Capacity Increasement of Trellis Coded 16 QAM Multi-Carrier CDMA System due to SC/MRC Diversity in Multiuser Interference and Rician Fading Channel

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ABSTRACT

In this paper, trellis coded 16 QAM Multi-Carrier CDMA system is proposed. Using the equivalent signal-to-noise plus interference Power ratio (SNIR) of Multi-Carrier CDMA system in the reverse link, capacity and BER performance of trellis coded 16 QAM Multi-Carrier CDMA system are analyzed taking into account the number of multi-carrier, the number of multiple access user, the number of SC/MRC diversity branch, and Rician fading parameter in multiuser interference and Rician fading channel. And the capacity and the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system using selection combining (SC) and maximal ratio combining (MRC) diversity are numerically compared.

Obtained results show that the capacity of proposed system depends on the number of Multi-Carrier. It is found that the trellis coded 16 QAM Multi-Carrier CDMA system with SC/MRC antenna diversity scheme is efficient to combat multipath fading and to increase the maximum number of users in high speed data communication. With the results of analysis, MRC diversity technique provides the performance improvement of about 2~3 dB in SNR over SC diversity technique in order to achieve good error performance for high speed data communications. Finally, we present a numerical approach to derive the capacity and the BER performance and to find the maximum number of multiple access user for Multi-Carrier system in multiuser interference and Rician fading channel.

I. Introduction

Recently, there has been increasing interest in using CDMA for commercial applications. CDMA is proposed for cellular, micro-cellular, indoor and satellite communications. CDMA is also a candidate for high data rate applications, such as wireless local area networks (LAN) and video phones. The spread spectrum modulation is used to mitigate the several problems encountered in different communication media. Therefore, it is advantageous to design this signal in a flexible way to be adaptable to various communication channel conditions. The Multi-Carrier CDMA system proposed here is the one way of achieving this goal [1]-[3].

Multi-Carrier modulation is a promising technique for mobile communication system, since it has a strong immunity to multipath fading without employing complicated adaptive equalization. Recently, Multi-Carrier CDMA system has been proposed for high data rate applications to reduce the effect of ISI (Intersymbol Interference)

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and adapt to channel conditions in indoor and outdoor communication system. While a lot of contributions have been done for synchronous Multi-Carrier CDMA system, little attention has been paid for the asynchronous case, because in the reverse link, orthogonality of the spreading codes may be severely distorted, causing a strong multiuser interference (MUI)[2].

Many communication systems are subject to fading caused by multipath propagation due to reflections, refractions, scattering by buildings and other large structures. Thus, the received signal is a sum of different signals that arrive via different propagation paths. The Rician distribution is used to characterize the envelope of faded signals over small geographical areas or short term fades while the log-normal distribution is used when much wider geographical areas involved [4].

Diversity is a commonly used technique in mobile radio systems to combat signal fading. In this paper, we consider two types of combining schemes. One is called the "selection combining (SC) scheme" and the other is the "maximal ratio (MRC) combining scheme." The SC diversity is the simplest and the most frequently used form of diversity combining. The algorithm for the selection combining is based on the principle of selecting the best signal among all of the signals received from different branches, at the receiving end. And the MRC diversity is widely used at the base station to combat fading and is known to be optimal in the sense that it yields the best statistical reduction of fading of any linear diversity combining. Therefore, it is desirable to investigate the performance of the Multi-Carrier CDMA system using multiple SC/MRC diversity antenna in the presence of fading and multiuser interferences.

Ungerboeck demonstrated that trellis coded modulation (TCM) can achieve coding gain of 3~6 dB in the AWGN channel while avoiding the bandwidth expansion of traditional error correcting coding methods [5]. Recent research has shown that TCM can be an effective way to combat signal fading when transmitting over indoor wireless channels. For example, the use of TCM for these mobile communication channels, typically modeled as Rician or Rayleigh, has recently received wide attention. It was shown in [6] that the combination of TCM and diversity yields a significant reduction in required transmit power compared to equivalent uncoded systems assuming a slowly fading channel. It was also shown that the use of diversity reduces the need for interleaving of symbols in the coded system, since it combines approximately independent samples of the channel. For the slowly fading channel, interleaving can result in large delays which may preclude voice applications. Coded modulation is often used in fading channel communications to achieve robust performance and good power and bandwidth efficiency. The use of trellis coded modulation in fading channels has been proposed by many authors [6],[7].

An early paper [2] presents an analysis of a Multi-Carrier CDMA-BPSK signal and propose a simple quadrature Multi-Carrier CDMA system in AWGN channel. And other Multi-Carrier CDMA system was proposed in [3] to reduce multipath fading and to solve both the ISI and ICI (Inter chip Interference) problems using a small number of carriers.

In this paper, trellis coded 16 QAM Multi-Carrier CDMA system is proposed. BER performance of trellis coded 16 QAM Multi- Carrier CDMA system with MRC diversity reception is discussed in multiuser interference and Rician fading channel. And the maximum number of users for Multi-Carrier system in a reverse link channel are found. The motivation of this work is to propose a Multi-Carrier CDMA system for high speed data communication in radio channel environment.

Ⅱ. System Model

Multi-Carrier CDMA transmitter of the kth user is shown in Fig. 1, where $a^{(k)}$ and $C_i^{(k)}$ denote the information symbol and the ith spreading code of length M_C of the kth user, respectively. By using M_C orthogonal codes, the maximum number of users U is equal to M_C.

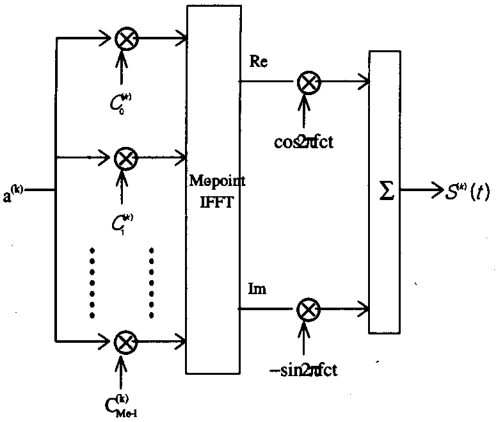

Fig. 1 Reverse link Multi-Carrier CDMA transmitter for the kth user.

The block diagram of Multi-Carrier CDMA system with U users is shown in figure 1. The transmitted signal of the kth user is in general shaped in the time domain by a window function $w(t)$ to minimize excessive out-of-band emissions. The quadrature sinusoidal carriers are then modulated by the real and imaginary part of the baseband signals generated from IFFT respectively, while the former component at the jth symbol instant can be described as

$$s_{I,j}^{(k)}(t) = \sqrt{\frac{2P}{M_C}}\, a_j^{(k)} \sum_{m=1}^{M_C} c_m^{(k)} \cos\left(\frac{2\pi mt}{T_S}\right) w(t-jT_S) \tag{1}$$

where $\{a_j^{(k)}\}$ is the bi-phase information sequence and $\{c_m^{(k)}\}$ is the spreading sequence over the alphabet $\{+1, -1\}$. It is assumed that the spreading gain M_C is the large and equals the number of carriers present. Also, the fundamental carrier frequency, f_o equals the symbol rate $1/T_S$ and the transmitted signal power P of every user is assumed to the same. Then, the jth transmitted symbol $s_j^{(k)}$ of the kth user with modulator phase shift θ_k is

$$\begin{aligned} s_j^{(k)}(t) &= s_{I,j}^{(k)}(t)\cos(2\pi f_c t + \theta_k) \\ &- s_{Q,j}^{(k)}(t)\sin(2\pi f_c t + \theta_k) \end{aligned} \tag{2}$$

where f_c to $f_c + M_C/T_S$ is the desired spectrum in used and $S_Q^{(k)}(t)$ equals (1) with $\cos\left(\frac{2\pi mt}{T_s}\right)$ replaced by $\sin\left(\frac{2\pi mt}{T_s}\right)$. For the sake of clarity, we let $u_k(t) = \sum_{m=1}^{M_C} c_m^{(k)}\cos\left(\frac{2\pi mt}{T_s}\right)$ and $v_k(t) = \sum_{n=1}^{M_C} c_n^{(k)}\sin\left(\frac{2\pi nt}{T_s}\right)$ in the analysis of the following sections.

For simplicity, we assume $w(t)$ in (1) equals $p_{T_s}(t)$. Where $w(t)$ is the pulse waveform of each symbol, given as

$$p_{T_s}(t) = \begin{cases} 1, & 0 \le t < T_s \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where T_s is a symbol period

For the quadrature modulator and the receiver, the transmitted data sequence, $\{a_j^{(1)}\}$ is coherently detected and multipath fading is not presented. To simplify our argument, neither the guard interval nor the influence of inter-symbol interference (ISI) of each user will be taken into account.

With a perfect power control, the jth transmitted symbol at each receiver is given by

$$\begin{aligned} r_j(t) &= \sum_{k=1}^{U}\{s_{I,j}^{(k)}(t-\tau_k)\cos(2\pi f_c t + \varphi_k) \\ &- s_{Q,j}^{(k)}(t-\tau_k)\sin(2\pi f_c t + \varphi_k)\} + N(t) \end{aligned} \tag{4}$$

where $N(t)$ is white Gaussian noise and $\varphi_k = \theta_k - 2\pi f_c \tau_k$. The delay and modified phase offset $\{\varphi_k\}$ of every transmitted signal are assumed to be uniformly distributed on the interval $[0, T_s]$ and $[0, 2\pi]$ respectively. It is further assumed that the parameters τ_1 and φ_1 equal zero. For simplicity, only the first symbol interval is considered and the demodulated signal at the intended receiver is given by

$$Z_O = S^{(1)} + \sum_{k=2}^{U} I^{(1,k)} + \int_0^{T_s} \sum_{n=1}^{M_C} N(t)\cos(2\pi n f_o t)\, dt \tag{5}$$

where $S^{(1)}$ is the useful output signal, $N(t)$ denotes the white Gaussian noise power term, and

$I^{(1,k)}$ are the MAI terms from the kth user.

From the Ref [8][9], the MAI from the kth user $I^{(1,k)}$ are given by

$$I^{(1,k)} = \sqrt{\frac{2P}{M_C}} \sum_{n=0}^{M_C} \left\{ A_n \sin\frac{2\pi n \tau_k}{T_s} + B_n \cos\frac{2\pi n \tau_k}{T_s} \right\} \tag{6}$$

where

$$\begin{aligned} A_n &= \frac{c_n^{(k)} c_n^{(1)} \sin\psi_k}{2} \{ a_{-1}^{(k)} \tau_k + a_0^{(k)} [T_s - \tau_k] \} \\ &+ \frac{T_s \cos\psi_k [a_{-1}^{(k)} - a_0^{(k)}]}{2\pi} \\ &\left\{ \sum_{i=1, i\neq n}^{M_C} \frac{n[c_n^{(k)} c_i^{(1)} + c_n^{(k)} c_n^{(1)}]}{n^2 - i^2} + \frac{c_n^{(k)} c_n^{(1)}}{2n} \right\} \end{aligned} \tag{7}$$

and

$$\begin{aligned} B_n &= \frac{c_n^{(k)} c_n^{(1)} \cos\psi_k}{2} \{ a_{-1}^{(k)} \tau_k + a_0^{(k)} [T_s - \tau_k] \} \\ &+ \frac{T_s \sin\psi_k}{2\pi} \{ [a_{-1}^{(k)} - a_0^{(k)}] \\ &\sum_{i=1, i\neq n}^{M_C} \frac{n c_n^{(k)} c_i^{(1)} + i c_n^{(1)} c_i^{(k)}}{i^2 - n^2} - \frac{c_n^{(k)} c_n^{(1)} a_0^{(k)}}{2n} \right\} \end{aligned} \tag{8}$$

Multi-Carrier signal consists of sum of M_C waveform, as M_C increases, its waveform will have a Gaussian distribution. That is, for asynchronous Multi-Carrier CDMA system, Gaussian Approximation is then used to estimate the probability of error in the Multi-Carrier CDMA system. For simplicity, we assume $a_j^{(k)}$ is equally distributed between '+1' and '-1' for $k \in \{2, \ldots, U\}$ and the random variables τ_k, $a_{j-1}^{(k)}$, $a_j^{(k)}$ are independent for $2 \le j \le U$. Without loss of generality, we have assumed the $\tau_0 = 0$ and $0 \le \tau_k < T_s$ for $k = 1, 2, \cdots, U-1$, and τ_k can be considered as independent, identically distributed (iid) random variables. In the analysis, random signature sequences are assumed in operation, and for asynchronous Multi-Carrier CDMA system, interference from other users can be well approximated as a Gaussian noise with zero mean and the average value of the variance in the Multi-Carrier CDMA system, $E[Var\{I^{(1,k)}\}]$ is as follow.

$$\begin{aligned} E[Var\{I^{(1,k)}\}] &= \frac{PT_s^2}{4\pi^2 M_c} \left\{ \left[\sum_{n=1}^{M_c} \sum_{i=1, i\neq n}^{M_c} \frac{3n^2 + i^2}{(n^2 - i^2)^2} \right] \right. \\ &\left. + \frac{2\pi^2}{3} \right\} \end{aligned} \tag{9}$$

By assuming the interference among all other users are independent, the total interference power would simply be the summation of every $Var\{I^{(1,k)}\}$. The equivalent signal-to noise plus interference power ratio $SNIR_{eq}$ at the receiver is then approximated as follow.

$$SNIR_{eq} = \frac{M_C P T_s^2 / 2}{\dfrac{(U-1)\, PT_s^2 A^*}{4\pi^2 M_C} + \dfrac{M_C N_0 T_s}{4}}$$

$$A^* = \left[\sum_{n=1}^{M_C} \sum_{i=1, i\neq n}^{M_C} \frac{3n^2 + i^2}{(n^2 - i^2)^2} \right] + \frac{2\pi^2}{3} \tag{10}$$

After simplification, we have

$$\begin{aligned} SNIR_{eq} &\approx \left(\frac{U-1}{2M_c^2 \pi^2} \left\{ \left[\sum_{n=1}^{M_c} \sum_{i=1, i\neq n}^{M_c} \frac{3n^2 + i^2}{(n^2 - i^2)^2} \right] \right. \right. \\ &\left. \left. + \frac{2\pi^2}{3} \right\} + \frac{N_0}{2E_b} \right. \end{aligned} \tag{11}$$

where E_b is transmitted signal energy in one symbol period.

The standard Gaussian approximation formula of uncoded Multi-Carrier BPSK system is therefore given by $P_b \approx Q(\sqrt{SNIR_{eq}})$, where $Q(x)$ is the complementary error function.

Ⅲ. Performance Evaluation

We evaluated the performance of asynchronous trellis coded 16 QAM Multi-Carrier CDMA based on the method in the reference [8],[9]. In what follows, we will take simple approach to derive the bit error performance of asynchronous Multi-Carrier CDMA.

A simplified block diagram of the proposed system is shown in Fig.2. The transmitted data bit stream is first converted to n-bit parallel data (n=3 for 16 QAM) and then fed into an $n/(n+1)$ trellis encoder, resulting in a baseband coded signal stream. At the Multi-Carrier CDMA transmitting part, the bit stream with bit duration

T_b is serial-to- parallel converted into M_C parallel streams. The new bit stream on each stream is $T=M_c T_b$.

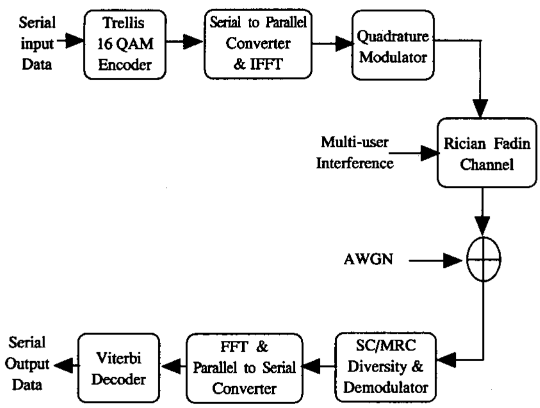

Fig. 2 Trellis coded Multi-Carrier CDMA block diagram.

The Rician fading model describes the situation where the composite received signal consists of a direct signal term and a diffused signal term characterized by independent Gaussian quadrature components (Rayleigh amplitude) with variance σ^2.

The Rician probability density function (pdf) is given by [10]

$$p(\gamma)=\frac{K_R+1}{\Gamma}\exp\left[-\frac{(K_R+1)\gamma}{\Gamma}-K_R\right]\cdot I_0\left(2\sqrt{\frac{K_R(K_R+1)\gamma}{\Gamma}}\right) \tag{12}$$

where $K_R=A^2/2\sigma^2$ is the direct signal power to diffused signal power ratio, γ is the instantaneous signal-to-noise ratio, Γ is the average signal-to-noise ratio, and $I_0(\cdot)$ is the zero-order modified Bessel function of the first kind. Note that if $K_R=0$, corresponding to no specular energy, K_R ranging from 6 *dB* to 12 *dB* corresponding to the range of values for indoor office building channels.

The received signals distributed by Rician fading and multiuser interference in each diversity branch are selected and combined by diversity circuit. Diversity reception is usually regarded as a means of combating fading in radio transmissions. In SC diversity which is the simplest method of space diversity, for instance, several antennas are used, separated in space to process the various received signals and the one of the B_S receivers having the highest signal-to-noise power ratio (SNR) is connected to the demodulator. The basic idea behind the concept is that the received signals on different antennas are statistically independent and therefore there is a good chance that they will not all fade at the same time.

Assuming that the received signal corrupted by Rician fading in each selection diversity branch are uncorrelated, we derived the pdf of the instantaneous output signal-to-noise power ratio, $p(\gamma\mid\Gamma,B_S)$, at the B_S-branch SC diversity reception circuit based on the procedure given in the reference [10].

$$\begin{aligned}P_{SC}(\gamma\mid\Gamma,B_S)&=\int_0^{\gamma}p(\gamma_1)d\gamma_1\int_0^{\gamma}p(\gamma_2)d\gamma_2\\&\quad\cdots\int_0^{\gamma}p(\gamma_{B_S})d\gamma_{B_S}=\prod_{l=0}^{B_S}\int_0^{\gamma}p(\gamma_l)d\gamma_l\\&=\prod_{l=0}^{B_S}\int_0^{\gamma}\frac{K_R+1}{\Gamma}\exp\left[-\frac{(K_R+1)\gamma_l}{\Gamma}-K_R\right]\\&\quad\cdot I_0\left(2\sqrt{\frac{K_R(K_R+1)\gamma_l}{\Gamma}}\right)d\gamma_l\end{aligned} \tag{13}$$

After derivation, we have

$$\begin{aligned}p_{SC}(\gamma\mid\Gamma,B_S)&=\frac{d}{d\gamma}P_{SC}(\gamma\mid\Gamma,B_S)\\&=B_S\left(\frac{K_R+1}{\Gamma}\right)\exp\left(K_R-\frac{(K_R+1)\gamma}{\Gamma}\right)\\&\quad I_0\left(2\frac{\sqrt{K_R(K_R+1)\gamma}}{\Gamma}\right)\cdot\{1-\exp(-K_R)\\&\quad\left.\sum_{n=0}^{\infty}\frac{K_R}{n!}\frac{\Gamma\left(n+1,\frac{(K_R+1)\gamma}{\Gamma}\right)}{\Gamma(n+1)}\right\}^{B_S-1}\end{aligned} \tag{14}$$

where B_S is the number of SC diversity branches, $\Gamma(\cdot,\cdot)$ is incomplite Gamma function, and $\Gamma(\cdot)$ is Gamma function.

The pdf of Rician distribution with $B_S=2$ branch SC diversity reception is shown Fig. 3.

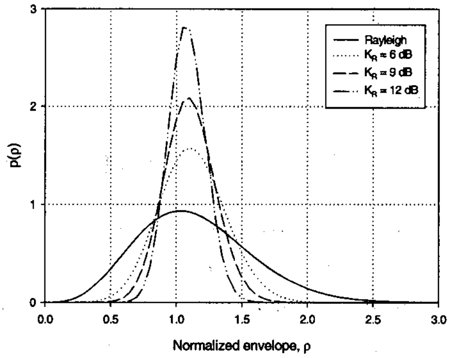

Fig. 3 SC diversity distribution curves.

The MRC diversity system is widely used to mitigate the fading in communication systems. In MRC diversity, the branch signals are weighted by a complex valued branch gain, that is, each signal is weighted according to its strength. We assume that the average signal power in each branch of a maximal ratio diversity system are identical. The assumption of identical average power is reasonable if the diversity channels are closely spaced.

The characteristic function of Rician fading is given by [10]

$$g_{(u)} \triangleq \overline{\exp(ju\gamma)} = \int_{-\infty}^{\infty} \exp(ju\gamma)p(\gamma)d\gamma$$
$$= \int_{0}^{\infty} \exp(ju\gamma)\,\frac{K_R+1}{\Gamma}\,\exp\left(-K_R-\frac{\gamma(K_R+1)}{\Gamma}\right) I_0\left(2\sqrt{\frac{\gamma K_R(K_R+1)}{\Gamma}}\right)d\gamma$$
$$= X\exp(-K_R)\int_{0}^{\infty} \exp(ju\gamma)\exp(X\gamma)\, I_0(2\sqrt{XK_R\gamma})d\gamma \qquad (15)$$

where, $X = (K_R + 1)/\Gamma$ and $I_0(\cdot)$ is modified Bessel function.

After derivation, we obtain the pdf of B_M branch MRC diversity in Rician fading as follow.

$$p_{MRC}(\gamma) = F[g(u)] = \frac{1}{2\pi}\int_{-\infty}^{\infty} g(u)\exp(-ju\gamma)du$$
$$= \frac{1}{2\pi}X^{B_M}\exp(-K_RB_M)\int_{-\infty}^{\infty}\left(\frac{1}{X-ju}\right)^{B_M} \exp\left(-ju\gamma+\frac{XK_RB_M}{X-ju}\right)du$$
$$= X^{B_M}\exp(-K_RB_M)\exp(-X\gamma)\left(\frac{a}{b}\right)^{n} \cdot\frac{1}{2\pi j}\left(\frac{b}{a}\right)^{n}\int_{A-j\infty}^{A+j\infty}\frac{1}{s^{n+1}}\exp\left(\frac{a^2}{2}s+\frac{b^2}{2}\frac{1}{s}\right)ds \qquad (16)$$

where, $X - ju = S$, $n = B_M - 1$, $a^2/2 = \gamma$, and $b^2/2 = XK_RB_M$.

The SNR at the output of MRC is proportional to the short-term power of the kth channel. When the branch fading are assumed to be statistically independent, the pdf of MRC diversity in Rician fading is known to be given by

$$p_{MRC}(\gamma \mid \Gamma, B_M) = \frac{K_R+1}{\Gamma}\cdot\left(\frac{(K_R+1)\gamma}{K_RB_M\Gamma}\right)^{\frac{B_M-1}{2}} \exp\left[-\frac{(K_R+1)\gamma}{\Gamma}-K_RB_M\right] I_{B_M-1}\left(2\sqrt{\frac{B_MK_R(K_R+1)\gamma}{\Gamma}}\right) \qquad (17)$$

where B_M is the number of MRC diversity branches, separated by a minimum of half a wavelength, used to exploit the space diversity.

The pdf of Rician distribution with $B_M = 2$ branch MRC diversity reception is shown Fig. 4.

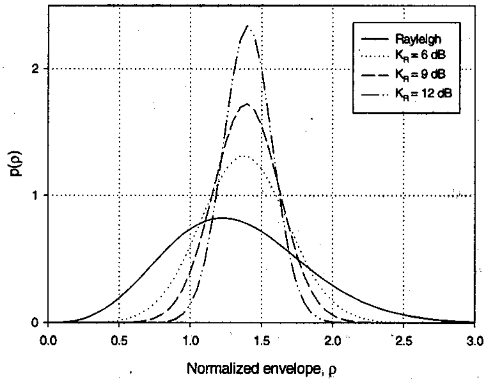

Fig. 4 MRC diversity distribution curves.

For trellis coded multi-carrier CDMA 16 QAM modulation, the bit-error probability P_b can be approximated by truncating the union bound to include a finite set of dominant (short) error event. Note that this bound can be readily used with a union bound to get an upper bound of the bit-error probability [12].

$$P_b \le \frac{1}{n}\sum_{j=1}^{\infty} w(j)\,P_j(x \rightarrow \hat{x}) \qquad (18)$$

where $w(j)$ is the number of bit errors associated with the *j*th error event with Euclidean distance d_i which on average may start as a state in the decoder trellis, and let $d_1 = d_{free} < d_2 < d_3 \ldots$. We then have

$$\frac{N(d_{free})}{n} Q\left(\sqrt{\frac{n\ d_{free}^2\ SNIR_{eq}}{2}}\right) \le P_b(e) \le \frac{1}{n} \sum_{j=1}^{\infty} w(j)\, P_j(x \to \hat{x}) \qquad (19)$$

The two bounds will merge at high signal-to-noise power ratios. And n is the number of information bits per encoding interval. Obviously, in order to limit computations, this summation must be terminated after a finite number of error events, assuming that the remainder is negligible. As observed in [13], for sufficiently large signal-to-noise power ratio, the union bound is dominated by a small set of error events. However, for low values of signal-to-noise power ratio, the union bound itself becomes loose.

For high signal-to-noise power ratio, the bit error probability in AWGN channel is well approximated by

$$P_b \approx \frac{N(d_{free})}{n} \cdot Q\left(\sqrt{\frac{n\ d_{free}^2\ SNIR_{eq}}{2}}\right) \qquad (20)$$

where $Q(x)$ is defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-y^2/2} dy \qquad (21)$$

and d_{free} represents the Euclidean distance between coded signal sequences and $N(d_{free})$ represents the average number of information bits of the whole coded sequence paths having distance d_{free} from the correct path.

Assuming that signal power to noise power ratio is constant over a decoding span, the BER performance for trellis coded 16 QAM Multi-Carrier CDMA with SC/MRC diversity reception in Rician fading channel can be obtained by averaging (20) over the pdf in (14) and (17), respectively

$$P_{e(MRC)} = \int_0^{\infty} P_b \cdot p_{MRC}(\gamma \mid \Gamma, B_M)\, d\gamma \qquad (22)$$

$$P_{e(SC)} = \int_0^{\infty} P_b \cdot p_{SC}(\gamma \mid \Gamma, B_S)\, d\gamma \qquad (23)$$

where Γ is average signal-to-noise power ratio.

Ⅳ. Numerical Results

Following numerical results based on the above analysis are presented to demonstrate the impact of the number of Multi-Carrier (M_C), the number of multiple access users (U), Rician fading parameter (K_R), the number of selection combine antenna branches (B_S), the number of maximum combine antenna branches (B_M), and required BER on system. Although the required BER of acceptable system performance varies with the different services, we have chosen a required BER value of 10^{-5} for the data communication. In this paper, radio channel is modeled by Rician fading channel with fading parameter range from $K_R = 6\ dB$ to $K_R = 12\ dB$ for indoor communication environment.

For the purpose of illustration we select a simple 8-state trellis coded 16 QAM signal [5]. The connect coefficient of trellis encoder is given in octal notation : e.g., $(h^{(0)}, h^{(1)}, h^{(2)}) = (11, 2, 4)$. In the AWGN channel, this code provides an asymptotic coding gain of 5.3 dB over the corresponding uncoded system using 8PSK while maintaining the same throughput and bandwidth.

Figure 5 and 6 represent the BER performance comparison of trellis coded 16 QAM, uncoded BPSK, and uncoded 8PSK Multi-Carrier CDMA system in multiple access user interference and Rician fading channel. Trellis coded 16 QAM Multi-Carrier CDMA system is superior to both the uncoded BPSK and uncoded 8 PSK Multi-Carrier CDMA system. Therefore, a larger trellis coding gain is obtained in trellis coded 16 QAM Multi-Carrier CDMA system. In figure 6, by employing trelllis coding, we obtain asymptotic E_b/N_o reductions of about 8 dB and 9 dB for $BER = 1 \times 10^{-3}$ and $BER = 1 \times 10^{-4}$, respectively in U=20 multiple access user interference and $K_R = 6\ dB$ Rician fading channel.

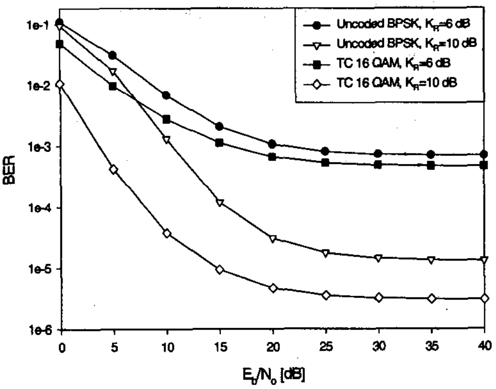

Fig. 5 Performance comparision of trellis coded 16 QAM and uncoded BPSK Multi-Carrier CDMA system in multiple access user interference and Rician fading channel (U=10, M_C=127).

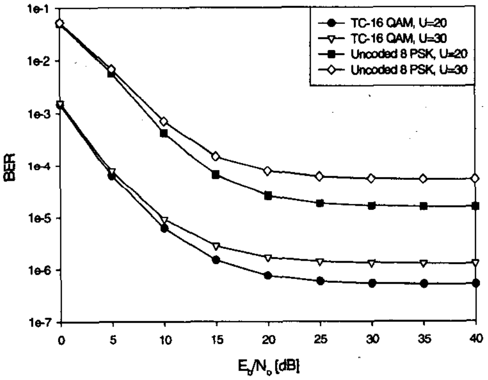

Fig. 6 Performance comparision of trellis coded 16 QAM and uncoded 8 PSK Multi-Carrier CDMA system using MRC diversity with different number of multiple access user (U=20, 30, K_R= 6 dB, $B_M=2$, M_C=127).

Figure 7 and 8 show the relationship between BER and the number of multiple access user in trellis coded 16 QAM Multi-Carrier CDMA system using SC and MRC diversity, respectively. As the number of multiple access user increases the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system degrades. When MRC diversity is used, we know that more than E_b/N_o= 13 *dB*, the BER performance ($P_e < 10^{-5}$) can be easily achieved in $U=50$ multiple access user and $K_R=6\ dB$ Rician fading environment. And when SC diversity is used, we know that more than E_b/N_o=11.5 *dB*, the BER performance ($P_e < 10^{-5}$) can be easily achieved in $U=20$ multiple access user and $K_R=6\ dB$ Rician fading environment.

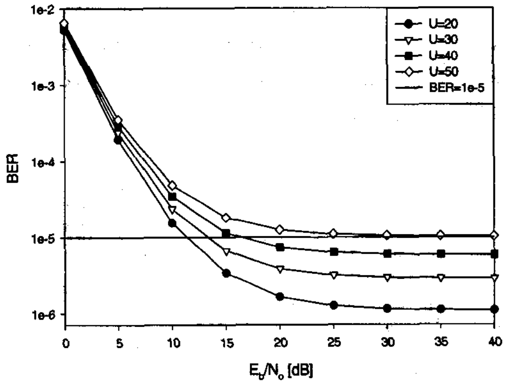

Fig. 7 Performance of trellis coded 16 QAM Multi-Carrier CDMA system using SC diversity with different number of multiple access user (U=20, 30, 40, 50, K_R= 6 dB, $B_S=2$, M_C=127).

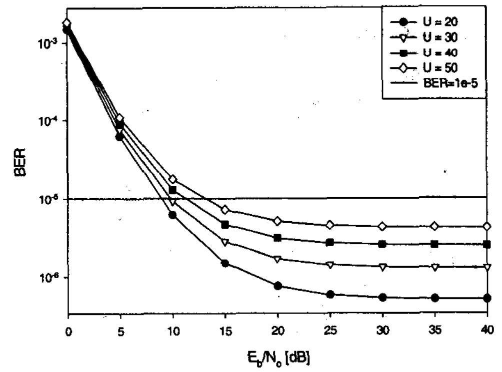

Fig. 8 Performance of trellis coded 16 QAM Multi-Carrier CDMA system using MRC diversity with different number of multiple access user (U=20, 30, 40, 50, K_R= 6 dB, $B_M=2$, M_C=127).

Figure 9 and 10 show the performance of trellis coded 16 QAM Multi-Carrier CDMA system using SC and MRC diversity with different Rician fading parameter. As the Rician fading parameter increases from $K_R=6\ dB$ to $K_R=10\ dB$ the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system improves. And we know that more than E_b/N_o=10 *dB*, the BER performance ($P_e < 10^{-5}$) can be easily achieved in $U=20$ multiple access user and $K_R=6\ dB$ Rician fading environment. And more than E_b/N_o=25 *dB*, the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system is not improve in multiuser interference and Rician fading environment, regardless of a diversity combining technique. This means that Multi-Carrier CDMA system is limited by multiuser interference.

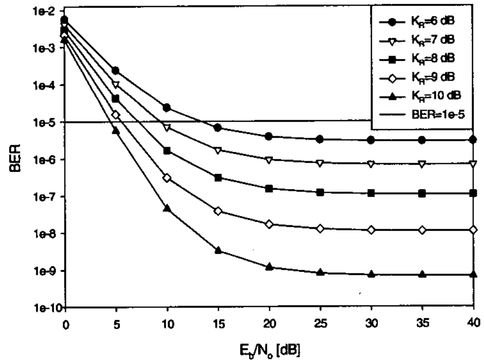

Fig. 9 Performance of trellis coded 16 QAM Multi-Carrier CDMA system using SC diversity with different Rician fading parameter (K_R = 6, 7, 8, 9, 10 *dB*, *U*=30, B_S=2, M_C=127).

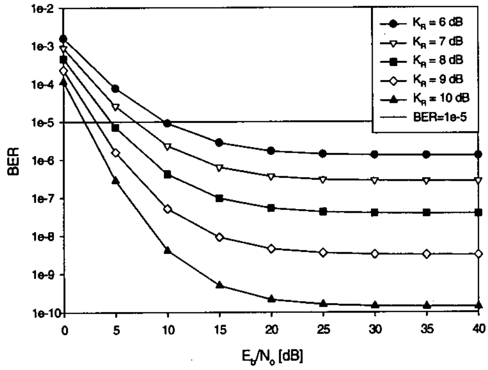

Fig. 10 Performance of trellis coded 16 QAM Multi-Carrier CDMA system using MRC diversity with different Rician fading parameter (K_R = 6, 7, 8, 9, 10 dB, U=30, B_M=2 , M_C=127).

Figure 11 and 12 show the effects of diversity branch on the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system. The B_S =1 and B_M=1 case, where the diversity effect is absent, is also included for reference. It is found that an increase in diversity branch B_S and B_M from 1 to 3 improves the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system in a large extent. Diversity reception is found to improve the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system. However, the overall performance enhancement is reduced with increase of diversity branch.

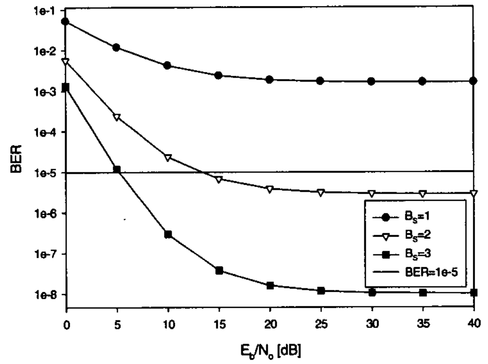

Fig. 11 Performance of trellis coded 16 QAM Multi-Carrier CDMA system using SC diversity with different number of diversity branch (M_C=127, K_R= 6 *dB*, *U*=30).

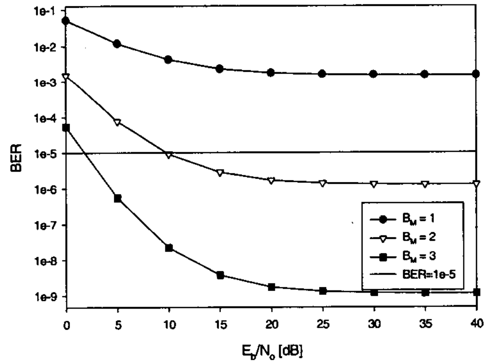

Fig. 12 Performance of trellis coded 16 QAM Multi-Carrier CDMA system using MRC diversity with different number of diversity branch (M_C =127, K_R=6 *dB*, *U*=30).

Figure 13 and 14 show the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system with different number of multi-carrier. As the number of multi-carrier increases from M_C =31 to M_C=255 the BER performance of trellis coded 16 QAM Multi-Carrier CDMA system improves. And using the MRC diversity, we know that more than E_b/N_o=8.5 *dB*, the BER performance ($P_e < 10^{-5}$) can be achieved when M_C=255, K_R=6, *U*=30, and B_M=2 .

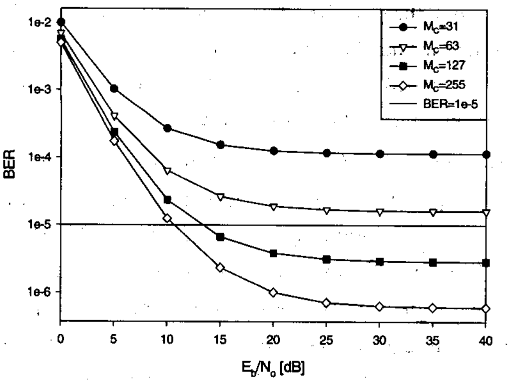

Fig. 13 Performance of trellis coded 16 QAM Multi-Carrier CDMA system using SC diversity with different number of Multi-Carrier (M_C=31, 63, 127, 255, K_R= 6 *dB*, *U*=30, B_S=2).

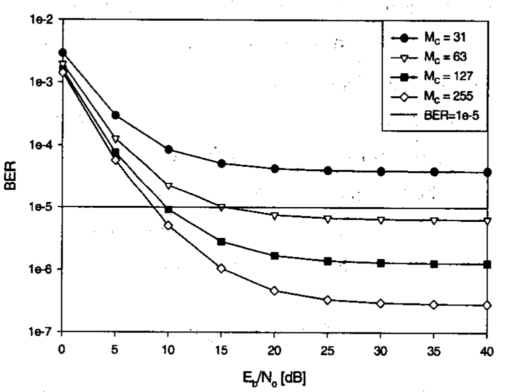

Fig. 14 Performance of trellis coded 16 QAM Multi-Carrier CDMA system using MRC diversity with different number of Multi-Carrier (M_C=31, 63, 127, 255, K_R=6 dB, U=30, B_M=2).

Figure 15 and 16 show the relationship between maximum number of user and E_b/N_o of the trellis coded 16 QAM Multi-Carrier CDMA system with different number of multi-carriers under the constraint of $P_e < 10^{-5}$. The maximum number of users can be supported in the trellis coded 16 QAM Multi-Carrier CDMA system varies with the E_b/N_o and the number of Multi-Carriers. Especially, we know that the number of multi-carriers is a dominant factor of maximum number of user in trellis coded 16 QAM Multi-Carrier CDMA system. And more than E_b/N_o=25 dB, the maximum number of users is not sensitive to the E_b/N_o in multiuser interference and Rician fading environment.

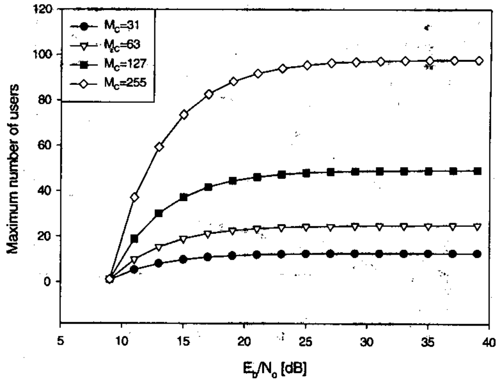

Fig. 15 Maximum number of multiple access user for trellis coded 16 QAM Multi-Carrier CDMA system using SC diversity under the constraint of $P_e < 10^{-5}$ (K_R=6 dB, B_S=2, M_C= 31, 63, 127, 255).

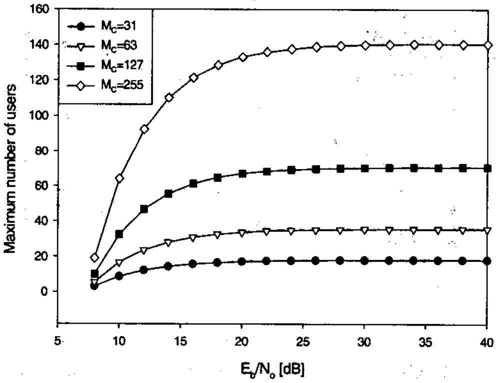

Fig. 16 Maximum number of multiple access user for trellis coded 16 QAM Multi-Carrier CDMA system using MRC diversity under the constraint of $P_e < 10^{-5}$ (K_R=6 dB , B_M=2 , M_C= 31, 63, 127, 255)

Figure 17 and 18 show the relationship between the BER performance with different number of multi-carrier and the number of multiple access user in trellis coded 16 QAM Multi-Carrier CDMA system. As expected the number of multi-carrier has a significant impact on the capacity of Multi-Carrier CDMA system. For example, if the target BER is 10^{-5}, the number of user must be smaller than 32 when the number of Multi-Carrier is 127 and E_b/N_o is 10 *dB*. Here we note that by selecting an appropriate number of Multi-Carriers, the BER performance ($P_e < 10^{-5}$) can be effectively achieved in multiuser interference and Rician fading environment.

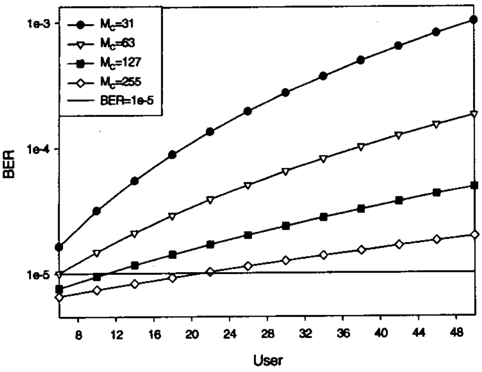

Fig. 17 Capacity of trellis coded 16 QAM Multi-Carrier CDMA system using SC diversity with different number of Multi-Carrier (M_C = 31, 63, 127, 255, K_R =6 dB, E_b/N_o =10 dB, B_S=2).

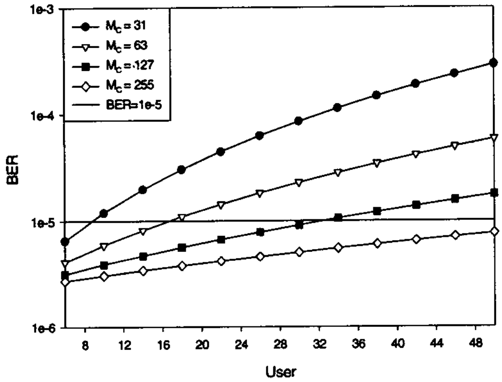

Fig. 18 Capacity of trellis coded 16 QAM Multi-Carrier CDMA system using MRC diversity with different number of Multi-Carrier (M_C = 31, 63, 127, 255, K_R =6 dB, E_b/N_o =10 dB, B_M=2).

V. Conclusions

In this paper, trellis coded 16 QAM Multi-Carrier CDMA system using quadrature modulation and spatial diversity is proposed and the BER performance of trellis coded Multi-Carrier CDMA with MRC diversity is numerically calculated in the presence of multiuser interference and Rician fading channel. It is found that the BER performance of proposed system enhances as the number of multi-carrier (M_C) and Rician fading parameter (K_R) increases. And the proposed system is efficient to combat multipath fading and to increase the maximum number of users in high speed data communication.

From the proposed system, we found the maximum number of multiple access user for trellis coded 16 QAM Multi-Carrier CDMA system with SC/MRC diversity under the constraint of $P_e < 10^{-5}$. With the results of analysis, MRC diversity technique provides the performance improvement of about 2~3 dB in SNR over SC diversity technique in order to achieve good error performance for high speed data communications. Obtained results show that the capacity of proposed system depends on the number of multi- carrier. However, the maximum number of users is dependent on the number of multi-carrier but is not sensitive to the E_b/N_o which is larger than 20 *dB*. In addition, there is a considerable coding gain at high E_b/N_o for the trellis coded Multi- Carrier system over the uncoded Multi- Carrier system. Therefore, we know that trellis coded scheme with diversity achieve better performance in bit error probability than uncoded scheme in multiple access user interference and Rician fading channel.

References

[1] N. Yee, J. P. Linnartz, and G. P. Fettweis, "Multi-Carrier CDMA in indoor wireless radio networks," *IEICE Trans., Commun.*, vol. E77-B, no. 7, pp. 900-904, July 1994.

[2] K. Fazel and G. P. Fettweis, *Multi-Carrier Spread-Spectrum*, Kluwer Academic Publishers, 1997.

[3] E. A. Sourour and M. Nakagawa, "Perofrmance of orthogonal Multi-Carrier CDMA in a multipath fading channel," *IEEE Trans. on Comm.* vol. COM-44, pp. 356-367, Mar. 1996.

[4] S. Sampei, *Applications of digital wireless technologies to global wireless communications*, Prentice Hall, 1997.

[5] E. Biglieri, D. Divsalar, P. J. Mclane, and M. K. Simon, *Introduction to Trellis Coded Modulation with Applications*, New York : Macmillan, 1991.

[6] J. M. Bargallo and J. A. Roberts, "Performance of BPSK and TCM using the exponential

multipath profile model for spread-spectrum indoor radio channels," *IEEE Trans. on Comm.*, vol. COM-43, pp. 615-623, Feb./Mar./Apr. 1995.

[7] D. Divsalar and M. K. Simon, "Trellis coded modulation for 4800-9600 bits/s transmission over a fading mobile satellite channel," *IEEE J. Select. Areas Comm.*, vol. JSAC-5, pp. 162-175, Feb. 1987.

[8] M. B. Pursley, "Performance evaluation for phase-coded spread-spectrum miltiple access communication-part I : system analysis," *IEEE Trans. on Comm.* vol. COM-25, pp. 795-799, Aug. 1977.

[9] T. F. Ho, "Performance evaluation for multi-carrier CDMA system," *Proc. IEEE VTC'96*, pp. 1101-1105, 1996.

[10] M. Schwartz, *Communication Systems and Techniques*, New York : McGraw - Hill, 1966.

[11] V. Aalo, G. Efthymoglou, and H. Helmken, "Path diversity performance of a DS-CDMA based land-mobile satellite system in a shadowed Rician-fading channel," *Wireless Communication-96*, pp. 133-140, 1996.

[12] C. Tellambura and K. Bhargava, "Error performance of MPSK trellis-coded modulation over nonindependent Rician fading channels," *IEEE Trans. on Veh. Technol.*, vol. 47, pp. 152-162, Feb. 1998.

[13] F. Gagnon and D. Haccoun, "Bounds on the error performance of coding for nonindependent Rician fading channels," *IEEE Trans. on Comm.* vol. COM-40, pp. 351-360, Feb. 1992.

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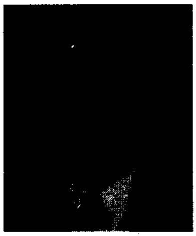

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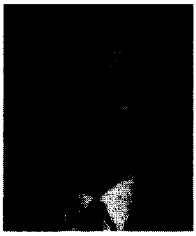

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