Finding MIMO

Dragoș Niculescu
ETTI, Universitatea POLITEHNICA din Bucureşti, România

***Abstract*— Availability of multiple antennas enables increased capacity or increased resilience for modern radios. This advantage depends on the deployment of the antennas at the sender and receiver. But there is a performance gap between most simulated results and the actual performance obtained in practice. This is due to the rank of the channel obtained in deployments, which depends on local propagation conditions, and on the placement of the senders and receivers. Using implementation on top of USRP platform, and mobile antennas, we show that it is possible to find 'good' antenna positions within a search space of a few carrier wavelengths. This opens the possibility for adaptive methods in antenna position and coding/modulation techniques to feed back to each other to reduce the gap between theoretical and practical MIMO performance.**

I. Introduction

It is an established fact that radio signal reception varies in both space and time. Spatial variation is due either to user mobility or to scattering effects. As they move, mobile users experience signal and coverage changes due to fading and multipath effects. Reception varies with position and speed of the antennas, and with the quality of the environment. But even for static users, there is spatial variation due to multipath, and temporal variation due to changing patterns of human activity (indoors), or atmospheric conditions (outdoors). In all these cases, wireless links experience degradation which translate in lower QoS for the users. Long term outdoor point to point links require manual tuning and maintenance, while indoor links require site surveys or over-provisioning to account for this variability in link quality.

Use of multiple antennas on the senders and receivers (MIMO) has been a way to increase capacity and resilience. However, when operating on the same carrier wave, these antennas interfere with each other, and the achieved channel does not always have a high rank. The rank of the achieved channel depends on the actual deployment geometry of the sender and receiver, and on the environment in between, all of which determine the correlation of the multipath signal. One class of approaches to improve performance is to use adaptive coding and modulation techniques that are tailored for the given channel [1]. Another direction is to increase the diversity of the achieved channels [2], and our current proposal falls in to this category.

One method is to increase the spatial diversity, and MIMO itself implies spatial diversity by use of multiple elements. Spacing of elements is a subject of research and values between 0.1λ and 10λ are deemed appropriate for different scattering and SNR conditions. A second way of improving diversity is the use of different polarization. This decreases mutual coupling between close by elements, and increases the likelihood of uncorrelated paths. Pattern diversity is yet another way of minimizing the correlation of achieved channels. Usage of different patterns, or directional antennas is a technique that works for beamforming, and for SISO systems as well.

In this article we explore yet another way to increase the diversity of the channels, by mechanically changing the position of the antenna elements. This adds yet another degree of freedom to the joint optimization of coding, modulation, and diversity techniques that have been used so far. In highly scattered indoor environments the quality of the signal from a source may change on a scale less than the carrier wavelength [3]. This is generally seen as a degrading factor for indoor wireless, as it induces coverage dead zones and unexpected variability. **We exploit this existing diversity in propagation to find antenna element spots that produce 'better' channels.** For the SISO case, these are simply channels with better delivery ratios. The advantages of a reconfigurable antenna are that:

- it requires no manual intervention or technical expertise.
- adapts to changes automatically.
- can be retrofitted to existing antenna technology.
- is low cost - only a servomotor, and a controlling algorithm.

For the MIMO case, 'better' channels mean less correlated for the purpose of increased capacity. The advantages are:

- mobile antenna elements are a complementary technology, and it can be coupled with most other diversity techniques mentioned.
- the channels that can be obtained are simply not available to traditional MIMO techniques that only optimize using weights, phases, or gains.
- antenna element position and coding/modulation are both optimization techniques. They can both make use of feedback to each other to improve the end to end channel.

There are a number of applications where a mobile antenna can be easily implemented (Figure I):

- ceiling mounted access points with micro-motors could allow changing of the antenna positions on a centimeter scale. They can automatically tune to provide better service to user populations that are mostly static.

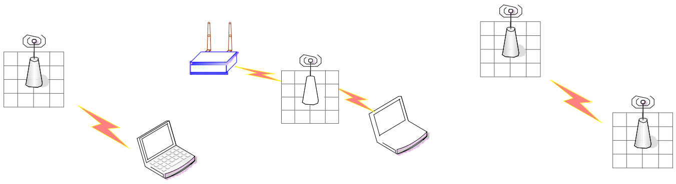

Fig. 1. Applications for mobile antenna/mobile element technique: at access point, for mostly static clients; at relay points to optimize both links; at long term point to point outdoor links.

- in relays: adaptation of uplink and downlink could enhance relay performance.
- long term point to point links that require periodic adaptation and optimization.
- mobile antennas could be implemented on larger mobiles (laptops) as well, as they are usually embedded in the screen, therefore providing a large search space.

For both SISO and MIMO we experimentally show that due to the diversity of the indoor signal, there is ample opportunity for optimization if antenna elements are mobile, even on a small scale.

II. Related work

The quest for improving MIMO performance through antenna enhancement is mainly based on improving diversity along three main directions: spatial, polarization and pattern. For a short review on various diversity techniques for MIMO antennas, see [2]. Reference [4] shows the advantages a reconfigurable antenna that can change its frequency and polarization. They claim a performance gain of up to 30dB over conventional fixed antenna MIMO. Reference [5] shows that adapting the antenna element spacing to the level of sparsity in the physical multipath environment has a profound impact on capacity. The authors claim that three canonical array configurations are enough for near optimum performance over the entire SNR range. Zangi [6] analytically investigates effect of antenna element geometry to the capacity of MIMO channels. For the 2×2 case, they find that spacing of antenna elements between $\lambda/2$ and 10λ are beneficial for low, respectively high SNR situations. For pattern diversity, Liang [7] explores ways to use antennas with dissimilar radiation patterns to induce decorrelation that could favor MIMO systems. They show that the achievable decorrelation is limited by the scattering environment. In her master thesis [8], Cotanda finds that using parasitic elements with small displacements ($< 0.4\lambda$) can have significant decorrelating effects. She found that the optimal element spacing was 0.1λ at the receiver, and 7.5λ at the transmitter for $SNR = 20dB$. [9] shows that an antenna consisting of two microstrip dipoles with variable electrical length, at a fixed $\lambda/4$ spacing can be used to increase capacity in an indoor environment, mainly for low SNR situations.

While most of existing work is either analytical, or based on simulation, we aim at quantifying experimentally the gains obtainable through antenna mobility, and the scale of mobility that is necessary. In high scattering environments, particularly indoors, we have shown in previous work that because packet delivery ratios can vary wildly within distances as small as the carrier wavelength, wireless multihop paths can be optimized for increased capacity [3].

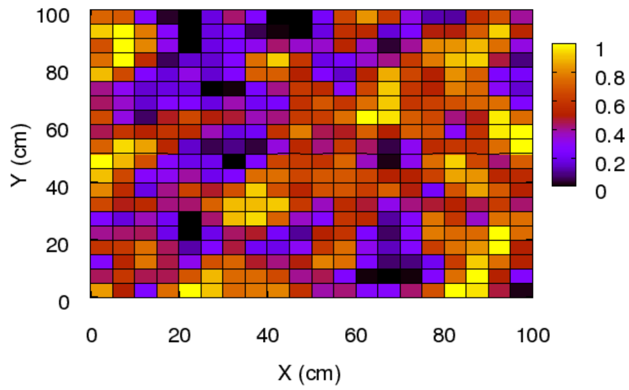

Fig. 2. Packet delivery ratio is measured from a robot mounted access point that changes positions across a $1m^2$grid. The access point and the receiver are fixed for each measurement.

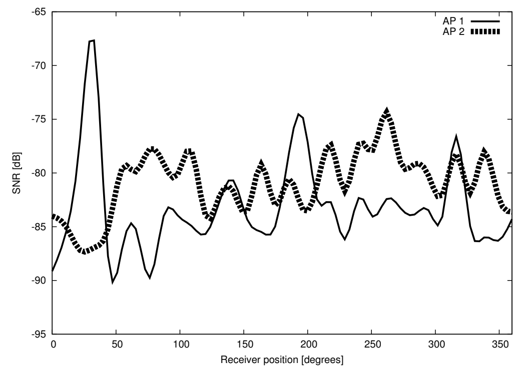

Fig. 3. A client rotating around its own axis can find a signal up to $20dB$ stronger. Both access points and the client are fixed for each measurement.

III. Indoor signal variation across larger scales

Variation in signal quality across indoor spaces is experienced by most users of the popular unlicensed frequencies at 2.4GHz. To get a sense of the amount of variation, we used a robot mounted 802.11g access point and recorded the packet delivery ratio (PDR) to a fixed client. Measurements were performed with the access point assuming different position at grid points across a patch of $1m^2$ at carpet level. For 2.4GHz the corresponding wavelength is approximately $12.5cm$, and as shown in Figure II, PDR can vary from 0% to 100% in distances within a few multiples of the carrier wavelength.

In a second experiment, we used the robot as a client, but restricted its movement to merely rotating around its own axis. The antenna is placed $20cm$ out of the axis of rotation. In Figure III, we plot the RSSI of the received packets from two different fixed access points. At different angles of rotation the power of the signal received routinely varies with 10dB, but can vary as high as 20dB. The pattern of variation depends on the particular features of the space between the AP and the receiver, and different APs are likely to produce different patterns.

These examples show that even with small antenna displacements it is possible to find a better channel. The size of the searchable space depends on where the functionality is implemented - on the access point, or on the receiver. While the access point may be larger and offer more potential for optimization, a client usually has fewer degrees of freedom. In laptops, which exhibit rather nomadic mobility patterns, antenna is mounted in the screen, so a degree of freedom can be achieved with a simple translation of antenna elements.

IV. MIMO Implementation

Having established that high signal variation can be found on a scale of the carrier wavelengh, we now look at how a MIMO system can take advantage of creating uncorrelated channels. We aim at measuring performance with full diversity sending of two independent streams on a 2×2 system, 0→0 and 1→1.

We used GNUradio [10] libraries, driving an USRP v1 board equipped with two 2.4GHz daughter-boards. The MIMO system described here is based on SISO examples that came with the library. A block diagram of the sender is shown in Figure IV. For the purposes of measuring the channel in a 2×2 MIMO system, we haven't built a full fledged MAC, but a more basic system system that is lacking any multiuser capability such as carrier sense, acknowledgments, etc. The system could accept data from a file, or generate data on the fly, that is then encoded using BPSK, filtered through a root-raised cosine, and then sent to the antenna, with the desired amplitude. To facilitate computing of BER at the destination, we use a simple framing scheme in which the first 10 bytes are used to detect the beginning of the frame. Out of these 80 bits, we only consider frames that match in at least 77 positions. A false positive in the preamble detection could generate abnormally high BER if a frame is merely shifted in time. BER is computed at the receiver only over the body of the frame, if the header shows some consistency among its fields. The next fields contain the length of the data portion of the frame, and the antenna used at the sender (0x00 or 0xFF). These are only used for reference since we know that our independent streams are sent 0→0 and 1→1. Data of up to 1500 bytes is then trailed with a CRC code, and padding required for transferring across the USB to the USRP board. This picture is repeated for each antenna at the sender, and the streams are then interleaved before being sent to USRP, where there they are separated and sent to the respective antennas.

For the receiver (Figure IV), the complementary blocks are present: BPSK demodulator, preceded by the RRC filter, and automatic gain control. Again, we have two such chains, one for each antenna. Due to oscillator and phase shifts between the sender and the receiver, we had to employ a Costas loop before the demodulation.

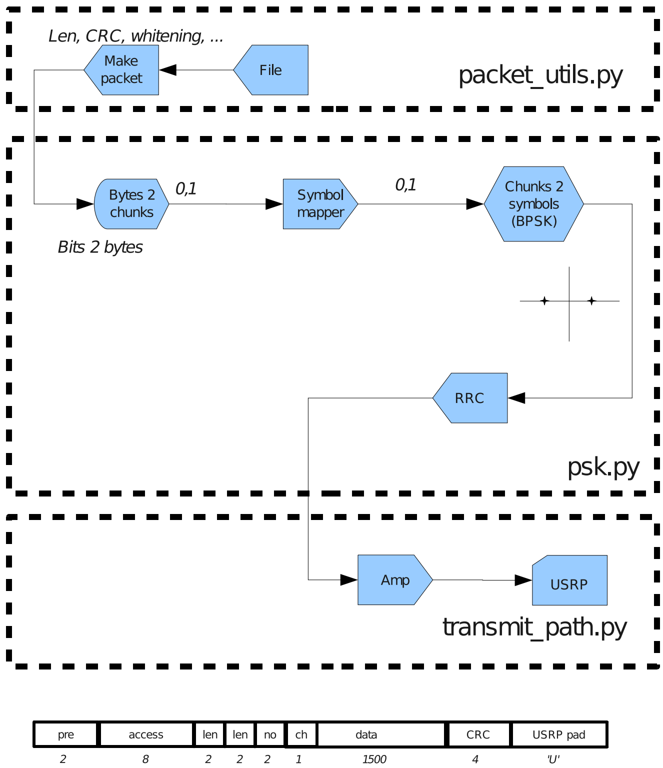

Fig. 4. Top: Sender using BPSK modulation and simple framing. These components are present for each independent stream sent from each antenna. Bottom: frame format.

A. BER Computation

BER computation is performed off-line, using a combination of C and GNU Octave code. The 80bits of the preamble are used to detect the beginning of the frame, and the body of the frame is then used to compute BER when the CRC fails. Since stream 0 is always sent from antenna 0 for the destination antenna 0, the content of each bit is known at the destination. Under low SNR conditions, the procedure is complicated by the demodulator either missing some symbols, or adding fake extra symbols, which leads to desynchronization for the rest of the frame. We detect such situations by looking for shifted versions of the expected bytes, and discarding the frame from the BER computation. A frame is deemed "acceptable" if it does not contain shifted versions of the expected data, it has the proper length, and the next frame starts at the appropriate symbol number.

B. Channel estimation

We implemented Zero Forcing (ZF) channel estimation offline using mostly Octave code. As shown in Figure IV-B, we run three runs of packets, each 10 seconds long, as we found that channel changes are negligible within these intervals. The first two runs are used to measure the channel, and the third run is for the actual MIMO sending and receiving.

In a first run, we measure the h_{00} and h_{01} components by sending a stream from the antenna 0 on the sender, while

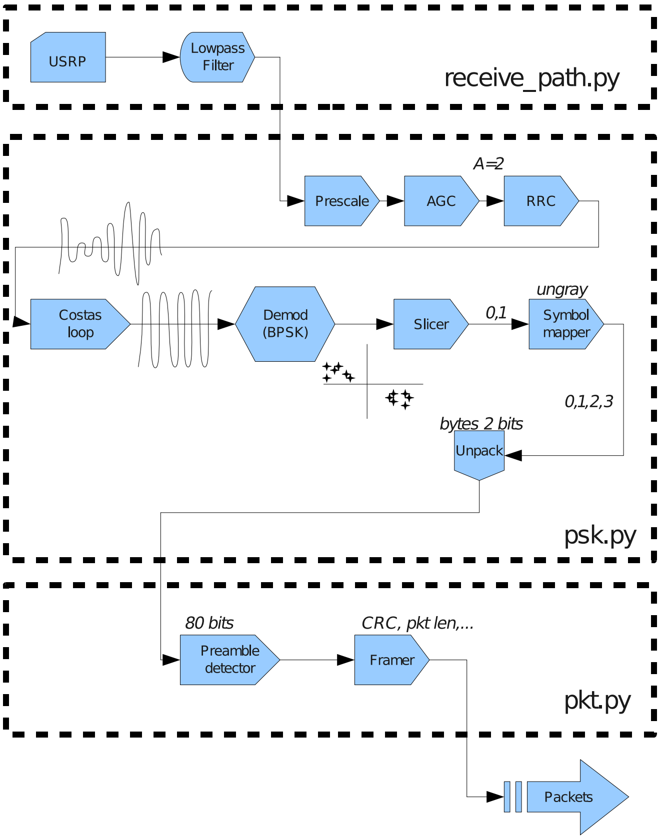

Fig. 5. BPSK receiver block diagram for each antenna. Channel estimation matrix linking the two streams gets plugged in between the demodulator and the hard decision slicer.

keeping antenna 1 inactive. The value of $y_0$is read at the output of the decoder, and the value of $x_0$is known from the training sequence.

$$
\begin{aligned}
y_0 &= x_0 h_{00} + n_0 \\
y_1 &= x_0 h_{01} + n_1
\end{aligned}
$$

Then, h_{01} and h_{00} is obtained over all training sequences of the 'acceptable' frames as:

$$h_{00} \quad = P_{00} \quad mean(\frac{y_0}{x_0})$$

These values are measured using the 80bit frame preamble which can be seen here as a training sequence. Because the BPSK decoder implemented by GNU radio requires values around 1, the gain control block (AGC) is employed before decoding. To capture the gain of the channel, we read the power P_{00} at the entry of AGC. In the second run, we send a stream on antenna 1 and keep antenna 0 inactive in order to measure h_{11} and h_{10} with a similar procedure.

In a third run two independent streams are sent from each antenna and the channel estimation is used at the receiver to combine the symbols from the two antennas. The MIMO channel is then assembled in the following manner:

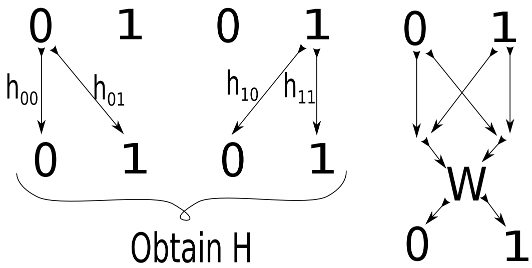

Fig. 6. The receiver uses both antennas for all the runs. The first run estimates h_{00} and h_{01} by only exciting antenna 0 at the sender. The second run estimates h_{10} and h_{11}. The third run uses the estimated channel to demodulate the distinct streams sent from each antenna.

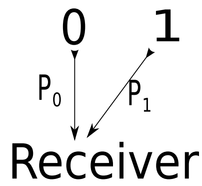

Fig. 7. Each of the sender antennas emits a different tone - and their power is recorded at the destination antenna.

$$
\begin{aligned}
y_0 &= x_0 h_{00} + x_1 h_{10} + n_0 \\
y_1 &= x_0 h_{01} + x_1 h_{11} + n_1 \\
y &= Hx + n \\
x &= (H^T H)^{-1} H^T y
\end{aligned}
$$

The matrix $W = (H^T H)^{-1} H^T$ gets y symbols from each antenna and feeds the x values obtained further to the slicer that performs the hard decision. After each of the three runs, BER is computed as described in the previous section.

C. Indoor signal variation across small scales

In this section we quantify the performance obtained by exploring diversity of antenna positions over small spaces. For these experiments, spacing of the sender antenna is fixed at 1.5λ, whereas for the receiver we move only one element across a square lattice (the elements are spaced so that the average distance between them is 4λ on average). Sender and receiver are within LOS, at 2.5m of each other, in a typical office environment.

In order to identify good orthogonal channels, we send two different tones of equal power from each of the antennas and measure the power at each receiver antenna (Figure 7). For antenna 0, the recorded powers would correspond to P_{00} and P_{10}. An FFT of the spectrum visible at each receiver antenna is shown in Figure IV-C. The origin of each tone of interest is labeled using a '0' or a '1' in the figure. In this example, the power difference at receiver 0 between the signals from the sender is of 9dB in the favor of 0→0 signal over 1→0 (upper Figure IV-C). In the lower figure, we see the reading of the same two tones at receiver antenna 1 - now the 1→1 signal is 10dB stronger than 0→1. This provides a good isolation

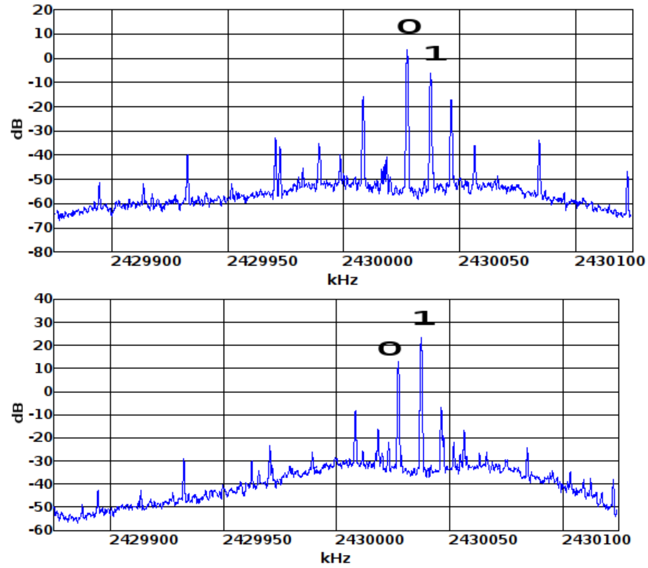

Fig. 8. FFT of two tones as seen at antenna 0 (top) and antenna 1(bottom). The tones are sent from the antenna 0 and 1 respectively at the sender. This is an uncorrelated, high capacity MIMO channel.

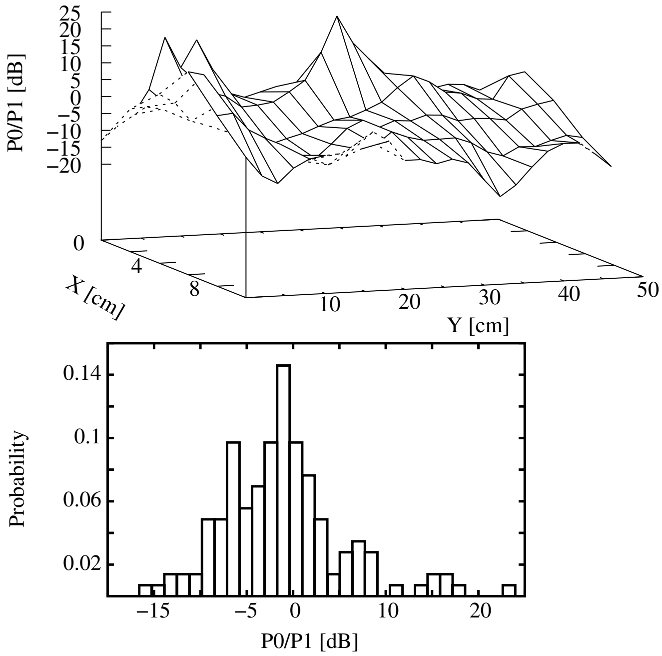

Fig. 9. Upper: gain difference at the receiver antenna between the two sending antennas. The receiver antenna takes different positions one grid spanning a $500cm^2$area. Lower: Power difference distribution histogram. 11% of the points exhibit more than 10dB absolute difference in the power received from the two sender antennas.

between 0→0 and 1→1, but in most situations, channels are not as orthogonal as in this example.

We measured the ratio of the power of the two tones P_0/P_1 for different positions of one receiver antenna, and summarized the results in Figure IV-C. It is only necessary to explore this space for one receiver antenna, as the gain difference for a given position would be the same if we measure it with another (second) receiver antenna. The area explored is about $500cm^2$. The top figure shows a 3D view of the power difference for each point, with a range of -17dB to +24dB. The lower part of the figure shows a histogram of all the differences measured in the explored space. Out of a total of 144 positions, 16 exhibit an absolute difference of at least 10dB between P_0 and P_1.

Using positions identified using the above procedure, we compute the BER for different amplitudes of the signal at the sender. In Figure IV-C we look at the performance of two such realizations. The top one is for an uncorrelated channel, like the one identified in Figure IV-C, which achieves 200% capacity compared with the SISO case, for the same power used per sender antenna. The one in the lower figure corresponds to a channel which has some correlation, the power difference at the two receiver antennas being only about 5dB.

V. Summary and Future Work

Antennas with mobile elements can achieve better performance for both SISO and MIMO cases. This is especially true indoors for the popular 2.4GHz carrier, where a difference of a few centimeters reaches a completely different channel. On a large scale of movement (above 1λ) the method is applicable to ceiling mounted access points, long term links, and the gains can be made available to any existing receiver antennas. On a small scale, the idea can be used to achieve higher capacity in MIMO systems by finding channels with high rank correlation matrices. We have shown experimentally that it is easy to find good (orthogonal) channels within a small search space, and differences of 10dB can easily be obtained through small scale movements of antenna elements. These results could improve both access point and mobile station antennas, and the work can be continued in a few directions:

- more extensive evaluations for different LOS/NLOS conditions, carrier frequencies, and bandwidths. Since the high variation per unit of distance is produced by indoor fading and multipath, it is likely to be available for other carriers, and NLOS conditions. The use of spreading however, might complicate the search procedure under frequency selective fading conditions.
- apply the same principle of "finding" good channels for the problems of beamforming, multiple users, and canceling interference. Any problem that involves a form of channel estimation and then optimization can benefit from an extra parameter to drive the optimization process.
- actual algorithms to explore the space of antenna positions, depending on the capabilities. They would have to consider the scalability with number of antennas, the degree of mobility, which brings a trade-off between the time to optimize and the time for the channel to remain stable.
- antenna position adaptation and coding/modulation adap-

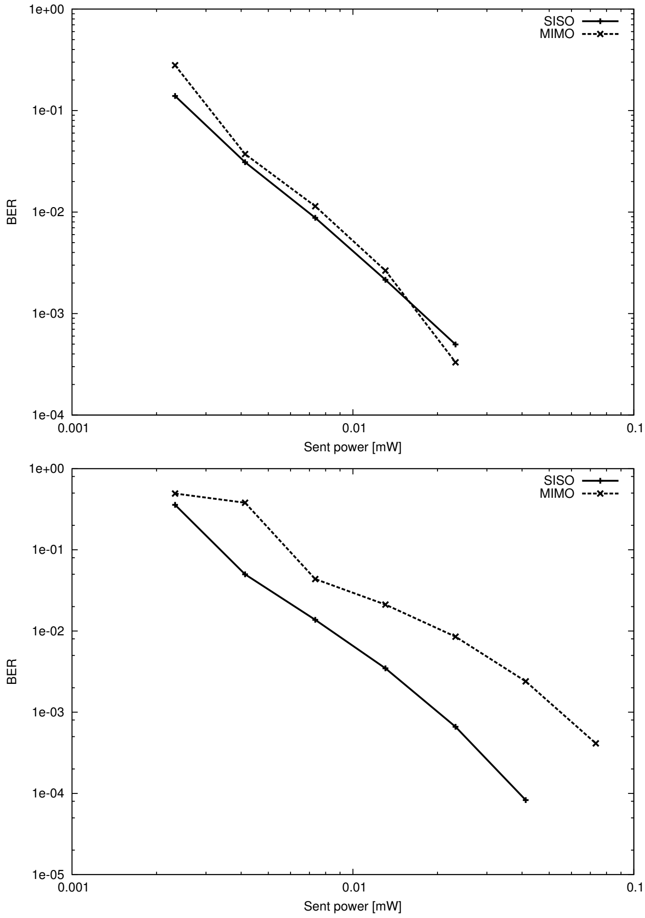

Fig. 10. BER plot for a decorrelated channel (upper), and for a channel with some correlation (lower).

tation can feed back to each other to achieve the optimum for a long term link. Essentially different element positions offer (almost) different channels, each of them with a different optimal coding and modulation strategy. Reciprocal feedback between these optimization processes offers the possibility of even higher gains.

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