MIMO COMMUNICATIONS
Next Generation Wireless Technology

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Abstract:

The world of wireless devices is moving fast and 802.11n or Wireless 'N' is the hottest new technology to hit the shelves. The 802.11n standard uses some new technology and tweaks existing technologies to give Wi-Fi more speed and range. The most notable new technology is called multiple input, multiple output (MIMO). MIMO uses several antennas to move multiple data streams from one place to another. In the last couple of decades a large percentage of researchers in the wireless field have been concentrating their energies in this direction.

In this paper we first investigate the need for this new technology and the benefits it provides. We explain the concepts of Fading and Diversity which play a crucial role in the development of MIMO systems. Multiple antenna arrays provide a diversity gain by reducing fading and thus increase link reliability. We explore how to exploit this diversity on both the transmitter and receiver side. We study spatial multiplexing which is a technique that provides tremendous increases in data rates. We finally conclude that a system which provides both diversity gain and spatial multiplexing provides us with the best of both techniques.

Introduction:

Wireless Communication is one of the most vibrant areas in the communication field today. While it has been a topic of study since the sixties, the past decade has seen a surge of research activities in the area. There has been an explosive increase in the demand for tetherless connectivity, driven so far mainly by *cellular telephony.* The research thrust in the past decade has led to a much richer set of perspectives and tools on how to communicate over wireless channels, and the picture is still very much evolving.

Our ultimate goal is to communicate information with anyone, at anytime, from anywhere. In the 1990's rapid development of portable computer technology and the huge success of the Internet and the World Wide Web signaled that people want their information (voice, video and data) to be as portable as they are. This decade will see the *convergence* of wireless communications and the Internet.

This paper looks at **MIMO communications**, an advanced wireless technology that may make it possible to realize a true wireless multimedia society in the future.

There are two fundamental aspects of wireless communication that make the problem challenging and interesting. First is the phenomenon of *fading*: the time variation of the channel strengths due to small-scale effect of multipath fading as well as large scale effects such as path loss via distance attenuation and shadowing by obstacles. Second, the significant *interference* between signals of different users which is a new problem that does not occur in the wired world.

Traditionally the design of wireless systems has been such that fading and interference are viewed as nuisances to be encountered. Modern research , such as **Multi-input Multi-output (MIMO) communication**, provides a new point of view that fading can be viewed as an opportunity to be exploited, as a result of which it is possible to get tremendous benefits in data throughput and link range without additional bandwidth or transmit power. It is these benefits that will help us make advances in the field of mobile wireless computing.

MIMO Communications – A short history:

The earliest ideas in this field go back to work by A.R. Kaye and D.A. George (1970) and W. van Etten (1975, 1976). Arogyaswami Paulraj and Thomas Kailath proposed the concept of Spatial Multiplexing using MIMO in 1993. In 1996, Greg Raleigh and Gerard J. Foschini refined a new approach to MIMO technology, involving multiple transmit antennas co-located at one transmitter to improve the link throughput effectively. Bell Labs was the first to demonstrate a laboratory prototype of spatial multiplexing (SM) in 1998, where spatial multiplexing is a principal technology to improve the performance of MIMO communication systems. In 2006, several companies (Broadcom, Intel,..) have fielded a MIMO-OFDM solution based on a pre-standard for **IEEE 802.11n WiFi standard.**

Fading and Diversity:

Due to interaction with the surrounding environment, a radio signal transmitted from a wireless antenna usually propagates through several paths before it reaches the receiver. The superposition of various multipaths at the receiver results in attenuation of the received signal. This phenomenon is known as **multipath fading**.

Diversity is a powerful technique for mitigating the effects of fading. The basic idea behind diversity is to simultaneously transmit across multiple channels that are fading independently; that way it is very unlikely that all channels fade simultaneously. If the probability that any one channel fades is p, the probability that m independent channels fade simultaneously is p^m.

Three important forms of diversity are time, frequency and space diversity. Time diversity exploits the time-varying nature of the fading channel by sending the same symbol at different times (repetitive coding) such that different transmissions experience independent fading. Frequency diversity exploits the frequency-selective nature of multipath fading channels. Well known applications of this concept include OFDM and spread spectrum modulation (eg: CDMA). However time and frequency diversity are not always available, because they depend on variations of the channel. In extreme cases, such as static environments or memoryless channels you have no time or frequency diversity at all.

Spatial diversity exploits the fact that fading experienced by multiple antennas at a receiver will be independent when the distance between antennas is sufficiently large. This leads to a considerable gain in the performance without affecting the data rate of the system and is known as **receive diversity**. The data rate of the system can also be increased by a concept known as **spatial multiplexing**. This involves transmitting several different data streams over several independent spatial channels. Data rate increases *linearly* with the number of transmit antennas without affecting the bandwidth. This is also known as **transmit diversity.** Spatial diversity can be exploited in any system and without the need of additional signal processing such as OFDM or repetitive coding.

Receive Diversity (SIMO Model):

Consider the wireless link with receiver diversity shown in Fig 1. consisting of a single antenna and a receiver with *m* antennas transmitting over a flat-fading Raleigh channel with channel gains shown in the figure leading to the following memoryless Single Input Multiple Output (SIMO) Model

$$\mathbf{r} = a\mathbf{h} + \mathbf{n} \qquad \textbf{(1)}$$

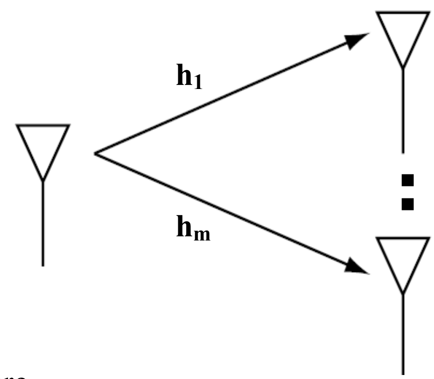


Fig 1

where a is the transmitted symbol chosen from a finite alphabet (in this case we shall assume a binary antipodal signal with alphabet {+1,-1}), where $\mathbf{h}= [h_1, \ldots\ldots, hm]^T$ is a vector of channel gains, and where **n** is the noise vector with elements that are complex Gaussian random variables with mean 0 and variance N_0 i.e CN~$(0,N_0)$.

For this model the receiver design that minimizes the probability of error, given knowledge of **h** is the **Matrix Matched Filter**, which is nothing but the extension of the matched filter concept to matrix/vector valued signals or channels. Hence the optimum receiver in our case would be $\mathbf{h}^*$ leading to

$$\begin{aligned} y &= \mathbf{h}^*\mathbf{r} \\ &= \|\mathbf{h}\|^2 a + \tilde{n}, \end{aligned} \qquad \textbf{(2)}$$

where $\tilde{n} = \mathbf{h}^*\mathbf{n}$ is a complex Gaussian random variable with mean 0 and variance $\|\mathbf{h}\|^2 N_0$ i.e CN~ $(0, \|\mathbf{h}\|^2 N_0)$, where $\|\mathbf{h}\|^2 = |h_1|^2 + |h_2|^2 + \ldots + |h_m|^2$. This method is also known as **Maximal Ratio combining.**

Note: A* denotes the conjugate transpose of a matrix A.

Performance of SIMO system:

The SIMO system can be viewed as the equation for an effective SISO channel whose instantaneous SNR per bit is

$$\gamma_{eff} = \| h \|^2 \frac{E_b}{N_0} \qquad \textbf{(3)}$$

Given **h,** the instantaneous BER of this effective SISO channel is given by

$$\Pr[error \mid h] = Q(\sqrt{2\gamma_{eff}}) \qquad \textbf{(4)}$$

Since γ_{eff} is a random variable that depends on the channel, the above conditional probability is also a random variable. To find the average BER, this expression must be averaged over the pdf i.e.

$$BER = \int_0^{\infty} f_{\gamma_{eff}}(t) Q(\sqrt{2t})dt \qquad \textbf{(5)}$$

for γ_{eff} which is a chi-squared distribution with 2*m* degrees of freedom.

$$f_{\gamma_{eff}} = \frac{1}{(m-1)!(E_b/N_0)^m} t^{m-1} e^{-tN_0/E_b}, t \geq 0 \qquad \textbf{(6)}$$

repeated integration by parts of (5) with (6) leads to the following closed-form expression for average BER on Raleigh-fading channels with diversity order ***m***:

$$BER = p^m \sum_{k=0}^{m-1} \binom{m-1+k}{k} (1-p)^k \qquad \textbf{(7)}$$

where we have introduced:

$$p = \frac{1}{2} - \frac{1}{2}\left(1 + \frac{1}{E_b/N_0}\right)^{-1/2} \qquad \textbf{(8)}$$

we can derive a simplified expression when the SNR is high. specifically, if Eb/N_0 is so large that the term (1-p) can be approximated by 1, then **(7)** simplifies to:

$$BER = K_m \left(\frac{1}{4E_b/N_0}\right)^m \qquad \textbf{(9)}$$

where, Km= $\binom{2m-1}{m}$

Hence, by averaging over ***m*** independent signal paths, the overall probability of error is decreased significantly i.e. exponentially by a factor of ***m***. This factor ***m*** is known as diversity gain.

Transmit Diversity (MISO Model):

Consider the wireless link with receiver diversity shown in Fig 2. Consisting of a single receiver and a transmitter with *m* antennas transmitting over a flat-fading Raleigh channel with channel gains shown in the figure leading to the following memoryless Multiple Input Single Output (MISO) Model.

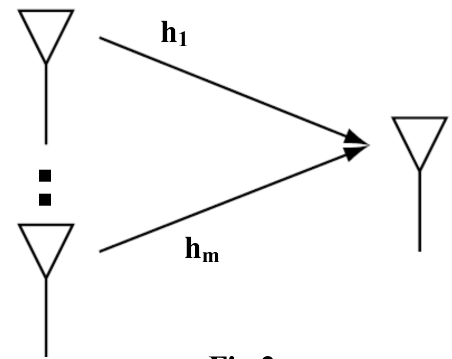


Fig 2

This is common in downlink of a cellular system since it is often cheaper to have multiple antennas at the base than to have antennas at every handset. The simplest method in which the transmit diversity can be exploited in this case is by repetitive coding i.e. simply transmit the same symbol over the *m* different antennas during *m* symbol times.

In *space-time coding* a vector of symbols is transmitted from the *m* antennas over a certain number of signaling intervals i.e L. One of the most elegant *space-time codes* is the **Alamouti Scheme**. This scheme is designed for 2 transmit antennas that transmit two symbols in two signaling intervals providing a diversity gain of 2. Generalization of this scheme to more than 2 antennas is possible, to some extent. The Alamouti scheme has been proposed in several 3G cellular standards.

Alamouti Scheme:

With flat fading, the two transmit, single receive channel is written as

$$y[m] = h_1[m]x_1[m] + h_2[m]x_2[m] + w[m] \qquad \textbf{(10)}$$

where h_i is the channel gain from transmit antenna i. The Alamouti Scheme transmits two complex symbols u_1 and u_2 over two symbol times:

- at time 1, $x_1[1] = u_{1,} x_2[1] = u_2$;
- At time 2, $x_1[2] = -u_2^*, x_2[2] = u_1^*$.

If we assume that the channel remains constant over the two symbol times and set $h_1 = h_1[1] = h_1[2], h_2 = h_2[1] = h_2[2]$, then we can write in matrix from:

$$[y[1] \quad y[2]] = [h_1 \quad h_2]\begin{bmatrix} u_1 & -u_2^* \\ u_2 & u_1^* \end{bmatrix} + [w[1] \quad w[2]]. \qquad \textbf{(11)}$$

We are interested in detecting u_1, u_2, so we rewrite this equation as

$$\begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} w[1] \\ w[2]^* \end{bmatrix}. \quad \textbf{(12)}$$

which is equivalent to

$$\mathbf{r} = \mathbf{H}_{eff}\,\mathbf{x} + \mathbf{n} \quad \textbf{(13)}$$

We observe that the columns of the square matrix are orthogonal. Specifically

$$\mathbf{H}_{eff}^{\;*}\mathbf{H}_{eff} = \|\mathbf{H}\|^2\ \mathbf{I} \quad \textbf{(14)}$$

where $\mathbf{H} = [h_1\ h_2]$. As before we use the Matrix Matched filter $Heff^*$ to get

$$\mathbf{y} = \|\mathbf{H}\|^2\ \mathbf{x} + \tilde{\mathbf{n}} \quad \textbf{(15)}$$

where $\tilde{\mathbf{n}} = \mathbf{H}_{\mathbf{eff}}^{\;*}\mathbf{n}$ is a vector valued complex Gaussian random variable with mean 0 and variance $N_0\|\mathbf{H}\|^2\ \mathbf{I}$ i.e CN~ $(0,\ N_0\|\mathbf{H}\|^2\ \mathbf{I})$, where $\|\mathbf{H}\|^2 = |h_1|^2 + |h_2|^2$. The above equation is statistically identical to the SIMO model with 2 receive antennas. Hence the BER in this case from ….. is

$$BER = K_2\left(\frac{1}{4E_b / N_0}\right)^2 \quad \textbf{(16)}$$

Hence the Alamouti scheme leads to order 2 diversity ***without channel knowledge at the transmitter.***

Although the Alamouti scheme does provide transmit diversity in a very simple fashion, it does not fully exploit the advantages that having multiple transmit antennas give us. For this purpose we shall explore ***spatial multiplexing*** which was first proposed by Foschini & Co in 1996 through an architecture known as V-BLAST.

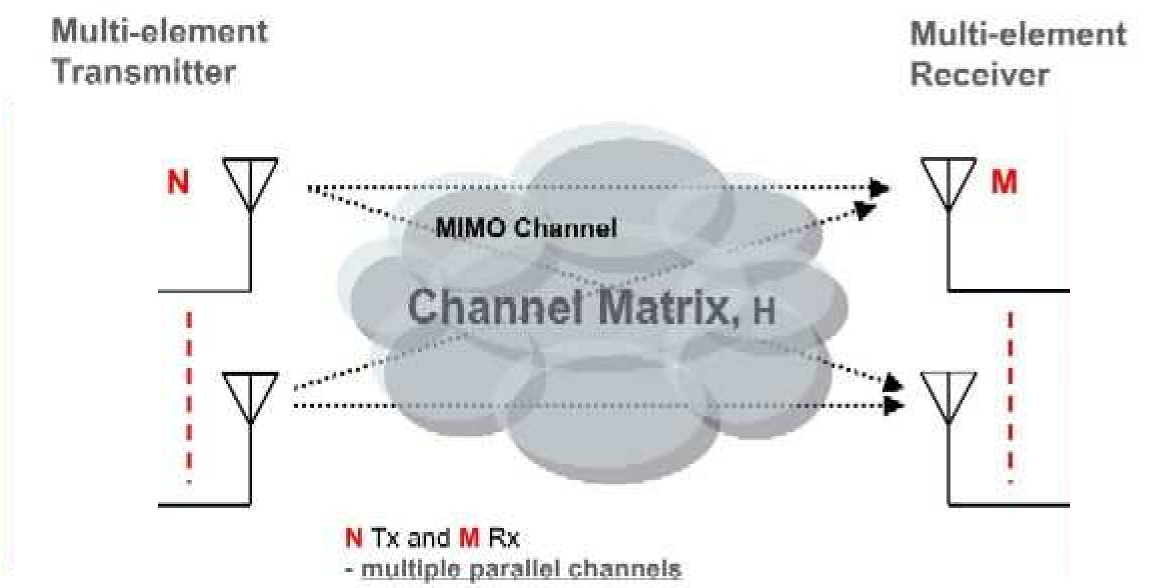
Layered Space Time Architecture – V-BLAST:

Vertical Bell Labs Layered Space Time (V-BLAST) architecture is the simplest form of spatial multiplexing. The architecture accomplishes this by splitting a single user's data stream into multiple substreams and using an array of transmitter antennas to simultaneously launch the parallel substreams. All the substreams are transmitted in same frequency band, so spectrum is used very efficiently. Since the user's data is being sent in parallel over multiple antennas, the effective transmission rate is increased in roughly in proportion to the number of transmitter antennas used. On the receiver side, each receiver antenna "sees" all of transmitted substreams superimposed, not separately. However, if multipath scattering is sufficient, then the multiple substreams are all scattered slightly differently, since they originate from different transmit antennas that are located at different points in space. These slight differences in scattering allow the substreams to be identified and recovered. In effect, the unavoidable multipath is exploited to provide a very useful spatial parallelism that is used to greatly improve data transmission rates. Thus, when using the V-BLAST architecture, the more multipath, the better, just the opposite of conventional systems. In the MISO model considered earlier the transmission symbol rate becomes *m* times the symbol rate of the original data stream. Therefore the data rate grows linearly with number of transmitter antennas.

MIMO Model – The best of Both Worlds:

In the previous sections we have studied how exploiting spatial diversity provides a reliable link by decreasing probability of error; and how spatial multiplexing provides great benefits in data rate. Although it is possible to use transmit diversity to mitigate fading effect of the channel, in schemes other than the Alamouti Scheme, channel knowledge at the receiver is required. Additionally spatial multiplexing cannot be used if we are using transmit diversity to reduce fading.

On the other hand, consider a Multiple Input Multiple Output system with multiple antenna arrays at both receiver (*m*) and transmitter (*n*). The receive antennas provide a diversity gain of *m* and the transmit antennas increase the data rate by a factor of *n*, hence giving us the best of both models.



Applications and Scope:

Wireless networking using the 802.11 standard, also known by its trade name, Wi-Fi, has become common in the home and has a significant and growing role in corporate settings. But the existing standard, 802.11g, was ratified in 2003 and is increasingly seen as inadequate as applications become more complex and require more bandwidth. For instance, streaming video -- whether it's a feature-length movie at home or videoconferencing at work -- is a dicey proposition with 802.11g. So-called "g" products have a theoretical maximum throughput speed of 54Mbit/sec. but real-world speeds of half that or even slower, which isn't quite enough for video. To the rescue, eventually, will be **802.11n**, which promises significantly higher speed and range. MIMO techniques are the most significant difference between the g and n standards. The proposed systems are expected to have a maximum data rate of up to 250 Mbps with real time condition speeds up to 100 Mbps, which is almost five times the data rate of the earlier standard. Several research groups have also demonstrated over 1Gbps prototypes. All 4G systems will also be incorporating MIMO communication.

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