Transmit Diversity in 3G CDMA Systems

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ABSTRACT

Transmit diversity (TD) is one of the key contributing technologies to defining the ITU endorsed 3G systems W-CDMA and cdma2000. Spatial diversity is introduced into the signal by transmitting through multiple antennas. The antennas are spaced far enough apart that the signals emanating from them can be assumed to undergo independent fading. In addition to diversity gain, antenna gain can also be incorporated through channel state feedback. This leads to the categorization of TD methods into open loop and closed loop methods. Several methods of transmit diversity in the forward link have been either under consideration or adopted for the various 3G standards. This article describes the concept of transmit diversity and explains the features of selected TD techniques.

INTRODUCTION

The World Wide Web and increasing demand for wireless services (e.g., voice and data) are driving the demand for increased system capacity, data rates, and multimedia services. The International Mobile Telecommunications in 2000 (IMT-2000) standards development process, within the International Telecommunication Union (ITU), is driving the development of enhanced third-generation (3G) standards in order to address current and future wireless service needs. Particularly the Third Generation Partnership Project (3GPP) and Third Generation Partnership Project Two (3GPP2) are developing the wideband code-division multiple access (WCDMA) technologies and CDMA2000, respectively. Improvement of downlink capacity is one of the main challenges facing the effort toward 3G evolution. Many of the proposed services are expected to be downlink-intensive, and moreover likely to be used in low-mobility environments under single-path conditions. Poor performance due to prolonged deep fading of the channel is one of the problems associated with this model. Transmit diversity (TD) is one of the key contributing technologies to addressing this problem in these proposed 3G CDMA systems.

Multiple antennas can improve the performance of a wireless communication system in a fading environment [1]. Although multiple antennas may be employed at either the base station, mobile station, or both, it is most cost effective and practical to employ multiple antennas at the base station. Hence, the topic matter of this article is restricted to the case of employing multiple antennas at the base station.

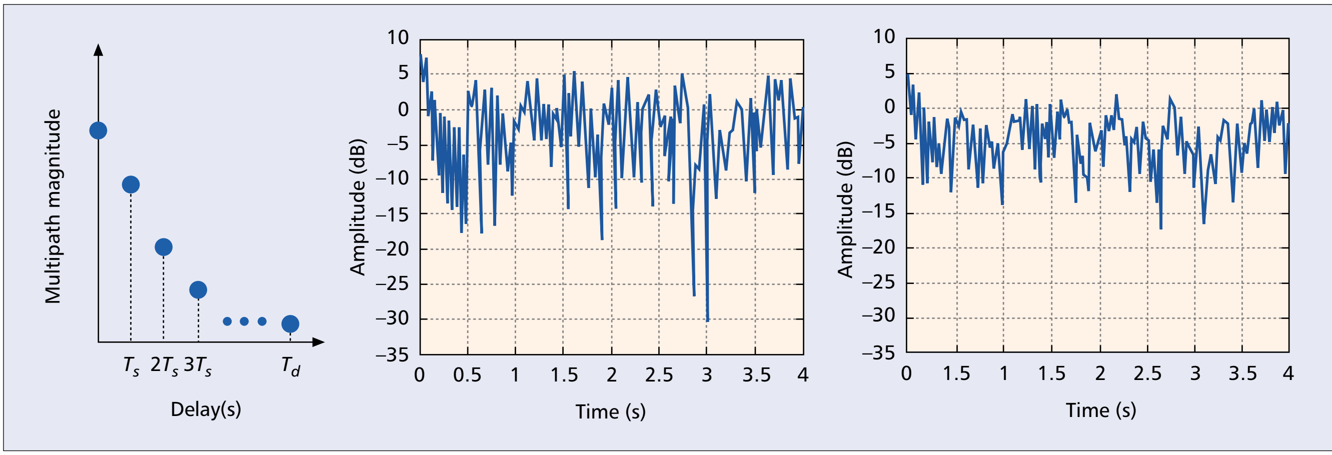
The spacing of the antennas also affects the degree of correlation between the channels from the antennas to the mobile. Large antenna spacing, on the order of several carrier wavelengths, leads to uncorrelated fading, which leads to maximum performance gain due to spatial diversity. Beamforming methods, on the other hand, utilize antenna spacing less than the carrier wavelength, typically half the wavelength.

The rest of this article is organized as follows. We provide the reader with an introductory overview of diversity in general. We describe the different classes of TD and make summary remarks.

TRANSMIT DIVERSITY BASICS

THE CHANNEL

Most mobile communication channels must combat the effects of fading caused by multipath propagation. An important way of quantifying fading is in terms of a measure called the *coherence bandwidth* which indicates the amount of bandwidth that will fade in a correlated fashion at any instant in time. To define this correlation, consider a linear model of a communication channel; Fig. 1a illustrates what is termed the *delay spread* of the channel. Figure 1 offers a model where the multipath arrivals decrease in power as a function of a discrete time index and T_d is the maximum duration of the mobile communication channel. The time index is a measure of the time of arrival relative to the first multipath component at time 0. Often, the "direct path" arrives first, and subsequent paths represent paths reflected at increasing distances from the receiver. Given Fig. 1, the coherence bandwidth is approximated by (typically path powers less than 5–10 percent of the total power are ignored)



■ **Figure 1.** *a) Delay profile; b) single-path envelope; c) two-path envelope.*

$$B_c \approx \frac{1}{T_d}.$$

Considering a communication system with bandwidth B_w, if $B_c > B_w$, the channel between the transmitter and receiver is called a *flat fading channel* and if $B_c < B_w$ the channel is called a *frequency selective channel*.

Flat fading channels are problematic for systems without TD, because a deep fade can result in a received signal that is below the background noise level, making communication unreliable. The worst type of channel conditions for many communication systems are slowly changing flat fading channels; this is due to the length of time the receiver cannot reliably demodulate the bits sent by the transmitter. Using a simple model of the complex baseband communication signal $S(t)$, the signal at a receiver from a flat fading channel is given by

$$X(t) = a(t)\, S(t) + \gamma(t),$$

where $a(t)$ represents the channel coefficient subject to fading, and $\gamma(t)$ is an additive noise process. Figure 1b offers an example of a flat Rayleigh fading channel where $a(t)$ is a complex Gaussian random process and $|a(t)|$ is Rayleigh distributed. When $\int |a(t)|^2\, dt < \int |\gamma(t)|^2\, dt$, the strength of the communication signal is less than the background noise, making it difficult, in many cases, to recover $S(t)$.

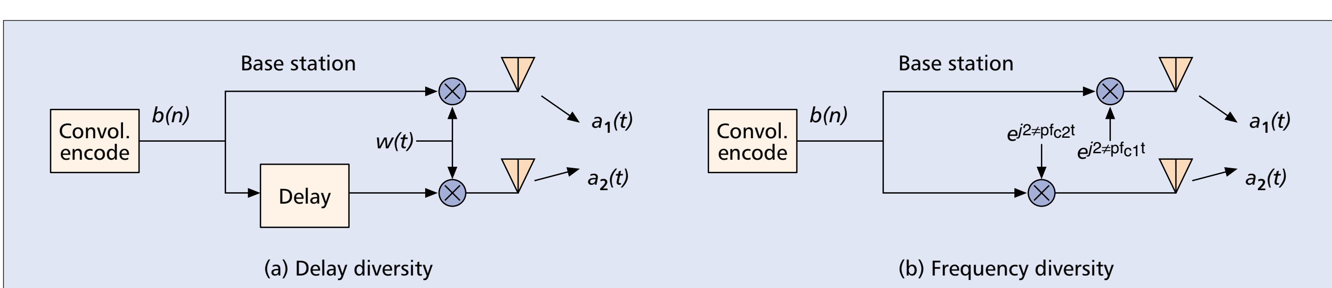
Transmit diversity can improve the receiver performance in the presence of flat fading. It reduces the impact of fading by offering multiple independent copies of the digitally modulated waveform at the receiver, where the chance that all copies are simultaneously in a fade is very small. Common methods of TD employing spatially separated antennas utilize either temporal or frequency techniques, or combinations of these techniques.

Temporal (Delay) Diversity

Delay diversity for two antennas, shown in Fig. 2, is a simple TD scheme that helps combat flat fading. Bits in Fig. 2 are generated by a source consisting of information from a computer, a digitized speech signal, or after being encoded by a channel encoder. The bits are numbered such that a bit at time instant n is denoted $b[n]$. The original bits are transmitted using two antennas, where the first antenna transmits without delay and the second sends $b[n]$ after a delay of one or more sample instants. The resulting waveform at the input to the receiver is

$$\begin{aligned} &X_d(t) \\ &= a_1(t)\sum_n b[n]w(t-nT) + a_2(t)\sum_n b[n-1]w(t-nT) + \gamma(t) \\ &= \sum_n b[n]\{a_1(t)w(t-nT) + a_2(t)w(t-(n+1)T)\} + \gamma(t), \end{aligned}$$

where a_k is the fading coefficient for an independent flat fading channels, $w(t)$ is the modulating waveform for each bit, and T is the amount of time each bit is transmitted before moving to the next bit. The effect of delay diversity on a slowly fading channel is to allow the receiver to coherently add the two independent fading channels together to aid in demodulation. Typically, unique pilot symbols are sent on each antenna,



■ **Figure 2.** *Delay diversity and frequency diversity.*

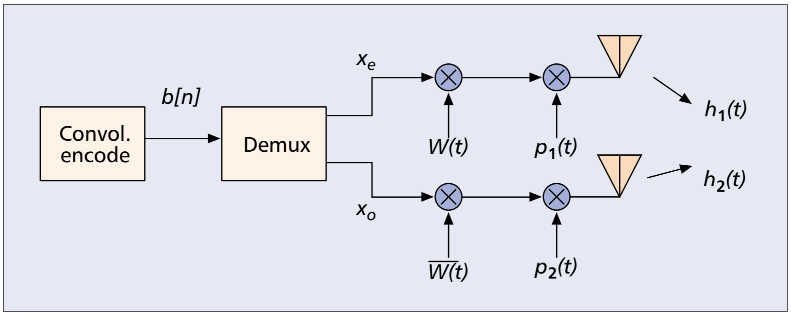


Figure 3. *OTD transmitter.*

allowing the receiver to characterize the two channels formed between each antenna and the mobile. Considering a case where $a_1(t)$ and $a_2(t)$ are identically distributed complex Gaussian random processes, Fig. 1c shows the response of $\alpha(t) = (|a_1(t)|^2 + |a_2(t)|^2)^{1/2}$. The fade depth, difference between the peaks and valleys, is less in Fig. 1c than that experienced in Fig. 1b. Thus, the resultant channel is more reliable from a communication perspective.

This approach suffers from reduced throughput due to multiple transmissions of the same symbol over time. Another instance of temporal diversity may be achieved in multipath channels where the signal bandwidth is larger than the coherence bandwidth of the channel; in this case the multipaths are resolvable and may be recovered by a rake receiver. Frequency diversity methods similarly can improve the receiver performance in the presence of flat fading.

Frequency Diversity

Frequency diversity methods (Fig. 2b) employ transmission of multiple symbol replicas over multiple carriers, each separated in frequency by a sufficiently large amount to ensure independent fading. To ensure independent fading employing this technique, the difference between the two carriers, f_{c1} and f_{c2}, must be greater than the coherence bandwidth (i.e., $|f_{c1} - f_{c2}| \geq B_c$).

Using notation as described in the previous section, the resulting waveform at the input to the receiver is

$$\begin{aligned} &X_d(t) \\ &= a_1(t)\sum_n b[n]e^{j2\pi f_{c1}(t-nT)} + a_2(t)\sum_n b[n]e^{j2\pi f_{c2}(t-nT)} \\ &+\gamma(t) \\ &= \sum_n b[n]\left\{a_1(t)e^{j2\pi f_{c1}(t-nT)} + a_2(t)e^{j2\pi f_{c2}(t-nT)}\right\} + \gamma(t). \end{aligned}$$

Similar to TD, the effect of frequency diversity for a slowly fading channel is to allow the receiver to coherently add the two independent fading channels together to aid in demodulation. This approach is accompanied by the additional cost of increased complexity at both the transmitter and receiver, along with the fact that it may be difficult to implement in bandwidth-limited systems. Given this brief overview of TD basics, our attention focuses more specifically on the issues of TD in the context of 3G CDMA evolution.

Several methods of TD have been proposed for 3G CDMA evolution. These can be broadly categorized into *open loop* and *closed loop* techniques.

Open Loop Transmit Diversity in 3G

In open loop diversity methods, a predetermined form of diversity is introduced using multiple antennas. Advantages of this class of methods include:
- Signaling overhead is not required to achieve this form of diversity.
- The *mobile station* (MS) receiver complexity is kept relatively low.

The most obvious disadvantage is that the channel environment information is not utilized; that is, open loop techniques are a *one-size fits all* approach to achieving TD for all mobile users.

The earliest open loop diversity techniques were simple in their configuration, for example, *phase-switched TD* (PSTD) and *time-switched TD* (TSTD). PSTD introduces a known periodically varying phase difference between the symbols transmitted through different antennas to simulate fast fading. In TSTD the transmission is switched among the different antennas with a known periodicity. All antennas transmit the same symbol simultaneously at reduced power, so the total power remains unchanged. Each of these methods has been proposed at one time or another in the 3G CDMA standards bodies. TSTD was adopted for use on the synchronization channel in 3GPP. However, PSTD was not adopted in favor of other techniques such as *orthogonal TD* (OTD) [2], *space-time TD* (STTD) [3], and *space-time spreading* (STS) [2].

Orthogonal Transmit Diversity

Orthogonal TD [2] is an open loop method in which coded interleaved symbols are split into even and odd symbol streams and transmitted using two different Walsh codes. The length of the Walsh code is doubled so that the total number of Walsh codes available is not reduced as a result of splitting the data, and the data rate will remain more constant than is the case with no data splitting. Consider the two-antenna case. Let x_o and x_e be the odd and even symbols, respectively. Then the symbols transmitted over the two antennas, S_1 and S_2, are given by

$$S_1 = x_e W,$$
$$S_2 = x_o \overline{W},$$

where $W, \overline{W}$ are complementary Walsh codes used (same chip rate, covering twice as many chips as in the absence of OTD, but in the same number). The signal received at the mobile receiver will be

$$r = h_1 s_1 + h_2 s_2 + \gamma,$$

where h_1, h_2 are the channels from the two antennas to the MS, and $p_1(t)$ and $p_2(t)$ are the antenna-specific pilot signals, as shown in Fig. 3. The time subscripts have been left out for brevity. The received signal from the two antennas is despread using the same Walsh codes, and then combined to recover the original symbol stream.

Transmit Diversity via Space-Time Coding

Space-time coding is a means of enhancing the level of diversity presented to a receiver in a wireless link, via the addition of TD and in order to more efficiently combat the signal fading inherent to wireless communication channels. Motivated by the information-theoretic results by Foschini and Gans [4] and Telatar [5], early ideas on TD schemes (e.g., delay diversity, in which a second antenna transmits a delayed replica of another transmit antenna's signal) have been refined by the work of Tarokh *et al.* [6]. Since it is advantageous to separate the problem of combating fades from that of channel equalization, the criteria for designing space-time codes are usually derived in the context of narrowband modulation and frequency nonselective fading. The noteworthy fact about this approach is that it isolates TD from those forms of diversity associated with the radio channel (e.g., due to multipath). Nevertheless, spread spectrum systems in frequency selective channels can benefit equally from coding with space and time redundancy, as outlined below.

In general, coding with space and time redundancy is accomplished by finding an efficient way to allocate different symbols to different antennas while adding, jointly across antennas, some type of time redundancy for implementing forward error correction. For each of the symbol streams associated with different antennas, the system can then resort to other means to combat frequency selective fading. For example, orthogonal frequency-division multiplexing (OFDM) naturally lends itself to being used in conjunction with TD; likewise, when the excess delay is small, space-time block coding (see below) can easily be used in a maximal ratio combining receiver for frequency selective channels.

Space-time coding can be implemented in either block [3, 6], or trellis form [7]. Irrespective of form, transmission over L transmit antennas can be represented by a code matrix,

$$\mathbf{D_c} = \begin{bmatrix} c_k^{(1)} & c_k^{(2)} & \cdots & c_k^{(L)} \\ c_{k+1}^{(1)} & c_{k+1}^{(2)} & \cdots & c_{k+1}^{(L)} \\ \vdots & \vdots & \ddots & \vdots \\ c_{k+l-1}^{(1)} & c_{k+l-1}^{(2)} & \cdots & c_{k+l-1}^{(L)} \end{bmatrix},$$

where the columns represent antennas and the rows correspond to modulator symbol epochs; here, $c_n^{(1)}$ is the complex symbol, transmitted at symbol epoch n, from the modulator constellation used on the ith transmit antenna, and $\mathbf{c}$ refers to the vector obtained by reading $\mathbf{D_c}$ row-wise. A code matrix covers l symbol epochs, starting with the kth symbol and ending with the one indexed by $(k + l - 1)$; here, l is a meaningful number of epochs. For example, in a trellis-based implementation, l could cover a codeword or frame forced to start and end in the zeroth state; in a block space-time code, l spans a block of symbols that are processed together during detection [6].

Space-time block codes of rate one are based on constructing code matrices of size $L \times L$, such that each complex symbol (arising from a group of encoder output symbols after mapping to the relevant modulator constellation) is transmitted by any one antenna only once (possibly complex conjugated and/or scaled by ± 1, $\pm j$; here j denotes $\sqrt{-1}$). In effect, this implements a modulator that takes advantage of the uncorrelated fading across the L transmit antennas without incurring any bandwidth expansion.

In the case of full rate transmission, $L = l$. In this situation, an orthogonality property for the square space-time block code matrices [6], allows easy recovery of the symbols arriving from different transmit antennas despite their superposition (in time) at the receiver's input. For complex modulator constellations the only known rate one constructions are 2×2 (i.e., for two transmit antennas). The construction for two transmit antennas was first proposed by Alamouti in [3] and is defined by the simple 2×2 pattern,

$$\begin{bmatrix} x_o & x_e \\ -x_e^* & x_o^* \end{bmatrix},$$

where x_o, x_e are valid complex symbols from the signal constellation (same on both antennas). Matrices like this are unitary, cover two symbol epochs, and allow easy recovery of x_o, x_e at the receiver given the channel state [3, 6]. Alamouti's idea, based on the Hurwitz-Radon transform, was further refined by Tarokh *et al.* [6].

Space-Time Transmit Diversity — STTD is an open loop technique in which the symbols are modulated using the technique described in [3]. This type of open loop TD has been adopted by the 3GPP because this type of transformation maximizes diversity gain.

STTD is defined for two antennas. Assume once again that x_o and x_e are the odd and even symbols, respectively. Then the transmissions over the two antennas, s_1 and s_2 are given by

$$\begin{aligned} s_{1e} &= x_o W, \\ s_{2e} &= x_e W, \\ s_{1o} &= -x_e^* W, \\ s_{2o} &= x_o^* W, \end{aligned}$$

where W is the orthogonal Walsh code used (Fig. 4).

The received symbol is decoded over two consecutive time epochs. The received symbol may be represented in vector form as

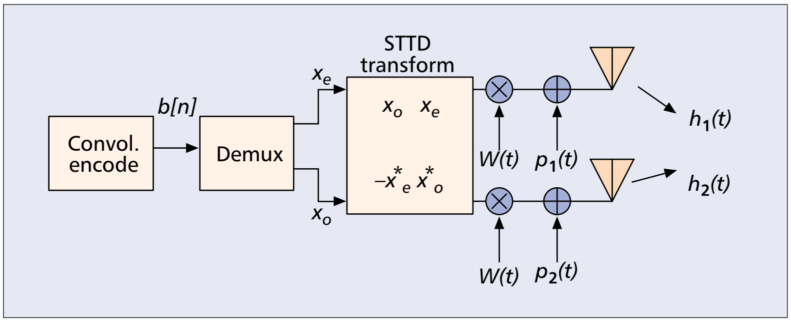
$$\begin{bmatrix} r_e \\ r_o \end{bmatrix} = \begin{bmatrix} h_1 x_o W + h_2 x_e W \\ -h_1 x_e^* W - h_2 x_o^* W \end{bmatrix} + \begin{bmatrix} \gamma_e \\ \gamma_o \end{bmatrix}.$$

Neglecting the Walsh codes, an estimate of the transmitted symbols may be formed as

$$\begin{bmatrix} \hat{x}_e \\ \hat{x}_o \end{bmatrix} = \begin{bmatrix} h_2^* r_e - h_1 r_o^* \\ h_1^* r_e + h_2 r_o^* \end{bmatrix}.$$

The STTD scheme is particularly simple, in the sense that it implements Alamouti's space-time block code (2×2 code matrices, see above) and follows it by separate spreading and scrambling, as in the nondiversity mode. The orthogonality property of the code matrices allows the symbols from the two transmit antennas to be separated at the receiver front-end. There is no need for separate Walsh codes on the two trans-

STTD is an open-loop technique in which the symbols are modulated using the technique described in. This type of open-loop transmit diversity has been adopted by the 3GPP, due to the fact that this type of transformation maximizes diversity gain.



■ **Figure 4.** *STTD transmitter.*

mit antennas for the traffic channel because the orthogonality between space-time code matrices is realized in the time domain, just as in frequency nonselective fading. However, separate Walsh codes are needed for the antenna pilot signals in order to distinguish the channels.

Space-Time Spreading — STS [2] is another open-loop technique in which the symbols are spread using multiple Walsh codes. It differs slightly from STTD, as explained below. Of course, apart from Walsh spreading, the symbols are spread by a long spreading code, but this will be self-understood and omitted here for simplicity. The differences from STTD arise in the need for STS to be compatible with certain details of the IS-2000 specifications, in particular OTD. This was not the case within the 3GPP standard, which made the implementation of STTD much more straightforward.

Using similar notation as in an earlier section, the symbols transmitted over the two antennas are

$$s_1 = x_o W - x_e^* \overline{W},$$
$$s_2 = x_e W + x_o^* \overline{W},$$

where (.)* stands for the conjugate operator. STS is another simple implementation of Alamouti's construction [3], based on the Hurwitz-Radon transform [6]. If one views $W, \overline{W}$ as playing the roles of the two transmit antennas, the Alamouti pattern in terms of x_e, x_o is easily recognizable; this is no surprise since $W, \overline{W}$ are, *de facto*, associated with the two antennas. The trick is that although the symbols in the even and odd streams completely overlap in time (just as in OTD), they are distinguishable due to spreading by the orthogonal Walsh codes $W, \overline{W}$. In other words, we do not need two symbol epochs to implement the orthogonal space-time block pattern; orthogonality of two disjoint time epochs has been replaced by orthogonality in the spreading code domain. The result is that any symbol in both the even and odd streams is exposed to both fading channels, thereby experiencing diversity due to lack of fading correlation across transmit antennas and independent of interleaving.

The recovery of the symbol stream is as shown below:

$$\hat{x}_o = rWh_1^* + (r\overline{W}h_2^*)^*,$$
$$\hat{x}_e = rWh_2^* - (r\overline{W}h_1^*)^*.$$

Now $\hat{x}_e$, $\hat{x}_o$ are concatenated and input to the decoder for demodulation. We stress that the advantage of STS over OTD is that all symbols are transmitted over all antennas; hence, it provides the addition of temporal diversity in the form of repetition coding prior to the decoding process.

Schemes for More than Two Antennas

Theoretically, the number of antenna elements through which independent channels can be transmitted bound the achievable order of spatial diversity. A few open loop schemes have been proposed for four antennas:

- A concatenation of the OTD scheme mentioned earlier and the STS scheme has been proposed as a diversity technique using four antennas [8].
- An extension of the Alamouti scheme in an earlier section for three or four antennas called *ABBA* has been proposed [9]. It has been proven that orthogonal designs do not exist for complex channels for four antennas. Hence, this is a suboptimal construction, which involves some interference cancellation along with space-time decoding.

Closed Loop Transmit Diversity in 3G

Closed loop diversity techniques are adaptive in nature. The BS obtains knowledge of the downlink channel from the MS via feedback signaling, and uses this knowledge to its advantage. The use of feedback in transmit antenna arrays was first proposed by Gerlach and Paulraj [10] as *transmit beamforming*. They proposed that training signals be transmitted periodically on the downlink and the responses of the various MSs fed back to the BS. This information is used to calculate the optimal transmit weights for each mobile such that the received power at the desired MS is maximized and interference to other MSs is minimized. These TD techniques can be described as customized to fit the channel conditions for each mobile user.

As explained at the beginning, the goal of inducing diversity runs somewhat contrary to that of inducing directionality using beamforming in that the antennas have to be spaced far apart. But the problem formulation for calculating the antenna weights remains the same if one recognizes the fact that knowledge of the different channel coefficients is equivalent to knowledge of the directional array manifold vector in the case of beamforming. In this sense, the closed loop diversity techniques considered in the 3G standards are variants of the approach in [10]. In fact, correlated fading models for multiple antennas and closed loop solutions for the same have been considered recently in these fora, arising when operators are constrained by considerations of space from placing antennas close to each other at the BS.

Switched Transmit Diversity

Switched TD (STD) is an extension of the open loop technique, TSTD. In this scheme, the symbols are transmitted over one antenna at any given time. The MS uses the average received power from the common pilots from each antenna, and makes a decision as to from which antenna it would like the BS to transmit. This decision is then conveyed to the BS through a feedback channel. This technique has been proposed in the 3G CDMA standards bodies, but a more general and aggressive form of STD was adopted by 3GPP: TXAA.

Transmit Adaptive Array

Transmit adaptive array (TXAA) is a technique in which the MS periodically sends quantized estimates of the optimal transmit weights to the BS via a feedback channel The transmitter weights are optimized to deliver maximum power to the MS. Figure 5 depicts the concept of TXAA.

Proceeding into more detail, consider a channel model with a single path channel emanating from each of the two BS antennas denoted $h_1(t)$, $h_2(t)$ and depicted in Fig. 5. The discussion can also easily be extended to the case of M antennas ($M > 2$). Since artificially induced diversity is most advantageous in the case of flat fading, we will consider the one path case here. Results can also be demonstrated for multipath channels. Let the transmitter antenna weights for the current instant be $w_1[l]$, $w_2[l]$. Let $b[n]$ be the data symbol at the current instant and $v(t)$ the user's specific spreading sequence. The discrete time subscripts on w and b are different since their periodicities are different. We assume that the paths from the two antennas are so closely spaced in time of arrival at the MS that they are indistinguishable. Ignoring the time subscripts, the signal received at the MS will be

$$y = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} b + \gamma$$
$$= \mathbf{hw}b + \gamma,$$

where γ refers to the additive noise. In order to maximize the received signal power, the optimal transmit weights are given by $\mathbf{w} = \mathbf{h}^H/\mathbf{hh}^H$.

The weights are normalized so that the total transmitted power is not altered. In the case of multipath channels emanating from each antenna (if $\mathbf{h}$ were a matrix instead of a vector), the optimal weights will be given by the principal eigenvector of the channel correlation matrix $\mathbf{h}^H\mathbf{h}$.

Thus, the MS calculates the weights at periodic intervals from the information $\mathbf{h}$ obtained through the two strong pilot signals P_1 and P_2. These weights are quantized and then fed back to the BS on the reverse link control channel. It is also worth noting that the STD method described previously is actually a subset of TXAA, with the weights being [0 1] or [1 0].

If one assumes that the feedback mechanism in TXAA perfectly tracks the channel conditions of the downlink, the signal-to-noise ratio (SNR) after demodulation and channel estimation is bounded as

$$SNR \le \left(\frac{|h_1|^2 + |h_2|^2}{\sqrt{|h_1|^2 + |h_2|^2}} \right)^2 \frac{Es}{N0} = \left(|h_1|^2 + |h_2|^2 \right) \frac{Es}{N0},$$

where E_s/N_0 is the symbol SNR based solely on transmitted signal energy. In comparison, from an earlier section it can be shown that the maximum achievable SNR of STTD after channel estimation is

$$SNR \le \frac{|h_1|^2 + |h_2|^2}{2} \frac{Es}{N0}.$$

Clearly, the maximum SNR of STTD cannot be greater than the maximum SNR of TXAA. Details of TXAA may be found in [11] and its associated references.

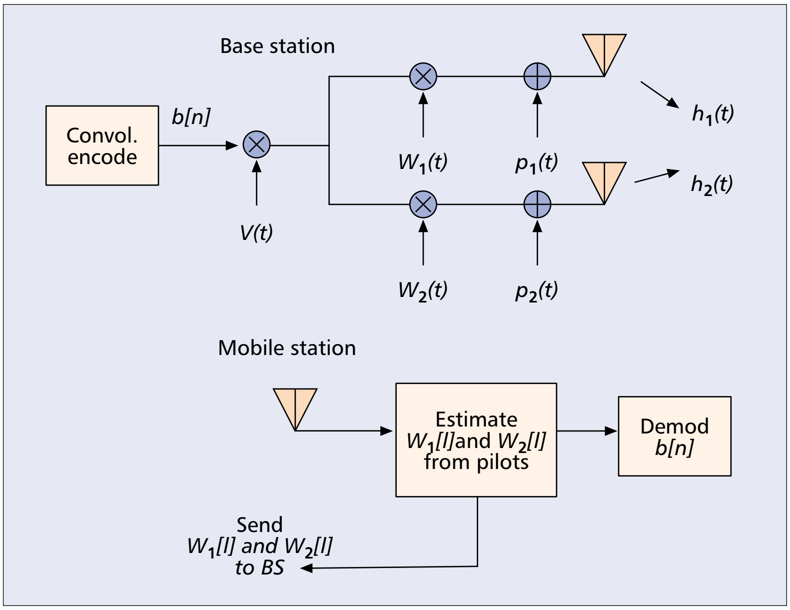


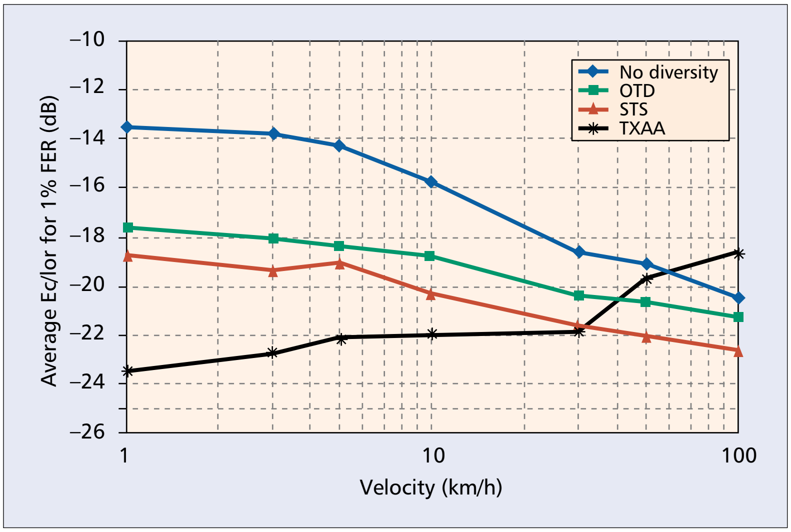
Figure 5. *Transmit adaptive array method.*

Issues and Solutions

Precision — Under the ideal conditions of infinite precision instantaneous feedback, closed loop schemes with feedback offer a substantial performance advantage over schemes without feedback under slow flat fading conditions. However, several issues arise in the practical implementation of these schemes. Limited availability of feedback capacity makes the precision of the feedback an important factor. In fact, in WCDMA, a feedback capacity of 1500 b/s is assumed, which amounts to 1 b/slot. Several methods have been used to convey channel information at this bit rate:

- Quantize the complex feedback coefficient to 1 bit of magnitude and 3 bits of phase and send them over successive slots [12].
- Feedback only the phase information for the complex coefficients. Set partitioning is done on the phase constellation, and the transmit weighting is calculated by filtering over multiple feedback bits [12].

Feedback Error — The feedback bits are not protected through FEC; hence, the weights applied at the BS transmitter antennas might be different from the weights the MS expects it to apply. This causes the composite channel estimate at the MS receiver to be in error. In order to avoid this situation, *verification* of the weights is necessary at the MS. Using the channel esti-



■ **Figure 6.** *Performance of TD methods.*

Number of base station antennas	2
Carrier frequency	2 GHz
Bit bate	9600 b/s
Chip rate	1.2288 Mchip/s
Walsh code length	128 chips
Convolutional code	Rate 1/4, $K = 9$
Frame duration	20 ms.
Pilot Ec/Ior	–7 dB
Power control	On
Channel estimation	Windowed (nonideal)
Channel model	Flat Rayleigh fading
Fading correlation	0
Feedback error rate	4%

■ **Table 1.** *Simulation parameters.*

mates from the common pilots as well as the dedicated pilot symbols embedded in the traffic channels, the applied weight may be estimated using hypothesis testing.

Another solution proposed for the feedback error problem was to use a decision-directed method wherein, in case of a frame error, the erroneous output bits are used to create a replica of the frame and compared with the received frame in order to determine the weights used in each slot in the frame [11].

Feedback Delay — The MS using channel state information available to it at any given instant estimates the required feedack. But there is a definite delay involved in transmitting the information back to the BS. In fast fading conditions, this delay causes the transmit weights to be outdated by the time they are applied at the BS [13]. One possible solution to this problem is to use the fact that the fading channel can be modeled as an auto-regressive (AR) process [14]. Linear prediction techniques can be used to estimate the AR coefficients and also to predict the future state of the channel. The mobile can calculate the feedback based on the predicted future channel state, thus reducing the effect of feedback delay.

Schemes for More than Two Antennas

The same principles discussed so far for two antenna elements can be used for extensions of closed loop schemes to more than two transmit antennas. One method being contemplated is the direct extension of the filtered phase feedback scheme in a previous section with a lower feedback rate per antenna.

There is a question about the feasibility of placing many antennas spaced far enough to provide independent fading paths due to space constraints. Closer spacing can induce partial correlation between diversity paths. A method called the *eigen-beamformer* has been proposed by Siemens to take advantage of the quasi-stationary property of this correlation. The eigenvectors of the correlation matrix are fed back at a slow rate. The short-term feedback indicates to the BS some linear combination of the vectors to be used as the antenna weights. A similar concept involving multiple banks of beamforming antenna arrays has been proposed by Fujitsu. Details of the schemes briefly described in this subsection may be found in [15] and its associated references.

A Comparison of Transmit Diversity Methods

This section compares the performance of different OL and CL methods. The results were generated in a symbol-level simulation environment for the CDMA2000 standard. The simulation parameters are given in Table 1. Figure 6 shows the average power per chip required to transmit at a given frame error rate with power control. It can be seen that the open loop methods are robust at higher velocities, while TXAA provides the biggest benefit at the lower velocities. To optimize the system performance the curves in Fig. 6 suggest that a mixture of open and closed loop diversity could be entertained to combat fast and slow fading, but this would require Doppler estimation at either the BS or MS as well as additional signaling overhead to facilitate dynamic switching between open and closed loop TD.

Conclusions

An attempt has been made to capture the essential elements of transmit diversity in 3G CDMA systems as they are evolving. An overview of the various transmit diversity methods is provided. Performance comparisons are given, and issues related to these methods were discussed.

More recently, MIMO technology, which is the use of multiple antennas at both the transmitter and the receiver, is being considered. Polarization diversity, space-time trellis coding and modulation, and the combination of intelligent beamforming with transmit diversity are some other technology areas that are promising for future evolution.

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Polarization diversity, space-time trellis coding and modulation, and the combination of intelligent beamforming with transmit diversity are technology areas that are promising for future evolution.