however, the received signal is typically contaminated by Multi-User Interference (MUI) and hence it may be an arduous task to accurately determine the individual users' received signal powers. Moreover, to the best of the authors' knowledge, no investigations have been reported on MS-MUD FH/MFSK systems in the context of fading channels.

In our proposed MUD scheme, a constant weighting factor is invoked for mitigating the effects of the interferers, as it will be detailed hereafter. Specifically, in the proposed system two matrices are constructed, which host the desired signal and the estimated interference in a manner similar to that used in the MS-MUD described in [4], with the important exception that we eliminate the requirement of knowing the received signal powers.

In this paper, we commence our discourse by describing the system model in Section II. In Section III, we first introduce our proposed MUD algorithm in the context of an Additive White Gaussian Noise (AWGN) channel. Furthermore, we define a variable threshold for employment in the MUD as well as a space-diversity scheme contrived for improving the BER performance when communicating in frequency-selective fading channels. In Section IV we compare the BER performance of the proposed MUD scheme to that of various benchmarkers, when communicating over the AWGN channel, as well as over channels exhibiting non-dispersive correlated time-domain fading, and uncorrelated frequency-domain fading channels. Finally, we present our conclusions in Section V.

II. Fast-FH/MFSK System

Let us consider a time-frequency coded system [5], where K number of users are supported and the transmitted signal of each user is constituted by a sequence of L chips, selected from a set of Q legitimate frequencies. Furthermore, we assume that the L-chip sequences of all the users arrive at the receiver's input at the same instant, i.e. that we employ a synchronous system. A matrix having Q rows and L columns, representing the legitimate frequencies and time slots, respectively, contains the received signals of the system.

We assume that $x_k(m)=\{0, 1, 2, \ldots, Q-1\}$ represents a data symbol of the k-th user transmitted at the time instant of $t=mL\Delta t_0$, where m, Δ, and t_0 represent the transmitted symbol index, the chip duration and the initial time offset, respectively. Let $\mathbf{a}_k=(a_{k,1}, a_{k,2}, \ldots, a_{k,L})$ be the MUD address assigned for user k, and let the received signal of user k be denoted by $\mathbf{s}_k(m)=(s_{k,1}(m), s_{k,2}(m), \ldots, s_{k,L}(m))$, which may be written as

$$\mathbf{s}_k(m) = x_k(m)\cdot\mathbf{1}+\mathbf{a}_k, \qquad (1)$$

where we have $\mathbf{1}=(1,1,\ldots,1)$, representing a unit-vector, while '+' indicates addition over the Galois Field GF(Q).

The receiver processes the received signal for the sake of constructing the ($Q \times L$)-element received signal matrix of $\mathbf{R}(m)=\{r_{q,l}(m)\}$, in which each matrix element stores the corresponding received signal components associated with a legitimate frequency and time slot, each having a different detected power level, where we have $1 \le q \le Q$ and $1 \le l \le L$. In order to

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simplify our discourse, we omit the transmitted symbol index m. Here, we assume that $r_{q,l}$ is expressed as:

$$r_{q,l} = \gamma_{q,l} s_{q,l} + n_{q,l}, \tag{2}$$

where $\gamma_{q,l}$ and $n_{q,l}$ are the fading envelope and the receiver's thermal noise, respectively. Given the received signal matrix $\mathbf{R}$, the data symbols may be estimated by using the detection scheme described in Section III.

III. The Proposed MUD Scheme

A. MUD for AWGN channels

First of all, we consider the scenario, where $\gamma_{q,l}$ is constant (i.e., there is no fading). Fig. 1 illustrates the block diagram of the proposed MUD scheme. The elements of the received signal matrix, $\mathbf{R}^{(i)} = \{r_{q,l}{}^{(i)}\}$, where the matrix is valid for detection stage i, are compared to a constant-valued positive threshold δ, so as to generate $\hat{\mathbf{R}}^{(i)} = \{\hat{r}_{q,l}{}^{(i)}\}$, where we have $\hat{r}_{q,l}{}^{(i)} = 1$ for $r_{q,l} > \delta$, and zero otherwise. Next, $\hat{\mathbf{R}}^{(i)}$ is used for generating the data of user k by subtracting $\mathbf{a}_k$ from $\hat{\mathbf{R}}^{(i)}$ on a chip-by-chip basis over GF(Q), producing the decoded data matrix $\mathbf{D}_k{}^{(i)} = \{\hat{r}_{(q-a_{k,l}),l}{}^{(i)}\}$, as seen in Fig. 1. If the received signal does not suffer from any noise or other channel impairments, $\mathbf{D}_k{}^{(i)}$ contains a complete row of binary one values at the received signal matrix positions corresponding to the desired user's symbol $x_k(m)$. In practice, however, the received signals do suffer from MUI imposed by both undesired users, as well as from AWGN and other channel impairments. Hence the received signal matrix may contain incomplete rows, as well as multiple non-zero rows, which render the detection process prone to detection errors. By contrast, in a perfect reception scenario one and only one complete row having non-zero values exists, which allows us to unambiguously estimate the data symbol, $\hat{x}_v{}^{(i)}$, for $1 \le v \le K, v \ne k$.

In the next detection step we construct the estimated interference matrix, $\mathbf{C}_k{}^{(i)} = \{c_{q,l}{}^{(i)}\}$ of user k, where we have $c^{(i)}{}_{\hat{x}_v{}^{(i)}+a_{v,l},l} = 1$, and zero otherwise. Using this matrix, we proceed by assuming that if the (q, l)-th element of the matrix containing the interference, namely $\mathbf{C}_k{}^{(i)}$, is non-zero, then this particular element of the received signal matrix, $\mathbf{R}^{(i)}$, will be corrupted by MUI with a high probability. Thus, we propose that the (q, l)-th, and only the (q, l)-th element of $\mathbf{R}^{(i)}$ be updated by using the following relationship:

$$r_{q,l}{}^{(i+1)} = \rho \cdot r_{q,l}{}^{(i)}, \tag{3}$$

where ρ is a positive real-valued constant constrained to the range of $0<\rho<1$. Intuitively, a small value of ρ may necessitate the employment of a high number of detection stages, but this has the benefit of ensuring that low signal contributions are not inadvertently cancelled. By contrast, a high value of ρ may result in the desired signal being cancelled. It is worth noting that in the MUD described in [4] $r_{q,l}{}^{(i+1)} = 0$ was used when the condition of $|c^{(i)}{}_{\hat{x}_v{}^{(i)}+a_{v,l},l} - r^{(i)}{}_{\hat{x}_v{}^{(i)}+a_{v,l},l}| < \varepsilon_v$ was satisfied, where $c^{(i)}{}_{\hat{x}_v{}^{(i)}+a_{v,l},l} = E_v$. The variables E_v as well as ε_v, respectively, were defined as the received signal power and the detection threshold related to user v, $1 \le v \le K$, $v \ne k$.

The next detection stage invokes the above procedure again. When we curtail this iterative detection process at the $(i+1)$-th stage, the received signal hosted by $\mathbf{R}^{(i)}$ is decoded again. The final detection step is constituted by finding the specific row of $\hat{\mathbf{R}}^{(i+1)} = \{\hat{r}_{q,l}{}^{(i+1)}\}$, where we have $\hat{r}_{q,l}{}^{(i+1)} = 1$ for $r_{q,l} > \delta$, and zero otherwise, which exhibits the maximum decoded power that is expressed as:

$$x_k'^{(i+1)} = \max_n \left\{ \sum_{l=1}^{L} \hat{r}_{(n-a_{k,l}),l}{}^{(i+1)} \right\}. \tag{4}$$

B. MUD for fading channels

When we use MUD in fading channels, the received signal strength recorded at each received frequency and in each time-slot varies as the function of the channel conditions. Let us consider the interference cancellation mechanism of the MUD. The power of the interfering signal decreases in successive MUD stages, since the interfering signals can be detected by comparing them to the constant threshold δ and subtracting them from the received multi-user signal. For the sake of preventing false interference-detection in our MUD, the presence of an interfering signal is deemed to be recognized, when all L chips constituting a symbol can be detected. In other words, when the condition:

$$\delta \le \rho^i \cdot r^{(1)}{}_{\hat{x}_v{}^{(i)}+a_{v,l},l}, \tag{5}$$

is satisfied at the i-th stage for all values of the timeslot index l, the interference imposed on user v decreases by a factor of ρ, as we have seen in Equation (3). By contrast, when $\rho^i \cdot r^{(1)}{}_{\hat{x}_v{}^{(i)}+a_{v,l},l} < \delta$ is satisfied for at least one timeslot index l, the interfering signal of user

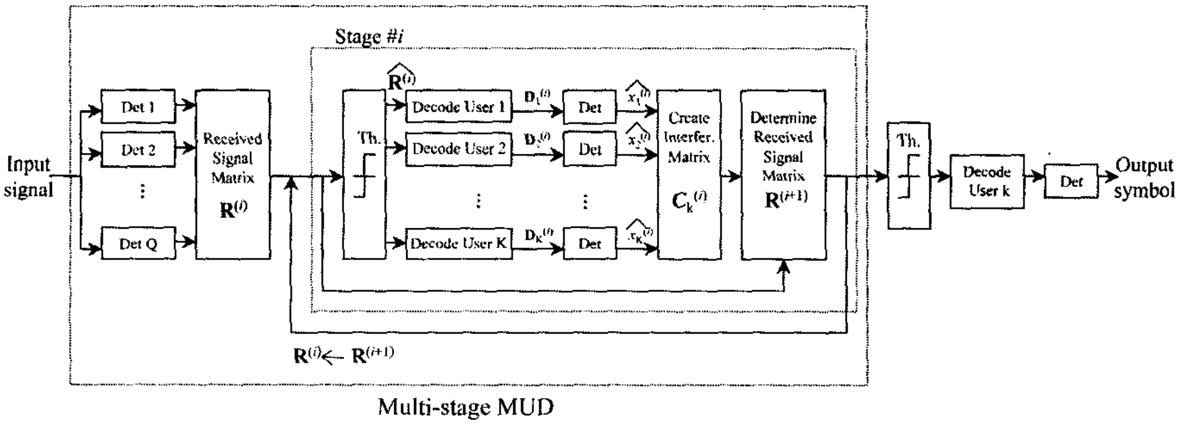

Fig. 1 Block diagram of the proposed MUD scheme.

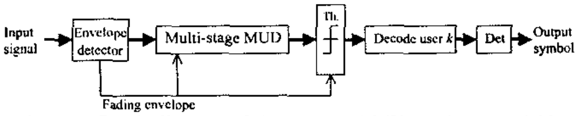

Fig. 2(a) Block diagram of the proposed MUD using a variable threshold.

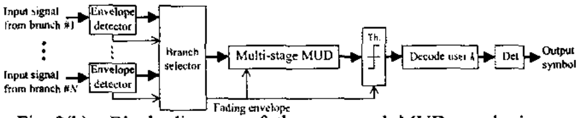

Fig. 2(b) Block diagram of the proposed MUD employing a selection diversity scheme and a variable threshold.

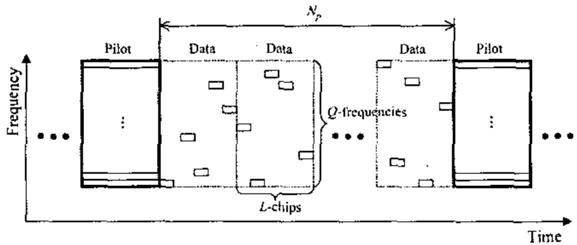

Fig. 3 Frequency-domain pilot symbol aided fading envelope detection.

ν does not decrease.

When a particular fading magnitude of $\gamma_{q,l}$ is small, the corresponding interfering signal becomes small and hence $\delta \le \rho^i \cdot r^{(i)}{}_{x_v^{(i)}+a_{v,j},l}$ may not be satisfied. In this case, no transmission quality improvement is achieved. In order to prevent this undesirable scenario, we propose to use the following variable threshold parameter instead of the constant scaling factor δ.

$$\delta_{q,l} = \frac{\delta}{\gamma_{q,l}}. \tag{6}$$

This variable parameter is applicable not only for employment in fading channels, but also for communicating over AWGN channels, because $\gamma_{q,l}$ automatically becomes a constant for transmission over AWGN channels. Fig. 2(a) shows the block diagram of the MUD employing this variable threshold based scheme. The detected fading envelopes recorded at the various FH frequencies are used by the MUD scheme and also during the final signal detection stage as the variable threshold parameter.

As a further powerful anti-fading technique, spatial diversity has been often used for mitigating the fading-induced signal-level fluctuation in wireless communications [7]. When using this technique, the condition stipulated in Equation (5) may be relaxed and the BER performance may be substantially improved. Fig. 2(b) shows the corresponding block diagram, when selection diversity is invoked at the receiver. More explicitly, when selection-combining is used, we detect the signal of the specific diversity branch in Fig. 2(b), which has the highest received signal magnitude.

In considering whether to enable or disable the employment of the variable threshold, we have to evaluate all the fading amplitudes corresponding to all FH frequencies in the L chips. For this reason we invoked a pilot-symbol insertion scheme, which has often been used in multi-carrier transmission systems [7]. Fig. 3 shows the frequency-time plane of the fast-FH/MFSK system using pilot-aided frequency-domain fading estimation, where pilot symbol spacing is represented as N_p. The fading envelope $\gamma_{q,l}$ can be estimated using frequency-domain interpolation for determining all the necessary frequency-domain fading envelope estimates.

IV. Results and Discussions

Since the proposed detection procedure involves non-linear processes, it does not readily lend itself to theoretical analysis. Hence we used computer simulations for evaluating its BER performance. This section characterizes the BER performance of a fast-FH/MFSK system employing the proposed MUD scheme, as well as a Single-User Detection (SUD) scheme [4] and the MS-MUD scheme of [4] as benchmarker schemes, where the SUD scheme simply finds the specific row of $\mathbf{D}_k$ containing the highest number of non-zero elements.

In this Section, we use the terminology of 'flat fading' for a non-dispersive correlated time-domain fading channel, where all frequencies fade together. By contrast, we refer to the channel exhibiting uncorrelated Rayleigh fading in the frequency-domain simply as an 'uncorrelated frequency-domain (FD) fading' channel.

A. Performance for an AWGN channel

Fig. 4 shows the BER versus the scaling factor ρ performance of the proposed system, where we have Q=16, L=5, and Einarsson's multi-user addressing scheme [6] was used for minimizing the chip collisions. An AWGN channel was used, where C/N was 16 dB and the number of users was 12. The threshold parameter δ was defined in the same manner as in [4], where the false alarm threshold introduced for detecting the presence of noise rather than a useful signal was set to 1 %. The power of the desired signal and that of each interfering signal was the same in both cases. In this environment, we can see that when we set ρ to 0.3, the achievable BER is lower, despite invoking a lower number of detection stages.

Fig. 5 shows the BER results obtained under the same conditions as those shown in Fig. 4. In this figure ρ was set to 0.3. Since the SUD is the simplest detection scheme, its BER is the highest among the detection schemes we studied, particularly when the number of users is relatively low and hence the MUDs perform well. The MS-MUD scheme described in [4] performs better than the SUD scheme, because with the advent of MS-MUD the effects of interference are efficiently cancelled. However, as it can be seen in Fig. 5, the achievable BER is slightly degraded, when the number of detection stages is increased. This is because the MS-MUD scheme tends to set certain elements of the received signal matrix to zero during the first detection stage and hence the achievable BER does not improve during the successive detection stages. The proposed MUD achieves substantial BER improvements in comparison to the MS-MUD of [4], which improves as the number of detection stages is increased from 1 to 4. This is particularly true, when the number of users supported is in excess of 13.

B. Performance for Rayleigh-fading channels

Figs. 6 and 7, respectively, show the BER performances attained both with and without employing the variable threshold parameter ρ, when communicating over a flat Rayleigh fading channel and over an uncorrelated frequency-domain Rayleigh fading channel. We set the normalized Doppler frequency of f_dT to 0.01, where T=$L\Delta$ is the symbol duration time. In order to confirm the effect of the variable threshold in Fig. 7, we assume that the fading envelope was perfectly recovered at the receiver. From these figures we can see that the BER performance attained by the MS-MUD without introducing the variable threshold does not improve in comparison to the SUD's BER performance, regardless, whether correlated or uncorrelated frequency-domain channels are considered. However, it can be seen in Fig. 7 that the BER performance of the proposed MUD employing the variable threshold is considerably improved, which is particularly so for the channel exhibiting uncorrelated frequency-domain fading. It can also be seen that the BER performance recorded for transmission over flat fading channels is similar in both cases. This is because in the flat fading scenario $\gamma_{q,l}$ becomes almost the same as γ. These figures demonstrate the efficiency of introducing the variable threshold $\delta_{q,l}$, especially when communicating over channels exhibiting uncorrelated frequency-domain fading.

C. Performance of combined MUD and space diversity over Rayleigh-fading channels

In order to demonstrate the beneficial effect of space diversity in the context of the proposed MUD scheme in Figs. 8 and 9, we characterize the achievable BER performance, when combining the proposed MUD scheme with 2-branch space diversity. We assumed that the two frequency-domain diversity channels faded independently. From Fig. 8, it can be seen that when we use diversity, the performance improved even when dispensing with the employment of the variable threshold. On the other hand, when incorporating the variable threshold into the space diversity assisted MUD, the performance attained was further improved. This seems to indicate that combining the space diversity and the variable threshold assisted schemes results in reduced noise and reduced false signal detection.

Finally, in order to investigate the effect of incorporating the fading envelope aided signal-scaling into the proposed MUD scheme, we show the BER performance obtained by combining the MUD scheme with the pilot insertion scheme in Fig. 10. In these experiments, we set f_dT to 0.1 and to 0.01. We also estimated the fading envelope of the data symbols between the two pilot symbols seen in Fig. 3 by using a simple linear interpolator [8]. We can see that as the pilot symbol spacing N_p representing the number of data symbols between pilot symbols increases, the BER performance gradually degrades. This is a consequence of the associated increased fading estimation error, which is higher for f_dT=0.1 than for f_dT=0.01. For the sake of obtaining a more accurate estimate of the fading envelope at higher normalized Doppler frequencies of f_dT, we can apply a higher order interpolation operation, which is associated with an increased computational complexity.

V. Conclusions

A multi-stage MUD scheme was proposed for employment in fast-FH/MFSK systems. In the proposed scheme the received signal level is attenuated by a constant scaling factor, when it is deemed to be overwhelmed by MUI. In the investigated scenario the achievable BER of the proposed MUD scheme was reduced by as much as an order of magnitude in comparison to the single-user detection based benchmarker scheme. We also introduced and evaluated the effect of a variable threshold for assisting the operation of the MUD detector, which is calculated with the aid of the pilot-assisted estimate of the fading envelope. Our simulation results showed that the proposed MUD scheme invoking a variable threshold attains a good performance, which may be further improved with the aid of space diversity.

Acknowledgment

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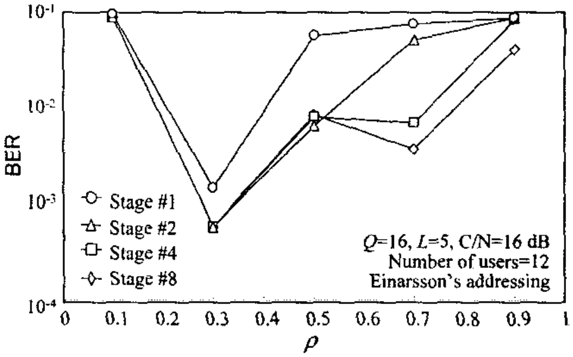

Fig. 4 BER versus the scaling factor ρ for the fast-FH/MFSK system involved in the proposed MUD scheme for transmission over an AWGN channel at C/N=16 dB, while supporting 12 users.

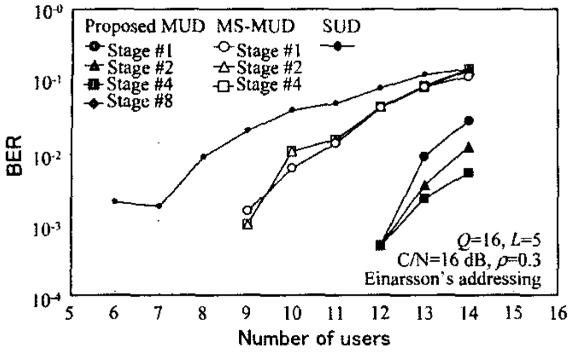

Fig. 5 BER versus the number of users in the fast-FH/MFSK system used in the proposed MUD scheme, as well as in the MS-MUD scheme described in [4], and in the SUD described in [4] for transmission over an AWGN channel at C/N=16 dB.

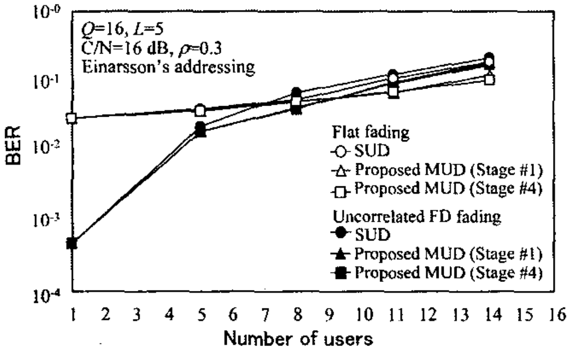

Fig. 6 BER versus the number of users in the fast-FH/MFSK system used in the proposed MUD scheme without fading compensation, and in the SUD scheme described in [4] for transmission over channels exhibiting flat, uncorrelated fading in the frequency domain at C/N=16 dB.

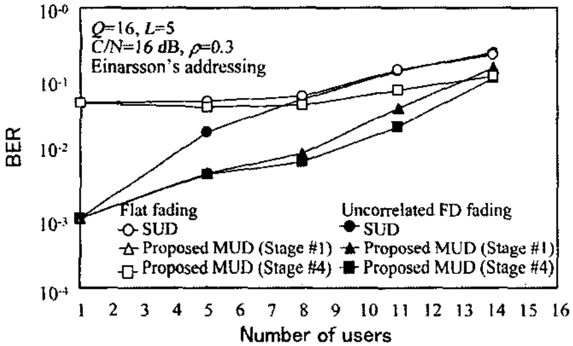

Fig. 7 BER versus the number of users in the fast-FH/MFSK system used in both the proposed MUD scheme in conjunction with fading compensation, and in the SUD scheme described in [4] for transmission over channels exhibiting flat, uncorrelated fading in the frequency domain at C/N=16 dB.

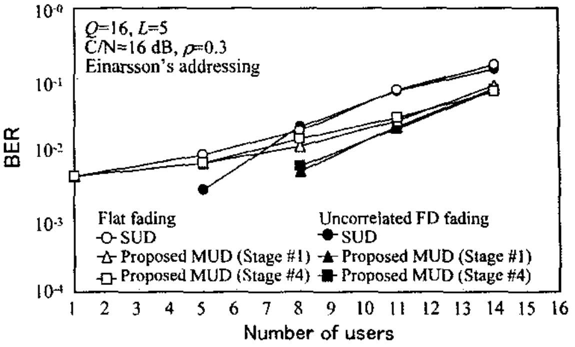

Fig. 8 BER versus the number of users in the fast-FH/MFSK system used in the proposed MUD scheme (2-banch selection diversity) without fading compensation, and in the SUD scheme described in [4] for transmission over channels exhibiting flat, uncorrelated fading in the frequency domain at C/N=16 dB.

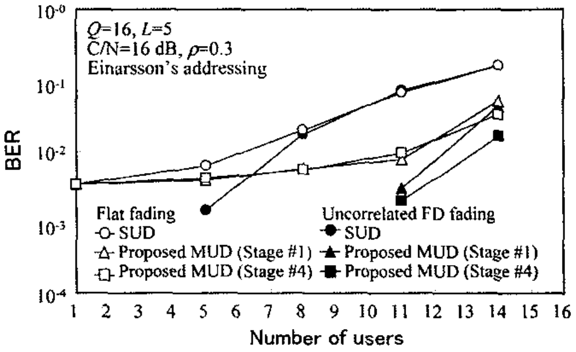

Fig. 9 BER versus the number of users in the fast-FH/MFSK system used in the proposed MUD scheme (2-branch selection diversity) with fading compensation, and in the SUD described in [4] for transmission over channels exhibiting flat, uncorrelated fading in the frequency domain at C/N=16 dB.

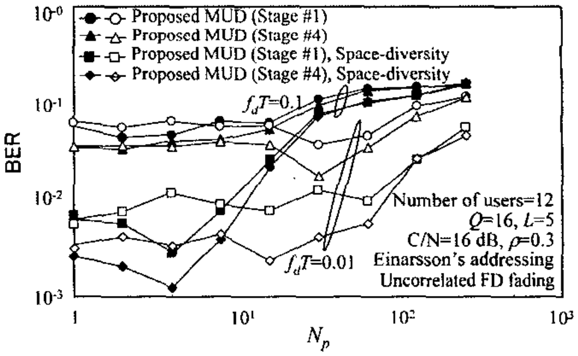

Fig. 10 BER versus the pilot symbol spacing N_p in the fast-FH/MFSK system used in both the proposed MUD scheme in conjunction with space diversity (2-branch selection diversity) for transmission over an uncorrelated fading channel in the frequency domain at C/N=16 dB.