DIFFERENTIAL SPACE-TIME MODULATION SCHEMES FOR DS-CDMA SYSTEMS

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ABSTRACT

Differential space-time modulation (DSTM) schemes were recently proposed to fully exploit the receive and transmit antenna diversities without the need for channel state information. DSTM is attractive in fast flat fading channels since accurate channel estimation is difficult to achieve. In this paper, we propose a new modulation scheme to improve the performance of DS-CDMA systems in fast time-dispersive fading channels, referred to as the *differential space-time modulation for DS-CDMA* (DST-CDMA). We present two new demodulation schemes, referred to as the *differential space-time Rake receiver* (DSTR) and *differential space-time deterministic receiver* (DSTD), respectively. DSTD exploits the known information of the spreading sequences and their delayed paths deterministically besides the Rake type combination. Consequently, it outperforms DSTR, which employs the Rake type combination only. The new modulation and demodulation schemes are especially suited for the fast fading down-link transmission in DS-CDMA systems employing multiple transmit antennas and one receive antenna.

1. INTRODUCTION

The information capacity of wireless communications systems increases drastically by employing multiple transmit and receive antennas [1]. Traditionally, research work in spatial diversity mainly focused on the receiving diversity. In fact, receive antenna diversity has already been used in base stations to improve receptions in current cellular systems [2]. In contrast, transmit diversity is just beginning to attract researchers' attention [2].

Recently, Alamouti [3] proposed a simple and useful transmit diversity scheme to improve the overall performance of wireless communication systems in flat fading channels. This scheme is one of many interesting techniques emerging in the field of space-time coding, a new coding and signal processing technique that is designed for use with multiple transmit antennas (see, e.g., [2] and the references therein). It introduces temporal and spatial correlation into signals transmitted from different antennas, in order to provide transmitter diversity and coding gain over an uncoded system.

However, Alamouti's method as well as many other transmit diversity schemes, such as those in [4, 5], are based on the assumption that perfect channel state information (CSI) is available at the receiver. Although training is a feasible way to obtain CSI when the channel is stationary or changes slowly, it will incur excessive overhead or even fail when the channel experiences fast fading.

More recently, differential space-time modulation (DSTM) schemes were introduced as extensions of the traditional differential phase shift keying (DPSK) in flat fading channels [6, 7, 8]. DSTM schemes obviate the need for channel estimation at the receiver, while maintaining the desired properties of space-time coding techniques.

By combining the merits of the DSTM scheme and the spread spectrum technology, we devised a differential space-code modulation (DSCM) scheme [9] to combat unknown interferences and jamming in *flat fading* channels. In this paper, we combine the merits of DSTM and the spread spectrum technology in a similar way to propose a new modulation scheme to improve the performance of DS-CDMA systems in fast *time-dispersive fading* channels, referred to as the *differential space-time modulation for DS-CDMA* (DST-CDMA). We employ code difference to convey information in DSCM, but use time difference to modulate the information code herein. Based on DST-CDMA, we devise two demodulation schemes, referred to as the *differential space-time Rake receiver* (DSTR) and *differential space-time deterministic receiver* (DSTD), respectively. By making use of the unitary group codes [10], the proposed modulation and demodulation schemes yield simple receivers.

We demonstrate with simulation examples that DSTD performs better than DSTR in that DSTD offers lower bit-error-rate (BER) at fairly high SNR. The reason is that DSTR employs the Rake combination only, whereas DSTD not only employs Rake combination, but exploits the known information of spreading sequences and their delayed paths deterministically as well.

The new modulation and demodulation schemes are especially desirable for down-link transmission of DS-CDMA systems with multiple transmit antennas at the base station and one receive antenna at mobile units, operating in fast time-dispersive fading channels.

The rest of the paper is organized as follows. Section 2 briefly reviews the unitary group code based DSTM scheme. Section 3 presents the DST-CDMA scheme and gives two data models for DST-CDMA down-link signals. Two demodulation schemes, DSTR and DSTD, are given in Section 4. Simulation results are presented in Section 5. Finally, we deliver our comments and conclusions in Section 6.

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2. REVIEW OF DSTM

To facilitate our presentation, we first briefly review the unitary group code based differential space-time modulation of [6]. Let M, N, and L denote the number of transmit antennas, the number of receive antennas, and the time length of a space-time code, respectively. Let $\mathbf{C}_k$ be the $M \times L$ space-time code to be transmitted by the M antennas over L time samples of the kth time slot. For differential space-time coding, we have [6]

$$\mathbf{C}_k\mathbf{C}_k^H = L\mathbf{I}_M, \quad \mathbf{C}_k = \mathbf{C}_{k-1}\mathbf{G}_k, \qquad \forall k, \tag{1}$$

where $(\cdot)^H$ denotes the conjugate transpose, $\mathbf{I}_M$ is an $M \times M$ identity matrix, and $\mathbf{G}_k$ is the information bearing unitary group code. For example, in the case of $M = L = 2$, the code

$$\mathcal{G} = \left\{ \pm \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \pm \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \right\}, \tag{2}$$

is a unitary group code over the BPSK constellation $\{1, -1\}$. Each information bit pair in {00, 01, 10, 11} corresponds to an element in $\mathcal{G}$. At the start of transmission, we transmit the initial space-time code matrix

$$\mathbf{C}_0 = \mathbf{D} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}. \tag{3}$$

Let $\mathbf{H} \in \mathcal{C}^{N\times M}$ be the unknown fading matrix in a flat fading environment and let $\mathbf{E}_k \in \mathcal{C}^{N\times L}$ be the additive noise matrix. The array received data matrix $\mathbf{Y}_k \in \mathcal{C}^{N\times L}$ has the form [6]

$$\mathbf{Y}_k = \sqrt{\rho_M}\mathbf{H}\mathbf{C}_k + \mathbf{E}_k, \tag{4}$$

where $\rho_M = \rho/M$ with ρ denoting the signal-to-noise ratio (SNR) per receive antenna. Each of the elements of $\mathbf{H}$ and $\mathbf{E}_k$ is assumed to be an independently and identically distributed complex Gaussian random variable with zero-mean and *unit* variance, i.e.,

$$\text{vec}(\mathbf{H}) \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_{MN}), \quad \text{vec}(\mathbf{E}_k) \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_{NL}), \tag{5}$$

where $\text{vec}(\cdot)$ denotes the column vector obtained by stacking the columns of a matrix. In this case, a simple differential receiver has the form [6]

$$\widehat{\mathbf{G}}_k = \arg\max_{\mathbf{G}_k\in\mathcal{G}} \text{Re}\left\{ \text{tr}\left(\mathbf{Y}_k^H\mathbf{Y}_{k-1}\mathbf{G}_k \right) \right\}, \tag{6}$$

where $\text{Re}\{\cdot\}$ denotes the real part of the argument and $\text{tr}(\cdot)$ denotes the trace of a matrix.

3. MODULATION AND DATA MODELS

The above DSTM can be readily modified to be used in the down-link transmissions in DS-CDMA systems, where multiple transmit antennas are easy to deploy at base stations. In view of this, we consider the down-link case only in this paper though the schemes proposed herein can be applied to the up-link case as well.

Let U be the number of synchronous down-link users, and $\mathbf{C}_{k,u}$ be the space-time code for user u, $u = 1, 2, \cdots, U$, at the kth time slot. By means of using L spreading sequences to spread the L columns of $\mathbf{C}_{k,u}$ and transmit the space-time codes of all the users together, we have the new modulation scheme – DST-CDMA. At the jth time sample of the kth time slot, the transmitted signal is

$$\mathbf{s}_k(j) = \sum_{u=1}^{U} \mathbf{C}_{k,u}\mathbf{d}_u(j), \quad j = 1, 2, \cdots, J, \tag{7}$$

where $\mathbf{d}_u(j) \in \mathcal{C}^L$ is the unit-energy spreading sequence vector which spreads each of the columns of $\mathbf{C}_{k,u}$, and J is the length of the spreading sequences. (Note that we do not constrain the spreading sequences to be short ones and hence this scheme is also applicable to long sequences.) The unitary group code $\mathbf{G}_{k,u}$ is related to $\mathbf{C}_{k,u}$ and $\mathbf{C}_{k-1,u}$ as follows:

$$\mathbf{C}_{k,u} = \mathbf{C}_{k-1,u}\mathbf{G}_{k,u}, \quad u = 1, 2, \cdots, U. \tag{8}$$

We consider herein the case of only one receive antenna. We consider the time-dispersive fading channels by modeling the channel impulse response as a finite impulse response (FIR) filter with length L_f. Let $y_{k,l}(j)$ denote the receiver output (noise free) of the lth tap of the FIR filter, $l = 0, 1, \cdots, L_f - 1$. At the kth time slot, the jth sample of the received signal from the lth tap is

$$y_{k,l}(j) = \sum_{u=1}^{U} \sqrt{\rho_l}\mathbf{h}_l\mathbf{C}_{k,u}\mathbf{d}_u(j-l), \tag{9}$$

where ρ_l denotes the SNR per receive antenna of the lth tap, $\mathbf{h}_l \in \mathcal{C}^{1\times M}$ is the unknown channel row vector of the lth tap from the M transmit antennas. Hence the output of the receiver antenna is

$$\begin{aligned} y_k(j) &= \sum_{l=0}^{L_f-1} y_{k,l}(j) + e_k(j) \\ &= \sum_{l=0}^{L_f-1} \sqrt{\rho_l}\mathbf{h}_l\mathbf{C}_k\mathbf{d}(j-l) + e_k(j), \quad j = 1, 2, \cdots, J, \end{aligned} \tag{10}$$

where $\mathbf{C}_k = [\mathbf{C}_{k,1} \ \ \mathbf{C}_{k,2} \ \ \cdots \ \ \mathbf{C}_{k,U}]$ and $\mathbf{d}(j) = [\mathbf{d}_1^T(j) \ \ \mathbf{d}_2^T(j) \ \ \cdots \ \ \mathbf{d}_U^T(j)]^T$ with $(\cdot)^T$ denoting the transpose.

From Equation (10), we obtain two slightly different data models, referred to as *Model A* and *Model B*.

Model A By employing the tap-delay expression, Equation (10) becomes:

$$\begin{aligned} \mathbf{x}_k(j) &\triangleq \begin{bmatrix} y_k(j) \\ y_k(j+1) \\ \cdots \\ y_k(j+L_f-1) \end{bmatrix} \\ &= \begin{bmatrix} \sqrt{\rho_0}\mathbf{h}_0\mathbf{C}_k\mathbf{d}(j) + e_{k,0}(j) \\ \sqrt{\rho_1}\mathbf{h}_1\mathbf{C}_k\mathbf{d}(j) + e_{k,1}(j) \\ \cdots \\ \sqrt{\rho_{L_f-1}}\mathbf{h}_{L_f-1}\mathbf{C}_k\mathbf{d}(j) + e_{k,L_f-1}(j) \end{bmatrix}, \\ & \quad j = 1, 2, \cdots, J, \end{aligned} \tag{11}$$

where for $p = 0, 1, \cdots, L_f - 1$,

$$e_{k,p}(j) = \sum_{l=0, l\neq p}^{L_f-1} \sqrt{\rho_l}\mathbf{h}_l\mathbf{C}_k\mathbf{d}(j-l+p) + e_k(j+p). \tag{12}$$

In the above equation, we lump the delayed paths of each signal as part of the noise by assuming that the auto- and cross-correlation functions of the spreading sequences are low. Note that for some j and p, $e_{k,p}(j)$ contains also the tails of the previous modulated space-time codes $\mathbf{C}_{k-1}$ or the heads of the next modulated space-time code $\mathbf{C}_{k+1}$.

Let $\mathbf{\Omega} = \mathrm{diag}\{\sqrt{\rho_0}, \ \sqrt{\rho_1}, \ \cdots, \ \sqrt{\rho_{L_f-1}}\}$, $\mathbf{H} = [\mathbf{h}_0^T \ \ \mathbf{h}_1^T \ \cdots \ \mathbf{h}_{L_f-1}^T]^T$, and $\mathbf{e}_{\mathrm{A},k}(j) = [e_{k,0}(j) \ \ e_{k,1}(j) \ \ \cdots \ \ e_{k,L_f-1}(j)]^T$. We have

$$\mathbf{x}_k(j) = \mathbf{\Omega}\mathbf{H}\mathbf{C}_k\mathbf{d}(j) + \mathbf{e}_{\mathrm{A},k}(j). \tag{13}$$

By denoting $\mathbf{X}_k = [\mathbf{x}_k(1) \ \ \mathbf{x}_k(2) \ \ \cdots \ \ \mathbf{x}_k(J)]$, $\mathbf{D} = [\mathbf{d}(1) \ \ \mathbf{d}(2) \ \cdots \ \mathbf{d}(J)]$, and $\mathbf{E}_{\mathrm{A},k} = [\mathbf{e}_{\mathrm{A},k}(1) \ \ \mathbf{e}_{\mathrm{A},k}(2) \ \ \cdots \ \ \mathbf{e}_{\mathrm{A},k}(J)]$, Model A has the form

$$\mathbf{X}_k = \mathbf{\Omega}\mathbf{H}\mathbf{C}_k\mathbf{D} + \mathbf{E}_{\mathrm{A},k}. \tag{14}$$

Model B Equation (10) can also be written as

$$y_k(j) = \mathbf{h}\left(\mathbf{I}_L \otimes \mathbf{C}_k\right)\bar{\mathbf{d}}(j) + e_k(j), \quad j = 1, 2, \cdots, J, \tag{15}$$

where $\otimes$ denotes the matrix Kronecker product,

$$\mathbf{h} = \left[\sqrt{\rho_0}\mathbf{h}_0 \quad \sqrt{\rho_1}\mathbf{h}_1 \quad \cdots \quad \sqrt{\rho_{L_f-1}}\mathbf{h}_{L_f-1}\right], \tag{16}$$

and

$$\bar{\mathbf{d}}(j) = \begin{bmatrix} \mathbf{d}(j) \\ \mathbf{d}(j-1) \\ \cdots \\ \mathbf{d}(j-L_f-1) \end{bmatrix}. \tag{17}$$

(Note that $\mathbf{d}(j-L_f-1) = \mathbf{d}(J+j-L_f-1), \forall j-L_f-1 \le 0$ in Equation (17) for short sequences.) Similar to (14), Model B has the form

$$\begin{aligned} \mathbf{y}_k &= [\ y_k(1) \quad y_k(2) \quad \cdots \quad y_k(J)\ ] \\ &= \mathbf{h}\left(\mathbf{I}_L \otimes \mathbf{C}_k\right)\bar{\mathbf{D}} + \mathbf{e}_{\mathrm{B},k}, \end{aligned} \tag{18}$$

where $\bar{\mathbf{D}} = [\bar{\mathbf{d}}(1) \ \ \bar{\mathbf{d}}(2) \ \ \cdots \ \ \bar{\mathbf{d}}(J)]$, and $\mathbf{e}_{\mathrm{B},k} \simeq [e_k(1) \ \ e_k(2) \ \cdots \ e_k(J)]$ with $\simeq$ meaning that although $\mathbf{e}_{\mathrm{B},k}$ does not contain the major part of the delayed paths of the signals, it still contains the tails of the modulated space-time codes of the $(k-1)$th slot.

4. DEMODULATION SCHEMES

Based on the data models given in the previous section, we can readily obtain two demodulation schemes and their corresponding receivers.

DSTR receiver From (14) we have the unstructured maximum likelihood (ML) estimate of $\mathbf{\Omega}\mathbf{H}\mathbf{C}_k$ as

$$\mathbf{V}_k \stackrel{\triangle}{=} \mathbf{X}_k\mathbf{D}^H(\mathbf{D}\mathbf{D}^H)^{-1} = \mathbf{\Omega}\mathbf{H}\mathbf{C}_k + \mathbf{E}_{\mathrm{R},k}, \tag{19}$$

where $\mathbf{E}_{\mathrm{R},k} = \mathbf{E}_{\mathrm{A},k}\mathbf{D}^H(\mathbf{D}\mathbf{D}^H)^{-1}$ and we have assumed that $\mathbf{D}\mathbf{D}^H$ has full rank.

Exploiting the similarity between (4) and (19) and using the RAKE combination technique, we readily have the DSTR receiver

$$\begin{aligned} \widehat{\mathbf{G}}_{k,u} &= \arg\max_{\mathbf{G}_k \in \mathcal{G}} \mathrm{Re}\ \mathrm{tr}\left\{\mathbf{G}_k\mathbf{V}_{k,u}^H\widehat{\mathbf{\Omega}}^2\mathbf{V}_{k-1,u}\right\}, \\ & \qquad u = 1, \cdots, U, \end{aligned} \tag{20}$$

where $\mathbf{V}_{k,u} = \mathbf{V}_k(:, (u-1)L+1 : uL)$ is the *processed* data block corresponding to the uth user and $\widehat{\mathbf{\Omega}}^2 = \mathrm{diag}\{\hat{\rho}_0, \ \hat{\rho}_1, \ \cdots, \ \hat{\rho}_{L_f-1}\}$ is the weighting matrix related to the power of each taps of the FIR filter with $\hat{\rho}_l$, $l = 0, 1, \cdots, L_f-1$, being a consistent estimate of ρ_l given by

$$\hat{\rho}_l = \mathbf{V}_k(l+1,:)\mathbf{V}_k^H(l+1,:)/(2LM). \tag{21}$$

(Note that we have used the MATLAB conventions in expressing the blocks of matrices.)

DSTD receiver From (18) we have the unstructured ML estimate of $\mathbf{h}(\mathbf{I}_L \otimes \mathbf{C}_k)$ as

$$\mathbf{z}_k \stackrel{\triangle}{=} \mathbf{y}_k\bar{\mathbf{D}}^H(\bar{\mathbf{D}}\bar{\mathbf{D}}^H)^{-1} = \mathbf{h}(\mathbf{I}_L \otimes \mathbf{C}_k) + \mathbf{e}_{\mathrm{D},k}, \tag{22}$$

where $\mathbf{e}_{\mathrm{D},k} = \mathbf{e}_{\mathrm{B},k}\bar{\mathbf{D}}^H(\bar{\mathbf{D}}\bar{\mathbf{D}}^H)^{-1}$. As above, we also assume that $\bar{\mathbf{D}}\bar{\mathbf{D}}^H$ has full rank. It seems from this assumption that DSTD intrinsically has lower subscriber capacity than DSTR. Yet this drawback is not serious at all because DS-CDMA systems usually work in quite light load conditions [11].

Let

$$\begin{aligned} \mathbf{z}_k &\stackrel{\triangle}{=} \left[\mathbf{z}_{k,0} \quad \mathbf{z}_{k,1} \quad \cdots \quad \mathbf{z}_{k,L_f-1}\right] \\ &= \left[\sqrt{\rho_0}\mathbf{h}_0\mathbf{C}_k \quad \sqrt{\rho_1}\mathbf{h}_1\mathbf{C}_k \quad \cdots \quad \sqrt{\rho_{L_f-1}}\mathbf{h}_{L_f-1}\mathbf{C}_k\right] \\ &\quad + \left[\mathbf{e}_{k,0} \quad \mathbf{e}_{k,1} \quad \cdots \quad \mathbf{e}_{k,L_f-1}\right]. \end{aligned} \tag{23}$$

Stacking up $\mathbf{z}_{k,l}$ as the $(l+1)$th row of $\mathbf{Z}_k$, we have

$$\mathbf{Z}_k = \mathbf{\Omega}\mathbf{H}\mathbf{C}_k + \mathbf{E}_{\mathrm{D},k}. \tag{24}$$

Comparing (19) and (24), we note that the only difference between $\mathbf{V}_k$ and $\mathbf{Z}_k$ is their noise. Hence it is straightforward to obtain the DSTR receiver.

Note that, besides the RAKE combination, DSTD exploits the known information of the spreading sequences and their delayed paths deterministically as well. Hence DSTD is superior to DSTR because it uses a more accurate data than DSTR.

5. NUMERICAL RESULTS

We present numerical examples to demonstrate the performance of the proposed DSTR and DSTD schemes for DST-CDMA. Two sets of examples are given in this section: DSTR and DSTD for time-invariant channels, as well as DSTR and DSTD for time-varying channels.

The DST-CDMA based communications systems considered herein are all equipped with $M = 2$ transmit antennas and employ the 2×2 unitary group code over the BPSK constellation, as described by (2). The space-time codes are constructed by using (8). Unit-energy Gold sequences with length 63 are used as spreading sequences in all of the simulations. We choose $L_f = 3$, and assume $\mathrm{vec}(\mathbf{h}_l) \sim \mathcal{CN}\left(0, \mathbf{I}_2\right), l = 0, 1, 2$, and the attenuation between taps is 3 dB.

When the time-varying fading is considered, the channel vectors change from time sample to time sample.

DSTR and DSTD for time-invariant channels Figure 1 shows the BER comparison between DSCM and DSTM as a function of the SNR for time-invariant fading channels when $U = 6$. Note that DSTD performs better than DSTR since DSTD offers lower BER at higher SNR. The reason is, as mentioned above, that DSTD not only employs a kind of combination similar to RAKE, but exploits the known information of the spreading sequences and their delayed paths deterministically as well; whereas DSTR employs the RAKE combination only.

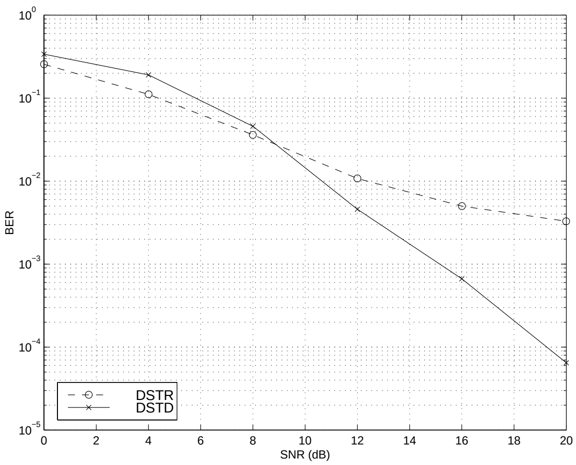

Fig. 1. BER vs. SNR comparison between DSTR and DSTD for time-invariant fading channels when $U = 6$.

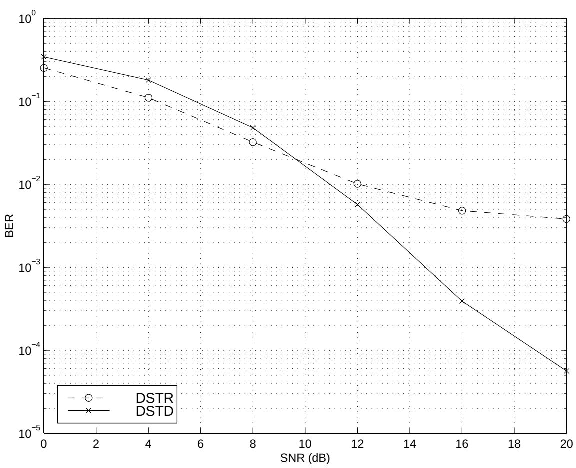

Fig. 2. BER vs. SNR comparison between DSTR and DSTD for time-varying fading channels when $U = 6$.

DSTR and DSTD for time-varying channels The simulated channels in the following case experience time-varying fading risen from the Doppler frequencies caused by the relative motions of mobiles and/or surroundings. It is charactered by the normalized Doppler frequency of $f_D T_c$, where f_D is the Doppler frequency and T_c is the chip duration of the spreading sequences. In the simulations, we choose $1/T_c = 1.2288$ MHz, and f_D=200 Hz (corresponding to a vehicle moving at 71 mph (miles per hour) with the carrier frequency being 1.9 GHz).

Figure 2 shows the BER comparison between DSCM and DSTM as a function of the SNR for time-varying fading channels when $U = 6$. Again, DSTD still performs better than DSTR. Also, the demodulation schemes are quite robust against fast fading.

6. CONCLUSIONS

We have proposed a new spatial and temporal modulation scheme for DS-CDMA systems, referred to as the *differential space-time modulation for DS-CDMA* (DST-CDMA). We have devised two demodulation schemes, referred to as the *differential space-time Rake receiver* (DSTR) and *differential space-time deterministic receiver* (DSTD). Simulation results shown that DSTD is superior to DSTR in that DSTD offers lower BER at higher SNR. The reason is that DSTD exploits the known information of the spreading sequences and their delayed paths deterministically in addition to RAKE combination. The new modulation and demodulation schemes are especially desirable for down-link transmission of DS-CDMA systems with multiple transmit antennas and one receive antenna, operating in fast time-dispersive fading channels.

7. REFERENCES

[1] G. J. Foschini, Jr. and M. J. Gans, “On the limits of wireless communications in a fading environment when using multiple antennas,” *Wireless Personal Communications*, March 1998.

[2] A. F. Naguib, N. Seshadri, and A. R. Calderbank, “Increasing data rate over wireless channels,” *IEEE Signal Processing Magazine*, vol. 17, no. 3, pp. 76–92, May 2000.

[3] S. M. Alamouti, “A simple transmit diversity techniques for wireless communications,” *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, October 1998.

[4] J. C. Guey, M. P. Fitz, M. R. Bell, and W. Y. Kuo, “Signal design for transmitter diversity wireless communication systems over rayleigh fading channels,” *Proc. IEEE VTC’96*, pp. 136–140, 1996.

[5] N. Seshadri and J. J. Winters, “Two signaling schemes for improving the error performance of frequency-division-duplex (fdd) transmission systems using transmitter antenna diversity,” *Int. J. Wireless Inform. Networks*, vol. 1, no. 1, 1994.

[6] B. L. Hughes, “Differential space-time modulation,” *Proc. 1999 IEEE Wireless Communications and Networking Conference (WCNC9́9)*, New Orleans, LA, September 22-29 1999.

[7] B. M. Hochwald and W. Sweldens, “Differential unitary space-time modulation,” *IEEE Transactions on Communications*, to appear 2000.

[8] V. Tarokh and H. Jafarkhani, “A differential detection scheme for transmit diversity,” *IEEE J. Sel. Areas Commun.*, 2000, submitted.

[9] J. Li, J. Liu, and H. Li, “Differential space-code mudulation for interference suppression,” *Proceedings of the 34th Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, 2000.

[10] B. M. Hochwald, T. L. Marzetta, T. Richardson, W. Sweldens, and R. Urbanke, “Systematic design of unitary space-time constellations,” *IEEE Transactions on Information Theory*, vol. 46, no. 6, pp. 1962–1973, 2000.

[11] J. C. Liberti, Jr. and T. S. Rappaport, *Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications*, Prentice Hall PTR, Upper Saddle River, NJ 07458, 1999.