Simulating MIMO Techniques in a Reverberation Chamber

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Abstract—**We present a general method for over-the-air test of antenna setups and/or post-processing algorithms used in advanced transmission schemes. The method utilizes a reverberation chamber to simulate various levels of multipath in the propagation environment. Multipath is essential for correctly estimating the performance of multiple-antenna systems. Our test set-up enables measurement of data throughput with standard laboratory instruments. With this test set-up, antenna setups can be studied while isolated from any specific system hardware implementation.**

Index Terms—**antenna array, antenna diversity, beam forming, bit error rate, multipath, multiple-input, multiple-output wireless system, reverberation chamber, wireless system.**

I. INTRODUCTION

Given the large increase of data rates in wireless communication systems in recent years, new technologies have become necessary to solve bandwidth and data throughput problems. To increase the received data rate without the need for linearly increasing the bandwidth, systems that utilize multiple antenna elements are now being utilized. The use of multiple elements can optimize system throughput in the presence of channel impairments such as multipath or spatially distinct weak-signal conditions.

Unlike other wireless systems, where system characteristics such as output power or receiver sensitivity are sufficient to describe system performance, data throughput is a natural metric to use to describe the enhancement of signal transmission from multiple-input, multiple-output (MIMO) systems. This is because the successful transmission of data in a MIMO system is based on other parameters in addition to power and receiver sensitivity, such as the instantaneous vector relationship between multiple received-signal components. Use of data throughput as a metric can be challenging, because successful demodulation and decoding of a signal depends not only on the impairment introduced by the propagation channel and the antenna system used, but may also depend on transmitter- or receiver-specific implementations of modulation, demodulation and error-correction algorithms.

To isolate the effects of the channel on multiple-antenna system performance, we have developed a test environment that does not depend on the use of a commercially developed MIMO device or base-station simulator to measure the throughput. Rather, it uses laboratory-grade test equipment and the well-characterized, repeatable multipath propagation environment of the reverberation chamber.

The use of reverberation chambers for MIMO system testing has been discussed in prior publications, for example, [1-5]. Most publications predict the maximum capacity of MIMO systems based on knowledge of the antenna radiation pattern (measured, modeled, or simulated), coupled with the channel response. In some cases, the channel response is measured [1-3], and in other cases it is modeled [1, 2, 4]. Using this "two stage" method, data throughput is inferred, rather than directly measured. The test system introduced here directly reports the change in data throughput in the presence of realistic channel impairments, yet remains isolated from receiver-specific algorithms, such as those reported in [5]. The test system enables evaluation and optimization of MIMO antenna systems and can also be used to test wireless systems that utilize other types of antenna diversity.

II. MULTIPLE-ELEMENT TRANSMISSION SYSTEMS

In a standard single-input, single-output (SISO) transmission system, one transmit antenna and one receive antenna are used, as illustrated in the top configuration in Figure 1. To measure the link quality, the bit error rate of the received signal is calculated as a function of transmitted power and/or receiver sensitivity. For a fixed transmitted data rate, the bit error rate (BER) also can be measured.

Several different techniques can be used to increase data throughput with multiple antenna systems. One such technique is *beam forming*. Multiple antennas can improve link quality because of the higher signal levels introduced by the directivity gain of the phased array. One common implementation makes use of multiple transmit antennas and one receive antenna, as illustrated in the multiple-input, single-output (MISO) system in the second diagram of Figure 1. Note that beam forming requires real-time feedback from the transmitter to the receiver (or vice versa) to optimize the phasing in the antenna array as channel conditions change.

A second technique for increasing data throughput is based on *receive diversity*. This technique can increase the quality of the link dynamically for a strongly fading multipath environment by use of multiple receive antennas instead of one. If the received power for the two paths taken by the signal differs because of independent, spatially distinct impairments in the propagation channel, the receiver demodulates the stronger signal. In one common implementation, the wireless channel has one transmit antenna and two receive antennas, this technology is called single-input, multiple-output (SIMO), as shown in the third diagram in Figure 1. Note that beam forming using two receive antennas could also be called SIMO, but this is a less common designation.
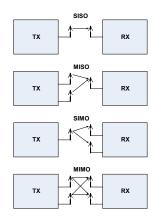
Figure 1: Different types of wireless system configurations. In each system, "S" refers to "single," and "M" refers to "multiple." These refer to the number of antennas used at each end of the wireless system. Many new cellular telephone systems use a combination of receive diversity (SIMO) and will soon utilize MIMO.

Finally, a MIMO system uses multiple receive and multiple transmit antennas. These systems may combine all techniques mentioned above. MIMO system may include additional methods to increase throughput as well such as:

Spatial multiplexing, where a high-data-rate signal is split into several lower-data-rate signals. Those streams are transmitted with different, spatially distinct antennas operating on the same frequency. To derive maximum benefit from spatial multiplexing, the channel seen by each transmit/receive antenna pair should be independent. Knowledge of the different channel characteristics allows the receivers to demodulate the multiple transmissions separately, increasing the total data rate of the transmission without increasing the bandwidth.

Diversity coding, where the same information is transmitted simultaneously from different antennas is another common MIMO system technique. Each transmitter uses a modulation scheme that is orthogonal to the others. Because of the orthogonal coding, the receiver is capable of separating the incoming signal into two data streams. The stream with the higher channel quality is demodulated. For this technology, no knowledge of the wireless channel is necessary.

In the next sections, we describe our reverberation-chamber-based test set-up. We then show how each of the above techniques can be simulated individually or in concert.

II. SIMULATING A MULTIPATH ENVIRONMENT WITH A REVERBERATION CHAMBER

Wireless signals in a real environment are reflected by both fixed structures and moving objects such as cars and/or people. A portion of the energy of each reflection may be absorbed by the objects and the remainder is re-reflected. A high-multipath wireless channel can be described by its impulse response, consisting of the primary transmitted impulse signal and its reflections. The output $y(t)$ of a static radio channel at time t can be written as

$$y(t) = u(t) * h(t) = \int_{-\infty}^{\infty} h(\tau)u(t-\tau)d\tau \quad , \qquad (1)$$

where $u(t)$ is the input time signal and $h(t)$ is the impulse response of the propagation channel. To include the effects due to time- and/or spatially varying multipath, we carry out an ensemble average over several different realizations of the channel. These realizations correspond to different locations in the field environment and different paddle positions in the reverberation chamber. The ensemble average of the magnitude squared of the impulse response of different channel realizations is referred to as the power delay profile (*PDP*) and is given by

$$PDP(t) = \left\langle |h(t)|^2 \right\rangle \quad . \qquad (2)$$

The *PDP* quantifies how long it takes for signal reflections to decay inside a multipath environment.

Different types of radio propagation environments produce *PDP*s having different distributions. One characteristic of the *PDP* that has been shown to be particularly important in wideband modulated-signal wireless systems is the root-mean-square (RMS) delay spread of the *PDP* (which is the square root of the second central moment of the *PDP*).

In the reverberation chamber, we take the ensemble average over multiple positions of the mode stirring paddles. As the paddles rotate, they change the boundary conditions of the chamber. If the stirrers are able to change the boundary conditions sufficiently, the measured power averaged over all positions is ideally equal at every location in the chamber. In this case, an object placed at any location in the reverberation chamber will be exposed to the same field over time.

Previous work has shown that by loading the chamber with RF absorbing material, the *PDP* of the chamber can be modified in order to simulate a wide range of real-world multipath wireless channels. References [6, 7] show that the time it takes for a signal to decrease inside the chamber can be manipulated by adjustment of the "loading," or placement of absorbing material inside the chamber.

In wireless systems that use multiple-antenna techniques, second-order statistics such as Doppler spread (related to coherence time), level crossing rate, and average fade duration become important [8]. These metrics can be quantified and, generally, tuned within the reverberation chamber. As an example, Figure 2 shows the level crossing rate (the expected rate at which the signal envelope crosses a threshold level) and the average fade duration (the typical time that the signal envelope spends below a threshold level) measured in two different single-cavity reverberation chambers (one at NIST, one at Chalmers University in Sweden) by use of different stirrer sequences. The range of values presented here are on the order of the level crossing rate and average fade duration found in many indoor environments [9]. Techniques for tuning these second-order metrics to arbitrary values are currently being developed by simulating larger environments [4, 10] and faster speeds for wireless device movement [11].
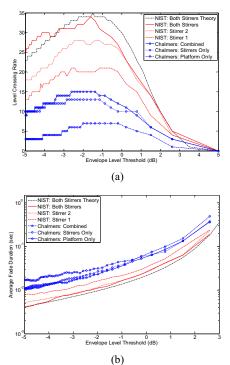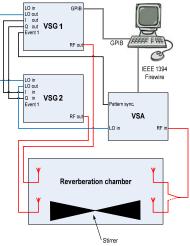
Figure 2: (a) Level crossing rate, in threshold crossings per second, and (b) average fade duration, in seconds, illustrating single-chamber measurements of higher-order multipath statistics. A higher value of level crossing rate is enabled with physically larger reverberation chambers, shown in the top curves.

In the present work, we focus on reverberation-chamber-based tests to assess the performance of antenna subsystems used in multiple-antenna systems, rather than tests for the entire system. These systems have been specifically developed to perform well in environments that where the incoming multipath signals at each receive antenna are independent of each other, that is, the received signals are uncorrelated. As discussed in the following section, we replicate a multiple-antenna system by taking advantage of the good repeatability of the paddle positions in the reverberation chamber.

III. EXPERIMENT SET-UP

Our experiment setup for multiple-antenna testing in a reverberation chamber is shown in Figure 3. The system consists of two vector signal generators (VSGs) that simulate multiple transmitters in a MIMO or MISO system. For some MIMO implementations, both instruments transmit at the same carrier frequency. For others, the transmitted signals have a known phase relationship relative to each other. Therefore, in our implementation, the local oscillator (LO) of one instrument is used to drive both VSGs. We do this by connecting the "LO out" port of one VSG to the "LO in" port of the other. With this method, we can also connect additional VSGs together if necessary.

Figure 3: Experimental setup. The two vector signal generators simulate multiple transmitters, while the receiver, a single vector signal analyzer, is switched between the two receive antennas. The repeatability of the reverberation chamber paddle positions allows the use of a single receiver. MIMO algorithms are implemented in post processing.

The VSGs are connected to antennas located within the chamber with coaxial cables that pass into the chamber through bulkheads. In our experiments, we used two omnidirectional antennas at both the transmitter and receiver sides of the system. For the tests reported here, we used collinear antennas. They were mounted on a nonconductive fiberglass rod, and the distance between them could be varied, as shown in Figure 4.

As in [1], we take advantage of repeatable positioning of the mode-stirring paddles to simulate a MIMO system in a reverberation chamber with only one receiver. We use a single-channel vector signal analyzer (VSA) for our receiver, as discussed in [12]. Each receive antenna is connected either to the receiver input or to a matched termination simulating a second receiver input. It is necessary that the non-driven antennas be located in their final array location to provide the correct loading (coupling) for the array. For every antenna, the measured data are recorded and the datasets from all receive antennas are combined in post-processing.

This single-receiver set-up has some advantages: First, it is an inexpensive alternative to the use of multiple-channel receivers, few of which are currently being produced commercially. Also, because the data are recorded and the MIMO algorithms implemented in post-processing, we can test various algorithms or combinations of algorithms. However, one disadvantage is that receiver-based beam forming cannot be implemented.

A computer is used to control the measurement operation and to record the data. For every recorded set of data, the received power is computed by use of the VSA software. This information may be used in post-processing as an indicator of channel quality. For example, in the beam-forming mode, the control software reads the received-signal power in real time

This information is used to find the maximum received signal by adjusting the phase of the antenna array at the transmit site.

During the beam-forming operation, it is necessary for both instruments to transmit the same modulated signal at the same time. For this task, the bit pattern that should be transmitted is stored in the first VSG. The baseband version of this signal, appearing at the input to the I/Q modulator of the instrument, is split and routed to the second VSG. There, it is injected into its I/Q modulator directly. Because the cables transporting the I and Q signals are 1 m long, in our case, the delay introduced by them is much shorter than the duration of a symbol and can be neglected.

Figure 4: Antennas used at receive and transmit locations. Omnidirectional antennas were mounted on a fiberglass rod. The spacing between them was variable.

Every time the bit pattern, or frame, is transmitted, the VSG triggers data acquisition by the VSA. The VSA is also configured to use the local oscillator of the first VSG to prevent frequency drift. We used a switch to sequentially record the signals from both receive antennas. It connects the antenna either to the input of the VSA or to a 50 Ω termination.

In post processing, the BER is calculated from the recorded data acquired from the different MIMO schemes. BER is used as a metric to determine the effectiveness of the MIMO or diversity transmission operation.

We next discuss implementation of the various throughput-enhancing schemes discussed in Section II using our test system. As discussed above, a key aspect is the use of a repeatable channel provided by the reverberation chamber to test schemes that require multiple receivers.

SISO: One transmit antenna and one receive antenna are used. The power delay profile of a real environment is simulated in the reverberation chamber, tuned by use of RF absorber. To measure the link quality, the bit error rate of the received signal is calculated.

TX beam forming (MISO):
In a real system, the transmitter uses several antennas all fed by the same signal but at different phases. The receiver measures and transmits the value of the current received power back to the transmitter in order to maximize the signal

level at the receive antenna. In our simulated system, the control program changes the phase of one of the two transmitted signals relative to the other in user-specified increments from 0 ° to 360 °. For each phase, the received power is recorded. Once all steps are completed, the control software then finds the maximum, adjusts the phase and starts the transmission. The paddle is then incremented to the next position. In this scenario, we assume that the active interference from one antenna to the other is negligible.

Receive Diversity (SIMO):
In a real environment, one transmit antenna is used while the receiver uses multiple antennas and monitors the signal strength at each antenna continuously. The strongest signal is used for demodulation. Our simulated setup records the data stream and the power level of the signals from each receive antenna. In post processing, the dataset with the strongest signal is used to calculate the bit error rate of the transmission.

RX beam forming:
The receiver uses multiple antennas connected to phase shifters. The phase of each antenna is adjusted to maximize the sum of the received signal. This feature is not implemented in the experimental setup.

MIMO:
In a real MIMO system, at least two receive and two transmit antennas are used at the same time. The receiver uses the signal from all receive antennas to generate the resulting data stream. If spatial multiplexing is used (see Section II), all different data streams are received and combined into a new data stream having a higher data rate. If diversity coding is used, each receiver uses only the part of the signal that fits its coding. The raw data streams of all receivers are processed and combined into one stream having a lower bit error rate. Because our simulated system uses only one receiver, no real-time processing of MIMO signals is possible. As described above, an RF switch connects each antenna to the receiver, serially. However, the channel response between all four transmit and receive paths are found, enabling test of multiple antenna systems and MIMO algorithms off line. In our implementation, this is facilitated by prior knowledge of the transmitted data stream. This data stream is compared to the transmitted bit pattern in order to calculate the BER.

IV. EXPERIMENTAL RESULTS

We report on a series of measurements in which the reverberation-chamber-based system described above was used to implement the techniques described in Section II. Measurements were made by implementing individual techniques or combinations of techniques in order to test their effectiveness in reducing BER in a high-multipath environment.

For all measurements, we used a carrier frequency of $f = 2.4$ GHz. The antenna spacing was greater than one-half wavelength (the wavelength is 0.125 m at 2.4 GHz). We tested a digitally modulated signal that utilized binary phase-shift keying (BPSK) by use of the method of [12]. In this method, no standardized transmission access scheme or error

correction was used, in order to evaluate the most basic form of the received signal. Only a very basic form of error correction is used to correct the bit stream when the receiver loses its lock to constellation definitions after recovering from a deep fade.

The results reported below are representative values provided simply to illustrate the rough level of improvement that throughput-enhancing techniques can offer when compared to SISO systems. However, even though we do not report uncertainties, we can assess the expected significance of components of the uncertainty. For example, repeatability of our measurement system will contribute to uncertainty in the calculated BER. As discussed in [13], the repeatability of the BER measurements for the VSG/VSA system described here depends on the data rate, modulation format, and received power level. In our chamber, this source of uncertainty in BER is generally less than 0.001 % for higher received power levels such as those considered here. We ensured that our received power was well above the noise floor of the receiver in order to minimize this component of measurement uncertainty.

One additional source of uncertainty in the measurements described here is the repeatability of the paddle movement in the reverberation chamber. For the tests shown here, the paddle positioning may have been different by up to 6 degrees from one measurement to the next. This could affect the beam forming algorithm, for example. Still the results below illustrate an improvement in data throughput as compared to SISO. We would expect even better performance once the paddle repeatability is improved. Analysis of paddle position errors on BER for multiple antenna systems is the subject of ongoing research at NIST.

In order to evaluate the MIMO techniques for different power delay profiles, the loading of the chamber was varied. For these measurements, a transmitted bit rate of 768 ksps was used. Figure 5 compares the BER for the different SISO and MIMO techniques for various levels of loading. In the MIMO mode, the received data of both antennas were combined using the received signal strength as a weighting coefficient.
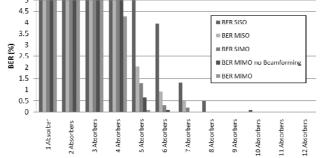
Figure 5 shows that for higher values of loading, there is a decrease in the BER when the advanced transmission techniques are used. This decrease can be considered significant because the repeatability of the paddle, our largest expected source of error, would not affect the SISO measurements. That is, the multiple-antenna measurements should be negatively affected by paddle position errors, yet they still present reduced BER values. Even the use of a simple MISO system, where the strongest of two signals is chosen, results in reduced BER. In fact, the reduction in BER is the most pronounced when any advanced technique is used, compared to the additional improvement when two or more techniques are used. The large increase in the bit error rate for lower values of loading can be explained by the limited coherence bandwidth of the reverberation chamber under these conditions [13].

The bandwidth of a BPSK-modulated signal can be calculated with the following formula:

$$BW = BR * (1 + R) * M , \qquad (3)$$

where BW is the bandwidth of the modulated signal, BR is the bit rate of the information, R is the roll-off factor of the modulation scheme (0.5 for the experiments reported here), and M is the modulation efficiency, which is one for BPSK because one state ($0°$ or $180°$) represents only one bit. Example results of the expression are given in Table 1.

Figure 6 shows a set of measurements performed with the different data rates given in Table 1 in order to assess the connection between link quality and transmission speed. For this experiment, the chamber was loaded with five blocks of absorber, which leads to a Q-factor of around 3000 and a coherence bandwidth of around 10.71 MHz.

Figure 5: The bit error rate for various values of reverberation chamber loading, where different numbers of blocks of RF absorber were added. For unloaded case, the coherence bandwidth of the channel is smaller than the signal bandwidth and the BER was artificially high. Those results are not considered here. The columns represent the use of different advanced transmission schemes: MISO = beam forming; SIMO = receive diversity; MIMO = spatial multiplexing and diversity coding, with and without beam forming.

Table 1: Bit rate versus bandwidth for a BPSK-modulated signal.

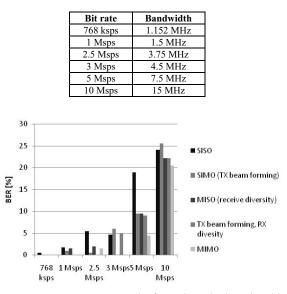| Bit rate	Bandwidth
768 ksps	1.152 MHz
1 Msps	1.5 MHz
2.5 Msps	3.75 MHz
3 Msps	4.5 MHz
5 Msps	7.5 MHz
10 Msps	15 MHz

Figure 6: BER measurement results for various single and multiple antenna systems and various advanced transmission schemes.

In Figure 6, we again see that the use of advanced transmission techniques reduces BER, especially for higher data rates. Note that the highest data rates have correspondingly wide occupied bandwidths. As discussed above, once the coherence bandwidth of the reverberation chamber is exceeded, the BER becomes much higher for all types of transmissions. In spite of this, Figures 5 and 6 demonstrate that the reverberation-chamber-based test environment developed can be used to directly assess various transmission schemes and antenna systems via the metric of BER, independent of any commercial implementation.

V. LIMITATIONS

In real wireless communication systems, Doppler shift occurs due to the movement of the transmitter or receiver. In the reverberation chamber set-up discussed here, Doppler shift is not simulated. Consequently, in the test set-up discussed here, we assume that the wireless channel remains stable during the transmission of one frame. The minimum period the channel has to remain stable can be calculated as

$$\Delta t = \frac{n}{BR}, \qquad (5)$$

where BR is again the data rate, and n is the number of symbols in the transmitted frame. In the experiments described in this paper, data rates up to 10 Mb/s were used. The frame was set to a length of 2048 bits. Therefore, the real transmission channel we are simulating must be assumed to remain stable for at least 200 μs. As mentioned above, use of other set-ups, *e.g.,* [4, 11, 13] can circumvent this limitation in reverberation chambers.

As discussed above, another limitation of the measurement system arises from our use of one receiver. Our test system requires a reflective environment that is repeatable. In the reverberation chamber, we do this by using the same stirrer positions for every receive antenna. Because multiple antennas algorithms are calculated in post processing, forms of real-time correction cannot be tested.

Finally, the system described in this paper does not implement beam forming at the receive antennas. Use of a phased array at the receive site would require remote-controllable phase shifters and a combiner to sum the signals of all receive antennas.

VI. CONCLUSION

We have illustrated methods in which the reverberation chamber can be used to test multiple-antenna systems. Although this system uses only one receiver, many advanced transmission system features can be simulated. The system allows the user to directly compare conventional SISO transmission, diversity reception, beam forming and MIMO, with and without beam forming.

The metric of BER is used to directly measure the link quality of the wireless connection. Different modulation schemes, carrier frequencies, and power levels can be used; therefore, a direct comparison of the performance of an antenna system or processing algorithm in a given reflective environment can be made. The vector signal generators and the vector signal analyzer provide operation from several hundred kilohertz up to 6 GHz. If more than two antennas are necessary, the system can be easily upgraded due to its modular structure. While we studied antenna spacings greater than 0.5 λ here, current NIST research is engaged in the study of spacings in which correlation exists between channels. These narrower spacings represent a more realistic physical arrangement for some portable applications

The system discussed here is intended to help reduce development time and cost for wireless system designers and antenna specialists. New antennas and system configurations can easily and quickly be tested under realistic conditions, enabling easy evaluation of new system designs when real-time feedback is not a priority.

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