Space-Time Spreading Assisted Broadband MC DS-CDMA

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***Abstract*— In this contribution multicarrier direct-sequence code-division multiple-access (MC DS-CDMA) using space-time spreading (STS) is investigated in the context of broadband communications over frequency-selective Rayleigh fading channels. We consider a range of design issues as well as the achievable Bit Error Rate (BER) performance for the down-link, by assuming synchronous transmission of the user signals. The BER performance of STS assisted broadband MC DS-CDMA using Binary Phase Shift Keying (BPSK) modulation is investigated by simulation for a range of parameter values. Our study shows that by appropriately selecting the system parameters, STS assisted broadband MC DS-CDMA is capable of supporting ubiquitous communications in various communication environments including indoor, open rural, suburban and urban areas without BER performance degradation. Furthermore, the STS based transmit diversity schemes can be designed for attaining a certain required diversity gain, while maintaining a near-constant BER in various communication environments, provided that frequency-selective Rayleigh fading channels are encountered.**

I. INTRODUCTION

Broadband mobile wireless systems aim for supporting a wide range of services and bit rates by employing techniques capable of achieving the highest possible spectral efficiency. In the context of CDMA assisted broadband wireless communications three multiple-access options might be employed, provided that we refrain from using frequency hopping. Specifically, these three multiple-access schemes are single-carrier DS-CDMA [1], multicarrier CDMA (MC-CDMA) using frequency-domain (F-domain) spreading [2], which will be simply referred to as MC-CDMA and finally, multicarrier DS-CDMA (MC DS-CDMA) using DS spreading of the subcarriers' signal [2].

In the context of broadband wireless mobile systems supporting ubiquitous transmissions in various communications environments, as indicated in [3], both single-carrier DS-CDMA and MC-CDMA exhibit certain limitations that are hard to circumvent. In this contribution we consider a range of design and performance issues in the context of broadband MC DS-CDMA using space-time spreading (STS) [3], [4] assisted transmit diversity. Specifically, synchronous down-link (base-to-mobile) transmission of the user signals is considered and the BER performance is evaluated for a range of parameter values. Our study shows that by appropriately selecting the system parameters, STS assisted broadband MC DS-CDMA is capable of mitigating the problems encountered by both single-carrier DS-CDMA and MC-CDMA. Specifically, STS assisted broadband MC DS-CDMA is capable of supporting ubiquitous communication in indoor, open rural, suburban and urban areas. This is achieved by avoiding or at least mitigating the problems imposed by the fading channels associated with the above communication environments. Furthermore, the transmit diversity scheme using STS can be designed for satisfying a constant diversity gain requirement. The required diversity gain is achieved, when communicating over a variety of fading channels, provided that the delay-spread encountered is distributed within a certain limited range.

II. SYSTEM DESCRIPTION

A. Transmitter Model

The system considered in this paper is an orthogonal MC DS-CDMA scheme [5] using $U \cdot S$ number of subcarriers, T_x number of transmitter antennas and one receiver antenna. Furthermore, in this paper a synchronous MC DS-CDMA scheme is investigated, where the K user signals are transmitted synchronously. The transmitter schematic of the kth user is shown in Fig.1, where real-valued data symbols using BPSK modulation and real-valued spreading [4] were considered. Fig.2 shows the frequency arrangement of the $U \cdot S$ subcarriers. As shown in Fig.1, at the transmitter side a block of $U \cdot L_x$ data bits each having a bit duration of T_b is S-P converted to U parallel sub-blocks. Each parallel sub-block has L_x data bits, which are space-time spread using the schemes of [4] with the aid of M_x orthogonal spreading codes - for example Walsh codes - $\left\{c_{k,1}^I(t), c_{k,2}^I(t), \ldots, c_{k,M_x}^I(t)\right\}$, $k = 1, 2, \ldots, K$ and mapped to T_x transmitter antennas. The symbol duration of the STS signals is UL_xT_b, and the discrete period of the orthogonal codes is $UL_xT_b/T_c = UL_xN$, where $N = T_b/T_c$ and T_c represents the chip-duration of the orthogonal spreading codes. The orthogonal codes take the form of $c_{k,i}^I(t) = \sum_{j=0}^{UL_xN-1} c_{k,i}^I[j]P_{T_c}(t - jT_c)$, where $c_{k,i}^I[j] \in \{+1, -1\}$ and they obey the relationship of $\sum_{l=0}^{UL_xN} c_{i,m}[l]c_{j,n}[l] = 0$, whenever $i \neq j$ or $m \neq n$. Furthermore, $P_{T_c}(t)$ represents the chip impulse waveform defined over the interval of $[0, T_c)$. As seen in Fig.1, following STS, each STS block generates T_x parallel signals to be mapped to the T_x transmitter antennas. The specific U STS signals of Fig.1, which are output by the U STS blocks and which will be transmitted using the same antenna

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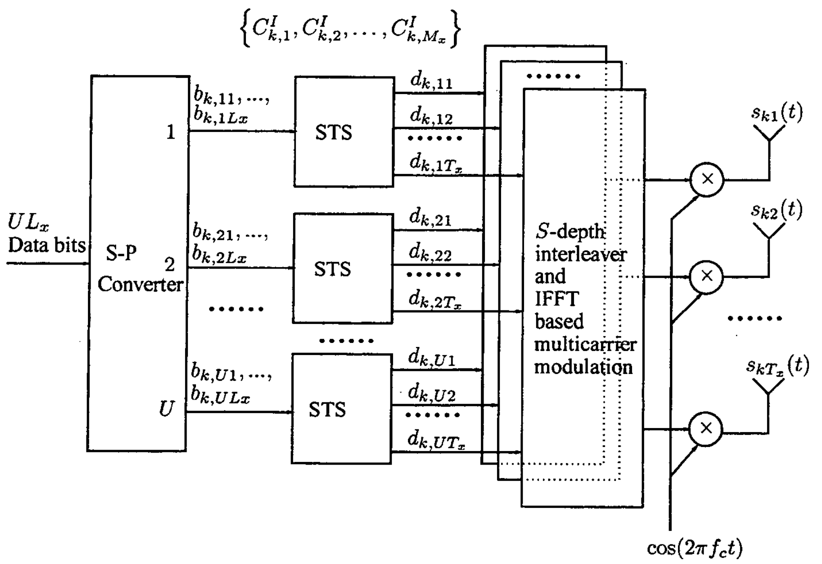

Fig. 1. The transmitter schematic of the MC DS-CDMA system using space-time spreading.

from the set $1, 2, \ldots, T_x$ are then interleaved by an S-depth interleaver, so that each STS signal is transmitted on S subcarriers. The interleavers guarantee that the same STS signal is transmitted by the specific S subcarriers having the maximum possible frequency spacing, so that they experience independent fading and hence achieve maximum frequency diversity. Specifically, let $\{f_1, f_2, \ldots, f_{US}\}$ be the subcarrier frequencies, which are arranged according to Fig.2. These subcarrier frequencies can be written in the form of a matrix as

$$\{f_i\} = \begin{pmatrix} f_1 & f_{U+1} & \cdots & f_{(S-1)U+1} \\ f_2 & f_{U+2} & \cdots & f_{(S-1)U+2} \\ \vdots & \vdots & \ddots & \vdots \\ f_U & f_{2U} & \cdots & f_{SU} \end{pmatrix}. \quad (1)$$

Then, a STS signal will be transmitted using the subcarrier frequencies from the same row of (1). Finally, as shown in Fig.1, the Inverse Fast Fourier Transform (IFFT) is invoked for carrying out multicarrier modulation, and the IFFT block's output signal is transmitted using one of the transmitter antennas.

It can be shown that the general form of the kth user's transmitted signal corresponding to the T_x transmitter antennas may be expressed as

$$\mathbf{s}_k(t) = \mathrm{Re}\left\{\sqrt{\frac{2E_b}{UT_b}\frac{1}{SM_xT_x}}\,[\mathbf{C}_k\mathbf{B}_k]^T\,\mathbf{P}\mathbf{w}\cdot e^{j2\pi f_c t}\right\}, \quad (2)$$

where E_b/UT_b represents the transmitted power per subcarrier expressed as $L_xE_b/UL_xT_b = E_b/UT_b$, the factor S in the denominator is due to the S-depth interleaving, while the factor of M_xT_x represents STS using M_x orthogonal codes and T_x transmitter antennas. In (2) $\mathbf{s}_k(t) = [s_{k1}(t)\ s_{k2}(t) \ldots s_{kT_x}(t)]^T$ - where the superscript T denotes the vector or matrix transpose - represents the transmitted signal vector of the T_x transmitter antennas, $\mathbf{P}$ represents the S-depth interleaving operation, which is a $U \times US$ matrix expressed as $\mathbf{P} = [\mathbf{I}_U\ \mathbf{I}_U\ \ldots\ \mathbf{I}_U]$ with $\mathbf{I}_U$ being a unity matrix of rank U. Furthermore, $\mathbf{C}_k$ is a $U \times UM_x$ dimensional matrix constituted by the orthogonal codes, which can be expressed as

$$\mathbf{C}_k^T = \begin{pmatrix} c^I_{k,1}(t) & 0 & \ldots & 0 \\ c^I_{k,2}(t) & 0 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ c^I_{k,M_x}(t) & 0 & \ldots & 0 \\ 0 & c^I_{k,1}(t) & \ldots & 0 \\ 0 & c^I_{k,2}(t) & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & c^I_{k,M_x}(t) & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \vdots & c^I_{k,1}(t) \\ 0 & 0 & \vdots & c^I_{k,2}(t) \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \vdots & c^I_{k,M_x}(t) \end{pmatrix}. \quad (3)$$

In (2) $\mathbf{B}_k$ is a $UM_x \times T_x$ matrix mapped from the U sub-block data bits, according to the requirements of the STS [4]. Specifically, the matrix $\mathbf{B}_k$ can be expressed as

$$\mathbf{B}_k = \left[\mathbf{B}^T_{k1}\ \mathbf{B}^T_{k2}\ \ldots\ \mathbf{B}^T_{kU}\right]^T, \quad (4)$$

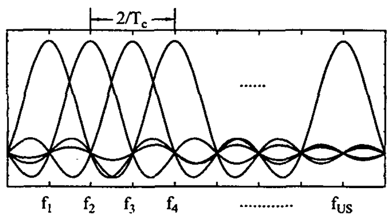

Fig. 2. Spectrum of orthogonal MC DS-CDMA signals having a minimum subcarrier spacing of $1/T_c$, where the zero-to-zero bandwidth of each DS spread signal is $2/T_c$.

where $\mathbf{B}_{ku}$ for $u = 1, 2, \ldots, U$ are $M_x \times T_x$ dimensional matrices, which obey the structure of

$$\mathbf{B}_{ku} = \begin{pmatrix} a_{11}b'_{k,11} & a_{12}b'_{k,12} & \cdots & a_{1L_x}b'_{k,1T_x} \\ a_{21}b'_{k,21} & a_{22}b'_{k,22} & \cdots & a_{2L_x}b'_{k,2T_x} \\ \vdots & \vdots & \ddots & \vdots \\ a_{M_x1}b'_{k,M_x1} & a_{U2}b'_{k,M_x2} & \cdots & a_{M_xL_x}b'_{k,M_xT_x} \end{pmatrix},$$

where a_{ij} represents the sign of the element at the ith row and the jth column, which is determined by the STS design rule, while $b'_{k,ij}$ in $\mathbf{B}_{ku}$ is the data bit assigned to the (i, j)th element, which is one of the L_x input data bits $\{b_{k,u1}, b_{k,u2}, \ldots, b_{kL_x}\}$ of user k.

Equation (2) represents the general form of the transmitted signals using STS, regardless of the values of L_x, M_x and T_x. However, the study conducted in [4] has shown that STS schemes using $L_x = M_x = T_x$, i.e. those having an equal number of data bits, orthogonal STS-related spreading sequences as well as transmission antennas constitute attractive schemes, since they are capable of providing maximal transmit diversity without requiring extra STS codes. Hence, in this contribution we only investigate these attractive STS schemes, and our results are mainly based on MC DS-CDMA systems using two or four transmitter antennas.

B. Channel Model and System Parameter Design

The channels are assumed to be slowly varying frequency-selective Rayleigh fading channels and the delay-spreads are assumed to be limited to the range of $[T_m, T_M]$, where T_m corresponds to the environments having the shortest delay-spread considered, for example in an indoor environment, while T_M is associated with an environment having the highest possible delay-spread, as in an urban area. For single carrier DS-CDMA systems using STS assisted transmit diversity, the results of [4] and [6] demonstrated that the achievable transmit diversity gain is independent of the frequency-selective diversity gain and that both the transmit diversity and the frequency-selective diversity have the same order of importance. However, the results of [6] have also shown that the STS scheme designed on the basis of a low number of resolvable paths, or even based on a relatively high but fixed number of resolvable paths, may waste some of the available diversity potential and hence cannot maximize the achievable throughput. This is because the delay spread experienced in practical communication environments may vary over a wide range, when moving from indoor to outdoor, or from urban to suburban scenarios. An efficient wireless system has to be capable of adapting to different communication environments. For example, a broadband wireless communication system based on single-carrier DS-CDMA and having a data rate of 1 Mbits/s may not exhibit a high transmission integrity in an urban area, where the delay-spread is higher than $3\mu s$ [7], since each received symbol is overlapped by more than two previously transmitted symbols. By contrast, a MC-CDMA scheme [2] using frequency-domain spreading cannot operate efficiently in an indoor environment, where the delay-spread (coherence bandwidth) may be lower (higher) than $0.1\mu s$ $(1/0.1\mu s = 10\ MHz)$ without a high-latency interleaver. Consequently, the fading envelope of adjacent subcarrier signals is highly correlated and the diversity gain achieved by combining the subcarrier signals is significantly degraded. Fortunately, MC DS-CDMA exhibits a high design flexibility, since it possesses a range of parameters that can be adjusted for satisfying the required design trade-offs. Let us now demonstrate how we can adjust the set of parameters in STS-assisted MC DS-CDMA, in order to ensure that MC DS-CDMA operates efficiently in different communication environments.

Firstly, in order to ensure that STS maintains the required frequency-diversity order in different communication environments, the simplest approach is to configure the system such that each sub-carrier signal is guaranteed to experience flat-fading. Then the required grade of frequency-diversity is attained by combining a number of independently faded subcarrier signals, which is achieved with the aid of F-domain interleaving. Let the delay-spread be limited to the range of $[T_m, T_M]$. The flat-fading condition of each subcarrier is satisfied, if $T_c > T_M$.

Secondly, in order to achieve the highest grade of frequency-diversity, as we mentioned above, the subcarrier signals combined must experience independent fading. This implies that the F-domain spacing between the combined subcarriers must be higher, than the maximum coherence bandwidth of $(\Delta f)_{cM} \approx 1/T_m$ [8]. Let U be the number of sub-blocks after the S-P conversion stage of Fig.1. Then, according to Fig.2 and (1) the above condition is satisfied if $\frac{U}{T_c} \geq \frac{1}{T_m}$, i.e. if $U \geq \frac{T_c}{T_m}$.

The above philosophy might be augmented with the aid of an example. Let us assume that the total bandwidth of the broadband MC DS-CDMA system is about 20 MHz, the required diversity order is four, and the number of transmitter antennas is two. Furthermore, we assume that the delay-spread is limited to the range of $[T_m = 0.1\mu s, T_M = 3\mu s]$, which includes the typical delay-spread values experienced in indoor, open rural, suburban and urban areas. Based on the philosophy discussed in this subsection, we can set $T_c = 4\mu s > T_M = 3\mu s$ and $U = T_c/T_m = 4\mu s/0.1\mu s = 40$. When 80 subcarriers occupying the spectrum of Fig.2 and having a total system bandwidth of about 20 MHz $(= (80 + 1)/T_c)$ are employed, then the interleaving depth is two, i.e. after STS each signal can be transmitted on two subcarriers. Consequently, this MC

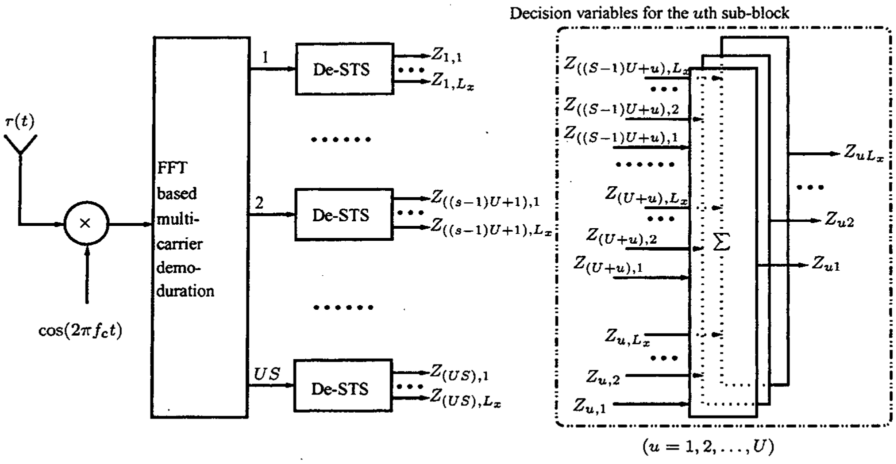

Fig. 3. The receiver schematic of the MC DS-CDMA system using space-time spreading.

DS-CDMA system will operate efficiently over a wide range communication environments and will achieve a total diversity order of four, provided that the delay-spread of the specific environment encountered is in the range of $[0.1\mu s, 3\mu s]$, where the total diversity order of four was contributed by the transmit diversity order of two achieved on both of the interleaved subcarriers. Furthermore, if four transmitter antennas are employed, a total diversity order of eight can be achieved, which is the result of the transmit diversity order of four on both of the interleaved subcarriers.

Assuming that K user signals in the form of (2) are transmitted synchronously over Rayleigh fading channels, it can be shown that the received complex low-pass equivalent signal may be expressed as

$$R(t) = \sum_{k=1}^{K}\sum_{g=1}^{T_x}\sqrt{\frac{2E_b}{UT_b}\frac{1}{SM_xT_x}}\left([\mathbf{C}_k\mathbf{B}_k]^T\mathbf{P}\right)_g \mathbf{H}\mathbf{w} + N(t), \qquad (5)$$

where $(\mathbf{X})_g$ represents the gth row of the matrix $\mathbf{X}$, $N(t)$ is the complex valued low-pass-equivalent Additive White Gaussian Noise (AWGN) having a double-sided spectral density of N_0, while

$$\begin{aligned}\mathbf{H} \;=\;& \operatorname{diag}\{h_{1g}\exp(j\psi_{1g}), h_{2g}\exp(j\psi_{2g}), \ldots, \\ & h_{(US)g}\exp(j\psi_{(US)g})\}, \; g = 1, 2, \ldots, T_x, \quad (6)\end{aligned}$$

is a diagonal matrix of rank US, which represents the channel's complex impulse response in the context of the gth antenna. The coefficients h_{ig}, $i = 1, 2, \ldots, US$; $g = 1, 2, \ldots, T_x$ in $\mathbf{H}$ are independent identically distributed (i.i.d) random variables obeying the Rayleigh distribution, which can be expressed as

$$f_{h_{ig}}(y) = \frac{2y}{\Omega}\exp\left(-\frac{y^2}{\Omega}\right), \; y \geq 0, \qquad (7)$$

where $\Omega = E[(h_{ig})^2]$. Furthermore, the phases ψ_{ig}, $i = 1, 2, \ldots, US$; $g = 1, 2, \ldots, T_x$ are introduced by the fading channels and are uniformly distributed in the interval $(0, 2\pi)$.

C. Receiver Model

Let the first user be the user-of-interest and consider a receiver employing FFT based multicarrier demodulation, space-time de-spreading as well as diversity combining, as shown in Fig.3. The receiver of Fig.3 essentially carries out the inverse operations of those seen in Fig.1. In Fig.3 the received signal is first down-converted using the carrier frequency f_c, and then demodulated using FFT based multicarrier demodulation. After FFT based multicarrier demodulation we obtain US number of parallel streams corresponding to the signals transmitted on US subcarriers, and each stream is space-time de-spread using the approach of [4], in order to obtain L_x separate variables, $\{Z_{u,1}, Z_{u,2}, \ldots, Z_{u,L_x}\}_{u=1}^{US}$, corresponding to the L_x data bits transmitted on the uth stream, where $u = 1, 2, \ldots, US$, respectively. Following space-time de-spreading, a decision variable is formed for each transmitted data bit $\{b_{u1}, b_{u2}, \ldots, b_{uL_x}\}_{u=1}^{U}$ by combining the corresponding variables associated with the S interleaved subcarriers, which can be expressed as

$$\begin{aligned} Z_{ui} = \sum_{s=1}^{S} Z_{((s-1)U+u),i}, \; & u = 1, 2, \ldots, U; \\ & i = 1, 2, \ldots, L_x. \qquad (8)\end{aligned}$$

Finally, the UL_x number of transmitted data bits can be decided based on the decision variables $\{Z_{ui},\ u = 1, 2, \ldots, U;\ i = 1, 2, \ldots, L_x\}$ using the conventional decision rule of a BPSK scheme.

For the cases of $L_x = M_x = T_x = 2, 4, 8$, etc. the average

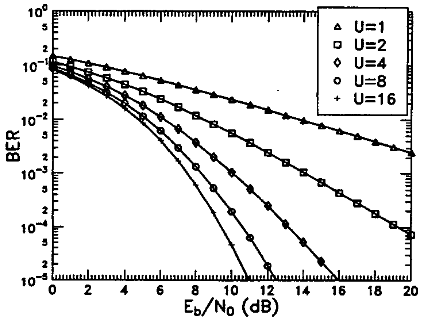

Fig. 4. Numerical (lines) and simulated (markers) BER versus the SNR per bit, E_b/N_0, performance for the STS assisted broadband MC DS-CDMA without frequency-domain interleaving ($S = 1$), when communicating over frequency-selective Rayleigh fading channels evaluated from (9).

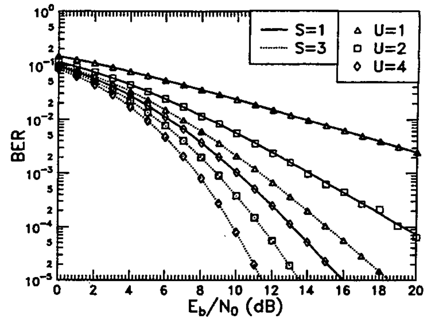

Fig. 5. Numerical (lines) and simulated (markers) BER versus the SNR per bit, E_b/N_0, performance for the broadband MC DS-CDMA using STS based transmit diversity, when communicating over frequency-selective Rayleigh fading channels evaluated from (9).

BER can be expressed as

$$P_b = \left[\frac{1-\mu}{2}\right]^{T_xS} \sum_{k=0}^{T_xS-1} \binom{T_xS-1+k}{k} \left[\frac{1+\mu}{2}\right]^k, \quad (9)$$

where $\mu = \sqrt{\overline{\gamma}/(1+\overline{\gamma})}$ with $\overline{\gamma} = E_b\Omega/SN_0$.

We note that according to (9), by using STS and F-domain subcarrier interleaving, the diversity order achieved is T_xS, provided that T_x transmitter antennas and S-depth F-domain interleaving schemes were used. Furthermore, the diversity gains achieved by the T_x transmitter antennas and by the process of interleaving over S subcarriers are independent and hence their product determines the total diversity order.

III. Performance Results

In this section we provide both simulation as well as numerical results for characterizing the performance of the proposed broadband MC DS-CDMA using STS assisted transmit diversity. In Fig.4 we evaluated the effects of the number of transmission antennas on the BER performance of the orthogonal MC DS-CDMA scheme, where we assumed that the transmitter used no F-domain interleaving, i.e. we set $S = 1$, but employed $T_x = 1, 2, 4, 8$, or 16 transmission antennas. From the results we observe that the BER performance is significantly improved, when increasing the number of transmission antennas. It is seen that at the BER of 10^{-3} the STS scheme using two transmission antennas gives about 9.5dB gain over that using one transmission antenna. By contrast, if the number of the transmission antennas is increased, we find that at the BER of 10^{-3} the STS scheme using 16 transmission antennas only gives about 1dB gain over that using 8 transmission antennas. The reason is that much of the total achievable diversity gain is already attained using a relatively low number of transmission antennas.

Fig.5 shows both the numerical and simulation based BER results, which were drawn using lines and markers, respectively, for $S = 1$, $T_x = 1, 2, 4$ as well as for $S = 3$, $T_x = 1, 2, 4$. From the results we observe that at a BER of 0.01, using two transmitter antennas rather than one yields a gain of approximately 5.0 dB. Furthermore, when $T_x = 4$ transmitter antennas and an interleaving depth of $S = 3$ are considered instead of $T_x = 1, S = 1$, the diversity gain achieved is approximately 9.0 dB.

In conclusion, in this contribution we have investigated the performance of a broadband MC DS-CDMA system using STS, when frequency-selective Rayleigh fading channels are considered. Our performance studies suggest that broadband MC DS-CDMA using STS constitutes a promising multiple-access option, which is capable of avoiding various design limitations that are unavoidable, when using single-carrier DS-CDMA or MC-CDMA.

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