STTD Decoding Combined with MMSE Equalization and Diversity Reception for MC-CDMA in the Presence of Multiple Users

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Abstract In this paper, the space time transmit diversity (STTD) decoding combined with minimum mean square error (MMSE) equalization and antenna diversity reception is presented for MC-CDMA downlink and uplink in the presence of multiple users. The equalization weights that minimize the mean square error (MSE) for each subcarrier are used. From computer simulation, it was found that the downlink BER performance of STTD decoding combined with MMSE equalization and M_r-antenna diversity reception using the weights derived in this paper provides the same diversity order as $2M_r$-antenna receive diversity with MMSE equalization but with 3dB performance penalty. The uplink BER performance can also be improved with STTD, but the error floor still exists. However, with 2-receive antennas in addition to 2-antenna STTD, the BER floor can be reduced to around 10^{-5} even for uplink MC-CDMA.

Keywords *mobile radio, MC-CDMA, MMSE equalization, space-time coding, transmit diversity.*

1. Introduction

Recently, the combination of multicarrier (MC) modulation based on orthogonal frequency division multiplexing and code division multiple access (CDMA), called MC-CDMA [1, 2], has gained a lot of attention because of its ability to allow high data rate transmission in a harsh mobile environment and has emerged as the most promising candidate for the forth generation of mobile communication systems [3]. In MC-CDMA, each user's data-modulated symbol to be transmitted is spread over a number of subcarriers using an orthogonal spreading code defined in the frequency-domain. Since the received signal suffers from frequency-selective multipath fading, the orthogonality among different users' signals is partially lost, producing a large multi-user interference (MUI). However, the orthogonality property can be partially restored while achieving the frequency diversity effect by using the minimum mean square error (MMSE) equalization per subcarrier [4] and hence, a better bit error rate (BER) performance can be achieved.

Multiple antennas can be used to reduce the adverse effect of multipath fading. Receive diversity has been successfully used in practical systems. However, recently, transmit antenna diversity has been gaining much attention since the use of transmit diversity at a base station alleviates the complexity problem of mobile receivers [5]. Space-time transmit diversity (STTD) [6] offers a way to introduce a degree of space diversity without going to the complexity of closed-loop transmit diversity solutions. In MC-CDMA, STTD decoding can be performed in conjunction with MMSE equalization to further improve the BER performance. In [7], STTD is applied to downlink MC-CDMA and it is shown that MMSE equalization is the best tradeoff between performance and complexity [7]. However in [7], the receive diversity has not been considered and furthermore, the uplink MC-CDMA case has not been treated.

In this paper, we derive the weights for joint STTD decoding and MMSE equalization (henceforth, referred to as joint STTD and MMSE equalization) for downlink and uplink MC-CDMA with multiple receive antennas. In the downlink case, all the users' data are spread using orthogonal codes and transmitted synchronously from the base station. At the receiver in the mobile terminal, the orthogonality among the users is partially lost, however frequency domain equalization can be utilized to restore the orthogonality. The orthogonality can be completely restored by the zero-forcing equalization, but it cannot take advantage of the frequency diversity effect that is present in a frequency-selective channel. MMSE equalization, on the other hand, restores orthogonality to a certain extent and also improves the performance owing to frequency diversity effect.

The uplink scenario is a little different. In the uplink case, users located at geographically different locations transmit asynchronously. Even when orthogonal codes are used, the orthogonality is completely destroyed as the users' channel gains and transmit timings are different. Hence for the uplink case, using orthogonal codes is not necessary; only the long scramble codes can be used. If two antennas are available for diversity reception in the downlink case at the mobile terminal, these two antennas can be used for transmit diversity in the uplink case. Hence, in this paper we apply STTD for both the downlink and the uplink cases and combine the STTD decoding with the MMSE equalization and antenna diversity reception. In this paper, the weights for joint STTD and MMSE equalization are derived and the performance evaluated by computer simulations for various conditions.

The remainder of this paper is organized as follows. The transmission system model for MC-CDMA with joint STTD and MMSE equalization is presented in Section 2. In Section 3, the simulation results for the downlink and uplink cases are presented and discussed. Section 4 concludes the paper.

2. Transmission System Model with Joint STTD and MMSE Equalization

Figure 1 shows the transmission system model with joint STTD and MMSE equalization. We consider MC-CDMA having N_c subcarriers with a carrier spacing of $1/T_s$ to transmit U users' data in parallel. Without loss of generality, we consider the two MC-CDMA signaling intervals, i.e., $0 \le t < 2T$ with $T=T_s+T_g$, where T_s and T_g are respectively the effective symbol length and the guard interval (GI). Throughout the paper, discrete-time representation of the MC-CDMA signal is used.

A. Transmit signal

At the transmitter, each user's data is spread using the frequency-domain orthogonal spreading code with a spreading factor SF. Let $d^u(n)$ be the uth user's nth data-modulated symbol with $\left|d^u(n)\right| = 1$. The STTD encoder encodes the modulated symbols $\{d^u(n); n=0\sim 2(N_c/SF)-1\}$ for transmission during the signaling interval $0\le t<2T$ from the two antennas over the N_c subcarriers, where N_c/SF is an integer. The serial-to-parallel (S/P) converter converts the STTD encoded data into N_c/SF parallel data streams, each of which is copied SF times and multiplied by the orthogonal spreading code $\{c^u(k);k=0\sim SF-1\}$ for the uth user. It is then further multiplied by a long scramble sequence $\{pn(k); k=\Lambda, -1, 0, 1, \Lambda\}$. (For the uplink case, as stated earlier, the orthogonal spreading code is not necessary, but here, it is used.) The STTD encoded data waveform $y^u_m(n,t)$, to be transmitted from the mth antenna, m=0,1, over the $q\cdot SF$ th ~ $((q+1)\cdot SF-1)$ th subcarriers, $q=0\sim N_c/SF-1$, is as shown in Table 1.

Uplink is considered first. The uth user's kth subcarrier component $\{x^u_{m_t}(k,t); k=0\sim N_c-1\}$, transmitted on the m_tth antenna during the time interval t=0~T and t=T~2T, may be expressed using the equivalent baseband representation as

$$x^u_{m_t}(k,t)=\sqrt{\frac{A}{SF}}c^u(k \bmod SF)\,pn(k)\,y^u_{m_t}\left(\left\lfloor\frac{k}{SF}\right\rfloor,t\right)$$

for uplink, (1)

where A represents the total transmit power of each user, $y^u_{m_t}(n,t)$ is as shown in Table 1 for the respective signaling interval and antenna, and $\lfloor a\rfloor$ denotes the largest integer smaller than or equal to a. In Table 1 and henceforth, $(.)^*$ denotes the complex conjugate operation. N_c-point inverse fast Fourier transform (IFFT) is applied to the sequence $\{x^u_{m_t}(k,t); k=0\sim N_c-1\}$ to generate the MC-CDMA signal $\{s^u_{m_t}(i,t); i=0\sim N_c-1\}$:

$$s^u_{m_t}(i,t)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}x^u_{m_t}(k,t)\exp\left(j2\pi k\frac{i}{N_c}\right),\quad (2)$$

where i represents the sample position in the signaling intervals t=0~T and t=T~2T. After insertion of the N_g-sample guard interval (GI), the resultant MC-CDMA signal $\{\tilde{s}^u_{m_t}(i,t); i=-N_g\sim N_c-1\}$ is transmitted over a propagation channel, where

$$\tilde{s}^u_{m_t}(i,t)=s^u_{m_t}(i \bmod N_c, t).\quad (3)$$

In the downlink case, the U users' symbols spread on each subcarrier are added and then multiplied by the long scramble sequence. Hence the resultant kth subcarrier component $x_{m_t}(k,t)$ is given by

$$x_{m_t}(k,t)=\sqrt{\frac{A}{SF}}\sum_{u=0}^{U-1}c^u(k \bmod SF)\,pn(k)\,y^u_{m_t}\left(\left\lfloor\frac{k}{SF}\right\rfloor,t\right)$$

for downlink. (4)

The resulting MC-CDMA signal $\{s_{m_t}(i,t); i=0\sim N_c-1\}$ and the GI-inserted MC-CDMA signal $\{\tilde{s}_{m_t}(i,t); i=-N_g\sim N_c-1\}$ are given by Eqs. (2) and (3), respectively, with $\{x^u_{m_t}(k,t)\}$ replaced by $\{x_{m_t}(k,t)\}$. The IFFT sampling period is taken to be $\Delta T=T_s/N_c$, such that $T_g=N_g\,\Delta T$ and $T=T_s+T_g=T_s(1+N_g/N_c)$.

Table 1 STTD encoded data waveform $y^u_{m_t}(n,t)$.

time | antenna	m_t=0	m_t=1
t=0~T	$d^u_e=d^u(2q)$	$d^u_o=d^u(2q+1)$
t=T~2T	$-d^{u*}_o=-d^{u*}(2q+1)$	$d^{u*}_e=d^{u*}(2q)$

B. Channel model

L independent propagation paths with distinct time delays $\{\tau^u_l\}$ is assumed. For the uplink case, the discrete time impulse response $\xi^u_m(\tau)$ of the multipath channel between the m_tth transmit antenna and the m_rth receive antenna for the uth user may be expressed as

$$\xi^u_{m_t,m_r}(\tau)=\sum_{l=0}^{L-1}\xi^u_{m_t,m_r,l}\,\delta(\tau-\tau^u_l)\quad (5)$$

with $\sum_{l=0}^{L-1}\mathbf{E}[|\xi^u_{m_t,m_r,l}|^2]=1$, where $\delta(t)$ is the delta function and E[.] denotes ensemble average. It is assumed that the channel impulse response remains the same for the two signaling intervals t=0~T and t=T~2T. The time delays $\{\tau^u_l\}$ are assumed to be multiples of the FFT sampling period ΔT.

For the downlink case, all users' signals go through the same channel and therefore, the superscript u representing the uth user is omitted from Eq. (5).

C. Received signal

Uplink is considered first. We assume M_r-antenna receive diversity. The received MC-CDMA signal is sampled at the rate of $\Delta T^{-1}=N_c/T_s$ to obtain $\{\tilde{r}_{m_r}(i,t); i=-N_g\sim N_c-1\}$ which is expressed as

$$\tilde{r}_{m_r}(i,t)=\sum_{m_t=0}^{1}\sum_{u=0}^{U-1}\sum_{l=0}^{L-1}\xi^u_{m_t,m_r,l}\,\tilde{s}^u_{m_t}(i-\tau^u_l/\Delta T,t)+\eta_{m_r}(i,t),\ (6)$$

where $\eta_{m_r}(i,t)$ represents the additive white Gaussian noise (AWGN) process at the sampling instant i within the signaling interval t for the m_rth receive antenna and has zero mean and variance $2N_0/T_s$, with N_0 representing the single sided AWGN power spectrum density. It is assumed for simplicity that even for uplink, all the users are synchronized, but the impact of transmit timing asynchronism is evaluated by computer simulations in Sect. 3. On the other hand, the received MC-CDMA signal for the downlink can be given by Eq. (6) with $\xi^u_{m_t,m_r}(\tau)$ and $\{\tau^u_l\}$ replaced by $\xi_{m_t,m_r}(\tau)$ and $\{\tau_l\}$, respectively.

The N_g-sample GI is removed and the N_c-point FFT is applied to decompose the received MC-CDMA signal into the N_c-subcarrier components $\{r_{m_r}(k,t); k=0\sim N_c-1\}$:

$$r_{m_r}(k,t)=\sum_{i=0}^{N_c-1}\tilde{r}_{m_r}(i,t)\exp\left(-j2\pi k\frac{i}{N_c}\right).\quad (7)$$

Denoting the uth user's channel gain at the kth subcarrier for the m_tth transmit antenna and m_rth receive antenna by $H^u_{m_t,m_r}(k)$, the kth subcarrier component $r_{m_r}(k,t)$ received in the signaling interval t=0~T and t=T~2T by the m_rth antenna may be represented as

$$r_{m_r}(k,t)=\sum_{m_t=0}^{1}\sum_{u=0}^{U-1}H^u_{m_t,m_r}(k)x^u_{m_t}(k,t)+\Lambda_{m_r}(k,t),\ \text{for uplink}\quad , \tag{8}$$

where $x^u_{m_t}(k,t)$ is as defined in Eq. (1). In Eq. (8), $\{H^u_{m_t,m_r}(k);\ k=0\sim N_c-1\}$ and $\{\Lambda_{m_r}(k,t); k=0\sim N_c-1\}$ are respectively the fast Fourier transforms of the channel impulse response $\xi^u_{m_t,m_r}(\tau)$ and the AWGN process $\eta_{m_r}(i,t)$. They are given by

$$\begin{cases} H^u_{m_t,m_r}(k)=\sum_{l=0}^{L-1}\xi^u_{m_t,m_r,l}\exp\left(-j2\pi k\dfrac{\tau^u_l/\Delta T}{N_c}\right) \\ \Lambda_{m_r}(k,t)=\sum_{i=0}^{N_c-1}\eta_{m_r}(i,t)\exp\left(-j2\pi k\dfrac{i}{N_c}\right) \end{cases}. \tag{9}$$

For the downlink, the kth subcarrier components $r_{m_r}(k,0)$ and $r_{m_r}(k,T)$ received in the signaling intervals t=0~T and t=T~2T may be represented as

$$r_{m_r}(k,t)=\sum_{m_t=0}^{1}H_{m_t,m_r}(k)x_{m_t}(k,t)+\Lambda_{m_r}(k,t),\ \text{for downlink} \tag{10}$$

where $H_{m_t,m_r}(k)$ is the channel gain of the downlink at the kth subcarrier for the m_tth transmit antenna and m_rth receive antenna and $x_{m_t}(k,t)$ is as defined in Eq. (4).

The STTD decoding is carried out as follows:

$$\begin{cases} \tilde{x}_{m_r}(k,0)=w^*_{0,m_r}(k)r_{m_r}(k,0)+w_{1,m_r}(k)r^*_{m_r}(k,T) \\ \tilde{x}_{m_r}(k,T)=w^*_{1,m_r}(k)r_{m_r}(k,0)-w_{0,m_r}(k)r^*_{m_r}(k,T) \end{cases}, \tag{13}$$

where w_{0,m_r} and w_{1,m_r} are the weights for joint STTD decoding and MMSE equalization. They are obtained as follows (derivation not shown).

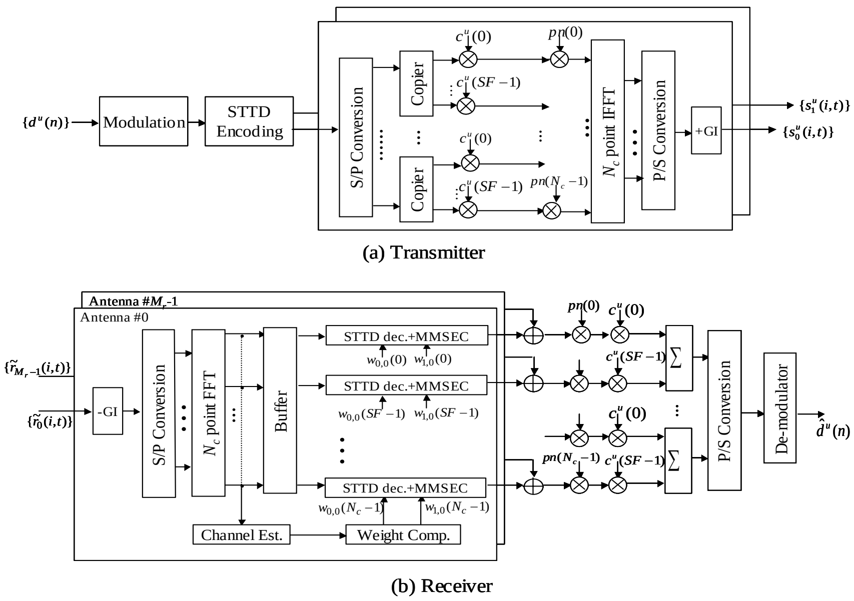
$$w_{m_t,m_r}(k)=\begin{cases} \dfrac{H_{m_t,m_r}}{\sum_{m_r=0}^{M_r-1}\sum_{m_t=0}^{M_t-1}\left|H_{0,m_r}(k)\right|^2+\left(\dfrac{U}{SF}\dfrac{T_sA}{2N_0}\right)^{-1}},\ \text{downlink} \\ \dfrac{H^0_{m_t,m_r}}{\sum_{m_t=0}^{M_t-1}\sum_{u=0}^{U-1}\left|H^u_{0,m_r}(k)\right|^2+\left(\dfrac{1}{SF}\dfrac{T_sA}{2N_0}\right)^{-1}},\ \text{uplink} \end{cases} \tag{14}$$

Note that the above weights for the uplink case were derived when the users are synchronous. However, in actuality, the users' transmitting timings are asynchronous. It was found from our preliminary simulation that the BER performances for the synchronous and asynchronous cases are almost identical because the error floor which occurs in the uplink BER is due to the orthogonality destruction resulting because of the different fading channels for different users.

The resulting soft samples, obtained as in Eq. (13), received by M_r-antennas are added and then despread, i.e., multiplied by the scramble sequence $\{pn(k)\}$ and the orthogonal spreading code { $c^u(k \bmod SF)$; k=qSF~(q+1)SF-1} and summed, to obtain the decision variable $\tilde{d}^u(q,t)$ for the qth data-modulated symbol of the uth user transmitted in the signaling interval t given as

$$\tilde{d}^u(q,t)=\sum_{k=qSF}^{(q+1)SF-1}\sum_{m_r=0}^{M_r-1}\tilde{x}_{m_r}(k,t)c^{u*}(k \bmod SF)pn^*(k)\ . \tag{15}$$

The recovered modulated symbols for the two signaling intervals t=0~T and t=T~2T are then aligned to obtain the nth data-modulated symbol $\hat{d}^u(n)$ as



(a) Transmitter

(b) Receiver

Figure 1. Transmission system model

$$\hat{d}^u(n) = \begin{cases} \tilde{d}^u(q,0), & \text{if } n = 2q \\ \tilde{d}^u(q,T), & \text{if } n = 2q+1 \end{cases} \quad (16)$$

for n=0 ~ 2(N_c/SF)-1.

3. Simulation Results

Table 2 shows the computer simulation conditions. We assume MC-CDMA using N_c=256 subcarriers with a subcarrier spacing of 1/T_s, GI of T_g=T_s/8 (i.e., N_g=32), and ideal coherent BPSK data-modulation. IFFT and FFT sampling period ΔT is ΔT=T_s/256. A frequency-selective Rayleigh fading channel having L=16-path uniform power delay profile with τ_l=2$l\Delta T$ for downlink ($\tau_l^u = 2l\Delta T, u = 0 \sim U-1$, for uplink), and the normalized maximum Doppler frequency f_DT = 0.01 is assumed. The estimations of the channel gains, AWGN power spectrum density and the number of users are assumed to be ideal.

Table 2: Simulation conditions

Data modulation	Coherent BPSK	
MC-CDMA	No. of subcarriers	N_c=256
	Effective symbol length	T_s=256ΔT
	GI	T_g=32ΔT (T_g/T_s=1/8)
	Spreading factor	SF=1~256
Channel model	Rayleigh fading (L=16) τ_l = 2$l\Delta T$ f_DT=0.01	

A. Downlink

Figure 2 plots the downlink BER performance as a function of the average received signal energy per bit-to-the AWGN power spectrum density ratio (E_b/N_0), where $E_b / N_0 = (AT_s / N_0)(1+T_g / T_s)$, for SF=32 with the number U of communicating users as a parameter. For reference, the BER with MMSE equalization but for no diversity and that for 2-antenna receive diversity combined with MMSE equalization as in [8] are also plotted. The BER performance worsens with the increase in the number of users due to increasing MUI. However, it is seen that the STTD achieves the performance of 2-antenna receive diversity but with a penalty of 3dB.

In the downlink, all users' signal transmissions are synchronous and orthogonal spreading codes can be used to reduce the MUI. This suggests that as many as SF users can be multiplexed on the downlink without significant performance degradation. Figure 3 plots the downlink BER performance as a function of the average received E_b/N_0 with SF as a parameter when the number U of users is the same as SF. SF=U=1 corresponds to the well-known OFDM. It is interesting to note that the BER performance of MC-CDMA with SF>1 with U=SF is seen to be better than that of SF=1 in spite of the increase in MUI. This is because as the value of SF increases the increase in frequency diversity effect becomes large enough to offset the increase in MUI and also provide additional improvement [9]. With STTD, the average received E_b/N_0 for a BER of 10^{-4} is 8dB less for SF=256 than that for SF=1. The no diversity and 2-antenna receive diversity curves are also plotted. It is again seen that the STTD achieves the performance of 2-antenna receive diversity but with a 3dB penalty.

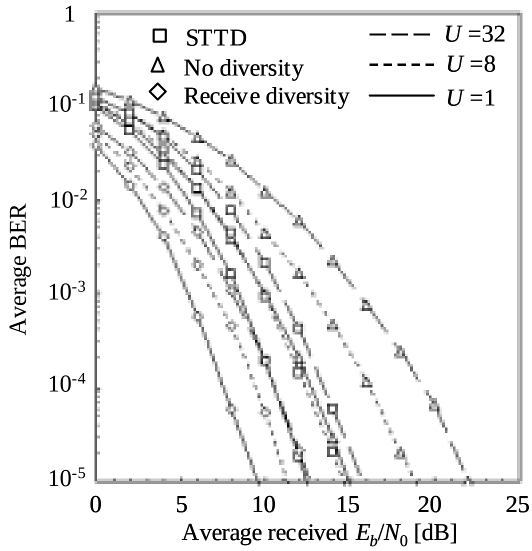


Figure 2. Downlink BER performance for SF=32.

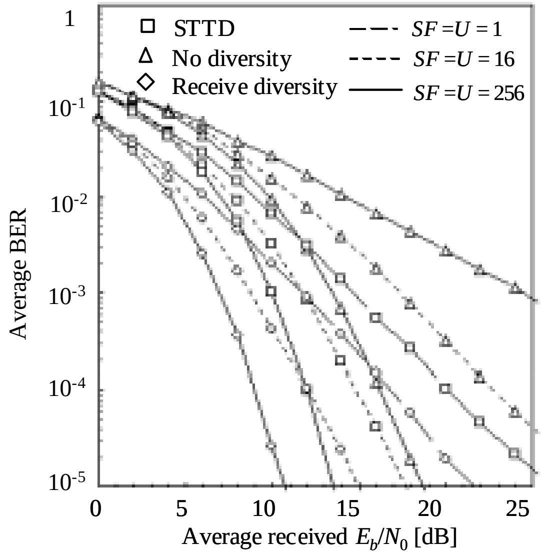


Figure 3. Downlink BER performance for U =SF.

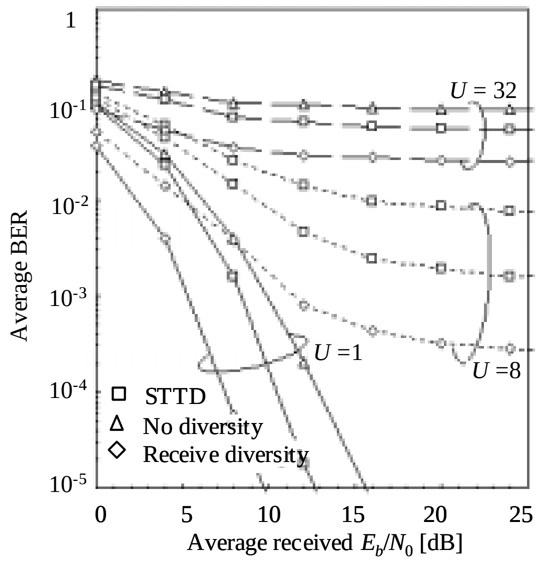


Figure 4. Uplink BER performance for SF=32.

B. Uplink

In the uplink case, the orthogonality among the users cannot be maintained in a frequency-selective channel. Hence, a BER error floor occurs when more than one user are in communication at the same time. Fig. 4 plots the uplink BER performance as a function of the average received E_b/N_0 for SF=32 with U as a parameter for the asynchronous case when the users' timing are uniformly distributed over 0~T. For reference, the BER performances for no diversity with MMSE equalization and for 2-antenna receive diversity combined with MMSE equalization are also plotted. Using joint STTD and MMSE equalization improves the BER performance, however the BER floor still exists.

C. Combined effect of STTD and Diversity reception

So far, we have treated STTD and antenna receive diversity separately. Below, we evaluate the combined effect of STTD and receive antenna diversity. If two-antenna receive diversity is used at the mobile receiver, then an interesting question is what performance improvement can be seen for the uplink with two transmit antennas. Since two antennas are available both at the mobile terminal (MT) and base station (BS), STTD can be applied at the MT as well. Figure 5 plots the average BER performance as a function of average received E_b/N_0 per antenna for both uplink and downlink when SF=32 and U=8. Three cases are considered: (BS, MT) = (1, 1), i.e., 1-antenna at both BS and MT, (BS, MT) = (2, 1) and (BS, MT) = (2, 2). With (BS, MT) = (2, 1) the downlink performance improves due to STTD gain and the uplink performance improves due to receive diversity gain. With (BS, MT) = (2, 2), a large improvement is attained for both downlink and uplink because of the combined effect of STTD and receive diversity. The uplink error floor is reduced to around 10^{-5}. The result encourages the use of two antennas at the mobile station for receive diversity on the downlink and for STTD on the uplink.

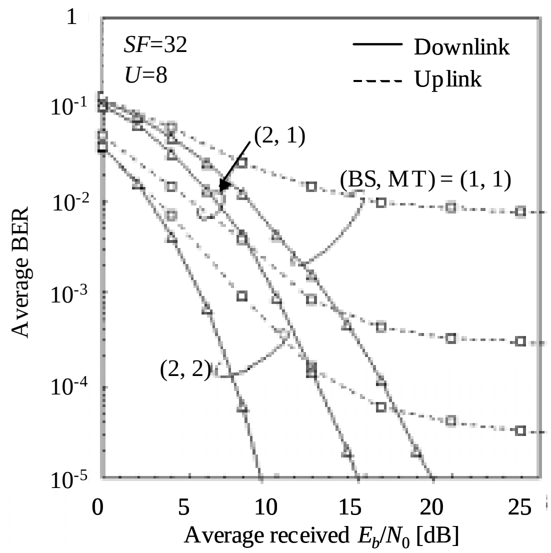


Figure 5. BER performance with STTD and 2-antenna receive diversity.

4. Conclusion

In this paper, per-subcarrier joint STTD and MMSE equalization was presented for MC-CDMA. It was found that the equalization weights for downlink and uplink are different. From computer simulation, it was found that the downlink BER performance of joint STTD and MMSE equalization combined with M_r-antenna diversity reception provides the same diversity order as $2M_r$-antenna receive diversity with MMSE equalization but with 3dB performance penalty. The uplink BER performance can also be improved with STTD, but the error floor still exists. However, with 2-receive antennas in addition to 2-antenna STTD, the BER floor can be significantly reduced to around 10^{-5} even for uplink MC-CDMA.

In this paper, the estimations of the channel gains, AWGN power spectrum density and the number of users were assumed to be ideal. The estimation errors would result in performance degradation. It is interesting to see how much the performance would degrade in an MC-CDMA system with STTD when a practical channel estimator is used. This is a practically important future study.

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