PAPER

Orthogonal Space-Time Spreading Transmit Diversity

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SUMMARY In this paper, a new 2-antenna transmit diversity, called orthogonal space-time spreading transmit diversity (OSTSTD) combined with delay transmission, is proposed. At the transmitter, N data symbols to be transmitted are spread using N different orthogonal space-time spreading codes (each represented by $N \times N$ matrix) and are transmitted from two transmit antennas after adding different time delays. At the receiver, 2-step space-time despreading is carried out to recover the N transmitted data symbols. The first step recovers the N orthogonal spatial channels by taking the correlation between the received space-time spread signal and the time-domain spreading codes. The second step recovers the N transmitted data symbols using minimum mean square error (MMSE) despreading. The average bit error rate (BER) performance in a Rayleigh fading channel is evaluated by computer simulation. It is confirmed that the OSTSTD provides better BER performance than the Alamouti's space-time transmit diversity (STTD) at the cost of transmission time delay.
key words: *transmit diversity, space-time spreading, fading channel*

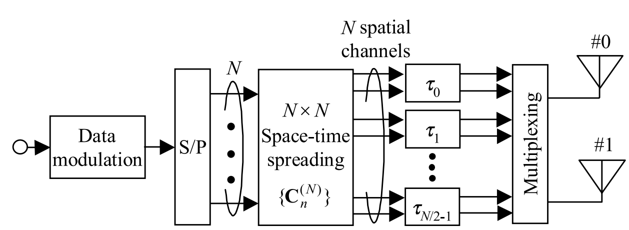
1. Introduction

In mobile radio communications, the transmitted signal is scattered by many obstacles located between a transmitter and a receiver, thereby creating a multipath channel and severely degrading the transmission performance [1]. Multiple diversity antennas at a transmitter and/or a receiver can be used to reduce the adverse effect of multipath fading. Receive antenna 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 [2]. The transmit diversity technique employing orthogonal space-time block code (STBC) is well-known [3]–[5]. Especially, the Alamouti's space-time transmit diversity (STTD) [3] has a simple coding and decoding algorithm and provides full transmission rate and full diversity gain. In Alamouti's STTD, the data modulated symbol sequence to be transmitted is space-time block coded and transmitted from two spatially separated antennas. At the receiver, a simple decoding operation is applied to achieve the 2-branch maximal ratio combining (MRC) diversity effect but with 3 dB power penalty. The space-time spreading transmit diversity (STSTD) technique was proposed for direct sequence code division multiple access (DS-CDMA) systems [6]. Although the STSTD using real data modulation, e.g., binary phase shift keying (BPSK), works even with four and eight transmit antennas, the STSTD using complex data modulation, e.g., quadrature PSK (QPSK), can offer the full diversity gain and full transmission rate only for the two transmit antenna case [6].

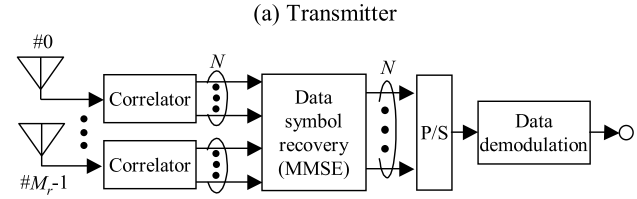
In this paper, we combine space-time spreading and delay transmission to exploit the time-selective fading and propose orthogonal space-time spreading transmit diversity (OSTSTD). In Sect. 2, orthogonal space-time spreading and despreading based on minimum mean square error (MMSE) criterion is presented. The difference between OSTSTD and the STSTD of [6] is also discussed. Section 3 evaluates by computer simulation the achievable bit error rate (BER) performance in a Rayleigh fading channel to show that BER performance better than Alamouti's STTD can be obtained. Section 4 concludes the paper.

2. OSTSTD

Figure 1 illustrates the transmission system model of OSTSTD with two transmit antennas and M_r receive antennas. At a transmitter, the data-modulated symbol sequence with symbol rate $1/T_s$ is transformed into N parallel data symbol sequences with symbol rate $1/(NT_s)$. Each symbol sequence is spread using orthogonal space-time spreading code $\boldsymbol{C}_n^{(N)}$, $n = 0 \sim N-1$, with chip rate $1/T_s$ and then the resultant N space-time spread signals are multiplexed to produce N spatial channels. Direct application of space-time spreading requires N transmit antennas. In this paper,



(a) Transmitter



(b) Receiver

Fig. 1 Transmission system model of OSTSTD.

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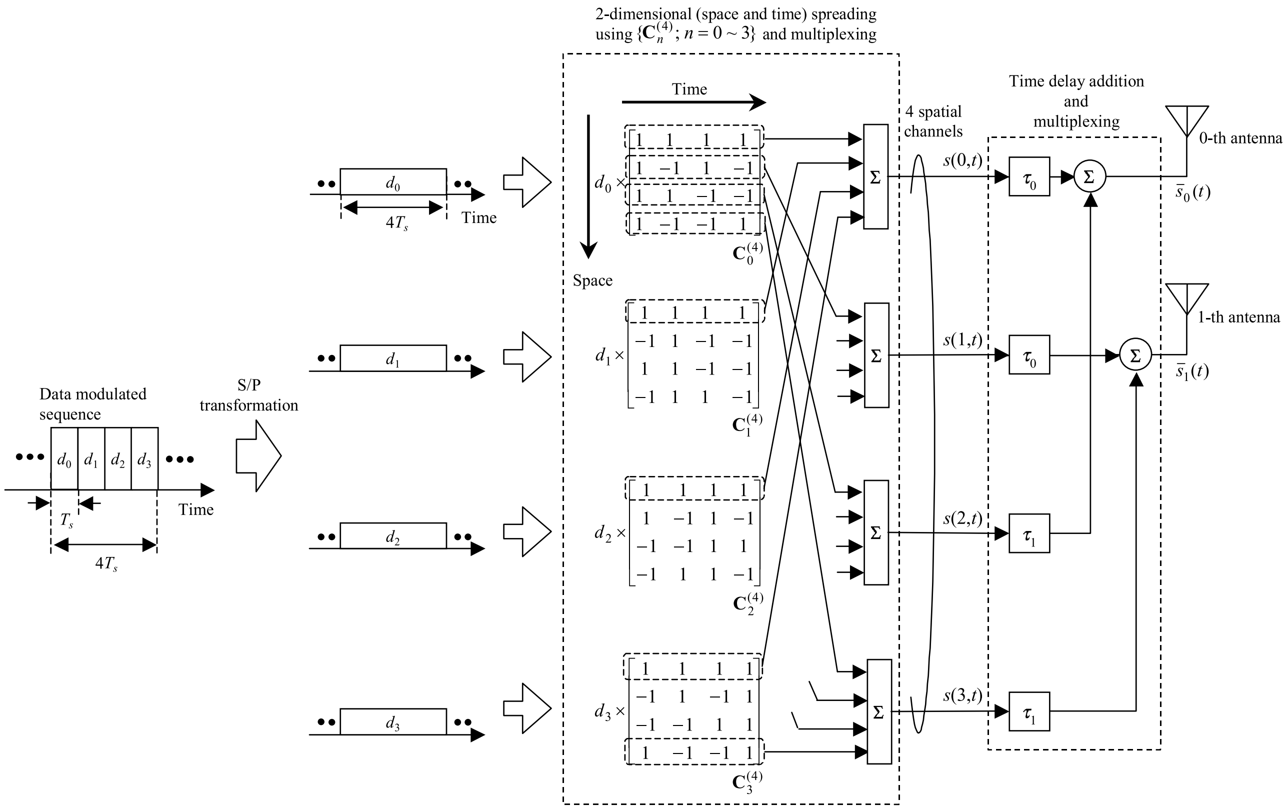


Fig. 2 Space-time spreading and delay transmission when N = 4.

to reduce the number of transmit antennas to two, time delay is added to each spatial channel and combined into two streams of orthogonal space-time spread signals. For a better understanding of the proposed OSTSTD, the space-time spreading and delay transmission process is illustrated for N=4 in Fig. 2.

2.1 Orthogonal Space-Time Spreading Codes

Orthogonal $N \times N$ space-time spreading codes $\boldsymbol{C}_n^{(N)}$, $n = 0 \sim N-1$, are constructed using the $N \times N$-Hadamard matrix $\boldsymbol{H}^{(N)}$. The element $c_n^{(N)}(m,t) = \pm 1$ of $\boldsymbol{C}_n^{(N)}$ at the m-th row and t-th column is generated as [7]

$$c_n^{(N)}(m,t) = h^{(N)}(m,t)h^{(N)}(n,m), \tag{1}$$

where $h^{(N)}(m,t) = \pm 1$ is the element of $\boldsymbol{H}^{(N)}$ at the m-th row and t-th column. $h^{(N)}(m,t)$ (or $h^{(N)}(n,m)$) is used for orthogonal temporal (or spatial)-spreading of the transmitted data. For a better understanding of orthogonal space-time spreading codes, the case of N=4 is shown below:

$$\begin{aligned} \boldsymbol{C}_0^{(4)} &= \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}, \boldsymbol{C}_1^{(4)} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 \end{bmatrix} \\ \boldsymbol{C}_2^{(4)} &= \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ -1 & -1 & 1 & 1 \\ -1 & 1 & 1 & -1 \end{bmatrix}, \boldsymbol{C}_3^{(4)} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 \\ -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \end{aligned}. \tag{2}$$

2.2 Spreading and Despreading

We consider the transmission of N data-modulated symbols $\{d_n; n = 0 \sim N-1\}$ during a period of NT_s. Symbol (T_s)-spaced discrete time representation of the space-time spread signal is used. The space-time spreading code of length N in time (chip length is T_s) for the transmission of the nth data symbol d_n on the m-th spatial channel is represented by $\{c_n^{(N)}(m,t);\ t = 0 \sim N-1\}$. Thus, the space-time spread signal $s(m,t)$ of the m-th spatial channel can be expressed in the equivalent lowpass representation as

$$s(m,t) = \sqrt{2S/N^2} \sum_{n=0}^{N-1} d_n c_n^{(N)}(m, t \mod N) \tag{3}$$

for m=0$\sim N-1$, where S is the total transmit power. Since the chip rate of the space-time spreading code is $1/T_s$ and equals the transmit data symbol rate, there is no bandwidth expansion in OSTSTD. Orthogonal space-time spreading codes have the property that any two rows taken from either the same spreading code or a different spreading code are orthogonal to each other, i.e.,

$$(1/N) \sum_{t=0}^{N-1} h^{(N)}(m,t)h^{(N)}(m',t) = 0 \quad \text{if } m \neq m'. \tag{4}$$

This allows simple recovery of the N transmitted symbols using the well-known MMSE despreading as in multicarrier

CDMA (MC-CDMA) [8].

The space-time spread signals $s(m,t)$'s with m=2i and 2i+1 to be transmitted are added the same time delay $\tau_i = iDN$ for delay transmission (note that the delay transmission does not decrease the transmit symbol rate), where D denotes the time delay separation and i is the integer. Then, $N/2$ space-time spread signals with $m = 2i$, $i = 0 \sim N/2-1$, are added, and those with $m = 2i+1$, $i = 0 \sim N/2-1$, are also added to produce two spread signal sequences, $\bar{s}_0(t)$ and $\bar{s}_1(t)$, for transmission from two transmit antennas, respectively, where

$$\bar{s}_{m_t}(t) = \sum_{i=0}^{N/2-1} s(2i+m_t, t-\tau_i) \quad \text{for } m_t = 0 \text{ and } 1. \tag{5}$$

M_r receive antennas are used at the receiver. The complex-valued propagation channel gain experienced between the m_t-th transmit antenna and the m_r-th receive antenna is represented by $\xi_{m_t,m_r}(t)$ with the ensemble average of $\left|\xi_{m_t,m_r}(t)\right|^2$ being unity for all m_t and m_r ($m_t = 0 \sim 1$ and $m_r = 0 \sim M_r-1$). The received signal on the m_r-th receive antenna at time t can be represented as

$$r_{m_r}(t) = \xi_{0,m_r}(t)\bar{s}_0(t) + \xi_{1,m_r}(t)\bar{s}_1(t) + \eta(t), \tag{6}$$

where $\eta(t)$ is the additive white Gaussian noise (AWGN) process with zero mean and a variance of $2N_0/T_s$ with N_0 being the AWGN power spectrum density.

Space-time despreading of N transmitted data symbols consists of two steps. The first step (time-domain despreading) recovers the N spatial channels by taking the correlation between the received signal $r_{m_r}(t)$ and N time-domain spreading codes $\{h^{(N)}(m,t);\ m = 0 \sim N-1\}$. Using Eq. (6), we obtain

$$\tilde{r}_{m_r}(m) = (1/N)\sum_{t=0}^{N-1} r_{m_r}(t+\tau_{\lfloor m/2\rfloor})h^{(N)}(m,t) \tag{7}$$

for $m = 0 \sim N-1$, where $\lfloor x\rfloor$ denotes the largest integer smaller than or equal to x. N transmitted data symbols $\{d_n:\ n = 0 \sim N-1\}$ are spread over the N spatial channels using the spatial-domain spreading codes $\{h^{(N)}(n,m);\ n = 0 \sim N-1\}$. Therefore, $\tilde{r}_{m_r}(m)$ can be treated as the m-th subcarrier component in MC-CDMA with N subcarriers and N code-multiplexing (the spatial-domain spreading in the OSTSTD corresponds to the frequency-domain spreading in the MC-CDMA). Thus, frequency-domain despreading used in MC-CDMA can be applied to the spatial-domain despreading in OSTSTD. Among the various despreding methods, e.g., zero forcing (ZF), maximum ratio combining (MRC) and MMSE combining as in MC-CDMA [9], this paper employs the MMSE despreading, since MMSE despreading provides a superior BER performance than other despreading methods [8], [9]. With the increase in N, the BER performance of OSTSTD improves as in multicode MC-CDMA [10] (this is because as the spreading factor increases, the frequency diversity gain becomes larger and thus the BER of MC-CDMA improves).

The second step (spatial-domain despreading) yields the decision variable $\{\tilde{d}_n;\ n = 0 \sim N-1\}$ for the recovery of the n-th transmitted data symbol using MMSE:

$$\tilde{d}_n = (1/N)\sum_{m=0}^{N-1}\left(\sum_{m_r=0}^{M_r-1} w_{m_r}(m)\tilde{r}_{m_r}(m)\right)h^{(N)}(n,m) \tag{8}$$

for $n = 0 \sim N-1$, where

$$w_{m_r}(m) = \frac{\hat{\xi}^*_{m_r}(m)}{\sum_{m_r=0}^{M_r-1}\left|\hat{\xi}_{m_r}(m)\right|^2 + \left(\frac{E_s}{N_0}\right)^{-1}} \tag{9}$$

is the MMSE weight [9] with E_s/N_0 being the average symbol energy-to-AWGN power spectrum density ratio, * denotes the complex conjugate, and

$$\hat{\xi}_{m_r}(m) = \begin{cases} \xi_{0,m_r}(\tau_{\lfloor m/2\rfloor} + (N-1)/2) & \text{if } m = \text{even} \\ \xi_{1,m_r}(\tau_{\lfloor m/2\rfloor} + (N-1)/2) & \text{if } m = \text{odd} \end{cases}. \tag{10}$$

Performance degradation in OSTSTD is due to orthogonality destruction of space-time spreading codes. Spatial orthogonality destruction is produced since N spatial channels are subjected to different fading (in MC-CDMA, this corresponds to a severe frequency-selective channel). Temporal orthogonality destruction is caused by the time-selective fading. However, the fading variation over N-symbol period is almost negligible (the normalized maximum Doppler frequency f_DT_sN is 0.0096 (N=16) and 0.0192 (N=32) for a vehicular speed of 40 km/h, a carrier frequency of 2 GHz and the transmission symbol rate of $1/T_s$=128 ksps) and thus, temporal orthogonality destruction can be negligible in most cases.

2.3 Comparison with STSTD

The space-time spreading and despreading of OSTSTD is different from STSTD [6]. For simplicity, we consider OSTSTD with N=2 and M_r=1, which corresponds to the special case of no delay transmission. We assume that fading channel stays constant during two symbols, $2T_s$. OSTSTD uses the 2×2 orthogonal space-time spreading code matrices given by

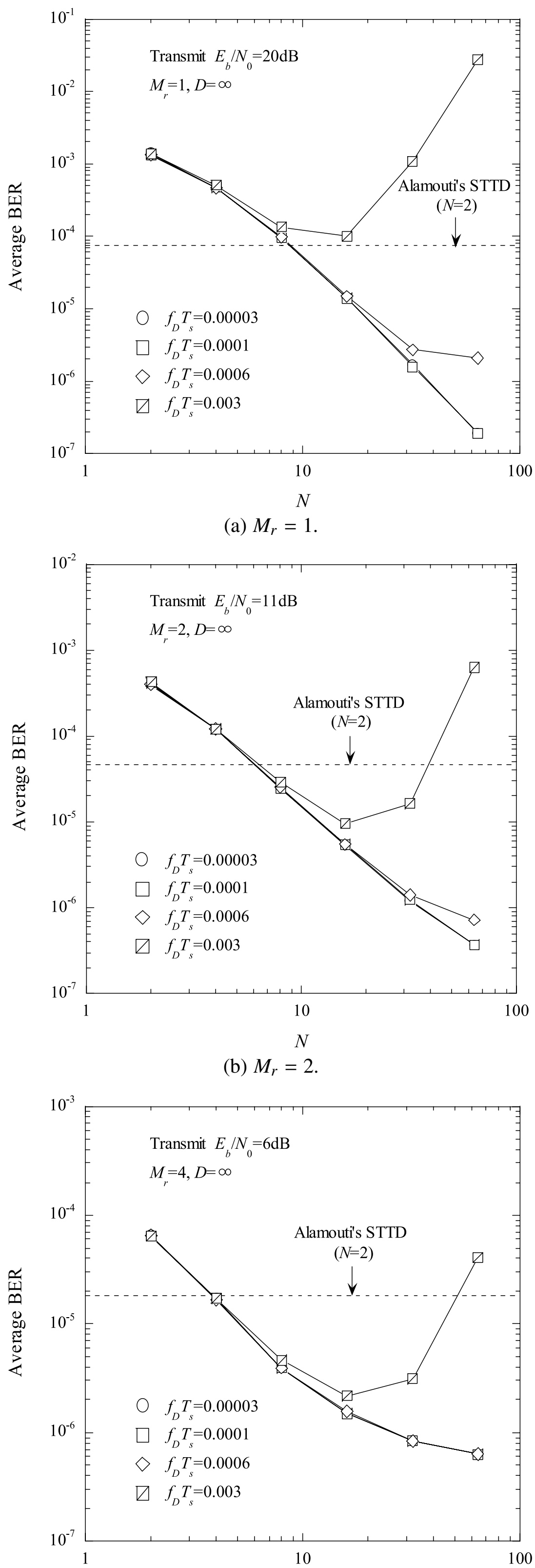
$$\boldsymbol{C}_0^{(2)} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix},\ \boldsymbol{C}_1^{(2)} = \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}. \tag{11}$$

The space-time spread signals $\bar{s}_0(t)$ and $\bar{s}_1(t)$ of OSTSTD become

$$\begin{cases} \bar{s}_0(t) = \sqrt{S/2}(d_0+d_1)c_0 \\ \bar{s}_1(t) = \sqrt{S/2}(d_0-d_1)c_1 \end{cases}, \tag{12}$$

where c_0={1,1} and c_1={1, −1} are time-domain orthogonal spreading codes. At the receiver, using Eq. (7), we obtain

$$\begin{cases} \tilde{r}_0(0) = (\sqrt{S/2}/2)(d_0+d_1)\xi_{0,0} + \eta(0) \\ \tilde{r}_0(1) = (\sqrt{S/2}/2)(d_0-d_1)\xi_{1,0} + \eta(1) \end{cases}. \tag{13}$$



(a) $M_r = 1$.

(b) $M_r = 2$.

(c) $M_r = 4$.

Fig. 3 Effect of space-time spreading code size N.

Then, MMSE despreading is carried out to recover the 2 transmitted data symbols. OSTSTD has a tradeoff relationship between the diversity effect and the code orthogonality destruction. But, by using MMSE despresding, the BER performance continuously improves as the space-time spreading code size N increases (this will be understood later in Fig. 3) since the improvement in diversity effect exceeds the degradation due to the code orthogonality destruction.

On the other hand, STSTD uses the 2×2 space-time spreading code matrices given by

$$\boldsymbol{C'}^{(2)}_0 = \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}, \ \boldsymbol{C'}^{(2)}_1 = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}. \tag{14}$$

The space-time spread signals $\tilde{s}'_0(t)$ and $\tilde{s}'_1(t)$ of STSTD are given by

$$\begin{cases} \tilde{s}'_0(t) = \sqrt{S}(d_0 c_0 + d_1^* c_1) \\ \tilde{s}'_1(t) = \sqrt{S}(d_1 c_0 - d_0^* c_1) \end{cases}. \tag{15}$$

At the receiver, similar to Eq. (7), taking the correlation between the received space-time spread signal and time-domain spreading sequence, we obtain

$$\begin{cases} \tilde{r}'_0(0) = (\sqrt{S}/2)(\xi_{0,0} d_0 + \xi_{1,0} d_1) + \eta'(0) \\ \tilde{r}'_0(1) = (\sqrt{S}/2)(-\xi_{1,0} d_0^* + \xi_{0,0} d_1^*) + \eta'(1) \end{cases}. \tag{16}$$

The decoding for recovering the data symbol is carried out as shown below:

$$\begin{cases} \tilde{d}'_0 = \tilde{r}'_0(0)\xi^*_{0,0} - \left(\tilde{r}'_0(1)\xi^*_{1,0}\right)^* \\ \quad = \frac{\sqrt{S}}{2}\left(\left|\xi_{0,0}\right|^2 + \left|\xi_{1,0}\right|^2\right) d_0 + (\eta'(0)\xi^*_{0,0} - \eta'^*(1)\xi_{1,0}) \\ \tilde{d}'_1 = \tilde{r}'_0(0)\xi^*_{1,0} + \left(\tilde{r}'_0(1)\xi^*_{0,0}\right)^* \\ \quad = \frac{\sqrt{S}}{2}\left(\left|\xi_{0,0}\right|^2 + \left|\xi_{1,0}\right|^2\right) d_1 + (\eta'(0)\xi^*_{1,0} + \eta'^*(1)\xi_{0,0}) \end{cases}. \tag{17}$$

It is understood from Eq. (17) that STSTD achieves the two-fold diversity gain, and thus provides the same BER performance as Alamouti's STTD. Therefore, for performance comparison in Sect. 3, we only present the BER performance result of Alamouti's STTD.

It is obvious from Eqs. (11) and (14) that the space-time spreading code matrices of OSTSTD are different from that of STSTD, thereby producing different space-time spread signals to be transmitted from two antennas. When the space-time spreading code size N is small, it is expected that the STSTD (or Alamouti's STTD) provides superior BER performance to OSTSTD, since OSTSTD is severely affected by the code orthogonality destruction while the STSTD can offer the two-fold diversity. However, as N increases, OSTSTD can acquire more-than-two-fold diversity gain due to delay transmission even if two transmit antennas are used. Hence, it can be expected that OSTSTD outperforms STSTD (or Alamouti's STTD).

3. Computer Simulation

Table 1 shows the simulation condition. QPSK data modulation is used. Propagation channels between each transmit

Table 1 Simulation condition.

Data modulation	QPSK
Orthogonal code	Walsh-Hadamard code
No. of transmit antennas	2
Propagation channel model	Frequency non-selective Rayleigh fading
No. of receive antennas	M_r=1,2 and 4
Channel estimation	Ideal

antenna and M_r receive antennas are assumed to be characterized by independent frequency-nonselective Rayleigh fading processes. Channel estimation is assumed to be ideal.

OSTSTD spreads N data symbols spatially and temporally and transmits them from two transmit antennas using delay transmission. As the space-time spreading code size N becomes larger, the achievable BER performance improves due to increasing time diversity effect. However, since we take the correlation between the received signals and time-domain spreading codes at the receiver in order to separate the N orthogonal spatial channels, the use of the large space-time spreading code size causes the code orthogonality destruction in time if fading becomes faster. Hence, there is a tradeoff relationship between the time diversity effect and the code orthogonality in time. First, we evaluate the effect of the space-time spreading code size N on the average BER performance. Next, we show how the fading rate impacts the BER performance of OSTSTD. Finally, we compare OSTSTD with DS-CDMA using STTD.

3.1 Effect of Space-Time Spreading Code Size

Figure 3 plots the simulated average BER of OSTSTD as a function of N with the normalized maximum Doppler frequency $f_D T_s$ as a parameter. We set the transmit E_b/N_0 to 20, 11 and 6 dB for M_r=1, 2 and 4, respectively, so that similar average BER is achieved when N=32. The time delay separation D between the adjacent space-time spread signals is assumed to be infinite. This implies that N independent spatial channels are constructed. For comparison, the average BER of Alamouti's STTD is also plotted. When N=2, OSTSTD is inferior to STTD because of severe orthogonality destruction of spatial-domain spreading codes. When N=4, 4 space-time spread signals are divided into 2 groups and delay transmission is applied to obtain both space and time diversity effects. But, since the number of time diversity branches is only two and cannot achieve sufficient time diversity gain, OSTSTD is still inferior to STTD. However, by increasing N, time diversity gain increases and thus, OSTSTD outperforms STTD even for small $f_D T_s$ values when $N \geq 16$, 8 and 8 for M_r=1, 2 and 4, respectively.

It can be seen from Fig. 3 that the BER increases rapidly as $f_D T_s$ increases beyond a certain value and becomes larger than that of STTD. This is because of the increased code orthogonality destruction in time. However, the value of $f_D T_s$ at which the BER starts to increase becomes larger as M_r increases. Thus, the use of the receive diversity reception is always beneficial. In the following, N=16 and 32 are used.

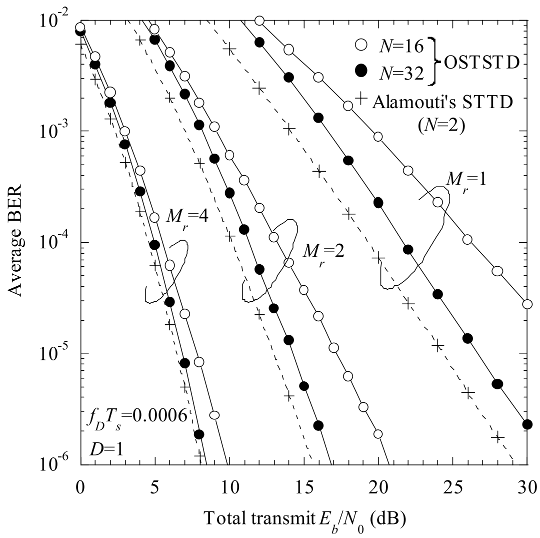
Figure 4 plots the average BER performance as a function of the total transmit E_b/N_0 (=0.5 E_s/N_0) with M_r as a parameter for the normalized maximum Doppler frequency $f_D T_s$=0.0006 (which corresponds to a mobile speed of approximately 40km/h for a carrier frequency of 2 GHz and a transmission symbol rate of $1/T_s$=128 ksps). When D=1, OSTSTD provides a BER performance worse than Alamouti's STTD since the time diversity effect cannot be obtained. As D increases, however, the average BER performance improves since each data symbol is spread over N independently faded spatial channels. When M_r=2 and D=20, the total transmit E_b/N_0 required for the average BER=10^{-5} is 11.0 (9.8) dB when N=16 (32). OSTSTD provides better BER performance than Alamouti's STTD. The gain in terms of the required average transmit E_b/N_0 compared with Alamouti's STTD is as much as 2.0 (3.1) dB when N=16 (32).

3.2 Impact of Fading Rate

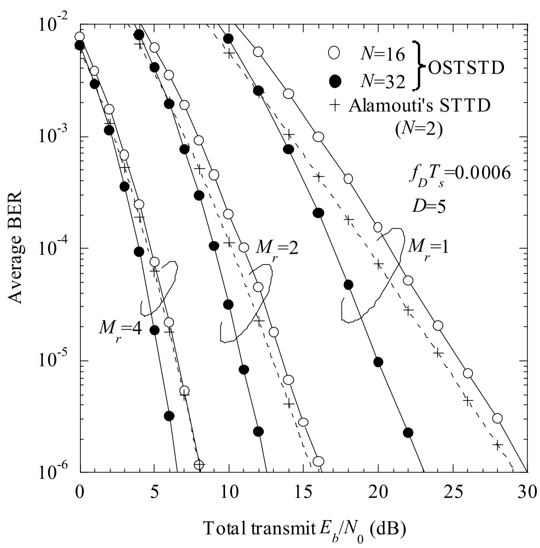
The average BERs are plotted with D as a parameter in Fig. 5. The BER performance of OSTSTD improves due to space and time diversity effects. Assuming that antenna spacing is large enough so that each channel between a transmit antenna and a receive antenna is statistically independant, OSTSTD can always achieve the maximum space diversity gain. However, the time diversity effect depends on the fading rate ($f_D T_s$) and the BER of OSTSTD degrades compared to Alamouti's STTD which can always achieve 2-branch space diversity gain irrespective of the fading rate. However, it can be seen from Fig. 5 that OSTSTD achieves superior performance than Alamouti's STTD by properly setting the transmit time delays. As a consequence, the OSTSTD can improve the BER performance and outperforms Alamouti's STTD at the cost of the transmission delay, but with the same transmit symbol rate.

3.3 Comparison with DS-CDMA Using STTD

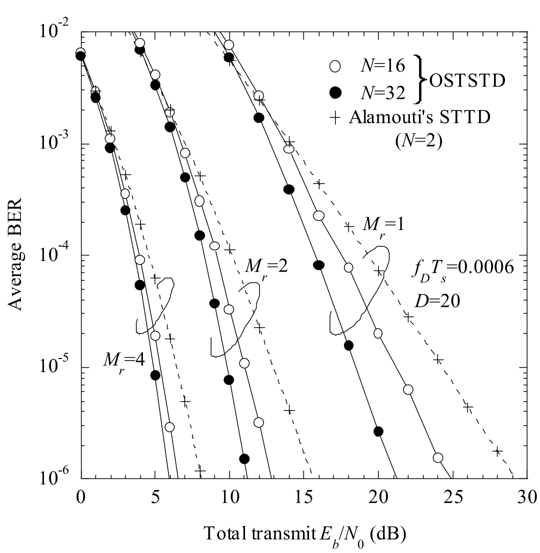
Our proposed OSTSTD uses space-time spreading to obtain diversity gain without bandwidth expansion. Another possible transmit diversity is multicode DS-CDMA using STTD [11]; however, there is bandwidth expansion unless the full code multiplexing is used (the number of codes to be multiplexed is equal to the spreading factor). For performance comparison, the full code multiplexing is assumed for multicode DS-CDMA using STTD (i.e., the transmit symbol rate is equal to the chip rate). First, we consider no delay transmission for multicode DS-CDMA using STTD. Figure 6 compares the BER performances achievable with OSTSTD and multicode DS-CDMA using STTD. The spreading factor N for multicode DS-CDMA is assumed to be 16. Mul-



(a) D = 1.

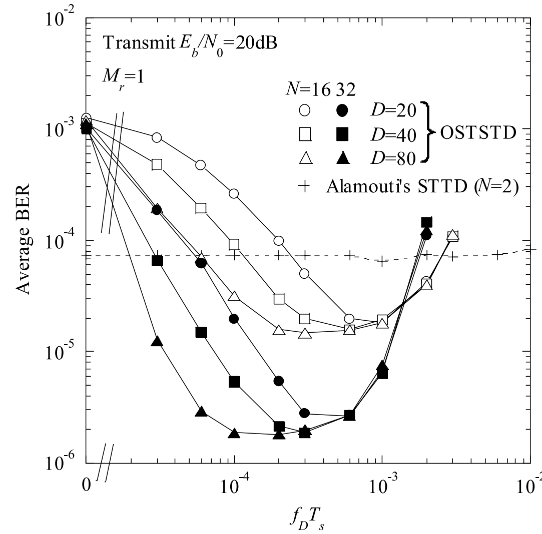


(b) D = 5.

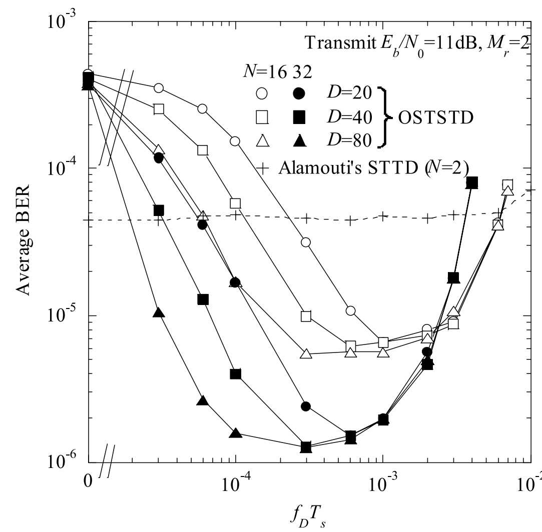


(c) D = 20.

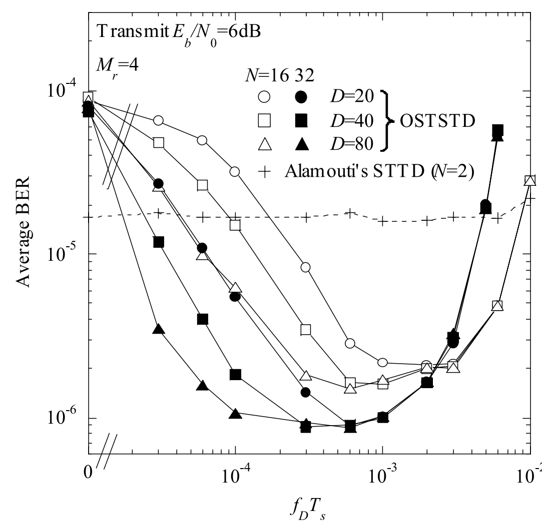
Fig. 4 Average BER performance.



(a) M_r = 1.



(b) M_r = 2.



(c) M_r = 4.

Fig. 5 Impact of fading rate.

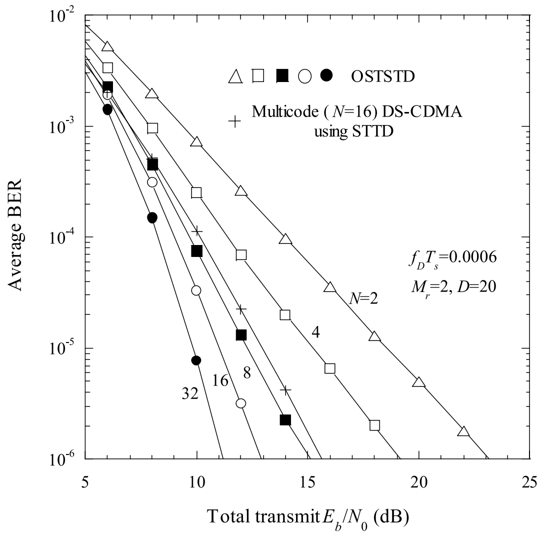


Fig. 6 Performance comparison between OSTSTD and multicode DS-CDMA using STTD.

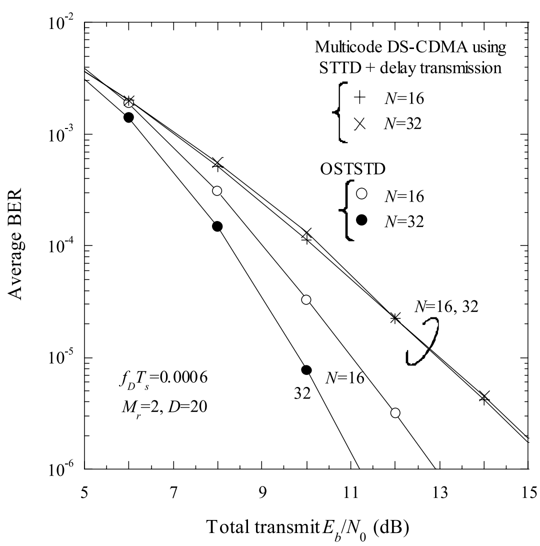


Fig. 7 Performance comparison between OSTSTD and multicode DS-CDMA using STTD both applying delay transmission.

ticode DS-CDMA using STTD can achieve 2-branch space diversity gain and thus, can obtain the same BER performance as STTD. Notice that, when $N \leq 4$, OSTSTD is inferior to multicode DS-CDMA using STTD. However, OSTSTD can increase N by using delay transmission with two transmit antennas. OSTSTD with $N \geq 8$ can obtain a BER performance superior to both STTD and multicode DS-CDMA using STTD.

Next, we consider the use of delay transmission in multicode DS-CDMA using STTD. N orthogonal spatial channels are divided into 2 channel groups; each group consists of $N/2$ spatial channels. The time delay is added to one group and 2 channel groups are multiplexed for delay transmission in multicode DS-CDMA using STTD. However, each data symbol to be transmitted is spread only over one dimension (i.e., time-domain) and therefore, the time diversity gain cannot be obtained. If each data symbol could be spread over two dimensions, time diversity gain could be obtained; this idea is used in OSTSTD. Figure 7 compares the BER performances of OSTSTD and multicode DS-CDMA using STTD both applying delay transmission. N=16 and 32 is assumed (note that N for DS-CDMA is the spreading factor). It can be seen from Fig. 7 that with increasing N, OSTSTD can improve the BER performance by using delay transmission, but multicode DS-CDMA using STTD cannot improve the performance.

4. Conclusion

In this paper, orthogonal space-time spreading transmit diversity (OSTSTD) combined with delay transmission and using two transmit antennas was proposed. 2-step space-time despreading based on MMSE criterion was presented to recover the transmitted data symbols spread over a number of independent spatial channels constructed by orthogonal spreading and delay transmission. The average BER performance achievable with the proposed OSTSTD in a Rayleigh fading channel was evaluated by computer simulation. It was confirmed that, by properly setting the transmission delays, OSTSTD provides BER performance superior to Alamouti's STTD at the cost of the transmission time delay.

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