

Uplink Performance of Multiband Complex Wavelet Based Multicarrier DS-CDMA System in Fading Channel

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Abstract—On the basis of analyzing the principle of multicarrier DS-CDMA (MC-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 fading channel. Without any cyclic prefix (CP), the proposed system can avoid the decrease of spectrum efficiency and data rate of conventional MC-DS-CDMA with CP. Consider the uplink, the space diversity combining (SDC) technique based multi-antenna receiver is employed to improve the system performance further. Theoretical analysis and simulation results show that the proposed multicarrier system outperforms the conventional MC-DS-CDMA system and real wavelet packet based MC-DS-CDMA system. Especially, the application of SDC technique can effectively improve the system ability against spatial fading and various interferences, and thus lower BER is obtained.

Keywords- Multiband complex wavelet; multicarrier DS-CDMA; space-diversity combining; OFDM; wavelet packet

I. INTRODUCTION

Recently, the multicarrier direct sequence code division multiple access (multicarrier DS-CDMA) technique based on the combination of conventional CDMA and OFDM 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]. It will be a good candidate technology for the future wideband communications beyond 3G [1]. 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, the 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 packet based multicarrier DS-CDMA [3] and wavelet based multicarrier DS-CDMA [4] 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 due to the spectrum characteristic of real wavelet. For this, we present a class of multiband complex wavelet via optimization in [5]. 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 [5]. But the above scheme only gives the performance analysis in Rayleigh fading channel. The scheme is limited in multicarrier CDMA scheme, and not suitable for multicarrier DS-CDMA scheme. For this, a 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 fading channel. Considering that the base station (BS) can perform multi-antenna receiver in the uplink, we use the space diversity combining (SDC) technique to effectively cope with channel fading and various interferences. Thus the proposed system performance is enhanced further. 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.

II. UPLINK PERFORMANCE OF MULTIBAND COMPLEX WAVELET BASED MC-DS-CDMA SYSTEM

A. System model

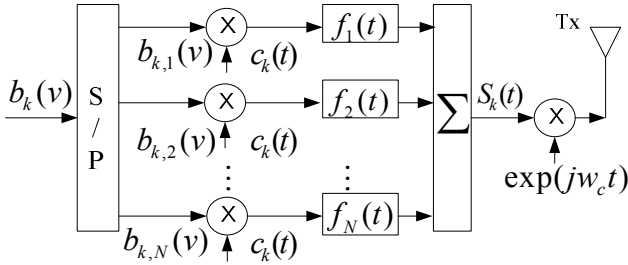
In this section, we develop a multicarrier DS-CDMA scheme based on the optimized multiband complex wavelet [5] and the modulation principle of multicarrier DS-CDMA [2] for uplink, and conventional DFT/IDFT is replaced by multiband complex wavelet transform (MBCWT)/ $\hat{M}MBCWT$ (inverse MBCWT) accordingly. Based on this scheme, we will investigate the system performance with K asynchronous CDMA users (K is the number of active 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

This work is supported by the open research fund of National Mobile Communications Research Laboratory, Southeast University (Grant No. N200904) and startup fund of NUAU (S0855-041).

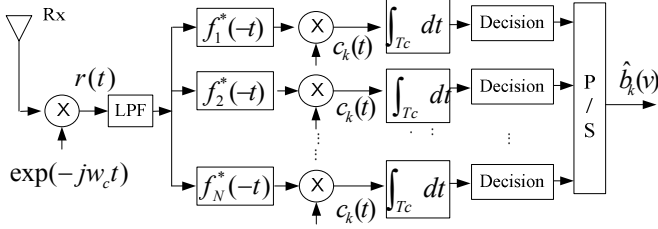
$f_n(t)$ is taken as the signature waveform, and the shifting orthogonality among $f_n(t)$ ($n=1, \dots, N$) can be given as $\langle f_m(t), f_n^*(t-uT_s) \rangle = \delta(n-m)\delta(u)$ [5], where $\langle \cdot, \cdot \rangle$ denotes the inner product, δ is Kronecker function, and superscript * represents the complex conjugate operation. The transmitted baseband signal of user k is written as

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

where $b_k(v)$ corresponds to the QPSK complex signal, which denotes the v th data symbol of the k th user (where $k=1, \dots, K$), and $\{b_k(v)\}$ are assumed to be independent, identically distributed (*i.i.d.*) taking values $\{\pm 2^{-1/2} \pm j2^{-1/2}\}$ with equal probability. T_b is the symbols period. $C_k = \{c_k(q), q=1, \dots, L\}$ represents the k th user 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; E_c is the mean energy over a chip. So the period of the subcarrier symbol $T = NT_b = LT_c$, N is the number of subcarriers.



(a) Transmitter structure



(b) Receiver structure

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

B. Performance analysis

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 [6], the fading coefficients of n th subcarrier from transmitter antenna to the receiver antenna for user k can be repressed as

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

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 [6-7]

$$p(\beta) = (2/\Gamma(m))(m/\Omega)^m \beta^{2m-1} \exp(-m\beta^2/\Omega) \quad (3)$$

where $\Gamma(\cdot)$ is the Gamma function and $m \geq 1/2$ [6-7]. 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

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

where $z(t)$ is AWGN noise terms with zero-mean and variance σ^2 . 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 user1 be the desired user and reference user whose t_1 is zero. After passing through lowpass filter (LPF) and the multiband complex wavelet transform (which is used for multicarrier demodulation) as well as despreading, the decision variable of the i th data symbol of u th subcarrier can be given by

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

where $R_f^{nu}(\tau) = \int_{T_c} f_n(t + \tau) f_u^*(t) dt$ represents the cross-correlation of the multiband complex wavelets,

$w = \sum_{l=1}^L \int_{T_c} z(t) c_1(l) f_u^*(t - iT - lT_c - \varepsilon_1) dt$ is a Gaussian random variable with zero-mean and variance $Var\{w\} = E\{ww^*\} = L\sigma^2$, $D = \sum_{l=1}^L \sqrt{2E_c} b_{1,u}(i) \alpha_{1,u} c_1^2(l) = \sqrt{2E_c} L b_{1,u}(i) \alpha_{1,u}$ is the desired

output. After making compensation for channel phase, D is changed as $D = \sqrt{2E_c} L b_{1,u}(i) \beta_{1,u}$.

$$I_1 = \sum_{k=2}^K \sum_{n=1}^N \sum_{v=-\infty}^{+\infty} \sum_{l=1}^L \sqrt{2E_c} b_{k,n}(i-v) \alpha_{k,n} c_k(l) c_1(l) R_f^{nu}(vT + \varepsilon_1 - t_k - \varepsilon_k)$$

is MAI from other user $k \neq 1$.

$$I_2 = \sum_{n=1, n \neq u}^N \sum_{v=-\infty}^{+\infty} \sum_{l=1}^L \sqrt{2E_c} b_{1,n}(i-v) \alpha_{1,n} c_1(l) c_1(l) R_f^{nu}(vT)$$

is the interference from other sub-carrier and same user $k=1$.

$$I_3 = \sum_{v=-\infty, v \neq 0}^{+\infty} \sum_{l=1}^L \sqrt{2E_c} b_{1,u}(i-v) \alpha_{1,u} c_1^2(l) R_f^{uu}(vT)$$

is the inter-symbol interference from same sub-carrier and same user $k=1$.

Obviously, the above three interference (i.e., I_1 , I_2 and I_3) have zero mean due to the zero mean of $\alpha_{k,n}$.

According to [5], the cross-correlation functions of the optimized multiband complex wavelet satisfy the equation $R_f^{uv}(iT_c) = \delta(u-v)\delta(i)$. Hence, we have:

$$I_2 = I_3 = 0; \quad Y_{1,u} = D + I_1 + w. \quad (6)$$

Considering that the number of sub-carriers 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

$$Var(I_1) \cong \sum_{k=2}^K \sum_{n=1}^N 2E_c \Omega F(k, i, n, u) \quad (7)$$

where

$$F(k, i, n, u) = E \left\{ \left[\sum_{v=-\infty}^{+\infty} b_{k,n}(i-v) R_c^{k,1} R_f^{nu}(vT + \varepsilon_1 - t_k - \varepsilon_k) \right]^2 \right\} \quad \text{and}$$

$R_c^{k,1} = \sum_{l=1}^L c_k(l) c_1(l)$ represents the correlation between user k and user 1's spreading code.

Therefore, the probability of bit error conditioned on $\{\beta_{1,u}, u=1, 2, \dots, N\}$ can be given by

$$\begin{aligned} P(e | \{\beta_{1,u}\}) &= 0.5 \operatorname{erfc} \left\{ \sqrt{E\{|D|^2\} / [2(Var(I_1) + Var(w))]} \right\} \\ &\cong 0.5 \operatorname{erfc} \left\{ \sqrt{E_c L^2 \lambda_u / \left[\sum_{k=2}^K \sum_{n=1}^N 2E_c \Omega F(k, i, n, u) + L\sigma^2 \right]} \right\} \\ &= P(e | \lambda_u) \end{aligned} \quad (8)$$

where $\lambda_u = \beta_{1,u}^2$, considering that $\beta_{1,u}$ is fading amplitude, it is Nakagami distributed variable with second moment Ω . From [7], 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 $E\{(\beta_{1,u}^{(a)})^2\} = \Omega/m$. 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 [6], the probability density function of λ_u is given by

$$p(\lambda_u) = \left[(m/\Omega)^m / \Gamma(m) \right] \lambda_u^{m-1} \exp(-m\lambda_u / \Omega) \quad (9)$$

Then the average BER is obtained via averaging (8) over $\{\lambda_u\}$ by means of (9).

III. MBCW-MC-DS-CDMA SYSTEM WITH SPACE DIVERSITY COMBINING

Considering in 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 [8-9]. 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. After these signals are combined effectively by maximum ratio combining (MRC) method at the receiver, the following various signals can be achieved. The desired signals D become

$$D = \sqrt{2E_c} L b_{1,u}(i) \sum_{a=1}^M \beta_{1,u,a}^2 \quad \text{and noise signal } w \text{ becomes}$$

$$w = \sum_{l=1}^L \int_{T_c} \sum_{a=1}^M (z_a(t) \alpha_{1,u,a}^* \mathcal{X}_1(l) f_u^*(t - iT - lT_c - \varepsilon_1)) dt, \quad \text{it is a}$$

Gaussian *r.v.s* with zero mean and variance $L\sigma^2 \sum_{a=1}^M \beta_{1,u,a}^2$.

Correspondingly, the MAI signal I_1 is changed into

$$\begin{aligned} I_1 &= \sum_{k=2}^K \sum_{n=1}^N \sum_{v=-\infty}^{+\infty} \sum_{l=1}^L \sum_{a=1}^M \sqrt{2E_c} b_{k,n}(i-v) \alpha_{k,n,a} \alpha_{1,u,a}^* \\ &\quad \times c_k(l) c_1(l) R_f^{nu}(vT + \varepsilon_1 - t_k - \varepsilon_k) \end{aligned} \quad (10)$$

The variance of I_1 can be approximately evaluated by

$$Var(I_1) \cong \sum_{k=2}^K \sum_{n=1}^N 2E_c \Omega F(k, i, n, u) \sum_{a=1}^M \beta_{1,u,a}^2 \quad (11)$$

Then, based on the performance analysis in subsection II-B, we can obtain the probability of bit error conditioned on $\{\beta_{1,u,a}, u=1, 2, \dots, N, a=1, 2, \dots, M\}$ as follows

$$\begin{aligned} P(e | \{\beta_{1,u,a}\}) &= 0.5 \operatorname{erfc} \left\{ \sqrt{E\{|D|^2\} / [2(Var(I_1) + Var(w))]} \right\} \\ &= 0.5 \operatorname{erfc} \left\{ \sqrt{E_c L^2 \lambda_u / \left[\sum_{k=2}^K \sum_{n=1}^N 2E_c \Omega F(k, i, n, u) + L\sigma^2 \right]} \right\} \end{aligned} \quad (12)$$

where $\lambda_u = \sum_{a=1}^M \beta_{1,u,a}^2$, using the probability density function of λ_u and (12), the BER of the system can be obtained. By comparing the signal-to-interference-plus-noise-ratio (SINR) in (8) and (12), it is found that the SINR in (12) may be approximately M times as the SINR in (8), thus M diversity degree will be attained.

Therefore, by employing multi-antenna receiver, the high diversity gain can be obtained. The transmitter structure of MBCW-MC-DS-CDMA system with SDC refers to Fig.1 (a), and the receiver structure is shown in Fig.2.

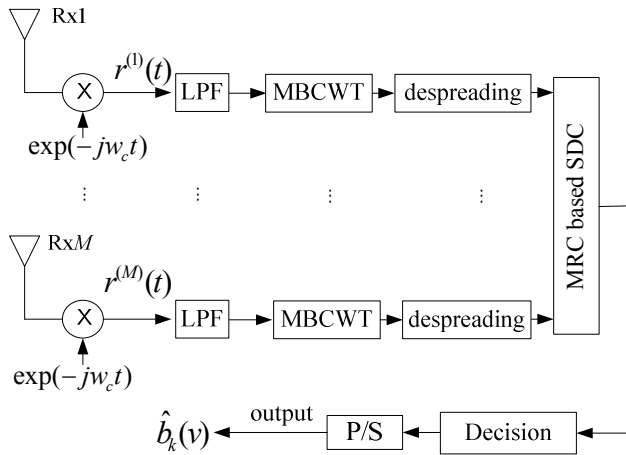


Figure 2. Receiver block diagram of MBCW-MC-DS-CDMA system with SDC technique

IV. 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 space diversity combining 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 [10]. It is assumed that different subcarriers experience independent slow fading. Conventional Gold codes are used for spreading code. The MRC with M receiver 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 $R_s=384\text{kbit/s}$. 16-band optimized complex wavelet [5] and real-valued Daubechies wavelet packet from 4-level binary wavelet packet tree are considered in Fig.3, 32-band optimized complex wavelet [5] and corresponding real-valued wavelet packet are compared in Fig.4. In simulation, we assume that the receiver has a perfect knowledge of channel. The simulation results are shown in Fig.3 and Fig.4, respectively.

In Fig.3, we give the average bit error probability as a function of SNR (E_b/σ^2) under the condition that N equals 16, where fading parameter m is set equal to 1 or 2. ‘‘DFTRx1’’ and ‘‘RWPRx1’’ represent the conventional MC-DS-CDMA system, real wavelet packet based MC-DS-CDMA (RWP-MC-DS-CDMA) system with single antenna receiver, respectively. ‘‘MBCWRx1’’ and ‘‘MBCWRx2’’ denote the proposed MBCW-

MC-DS-CDMA system with one and two receive antennas, respectively. As shown in Fig.3, 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-MC-DS-CDMA system with CP, where CP $_x$ denote x cyclic prefix symbols are inserted. Especially, MBCW-MC-DS-CDMA with SDC technique can improve the BER performance significantly via spatial diversity, it has lower BER than the single antenna multicarrier systems. Moreover, we can see that the BER performance of the proposed system improves as m becomes bigger. Namely, the system BER under $m=2$ case is lower than that under $m=1$ case, which accords with the fact that the fading severity decreases with an increase of the Nakagami parameter m .

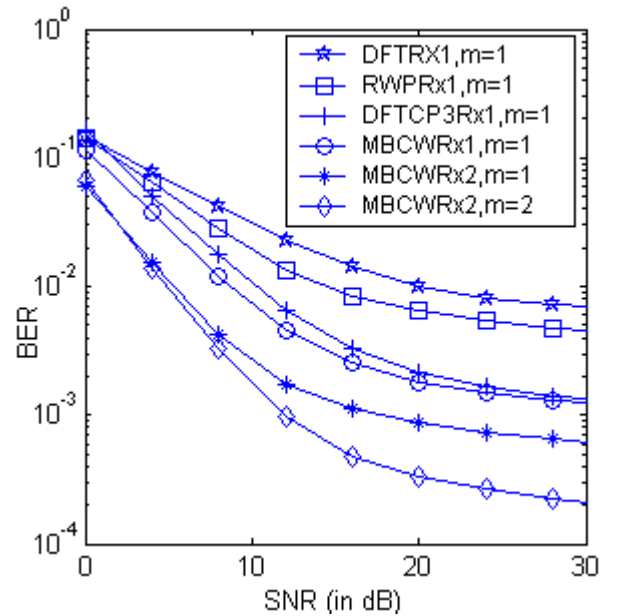


Figure 3. BER against SNR for different systems ($m=1$ or 2)

To further comparison, we also give the average bit error probability as a function of SNR under the condition that N equals 32, where fading parameter $m=2$. From Fig.4, we can observe that the proposed multicarrier DS-CDMA system still performs better than RWP-MC-DS-CDMA system, and obtains almost the same BER performance as the conventional MC-DS-CDMA with CP when m becomes big. Moreover, with the number of receiver antennas increasing, the system performance with SDC technique is obviously better than the other multicarrier system performance. 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 has error floors at high SNR. Despite all this, the application of SDC still effectively decreases the MAI to a certain extent, i.e., the multiple antennas system has much lower BER than the single antenna system at high SNR.

V. CONCLUSIONS

In this paper, we have presented a multicarrier DS-CDMA system based on multiband complex wavelet. The system uplink performance is investigated over Nakagami fading channel, and corresponding BER performance analysis is given. The system can avoid 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 to combat 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. Especially, MBCW-MC-DS-CDMA with SDC has superior performance. It obtains lower BER than the other single-antenna multicarrier systems due to the space diversity gain.

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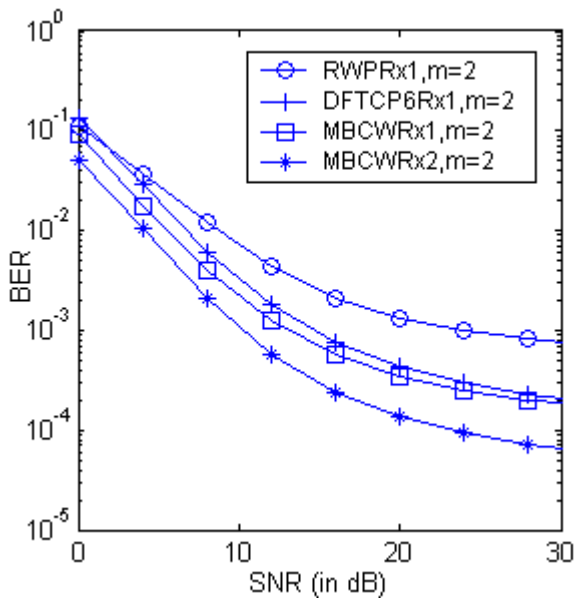


Figure 4. BER against SNR for different systems ($m=2$)

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