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PERFORMANCE OF MULTIBAND COMPLEX WAVELET BASED MULTICARRIER DS-CDMA SYSTEM WITH MULTI-ANTENNA RECEIVER OVER NAKAGAMI-m FADING CHANNEL

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Abstract—On the basis of analyzing the principle of multicarrier DS-CDMA, we propose a novel multiband complex wavelet based multicarrier DS-CDMA system in this paper by using the optimized multiband complex wavelet as multicarrier basis function. The system bit error rate (BER) performance is investigated over Nakagami-m fading channel. Without any cyclic prefix (CP), the proposed system can avoid the decrease of spectrum efficiency and data rate of conventional multicarrier DS-CDMA with CP. Meanwhile, the space diversity combining (SDC) technique based on multi-antenna receiver is employed to improve the system performance further. By the mathematical derivation, the BER analysis of the system with or without SDC is given in detail. Theoretical analysis and simulation results show that the proposed multicarrier system outperforms the conventional multicarrier DS-CDMA system and real wavelet packet based multicarrier DS-CDMA system due to the superior properties of the optimized multiband complex wavelet. Especially, the application of SDC technique can effectively improve the system ability against spatial fading and interferences, and thus the superior performance is obtained.

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1. INTRODUCTION

Recently, the multicarrier direct sequence code division multiple access (multicarrier DS-CDMA) technique based on the combination of conventional CDMA and OFDM (orthogonal frequency division multiplexing) technique has attracted great interests in both practical and theoretical studies of modern mobile communications due to its high spectral efficiency and high data rate transmission [1]. The multicarrier DS-CDMA technique exploits the spreading features of CDMA and high data rate parallel transmission of OFDM, it can implement frequency diversity, mitigation of delay spread and simpler receiver design in cellular environments [2, 3]. It will be a good candidate technology for the future wideband communications beyond 3G [4]. However, the conventional multicarrier DS-CDMA is implemented by means of IDFT and DFT operators. In its frequency spectrum, the main lobe doesn't concentrate energy effectively and side lobe attenuates slowly; the multipath fading or synchronization error will cause severe performance degradation due to the inter-channel interference (ICI), inter-symbol interference (ISI) and multi-access interference (MAI). Moreover, conventional multicarrier DS-CDMA often resorts to cyclic prefix (CP) to eliminate the ISI and maintain orthogonality between neighboring sub-carrier, which decreases the efficiency of spectrum utilization considerably in some communication scenarios. To search for an efficient multicarrier CDMA scheme, a number of improved multicarrier CDMA systems have been proposed. Among them, wavelet or wavelet packet based multicarrier DS-CDMA systems [5–7] attract some interests due to their better ability to combat ICI and ISI than conventional DFT based multicarrier DS-CDMA (DFT-MC-DS-CDMA) system. However, the performance of real wavelet system will be degraded in processing complex signal, and it can't adapt to complex channel well because of the spectrum characteristic of real wavelet. To overcome such a shortcoming, we present a class of multiband complex orthogonal wavelet through optimization in [8]. The optimized multiband complex wavelet not only has good properties that real wavelet packet possesses, such as shifting orthogonality, adaptability, time-frequency localization, etc., but also matches complex channel frequency spectrum well and suits multicarrier communications. Based on this, a multicarrier CDMA scheme based on the optimized multiband complex wavelet is developed in [8]. But the above scheme only gives the performance analysis in Rayleigh fading (a special case of Nakagami-m fading) channel. The scheme is limited in multicarrier CDMA scheme, and not suitable for multicarrier DS-CDMA scheme. For this, a novel multiband complex wavelet based multicarrier DS-CDMA (MBCW-MC-DS-CDMA) system is presented in this paper, and corresponding uplink performance of the system is investigated over Nakagami-m fading channel. Considering the uplink, we employ the multi-antenna receiver based space diversity combining (SDC) technique to effectively combat channel fading and various interferences, and thus the system performance will be enhanced greatly by the space diversity gain from SDC receiver. Moreover, the developed system has higher frequency band efficiency and data rate due to no need for CP when compared with conventional MC-DS-CDMA with CP.

2. MULTIBAND COMPLEX WAVELET BASED MULTICARRIER DS-CDMA SYSTEM

2.1. Multiband Complex Wavelet

Traditional real wavelet is designed for processing real-valued signals, and depends on the corresponding coefficients of wavelet filters. The real wavelet does not perform well when it processes complex signals or in the case of many sub-band wavelet transforms being adopted to transmit mobile communication signals [8]. To implement superior performance, on the constrained condition of shifting orthogonality, we have optimized the coefficients of wavelet prototype filters to minimize the stop-band energy of wavelet filters. By optimization, the complex wavelet prototype filters $\{f_p(l)\}$ are obtained, and then sub-band filters of multiband complex wavelet are formed by modulating the prototype filters to different frequency domain (i.e., $f_n(l) = f_p(l)\exp(-j2\pi(n-1)l/N)$, $n = 1, \ldots, N$.) [8]. Finally, the optimized multiband complex orthogonal wavelet is produced. The multiband complex wavelet functions have the following characteristics: The main lobe concentrates energy effectively and side lobe attenuates quickly; satisfying the shifting orthogonality; and their frequency responses occupy their own frequency bands and are not symmetric about the D.C. component. Thus the optimized multiband complex wavelet can match complex channel frequency spectrum and benefit multicarrier communications. More details on the optimized multiband complex orthogonal wavelet can be seen in [8].

2.2. MBCW-MC-DS-CDMA System

In this subsection, we develop a multicarrier DS-CDMA scheme based on the optimized multiband complex wavelet [8] and the modulation principle of multicarrier DS-CDMA [9] for the uplink, and conventional DFT/IDFT is replaced by multiband complex wavelet transform

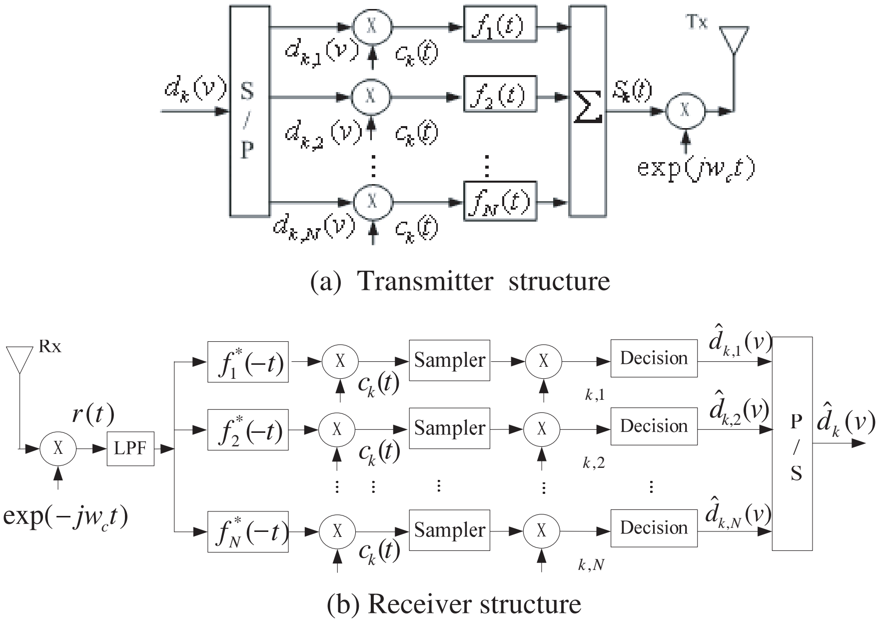

Figure 1. Block diagram of MBCW-MC-DS-CDMA system.

(MBCWT)/IMBCWT (inverse MBCWT) accordingly. Based on this scheme, we will investigate the system performance with multiple asynchronous CDMA users in Nakagami fading channel. Fig. 1 gives the principle diagrams of the developed MBCW-MC-DS-CDMA transmitter and receiver. At the transmitter, the multiband complex wavelet function $f_n(t)$ is taken as the signature waveform, and the shifting orthogonality among $f_n(t)$ $(n = 1, \ldots, N)$ can be given as $< f_n(t),\ f_m^*(t - uT_s) >= \delta(n - m)\delta(u)$ [8], where $<, >$ denotes the inner product, δ is Kronecker function, and superscript * represents the complex conjugate operation. The transmitted baseband signal of user k is written as

$$S_k(t) = \sum_{n=1}^{N} \sum_{v=-\infty}^{+\infty} \sum_{q=1}^{L} \sqrt{2E_c} d_{k,n}(v) c_k(q) f_n(t - vT - qT_c) \qquad (1)$$

where $k = 1, \ldots, K$, K is the number of active users; $d_k(v)$ corresponds to the QPSK complex signal, which denotes the vth data symbol of the kth user, and $\{d_k(v)\}$ are assumed to be independent, identically distributed $(i.i.d)$ taking values $\{\pm\sqrt{2}/2 \pm \sqrt{2}/2j\}$ with equal probability. $\{d_{k,n}(v),\ n = 1, \ldots, N\}$ are the subcarrier symbols after the data symbols $\{d_k(v)\}$ are performed Serial to Parallel (S/P) Conversion, N is the number of subcarriers. T_b is the symbols period.

$C_k = \{c_k(l),\ l = 1, \ldots, L\}$ represents the kth user's pseudo-random spreading code, the length of code, i.e., spread processing gain is equal to L; and the chip period T_c corresponds to the minimum orthogonal shifting defined in multiband complex wavelet. So the period of the subcarrier symbol $T = NT_b = LT_c$. E_c is the mean energy over a chip, and corresponding mean energy over a bit E_b is equal to LE_c.

3. PERFORMANCE ANALYSIS OF MULTIBAND COMPLEX WAVELET BASED MC-DS-CDMA SYSTEM

In this paper, we assume that the wireless channel from transmit antenna to receive antenna experience independent, slow time-varying frequency selective fading, whereas every subcarrier channel is considered to be flat and slow fading. So according to [10], the fading coefficients of nth subcarrier from transmit antenna to the receive antenna for user k can be repressed as

$$h_{k,n}(t) = \alpha_{k,n}\delta(t - \varepsilon_k) = \beta_{k,n} \exp(j\varphi_{k,n})\delta(t - \varepsilon_k) \tag{2}$$

where $\beta_{k,n}$ and $\varphi_{k,n}$ denote the amplitude and phase of $\alpha_{k,n}$, respectively. The fading amplitudes $\{\beta_{k,n}\}$ are *i.i.d* Nakagami-m random variables (r.v.s) with $E\{\beta_{k,n}^2\}=E\{|\alpha_{k,n}|^2\}= \Omega$, Ω is the average fading power. Phases $\{\varphi_{k,n}\}$ are *i.i.d* uniform variables in the interval $[0, 2\pi]$ for different k, n. For Nakagami distribution, the probability density function (pdf) of $\beta_{k,n}$ can be given by [10, 11]

$$p(\beta) = (2/\Gamma(m)) \, (m/\Omega)^m \, \beta^{2m-1} \exp\left(-m\beta^2/\Omega\right) \tag{3}$$

where $\Gamma(.)$ is the Gamma function [12] and $m \geq 1/2$ [10]. The Rayleigh distribution, which corresponds to $m = 1$, is a special case of Nakagami-m distribution.

At the receiver, after down-converting to baseband, the received signal can be written as

$$r(t) = \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{v=-\infty}^{+\infty}\sum_{q=1}^{L}\sqrt{2E_c}d_{k,n}(v)c_k(q)f_n(t-vT-qT_c-t_k-\varepsilon_k)\alpha_{k,n} + z(t) \tag{4}$$

where $z(t)$ is an AWGN noise term with zero-mean and variance N_0. Single-path delay ε_k is *i.i.d.* for different k and uniforms in $[0, T_c]$; and t_k is the time misalignment of user k with respect to the reference user at the receiver which is *i.i.d* for different k and uniforms in $[0, T]$.

Without loss of generality, let user 1 be the desired user and reference user whose t_1 is zero. After passing through lowpass filter (LPF) and corresponding multiband complex wavelet transform

(MBCWT, which is used for multicarrier demodulation) as well as despreading, by sampling and applying maximum ratio combining (MRC), the decision variable of the ith data symbol of the uth subcarrier at lth chip sampling interval can be given as $y_{1,u,l} = \int_{Tc} r(t) f_u^*(t - iT - lT_c - \varepsilon_1) c_1(l) \alpha_{1,u}^* dt$. Thus we can obtain the decision variable of the ith data symbol of the uth subcarrier as follows:

$$\begin{aligned}
Y_{1,u} &= \sum_{l=1}^{L} y_{1,u,l} \\
&= \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{v=-\infty}^{+\infty} \sum_{l=1}^{L} \int_{Tc} \sqrt{2E_c} d_{k,n}(v) f_n(t - vT - lT_c - t_k - \varepsilon_k) \\
&\quad f_u^*(t - iT - lT_c - \varepsilon_1) \alpha_{k,n} c_k(l) c_1(l) \alpha_{1,u}^* dt + w \\
&= \sum_{k=2}^{K} \sum_{n=1}^{N} \sum_{v=-\infty}^{+\infty} \sum_{l=1}^{L} \sqrt{2E_c} d_{k,n}(i - v) \alpha_{k,n} c_k(l) c_1(l) \alpha_{1,u}^* \\
&\quad R_f^{nu}(vT + \varepsilon_1 - t_k - \varepsilon_k) \\
&\quad + \sum_{n=1,\neq u}^{N} \sum_{v=-\infty}^{+\infty} \sum_{l=1}^{L} \sqrt{2E_c} d_{1,n}(i - v) \alpha_{1,n} c_1(l) c_1(l) \alpha_{1,u}^* R_f^{nu}(vT) \\
&\quad + \sum_{v=-\infty,\neq 0}^{+\infty} \sum_{l=1}^{L} \sqrt{2E_c} d_{1,u}(i - v) \beta_{1,u}^2 c_1^2(l) R_f^{uu}(vT) \\
&\quad + \sum_{l=1}^{L} \sqrt{2E_c} d_{1,u}(i) \beta_{1,u}^2 c_1^2(l) + w = I_1 + I_2 + I_3 + D + w \qquad (5)
\end{aligned}$$

where $\beta_{1,u}^2 = \alpha_{1,u} \alpha_{1,u}^*$, $R_f^{nu}(\tau) = \int_{Tc} f_n(t + \tau) f_u^*(t) dt$ represents the cross-correlation of the multiband complex wavelet, $w = \sum_{l=1}^{L} \int_{Tc} z(t) f_u^*(t - iT - lT_c - \varepsilon_1) c_1(l) \alpha_{1,u}^* dt$ is a Gaussian random variable with zero-mean and variance

$$\begin{aligned}
Var\{w\} &= E\{ww^*\} = \sum_{l'=1}^{L} \sum_{l=1}^{L} \int_{Tc} E\{z(t) z^*(t)\} c_1(l) c_1(l') \\
&\quad \beta_{1,u}^2 f_u^*(t - iT - lT_c - \varepsilon_1) f_u(t - iT - l'T_c - \varepsilon_1) dt \\
&= \sum_{l'=1}^{L} \sum_{l=1}^{L} c_1(l) c_1(l') N_0 \beta_{1,u}^2 R_f^{uu}\left((l - l')T_c\right) \qquad (6)
\end{aligned}$$

$$D = \sum_{l=1}^{L} \sqrt{2E_c} d_{1,u}(i) \beta_{1,u}^2 c_1^2(l) = \sqrt{2E_c} L d_{1,u}(i) \beta_{1,u}^2 \qquad (7)$$

is the desired output.

$I_1 = \sum_{k=2}^{K}\sum_{n=1}^{N}\sum_{v=-\infty}^{+\infty}\sum_{l=1}^{L}\sqrt{2E_c}d_{k,n}(i-v)\alpha_{k,n}c_k(l)c_1(l)R_f^{nu}(vT+\varepsilon_1-t_k-\varepsilon_k)\alpha_{1,u}^*$ is MAI from other user $k \neq 1$. It has zero mean due to the zero mean of $\alpha_{k,n}$.

$I_2 = \sum_{n=1,\neq u}^{N}\sum_{v=-\infty}^{+\infty}\sum_{l=1}^{L}\sqrt{2E_c}d_{1,n}(i-v)\alpha_{1,n}c_1(l)c_1(l)R_f^{nu}(vT)\alpha_{1,u}^*$ is the interference from other subcarrier and same user $k = 1$.

$I_3 = \sum_{v=-\infty,\neq 0}^{+\infty}\sum_{l=1}^{L}\sqrt{2E_c}d_{1,u}(i-v)\beta_{1,u}^2 c_1^2(l)R_f^{uu}(vT)$ is the inter-symbol interference from same subcarrier and same user $k = 1$.

According to [8], the cross-correlation functions of the optimized multiband complex wavelet satisfy the equation $R_f^{uv}(iT_c) = \delta(u-v)\delta(i)$ (which utilizes the shifting orthogonality of the multiband complex wavelet). Hence, we have the following equations

$$I_2 = I_3 = 0 \tag{8}$$

$$Y_{1,u} = D + I_1 + w. \tag{9}$$

and the variance of w in (6) becomes

$$Var(w) = LN_0\beta_{1,u}^2 \tag{10}$$

Considering that the number of subcarriers and users are generally large in practice, the interference from other users I_1 can be both approximated by a Gaussian random variable with zero-mean, and variance is

$$Var(I_1) \cong \sum\nolimits_{k=2}^{K}\sum\nolimits_{n=1}^{N} 2E_c\Omega X(k,n,u)\beta_{1,u}^2 \tag{11}$$

where $X(k,n,u) = E\{\sum_{v=-\infty}^{+\infty}|R_f^{nu}(vT+\varepsilon_1-t_k-\varepsilon_k)R_c^{k,1}|^2\}$, and $R_c^{k,1} = \sum_{l=1}^{L}c_k(l)c_1(l)$ represents the correlation between user k and user 1's spreading code.

Hence, utilizing (7), (10) and (11), we can evaluate the probability of bit error conditioned on $\{\beta_{1,u},\ u = 1,2,\ldots,N\}$ as follows

$$\begin{aligned} P(e|\{\beta_{1,u}\}) &= 0.5\text{erfc}\left\{\sqrt{0.5E\left\{|D|^2\right\}\big/[Var(I_1)+Var(w)]}\right\} \\ &\cong 0.5\text{erfc}\left\{\sqrt{E_cL^2\lambda_u\Big/\left[\sum\nolimits_{k=2}^{K}\sum\nolimits_{n=1}^{N}2E_c\Omega X(k,n,u)+LN_0\right]}\right\} \\ &= P(e|\lambda_u) \end{aligned} \tag{12}$$

where erfc$(\cdot)$ is a complementary error function [12], $\lambda_u = \beta_{1,u}^2$. Considering that $\beta_{1,u}$ is fading amplitude, it is a Nakagami distributed variable with second moment Ω. From [11], we know that a Nakagami random variable with integer parameter m can be modeled as the square root of the sum of squares m independent Rayleigh variables. Thus we have $\lambda_u = \sum_{a=1}^{m} (\beta_{1,u}^{(a)})^2$, where $\{\beta_{1,u}^{(a)}\}$ are m independent Rayleigh variables with $E\{(\beta_{1,n}^{(a)})^2\} = \Omega/m$. According to the relation of Rayleigh distribution and *chi-square* distribution, the variable λ_u can be a *chi-square* distribution with $2m$ degrees of freedom. From Eq. (2-1-110) in [10], the probability density function of λ_u is given by

$$p_{\lambda_u}(\lambda) = \left[(m/\Omega)^m / \Gamma(m)\right] \lambda^{m-1} \exp(-m\lambda/\Omega) \tag{13}$$

For non-integer m, using (3) and transformation of random variable, we can also evaluate the probability density function of λ_u, which is the same as (13). Then the average *BER* is obtained via averaging (12) over $\{\lambda_u\}$ by means of (13).

4. PERFORMANCE OF MBCW-MC-DS-CDMA SYSTEM WITH MULTI-ANTENNA RECIVER BASED SPACE DIVERSITY COMBINING

The space diversity combining technique based on multiple antenna receiver can add reliability effectively via obtaining multiple receiver chains. Should one of the receive chains fail, and the other receive chain is operational, and then the performance loss is on the order of the diversity gain. In other words, the signal may still be detected, but with inferior quality [13, 14]. Considering the uplink, multiple antennas that are spatially uncorrelated are placed at the base station (BS) to effectively estimate the transmitted data for each user. Thus, the SDC technique can be employed in the proposed system to reject the involved various interferences and deep fading efficiently by achieving both spatial and temporal signal processing as well as diversity gains [15, 16].

Let M be the number of receive antenna, and sufficient space separation between different antennas is supposed to obtain independent M receive chains. Then the received signals from each receive antenna is uncorrelated. Based on this, we assume that the wireless channel from transmit antenna to each receive antenna experience independent, slow time-varying frequency selective fading, whereas each subcarrier channel is considered to be flat and slow fading. So the fading coefficients of the nth subcarrier from transmit antenna to the receive antenna s for user k can be expressed as $\alpha_{k,n,s} =$

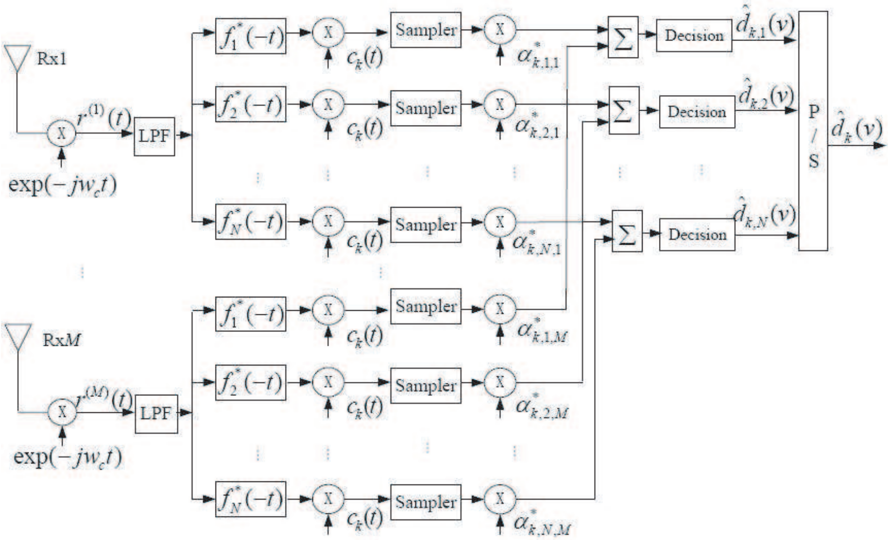

Figure 2. Receiver block diagram of MBCW-MC-DS-CDMA system with SDC technique.

$\beta_{k,n,s}\exp(j\varphi_{k,n,s})$, the fading amplitudes $\{\beta_{k,n,s}\}$ are *i.i.d.* Nakagami random variable and phases $\{\varphi_{k,n,s}\}$ are *i.i.d.* uniform variable in the interval $[0, 2\pi]$ for different s, k, n. The transmitter structure of MBCW-MC-DS-CDMA system with SDC refers to Fig. 1(a), and the receiver structure is illustrated in Fig. 2. At the transmitter, the transmitted baseband signal of user k is written as Eq. (1). At the receiver, after down-converting to baseband, the received signal from receive antenna s (Rxs) can be given by

$$r^{(s)}(t) = \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{v=-\infty}^{+\infty}\sum_{q=1}^{L}\sqrt{2E_c}d_{k,n}(v)c_k(q)f_n(t-vT-qT_c-t_k-\varepsilon_k)$$
$$\alpha_{k,n,s}+z^{(s)}(t), \quad s=1,\ldots,M. \tag{14}$$

where $z^{(s)}(t)$, $s = 1,\ldots,M$ is AWGN noise term for the sth receive antenna, and $\{z^{(s)}(t)\}$ are independent complex Gaussian random variables with zero-mean and variance N_0.

Without loss of generality, let user 1 be the desired user and reference user whose t_1 is zero. After passing through LPF, corresponding multiband complex wavelet transform and despreading, by sampling and applying MRC based SDC technique, the decision variable of the ith data symbol of the uth subcarrier can be given as

$$Y_{1,u} = \sum_{s=1}^{M}\sum_{l=1}^{L}\int_{Tc} r^{(s)}(t)f_u^*(t-iT-lT_c-\varepsilon_1)c_1(l)\alpha_{1,u,s}^*dt$$

$$=\sum_{s=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{v=-\infty}^{+\infty}\sum_{l=1}^{L}\sqrt{2E_c}d_{k,n}(i-v)\alpha_{k,n,s}c_k(l)c_1(l)\alpha_{1,u,s}^* R_f^{nu}(vT+\varepsilon_1-t_k-\varepsilon_k)$$
$$+\sum_{s=1}^{M}\sum_{l=1}^{L}\int_{Tc} z^{(s)}(t)f_u^*(t-iT-lT_c-\varepsilon_1)c_1(l)\alpha_{1,u,s}^*dt$$

$$=\sum_{s=1}^{M}\sum_{k=2}^{K}\sum_{n=1}^{N}\sum_{v=-\infty}^{+\infty}\sum_{l=1}^{L}\sqrt{2E_c}d_{k,n}(i-v)\alpha_{k,n,s}c_k(l)c_1(l)\alpha_{1,u,s}^* R_f^{nu}(vT+\varepsilon_1-t_k-\varepsilon_k)$$
$$+\sum_{s=1}^{M}\sum_{n=1,\neq u}^{N}\sum_{v=-\infty}^{+\infty}\sum_{l=1}^{L}\sqrt{2E_c}d_{1,n}(i-v)\alpha_{1,n,s}c_1(l)c_1(l)\alpha_{1,u,s}^*R_f^{nu}(vT)$$
$$+\sum_{s=1}^{M}\sum_{v=-\infty,\neq 0}^{+\infty}\sum_{l=1}^{L}\sqrt{2E_c}d_{1,u}(i-v)\beta_{1,u,s}^2c_1^2(l)R_f^{uu}(vT)$$
$$+\sum_{s=1}^{M}\sum_{l=1}^{L}\sqrt{2E_c}d_{1,u}(i)\beta_{1,u,s}^2c_1^2(l)+\tilde{w}$$
$$=\tilde{I}_1+\tilde{I}_2+\tilde{I}_3+\tilde{D}+\tilde{w} \tag{15}$$

where $\tilde{w}=\sum_{l=1}^{L}\int_{Tc}\sum_{s=1}^{M}(z^{(s)}(t)\alpha_{1,u,s}^*)c_1(l)f_u^*(t-iT-lT_c-\varepsilon_1)dt$, it is a Gaussian r.v.s with zero mean and variance $LN_0\sum_{s=1}^{M}\beta_{1,u,s}^2$. The three interference terms $\tilde{I}_1$, $\tilde{I}_2$ and $\tilde{I}_3$ are defined as in Section 3. Similarly, $\tilde{I}_2$ and $\tilde{I}_3$ will be equal to zero because of the cross-correlation property of the optimized multiband complex wavelet. The multiple access interference $\tilde{I}_1$ is

$$\tilde{I}_1 = \sum_{k=2}^{K}\sum_{n=1}^{N}\sum_{v=-\infty}^{+\infty}\sum_{l=1}^{L}\sum_{s=1}^{M}\sqrt{2E_c}d_{k,n}(i-v)\alpha_{k,n,s}\alpha_{1,u,s}^*c_k(l)c_1(l) R_f^{nu}(vT+\varepsilon_1-t_k-\varepsilon_k) \tag{16}$$

According to the theoretical analysis in Section 3, the variance of

$\tilde{I}_1$ can be approximately evaluated by

$$Var\left(\tilde{I}_1\right) \cong \sum\nolimits_{k=2}^{K} \sum\nolimits_{n=1}^{N} 2E_c \Omega X(k,n,u) \sum\nolimits_{s=1}^{M} \beta_{1,u,s}^2 \tag{17}$$

The desired signal $\tilde{D} = \sqrt{2E_c} L d_{1,u}(i) \sum_{s=1}^{M} \beta_{1,u,s}^2$, it may obtain M spatial diversity order when compared with D in (7). Hence, by introducing the SDC technique, MBCW-MC-DS-CDMA system will obtain more spatial diversity gain, and thus the performance will be greatly improved.

Using (15) and the variance of noise $\tilde{w}$ as well as the desired value $\tilde{D}$, the probability of bit error conditioned on $\{\beta_{1,u,s},\ u = 1, 2, \ldots, N,\ s = 1, 2, \ldots, M\}$ can be given by

$$\begin{aligned} P(e|\{\beta_{1,u,s}\}) &= 0.5\text{erfc}\left\{ \sqrt{0.5E\left\{\left|\tilde{D}\right|^2\right\} \Big/ \left[Var(\tilde{I}_1) + Var(\tilde{w})\right]} \right\} \\ &\cong 0.5\text{erfc}\left\{ \sqrt{E_c L^2 \tilde{\lambda}_u^2 \Big/ \left[\sum\nolimits_{k=2}^{K} \sum\nolimits_{n=1}^{N} 2E_c \Omega X(k,n,u) \tilde{\lambda}_u + \tilde{\lambda}_u L N_0\right]} \right\} \\ &= 0.5\text{erfc}\left\{ \sqrt{E_c L^2 \tilde{\lambda}_u \Big/ \left[\sum\nolimits_{k=2}^{K} \sum\nolimits_{n=1}^{N} 2E_c \Omega X(k,n,u) + L N_0\right]} \right\} \end{aligned} \tag{18}$$

where $\tilde{\lambda}_u = \sum_{s=1}^{M} \beta_{1,u,s}^2$, the probability density function of $\tilde{\lambda}_u$ is given by

$$p_{\tilde{\lambda}_u}(\lambda) = \left[(m/\Omega)^{mM} / \Gamma(mM)\right] \lambda^{mM-1} \exp(-m\lambda/\Omega) \tag{19}$$

Finally, the BER is obtained via averaging (18) over $\{\lambda_u\}$ by means of (19).

Based on the above analysis, the high diversity gain can be obtained by using multi-antenna receiver. Moreover, in the uplink, space diversity combining has many advantages, such as easy implementation and free selection the number of antenna as well as no extra power and bandwidth need, etc., which will perfect the uplink performance of the proposed system effectively.

5. SIMULATION RESULTS

In this section, we will evaluate the uplink performance of the MBCW-MC-DS-CDMA system as well as MBCW-MC-DS-CDMA system with SDC technique over Nakagami-m fading channel by means of computer simulation. For this fading channel, the related parameters set are based on the channel model A of pedestrian situation defined by ITU-R M.1225 [17]. It is assumed that different subcarriers experience independent slow fading. The MRC with M receive antennas is adopted for SDC at the receiver. QPSK is employed for information bits modulation scheme, the carrier frequency $f_c = 2\,\text{GHz}$, the mobile velocity $v = 20\,\text{km/h}$, sampling frequency $f_s = 3.84\,\text{MHz}$, and the bit rate $R_s = 384\,\text{kbit/s}$. $K = 8$, 16-band optimized complex wavelet [8] and real-valued Daubechies wavelet packet from 4-level binary wavelet packet tree [18] are considered in Figs. 3 and 4, while $K = 16$, 32-

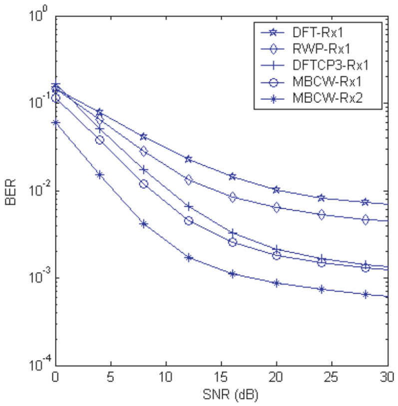

Figure 3. BER against SNR for different multicarrier systems ($m = 1$).

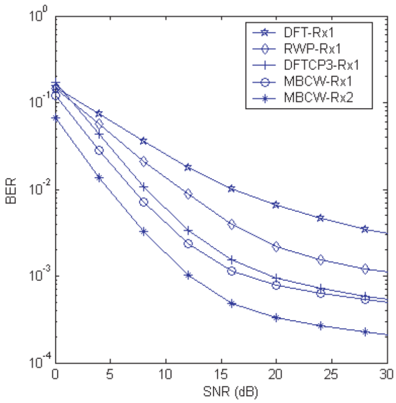

Figure 4. BER against SNR for different multicarrier systems ($m = 2$).

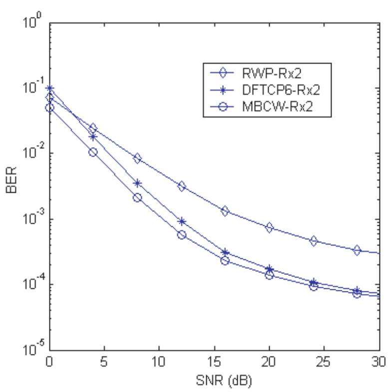

Figure 5. BER against SNR for different multicarrier systems with two receive antenna ($m = 2$).

band optimized complex wavelet and corresponding real-valued wavelet packet are compared in Fig. 5. PN code is used for spreading code. In simulation, we assume that the receiver has a perfect knowledge of channel. The simulation results are shown in Figs. 3, 4 and 5, respectively. In these figures, "DFTRx1" and "RWPRx1" represent the conventional MC-DS-CDMA system, real wavelet packet based MC-DS-CDMA (RWP-MC-DS-CDMA) system with single receive antenna, respectively. "MBCWRx1"and "MBCWRx2" denote the proposed MBCW-MC-DS-CDMA system with one and two receive antennas, respectively.

In Fig. 3, we give the average bit error rate as a function of SNR (E_b/N_0) under the condition that N is equal to 16, where fading parameter m is set equal to 1, one and two receive antenna are considered for different multicarrier systems. It is shown in Fig. 3 that the performance of MBCW-MC-DS-CDMA outperforms that of conventional DFT based MC-DS-CDMA systems and that of RWP-MC-DS-CDMA system, and is slightly superior to that of DFT based MC-DS-CDMA system with CP, where 'CPx' denote x cyclic prefix symbols are inserted. Especially, MBCW-MC-DS-CDMA with SDC technique can improve the BER performance significantly, at BER $=10^{-2}$, 2-antenna system can achieve 3 dB gains over single antenna system. Hence, with the number of receive antennas increasing, the proposed system with SDC will obtain more spatial diversity gains, thus it has stronger ability to combat fading and obtains lower BER.

In Fig. 4, we give the average bit error rate as a function of SNR (E_b/N_0) for different multicarrier DS-CDMA systems, where $N = 16$, and $m = 2$, one and two receive antenna are considered. From this figure, we can observe similar results as shown in Fig. 3. Namely, when the value of m becomes big, the performance of MBCW-MC-DS-CDMA still performs better than that of conventional DFT-MC-DS-CDMA and that of RWP-MC-DS-CDMA, and is slightly superior to that of DFT-MC-DS-CDMA with CP. Moreover, the application of SDC technique is also valid for improving the system performance, that is, the MBCW-MC-DS-CDMA with SDC is obviously superior to the other comparative multicarrier DS-CDMA systems. Besides, comparing the results of Figs. 3 and 4, we can see that the bigger the value of m, the lower the average BER is. Namely, the average BER under $m = 2$ case is lower than that under $m = 1$ case, the reason is that the fading severity decreases as the Nakagami parameter m increases. The above result show the presented system is effective, and the obtained results are reasonable. Besides, for high SNR, the interference from different users (i.e., corresponding to MAI) will become the dominate factor to affect the performance. Whereas MAI is not suppressed completely due to the asynchronization of active users in the uplink, thus the BER curve will have error floors at high SNR (which can be seen in Fig. 3 and following Fig. 5 as well). Despite all this, the application of SDC still effectively decreases the MAI to a certain extent, i.e., the multiple antenna system has much lower BER than the single antenna system at high SNR.

To further comparison, we also give the average bit error rate as a function of SNR (E_b/N_0) under the condition that N equals 32 in Fig. 5, where m is set equal to 2, and the comparative multicarrier DS-CDMA systems all employ the 2-antenna SDC technique. From Fig. 5, it is found that the proposed MBCW-MC-DS-CDMA system with SDC has superior performance; it obtains much lower BER than RWP-MC-DS-CDMA system with SDC. Moreover, at low SNR, the DFT-MC-DS-CDMA with CP and SDC is worse than our proposed scheme due to high noise interference and energy reduction of CP insertion, and at high SNR, our scheme still achieves almost the same BER performance as the DFT-MC-DS-CDMA with CP because of the superior characteristic of multiband complex wavelet although multipath channel may influence the orthogonality of subcarriers. All these results show that the MBCW-MC-DS-CDMA system with SDC can greatly improve the BER performance in the uplink. Furthermore, the presented system has much higher spectrum efficiency and data rate due to no need for CP.

In addition, we notice that our simulation is performed over Nakagami fading channel based on pedestrian-A channel model, it is a multipath fading channel, the channel model can be thought as nearly single path fading channel composed of one strong fading path and three weak paths. So the interferences from these weak paths, i.e., multipath interferences are weak, thus they produce less influence on orthogonality of multiband complex wavelet. Furthermore, our scheme is also not sensitive to these weak interferences due to the superior properties of the optimized multiband complex wavelet, and has strong ability and robustness against weak interferences. However, the orthogonality of multiband complex wavelet will not be guaranteed when multipath interferences are strong. For this, in future work, we will further study the uplink performance of the proposed system over multipath Nakagami fading channels.

6. CONCLUSION

On the basis of analyzing the principle of multicarrier DS-CDMA technology, utilizing the optimized multiband complex wavelet as multicarrier basis function, we have presented a multicarrier DS-

CDMA system based on multiband complex wavelet in this paper. The system uplink performance is investigated over Nakagami-m fading channel, and corresponding performance analysis and average BER derivation are given in detail, respectively. The system avoids the loss of spectrum efficiency of conventional MC-DS-CDMA due to inserting CP, and its performance is close or superior to that of conventional MC-DS-CDMA with CP. So the spectrum efficiency and system performance are obviously increased. Moreover, the application of SDC technique improves the ability against channel fading effectively and perfects the uplink performance further. Simulation results show that the proposed system performs better than conventional MC-DS-CDMA system and RWP-MC-DS-CDMA system because of its superior ability against interference. Furthermore, MBCW-MC-DS-CDMA system with SDC has superior performance; it outperforms RWP-MC-DS-CDMA system with SDC, and is slightly superior to DFT-MC-DS-CDMA system with CP and SDC.

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