Breaking the Barriers of Shannon's Capacity: An Overview of MIMO Wireless Systems

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Appearing a few years ago in a series of information theory articles published by members of the Bell Labs, multiple-input multiple-output (MIMO) systems have evolved quickly to both become one of the most popular topics among wireless communication researchers and reach a spot in today's 'hottest wireless technology' list. In this overview paper, we come back on the fundamentals of MIMO wireless systems and explain the reasons of their success, triggered mainly by the attraction of radio transmission capacities far greater than those available today. We also describe some practical transmission techniques used to signal data over MIMO links and address channel modeling issues. The challenges and limitations posed by deploying this technology in realistic propagation environment are discussed as well.

I. Introduction

Digital communications using MIMO (multiple-input multiple-output), or sometimes called "volume to volume" wireless links, has emerged as one of the most promising research areas in wireless communications. It also figures prominently on the list of hot technologies that may have a chance to resolve the bottlenecks of traffic capacity in the forthcoming high-speed broadband wireless Internet access networks (UMTS[1]) and beyond).

MIMO systems can be defined simply. Given an arbitrary wireless communication system, MIMO refers to a link for which the transmitting end as well as the receiving end is equipped with multiple antenna elements, as illustrated in Figure 1. The idea behind MIMO is that the signals on the transmit antennas on one end and that of the receive antennas on the other end are "combined" in such a way that the quality (Bit Error Rate) or the data rate (Bit/Sec) of the communication will be improved. MIMO systems use space-time processing techniques in that the time dimension (natural dimension of transmission signals) is completed with the spatial dimension brought by the multiple antennas. MIMO systems can be viewed as an extension of the so-called "smart antennas" [1], a popular technology for improving wireless transmission that was first invented in the 70s. However, as we will see here, the underlying mathematical nature of MIMO environments can give performance which goes well beyond that of conventional smart antennas. Perhaps the most striking property of MIMO systems is the ability to turn multipath propagation, usually a pitfall of wireless transmission, into an advantage for increasing the user's data rate, as was first shown in groundbreaking papers by J. Foschini [2], [3].

In this paper, we attempt to explain the promise of MIMO techniques and explain the mechanisms behind it. To highlight the specifics of MIMO systems and give the necessary intuition, we illustrate the difference between MIMO and conventional smart antennas in section II. A more theoretical (information theory) standpoint is taken in part III. Practical design of MIMO solutions involves both transmission algorithms and channel modeling to measure their performance. These issues are addressed in sections IV and V respectively. Radio network level considerations to evaluate the overall benefits of MIMO setups are finally discussed in section VI.

II. MIMO Systems: More Than Smart Antennas

In the conventional wireless terminology, smart antennas refer to those signal processing techniques exploiting the data captured by multiple antenna elements located on one end of the link

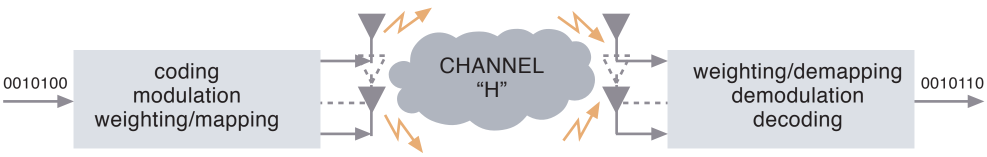


Figure 1 Diagram for a MIMO wireless transmission system. The transmitter and receiver are equipped with multiple antenna elements. Coding, modulation and mapping of the signals onto the antennas may be realized jointly or separately

[1]) *Universal Mobile Telephone Services.*

only, typically at the base station (BTS) where the extra cost and space are more easily affordable. The multiple signals are combined upon transmission before launching into the channel or upon reception. The goal is to offer a more reliable communications link in the presence of adverse propagation conditions such as multipath fading and interference. A key concept in smart antennas is that of beamforming by which one increases the average signal to noise ratio (SNR) through focusing energy into desired directions. Indeed, if one estimates the response of each antenna element to a desired transmitted signal, one can optimally combine the elements with weights selected as a function of each element response. One can then maximize the average desired signal level and minimize the level of other components (noise and/or interference).

Another powerful effect of smart antennas is called *spatial diversity*. In the presence of multipath, the received power level is a random function of the user location and, at times, experiences *fading*. When using antenna arrays, the probability of losing the signal altogether vanishes exponentially with the number of decorrelated antenna elements. The *diversity order* is defined by the number of decorrelated spatial branches.

When multiple antennas are added at the subscriber's side as well as to form a MIMO link, conventional benefits of smart antennas are retained since the optimization of the transmitting and receiving antenna elements can be carried out in a larger space. But in fact MIMO links offer advantages which go far beyond that of smart antennas [4]. Multiple antennas at both the transmitter and the receiver create a *matrix* channel (of size the number of receive antennas times the number of transmit antennas). The key advantage lies in the possibility of transmitting over several spatial *modes* of the matrix channel within the same time-frequency slot at no additional power expenditure.

While we use information theory below to demonstrate this rigorously, the best intuition is perhaps given by a simple example of a transmission algorithm over MIMO referred here as *spatial multiplexing*, which was initially described in [3], [5]. In Figure 2, a high rate bit stream (left) is decomposed into three independent bit sequences, which are then transmitted simultaneously using multiple antennas. The signals are launched and naturally mixed together into the wireless channel as they use the same frequency spectrum. At the receiver, after having identified the mixing channel matrix through training symbols, the individual bit streams are separated and estimated. This occurs in the same way, as three unknowns are resolved from a linear system of three equations. The separation is possible only if the equations are independent which can be interpreted by each antenna 'seeing' a sufficiently different channel. That is typi-

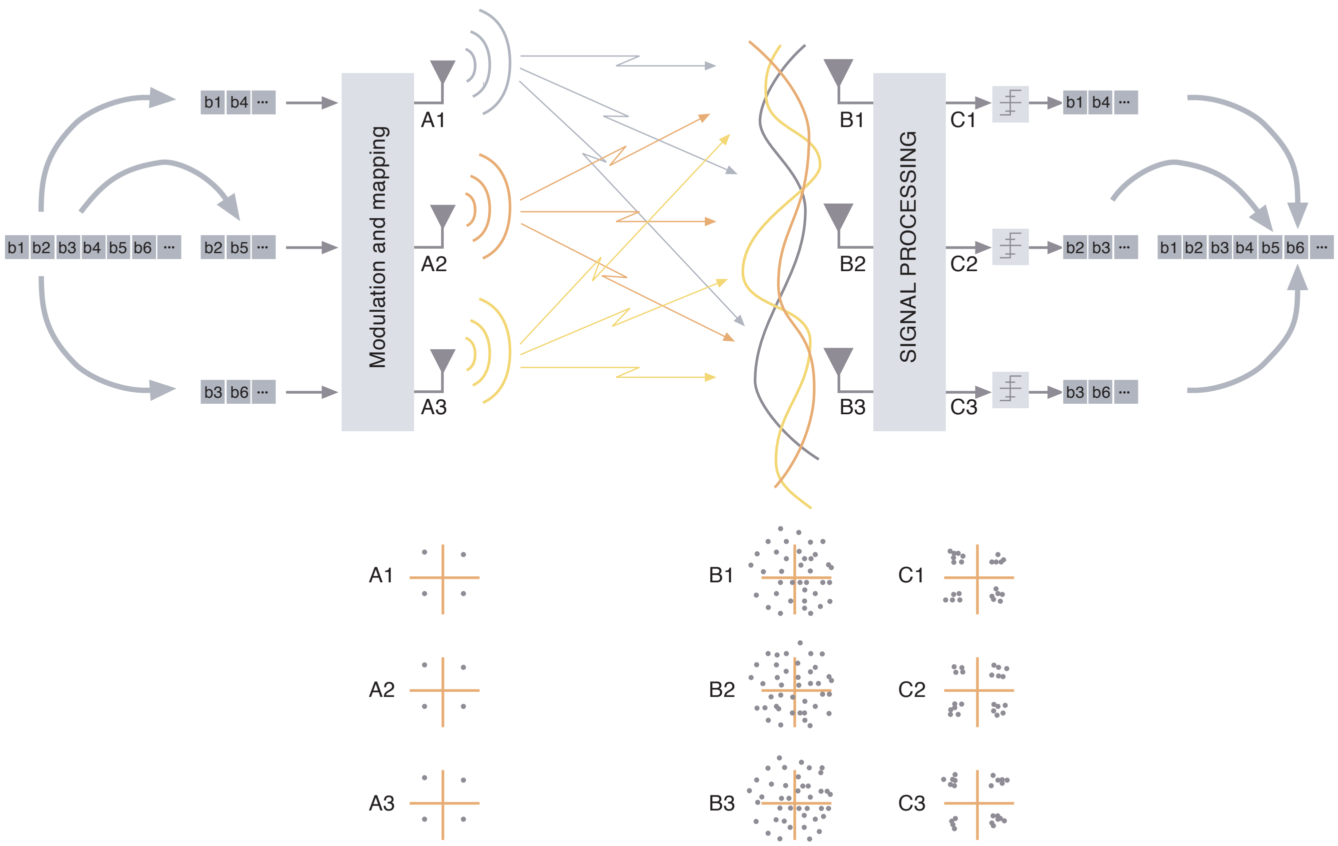


Figure 2 Basic spatial multiplexing (SM) scheme with 3 transmit and 3 receive antennas yielding three-fold improvement in spectral efficiency

cally the case in the presence of rich multipath. Finally the bits are merged together to yield the original high rate signal.

In general though, one will define the *rank* of the MIMO channel as the number of independent equations offered by the linear system mentioned above. It is also equal to the algebraic rank of the channel matrix. Clearly the rank is always both less than the number of transmit antennas and less than the number of receive antennas. In turn, the number of independent signals that one may safely transmit through the MIMO system is at most equal to the rank. In this example, the rank is assumed full (equal to three) and the system shows a spectrum efficiency gain of three. This surprising result can be demonstrated from an information theory standpoint.

III. Fundamental Limits of Wireless Transmission

Today's inspiration for research and applications of wireless MIMO systems was mostly triggered by the initial Shannon capacity results obtained independently by Bell Lab's researchers E. Telatar [6] and J. Foschini [3], further demonstrating the seminal role of information theory in telecommunications. The analysis of information theory-based channel capacity gives very useful, although idealistic, bounds on what is the maximum information transfer rate one is able to realize between two points of a communication link modeled by a given channel. Further, the analysis of theoretical capacity gives information on how the channel model or the antenna setup itself may influence the transmission rate. Finally it helps the system designer benchmark transmitter and receiver algorithm performance. Here we examine the capacity aspects of MIMO systems compared with single input single output (SISO), single input multiple output (SIMO) and multiple input single output (MISO) systems.

III.A Shannon Capacity of Wireless Channels

Given a single channel corrupted by an additive white Gaussian noise (AWGN), at a level of SNR denoted by ρ, the capacity (rate that can be achieved with no constraint on code or signaling complexity) can be written as [7]:

$$C = \log_2 (1 + \rho) \text{ Bit/Sec/Hz} \qquad (1)$$

This can be interpreted by an increase of 3 dB in SNR required for each extra bit per second per Hertz. In practice, wireless channels are time-varying and subject to random fading. In this case we denote h the unit-power complex Gaussian amplitude of the channel at the instant of observation. The capacity, written as:

$$C = \log_2 (1 + \rho \,|\, h \,|^2) \text{ Bit/Sec/Hz} \qquad (2)$$

becomes a *random* quantity, whose distribution can be computed. The cumulative distribution of this "1 × 1" case (one antenna on transmit and one on receive) is shown on the left in Figure 3. We notice that the capacity takes, at times, very small values, due to fading events.

Interesting statistics can be extracted from the random capacity related with different practical design aspects. The *average capacity* C_a, average of all occurrences of C, gives information on the average data rate offered by the link. The *outage capacity* C_o is defined as the data rate that can be guaranteed with a high level of certainty, for a reliable service:

$$\text{Prob}\{C \geq C_o\} = 99.9..9~\% \qquad (3)$$

We will now see that MIMO systems affect C_a and C_o in different ways than conventional smart antennas do. In particular MIMO systems have the unique property of significantly increasing both C_a and C_o.

III.B Multiple Antennas at One End

Given a set of M antennas at the receiver (SIMO system), the channel is now composed of M distinct coefficients $\mathbf{h} = [h_0, h_1, ..., h_{M-1}$ where h_i is the channel amplitude from the transmitter to the i-th receive antenna. The expression for the random capacity (2) can be generalized to [3]:

$$C = \log_2 (1 + \rho \mathbf{hh}^*) \text{ Bit/Sec/Hz} \qquad (4)$$

where * denotes the transpose conjugate. In Figure 3 we see the impact of multiple antennas on the capacity distribution with 8 and 19 antennas respectively. Both the outage area (bottom of the curve) and the average (middle) are improved. This is due to the spatial diversity which reduces fading and thanks to the higher SNR of the combined antennas. However going from 8 to 19 antennas does not give very significant improvement as spatial diversity benefits quickly level off. The increase in average capacity due to SNR improvement is also limited because the SNR is increasing inside the log function in (4). We also show the results obtained in the case of multiple transmit antennas and one receive antennas, "8 × 1" and "19 × 1" when the transmitter does not know the channel in advance (typical for a frequency duplex system). In such circumstances the outage performance is improved but not the average capacity. That is because multiple transmit antennas cannot beamform blindly.

In summary, conventional multiple antenna systems are good at improving the outage capacity performance, attributable to the spatial diversity effect but this effect saturates with the number of antennas.

III.C Capacity of MIMO Links

We now consider a full MIMO link as in Figure 1 with respectively N transmit and M receive antennas. The channel is represented by a matrix of size $M \times N$ with random independent elements denoted by $\mathbf{H}$. It was shown in [3] that the capacity, still in the absence of transmit channel information, is derived from:

$$C = \log_2\left[\det\left(\mathbf{I}_M + \frac{\rho}{N}\mathbf{HH}^*\right)\right], \qquad (5)$$

where ρ is the average SNR at any receiving antenna. In Figure 3 we have plotted the results for the 3×3 and the 10×10 case, giving the same total of 9 and 20 antennas as previously. The advantage of the MIMO case is significant, both in average and outage capacity. In fact, for a large number $M = N$ of antennas the average capacity increases linearly with M:

$$C_a <\approx M \log_2 (1 + \rho) \qquad (6)$$

In general the capacity will grow proportional with the smallest number of antennas min(N,M) outside and no longer inside the log function. Therefore in theory and in the case of idealized random channels, limitless capacities can be realized provided we can afford the cost and space of many antennas and RF chains. In reality the performance will be dictated by the practical transmission algorithms selected and by the physical channel characteristics.

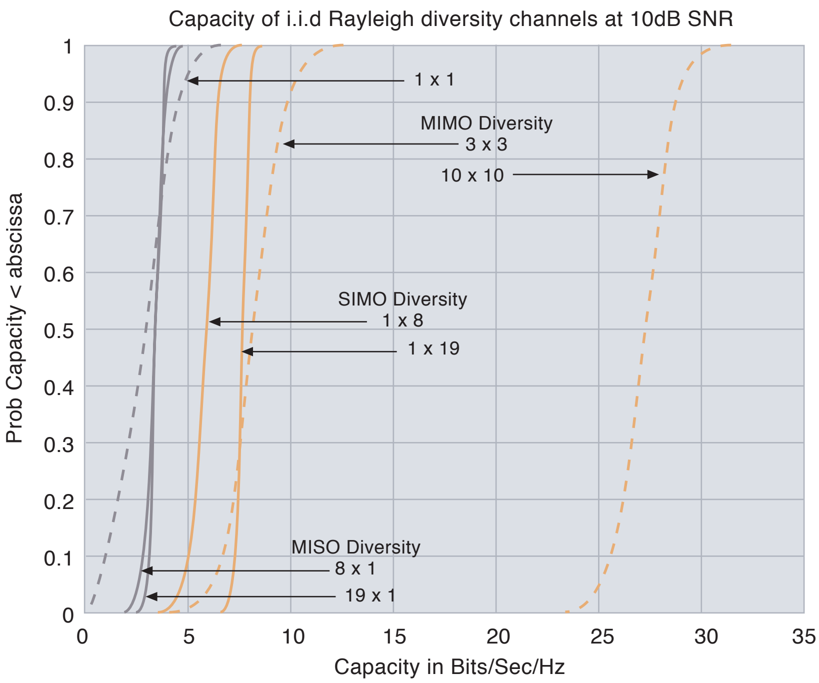


Figure 3 Shannon capacity as function of number of TX × RX antennas. The plots show the so-called cumulative distribution of capacity. For each curve, the bottom and the middle give indication of the outage performance and average data rate respectively

IV. Data Transmission over MIMO Systems

A usual pitfall of information theoretic analysis is that it does not reflect the performance achieved by actual transmission systems, since it is an upper bound realized by algorithms/ codes with boundless complexity. The development of algorithms with reasonable performance/complexity compromise is required to realize the MIMO gains in practice. Here we give the intuition behind key transmission algorithms and compare their performance.

IV.A General Principles

Current transmission schemes over MIMO typically fall into two categories: Data rate maximization or diversity maximization schemes. The first kind focuses on improving the average capacity behavior. For example in the case of Figure 2, the objective is just to perform spatial multiplexing as we send as many independent signals as we have antennas.

More generally, however, the individual streams should be encoded jointly in order to protect transmission against errors caused by channel fading. This leads to a second kind of approach in which one tries also to minimize the outage probability.

Note that if the level of coding is increased between the transmit antennas, the amount of independence between the signals decreases. Ultimately it is possible to code the signals so that the effective data rate is back to that of a single antenna system. Effectively each transmit antenna then sees a differently encoded version of the same signal. In this case the multiple antennas are only used as a source of spatial diversity and not to increase data rate directly.

The set of schemes allowing to adjust and optimize joint encoding of multiple transmit antennas are called *space-time codes* (STC). Although STC schemes were originally revealed in [8] in the form of convolutional codes for MISO systems, the popularity of such techniques really took off with the discovery of the so-called *space-time block codes* (STBC). In contrast to convolutional codes, which require computation-hungry trellis search algorithms at the receiver, STBC can be decoded with much simpler linear operators, at little loss of performance. In the interest of space and clarity we limit ourselves to an overview of STBC below. A more detailed summary of the whole area can be found in [9].

IV.B Maximizing Diversity with Space-Time Block Codes

The field of space-time block coding was initiated by Alamouti [10] in 1998. The objective behind this work was to place two antennas at the transmitter side and thereby provide an order two diversity advantage to a receiver with only a single antenna, with no *a priori* channel information at the transmitter. The very simple structure of Alamouti's method itself makes it a very attractive scheme that is currently being considered in UMTS standards.

The strategy behind Alamouti's code is as follows. The symbols to be transmitted are grouped in pairs. Because this scheme is a pure diversity scheme and results in no rate increase[2)] we take two symbol durations to transmit a pair of symbols, such as s_0 and s_1. We first transmit s_0 on the first antenna while sending s_1 simultaneously on the second one. In the next time-interval $-s_1^*$ is sent from the first antenna while s_0^* from the second one. In matrix notation, this scheme can be written as:

$$\mathbf{C} = \frac{1}{\sqrt{2}} \begin{pmatrix} s_0 & -s_1^* \\ s_1 & s_0^* \end{pmatrix}. \tag{7}$$

The rows in the code matrix **C** denote the antennas while the columns represent the symbol period indexes. As one can observe the block of symbols s_0 and s_1 are coded across time and space, giving the name space-time block code to such designs. The normalization factor additionally ensures that the total amount of energy transmitted remains at the same level as in the case of one transmitter.

The two (narrow-band) channels from the two antennas to the receiver can be placed in a vector format as $\mathbf{h} = [h_0, h_1]$. The receiver collects observations over two time frames in a vector **y** which can then be written as $\mathbf{y} = \mathbf{hC} + \mathbf{n}$ or equivalently as $\mathbf{y^t} = \hat{\mathbf{H}}\,\mathbf{s} + \mathbf{n}$, where

$$\hat{\mathbf{H}} = \frac{1}{\sqrt{2}} \begin{pmatrix} h_0 & h_1 \\ h_1^* & -h_0^* \end{pmatrix},$$ $\mathbf{s} = [s_0, s_1]^T$ and **n** is the noise vector.

Because the matrices $\mathbf{C}, \hat{\mathbf{H}}$ are orthogonal by design, the symbols can be separated/decoded in a simple manner from filtering of the observed vector **y**. Furthermore, each symbol comes with a diversity order of two exactly. Notice finally this happens despite the channel coefficients being unknown to the transmitter.

More recently some authors have tried to extend the work of Alamouti to more than two transmit antennas [11], [12]. It turns out however that in that case it is not possible to design a perfectly orthogonal code, except for real valued modulations (e.g. PAM). In the case of a general complex symbol constellation, full-rate orthogonal codes cannot be constructed. This has therefore led to a variety of code design strategies to prolong Alamouti's work where one either sacrifices the data rate to preserve a simple decoding structure or the orthogonality of the code to retain a full data rate [13], [14], [15]. Although transmit diversity codes have mainly been designed with multiple transmit and single receive antenna in mind, the same ideas can easily be expanded towards a full MIMO setup. The Alamouti code implemented on a system with two antennas at both transmitter and receiver side will for example give a four-order diversity advantage to the user and still has a simple decoding algorithm. However, in a MIMO situation, one would not only be interested in diversity but also in increasing the data rate as shown below.

IV.C Spatial Multiplexing

Spatial multiplexing, or V-BLAST (Vertical Bell Labs Layered Space-Time) [3], [16] can be regarded as a special class of space-time block codes where streams of independent data are transmitted over different antennas, thus maximizing the average data rate over the MIMO system. One may generalize the example given in II in the following way: Assuming a block of independent data **C** is transmitted over the $N \times M$ MIMO system, the receiver will obtain $\mathbf{Y} = \mathbf{HC} + \mathbf{N}$. In order to perform symbol detection, the receiver must un-mix the channel, in one of various possible ways. Zero-forcing techniques use a straight matrix inversion, a simple approach that can also result in poor results when the matrix **H** becomes very ill-conditioned in certain random fading events. The optimum decoding method on the other hand is known as maximum likelihood (ML) where the receiver compares all possible combinations of symbols that could have been transmitted with what is observed:

$$\hat{\mathbf{C}} = \arg \min_{\hat{\mathrm{C}}} \|\mathbf{Y} - \mathbf{H}\hat{\mathbf{C}}\| \tag{8}$$

The complexity of ML decoding is high, and even prohibitive when many antennas or high order modulations are used. Enhanced variants of this, like sphere decoding [17] have recently been proposed. Another popular decoding strategy proposed alongside V-BLAST is known as nulling and canceling which gives a reasonable tradeoff between complexity and performance. The matrix inversion process in nulling and canceling is performed in layers where one estimates a symbol, subtracts this symbol estimate from **Y** and continues the decoding successively [3].

Straight spatial multiplexing allows for full independent usage of the antennas, however it gives

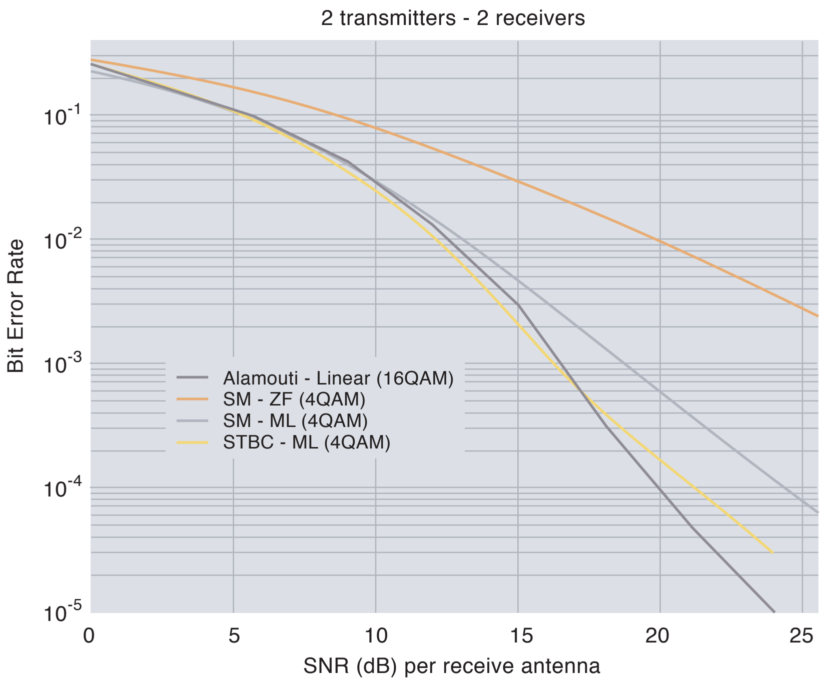
2) *Diversity gains can however be used to increase the order of the modulation.*

limited diversity benefit and is not always the best transmission scheme for a given BER target. Coding the symbols within a block can result in additional coding and diversity gain, which can help improve the performance, even though the data rate is kept at the same level. It is also possible to sacrifice some data rate for more diversity. Methods to design such codes start from a general structure where one often assumes that a weighted linear combination of symbols may be transmitted from any given antenna at any given time. The weights themselves are selected in different fashions by using analytical tools or optimizing various cost functions [11], [18], [19], [20].

In what follows we compare four transmission strategies over a 2 × 2 MIMO system with ideally uncorrelated elements. All schemes result in the same spectrum efficiency but offer different BER performance.

Figure 4 shows such a plot where the BER of various approaches are compared: The Alamouti code in [7], spatial multiplexing (SM) with zero forcing (ZF) and with maximum likelihood decoding (ML), and a combined STBC spatial multiplexing scheme [20]. A 4-QAM constellation is used for the symbols except for the Alamouti code, which is simulated under 16-QAM to keep the data rate at the same level. It can be seen from the figure that spatial multiplexing with zero-forcing returns rather poor results, while the curves for other coding methods are more or less closer to each other. Coding schemes, such as Alamouti and the block code give better results than what can be achieved with spatial multiplexing alone for the case of two antennas. The Alamouti curve has the best slope at high SNR because it focuses entirely on diversity (order four). At lower SNR, the scheme combining spatial multiplexing with some block coding is the best one.

Figure 4 Bit Error Rate (BER) comparisons for various transmission techniques over MIMO. All scheme results use the same transmission rate



It is important to note that as the number of antennas increases, the diversity effect will give diminishing returns, while the data rate gain of spatial multiplexing remains linear with the number of antennas. Therefore, for a larger number of antennas it is expected that more weight has to be put on spatial multiplexing and less on space-time coding. Interestingly, having a larger number of antennas does not need to result in a larger number of RF chains. By using antenna selection techniques (see for example [21]) it is possible to retain the benefits of a large MIMO array with just a subset of antennas being active at the same time.

V. Channel Modeling

Channel modeling has always been an important area in wireless communications and this area of research is particularly critical in the case of MIMO systems. In particular, as we have seen earlier, the promise of high MIMO capacities largely relies on decorrelation properties between antennas as well as the full-rankness of the MIMO channel matrix. The performance of MIMO algorithms such as those above can vary enormously depending on the realization or not of such properties. In particular, spatial multiplexing becomes completely inefficient if the channel has rank one. The final aim of channel modeling is therefore to get an understanding of, by the means of converting measurement data into tractable formulas, what performance can be reasonably expected from MIMO systems in practical propagation situations. The other role of channel models is to provide with the necessary tools to analyze the impact of selected antenna or propagation parameters (spacing, frequency, antenna height, etc.) onto the capacity to influence the system design in the best way. Finally, models are used to try out transmit and receive processing algorithms with more realistic simulation scenarios than those normally assumed in the literature.

V.A Theoretical Models

The original papers on MIMO capacity used an 'idealistic' channel matrix model consisting of perfectly uncorrelated (i.i.d.) random Gaussian elements. This corresponds to a rich multipath environment, yielding maximum excitation of all channel modes. It is also possible to define other types of theoretical models for the channel matrix **H**, which are not as ideal. In particular we emphasize the *separate* roles played by antenna correlation (on transmit or on receive) and the rank of the channel matrix. If fully correlated antennas will lead to a low rank channel, the converse is not true in general.

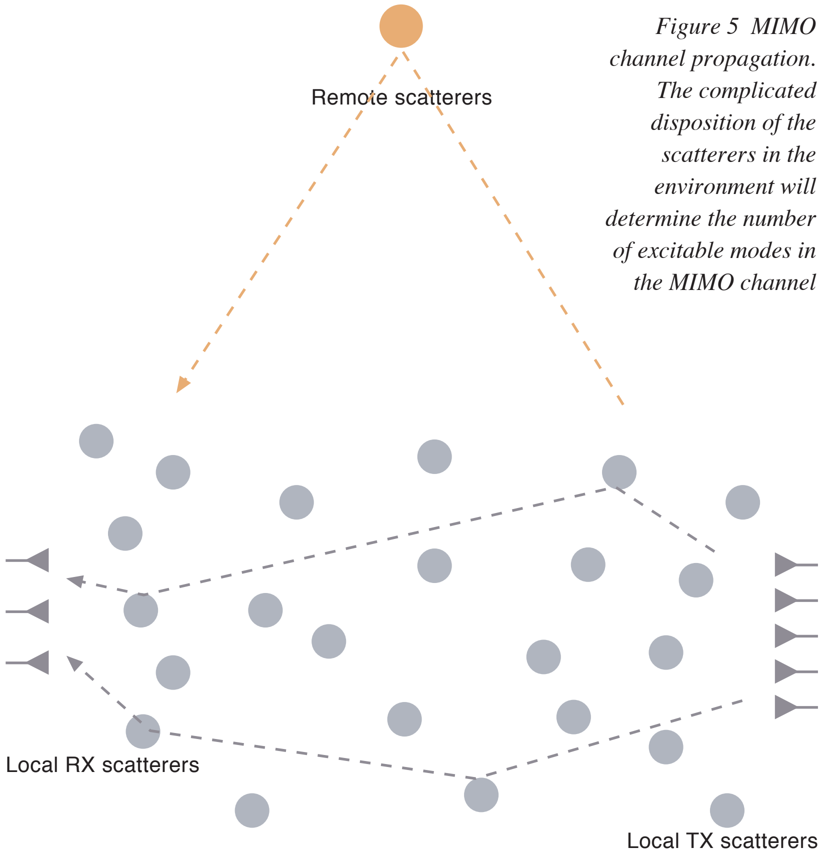


Figure 5 MIMO channel propagation. The complicated disposition of the scatterers in the environment will determine the number of excitable modes in the MIMO channel

Let us next consider the following MIMO theoretical model classification, starting from Foschini's ideal i.i.d. model, and interpret the performance. In each case below we consider a frequency-flat channel. In the case of broadband, frequency selective channels, a different frequency-flat channel can be defined at each frequency.

- *Uncorrelated High Rank* (UHR, a.k.a. i.i.d.) model: The elements of $\mathbf{H}$ are i.i.d. complex Gaussian.

- *Correlated Low Rank* (CLR) model: $\mathbf{H} = g_{rx}g^{*}_{tx}\mathbf{u}_{rx}\mathbf{u}^{*}_{tx}$ where g_{rx} and g_{tx} are independent Gaussian coefficients (receive and transmit fading) and $\mathbf{u}_{rx}$ and $\mathbf{u}_{tx}$ are fixed deterministic vectors of size $M \times 1$ and $N \times 1$, respectively, and with unit modulus entries. This model is obtained when antennas are placed too close to each other or there is too little angular spread at both the transmitter and the receiver. This case yields no diversity nor multiplexing gain whatsoever, just receive array / beamforming gain. We may also imagine the case of uncorrelated antennas at the transmitter and decorrelated at the receiver, or vice versa.

- *Uncorrelated Low Rank* (ULR) (or "pin-hole" [22]) model: $\mathbf{H} = \mathbf{g}_{rx}\mathbf{g}^{*}_{tx}$, where $\mathbf{g}_{rx}$ and $\mathbf{g}_{tx}$ are independent receive and transmit fading vectors with i.i.d. complex-valued components. In this model every realization of $\mathbf{H}$ has rank 1 despite uncorrelated transmit and receive antennas. Therefore, although diversity is present capacity must be expected to be less than in the UHR model since there is no multiplexing gain. Intuitively, in this case the diversity order is equal to min(M,N).

V.B Heuristic Models

In practice of course, the complexity of radio propagation is such that MIMO channels will not fall completely in either of the theoretical cases described above. Antenna correlation and matrix rank are influenced by as many parameters as the antenna spacing, the antenna height, the presence and disposition of local and remote scatterers, the degree of line of sight and more. Figure 5 depicts a general setting for MIMO propagation. The goal of heuristic models is to display a wide range of MIMO channel behaviors through the use of as few relevant parameters as possible with as much realism as possible.

A good model shall give us answers to the following problems: What is the typical capacity of an outdoor or indoor MIMO channel? What are the key parameters governing capacity? Under what simple conditions do we get a full rank channel? If possible the model parameters should be controllable (such as antenna spacing) or measurable (such as angular spread of multipath [23], [24], which is not always easy to achieve.

The literature on these problems is still very scarce. For the line-of-sight (LOS) case it has only been shown how very specific arrangements of the antenna arrays at the transmitter and the receiver can maximize the orthogonality between antenna signatures and produce maximum capacity as reported in [25]. But, in a general situation with fading, which is the true promising case, this work is not applicable.

In the presence of fading, the first step in increasing the model's realism consists in taking into account the correlation of antennas at either the transmit or receive side. The correlation can be modeled to be inversely proportional to the angular spread of the arriving/departing multipath. The experience suggests that higher correlation at the BTS side can be expected because the BTS antenna is usually higher above the clutter, causing reduced angular spread. In contrast the subscriber's antenna will be buried in the clutter (if installed at street level) and will experience more multipath angle spread, hence less correlation for the same spacing. The way

MIMO models can take correlation into account is similar to how usual smart antenna channel models do it. The channel matrix is pre- (or post-) multiplied by a correlation matrix controlling the antenna correlation as function of the path angles, the spacing and the wavelength. For example, for a MIMO channel with correlated receive antennas, we have:

$$\mathbf{H} = \mathbf{R}^{1/2}_{\theta_r,d_r}\mathbf{H}_0 \quad (9)$$

where $\mathbf{H}_0$ is an ideal i.i.d. MIMO channel matrix and $\mathbf{R}_{\theta_r,d_r}$ is the $M \times M$ correlation matrix. θ_r is the receive angle spread and d_r is the receive antenna spacing. Different assumptions on the statistics of the paths' directions of arrival (DOA) will yield different expressions for $\mathbf{R}_{\theta_r,d_r}$ [26], [27], [28]. For uniformly distributed DOAs, we find [27], [26]

$$\left[\mathbf{R}_{\theta_r,d_r}\right]_{m,k} = \frac{1}{S}\sum_{i=-\frac{S-1}{2}}^{i=\frac{S-1}{2}} e^{-2\pi j(k-m)d_r\cos\left(\frac{\pi}{2}+\theta_{r,i}\right)} \quad (10)$$

where S (assumed odd) is the number of paths with corresponding DOAs $\theta_{r,i}$. For "large" values of the angle spread and/or antenna spacing, $\mathbf{R}_{\theta_r,d_r}$ will converge to the identity matrix, which gives uncorrelated fading. For "small" values of θ_r,d_r, the correlation matrix becomes rank deficient (eventually rank one) causing fully correlated fading. The impact of the correlation on the capacity was analyzed in several papers, including [29]. Note that it is possible to generalize this model to include correlation on both sides by using two distinct correlation matrices:

$$\mathbf{H} = \mathbf{R}^{1/2}_{\theta_r,d_r}\mathbf{H}_0\mathbf{R}^{1/2}_{\theta_t,d_t} \quad (11)$$

V.B.1 Impact of Scattering Radius

One limitation of simple models like the one in (11) is that it implies that rank loss of $\mathbf{H}$ can only come from rank loss in $\mathbf{R}_{\theta_r,d_r}$ or in $\mathbf{R}_{\theta_t,d_t}$, i.e. a high correlation between the antennas. However as suggested by the theoretical model "ULR" above, it may not always be so. In practice such a situation can arise where there is significant local scattering around both the BTS and the subscriber's antenna and still only a low rank is realized by the channel matrix. That may happen because the energy travels through a narrow "pipe", i.e. if the scattering radius around the transmitter and receiver is small compared to the traveling distance. This is depicted in Figure 6. This situation is referred to as *pinhole* or *keyhole* channel in the literature [22], [30].

In order to describe the pinhole situation more, so-called *double scattering* models are developed that take into account the impact of the scattering radius at the transmitter and at the receiver. The model is based on a simplified version of Figure 5 shown in Figure 7 where only local scatterers contributing to the total aperture of the antenna as seen by the other end are considered. The model can be written as [22]:

$$\mathbf{H} = \frac{1}{\sqrt{S}}\mathbf{R}^{1/2}_{\theta_r,d_r}\mathbf{H}_{0,r}\mathbf{R}^{1/2}_{\theta_S,2D_r/S}\mathbf{H}_{0,t}\mathbf{R}^{1/2}_{\theta_t,d_t}, \quad (12)$$

where the presence of two (instead of one) i.i.d. random matrices $\mathbf{H}_{0,t}$ and $\mathbf{H}_{0,r}$ accounts for the double scattering effect. The matrix $\mathbf{R}_{\theta_S,2D_r/S}$ dictates the correlation between scattering elements, considered as *virtual* receive antennas with virtual aperture $2D_r$. When the virtual aperture is small, either on transmit or receive, the rank of the overall MIMO channel will fall regardless of whether the actual antennas are correlated or not.

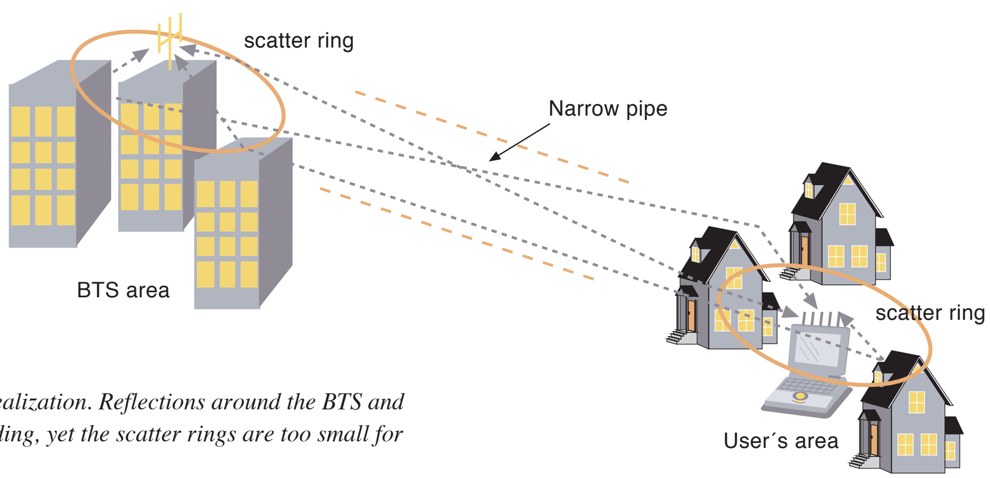


Figure 6 An example of pinhole realization. Reflections around the BTS and subscribers cause uncorrelated fading, yet the scatter rings are too small for the rank to build up

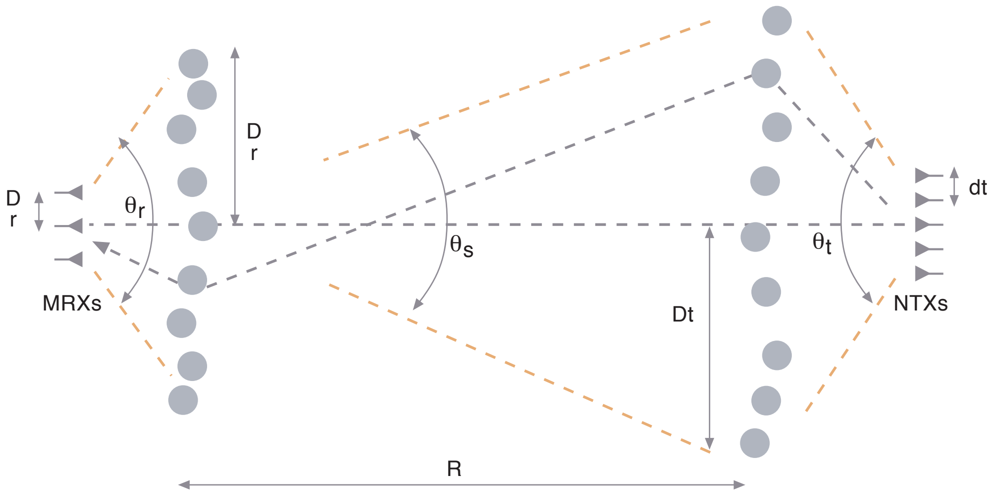


Figure 7 Double scattering MIMO channel model

V.C Broadband Channels

In broadband applications the channel experiences frequency selective fading. In this case the channel model can be written as **H**(*f*) where a new MIMO matrix is obtained at each frequency/sub-band. This type of model is of interest in the case of orthogonal frequency division multiplexing (OFDM) modulation with MIMO. It was shown that the MIMO capacity actually benefits from the frequency selectivity because the additional paths that contribute to the selectivity will also contribute to a greater overall angular spread and therefore improve the average rank of the MIMO channel across frequencies [31].

V.D Measured Channels

In order to validate the models as well as to foster the acceptance of MIMO systems into wireless standards, a number of MIMO measurement campaigns have been launched in the last two years, mainly led by Lucent and ATT Labs and by various smaller institutions or companies such as Iospan wireless in California. More recently Telenor R&D put together its own MIMO measurement capability.

Samples of analysis for UMTS type scenarios can be found in [32], [33], [34]. Measurements conducted at 2.5 GHz for broadband wireless access applications can be found in [35]. So far, the results reported largely confirm the high level of dormant capacity of MIMO arrays, at least in urban or suburban environments. Indoor scenarios lead to even better results due to a very rich multipath structure. Eigenvalues analyses reveal that a large number of the modes of MIMO channels can be exploited to transmit data. Which particular combination of spatial multiplexing and space time coding will lead to the best performance complexity trade-off over such channels remains however an area of active research.

VI. System Level Issues

VI.A Optimum Use of Multiple Antennas

Multiple antenna techniques are not new in commercial wireless networks. Spatial diversity systems, using two or three antenna elements, co- or cross-polarized, have been in use since the early stages of mobile network deployments. More recently, beamforming-type BTS products equipped with five to ten or more antennas have been offered on the market. These products are using diversity to improve the link budget and the beamforming capability to extend the cell range or help in load balancing.

Beyond the information theory aspects addressed earlier, there are significant network-level differences between the beamforming approach and the MIMO approach to using multiple antennas.

While beamforming systems tend to use a larger number of closely spaced antennas, MIMO will operate with typically fewer antennas (although the only true constraint is at the subscriber side rather than at the BTS side). Furthermore the MIMO antennas will use as much space as can be afforded to try and realize decorrelation between the elements while the directional-based beamforming operation imposes stringent limits on spacing. Also most MIMO algorithms focus on diversity or data rate maximization rather than just increasing the average SNR at the receiver or reducing interference. Finally, beamforming systems thrive in near line of sight environments because the beams can be more easily optimized to match one or two multipaths than a hundred of them. In contrast, MIMO systems turn rich multipath into an advantage and lose their multiplexing benefits in line of sight cases.

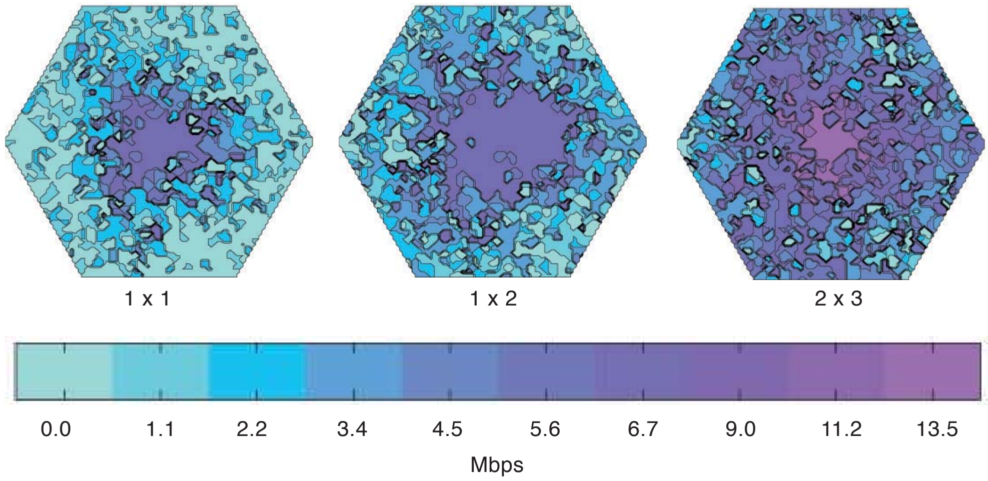


Figure 8 User rates in 2 MHz FDD channels in a fixed wireless access system. The plots show the relative gains between various number of antennas at transmitter × receiver (SISO, SIMO, MIMO)

Because of these differences, the optimal way of using multiple antenna systems, at least at the BTS, is likely to depend on the situation. The search for compromising solutions, in which the degrees of freedom offered by the multiple antennas are best used at each location, is an active area of work. A key to this problem resides in *adaptive* techniques, which through the tracking of environment/propagation characteristics are able to pick the right solution at all times.

VI.B MIMO in Broadband Internet Access

One unfavorable aspect of MIMO systems, when compared with traditional smart antennas, lies in the increased cost and size of the subscriber's equipment. Although a sensible design can extract significant gains with just two or three antennas at the user's side, it may already prove too much for simple mobile phone devices. Instead wireless LAN modems, PDAs and other high speed wireless Internet access, fixed or mobile, devices constitute the real opportunity for MIMO because of less stringent size and algorithmic complexity limitations. In Figure 8 we show the data rates achieved by a fixed broadband wireless access system with 2 × 3 MIMO. The realized user's data rates are color coded from 0 to 13.5 Mb/s in a 2 MHz RF channel[3)], function of the user's location. The access point is located in the middle of an idealized hexagonal cell. Detailed assumptions can be found in [36]. The figure illustrates the advantages over a system with just one transmit antenna and one or two receive antennas. Current studies demonstrating the system level advantages of MIMO in wireless Internet access focus mainly on performance. While very promising, the evaluation of overall benefits of MIMO systems, taking into account deployment and cost constraints, is still in progress.

VII. Conclusions

This paper reviews the major features of MIMO links for use in future wireless networks. Information theory reveals the great capacity gains which can be realized from MIMO. Whether we achieve this fully or at least partially in practice depends on a sensible design of transmit and receive signal processing algorithms. More progress in channel modeling will also be needed. In particular upcoming performance measurements in specific deployment conditions will be key to evaluate precisely the overall benefits of MIMO systems in real-world wireless systems scenarios such as UMTS.

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