# Multiple Antenna Systems: Their Role and Impact in Future Wireless Access

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## ABSTRACT

Multiple antennas play an important role in improving radio communications. In view of this role, the area of multiple antenna communication systems is in the forefront of wireless research. This article reviews two key related aspects of multiple antenna communication systems: multiple access interference mitigation at the receiver via multi-user beamforming; and space-time modulation and coding for MIMO systems. It is shown that both multi-user and MIMO receivers share similar signal processing and complexity tradeoffs. Following that, a general unified framework for assessing different types of space-time modulation for MIMO systems is introduced. These space-time modulation methods are then compared in terms of Shannon capacity over multipath channels. Key MIMO system performance and implementation issues are also highlighted.

## INTRODUCTION

Over the past decade, research related to applications of antenna arrays to wireless and cellular communications systems has exploded, largely due to new possibilities afforded by the combination of wideband digitization and available high-speed baseband digital signal processing. Multiple antenna systems have the potential of achieving high-rate data access for *last-mile* deployment and increased capacity of mobile services.

Initially, the goal of *smart antenna* systems was to improve link signal-to-noise ratios (SNRs) through directional *array gain*. By coherently combining the antenna signals, narrow beams can be formed to reject noise and interference between a mobile user terminal and base station. In addition to providing coverage extension during initial stages of system deployment, baseband digital signal processing enables new adaptive *multi-user beamforming*, a type of processing that has no equivalent in the analog radio frequency (RF) domain. As a result, in multiple access systems, smart antennas may be combined with interference-canceling multi-user receivers.

During the past several years, propagation studies of wireless channels in urban environments have demonstrated that beamforming gains are limited by *scattering*. In third-generation wideband code-division multiple access (WCDMA) systems [1], multi-access interference due to scattering and multipath is particularly problematic. However, when there is significant scattering, exploiting decorrelation of transmitted signals to increase system capacity becomes attractive. In particular, *space-time processing and coding* exploits the parallel transmission channels created by scattering. In theory, if scattering exists to the extent that channel matrix components can be modeled statistically as independent random variables, it can be shown that system capacities may increase proportionally with the number of antennas. Such systems are currently in early stages of outdoor testing [2]. To achieve high transmission rates, temporal dispersion due to multipath propagation also has to be addressed. Due to space limitations, however, we focus on exploiting spatial dispersion through the use of adaptive digital beamforming.

This article focuses on two key issues in multi-antenna systems that are critical for wireless data access systems: multi-user beamforming and space-time coded modulation. In a cellular system with multiple antennas at a base station, multi-user beamforming is efficient for the mobile-to-base-station uplink, while in the downlink, space-time coded modulation can be used effectively to provide high information rates. The first part of this article describes multibeamforming systems employing a single transmit antenna and multiple receive antennas, and highlights the advantages of employing CDMA. Techniques requiring conventional matched filter receivers without channel estimation are discussed as well as multi-user (joint) detection techniques with smart antennas, including the concept of layering. The second part of the article reviews the concept of space-time coded modulation. First, a

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framework is presented for classifying transmission techniques employing multiple transmit antennas and different modulation formats. Then theoretical capacities obtainable by using alternative space-time modulation formats for multiple-input multiple-output (MIMO) systems over multipath channels are compared. Finally, a brief outline of system implementation and performance issues of MIMO systems is presented.

## MULTI-USER BEAMFORMING

Beamforming refers to the coherent combination of signals from different sensors to increase the SNR. Until recently, beamforming was performed by analog techniques using precise phase shifters and amplifiers and focused on applications where high gain in a known direction is desired. For example, analog beamforming is suitable for broadband terrestrial LMCS/LMDS and satellite systems operating near 30 GHz. Digital signal processing, however, extends beamforming to environments where user and interferer locations are not known a priori, as is normally the case in mobile cellular applications.

*Narrowband* beamforming, where the inverse bandwidth of the signal is large relative to the propagation time across the antenna array receiver elements, implies that all signal frequencies experience similar gain. Narrowband beamforming amounts to complex scalar multiplication on each antenna signal. Most wireless and mobile communications systems are classified as narrowband.

Digital beamforming is implemented at baseband on complex-valued (in-phase and quadrature) signal components. Each antenna requires a low-noise amplifier, mixer, analog-to-digital conversion as well as carrier and symbol timing synchronization. For a single user, digital beamforming is neither low cost nor low power. However, for multi-user communications, economies of scale result because adding users does not add to hardware cost. A digital *multibeamformer* can be realized since each of the $N_R$ receive antennas can be assigned $M$ different sets of user-specific weights.

### MULTI-BEAMFORMERS FOR CONVENTIONAL RECEIVERS

With asynchronous users, the complex baseband vector signal received by the $N_R$ antennas is given by a superposition of $M$ user signals, each weighted by a unique complex-valued *steering vector* and flat fading channel gain. Multipath delay spread also may occur if wideband signaling is used, and is discussed later. Despite time delay among users, timing recovery can be readily achieved for the desired user. Zero mean (spatially) additive white Gaussian noise (AWGN) is also present due to receiver electronics. To extract each user's data bits, conventional matched filtering is performed. Digital combining of the $N_R$ received signals from $M$ users can occur in parallel at low cost.

In direct-sequence (DS)-CDMA, a bitstream is modulated by a pseudo-noise (PN) sequence unique to each user. Short or long codes may be used. Using short-code DS-DCMA, the same PN sequence of $D$ *PN-chips* modulates each user bit. A multi-user beamformer can use short PN sequences as user-identifying pilot signals operating continuously during data transmission to adapt each of the user's parameters independently. This is important as it eliminates the need to estimate channel parameters and the corresponding overhead from long training periods.

There are a number of possible design objectives in choosing each user's beamformer weights. Exploiting known CDMA code structure is a very powerful concept, as data can be recovered by simply observing output statistics. Neither explicit channel estimation, antenna array geometry, nor propagation path information is required. In particular, the spatial correlation matrix formed from time-averaging received matched-filtered data can be shown to have special structure whereby the desired signal's steering vector can readily be identified.

Algorithms involving *code filtering* or *subspace processing* choose beamforming weight vectors based on the fact that the steering vector lies in a subspace of the vector space spanned by the output correlation matrix. The weight vectors can be optimized to maximize the signal-to-interference plus noise ratio (SINR), which is a spatial analogy of *optimum combining* associated with diversity systems [3]. If interference is spatially anisotropic (e.g., when one or two strong interferers exist), maximizing SINR is most effective. In contrast, maximizing SNR in the direction of the desired transmitter's steering vector is the space domain equivalent to *maximum ratio combining*, and is optimum if the interference is spatially isotropic. Maximum SNR beamforming is simpler than maximum SINR as it does not require estimating the interference-plus-noise spatial covariance matrix. If not employing CDMA, a training sequence would be needed to estimate these weight vectors.

Figure 1 shows a prototype of a four-antenna digital beamformer developed in the Multirate Wireless Data Access project under the Canadian Institute for Telecommunications Research (CITR). Table 1 presents average SINR increases over that of a single antenna system achieved by the four-user four-receive-antenna system ($M = N_R = 4$), in an outdoor environment containing line-of-sight propagation in addition to large reflecting obstacles, averaged over 30 trials. Users A through D are located at azimuth angles of 0°, 60°, 90°, and 120°, respectively, at a radial distance of 50 ft. Short codes are used with spreading factor $D = 128$ in a high-rate 7 Mchip/s CDMA system sampled at 5 samples/PN chip. There is no training period, calibration, or other side information required beyond knowledge of the four PN sequences. Table 1 shows that a significant SINR increase can be obtained only if multi-access interference (MAI) is reduced through maximum SINR beamforming. Despite this, poor performance for users B and D can be explained by examining the beampatterns in Fig. 2a–d, where output power is plotted for the four users as a function of the beam weight vector, parameterized by azimuth angle of arrival, corresponding to each of the four users. Note that users B and D have very similar beampatterns. Also, it is clearly not possible to predict beampat-

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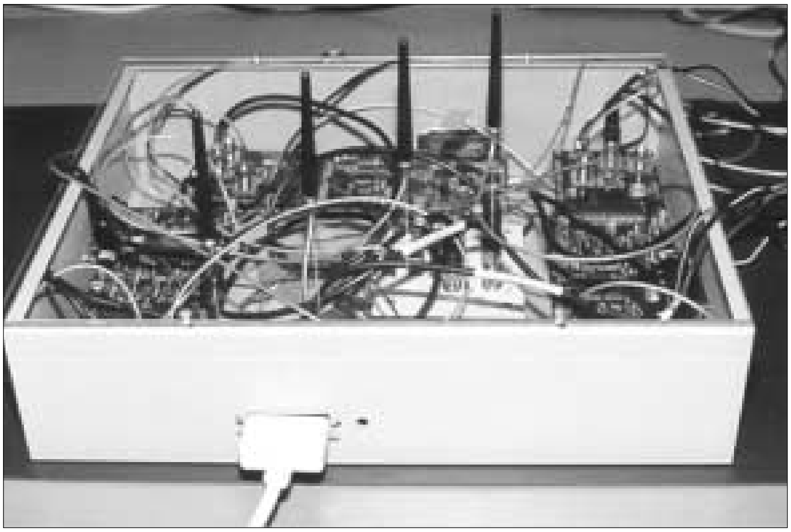

**Figure 1.** *A testbed for a four-antenna array beamforming receiver.*

| Beamforming | Average SINR gain (dB) | | | |
|---|---|---|---|---|
| criterion | User A | User B | User C | User D |
| Maximum SINR | 2.58 | 0.53 | 3.33 | 0.18 |
| Maximum SNR | 0.15 | 0.05 | 0.10 | 0.09 |

**Table 1.** *The effect of spatial signature and multi-user interference on beamforming.*

terns based on known geometry of the environment (i.e., the *array manifold*) due to the existence of multipath propagation and reflections.

### MULTI-USER BEAMFORMING RECEIVER

The receivers in the previous section use a conventional matched filter to detect each user's bits, while the other user signals are treated as noise. Joint detection of all bits from all users can overcome the limitations of multi-user interference. However, unlike the multibeamformer, a multi-user receiver normally requires estimation of channel parameters in addition to bit detection. A vector of samples received from $M$ users at the antenna array at time index $n$ can be expressed as an $N_R\,D$-dimensional vector

$$\mathbf{r}(n) = \mathbb{F}\,\mathbf{x}(n) + \mathbf{v}(n), \tag{1}$$

where $\mathbb{F}$ denotes an $N_R\,D \times M$ matrix of spreading codes multiplied by unknown channel gains, $\mathbf{x}(n) = [x_1(n)\,x_2(n),\ldots,x_M(n)]^T$ are the users' data bits, and $\mathbf{v}(n)$ is a noise vector. In Eq. 1, both channel matrix $\mathbb{F}$ and data $\mathbf{x}(n)$ are unknown, making the problem inherently ill posed. Even if $\mathbb{F}$ were known perfectly, optimal joint detection has exponential complexity. Even suboptimal linear detectors have high complexity, as they involve inversion of matrices with dimension proportional to $M$. To improve complexity-performance trade-offs, linear and adaptive multi-user detection can be introduced for single-input multiple-output systems as in [4].

Low-complexity approximate solutions to Eq. 1 have been developed. These approximations can be motivated theoretically in terms of either maximum likelihood estimation of hidden parameters, or alternatively as Gauss-Seidel iteration in nonlinear optimization. Receiver structures include the successive interference canceller (SIC), which is shown to be equivalent to the successive alternating generalized expectation (SAGE) method for maximum likelihood estimation [5], as well as the parallel interference canceller (PIC), which is shown to be equivalent to the expectation maximization (EM) algorithm. Figure 3 shows comparisons among SAGE, EM, and conventional single-user receivers for single and dual antenna systems in the presence of five strong interfering users. Clearly, significant gain can be achieved by multi-user receivers.

The SIC receiver starts with a very short (1–2 bit) training sequence and iteratively detects bits and estimates channel parameters user by user according to decreasing signal power. Within each iteration, a user's bit is detected, and its interference on remaining users is subtracted. In essence, each user has an *interference canceling unit* that is coupled to those of other users. Thus, as users are "peeled" off in layers, their effects on remaining users is removed, facilitating the detection of users at lower received powers. Layering exploits the fact that reliable channel transmission can be used in an interference cancellation structure. This concept can also be adapted to receive signals from multiple transmit antennas from a single user [6].

The above schemes are most effective for CDMA systems employing short PN spreading sequences. For asynchronous DS-CDMA systems employing long spreading sequences, a class of simple structures based on linear space-time filters has been found to be efficient in rejecting strong interference. In [7], the power spectral density shape of the MAI was exploited, resulting in space-time noise whitening matched filtering. Knowledge of chip delays of MAI components can also increase performance of linear temporal DS-CDMA receivers. Strong MAI components are most likely generated by users from the same cell as the desired users, and are therefore locked to the same base station. As such, the corresponding chip (or bit) delays are normally available at the base station. Such chip delays can be used for maximizing the SINR delivered by linear space-time receivers for DS-CDMA, resulting in a chip locked space-time filter. Chip locking, in this context, means that the MAI components are locked to the same base station as the desired user. With fixed and known chip delays, the MAI is a cyclostationary random process. This may be factored into SINR maximization for performance gains.

*Transmission beamforming* from base station to user (downlink) differs fundamentally from *receive beamforming* (uplink), discussed previously. In the uplink, the base station can optimize beamforming weights independently on a per-user basis. In the downlink, multi-user beamforming gains are more limited due to fewer available degrees of freedom, as the smart antenna system is constrained to transmit the same multiplex of signals to all users. However, transmit beamforming can be generalized to a more flexible form, say, by transmitting different signals on different antennas, or even structuring the signal transmission differently on each transmit antenna, depending on the extent of scatter-

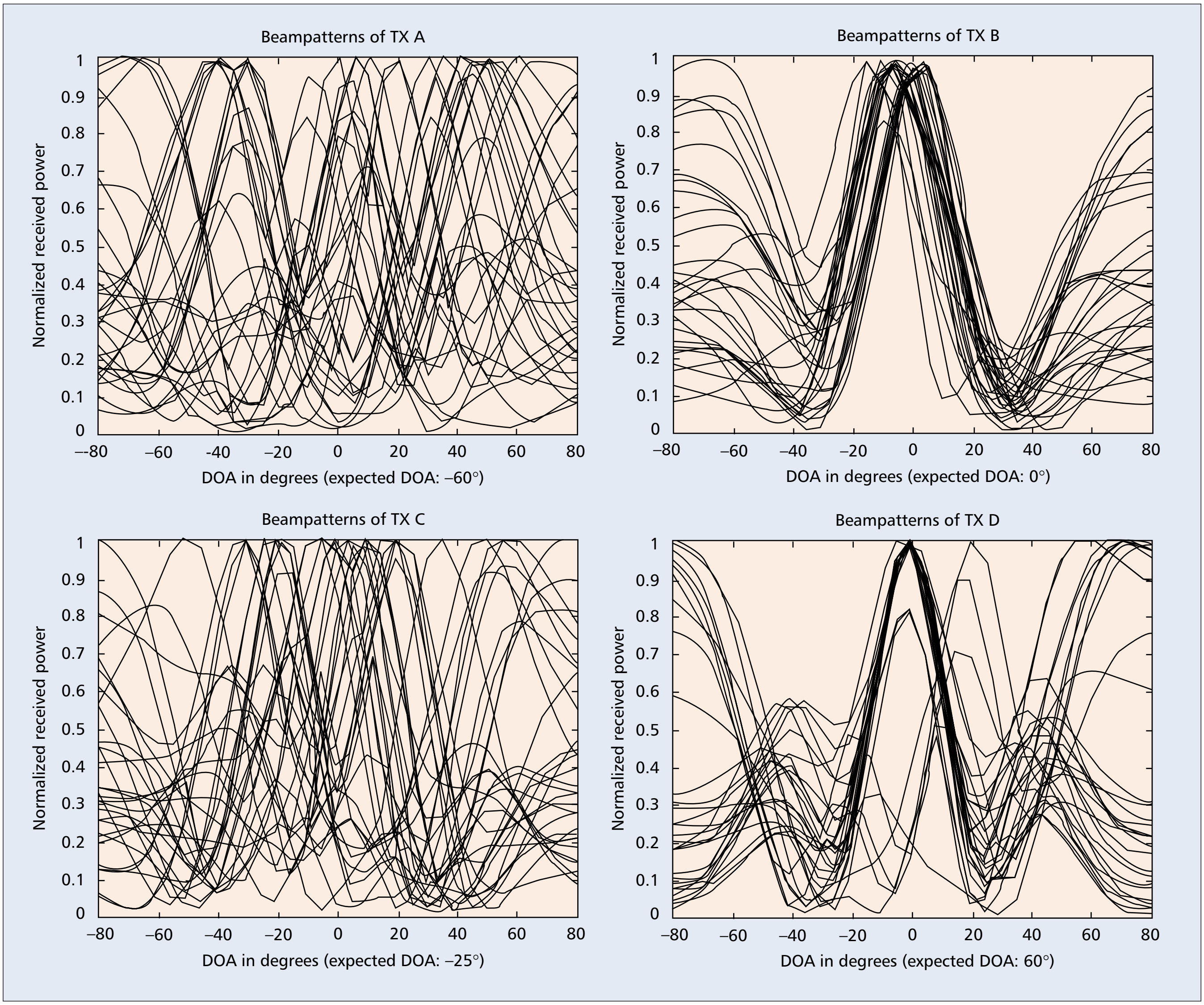

**Figure 2.** *Beam patterns produced by the system shown in Fig. 1 for four different transmitters, with a well separated in space line-of-sight component.*

ing in the channel. In this latter situation space-time signal processing, coding, and modulation can be designed to achieve transmit diversity and coding gain, as discussed later.

### EXPLOITING MULTIPATH PROPAGATION

Both fixed and mobile wireless channels encounter multipath propagation. A larger signaling bandwidth, however, temporally resolves multipath components. For example, in moving from standard 1.25 Mchip/s to the 7 Mchip/s experimental WCDMA system of Fig. 1, average delay spreads increase from less than one PN chip to several PN chips. Typically, two to four multipath components can reliably be detected within this delay spread interval.

The beamforming strategies described previously are less effective in multipath channels, where the transmitted signal power has been divided into several weaker components that arrive at the receiver at different times. Ideally, these signal components should be recombined in phase at the receiver. A RAKE receive structure is used to combine delayed signal components. Both spatial and temporal processing may be combined into a highly complex *beam-steered or 2D RAKE* receiver structure [8], requiring the optimization of $LMN_R$ parameters. Simplification resulting from separate optimization in spatial and temporal domains does not generally yield overall optimal (or even acceptable) space-time receiver performance.

To reduce the effects of multipath, the symbol duration can be increased, resulting in a frequency flat fading channel. However, this results in spatial dispersion, which can be parameterized by the *angle spread* of arriving multipath components. Ideal (single-path) plane wave propagation corresponds to zero angle spread, while correlation measurements from the experimental outdoor system described earlier yield an angle spread of approximately 20°.

In the next section, statistical decorrelation among antenna elements, as induced by high angle spread, is exploited. In this case, multiple transmit and receive antennas can create independent parallel transmission channels to increase information transfer rates [9].

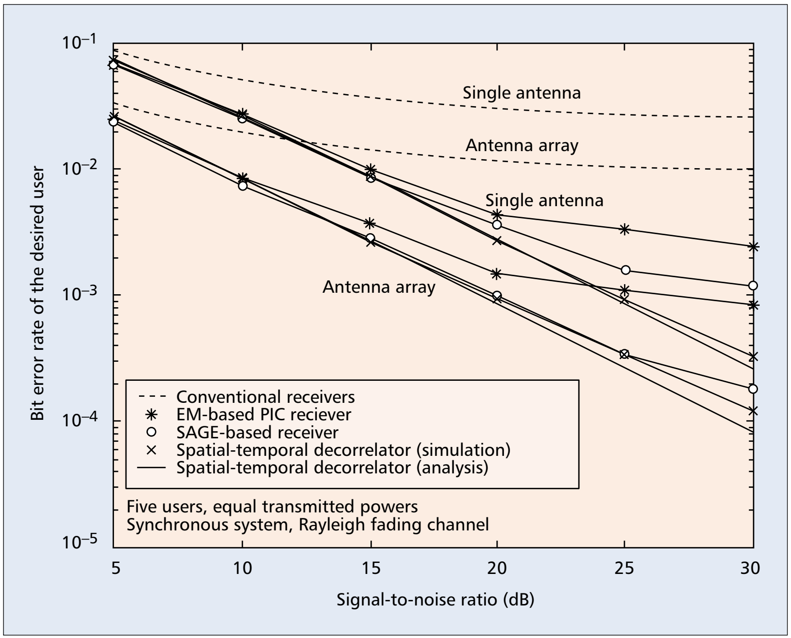

**Figure 3.** *Antenna array signal processing combined with multi-user detection: comparison among single and dual antenna receivers, conventional and multi-user receivers for the case of a five-user system.*

## SPACE-TIME CODED MODULATION FOR MIMO SYSTEMS

The downlink is a point-to-multipoint communication system where users' data may be multiplexed orthogonally on different signal dimensions. An important aspect of wireless communications is the increase in downlink information rates for delivery of services such as multimedia (e.g., the 3GPP initiative, High Speed Downlink Packet Access). Base stations equipped with multiple antennas using suitable space-time coded modulation are attractive for such applications due to possibilities of achieving high transmission rates in a restricted bandwidth. In multiple transmit antenna base stations, different signal dimensions may be allocated to different transmit antennas. Multidimensional space-time modulation formats may be classified in a framework describing the allocation of signal dimensions among transmit antennas. For simplicity, a single-user system was considered. Due to user orthogonality, conclusions can be extended easily to the multi-user case. In the following, the Shannon capacity is considered, illustrating the error-free information transfer capabilities of space-time modulation schemes over multipath channels, and presenting the transmitted signaling structure for achieving capacity. The relationship to transmit beamforming is also pointed out.

### THE FRAMEWORK AND SYSTEM MODEL

Consider the system in Fig. 4 employing $N_T$ transmit and $N_R$ receive antennas. We represent the signal transmitted through antenna $k$ as

$$S_k(t) = \sum_{n=-\infty}^{\infty} [\phi_1(t-nT)\ \phi_2(t-nT)\ \ldots\ldots\ \phi_D(t-nT)] \cdot \mathbf{A}_k^T \cdot \mathbf{x}_k(n), \quad k = 1,2\ldots,N_T, \tag{2}$$

where $\mathbf{x}_k(n)$ is the vector of transmitted data for antenna $k$ at symbol interval $n$, $\{\phi_1(t-n_T), \phi_2(t-n_T), \ldots, \phi_D(t-n_T)\}$ are orthonormal modulating waveforms (signal dimensions), $D$ is the number of available dimensions for a user, and $\mathbf{A}_k$ is a matrix of (0,1) components determining the modulating waveforms used on antenna $k$: all-zero columns correspond to a signal dimension not used on antenna $k$. The number of nonzero columns of $\mathbf{A}_k$ is equal to the dimension of vector $\mathbf{x}_k(n)$. A nonzero element in a column indicates the component of $\mathbf{x}_k(n)$ being used as a coefficient for the dimension corresponding to that column.

More generally, the set of matrices $\mathbf{A}_1, \mathbf{A}_2, \ldots, \mathbf{A}_{N_T}$ determines the modulating waveforms used on each transmit antenna, and as such defines a multidimensional space-time modulation format. Examples are illustrated in Fig. 5. In an orthogonal transmit antenna (OTA) format, each modulating waveform is allocated to only one transmit antenna, whereas all modulating waveforms are allocated to all antennas in an aggregate transmit antenna (ATA) format. A partially orthogonal transmit antenna (POTA) format combines OTA and ATA, in that subsets of antennas share subsets of signal dimensions. Although many other modulation formats can be described within this framework, only these three are considered. The space-time coded schemes in [10, 11] as well as delay diversity are examples of ATA. Transmission beamforming can be modeled as ATA with space repetition coding (i.e., the same information is transmitted through all antennas). The orthogonal transmit diversity employed in IS-2000 [12] is an example of OTA.

In addition, certain selections of the modulating waveforms $\{\phi_1(t), \phi_2(t), \ldots, \phi_D(t)\}$ can lead to different schemes. For example, if orthogonal complex exponentials at different frequencies are employed, an orthogonal multicarrier system results. If the modulating waveforms are constructed from Hadamard or other orthogonal codes, we have orthogonal CDMA (O-CDMA) systems. Combinations of these two types of modulation result in multicarrier CDMA systems. Furthermore, the DS-CDMA signal used in the multibeamforming section can be expressed in this framework with $N_T = 1$, $\phi_j(t) = \phi(t-(j-1)T_c)$, $j = 1, 2, \ldots, D$ the time-shifted modulated waveforms, $\mathbf{A}_1$ the identity matrix, and $\mathbf{x}_k(n)$ the data, modulated by its spreading sequence.

The ensuing discussion assumes a narrowband channel dispersive only in space. The waveform channel is specified by $N_R \times N_T$ channel complex transmission matrix $\mathbf{C}$, with zero-mean AWGN vector components having a constant power spectral density of $N_0$ W/Hz. The receiver shown in Fig. 4 employs a correlator bank on each antenna matched to waveforms (signal dimensions) $\{\phi_1(t-nT\}, \phi_2(t-nT), \ldots, \phi_D(t-nT)\}$. At time $n$, the $N_RD$-dimensional vector of matched filter outputs from all antennas can be specified by the equivalent discrete channel

$$\mathbf{r}(n) = \mathbf{H}\mathbf{x}(n) + \mathbf{v}(n), \tag{3}$$

where $\mathbf{H}$ is a function of both the channel matrix, $\mathbf{C}$, and multidimensional space-time format, $\mathbf{A}_1, \mathbf{A}_2, \ldots, \mathbf{A}_{N_T}$. In Eq. 3, $\mathbf{v}(n)$ is a zero-mean complex AWGN vector.

A transmit orthogonal group (TOG) is defined to be a group of transmit antennas that share a

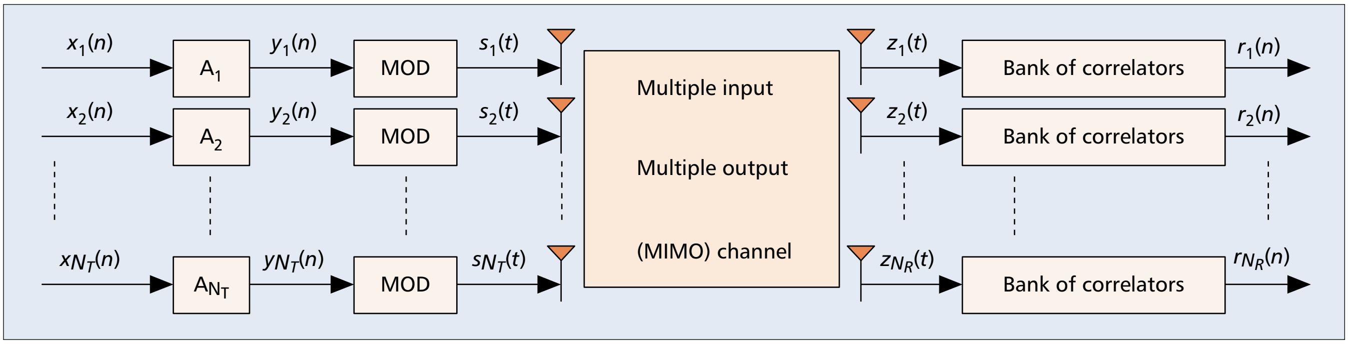

**Figure 4.** *A model of a space-time modulation system.*

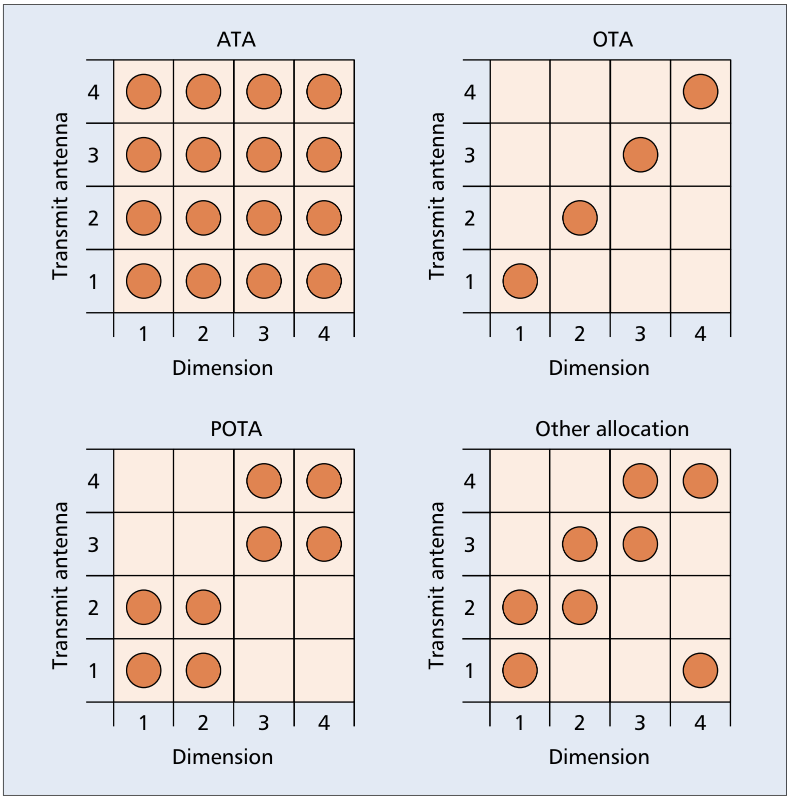

**Figure 5.** *Multidimensional space-time modulation formats.*

given subset of signal dimensions. Signals transmitted by antennas belonging to different TOGs are orthogonal. If all antennas share the same set of signal dimensions, as in ATA, we have only one TOG. If each antenna uses an orthogonal set of signal dimensions, the number of TOGs is $N_T$ and we have OTA. It will be seen that the number of TOGs, $N_G$, as well as the column rank of the channel matrix $\mathbf{H}$ are critical parameters that determine how capacity increases with SNR.

Comparing Eqs. 1 and 3, multi-user and MIMO system models appear similar. Indeed, the receiver side layered processing is closely related. However, Eq. 3 has additional transmit-side design flexibility due to the presence of a multidimensional space-time modulation format. The reliable information transmission rates made possible by these space-time modulation formats are considered next.

## COMPARISON OF SPACE-TIME MODULATION METHODS IN MULTIPATH CHANNELS

To investigate the effects of multipath propagation on error-free transmission rates of various space-time modulation schemes, a deterministic channel known at the transmitter and receiver is assumed. For simplicity, a deterministic multipath channel dispersive only in space is used to illustrate the capacity buildup with the number of multipath components. Let $\Sigma = \mathrm{E}[\mathbf{x}(n)\mathbf{x}^H(n)]$ be the channel input signal covariance matrix. With an average transmit power constraint on the sum of the diagonal elements of $\Sigma$ (i.e., $T_r(\Sigma) \le P_T$), we have from [9] that the Shannon capacity is given by

$$C = \frac{1}{D} \max_{\mathrm{Tr}(\Sigma)\le P_T} \log \left[\det\left(\mathbf{I}_{N_T D_G} + \frac{1}{N_0}\Sigma\mathbf{H}^H\mathbf{H}\right)\right] \quad \text{bps/Hz} \tag{4}$$

and $D_G = D/N_G$ is the number of dimensions per TOG. This capacity can be achieved by a Gaussian input $\mathbf{x}(n)$, with a transmit multibeam structure determined by the eigenvectors of the channel matrix product $\mathbf{H}^H\mathbf{H}$, where the superscript $H$ denotes conjugate-transpose.

In the capacity expression of Eq. 4, the link SNR appears in the term

$$\frac{1}{N_0}\Sigma\mathbf{H}^H\mathbf{H},$$

showing that capacity grows only logarithmically with increasing SNR. Since traditional receiver diversity and beamforming can only serve to increase SNR, it is clear that multiple transmit antennas employing receiver diversity can yield only logarithmical capacity gains. In certain circumstances, capacity can increase in proportion to the number of transmit and receive antennas, $N_T$ and $N_R$, respectively. The determinant in Eq. 4 is a product of terms corresponding to the nonzero eigenvalues of $\mathbf{H}^H\mathbf{H}$. For a full rank $\mathbf{H}$, corresponding to rich scattering, there can be at most $\min(N_T, N_R)$ such terms. In this case, with sufficiently large SNR, capacity can grow linearly with the minimum of the number of transmit and receive antennas. There are situations, however, when the rank of $\mathbf{H}$ (and hence the capacity) does not increase with $N_T$ and $N_R$ leading to the so-called *key hole* effect [13].

The signal maximizing Shannon capacity is structured as multiple transmit eigen-beams (i.e., eigenvectors of $\mathbf{H}^H\mathbf{H}$), each with *water-filling* [9]

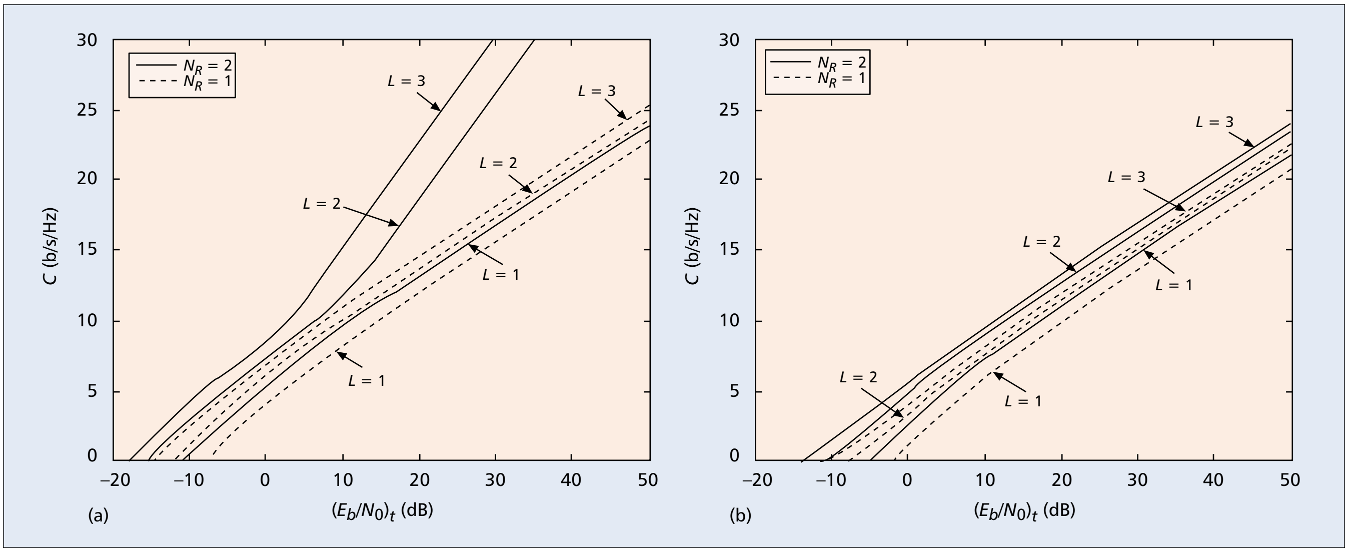

**Figure 6.** *Shannon capacity : a) ATA, b) OTA.*

allocated power determined by the corresponding eigenvalues. An eigen-beam corresponding to a small eigenvalue will receive less power. Depending on the total available power $P_T$, a small eigenvalue could result in an inactive corresponding eigen-beam. When $P_T$ is sufficiently large such that all the eigen-beams are active, capacity grows linearly with min($N_T$, $N_R$). Different space-time modulation formats induce different eigen-beam structures with different associated capacities. For a single-path channel this structure degenerates to transmission beamforming, as discussed earlier, along a single steering vector.

As an example, the Shannon capacity was evaluated for a plane-wave propagation channel with up to $L = 3$ equal gain paths propagating in different directions, four transmit antennas, and either one or two receive antennas. The capacity, $C$, in bits per second per hertz as a function of $(E_b/N_0)_t$, the SNR referenced at the transmitter, is plotted in Fig. 6 for the ATA and OTA formats. The capacity increase as a function of $L$ is clearly evident. With one receive antenna, the dependence of $C$ on $(E_b/N_0)_t$ and $L$ for both ATA and OTA is similar, and ATA provides larger capacity. For large SNR, the rate of increase of $C$ is the same. However, with two receive antennas with equal SNR, in addition to a 3 dB gain, we observe for two and three propagating paths that the ATA curves have an inflection point and show a larger rate of increase with $(E_b/N_0)_t$ than those of the corresponding OTA curves.

The asymptotic rate of increase in capacity for large $P_T$, when all available eigen-beams are active, can be calculated. For OTA, the rate of increase in $C$ is 1/3 b/s/Hz/dB regardless of the number of paths and receive antennas. With ATA, the rate of increase in $C$ depends on both the number of paths and receive antennas. With one receive antenna, $C$ increases at a rate of 1/3 b/s/Hz/dB, similar to OTA. With two receive antennas and one propagating path, ATA and OTA increase with $(E_b/N_0)_t$ at the same rate. However, for multiple propagating paths, the rate of increase in $C$ for ATA becomes 2/3 b/s/Hz/dB, or twice that for OTA. With three paths, we achieve a rate of increase in $C$ of 1 b/s/Hz/dB for ATA employing three receive antennas.

Among all space-time modulation formats, ATA has the largest Shannon capacity gains offered by multipath propagation in MIMO systems. Other space-time modulation formats may provide other advantages. For example, OTA can provide full transmit diversity with almost any temporal code to combat fading, without requiring special combined space-time domain designs, while POTA can offer a combination of desirable ATA Shannon capacity and OTA transmit diversity. The space-time block code construction in [11], limited to two transmit antennas, provides only order 2 transmit diversity. With four transmit antennas one could employ POTA where each TOG has two transmit antennas, each employing the scheme from [11]. The result is order 4 transmit diversity, but at only half the information transmission rate. An adaptive system is also possible that trades transmission rate with diversity order according to channel conditions.

## MIMO SYSTEM PERFORMANCE AND IMPLEMENTATION ISSUES

Traditionally, Shannon capacity represents an implementation-independent achievable performance upper bound, which in MIMO systems can be in the range of several tens of bits per second per hertz depending on SNR and the number of antennas. Unfortunately, knowing the Shannon limit does not provide a design of a high-capacity system. Optimum multichannel versions of maximum likelihood sequence estimation have exponential complexity in both time and space. Therefore, it is necessary to consider suboptimum methods.

For high SNR operation at short range, the BLAST system in [14] provided the first experimental achievement of capacities in the range 10–40 b/s/Hz. The experimental system in [15], STREAM, is reported to deliver up to 208 b/s/Hz with 40 transmit and 60 receive antennas at 30 dB SNR. In these systems, the richness of scattering in the channel is critical, as discussed earlier.

As MIMO processing involves an iterative solution of matrix equations, the same *layering* concept for multi-user detection can be used to extract independent bitstreams transmitted from multiple antennas belonging to a single user. This is known as the Bell Laboratories Layered Space-Time (BLAST) algorithm [6]. Variations of BLAST, in terms of how the data stream is mapped onto the parallel MIMO channels, include diagonal (D-BLAST) [6], vertical (V-BLAST) [14], random (R-BLAST), and others.

In addition to MIMO processing, channel coding is needed to approach MIMO system capacity. The STREAM system [15] employs serial concatenated channel coding, demultiplexing and mapping to quadrature amplitude modulation for each transmit antenna, temporal and spatial signal shaping, and channel estimation. The total overhead due to channel coding, training, and synchronization is reported to be 28 percent. Implementation complexity is an issue in such multi-antenna high capacity schemes, although [15] claims it is comparable to that of a single-antenna high-capacity OFDM system.

## FUTURE CHALLENGES

By exploiting properties of wireless channels, information rates and area coverage may be enhanced. In situations where scattering is low, a multibeamforming receiver is effective. If scattering is significant, potential gains from space-time coding and processing of MIMO systems are very large. Several issues that warrant further investigation include:

- The extent to which realistic wireless MIMO environments generate parallel independent channels
- How to exploit such propagation channels with small mobile terminals operated by batteries

Furthermore, the inclusion of implementation imperfections in MIMO channel models is important since it will enable more accurate capacity prediction. As promising as it is, achieving high capacity in practice while minimizing computational cost and latency seems challenging. Finally, space-time coding for multi-user environments should be investigated so that both spatial and temporal processing resources may be more flexibly exploited.

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> *Among all space-time modulation formats, ATA has the largest Shannon capacity gains offered by multipath propagation in MIMO systems. Other space-time modulation formats may provide other advantages.*