Measurements of Multiple-Input Multiple-Output (MIMO) Performance under Army Operational Conditions

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Abstract—This paper presents the results from a field measurement campaign that was conducted to provide an understanding of Multiple-Input Multiple-Output (MIMO) performance relative to that of a Single-Input Single-Output (SISO) system in military-type environments. The Space & Terrestrial Communications Directorate (STCD) MIMO system was used to conduct these experiments. The system has two antennas and operates at transmit frequencies of 430 and 1380MHz, which fall within military frequency bands. A variety of operational environments with many scenarios were considered. The experiments were conducted at C4ISR OTM testing facility, Fort Dix, New Jersey for transmissions along a wide road, a narrow road and through heavy foliage. These experiments measured the throughput gain of MIMO over SISO given the same transmit power and channel usage. The gain in throughput was corroborated by information-theoretic capacity calculations using channel estimates collected during the experimental campaign. In addition, the impact of the antenna spacing on throughput gain was also studied. Depending on the multipath-richness of the environment, the experimental results show that the 2-antenna system provides a throughput of 1.3 to 2.0 times that of a SISO system. On average, a range extension of 1.5 times could be realized for all the considered scenarios and transmit frequencies. The results suggest that antennas in MIMO systems should be placed at least a half of carrier wavelength apart, as indicated in open literature.

Keywords—MIMO, field experiments, military conditions, throughput gain, range extension, antenna separation

I. INTRODUCTION

As the Warfighter increasingly engages enemies in suburban and urban environments, the Warfighter, more than ever, needs a reliable and robust means of communication that overcome the inherent multipath effects and the environmental interference including unintentional, intentional, and self-interference. In addition, the need for a radio that can operate in highly mobile conditions such as those at vehicle and aircraft speeds is necessary for enabling the next generation of mobile communications and the ever-changing mission of the Warfighter in theatre.

In recent years, Multiple-Input Multiple-Output (MIMO) technology [1] has been attractive in wireless communications due to its ability to improve communication performance in rich scattering environments. It offers significant increases in communication throughput, reliability, and range. In contrast with conventional communication systems, which are equipped with a single transmit and receive antenna and thus called Single-Input Single-Output (SISO) systems, MIMO communication systems are equipped with multiple transmit and/or receive antennas. The use of multiple antennas provides means for simultaneous transmissions and spatial redundancy to the transmitted signals that helps to improve the performance of MIMO over SISO. In addition, multiple receive-antenna system can improve the interference mitigation capability, which is very important in military operations. As a result, MIMO technology increasingly becomes a future candidate for the Warfighter communications.

To understand MIMO performance in realistic environments that are relevant to the Warfighter, empirical measurements are needed. However, currently published measurements of MIMO performance have focused on indoor and urban environments and transmit frequencies of 2.4 and 5.0 GHz to support the development of commercial WiFi and WiMAX MIMO technologies [2], [3], [4]. The experiments in this project are thus aimed at understanding MIMO performance in environments of interest to the Army. Specifically, it is to understand how MIMO performs in comparison with SISO. In addition, the impact of antenna separation (AS) on the performance of MIMO was investigated. The antenna separation is defined here as the spacing between adjacent antenna elements of a linear array within a transceiver and measured by a fraction of carrier wavelength (λ).

For the purposes of conducting these experiments, the Space and Terrestrial Communications Directorate (STCD), working with the University of Texas, developed a MIMO Software Defined Radio (SDR) system on the Universal Software Radio Peripheral (USRP) platform [5]. The system has two antennas and is capable of transmitting within a range of frequencies. In this experimental campaign, 430MHz and 1380MHz transmit frequencies, which fall within military frequency bands, were chosen for the MIMO experiments. The experiments were conducted in simulated military environments at Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) On-The-Move (OTM) testing facility, Fort Dix, New Jersey. Various operational environments were considered, including transmissions along a wide road, a narrow road and through heavy foliage.

From the experimental results, several interesting points are worth noting. First, the results clearly show that MIMO outperforms SISO in all considered scenarios. In particular, MIMO achieves throughput gains, defined as a ratio of MIMO throughput over that of SISO, from 1.3 to 2.0 times, depending on the terrain. The more multipath-rich environment results in a higher gain of MIMO over SISO. The gains were achieved with the same total transmit power, channel condition, and spectrum usage of SISO, thereby verifying one of the major advantages of using MIMO over SISO. In addition to the throughput gain, the experimental results also reveal the possibility of using MIMO to achieve communication range extension over SISO given the same transmit power and throughput, thereby demonstrating another advantage of MIMO. For all the considered scenarios and transmit frequencies, a range extension of 1.5 times in average could be realized. The possible range extension and throughput improvement suggest that MIMO can yield large reductions in transmit power for the same spectrum usage and coverage which, depending on transmit/receive duty cycle, could result in significant battery life increases for the dismounted Warfighter. Lastly, the experimental results suggest that MIMO antennas should be placed at least a half wavelength apart, as indicated in open literature.

The rest of this paper is organized as follows. MIMO system and evaluation metrics are introduced in Section II. The experimental setup and results are reported in Section III. A discussion of the experimental results is also presented in this section. Lastly, summary of the main results and some concluding remarks are provided in Section IV.

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II. EXPERIMENTAL SYSTEM AND EVALUATION METRICS

A. STCD MIMO System

The STCD MIMO transceiver system, used for the experiments reported in this paper, is shown in Figure 1. Each transceiver is comprised of a laptop that hosts MIMO software, a USRP, and two antennas. In MIMO mode, both the transmitter and the receiver use two antennas. The antennas used in this experimental campaign were omni-directional antennas. The USRP is able to transmit and receive over a number of carrier frequency ranges by changing its Radio Frequency (RF) daughter-cards that are plugged into its motherboard. RFX400 and RFX1200 daughter-cards [5] were used for transmit frequencies of 430MHz and 1380MHz, respectively. These transmit frequencies fall within military frequency bands.

The MIMO software is based on Hydra [6], [7], the open-source software developed by University of Texas for use with the USRP. The Physical (PHY) layer of the system follows the MIMO-OFDM-based IEEE 802.11n standard [8]. The standard supports systems with four antennas and 20MHz bandwidth. Although USRP supports 20MHz bandwidth transmissions, the bandwidth limitation of the Universal Serial Bus (USB) interface between the USRP and the laptop constrains the STCD MIMO system to operate at only one MHz bandwidth. With two antennas, the STCD MIMO system supports sixteen modulation-coding schemes (MCS’s) that are comprised of different combinations of coding rates, modulation techniques, and varying numbers of data streams. These MCS’s are capable of providing data rates from 0.325 to 6.5 Mbps, as shown in Table 1.

The system is also capable of operating in SISO mode, where only one antenna per transceiver is used. In this mode, the system supports the first eight of the sixteen MCS’s in Table 1. These eight MCS’s are capable of supporting data rates from 0.325 to 3.25 Mbps. The maximum transmit power of the STCD MIMO system is 100mW (20dBm).

Table 1 - Data rate corresponding to MCS’s in the STCD MIMO system

<table>
<thead>
<tr>
<th>MCS</th>
<th>Number of Data Streams</th>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>BPSK</td>
<td>1/2</td>
<td>0.325</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>QPSK</td>
<td>1/2</td>
<td>0.650</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>QPSK</td>
<td>3/4</td>
<td>0.965</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>16-QAM</td>
<td>1/2</td>
<td>1.300</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>16-QAM</td>
<td>3/4</td>
<td>1.930</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>64-QAM</td>
<td>2/3</td>
<td>2.600</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>64-QAM</td>
<td>3/4</td>
<td>2.925</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>64-QAM</td>
<td>5/6</td>
<td>3.250</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>BPSK</td>
<td>1/2</td>
<td>0.650</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>QPSK</td>
<td>1/2</td>
<td>1.300</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>QPSK</td>
<td>3/4</td>
<td>1.930</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>16-QAM</td>
<td>1/2</td>
<td>2.600</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>16-QAM</td>
<td>3/4</td>
<td>3.900</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>64-QAM</td>
<td>2/3</td>
<td>5.200</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>64-QAM</td>
<td>3/4</td>
<td>5.850</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>64-QAM</td>
<td>5/6</td>
<td>6.500</td>
</tr>
</tbody>
</table>

B. Evaluation Metrics

To evaluate MIMO performance, a number of metrics were utilized. Below is a description of these performance metrics.

1) Throughput Gain: A throughput gain is a ratio of MIMO throughput over SISO throughput given the same total transmit power, spectrum usage, and channel condition. This metric was used to compare the throughput differences of MIMO versus SISO in such conditions. A throughput gain

\[ TPG = \frac{TP_{\text{MIMO}}}{TP_{\text{SISO}}} \]

where \( TP_{\text{MIMO}} \) and \( TP_{\text{SISO}} \) are the MIMO and SISO throughputs, respectively, which are computed based on the collected Packet Error Rate (PER) and the data rate (DataRate) associated with the transmission as

\[ TP = (1 - \text{PER}) \times \text{DataRate} \]

The PER was collected as follows. For a particular data rate, a large number of packets were transmitted, and the success or failure of the packet detection at the receiver was determined by a Cyclic Redundancy Check (CRC). The PER was a ratio of the number of successfully detected packets over the number of transmitted packets.

2) Capacity Gain: Like the throughput gain, a capacity gain is measured as a ratio of MIMO capacity over SISO capacity given the same transmit power, spectrum usage, and channel condition. Capacity of a system is an upper bound on the amount of information that is reliably transmitted through the communication channel. In this work, it is computed from the estimated channel coefficients, which were obtained for each packet transmission. The calculation of the capacity at each transmitter-receiver (Tx-Rx) location pair follows.

Let \( H(f,p) \) and \( h(f,p) \) be the normalized MIMO channel matrix and SISO channel coefficient at the \( f \)th sub-carrier of the \( p \)th packet for \( f = 1, 2, \ldots, N_f \) and \( p = 1, 2, \ldots, N_p \). The normalization is done on the estimated channel matrices and coefficients, which includes the gains and losses in the transmit and receive chains in addition to the actual propagation path loss. Let \( \lambda_1 \) and \( \lambda_2 \) be the eigenvalues of the matrix \( H(f,p)H(f,p)^H \), where \( H \) denotes the conjugate transpose of a matrix. Then, the MIMO and SISO capacities corresponding to the \( f \)th subcarrier and \( p \)th packet are

\[
C_{\text{MIMO}}(f, p) = \log_2 \left( 1 + \frac{\rho_{\text{MIMO}} \lambda_1^2}{2} \right) + \log_2 \left( 1 + \frac{\rho_{\text{MIMO}} \lambda_2^2}{2} \right)
\]

and

\[
C_{\text{SISO}}(f, p) = \log_2 \left( 1 + \rho_{\text{SISO}} h(f, p)^2 \right),
\]

respectively, where \( \rho_{\text{MIMO}} \) and \( \rho_{\text{SISO}} \) are the average Signal-to-Noise Ratio (SNR) values for MIMO and SISO cases, respectively. They are obtained by averaging the SNR values over all packets at the considered location. The dMIMO and SISO capacities at the location are then computed as

\[
C = \frac{1}{N_f N_p} \sum_{f=1}^{N_f} \sum_{p=1}^{N_p} C(f, p),
\]

where \( C(f, p) \) is as calculated in (2) or (3) for MIMO or SISO, respectively.

In this experimental campaign, the channel estimate was taken at several locations for each considered scenario. To obtain a capacity for a point between two measured locations, a linear interpolation for the average SNR at the intermediate location is performed. The capacity for the intermediate location is then calculated as before using the interpolated SNR value. Thus the data of capacity versus range are achieved for the intermediate locations. Based on the measured channel data, plots of capacity gain versus range and range extension versus capacity are provided in Section III.

3) Range Extension: Range extension is a ratio of the transmission range achieved by MIMO over that of SISO given the same capacity and total transmit power. In these experiments, range gain was not measured but calculated based on the computed capacities, as described above.

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III. EXPERIMENTAL SETUP, RESULTS, AND DISCUSSION

A. Experimental Setup

The first objective of the experiments was to determine if a throughput gain would be realized from running the system in MIMO mode versus SISO mode given the same transmit power for both. The second objective was to investigate the impact of antenna separations on MIMO performance. An antenna separation, usually measured in terms of the carrier wavelength (λ), is the space between the two antennas on a given transceiver and is not to be confused with the distance between the transmitter and the receiver. Military transmit frequencies of 430MHz and 1380MHz were used with wavelengths of 70 and 22 centimeters, respectively. A total transmit power of 63mW (18dBm) was set for both SISO and MIMO modes and kept the same for different Tx-Rx location pairs. In MIMO mode, the transmit power was divided equally between the two transmit antennas, each outputting a power of 31.5mW (15dBm).

In MIMO mode, the throughput gain was proportional to the number of antennas available. In addition, the two RF receive components in MIMO system employed. The MIMO experiments were conducted at the TAC11 area of the C4ISR OTM testing facility at Fort Dix, New Jersey. Three different RF transmission environments were represented by each of the three test scenarios. The scenarios included transmission along a wide road, transmission along a narrow road, and transmission through heavy foliage. In each scenario, the transmitter location was fixed while the receiver location was varied. At each receiver location, the system was first set to run in SISO mode. The transmitter cycled through one thousand packet transmissions for each of the first eight MCS’s listed in Table 1, and the maximum throughput resulting from one of the eight MCS’s was recorded as the SISO throughput at that location. The system was then set to run in MIMO mode. The transmitter cycled through a thousand packet transmissions for all sixteen MCS’s from Table 1, and the maximum throughput obtained from one of those sixteen MCS’s was recorded as the MIMO throughput. The MIMO transmissions were repeated for each antenna separation, and the throughput gains, defined in Section II, were computed.

Each packet transmission includes a preamble and a data payload following the framework of the IEEE 802.11n standard [8]. One of the purposes of the preamble is to estimate the channel coefficients, which are then used to detect the data in the payload. In this experimental campaign, the estimated channel coefficients were also collected and used to compute the capacity gain defined in Section II.

B. Experiments at 430MHz Transmit Frequency

Table 2 - Throughput gain with 430 MHz transmit frequency. A, B, B, D, and E denote the receiver location indices. AG: Average Gain for each AS, OMG: Overall Measured Gain (based on the measured throughputs), and OCG: Overall Calculated Gain (based on the calculated capacities).

<table>
<thead>
<tr>
<th>Receiver Locations</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>AG</th>
<th>OMG</th>
<th>OCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide Road Scenario</td>
<td>λ/2 AS</td>
<td>1.3</td>
<td>1.4</td>
<td>1.1</td>
<td>-</td>
<td>-</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>3λ/2 AS</td>
<td>1.3</td>
<td>1.2</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>1.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2λ AS</td>
<td>1.3</td>
<td>1.1</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>1.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Narrow Road Scenario</td>
<td>λ/4 AS</td>
<td>2.6</td>
<td>1.1</td>
<td>0.4</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>3λ/4 AS</td>
<td>2.2</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.5</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>λ AS</td>
<td>2.6</td>
<td>2.1</td>
<td>1.4</td>
<td>1.0</td>
<td>0.6</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heavy Foliage Scenario</td>
<td>λ/4 AS</td>
<td>2.5</td>
<td>2.0</td>
<td>1.8</td>
<td>1.4</td>
<td>-</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>3λ/4 AS</td>
<td>2.5</td>
<td>2.6</td>
<td>2.2</td>
<td>1.3</td>
<td>-</td>
<td>2.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>λ AS</td>
<td>2.5</td>
<td>2.2</td>
<td>2.5</td>
<td>1.4</td>
<td>-</td>
<td>1.9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2 presents the measured throughput gains and the calculated capacity gains of MIMO over SISO for transmit frequency of 430MHz. In the following, the experiments at 430MHz will be described in detail.

1) Wide-Road Scenario: Figure 2 shows the transmitter and receiver locations for the wide-road scenario. The transmitter-receiver (Tx-Rx) distances for these locations were 190, 360, and 500 meters. In this scenario, four antenna separations of 35, 70, 105, and 140 centimeters, corresponding to 1/2, 1, 3/2, and 2 wavelengths, were considered. The throughput gain of MIMO over SISO for these antenna separations is presented in Table 2. From the table, it is seen that MIMO at locations A and B outperformed SISO in terms of throughput for all antenna separations, as expected. This is mainly due to the use of multiple antennas to collect more RF energy in strong LOS environments, resulting in the power gain to improve the performance [9]. The throughput gain at location C, however, was about 1. Overall, a throughput gain of 1.3 was realized in this scenario.

The degradation in MIMO performance at C, which is also common at receiver locations that were far away from the transmitters in later scenarios, is possibly due to the power mismatch, frequency mismatch, and timing mismatch from the multiple transmit and receive components in MIMO system employed. The MIMO system contains two RF transmit cards, each with its own independent local oscillator. These transmit cards generate two transmit frequencies slightly different from one another and at slightly different transmit powers. In addition, the two RF receive cards do not have the same receiver sensitivity. As a result, the mismatches cause errors in MIMO symbol detection. Note that the same transmit power was used in these experiments. When the receiver is close to the transmitter, high received SNR overcomes the mismatch errors and yields a better MIMO performance over SISO, as expected. On the other hand, the received SNR drops when the receiver is placed far away from the transmitter. The mismatch errors in this case become dominant and degrade MIMO performance at these locations.

Figure 2 - Wide-Road Scenario with 430MHz Transmit Frequency – Transmitter and Receiver Locations

Figure 3 - Wide-Road Scenario with 430MHz Transmit Frequency – Capacity Gain (a) and Range Extension (b)

From Table 2, it can be seen that MIMO performance did not vary greatly for the different antenna separations considered. The average throughput gain over SISO for the three closest antenna separations is 1.3, while the gain for 2λ antenna separation is 1.1 times. In strong LOS environments, antennas within a transceiver should be placed as far as possible to provide independent paths to...
improve MIMO throughput through spatial multiplexing [9]. Clearly from the results, 2λ antenna separation is not enough to achieve such improvement. The throughput improvement of MIMO over SISO here was mainly due to the power gain when using multiple antennas [9].

Figure 3 presents the capacity gains achieved by using MIMO over SISO. Note that the capacity gains were computed based on the channel estimate acquired for packet transmissions. The figure clearly confirms the superior performance using MIMO over SISO reported in Table 2 for this scenario. Overall, a capacity gain of 1.3 times was achieved for this scenario, which agrees with the gain in throughput. It also shows that the gain decreases as the range increases. This behavior is possibly due to the component mismatches, as explained above.

The figure also shows the potential range extension using MIMO over SISO for the same capacity and transmit power for both. Overall, a range extension of 1.4 times was achieved.

2) Narrow-Road Scenario: In this scenario, the impact on throughput gain due to multipath scattering from trees along a narrow road was investigated. Both line-of-sight (LOS) and non-LOS (NLOS) propagation components were present in this scenario. LOS component was present at Locations A and B while Locations C, D, and E were under NLOS transmission due to the slight curve on the road, as seen in Figure 4 (between Locations B and C). The Tx-Rx distances for these locations were 40, 144, 223, 336, and 400 meters. Compared to the wide-road scenario, given that the two scenarios shared the same transmit power of 18dBm, the transmission range in narrow-road scenario was shorter due to the increase in the attenuation. In this scenario, four antenna separations of 17.5, 35, 52.5, and 70 centimeters, corresponding to 1/4, 1/2, 3/4, and 1 wavelength, were considered.

The throughput gain for MIMO over SISO is presented in Table 2. From the table, MIMO transmissions achieved higher throughput in comparison with SISO transmissions for most of the receiver locations and the antenna separations. Compared to the gain of 1.3 times from the wide-road scenario, narrow-road condition provided a slightly higher overall gain of 1.4 times. This is not expected since the increase in multipath due to the trees along the narrow-road as compared to the wide-road scenario should provide much gain to MIMO. As shown in Table 2 and Figure 5(a), the gain reduction was due to the bad performance of the λ/4 antenna separation at far away receiver locations. All other antenna separations provided high gains for MIMO over SISO. This suggests that in narrow-road operational conditions, antennas for MIMO systems should be placed at least a half wavelength apart to achieve a good performance gain over SISO systems.

Figure 5 presents the capacity gain of MIMO over SISO for different antenna separations. Overall, a capacity gain of 1.4 times was achieved. This agrees with the overall throughput gain in Table 2. The figure also shows a gain reduction as the range increased. This is possibly due to the component mismatches as discussed in Section III.B.1). Figure 5 also shows the potential range extension using MIMO over SISO in narrow-road scenario. Overall, a range extension of 1.7 times was achieved.

3) Heavy Foliage Scenario: In this scenario, throughputs of MIMO and SISO transmissions through heavy foliage were compared. Since there was no LOS component for these transmissions, this scenario represents the most difficult of the three environments for RF propagation. Figure 6 shows the transmitter and receiver locations with the distances of 58, 75, 97, and 120 meters. Compared among the three scenarios, given the same transmit power of 18dBm, the transmission range in this scenario was shortest due to the greatest attenuation. The experimental results in this operational terrain are presented in Table 2, which shows substantial throughput gains of MIMO over SISO for all the considered antenna separations. Overall, a throughput gain was 2.0 times greater for MIMO over SISO, the best among the three considered scenarios. These results clearly show the advantage of MIMO over SISO in an NLOS environment where multipath is consequential.

![Transmitter and Receiver Locations](Image)

Figure 6 – Heavy-Foliage Scenario with 430MHz Transmit Frequency – Transmitter and Receiver Locations

![Capacity Gain vs Range](Image)

Figure 7 – Heavy-Foliage Scenario with 430MHz Transmit Frequency – Capacity Gain (a) and Range Extension (b)

Figure 7 shows the capacity gain of MIMO over SISO for heavy-foliage scenario. Among the considered antenna separations, λ/2 AS provided the best gain, stable throughout the ranges. Antenna separations of λ/4 yielded a better gain than 3λ/4 and λ antenna separations. This implies that MIMO antennas can be placed as close as a quarter of wavelength apart without much degradation to the capacity gain. Note that a similar finding was reported in [10] for urban environments. In addition, the figure shows that large antenna separations are not needed to obtain performance gains of MIMO over SISO for environments with sufficient scattering. Overall, a capacity gain of 1.6 times was achieved, which is much lower than the overall throughput gain reported in Table 2. The reduction in the overall capacity gain is due to the bad performance of the 3λ/4 antenna separation. The figure also shows the potential range extension of using MIMO over SISO for the same total transmit power and required capacity. Overall, a range extension of 1.55 times was realized.
C. Experiments at 1380MHz Transmit Frequency

Table 3: Throughput gain with 1380 MHz transmit frequency. A, B, C, D, and E denote the receiver location indices. AG: Average Gain for each AS, OMG: Overall Measured Gain (based on the measured throughputs), and OCG: Overall Calculated Gain (based on the calculated capacities).

<table>
<thead>
<tr>
<th>Receiver Locations</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>AG</th>
<th>OMG</th>
<th>OCG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide Road Scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.3</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>3/2 AS</td>
<td>1.1</td>
<td>1.6</td>
<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/4 AS</td>
<td>1.2</td>
<td>1.8</td>
<td>1.3</td>
<td>1.4</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 AS</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/2 AS</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
<td>1.5</td>
<td>1.0</td>
<td></td>
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<td>Narrow Road Scenario</td>
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<td>Heavy Foliage</td>
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In these experiments, the same scenarios and experimental procedure used for the 430 MHz transmit frequency were repeated at 1380 MHz. Table 3 presents the throughput gains and the capacity gains of MIMO over SISO for 1380 MHz transmit frequency.

1) Wide-Road Scenario: Figure 8 shows the transmitter and receiver locations for the wide-road scenario with the Tx-Rx distances of 23, 44, 83, 110, 250 meters. Four antenna separations of 11, 22, 33, and 44 centimeters, corresponding to 1/2, 1, 3/2, and 2 wavelengths, were considered in this scenario. Throughput gains of MIMO over SISO for these antenna separations are presented in Table 3. From the table, MIMO mode outperformed SISO mode for most of the locations with an overall throughput gain of 1.3 times.

![Figure 8 - Wide-Road Scenario with 1380MHz Transmit Frequency – Transmitter and Receiver Locations](image)

Figure 8 - Wide-Road Scenario with 1380MHz Transmit Frequency – Transmitter and Receiver Locations

![Figure 9 - Wide-Road Scenario with 1380MHz Transmit Frequency – Capacity Gain (a) and Range Extension (b)](image)

Figure 9 - Wide-Road Scenario with 1380MHz Transmit Frequency – Capacity Gain (a) and Range Extension (b)

Table 3 also shows that MIMO performance did not vary much for the considered antenna separations. As a result, the antenna separation of a half of wavelength would be sufficient for MIMO in wide-road operations. Notice that similar conclusion was observed for 430MHz transmit frequency.

The MIMO throughput data observed in the field agrees with the computed capacity gain presented in Figure 9. All the considered antenna separations resulted in MIMO gains over SISO, and an overall gain of about 1.4 times was achieved. Notice that the gain reduced as the receiver moved further away from the transmitter. The reduction was possibly caused by the component mismatches discussed in Section III.B.1. Figure 9 also presents the potential range extension using MIMO over SISO with the same transmit power for both. Overall, a range extension of 1.6 times was realized.

2) Narrow-Road Scenario: In this scenario, the impact of trees along a road on MIMO performance is studied for a transmit frequency of 1380MHz. Figure 10 shows the transmitter and the receiver locations with the Tx-Rx distances of 27, 59, 85, and 120 meters. Note that the receiver was in LOS with the transmitter for all the considered locations. Three antenna separations of 11, 16.5, and 22 centimeters, corresponding with 1/2, 5/4, and 1 wavelength, were considered. From the table, MIMO provided throughput improvement over SISO for 1380MHz with the overall gain of slight higher than 1.3 times, which is not much improvement over the wide-road scenario. The reason for there not being much gain in this scenario is probably due to the presence of a strong LOS component.

![Figure 10 - Narrow-Road Scenario with 1380MHz Transmit Frequency – Transmitter and Receiver Locations](image)

Figure 10 - Narrow-Road Scenario with 1380MHz Transmit Frequency – Transmitter and Receiver Locations

![Figure 11 - Narrow-Road Scenario with 1380MHz Transmit Frequency – Capacity Gain (a) and Range Extension (b)](image)

Figure 11 - Narrow-Road Scenario with 1380MHz Transmit Frequency – Capacity Gain (a) and Range Extension (b)

3) Heavy Foliage Scenario: The heavy-foliage environment was the most challenging environment considered in this experimental campaign. The transmitter and receiver locations are shown in Figure 12 with the Tx-Rx distances of 34, 45, 54, and 65 meters. The throughput gains for MIMO and SISO modes are presented in Table 3. The gain for location D is not reported because the throughput of SISO mode was essentially zero while MIMO mode yielded 0.3, 0.9, and 1.2 Mbps for the considered antenna separation. From the table, similar performance improvement that was seen in this environment for the 430MHz transmit frequency was realized. Overall, a throughput gain of 1.8 times was achieved when considering all the locations and antenna separations. This gain is in agreement with the overall capacity gain shown in Figure 13.

Table 3 also shows that a 1/2 antenna separation provided the best throughput gains for MIMO, and that is in agreement with the capacity gain shown in Figure 13. In substantial multipath-rich environments with no LOS components, large antenna separations do not provide additional gain. Note that this also agrees with the finding in 430MHz transmit frequency.
The throughput gain by MIMO over SISO given the same total transmit power and channel condition can be used to extend the transmission range. Although the experiments were not set up to directly measure the range extension using MIMO over SISO, calculations of capacity versus range show that a 1.5-time improvement in range was possible for 2x2 MIMO systems in all the considered scenarios and transmit frequencies.

The throughput gain of MIMO over SISO can also be used to achieve transmit power savings for a given throughput and channel condition for both modes. As shown in [11, 14], a 4x4 MIMO system required 10 times less transmit power over SISO to provide a comparable throughput. The transmit power saving in turn can help extending the battery life in the tactical environment and consequently be of great benefit to the dismounted Warfighter.

The experimental results shown in Tables 2 and 3 suggest possible antenna separations for MIMO systems at 430 and 1380MHz. It is well-known in literature that antennas in MIMO systems should be separated by a half of wavelength. However, several previous works show that antenna separation can be smaller [10], [12]. The experiments with the STCD MIMO system showed possible throughput gains for antenna separations of a quarter of wavelength. However, the results show that the antennas should be placed at least a half wavelength apart to achieve good throughput gains.

Lastly, the experimental results show a reduction in throughput gain at receiver locations that were far away from the transmitter. The performance degradation could possibly be due to the component mismatches on MIMO system due to the use of multiple RF transmit and receive cards. The mismatches may include transmit power, transmit frequency, receiver sensitivity, and possible timing synchronization. The mismatch errors become dominant at locations with low SNR and degrade MIMO performance. This suggests that in developing MIMO systems, mechanisms to eliminate such mismatches should be strongly encouraged.

6. Conclusion

Field experiments on MIMO communications were conducted to provide the understanding of MIMO performance over SISO in simulated military environments at C4ISR OTM test facility, Fort Dix, New Jersey. Various operational environments with many scenarios were considered with MIMO systems operating at 430MHz and 1380MHz. The experimental results reveal that MIMO systems can provide good throughput gain over SISO given the same transmit power, channel condition, and spectrum usage. More multipath-rich operating environments result in higher gains of MIMO over SISO. The results also show the possibility of using MIMO for range extension and transmit power savings. In addition, antennas in MIMO systems should be placed at least a half wavelength apart to realize throughput and power savings gains, as revealed in the experiments. Lastly, mechanisms to eliminate component mismatches are strongly encouraged to realize the full potential of MIMO gains over SISO.

REFERENCES