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MIMO Architecture for Wireless Communication

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ABSTRACT

In this paper, we consider the use of multiple-input multiple-output (MIMO) architecture for wireless communication systems. We show how by employing MIMO architecture, architecture in which transmission and reception are carried out through multiple antennas, one can design a superior wireless communication system with respect to reliability, throughput, and power consumption.

INTRODUCTION

In recent years, wireless communication devices have become more and more popular. However, at the same time, the design of faster, more reliable, and power-efficient wireless communication systems has become evermore difficult. Wireless channels, as opposed to wireline channels, exhibit highly irregular amplitude behavior due to what is known as *fading*. The fading, essentially caused by the reception of multiple reflections of the transmitted signal (illustrated in Figure 1), is a key inherent problem of wireless channels, which, unfortunately, cannot be avoided. Fading causes the received signal power to change rapidly in time, making the task of information extraction from the received signal a fairly complicated endeavor. Furthermore, once the information is extracted, its reliability, manifested through error probability, is often poor.

In this paper, we demonstrate how by exploiting the spatial diversity, namely, using multiple antennas, one can improve reliability, increase transmission throughput, and reduce transmission power. We also briefly discuss the benefits of using MIMO architecture along with orthogonal frequency division multiplexing (OFDM) modulation, and low-density parity check (LDPC) coding.

First, we consider the reliability issue. We present a basic model for the wireless single-input single-output (SISO, single transmit antenna, single receive antenna) channel, and show how the corresponding error probability is critically damaged by fading. We then consider the single-input multiple-output (SIMO, single transmit antenna, multiple receive antennas) channel and describe the concept of maximal ratio combining (MRC) as a way to exploit the receive diversity offered by this type of channel. We calculate the error probability achieved by the MRC, showing it to be much smaller than the one corresponding to the SISO channel, in which no spatial diversity exists. Next, we consider the multiple-input single-output (MISO, multiple transmit antennas, single receive antenna) channel, and we present some mechanisms that exploit the transmit diversity offered by this channel. Specifically, the beamforming technique and Alamouti's [3] scheme are analyzed. Bringing together transmit and receive diversity, the MIMO channel is introduced. The beamforming technique and Alamouti-based scheme are shown to achieve full diversity, i.e., they take full advantage of both transmit and receive diversity provided by the MIMO channel. We discuss the performance of the aforementioned spatial diversity techniques, and we draw some conclusions as to when one should be preferred over the other.

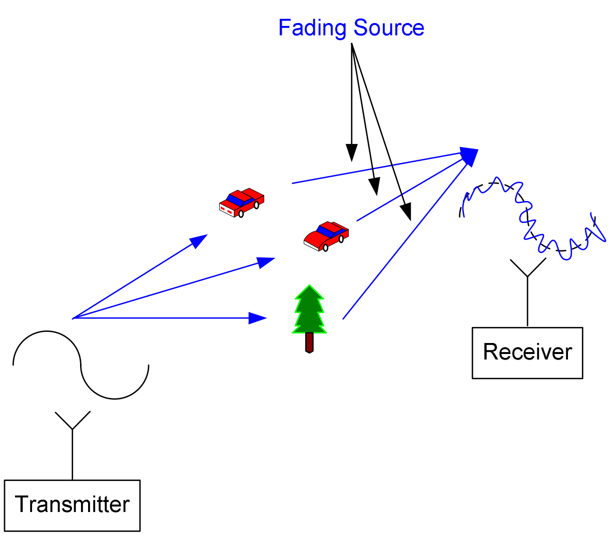

Figure 1: Wireless channel–fading problem due to multiple reflections

Improved reliability is not the only outcome of using multiple antennas. About ten years ago, a remarkable theoretical result regarding the capacity of MIMO channels [1] suggested that the transmission rate over wireless channels can be dramatically increased when using multiple antennas. It turns out that the ability to transmit and receive through multiple antennas does not only reject fading; better yet, it actually harnesses the fading itself in favor of increased throughput. We present the capacity of wireless MIMO channels, showing it to be greater than that of the wireline SISO channel. Moreover, the capacity formula is used to demonstrate how one can reduce transmission power by using multiple antenna systems.

Finally, we briefly explain how, in principal, integration between MIMO architecture, OFDM modulation, and LDPC coding (essentially the basic building blocks for the most advanced wireless communication standards, e.g., 802.11n, 802.16), can give rise to a superior wireless communication system.

The outline of the paper is as follows. We first present a basic model for the wireless SISO channel. We then consider the MRC technique, the beamforming technique, and Alamouti's scheme. After that, we present the capacity of MIMO channels and then discuss the benefits of using MIMO architecture along with OFDM modulation and LDPC coding. We conclude with some remarks on the performance of MIMO architecture and how the Intel® Centrino® mobile technology benefits by embracing it.

THE WIRELESS CHANNEL

In this section, we present a basic model for the wireless channel and show its performance to be inferior to that of the wireline channel.

The traditional wireline channel is modeled by the equation

$$y = x + n \tag{1.1}$$

where

x is the channel input. x is a complex number, referred to as *symbol*, representing two bits of information, i.e., it can take up to four different values according to the mapping (in general, x may be chosen to represent more than two bits of information):

$$\begin{aligned} "00" &\rightarrow x = -\sqrt{E_s} - j\sqrt{E_s} \\ "01" &\rightarrow x = -\sqrt{E_s} + j\sqrt{E_s} \\ "10" &\rightarrow x = \sqrt{E_s} - j\sqrt{E_s} \\ "11" &\rightarrow x = \sqrt{E_s} + j\sqrt{E_s} \end{aligned} \tag{1.2}$$

We assume that all the above possible realizations of x are equally probable.

n is the channel noise, accounting for the thermal noise induced by different parts of the receiver. n is modeled as a zero mean, complex Gaussian random variable with variance σ^2 per dimension, i.e., the real part of n and the imaginary part of n are zero mean, statistically independent Gaussian random variables with variance σ^2. Note that

$$\begin{aligned} En &= 0 \\ E|n|^2 &= E(nn^*) = 2\sigma^2 \end{aligned} \tag{1.3}$$

"E" and "*" denote statistical expectation and complex conjugate, respectively. The channel signal-to-noise-ratio (SNR) is given by

$$\begin{aligned} SNR &= \frac{E|x|^2}{E|n|^2} \\ &= \frac{E_s}{\sigma^2}. \end{aligned} \tag{1.4}$$

The receiver observes the channel's output y and decides which symbol, out of the four possible ones, was sent. The receiver tries to produce decisions with the best possible reliability. We measure reliability through error probability. Let $\hat{x}(y)$ be the receiver decision. The error probability, denoted here by $P_r\{\varepsilon\}$, is the probability that $\hat{x}(y)$ is different than x,

$$P_r\{\varepsilon\} = P_r\{\hat{x}(y) \neq x\}. \tag{1.5}$$

What receiver should we be using in order to achieve minimal error probability? The optimal receiver [2] decides that symbol x was sent, if the Euclidian distance between x and y is the smallest among all possible distances (total of four in our case). The optimal receiver, referred to as *the maximum likelihood (ML)* receiver, achieves error probability [2] satisfying

$$P_r\left\{\varepsilon\right\} \le \exp\left\{-\frac{SNR}{2}\right\}. \tag{1.6}$$

Throughout the paper, we provide upper bounds on the error probability. However, these bounds are tight for the mid-to-high SNR range [2], which is the interesting SNR range when targeting reliable, high-throughput communication. As we can see, for the wireline channel, the error probability decreases exponentially fast with the SNR. Does this excellent behavior remain intact when transmitting over wireless channels? Unfortunately, the answer is no. The fading, as shown next, dramatically increases the error probability.

The wireless channel model is similar to the wireline channel model, but with the input amplitude modified to account for the fading. The wireless channel is modeled with the equation

$$y = hx + n \tag{1.7}$$

where h represents the fading. We consider an environment in which there is no line of sight (NLOS) between the transmitter and the receiver. For this kind of environment, h is modeled as a zero mean, complex Gaussian random variable with variance 0.5 per dimension. Suppose for a moment, that the fading h is a fixed deterministic number rather than a random variable. In that case, the channel SNR would be given by

$$\begin{aligned} SNR\left(h\right) &= \frac{E\left|hx\right|^2}{E\left|n\right|^2} \\ &= SNR\left|h\right|^2 \end{aligned} \tag{1.8}$$

and, as for the wireline channel, the error probability satisfies

$$\begin{aligned} P_r\left\{\varepsilon \mid h\right\} &\le \exp\left\{-\frac{SNR\left(h\right)}{2}\right\} \\ &= \exp\left\{-\frac{\left|h\right|^2 SNR}{2}\right\}. \end{aligned} \tag{1.9}$$

Let

$$z = \left|h\right| \tag{1.10}$$

then

$$P_r\left\{\varepsilon \mid z\right\} \le \exp\left\{-\frac{z^2 SNR}{2}\right\}. \tag{1.11}$$

The above result accounts for the error probability for a given realization of the fading h. In order to obtain the error probability $P_r\left\{\varepsilon\right\}$ we must average the conditioned error probability (1.11) with respect to the probability low of z

$$P_r\left\{\varepsilon\right\} = \int P_r\left\{\varepsilon \mid z\right\} f\left(z\right) dz \tag{1.12}$$

$f\left(z\right)$ is the probability density function of z. Since h is Gaussian distributed, z is the squared root of the squared sum of two independent Gaussian random variables, which means [2] z is *Rayleigh* distributed

$$\begin{aligned} P_r\left\{z \le a\right\} &= \int_0^a f\left(\beta\right) d\beta \\ f(\beta) &= 2\beta \exp\left\{-\beta^2\right\}, \quad \beta \ge 0. \end{aligned} \tag{1.13}$$

Averaging (1.11) with respect to the Rayleigh distribution we have

$$\begin{aligned} P_r\left\{\varepsilon\right\} &\le \int_0^\infty \exp\left\{-\frac{z^2 SNR}{2}\right\} 2z \exp\left\{-z^2\right\} dz \\ &= \frac{1}{1+\frac{SNR}{2}}. \end{aligned} \tag{1.14}$$

It should be clear now how severe the damage caused by the fading is: instead of having an error probability that decreases exponentially fast with the SNR (1.6), we have an error probability which is only inversely proportional to the SNR. In the next section, we show how by using multiple antennas the situation can be rectified to some extent.

MIMO SYSTEMS RELIABILITY

In this section, we consider various spatial diversity techniques aimed at reducing the error probability.

Receive Diversity

Consider the SIMO channel depicted in Figure 2.

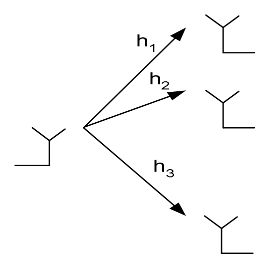

Figure 2: SIMO channel

Let N be the number of receive antennas. The signal received in antenna i is given by

$$y_i = h_i x + n_i, \quad i = 1, 2, \cdots, N \qquad (1.15)$$

where h_i and n_i are the fading and noise, respectively, as experienced by antenna i. We assume the fading is independent, which is the case, provided the antennas are sufficiently spaced from each other.

Consider the following weighted combination of the antennas' inputs

$$\begin{aligned} y &= \sum_{i=1}^{N} \alpha_i y_i \\ &= x\sum_{i=1}^{N} \alpha_i h_i + \sum_{i=1}^{N} \alpha_i n_i \end{aligned} \qquad (1.16)$$

where the α_i's are some deterministic numbers. The SNR of the above channel is given by

$$\begin{aligned} SNR(h_1, \cdots, h_N) &= \frac{E\left|x\sum_{i=1}^{N}\alpha_i h_i\right|^2}{E\left|\sum_{i=1}^{N}\alpha_i n_i\right|^2} \\ &= SNR\frac{\left|\sum_{i=1}^{N}\alpha_i h_i\right|^2}{\sum_{i=1}^{N}\left|\alpha_i\right|^2} \end{aligned} \qquad (1.17)$$

It is straightforward to verify (applying the Cauchy-Schwartz inequality) that by setting

$$\alpha_i = h_i^* \qquad (1.18)$$

the SNR is maximized. The weighted combination of the antennas' inputs with the above α_i's is referred to as *maximal ratio combining*. Substituting (1.18) into (1.17), the maximal SNR is given by

$$SNR(h_1, \cdots, h_N) = SNR\sum_{i=1}^{N}\left|h_i\right|^2. \qquad (1.19)$$

Thus, the error probability obtained by the ML receiver when applied to the MRC output satisfies

$$\begin{aligned} P_r\{\varepsilon \mid h_1, \cdots, h_N\} &\le \exp\left\{-\frac{SNR(h_1, \cdots, h_N)}{2}\right\} \\ &= \exp\left\{-\frac{SNR\sum_{i=1}^{N}\left|h_i\right|^2}{2}\right\}. \end{aligned} \qquad (1.20)$$

Let

$$z_i = \left|h_i\right|, \quad i = 1, 2, \cdots, N \qquad (1.21)$$

then

$$P_r\{\varepsilon \mid z_1, \cdots, z_2\} \le \exp\left\{-\frac{SNR\sum_{i=1}^{N} z_i^{\,2}}{2}\right\}. \qquad (1.22)$$

z_i's are statistically independent, Rayleigh distributed random variables. Thus, their joint density is simply given by the product of their individual densities

$$f(z_1, \cdots, z_2) = \prod_{i=1}^{N} 2z_i \exp\left\{-z_i^{\,2}\right\}. \qquad (1.23)$$

Averaging (1.22) with respect to (1.23) yields

$$\begin{aligned} P_r\{\varepsilon\} &\le \int_0^\infty .. \int_0^\infty \exp\left\{-\frac{SNR\sum_{i=1}^{N} z_i^{\,2}}{2}\right\} \\ &\quad \times \prod_{i=1}^{N} 2z_i \exp\left\{-z_i^{\,2}\right\} dz_1..dz_N \\ &= \frac{1}{\left(1+\frac{SNR}{2}\right)^N}. \end{aligned} \qquad (1.24)$$

As we can see, by using N receive antennas we have managed to substantially reduce the error probability. Note that in order to perform MRC, the receiver has to know the fading, or, in other words, the receiver has to have access to the *channel state information* (CSI). This is usually done by sending some known signal through the channel, called *pilot*, and measuring the channel's response. Cleary, such a procedure does not allow for having perfect CSI, but rather approximate CSI. However, empirical results indicate that using MRC with approximate CSI, instead of perfect CSI, slightly deteriorates performance. In general, the performance of spatial diversity techniques is measured using two terms: *diversity order*

$$\text{diversity order} = -\lim_{SNR\to\infty} \frac{\ln P_r\{\varepsilon\}}{\ln SNR} \quad (1.25)$$

and *antenna gain*

$$\text{antenna gain} = \frac{E\left(SNR\left(h_1,\cdots,h_N\right)\right)}{SNR}. \quad (1.26)$$

MRC achieves diversity order of N and antenna gain of N. If we draw a curve of the error probability as a function of the SNR on the logarithmic axis, the diversity order is the slope of the curve, and the antenna gain is the left-hand horizontal shift of the curve with respect to the curve

$$\frac{1}{\left(1+\frac{1}{N}\frac{SNR}{2}\right)^N}.$$

In some cases, it is not practical to have multiple antennas at the receiver. Consider for example handled devices: their small form factor does not allow for the positioning of multiple antennas that are spaced far enough from each other. Once the antennas are close, the fading seen by them is not independent, and then the error probability can not be made small as indicated by (1.24). Can we achieve the performance of MRC but with multiple antennas at the transmitter? The answer is yes. Essentially, the reason that MRC works is that it increases the SNR. By applying transmit diversity we can also increase the SNR and in turn decrease the error probability.

Transmit Diversity

Consider the MISO channel depicted in Figure 3. Let M be the number of transmit antennas. The received signal is given by

$$y = \sum_{j=1}^{M} h_j x_j + n \quad (1.27)$$

where h_j is the fading corresponding to transmit antenna j, and x_j is the symbol sent through antenna j. Again, we assume that the fading is independent. Suppose that we transmit

$$x w_j, \quad j = 1,2,\cdots,M \quad (1.28)$$

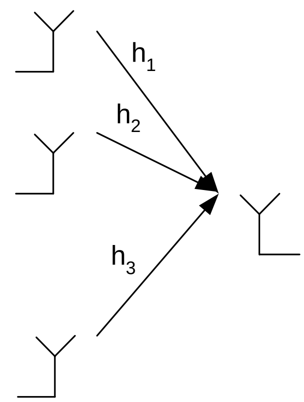

Figure 3: MISO channel

where w_j's are some weighting factors satisfying

$$\sum_{j=1}^{M} \left|w_j\right|^2 = 1. \quad (1.29)$$

The above constraint ensures we are not increasing the transmission power. Substituting (1.28) into (1.27) we have

$$y = x\sum_{j=1}^{M} h_j w_j + n. \quad (1.30)$$

The SNR of the above channel is given by

$$\begin{aligned} SNR\left(h_1,\cdots,h_M\right) &= \frac{E\left|x\sum_{j=1}^{M} h_j w_j\right|^2}{E\left|n\right|^2} \\ &= SNR\left|\sum_{j=1}^{M} h_j w_j\right|^2 \end{aligned} \quad (1.31)$$

As before, we would like to maximize the SNR. Setting

$$w_j = \frac{h_j^*}{\sqrt{\sum_{j=1}^{N}\left|h_j\right|^2}} \quad (1.32)$$

the SNR is maximized to the value

$$SNR\left(h_1,\cdots,h_M\right) = SNR\sum_{j=1}^{M}\left|h_j\right|^2. \quad (1.33)$$

Following the exact same steps as in the case of the MRC, we readily obtain

$$P_r\{\varepsilon\} \le \frac{1}{\left(1+\frac{SNR}{2}\right)^M}. \tag{1.34}$$

The procedure described in equation (1.28) with the optimal weighting factors of (1.32) is referred to as *transmit beamforming*. It is so named because the signal x is being formed before being transmitted. Transmit beamforming achieves a diversity order of M and an antenna gain of M, the same as MRC with M receive antennas. However, note that for transmit beamforming, the transmitter must have the CSI. This presents us with a bit of a problem, since in order for the transmitter to have the CSI, the receiver must send it to the transmitter, unavoidably reducing the throughput. Can we achieve transmit diversity without having to provide the transmitter with the CSI? Yes, we can, using Alamouti's scheme.

Alamouti's scheme consists of two transmit antennas and one receive antenna. It achieves the error probability

$$P_r\{\varepsilon\} \le \frac{1}{\left(1+\frac{SNR}{4}\right)^2} \tag{1.35}$$

while only requiring CSI to be at the receiver. It does so by employing transmission and reception mechanisms stretched across space and time. Alamouti's scheme achieves a diversity order of 2 and an antenna gain of 1, as opposed to an antenna gain of 2 for MRC 1×2 and transmit beamforming 2×1. This means that MRC 1×2 and transmit beamforming 2×1 outperform Alamouti's scheme by $3db$ (the SNR term in (1.35) is divided by 4 and not 2 as for MRC and transmit beamforming). However, as explained earlier, MRC needs the antennas to be sufficiently spaced, and transmit beamforming needs to know the CSI at the transmitter.

Transmit/Receive Diversity

Consider the MIMO channel depicted in Figure 4. Let M and N be the number of transmit and receive antennas, respectively. The received signal at antenna i is given by

$$y_i = \sum_{j=1}^{M} h_{ij}x_j + n_i, \quad i = 1,2,\cdots,N. \tag{1.36}$$

h_{ij} is the fading corresponding to the path from transmit antenna j to receive antenna i.

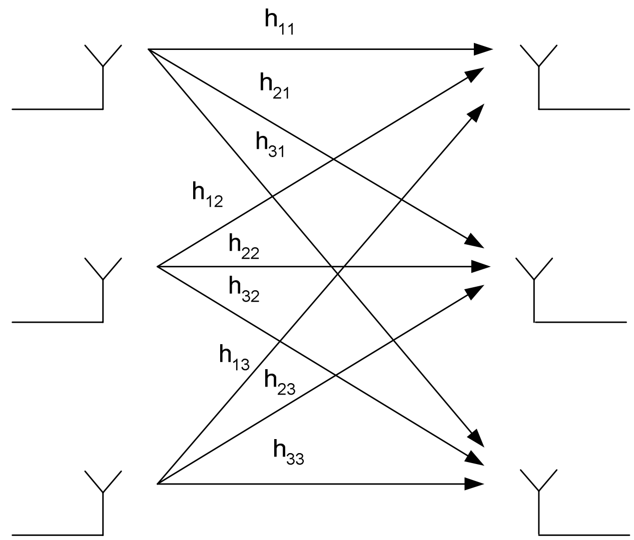

Figure 4: MIMO channel

As before, we assume the fading is independent. n_i is the noise corresponding to receive antenna i. Let

$$\underline{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}, \quad \underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_M \end{bmatrix}, \quad \underline{n} = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}, \tag{1.37}$$

$$H = \begin{bmatrix} h_{11}\ h_{12} \cdots h_{1M} \\ h_{21}\ h_{22} \cdots h_{2M} \\ \vdots \quad \vdots \quad \cdots \quad \vdots \\ h_{N1}\ h_{N2} \cdots h_{NM} \end{bmatrix}. \tag{1.38}$$

then

$$\underline{y} = H\underline{x} + \underline{n}. \tag{1.39}$$

We now describe the procedure of transmit/receive beamforming. The transmitter sends

$$\underline{v}x \tag{1.40}$$

where $\underline{v}$ is a vector of size $M\times1$ satisfying

$$E\left(\underline{v}^*\underline{v}\right) = 1. \tag{1.41}$$

For vectors and matrices "*" denotes the Hermitian conjugate, i.e., the vector, or matrix, is first transposed and then complex conjugated, entry by entry. The received signal is then

$$\underline{y} = H\underline{v}x + \underline{n}. \tag{1.42}$$

The receiver multiplies the received signal with a $N \times 1$ sized vector $\underline{u}$, creating the channel

$$\underline{u}^* \underline{y} = \underline{u}^* H \underline{v} x + \underline{u}^* \underline{n}. \quad (1.43)$$

The above channel SNR is given by

$$SNR(H) = \frac{E\left|\underline{u}^* H \underline{v} x\right|^2}{E\left|\underline{u}^* \underline{n}\right|^2} = SNR \frac{\left|\underline{u}^* H \underline{v}\right|^2}{\left|\underline{u}^* \underline{u}\right|^2} \quad (1.44)$$

How should one choose $\underline{v}$ and $\underline{u}$ such that the SNR is maximized? The maximizing vectors are derived from the *singular value decomposition (SVD)* of H [4], and the maximal SNR satisfies

$$\frac{1}{\min\{N,M\}} SNR\|H\|^2 \le SNR(H) \le SNR\|H\|^2 \quad (1.45)$$

where

$$\|H\|^2 = \sum_{i=1}^{N}\sum_{j=1}^{M}\left|h_{ij}\right|^2 . \quad (1.46)$$

The error probability is then bounded by

$$P_r\{\varepsilon \mid H\} \le \exp\left\{-\frac{SNR\|H\|^2}{2\min\{N,M\}}\right\}. \quad (1.47)$$

Averaging the error probability with respect to the fading yields

$$P_r\{\varepsilon\} \le \frac{1}{\left(1+\frac{SNR}{2\min\{N,M\}}\right)^{MN}} . \quad (1.48)$$

Thus, for transmit/receive beamforming we have a diversity order of MN, referred to as *full diversity*. The antenna gain on the other hand satisfies

$$\max\{M,N\} \le \text{antenna gain} \le MN . \quad (1.49)$$

Transmit/receive beamforming requires CSI at the receiver as well as in the transmitter. For a 2×2 setting, transmit/receive diversity can also be achieved by using 2×2 Alamouti-based scheme (obtained by an extension of the Alamouti's scheme) which achieves a diversity order of 4, an antenna gain of 2, and requires CSI only at the receiver. In Table 1, we summarize the antenna gain and diversity order for the different channel configurations.

MIMO SYSTEMS CAPACITY

In this section, we present the capacity of wireless MIMO channels and show that it is greater than that of the wireline SISO channel.

The capacity of a communication channel is the maximum throughput at which data can be sent over the channel while maintaining a low probability of error. The capacity is measured in bits per channel use. Clearly, we would like to transmit over channels with high capacity.

Table 1: Diversity order and antenna gain for various spatial channels

System	Antenna Gain	Diversity Order
SISO	1	1
SIMO CSI RX (MRC 1xN)	N	N
MISO CSI RX (ALAMOUTI 2x1)	1	M
MISO CSI RX & TX (TX BEAMFORMING Mx1)	M	M
MIMO CSI RX (ALAMOUTI-BASED 2x2)	N	MN
MIMO CSI RX & TX (TX/RX BEAMFORMING MxN)	$\le MN$	MN

The capacity of the wireline SISO channel (1.1) is given by [2]

$$C_{SISO} = \log_2\left(1+\frac{E|x|^2}{E|n|^2}\right) = \log_2\left(1+\frac{P}{2\sigma^2}\right) \quad (1.50)$$

where P is the transmission power

$$P = E|x|^2 . \quad (1.51)$$

As we can see, for the wireline SISO channel, the capacity can be increased only if the transmission power is increased. This is not the case for wireless MIMO channels as shown next. The capacity of the wireless MIMO channel (1.39) is given by [1]

$$C_{MIMO} = \log_2 \det\left(I + \frac{P}{2\sigma^2}\frac{1}{M}Q \right) \quad (1.52)$$

where

$$P = \sum_{j=1}^{M} E\left|x_j\right|^2 \quad (1.53)$$

is the total transmission power radiating from the transmit antennas

$$Q = \begin{cases} HH^* & \text{if } N < M \\ H^*H & \text{if } N \geq M \end{cases} \quad (1.54)$$

and I is the identity matrix of size

$$\left(\min\{M,N\} \times \min\{M,N\} \right) \quad (1.55)$$

"$\det$" denotes the determinant of the matrix. Averaging (1.52) with respect to the Rayleigh distribution of the fading yields [1]

$$C_{MIMO} = \min\{M,N\} \log_2 \left(1 + \frac{P}{2\sigma^2} \right) \quad (1.56)$$

(It should be pointed out that the above expression is an approximation; however. for mid-to-high values of P it is a fairly accurate one). We define the *multiplexing gain* as

$$\text{multiplexing gain} = \frac{C_{MIMO}}{C_{SISO}}. \quad (1.57)$$

Under the same transmission power P, the multiplexing gain is

$$\text{multiplexing gain} = \min\{M,N\}. \quad (1.58)$$

Thus, by using multiple antennas we can dramatically increase the throughput. If our main goal is power saving, and not increased throughput, we can use the MIMO architecture and have the same throughput as for the SISO channel, but with a much reduced transmission power. Usually, MIMO systems are used to simultaneously achieve both increased throughput and reduced power. In that case, we achieve multiplexing gain that is smaller than $\min\{M,N\}$.

MIMO SYSTEMS, OFDM, AND LDPC CODES

In this section, we briefly discuss the benefits of using MIMO architecture together with OFDM modulation and LDPC coding.

Wireless channels, in addition to the problem of fading, also suffer from the problem of *inter-symbol-interference (ISI)*. ISI is caused by the reception of a small number of reflections from remote objects (as opposed to the large number of reflections from nearby objects that causes fading). ISI causes the receiver to receive the original signal, overlapped by some delayed versions of the signal (illustrated in Figure 5). Traditionally, different types of *equalizers* were used to reject ISI. However, the complexity of good equalizers is usually high, making their employment fairly problematic. OFDM modulation [4] provides a fairly strong and simple ISI rejection mechanism. It essentially introduces a *guard interval* in between symbols, in which the interference can reside without critically distorting the original signal. The use of OFDM modulation within MIMO structured systems creates a strong system that has the ability to successfully reject fading as well as ISI.

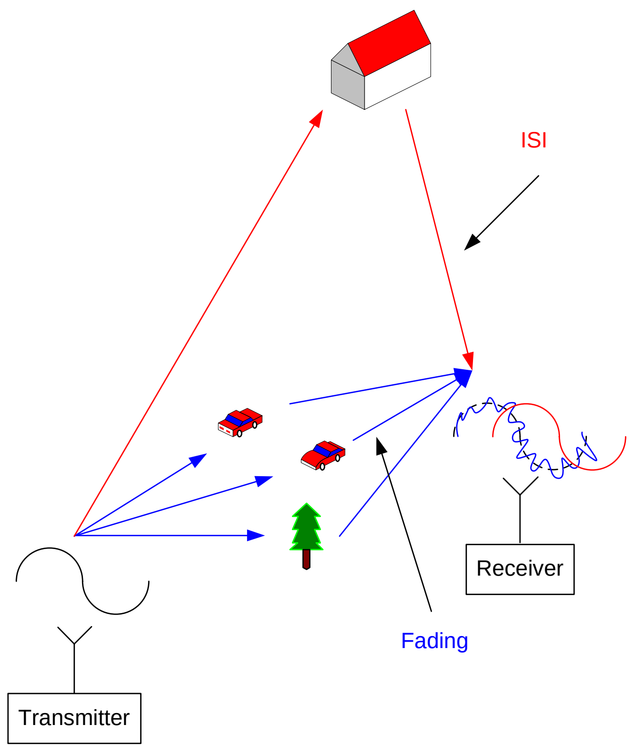

Figure 5: Wireless channel: ISI and fading problems

The increased capacity of MIMO channels can be translated into increased throughput provided that proper coding is used prior to transmission. The coding procedure essentially pads the transmitted data with some protection bits that help the receiver decide whether errors occurred during transmission. LDPC codes are highly efficient (with respect to encoding and decoding complexity) capacity-approaching codes. Using LDPC codes helps to fulfill the high-throughput potential of MIMO systems in a highly efficient manner.

The upcoming IEEE 802.11n Wireless Local Area Networks (WLAN) standard uses MIMO architecture, along with OFDM and LDPC coding. The standard has the ability to provide a stunning throughput of up to 600 Mbps as apposed to 54 Mbps provided by the older, non-MIMO IEEE 802.11a standard.

CONCLUSION

Wireless channels key problem is fading. The fading induces rapid changes in the SNR and in turn critically damages reliability. The ability to transmit and receive through multiple antennas enables us, while applying various spatial diversity techniques, to reject fading and ultimately have substantially improved reliability. Using multiple antennas does not only reject fading; better yet, it actually harnesses the fading itself in favor of increased capacity. The increased capacity, under proper coding, eventually translates into increased throughput. Employing multiple antennas also allows for power saving at the expense of reduced throughput or reduced reliability. In any case, the reduced throughput and reliability are well above those of the original single antenna channel. The joint use of MIMO architecture, OFDM modulation, and LDPC coding, creates a highly resilient communication system, which successfully rejects fading and ISI and fulfills the high-throughput potential offered by MIMO systems.

One of the key ingredients for current and future versions of Intel Centrino mobile technology is the ability to provide mobile users with fast and low-power communications. Intel achieves that goal by incorporating MIMO architecture into its line of wireless communication products.

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