MULTI-RATE MULTI-TONE-CDMA WITH MULTIUSER DETECTION FOR WIRELESS MULTIMEDIA COMMUNICATIONS

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Abstract – Multi-Tone CDMA is a spectrum-efficient multiuser transmission technique, and regarded as a promising platform for multimedia communications. We study the multi-rate physical-layer transmissions, based on Multi-Code (MC) and Variable-Spreading-Length (VSL) access. A general and systematic system model accommodating both access methods with multiuser detections (MUD) is constructed, which is useful for programmable system integration. We investigate the system characteristics under multi-rate transmission, including multiple access interference (MAI) and inter-carrier interference (ICI), and the performance comparisons between MC and VSL schemes in frequency-selective Rayleigh fading channels are studied.

Keywords – MT-CDMA, Multiuser detection, Multi-rate transmission, OFDM, CDMA.

I. INTRODUCTION

Multimedia services will predominate future wireless communications, including voice, image, data, and video etc., and varied data rates is one of the most significant features in multimedia systems. It inspired many researches of multi-rate transmission in DS-CDMA systems [1][2]. However, with the increased demand of wideband high speed and high transmission quality, some techniques based on the combining OFDM with CDMA were proposed for physical-layer platform, where three major types are classified in [3] and widely considered promising for future wireless multimedia communications. MT-CDMA is one of the alternatives of OFDM-CDMA with high spectrum efficiency [4]. Such combination not only retains the advantages of OFDM and CDMA, e.g. robustness to multi-path channel effect, efficient bandwidth utilization, and high capacity, but also mitigates the difficulties of equalization and the complicated rake structure in the receiver due to narrow bandwidth over sub-carriers. Time-domain Direct-Sequence Spread-Spectrum (DS-SS) and condensed sub-carrier spacing for spectrum efficiency is the feature of MT-CDMA, although the inter-carrier orthogonality is lost with respective to chip duration [4][3].

Upon the efficient multi-tone platform, we considered the realization of multi-rate transmission based on MC and VSL access [5]. Previous researches had shown the properties of multi-rate access over the other two types of OFDM-CDMA [6][7], however, the impact of raised MAI from MC access and the variation of interference-suppression ability due to unfixed spreading factor in VSL access result in different feature, and we investigated them in this paper. In addition, we construct a general and uniform system model for multi-rate MT-CDMA accommodating both access methods, and it helps the design of MUDs with identical structure for them, even including any other collateral signal processing. The programmability of this structure is contributive to the development in software radio.

Due to the strong overlap of sub-channel spectrum, inter-carrier interference (ICI) is the inherent disadvantage of MT-CDMA [3][4]. The ICI comes from the parallel transmitted symbols of all active users including the desired user it self. Increased sub-channel symbol duration enhances the immunity to multi-path effect, but the effectiveness is limited by more involved ICI. Therefore, interference cancellation is critical in designing an effective receiver, especially in multi-rate CDMA systems. We proposed an effective two-stage Decorrelaing type MUD with interference cancellation loop, whose complexity is appropriate in practical applications. The first stage aims to remove the ICI based on the bank of match filters and the second stage deals with multiple-access interference (MAI) by decorrelaing. The characteristic of the multi-rate MT-CDMA in both access methods and their performances with the proposed MUD are investigated in this paper.

II. MULTI-RATE MT-CDMA

We assume there is a basic data rate $1/T_s$ in the system and all data rates in the system fit integer multiples of the basic rate. A user with rate m represents a user whose data rate is m times the basic rate in this paper. The MC access and VSL access are described as follows:

A. Multi-Code Access

The data stream from a user with rate m is first multiplexed into m different streams of basic rate and each is treated as an individual (effective) user, and assigned individual spreading codes of length F. Symbols in each stream are serial-to-parallel converted to P sub-streams and then being spread in time domain (direct-sequence spreading) by the

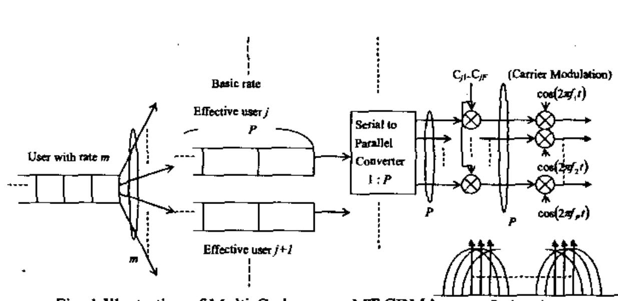


Fig. 1 Illustration of Multi-Code access MT-CDMA

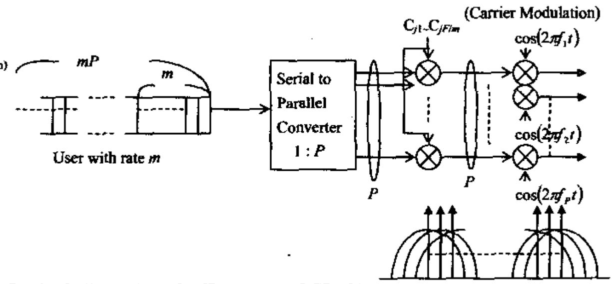


Fig. 2 Illustration of VSL access MT-CDMA

spreading codes assigned to this effective user. After correspondingly combining the spread signals from other effective users, they are transmitted in parallel by modulating P sub-carriers, where frequency spacing Δf between adjacent sub-carriers is $1/(PT_s)$. That is, the orthogonality only exists between symbols before spreading, and there are strong overlaps in spectrum. The transmitted signal of the user k with rate m is,

$$x_k(t)=\sum_{j=1}^{m}\sum_{p=1}^{P}A_k b_{jp}\sum_{f=1}^{F}c_{jf}\varphi(t-(f-1)T_c)e^{j2\pi(p-1)\Delta f t}, \qquad (1)$$

$0 \le t \le PT_s$, where b_{jp} is the pth symbol, $\{c_{jf}, f=1,2,\ldots,F\}$ is the assigned spreading codes of the jth effective user, and $\varphi(t)$ is the unit-rectangular function with duration T_c, where $T_c=(PT_s)/F$, $\Delta f=1/(PT_s)$, and totally P sub-carriers.

B. Variable-Spreading-Length Access

The data stream of a user with rate m is not multiplexed into basic-rate streams but directly serial-to-parallel converted to P sub-streams. Symbols at each sub-stream are then DS-spread by the spreading codes of length F/m assign to this user. The P parallel signals are transmitted by modulating P sub-carriers with frequency spacing $1/(PT_s)$. Regardless any date rate, no effective user multiplexing is performed and the length spreading codes is inversely proportional to the data rate, which keeps the number of sub-carriers and spectrum profile identical to MC access. The transmitted signal of the user k with rate m is:

$$x_k^{(m)}(t)=\sum_{p=1}^{Pm}A_k^{(m)}b_{kp}^{(m)}\sum_{f}^{F/m}c_{kf}^{(m)}\varphi\left(t-(f-1)T_c-\left(\left\lceil\frac{p}{P}\right\rceil-1\right)\frac{PT_s}{m}\right)e^{j2\pi((p-1)\bmod P+1)\Delta f t},$$

$$0 \le t \le PT_s, \qquad (2)$$

where $b_{kp}^{(m)}$ is the pth symbol and $A_k^{(m)}$ is the transmitted amplitude respectively, $T_c=(PT_s)/F$ and $\Delta f=1/(PT_s)$. $c_{kf}^{(m)}\in\{\pm 1\}$ denotes the fth bit of the assigned spreading codes.

It should be noticed that in our multi-rate Multi-Tone CDMA transmission, direct-sequence spread spectrum (DS-SS) is performed in priori to modulating orthogonal sub-carriers, which is contrary to conventional single rate MT-CDMA [4]. Since the chip rate is constant regardless MC access or VSL access, this exchange shows two major advantages: FFT-based modulation technique could be applied for digitally implementation with fixed spectrum profile upon various input data rates, the procedural consistency between MC and VSL increase the integerability for programmable design [5]

III. GENERAL SIGNAL MODEL FOR MULTI-RATE MT-CDMA

The complex formulation of VSL access in MT-CDMA due to various data rates is hard to handle and we make use of the concept of effective users for simplicity and further integrate it with MC access. A user with rate m can be decomposed as m effective users and the assigned spreading codes are expanded to m 'effective' spreading codes for each, where these effective users have the same code length and identical symbol durations after serial-to-parallel conversion. Fig. 3 illustrates the decomposition of effective users and expansion of spreading codes. VSL access resembles the MC access as multiple simultaneous effective users. By this way, the signal structure of MC access and VSL access MT-CDMA are identical and only the pattern of effective codes distinguishes them. Effective spreading codes of VSL access users contain zeros.

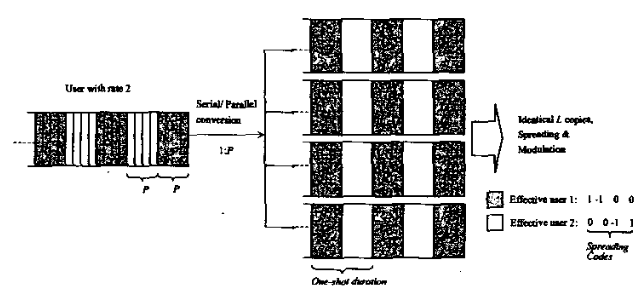


Fig. 3 Illustration of effective users in VSL access MT-CDMA systems.
A user of twice the basic rate with spreading codes 1 -1 is for example; Serial-to-parallel ratio $P=4$.

We consider the wireless channels frequency-selective fading with respect to the whole bandwidth. However, with

OFDM transmission we assume the signal at each sub-channel suffer from flat fading effective given enough number of sub-carriers are selected [3], which simplifies the study of multi-rate access of MT-CDMA without loss generality. Each sub-channel is modelled by a slow fading channel coefficient α_{kp}, denoting fading effect of the kth effective user over the pth sub-carrier of normalized expectation $E[|\alpha_{kp}|^2]=1$. With the re-defined notations b_{kp}, A_k, and $\{c_{kf}, f=1,2,\ldots,F\}$ for the kth effective user appropriately, the unified model of the received multi-rate MT-CDMA signal, regardless of MC or VSL access, is:

$$y(t)=\sum_{k=1}^{K}\sum_{p=1}^{P}A_k b_{kp}\sum_{f=1}^{F}c_{kf}\varphi(t-(f-1)T_c)\alpha_{kp}e^{j2\pi(p-1)\Delta ft}+n(t),\quad 0\le t\le PT_s \tag{3}$$

Let K_m denote the number of users with rate m, and there are totally $K=\sum_{m=1}^{M}mK_m$ effective users and P symbols for each within the considered "one-shot" duration in a system containing M different data rates. $n(t)$ is additive white Gaussian noise (AWGN) with power spectrum density $No/2$.

In each sub-carrier, there are involved ICI due to non-orthogonal spectrum overlapping, which could be treated as partial band interference and the dispreading operation with longer spreading codes could mitigate the effect. The match-filter bank corresponding to the signature waveforms of all effective users is used to span the signal space approximately [4] in the receiver, although they are no longer the complete bases since the chip-based waveforms are not orthogonal among sub-carriers. Actually, we further utilize the information contained in the ICI in our proposed MUD shown in the next section.

Focus on the pth sub-carrier, the output of the ith matched-filter with down-conversion is:

$$\begin{aligned}y_{pi}&=\int_0^{PT_s}y(t)S_i(t)e^{-j2\pi(p-1)\Delta ft}dt\\&=\sum_{k=1}^{K}A_k b_{kp}\alpha_{kp}\int_0^{PT_s}S_i(t)S_j(t)dt+\sum_{\substack{p'=1\\p\neq p'}}^{P}\sum_{k=1}^{K}A_k b_{kp'}\alpha_{kp'}\int_0^{PT_s}S_i(t)S_j(t)e^{j2\pi(p'-p)\Delta ft}dt\\&+\int_0^{PT_s}n(t)S_i(t)e^{-j2\pi(p-1)\Delta ft}dt,\end{aligned} \tag{4}$$

where the signature waveform of the ith effective user $S_i(t)\equiv\sum_{f=1}^{F}c_{if}\varphi(t-(f-1)T_c)$, and the second term is the inevitable ICI of MT-CDMA systems. Collect the outputs from the K matched filters, and we can form them as a vector:

$$\mathbf{y}_p=[y_{p1}y_{p2}\cdots y_{pK}]^T=\mathbf{R}\boldsymbol{\alpha}_p\mathbf{A}\mathbf{b}_p+\sum_{\substack{p'=1\\p'\neq p}}^{P}\boldsymbol{\eta}^{p'}\boldsymbol{\alpha}_{p'}\mathbf{A}\mathbf{b}_{p'}+\mathbf{n}_p \tag{5}$$

where $\mathbf{A}=diag(A_1A_2\cdots A_K)$, $\boldsymbol{\alpha}_p=diag(\alpha_{1p}\alpha_{2p}\cdots\alpha_{Kp})$, $\mathbf{R}$ and $\boldsymbol{\eta}^{p'}$ are respectively the correlation matrix and inter-carrier correlation matrix among signature waveforms of effective users. The dimensions of the two correlation matrices are $K\times K$ and their (ith, jth) element is defined as

$$R_{ij}=\int_0^{PT_s}S_i(t)S_j(t)dt=\sum_{f=1}^{F}c_{if}c_{jf} \tag{6}$$

and

$$\eta_{ij}^{p'}=\int_0^{PT_s}S_i(t)S_j(t)e^{j2\pi(p'-p)\Delta ft}dt=\sum_{f=1}^{F}c_{if}c_{jf}\varphi_{p'f}, \tag{7}$$

where $\varphi_{p'f}\equiv\int_{(f-1)T_c}^{fT_c}e^{j2\pi(p'-p)\Delta ft}dt$

Equation (5) is the uniform model for multi-rate MT-CDMA of both MC access and VSL access. The structure of $\mathbf{R}$ is the only obvious distinct between them, where $\mathbf{R}$ generally contains zero terms in VSL access. Since the ICI term is the accumulation of all effective users' signals over all other sub-carriers, it can be approximately modelled as Gaussian distribution with the increase of sub-carriers. Besides, the following MUD and even any other relative signal processing can be designed based on this model identically for the two access methods.

IV. TWO-STAGE DECORRELATING MUD

The optimal MUD of maximum-likelihood criterion [8] should observe signals at all sub-carriers due to the involved ICI, and a pre-whitening filter may be needed for establishing the ML detector because of the non-orthogonality. In addition, its complexity is exponentially increased with the number of total effective users. For practical application, we consider a suboptimal detector with lower complexity. The detector consists of two stages, where the first stage is prior decisions based on the bank of match-filters and the outputs are forwarded to the decorrelaing stage for final decisions. The detector structure is illustrated in Fig. 4. If the decisions of the first stage are precise enough, it greatly eliminates the ICI and enhances the performance of decorrelaing detection significantly.

Based on the outputs of match filters (5), the first-stage decisions on the all effective users at the pth sub-carrier are made by:

$$\hat{\mathbf{b}}_p^{(1)}=sign\{real(\boldsymbol{\alpha}_p^H\mathbf{y}_p)\} \tag{8}$$

With the existent channel information, spreading codes, and the first-stage results of all P sub-carriers, the signal to the second-stage is:

$$\left\{\mathbf{y}'_p=\mathbf{y}_p-\sum_{\substack{p'=1\\p'\neq p}}^{P}\boldsymbol{\eta}^{p'}\boldsymbol{\alpha}_{p'}\mathbf{A}\hat{\mathbf{b}}_{p'}^{(1)}\right\},p=1,2,\ldots,P \tag{9}$$

All the information required in (9) need not extra acquisition. Let $\mathbf{W}_p$ denote the second-stage decorrelating filter:

$$\mathbf{W}_p=inv(\mathbf{R}\boldsymbol{\alpha}_p\mathbf{A}) \tag{10}$$

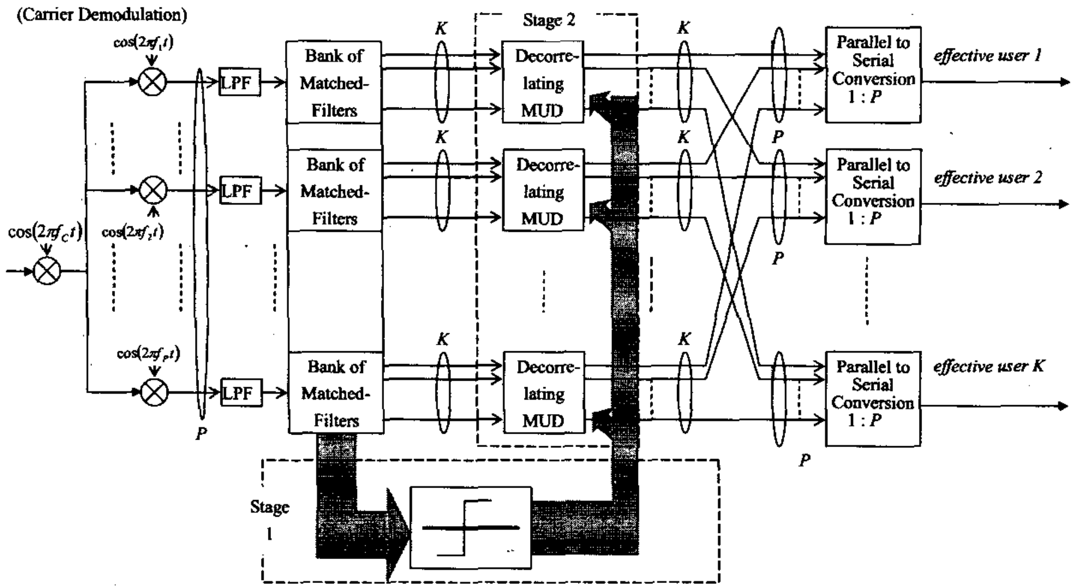


Fig. 3. Two-Stage multiuser receiver of Multi-rate MT-CDMA Systems

which yields the final decision variable

$$\tilde{\mathbf{b}}_p = \mathbf{W}_p\mathbf{y}_p = \mathbf{b}_p + 2\sum_{\substack{p'=1\\ p'\neq p}}^{P} \mathbf{W}_p \boldsymbol{\eta}^{p'} \boldsymbol{\alpha}_{p'} \mathbf{A}\boldsymbol{\varepsilon}_{p'} + \mathbf{W}_p\mathbf{n}_p \tag{11}$$

where $\boldsymbol{\varepsilon}_{p'}$ is defined as the error vector by $\boldsymbol{\varepsilon}_{p'} \equiv \frac{1}{2}\left(\mathbf{b}_{p'} - \hat{\mathbf{b}}_{p'}^{(1)}\right)$, and the decisions on all effective users are made by:

$$\hat{\mathbf{b}}_p = sign\left\{real\left(\tilde{\mathbf{b}}_p\right)\right\} \tag{12}$$

All detections are performed simultaneously on K effective users with respectively P symbols within the one-shot duration in either access method. The symbol decisions are de-multiplexed back to the original sequence of each real user. Deserved to be mentioned, the detection processing is the same in both MC access and VSL access, which is attributed to the uniform system model and appropriate for programmable adaptation to different system specifications. The performance bound of this two-stage MUD lies to the ultimate that the ICI terms are removed completely, where this bound of error rate is:

$$P_k = \int_{\alpha} Q\left(\frac{1}{\sqrt{No/2\,[\mathbf{W}\mathbf{R}\mathbf{W}^H]_{kk}}}\right) p(\boldsymbol{\alpha})d\boldsymbol{\alpha}, \tag{13}$$

where $(.)_{ij}$ denotes the (ith, jth) element of a matrix and $p(\boldsymbol{\alpha})$ is the probability density of the channels $\boldsymbol{\alpha}$.

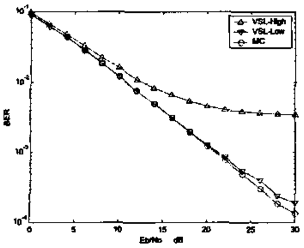
V. NUMERICAL SIMULATION

In this section, several examples are presented to show the properties of MC access and VSL access of multi-rate MT-CDMA, and compare their performance with the proposed two-stage decorrelaing MUD.

We simulated the cases over frequency-selective Rayleigh fading channels, and due to the strong spectrum overlapping, we assume the fading variables in adjacent sub-carriers are correlated with coefficient ρ and adopt auto-regressive (AR) model in frequency domain as:

$$\begin{cases} \alpha_{k(j+1)} = \dfrac{\sigma}{\sqrt{\sigma^2+\sigma_n^2}}\left(\alpha_{kj}+n\right) \\ \sigma_n^2 = \left(\dfrac{1-\rho^2}{\rho^2}\right)\sigma^2 \end{cases} \tag{14}$$

where $\sigma^2 = E[|\alpha_{kj}|^2], \sigma_n^2 = E[|n|^2]$ and n is white Gaussian noise. We first consider a two-data-rate system without loss of generality, where the data rate of the high-rate users is twice the low-rate (basic-rate) users. There are two users of each rate, which results in totally six effective users. In Fig. 4, it shows the performance of the two access methods with the two-stage MUD given equal energy per symbol E_b at ρ =0.9. The serial-to-parallel conversion ratio P is 32, and the spreading factor F of basic rate users is 256. In addition, Fig. 5 compares the 2-stage MUD in example of VSL access with the second-stage-only detection, which is indeed a pure decorrelaing MUD. The two figures show that in terms of detection performance, MC access is better than VSL access, especially for high-rate users. Compared with the decorrelaing-only MUD, two-stage operation significantly improves the performance and it is critical to VSL access.



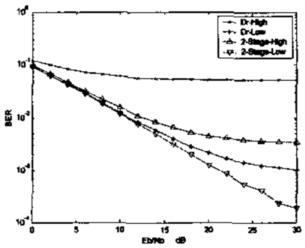


Fig. 4 Performance of Two-Stage MUD in multi-rate MT-CDMA Fig. 5 Two-Stage MUD vs. Decorrelating MUD in VSL MT-CDMA

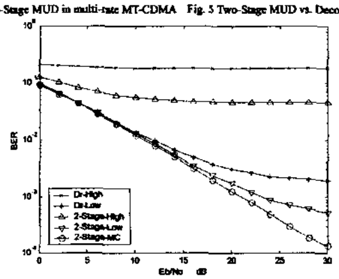


Fig.6 Performance of MUDs: 1 user with rate 4 & 2 basic-rate users

Furthermore, we consider another example where there are one user of rate 4 and two basic-ate users. There are still totally six effective users, and the spreading factors of basic-rate users and high-rate users are 256 and 64 respectively. Fig. 6 shows the 2-stage MUD performance in both access methods and the compared curves of the decorrelaing-only MUD in example of VSL access. With the increase of data rate, MC access gets better performance. The first-stage is indeed a SUD [4], and although the error floor of SUD restricts the precision of first-stage results, it shows that the performance of the decorreling detection is significantly improved, especially to VSL access. The length of spreading codes, in sum, dominates the system performance of multi-rate MT-CDMA due to server ICI, unlike the matter of diversity in multi-rate MC-CDMA [6].

VI. IMPLEMENTATION AND APPLICATION

From the previous section, the detection performance of MC access is better than VSL access, especially for high-rate users. Length of spreading codes dominates the results since the ICI is the major destruction under such highly efficient spectrum overlapping. The high-rate user is seriously degraded if only the decorrelaing stage is performed. This inherent limitation from interference makes MC-access comparatively appropriate to the applications of high fidelity, while VSL access, with less processing delay, is contrarily suitable to services of loose error rate requirement, such as voice applications. The high peak-to-average-power (PAP) ratio because of code multiplexing in MC access should be taken into consideration in practical utilizations.

In our transceiver design, the sub-carrier modulation and demodulation of multi-rate traffic can be efficiently implemented by IFFT/FFT [5]. Some parameters and numerical coefficients required for the two-stage detections could be stored in system memory, such as φ_{pf}, and then being acquired efficiently with other derived information to reduce the complexity of both hardware and algorithm. For system integration with the purpose on programmability, the function units of this transceiver structure are easily reused and co-designed with the decorrelaing receiver of multi-rate MC-DS-CDMA proposed in [7]. First-stage only or second-stage only detection can be adopted for different services of different nature and quality requirement. The further study turns to appropriate software control and data bus orientation.

VII. CONCLUSION

In this paper, we constructed a general model of multi-rate MT-CDMA system, which is uniform to MC access and VSL access. A two-stage decorrelaing MUD is proposed for multi-rate MT-CDMA based on this general model. The signal characteristic and detection behaviour are investigated, and MC access exhibit better performance than VSL access because of the high spectrum overlapping. With probable utilizations for various applications of different quality requirement, the implied programmability of this system structure is contributive to the evolution to software radio.

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