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Agenda item : AH24: HSDPA

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Title: Improved Double-STTD schemes using asymmetric modulation and antenna shuffling

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1. Introduction

Lucent proposed the multi-input multi-output (MIMO) scheme for high speed downlink packet access (HSDPA) in [1-4] for 2, 4 transmit antennas and 2 or more receive antennas. However, for systems with two transmit antennas, it has been demonstrated by Fujitsu and Texas Instruments in [5] and [6], respectively, that Release 99 space-time transmit diversity (STTD) outperforms Lucent's MIMO. For systems with four transmit antennas, Texas Instruments has proposed the double-STTD (DSTTD) scheme, which has been demonstrated to outperform Lucent's MIMO in a number of aspects [6]. One of the aspects is the robustness to correlated fading channels. The performance of DSTTD is much less sensitive to spatial channel correlation compared to Lucent's MIMO. This is particularly advantageous since correlated channels often occur in practice due to small angular spread and/or relatively small antenna spacing.

In this contribution, we propose to further improve the DSTTD in [6] for HSDPA applications employing two different techniques:

- *Asymmetric modulation:* Asymmetric modulation is applicable for 4.5 bps/Hz systems (10.8 Mbps data rate when 20 codes are used), by employing QPSK and 16QAM modulation for the first and the second STTD encoders, respectively instead of two 8PSK modulated streams.
- *Antenna shuffling*. Antenna shuffling is used to improve the performance of DSTTD in correlated fading channels. Antenna shuffling is choosing the right pairs of antennas at the transmitter across which STTD is to be applied. An antenna shuffling pattern is chosen at the transmitter depending upon the spatial channel correlation profile. To support antenna shuffling, some kind of signaling from the receiver to the transmitter is needed to signal the chosen shuffling pattern corresponding to the particular spatial channel correlation. Since channel correlation profile varies very slowly, the feedback on the antenna shuffling can be sent infrequently at a slow rate. Hence this scheme is applicable in fast fading channels. Examples of events that correspond to significant change in channel correlation profile are hand-offs and sudden change in angular spreads (terrain). We demonstrate via simulations that asymmetric modulation and antenna shuffling can offer significant performance gain for DSTTD (up to 2-dB for (4,4) and 3-dB for (4,2) scenarios).

2. The Double-STTD scheme

The transmitter structure for the DSTTD scheme in [6] with 4 transmit antennas is depicted in Figure 1. The data stream coming from the modulator is split into 2 streams and each stream is STTD-encoded. Then, multicode spreading is applied to each of the resulting 4 streams after twice STTD-encoding, where each stream uses the same set of spreading codes (similar to 'code reuse' concept in MIMO). The signal transmitted via antenna 1 and 2 are orthogonal due to STTD encoding. The same holds for antenna 3 and

4. Hence, signal on each transmit antenna is affected by the interference from two out of three other antennas. Also, due to STTD encoding, each data symbol is guaranteed to have (transmit) diversity of 2. It is easy to see that the regular STTD is a special case of DSTTD. At the receiver (see Figure 2), the signal at each receive antenna is despread. The signal from all receive antennas after despreading are coherently combined using two STTD decoders for each receive antenna. Equivalently, direct space-time rake combining can be used by exploiting the following equation for each receive antenna:

$$[r_n(0) \quad r_n(1)] = \frac{1}{\sqrt{2}}[h_{n1} \quad h_{n2} \quad h_{n3} \quad h_{n4}]\begin{bmatrix} x_1 & x_2 \\ -x_2{}^* & x_1{}^* \\ x_3 & x_4 \\ -x_4{}^* & x_3{}^* \end{bmatrix} + [w_n(0) \quad w_n(1)]$$

$$\Leftrightarrow \quad \begin{bmatrix} r_n(0) \\ r_n{}^*(1) \end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix} h_{n1} & -h_{n2} & h_{n3} & -h_{n4} \\ h_{n2}{}^* & h_{n1}{}^* & h_{n4}{}^* & h_{n3}{}^* \end{bmatrix}\begin{bmatrix} x_1 \\ x_2{}^* \\ x_3 \\ x_4{}^* \end{bmatrix} + \begin{bmatrix} w_n(0) \\ w_n{}^*(1) \end{bmatrix} \qquad \ldots\ldots(1)$$

where factor $\sqrt{2}$ is needed to normalize the transmit power after STTD encoding. The output of DSTTD combiner corresponding to each transmit antenna is contaminated with interference from two other transmit antennas. Interference-resistant detection algorithm such as iterative MMSE can be used right after the combining. Note that one DSTTD combining operation is done across 2 symbol intervals. Hence, the detector performs only 1 operation per 2 symbol intervals.

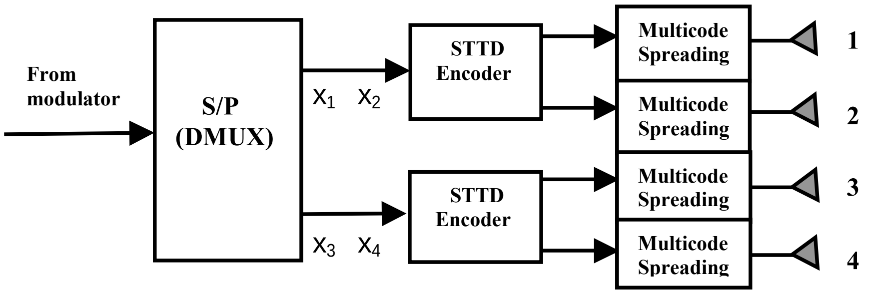


Figure 1. Transmitter structure for the *original DSTTD* [6] with 4 transmit antennas

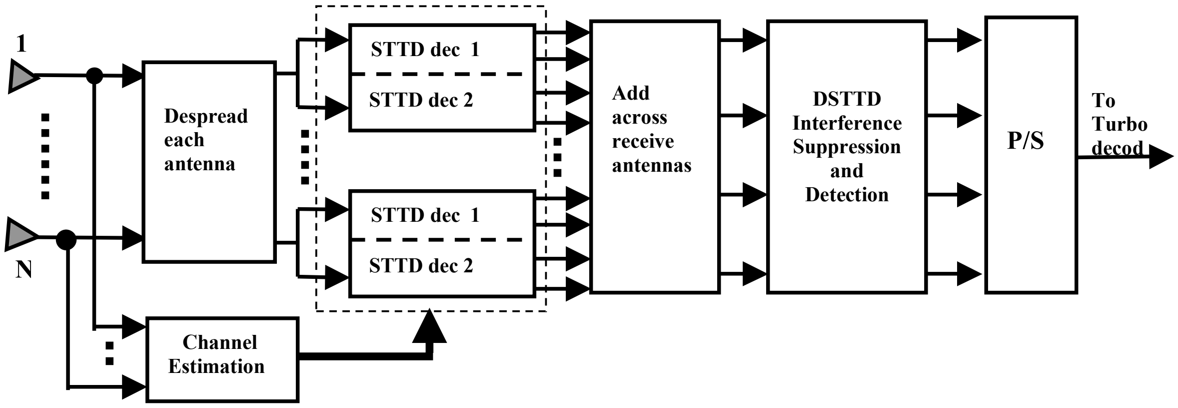


Figure 2. A receiver structure for the *original DSTTD* [6] with 4 transmit antennas

2.1. Asymmetric Modulation

In some cases, it is possible to obtain some performance gain by using different modulation schemes for the upper (x_1, x_2) and lower streams (x_3, x_4). For 4.5 bps/Hz (10.8 Mbps data rate when 20 codes are used), the original DSTTD presented in [6] uses 8-PSK modulation. That is, x_1, x_2, x_3, and x_4 in Figure 1 are all 8-PSK modulated. We term this as the *symmetric* modulation scheme. The corresponding asymmetric modulation scheme uses QPSK modulation for the upper stream (x_1, x_2) and 16-QAM for the lower stream (x_3, x_4). Note that there is no additional complexity at the transmitter when asymmetric modulation is used since both QPSK and 16-QAM modulation are supported for HSDPA (see Figure 3).

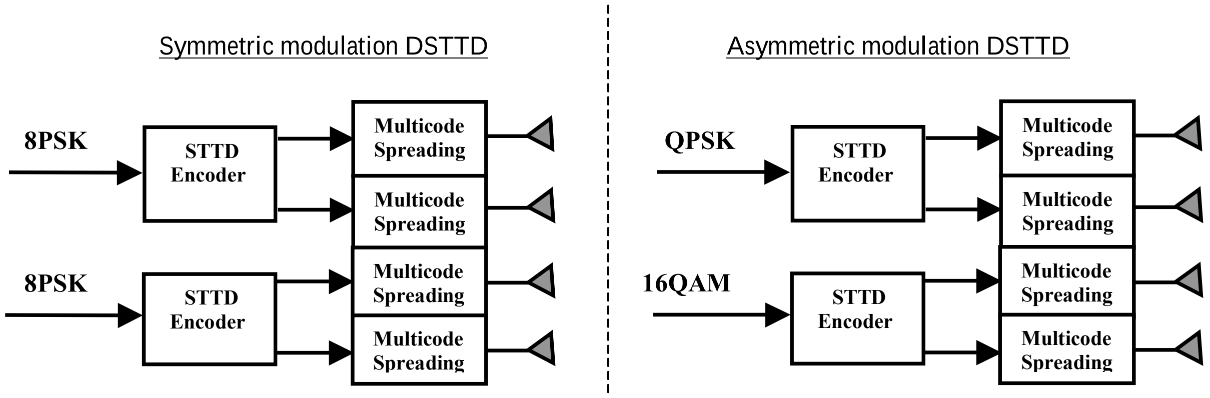


Figure 3. Symmetric and asymmetric modulation for 4.5 bps/Hz (10.8 Mbps) DSTTD

When iterative MMSE detector is used, different modulation schemes for different symbols must be taken into account. We found that the best detection ordering criterion is based on SINR per bit instead of SINR per symbol. This change does not result in additional receiver complexity. These two criteria are equivalent when the same modulation schemes are used for all the symbols.

2.2. Antenna Shuffling

The idea behind antenna shuffling is to choose the best ordering of the outputs of two STTD encoders with respect to four transmit antennas based upon the channel correlation profile. Essentially, antenna shuffling performs a linear transformation to the channel (see Figure 4). Defining

$$\mathbf{h}_n = \begin{bmatrix} h_{n1} & h_{n2} & h_{n3} & h_{n4} \end{bmatrix}^T \quad \ldots\ldots(2)$$

the new channel after antenna shuffling can be written as $\tilde{\mathbf{h}}_n = \mathbf{W}^T \mathbf{h}_n$ (superscript T denotes matrix transpose), where $\mathbf{W}$ is a 4×4 permutation matrix representing the shuffling operation. Although there are 4! = 24 different permutation matrices, by symmetry it suffices to consider the following 6 different permutation matrices:

$$\mathbf{\Pi}_{1234} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{\Pi}_{1243} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad \mathbf{\Pi}_{1324} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{\Pi}_{1342}=\begin{bmatrix}1&0&0&0\\0&0&0&1\\0&1&0&0\\0&0&1&0\end{bmatrix},\quad \mathbf{\Pi}_{1423}=\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&0&0&1\\0&1&0&0\end{bmatrix},\quad \mathbf{\Pi}_{1432}=\begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix}. \qquad ......(3)$$

as the candidates for **W**. An example with shuffling pattern (1,3,2,4) is depicted in Figure 5. For FDD systems, the choice of antenna shuffling pattern is determined at the receiver using some performance criteria which is based on the channel correlation profile. This choice is then signaled to the transmitter, either via some higher layer signaling or uplink feedback channel.

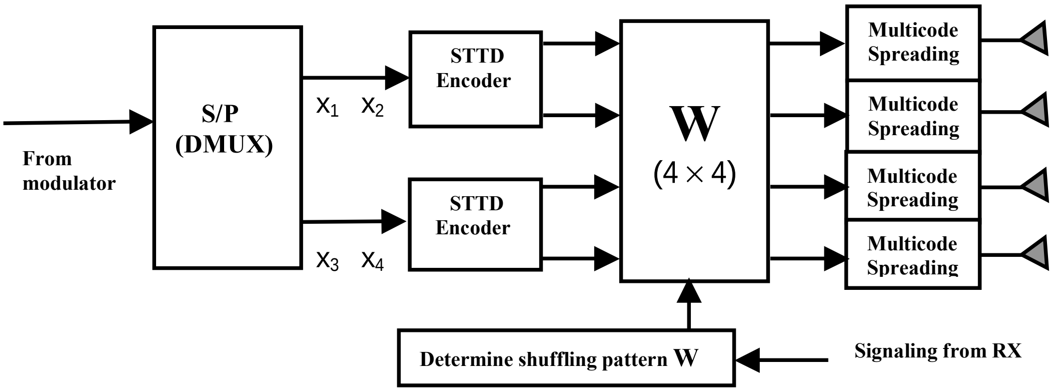


Figure 4. Transmitter structure for *DSTTD with shuffling* with 4 transmit antennas

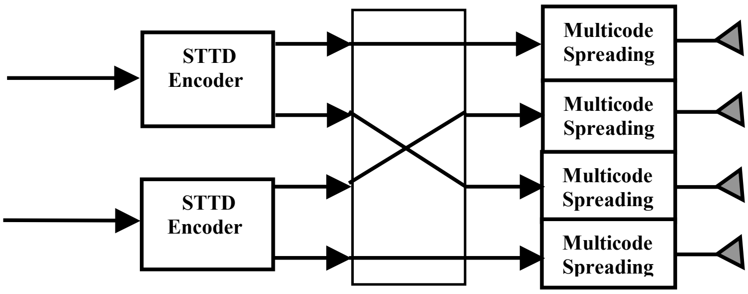


Figure 5. An example with shuffling pattern (1,3,2,4).

The channel correlation model proposed by Siemens in [7] suggests that the transmitter and receiver correlation are separable due to rich scattering in the channel. That is,

$$E\left[h_{nm}h_{n'm'}^{*}\right]=\rho_{RX}(n,n')\times\rho_{TX}(m,m') \qquad ...... (4)$$

Hence, we have the following from (4):

$$E\left[\mathbf{h}_n\mathbf{h}_n^{H}\right]=\rho_{RX}(n,n)\times\mathbf{R}_{TX}\ ,\quad E\left[\tilde{\mathbf{h}}_n\tilde{\mathbf{h}}_n^{H}\right]=\rho_{RX}(n,n)\times\tilde{\mathbf{R}}_{TX}\quad \text{with } \tilde{\mathbf{R}}_{TX}=\mathbf{W}^{T}\mathbf{R}_{TX}\mathbf{W} \qquad ......(5)$$

where superscript *H* denotes matrix complex conjugate. Since the channel vector for all receive antennas are affected in the same way by **W** and channel correlation at the transmitter and receiver are separable, it suffices to consider only $\tilde{\mathbf{R}}_{TX}$ for selecting the best $\mathbf{W}$ (see Figure 6). The same $\mathbf{W}$ should be used at the transmitter and receiver (for space-time rake combining).

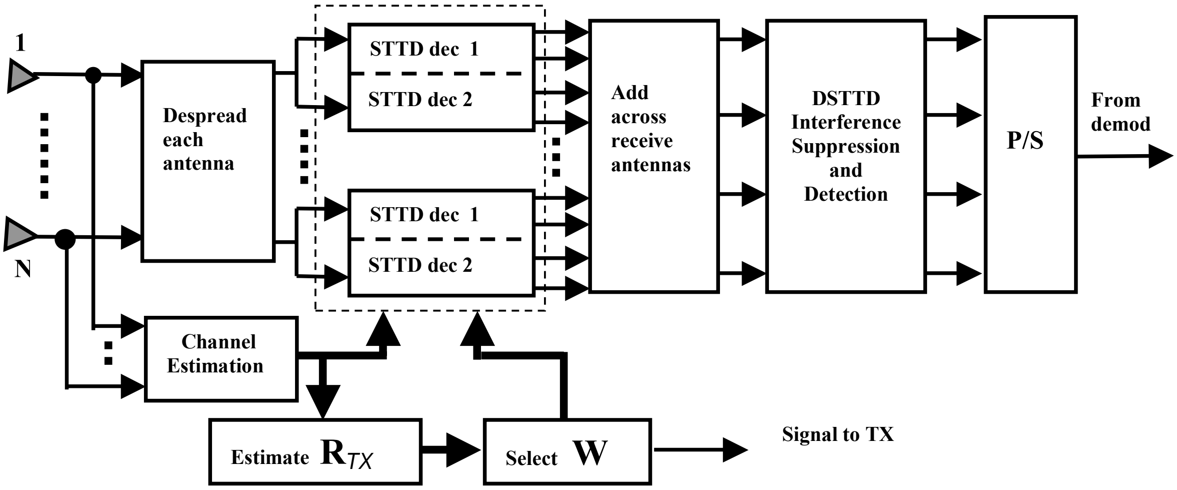


Figure 6. A receiver structure for *DSTTD with shuffling* with 4 transmit antennas

In IID channel, different ordering patterns will result in the same performance. In correlated fading, however, different ordering patterns may result in different performance. The key parameter which determines the scheme performance as a function of the shuffling pattern is the *expected value* of the channel matrix *after* space-time rake combining, which has the following form:

$$\mathbf{C}_n = \rho_{RX}(n,n) \times \begin{bmatrix} c_1 & 0 & a & b \\ 0 & c_1 & -b^* & a^* \\ a^* & -b & c_2 & 0 \\ b^* & a & 0 & c_2 \end{bmatrix}$$

$$c_1 = \tilde{\rho}_{TX}(1,1) + \tilde{\rho}_{TX}(2,2) \quad , \quad c_2 = \tilde{\rho}_{TX}(3,3) + \tilde{\rho}_{TX}(4,4)$$

$$a = \tilde{\rho}_{TX}(1,3)^* + \tilde{\rho}_{TX}(2,4) \quad , \quad b = -\tilde{\rho}_{TX}(1,4)^* + \tilde{\rho}_{TX}(2,3) \qquad \ldots\ldots(6)$$

The dependence of $\mathbf{C}_n$ upon $\mathbf{W}$ can be inferred from (5) as the elements of $\mathbf{C}_n$ are calculated according to (5) using an estimate of $\tilde{\mathbf{R}}_{TX}$. The shuffling pattern $\mathbf{W}$ can be chosen to satisfy the following optimality criterion:

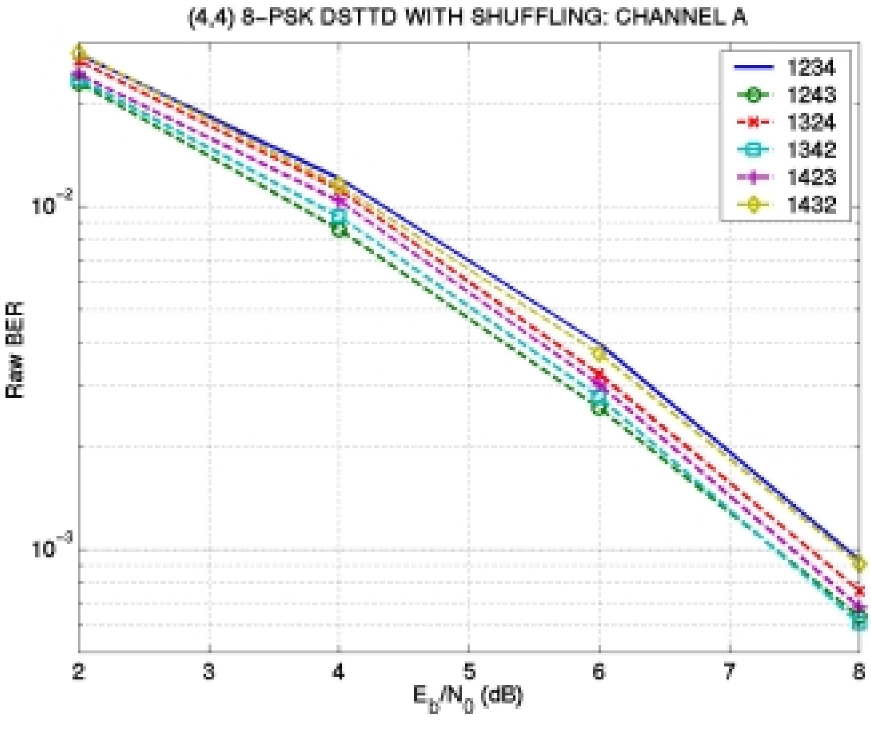
$$\mathbf{W} = \arg\min\left(|a|^2 + |b|^2\right) \quad s.t. \quad c_1 = c_2 = \frac{1}{4}\sum_{m=1}^{4} \rho_{TX}(m,m) \qquad \ldots\ldots(7)$$

The minimization in (7) suppresses the 'long-term' interference terms in $\mathbf{C}_n$, which are caused by channel correlation. For IID channels, $a = b = 0$. The constraint is intended to maintain uniform average received power across different streams. Note that this optimization problem does not depend on the number of receive antennas *N*. As an example, using Channel A and B model introduced in [3] we demonstrate that different shuffling patterns result in different performance. A (4,4) uncoded DSTTD system with 8PSK modulation is simulated with 6 different shuffling patterns in Channel A and B. The results (raw BER vs. E_b/N_0) are depicted in Figure 7 (a) and (b). Notice from Figure 7(a) that for Channel A, the best shuffling patterns are (1,2,4,3) and (1,3,4,2). It can be verified from (5)-(7) that these patterns indeed satisfy condition (7). Similarly, it can be verified for Channel B that shuffling pattern (1,4,3,2), which is the best according to simulation results Figure 7(b), satisfy condition (7). In both cases the performance for different shuffling patterns can be ranked according to $\left(|a|^2+|b|^2\right)$ as shown in Table 1 below:

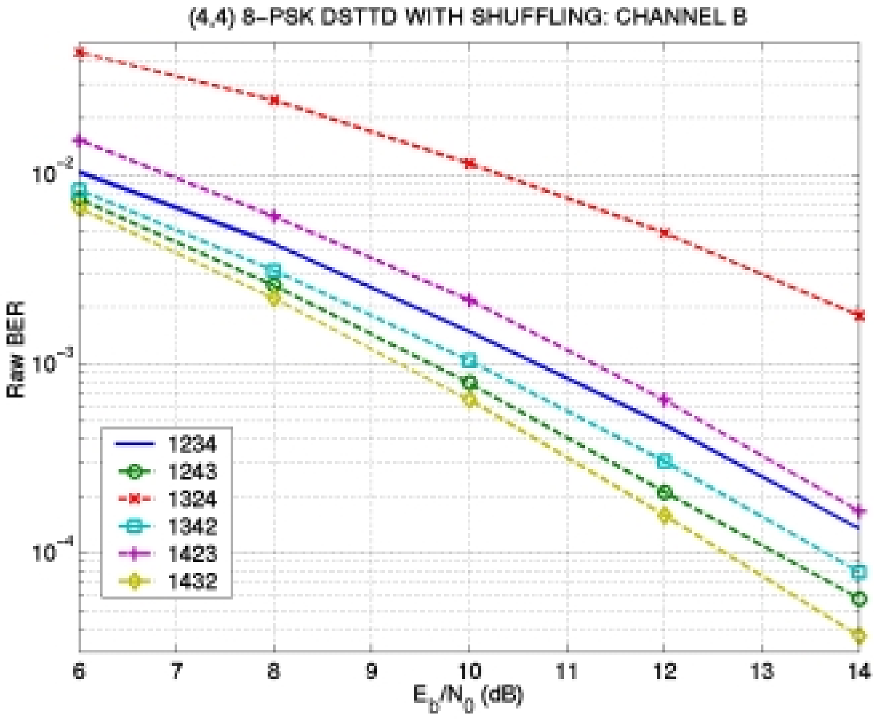
Table 1. Values of $\left(|a|^2+|b|^2\right)$ for different shuffling patterns in Channel A and B

Shuffling pattern	**Values of** $|a|^2+|b|^2$	
	Channel A	**Channel B**
1234	0.3533	0.5515
1243	0.0564	0.0289
1324	0.1990	1.3711
1342	0.0564	0.0289
1423	0.1689	0.8256
1432	0.3232	0.0060

We would like to note that different shuffling patterns will not result in different performance for Lucent's MIMO. This can be easily understood since antenna shuffling only introduces similarity transformation to the channel matrix after space-time rake combining.



(a)



(b)

Figure 7. Raw BER vs. E_b/N_0 for different shuffling patterns (a) Channel A (b) Channel B.

3. Assumptions and Simulation Parameters

We consider the following data rates and schemes shown in Table 2. Here, *M* and *N* denote the number of transmit and receive antennas, respectively. Frame-error rate (FER) vs. I_{or}/I_{oc} is used as performance measure. Additional assumptions and simulation parameters are shown in Table 3. For fair comparison among different schemes, the energy per information bit and the total transmit power are held constant. When antenna shuffling option is activated, the shuffling pattern is chosen according to (7).

Table 2. (4,N) schemes considered in this contribution: N=2,4

Scheme	**Code rate**	**Modulation**	**Spectral Efficiency**	**Total data rate**
Symmetric DSTTD	3/4	8PSK	4.5 bps/Hz	10.8 Mbps
Asymmetric DSTTD	3/4	QPSK-16QAM	4.5 bps/Hz	10.8 Mbps
Symmetric Shuffled DSTTD	3/4	8PSK	4.5 bps/Hz	10.8 Mbps
Asymmetric Shuffled DSTTD	3/4	QPSK-16QAM	4.5 bps/Hz	10.8 Mbps
Regular/Shuffled DSTTD	3/4	16QAM	6.0 bps/Hz	14.4 Mbps
Regular/Shuffled DSTTD	3/4	64QAM	9.0 bps/Hz	21.6 Mbps

Table 3. Simulation parameters

Carrier frequency	2 GHz
Chip rate	3.84 Mcps
Spreading factor	32
Number of multi-codes	20
Frame length	0.667 ms (1-TS)
CPICH power	10 % total
E_c / I_{or}	80 %
Channel coding / decoding	Turbo coding per 3GPP, R=1/2, and 3/4. Max-Log-Map decoding (8 iterations)
Fading model	1 path Rayleigh, 3kmph
Correlation model	IID, Channel A and B [3]
Channel estimation	Perfect Channel Estimation (PCE)
Detector for DSTTD	Iterative MMSE (VBLAST in [7])

4. Simulation Results

To test the proposed techniques for improving DSTTD, we simulate (4,4) and (4,2) systems for data rate of 10.8, 14.4, and 21.6 Mbps assuming perfect channel estimation and 3-kmph UE speed in IID channel, channel A, and channel B model. The correlation profile of channel A and B are fairly close to that of the measured channels in [4], which exhibit fairly strong spatial correlation. Asymmetric modulation is only applied to 10.8 Mbps. Antenna shuffling technique is not used for IID channel since it provides additional gain only for correlated channels.

Figure 8 and 9 depict the performance of (4,4) and (4,2) 10.8 Mbps systems. The results indicate that asymmetric modulation alone provides additional gain of 0.5-dB and 1.5-dB for (4,4) and (4,2) systems, respectively. Notice that in (4,4) scenario, the combination of asymmetric modulation and antenna shuffling results in 1.5-dB gain for channel A and 2.5-dB gain for channel B. In (4,2) scenario, this gain is even more significant: 2.5-dB in channel A and 3.5-dB in channel B. A summary of the results for 10.8 Mbps is given the Table 4 below:

Table 4. Performance of 10.8 Mbps DSTTD: asymmetric and shuffling

(M,N)	**Scheme**	**Required I_{or}/I_{oc} (dB), target FER = 1%**		
		IID channel	**Channel A**	**Channel B**
(4,4)	Symmetric	9.5	12.0	15.5
(4,4)	Asymmetric	9.0	11.5	15.0
(4,4)	Symmetric + Shuffling	-	11.5	14.5
(4,4)	Asymmetric + Shuffling	-	10.5	13.0
(4,2)	Symmetric	20.0	22.5	26.5
(4,2)	Asymmetric	18.5	20.5	25.0
(4,2)	Asymmetric + Shuffling	-	20.0	23.0

For 14.4 and 21.6 Mbps, (4,4) systems are simulated in channel A and B. The results indicate that by using antenna shuffling, additional 1-dB and 1.5-dB gain can be obtained in channel A and B. The results are summarized in Table 5 below:

Table 5. Performance of (4,4) 14.4 and 21.6 Mbps DSTTD with shuffling in Channel A and B

Scheme		**Required I_{or}/I_{oc} (dB), target FER = 1%**	
Rate	**Shuffling**	**Channel A**	**Channel B**
14.4 Mbps	No	15.0	18.5
14.4 Mbps	Yes	14.0	17.0
21.6 Mbps	No	21.0	24.5
21.6 Mbps	Yes	20.0	23.0

5. Implementation and Complexity

Asymmetric modulation for DSTTD does not result in additional transmitter and receiver complexity.

To support antenna shuffling for FDD, the receiver needs to signal the chosen shuffling pattern to the transmitter. Since there are only 6 candidates of shuffling patterns, 3-bit code word is sufficient to represent one shuffling pattern. The signaling can be done either via higher layer signaling or uplink (DPCCH) feedback channel as done in closed-loop transmit diversity. The second alternative can be exploited whenever closed-loop transmit diversity is not used, such as in fast fading scenario. Note that since channel correlation profile varies very slowly, antenna shuffling scheme is applicable for fast fading channels. Since antenna shuffling pattern does not require frequent update, the pattern can be repeated a number of times to combat the effect of feedback error. Additional protection can also be obtained by employing error correcting code.

The receiver selects the shuffling pattern $\mathbf{W}$ according to an optimality criterion, which depends on the transmit covariance matrix $\tilde{\mathbf{R}}_{TX}$. Since $\tilde{\mathbf{R}}_{TX}$ is Hermitian symmetric, only 10 of its upper triangular elements need to be estimated. The elements of $\tilde{\mathbf{R}}_{TX}$ can be estimated according to the relation in (4) where an estimate of $E\left[h_{nm}h_{n'm'}^{*}\right]$ can be obtained via some simple averaging of the channel estimates. Hence, the additional complexity required for supporting the antenna shuffling technique is marginal.

6. Conclusion

In this contribution, we have introduced two simple yet effective techniques to further improve the performance of double-STTD (DSTTD) scheme, which was proposed in [6]. The first technique is to use two different modulation schemes for the first and second streams (after twice STTD encoding). When applied to 4.5 bps/Hz (10.8 Mbps data rate) scenario, this technique results in significant gain regardless of the channel correlation profile, without any increase in complexity. The second technique is to apply antenna shuffling after twice STTD encoding based upon channel correlation profile. We have demonstrated that antenna shuffling by itself can provide additional gain up to 1.5-dB in channel B over the original DSTTD. When combined with asymmetric modulation for 10.8 Mbps DSTTD, it results in the total gain of 3.5-dB in channel B. We have also demonstrated that the additional computational and signaling requirement for supporting antenna shuffling technique is marginal.

In light of these facts and results, we propose that the following techniques be supported for HSDPA to supplement the open-loop DSTTD scheme proposed in [6]:

1. Asymmetric QPSK-16QAM modulation for 10.8 Mbps (4.5 bps/Hz) DSTTD.

2. Antenna shuffling technique in correlated fading channel. To support antenna shuffling technique, a feedback from the receiver to the transmitter is needed to signal the selected shuffling pattern, which can be done via higher layer signaling or uplink feedback channel.

References

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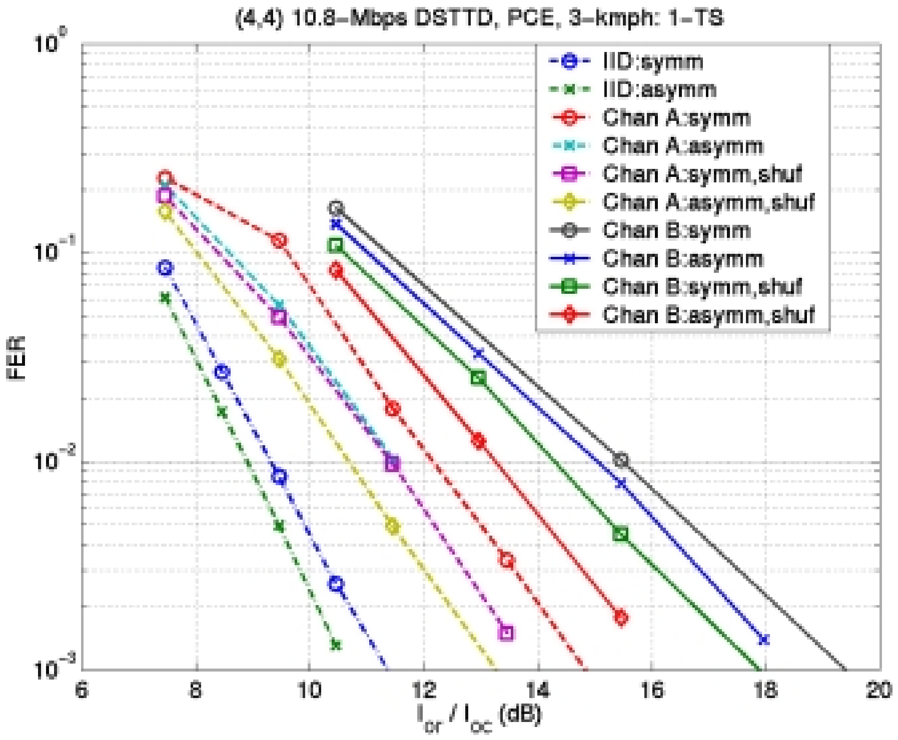

Figure 8. (4,4) DSTTD, data rate 10.8 Mbps

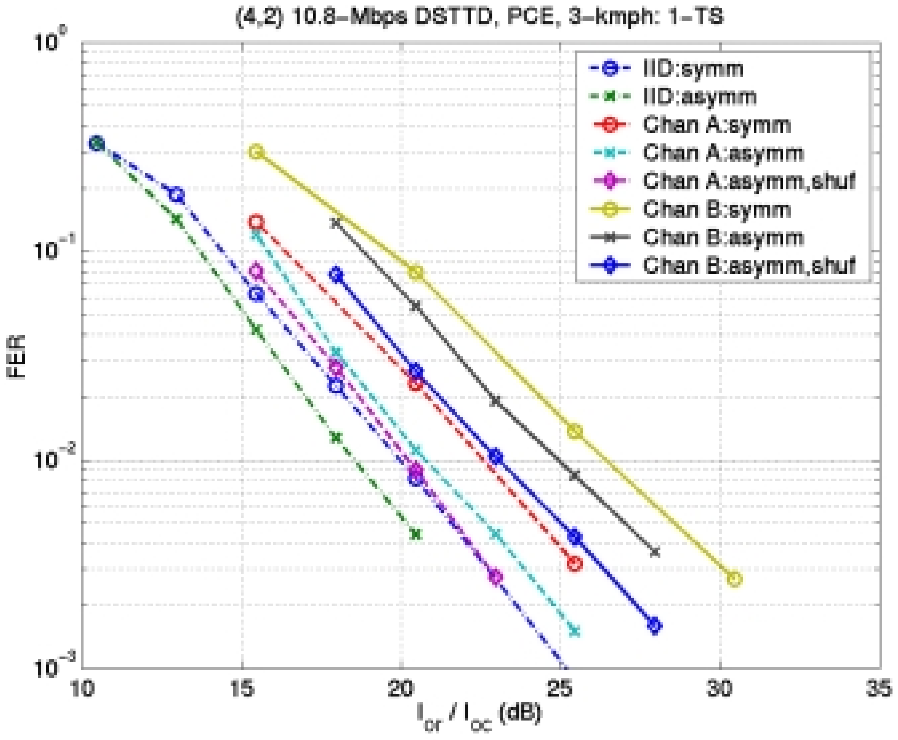

Figure 9. (4,2) DSTTD, data rate 10.8 Mbps

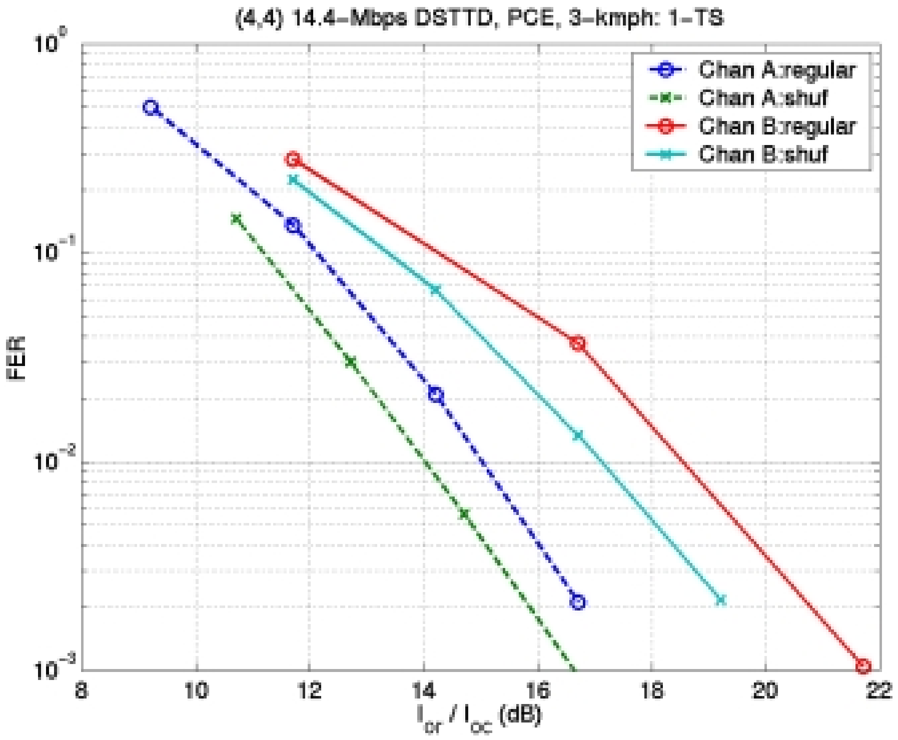

Figure 10. (4,4) DSTTD, data rate 14.4 Mbps

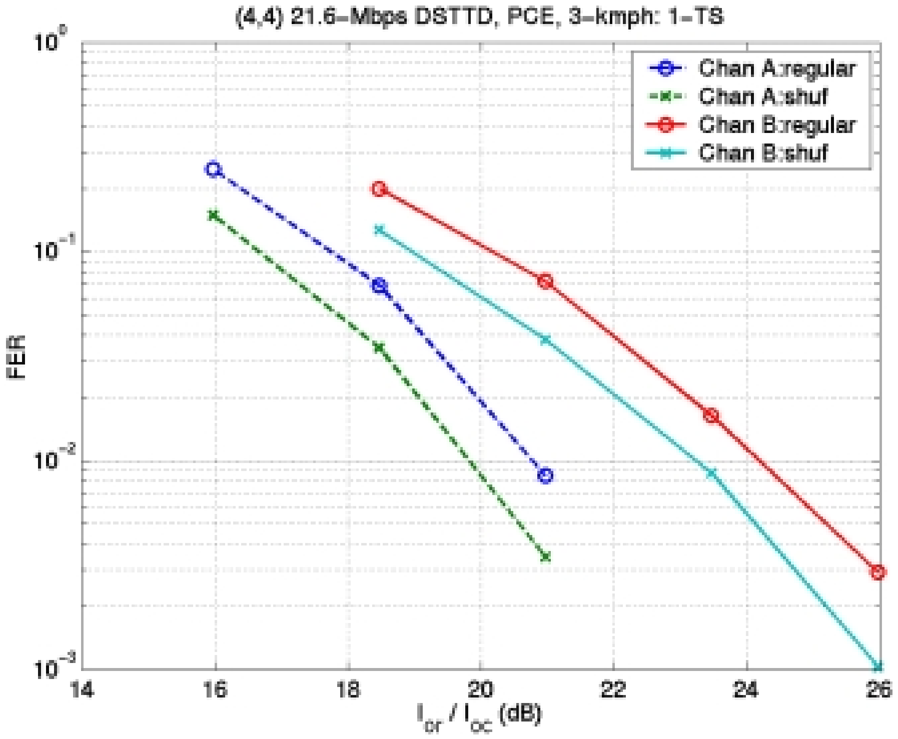

Figure 11. (4,4) DSTTD, data rate 21.6 Mbps