Article
Compact MIMO System Performances in Metallic Enclosures

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Abstract: In this work, we present a 2 × 2 near-field multi-input multiple-output (MIMO) prototype for bit-error-rate (BER) and error vector magnitude (EVM) measurements in a metal enclosure. The near-field MIMO prototype was developed using software-defined-radios (SDRs) for over-the-air transmission of QPSK modulated baseband waveforms. We checked the near-field MIMO BER and EVM measurements in three different scenarios in a highly reflecting metal enclosure environment. In the first scenario, the line-of-sight (LOS) communication link was investigated when the mode stirrer was stationary. In the stationary channel conditions, near-field MIMO BER and EVM measurements are performed. In the second scenario, BER and EVM measurements were performed in dynamic channel conditions when the mode stirrer was set to move continuously. In the third scenario, LOS communication near-field MIMO BER and EVM measurements were performed in stationary channel conditions but now in the presence of MIMO interference. In three different scenarios, near-field MIMO BER and EVM measurements were investigated at different Tx USRP gain values and in the presence of varying levels of MIMO interference.

Keywords: software-defined-radio; USRP; near-field; rich scattering; BER measurement; EVM measurement

1. Introduction

Wireless communication system deployment in highly reflective and complex propagation environments, such as in a metal enclosure or a compact box environment, is extremely challenging [1,2]. Near-field MIMO for high-data-rate communication is important for applications, such as wireless chip-to-chip communications and wireless network-on-chip (WNoC) [2–7]. Traditionally, near-field communication was used for short-range, low-rate, and power-constraint applications using magnetically coupled loop antennas [8]. Near-field magnetic induction (NFMI) communication also uses magnetically coupled loop antennas for data transfer [9]. However, such near-field communication systems operate in media with high permittivities, such as underground [10,11], biological masses [12], and underwater environments [13,14]. Near-field communications in such environments are sensitive to alignment errors and offer limited data rates. This scenario represents a complex propagation environment where, in addition to LOS, there exists rich scattering as well as forward propagation through materials with high permittivity. Near-field MIMO digital communication system designs in such environments are considerably challenging and expose the benefits of MIMO signal processing [15]. There are channel modeling and characterization efforts for applications, such as wireless chip-to-chip communications; however, end-to-end near-field MIMO BER performances have not been demonstrated. Rx power measurements in near-field and path-loss measurements are rare in the literature. There is a significant gap in the assessment of the effects of near-field coupling on the performances of wireless communication systems. We checked the performance of a near-field MIMO communication system (in terms of EVM and BER measurements) in various scenarios in a stirred metal enclosure environment. The near-field MIMO communication scenarios in the presence of rich scattering may arise in different applications, such as the industry environment, animal cages [16], ICT equipment [17], kiosks [18], computer chassis [19], metal cabinets [20], and...
wireless inter-board communication [21,22]. We previously presented over-the-air (OTA) testing of a QPSK receiver for the performance of baseband receiver design stages and the measurements were performed in a metal enclosure with all baseband receiver design stages [2]. In [1], we conducted near-field EVM measurements in a metal enclosure using a single transmit and a single receive antenna. We transmitted non-high throughput (non-HT) IEEE 802.11a OFDM packets for all modulation and coding techniques (MCS0-MCS7) in metal enclosures in different loading conditions. The measurements were performed with a single-channel full-duplex PlutoSDR from Analog Devices. In contrast, this work used two channels and a high-performance full-duplex X310 USRP from Ettus Research for EVM and end-to-end BER measurements in the metal enclosure in different channel conditions. Based on the application requirements X310 USRP can be interfaced with different RF cards, such as WBX and UBX-160. We used two UBX-160 per X310 USRP, which can offer an effective bandwidth of 160 MHz. We organized our paper into five sections. Section 1 highlights the near-field measurements in the metal enclosure. Section 2 discusses the X310 USRP-based $2 \times 2$ near-field MIMO measurement prototype and the experimental setup, including the USRPs, metal enclosure, type of antennas, and mode stirrer. Section 3 discusses the measurement process, the important prototype development steps, and the measurement stages. Section 4 presents the experimental results of four different metal enclosure scenarios. It contains a detailed discussion about the near-field MIMO BER and EVM measurements and presents two-channel measurement data. Section 5 concludes the study and presents future extensions of the prototype and recommendations for near-field measurement scenarios.

2. Measurement Setup

The measurement setup consists of two X310 USRPs, four wideband antennas, a mode stirrer, and a high-performance Intel Xeon PC with P400-quadro NVIDIA GPU. We used a brass metal enclosure with dimensions of $h \times \ell \times w$ of $45 \text{ cm} \times 37 \text{ cm} \times 55 \text{ cm}$. The metal enclosure is a perfectly reflecting environment; when excited at $5.6 \text{ GHz}$, it produces a rich multipath-fading environment. Near-field MIMO BER and EVM measurements were performed using wideband antennas at a frequency of $5.6 \text{ GHz}$ in the metal enclosure. The distance between the transmitter and receiver $D$ was kept fixed at $50 \text{ mm}$, and the distances between the transmit antenna elements $d_t$ and receive antenna elements $d_r$ were also kept fixed at $d_t = d_r = 45 \text{ mm}$ for all RF measurements. The overall MIMO measurement setups for the near-field BER and EVM measurements are shown in Figure 1, where the vertically polarized ultra-wideband (UWB) transmit and receive antennas were mounted on the metal lid of the enclosure, such that Tx and Rx antennas faced each other. This scenario depicts a confined propagation environment where Tx and Rx were deployed in the near-field, expecting direct coupling as well as rich scattering introduced by a metal enclosure. Tx and Rx UWB antennas were connected to Tx and Rx X310 USRPs. The data transfer between the host PC and the USRPs took place over a 1 gigabit Ethernet cable. Real-time streaming of the IQ data was important for EVM and end-to-end BER performance; we checked the effect of the channel in configuration. The presence of any dropped samples, i.e., overflows at the receiver, introduces inconsistent and intractable performances. In our measurements, we did not observe any underflow and overflow when the Tx and Rx ports were configured to transfer IQ data to the host PC at sampling rates of 400 ksp. Therefore, the two-channel EVM and BER values were functions of hardware impairments and the channel conditions in the enclosure.

Figure 1 shows the overall measurement setup, which consisted of two host PCs, two USRPs, OctoClock-G, metal enclosure, and ultra-wideband antennas.
Figure 1. Overall USRP-based 2 × 2 near-field MIMO measurement setup for BER and EVM measurements.

Figure 2 shows an internal view of the metal enclosure, including a stirrer and UWB antennas attached to the metal enclosure lid. It also shows the front view, side view, and top view of the broadband MIMO antenna configurations. Holes in the metal panel (other than what were used for different Tx and Rx inter-element spacings created for convenience) were covered with metal tape for RF shielding so that the measurements were not affected by external RF signals. BER measurements were performed using the QPSK receiver implemented in Simulink. Before running the model, the USRPs were frequency calibrated. The frequency offset of 17.19 Hz was found using the frequency calibration transmitter and receiver baseband models, which are tractable by the coarse frequency compensation block in the baseband receiver. The transmit baseband models were composed of frame generations, which contained the upsampled Barker-13 code as the frame header plus payload corresponding to the ASCII equivalent of ‘Hello World###’, where ### is the repeating sequence from 001 to 099. The generated frames were QPSK-modulated with Gray mapping. The QPSK-modulated symbols were upsampled by the transmit raise cosine filter producing a baseband rate of 400 ksps at the transmitter. The transmit USRP sample rate should match the baseband sampling rate by setting the DAC clock rate of 200 MHz with an interpolation factor of 500 or the DAC clock rate of 20 MHz and an interpolation factor of 100. In a nutshell, the USRP sampling rate was selected as:

\[
\text{Sampling Rate} = \frac{\text{DAC(ADC) Clock Rate}}{\text{Interpolation (Decimation)}}
\]

Over-the-air transmitted QPSK waveforms were received by the Rx USRP with a sample rate of 400 ksps for the baseband processing that took place in the MATLAB session. The baseband QPSK receiver was composed of different stages for BER measurements and information recovery. The baseband receiver stages were AGC, coarse-frequency compensation stage, fine-frequency compensation stage, timing recovery, frame synchronization, phase ambiguity resolution, and data recovery stage. We measured the EVM after the fine frequency stage where the received signal compensated for the negative or positive frequency offsets. The BER measurement is a critical key performance indicator (KPI) for a complete end-to-end system performance. The QPSK baseband transmitter and receiver Simulink models were configured for EVM and BER conditions in a MATLAB script. The Tx gain of the USRP changed after the current iterations of the BER and EVM measurements.
were finished. The BER and EVM measurements were stored in a database for further offline processing and statistical analysis.

![Image of MIMO antennas and cavity](image)

**Figure 2.** The $2 \times 2$ MIMO BER and EVM measurement setup inside the cavity (a) MIMO antennas and an inside view of the cavity, (b) front view of the antennas, (c) side view of the antennas, (d) top view of the antennas.


We used transmitter and receiver baseband models with the QPSK modulation for over-the-air transmission. After the Tx and Rx USRPs were initialized and configured in the MIMO mode, the Tx and Rx QPSK baseband models were also configured to operate in MIMO communications. The baseband transmitter generated two-column QPSK modulated waveforms that were passed to X310 USRP for the over-the-air transmission in the metal enclosure. Two-column QPSK modulated waveforms represent each channel of the USRP. Digital samples from the host PC to USRP for upconversion and transmission were transferred using a 1 Gig Ethernet cable. Another X310 USRP captured the received signals, which were digitally down-converted and passed to the host PC for baseband processing and two-channel BER and EVM measurements. Measurements were conditioned only to proceed when there were no underruns or overruns, respectively. Underruns and overruns affect the reliability of KPI measurements, particularly two-channel BER measurements. Underruns and overruns depend on the base sampling rates of the USRP, waveform design, speed of the cable connecting USRP, host PC, simulation time, and data-logging techniques in baseband software. X310 USRP can offer higher sampling rates to stream the data to and from the host PC, but in most of the cases, sample rates are limited by the speed of the Ether-
net cable or the general purpose processors, and are not configured to handle the maximum sampling rates of the USRPs. The Simulink Tx and Rx baseband models were configured to stop in case any single underrun and/or overrun event occurred. The USRP Tx gain was configured in Simulink and programmatically controlled so that two-channel near-field MIMO BER and EVM measurements were performed without lifting the metal lid off and creating any possibility of changing the EM environment and propagation conditions. The propagation environment could be changed after the BER and EVM measurements are performed. The flowchart of the measurement process is shown in Figure 3, which shows the critical design and measurement steps.

![Flowchart of MIMO BER and EVM measurements.](Figure 3)
4. Experimental Results and Discussions

In this section, we present near-field MIMO BER and EVM measurement results in different scenarios. Measurements were performed in an empty enclosure in the presence of a static mode stirrer and the near-field MIMO BER and EVM results are presented from when the mode stirrer moved continuously. In the third scenario, we present near-field MIMO BER and EVM measurements in the presence of MIMO interference. MIMO interference is continuously generated using B210 USRP at sampling rates of 400 ksps. Baseband interference signals were generated in the GNU Radio and passed to B210 USRP for the repeated transmission.

4.1. Near-Field MIMO BER and EVM in Empty Enclosure

In this scenario, a $2 \times 2$ MIMO setup was investigated for BER and EVM measurements in stationary channel conditions. This scenario has direct coupling and rich scattering. Table 1 shows the BER and EVM measurements of two USRP channels at a frequency of 5.6 GHz and AGC gain of 60. It can be seen that the BER and EVM of two USRP channels improved as the TX gain of the USRP increased.

Table 1. The $2 \times 2$ near-field MIMO BER and EVM measurements in the metal enclosure. Maximum power gain of AGC was set to 60 and the RF frequency was 5.6 GHz.

<table>
<thead>
<tr>
<th>Tx Gain (dB)</th>
<th>Channel 1</th>
<th>Channel 2</th>
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<tbody>
<tr>
<td></td>
<td>Prx (dB)</td>
<td>EVM (%)</td>
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<tr>
<td>2</td>
<td>-71</td>
<td>87</td>
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<tr>
<td>4</td>
<td>-69</td>
<td>84</td>
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<tr>
<td>6</td>
<td>-67</td>
<td>79</td>
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<tr>
<td>8</td>
<td>-61</td>
<td>58</td>
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Table 2 shows the BER and EVM measurements of two USRP channels at a frequency of 5.6 GHz and AGC gain of 80. It can be seen that the BER and EVM of the two USRP channels improved as the TX gain of the USRP increased. A noticeable difference in the measured BER and EVM values can be observed for the AGC gains of 60 and 80, respectively. For both cases, BER and EVM values improved; however, the BER values decreased faster for the AGC gain value of 80. This is because of the extra increase in the AGC gain.

Table 2. The $2 \times 2$ near-field MIMO BER and EVM measurements in the metal enclosure. A maximum power gain of AGC was set to 80 and the RF frequency was 5.6 GHz.

<table>
<thead>
<tr>
<th>Tx Gain (dB)</th>
<th>Channel 1</th>
<th>Channel 2</th>
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<tbody>
<tr>
<td></td>
<td>Prx (dB)</td>
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<tr>
<td>2</td>
<td>-67</td>
<td>22</td>
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<tr>
<td>4</td>
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<tr>
<td>6</td>
<td>-63</td>
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The measured QPSK constellations shown in this work were recorded after the carrier frequency synchronization. The QPSK constellation diagram was recorded after the carrier synchronizations for different TX gain values of the USRPs. It can be seen that USRP channel 2 is better than USRP channel 1. Additionally, the two USRP channel QPSK constellation diagrams improved as the TX gain of the USRP increased, which corresponds to improved BER and EVM measurements.

Similar to the theoretical predictions and previous measurements, the two USRP channel QPSK constellation diagrams improved as the TX gain of the USRP increased,
which corresponds to improved BER and EVM measurements. The measurements were performed at stationary channel conditions when the mode stirrer was off. The mode-stirrer rotation has direct implications on the measured BER and EVM values because when the mode stirrer rotates, the channel becomes non-stationary. The channel power gain of the MIMO communication link varied drastically; as a result, AGC the receiver tried to compensate for low and high gain values to stabilize the received signal for carrier frequency offset correction. Hence, the EVM measurements of two USRP channels were not stationary because of the time-varying channel power gain and time-varying frequency offset. The same measurements were repeated when the mode stirrer was turned on. In the presence of the mode-stirrer rotation, the MIMO channel was time-varying; therefore, the constellation diagram and MIMO digital receiver KPIs were also time-varying.

4.2. EVM Measurement-Moving Stirrer

EVM measurements of two USRP channels were measured when the stirrer was continuously moving. The movement of the stirrer created a time-varying channel, which had a direct implication on the two-channel EVM. Figure 4 shows the QPSK constellation diagram of two USRP channels. It can be seen that the QPSK constellation diagrams are also time-varying; as the mode stirrer rotates, the received power value changes. The effects are visualized in the form of a constellation diagram with low and high gain values. This means that the BER and EVM are also time-varying. Figure 5 shows the time-varying EVM of two USRP channels for Tx gain values from 2 to 8 dB, respectively. It can be seen that USRP channel 1 EVM had high variations in the max and min values of EVM. USRP channel 2 was more stable. For the Tx gain value of 2 dB (see Figure 5a), the standard deviation of the channel 1 EVM was $\sigma_{ch1} = 1.93$ and the standard of the channel 2 EVM was $\sigma_{ch2} = 1.01$. Similarly, for the Tx gain of 8 dB (see Figure 5b), the standard deviation of channel 1 was $\sigma_{ch1} = 1.11$ and the standard deviation of channel 2 was $\sigma_{ch2} = 0.414$. The standard deviation of channel 1 was higher for all of the Tx gain values. Note that the possible cable faults were ruled out by exchanging the two USRP channels, which resulted in exactly similar performances. In other words, the USRP channel 1 EVM was better than the USRP channel 2 EVM. In this way, we precisely restricted our two-channel EVM and BER values to be functions of the propagation environment.

Figure 4. Channel 1 and channel 2 QPSK constellation diagram at 5.6 GHz in a mode-stirred metal enclosure. AGC gain = 60 dB, Rx gain = 0 dB, and Tx gain varied from 2 dB to 8 dB with the step of 2 dB.
4.3. EVM Measurements in the Presence of Interference

The $2 \times 2$ MIMO EVM measurements are presented in the presence of the MIMO interference as functions of interference gain values. The QPSK receiver was tested in the presence of the MIMO interference generated by B210 USRP. The measurement setup is shown in Figure 6, which shows the MIMO antenna configuration and MIMO antenna interference antennas attached to the enclosure lid. B210 USRP, which generated MIMO interference, can also be seen on the enclosure lid. We used GNU radio-based signals, transmitted via B210 USRP as a source of interference. B210 USRP is a full-duplex fully
coherent $2 \times 2$ MIMO transceiver with an integrated RF agile direct conversion transceiver AD9361 chip. B210 USRP has RF coverage from 70 MHz to 6 GHz and it supports the instantaneous bandwidth of 56 MHz in the $1 \times 1$ configuration and 30.72 MHz instantaneous bandwidth in the $2 \times 2$ configuration. The Tx and Rx antennas were placed at a distance of 50 mm and the inter-element distance between the transmit and receiving elements was 45 mm. The MIMO interference signal, which is white Gaussian noise, was generated using B210 USRP. USRP channel 1 and USRP channel 2 constellation diagrams degraded as the interference increased. However, the QPSK constellation diagram can be improved by increasing the Tx gain of the communication link USRP with the direct implication of increasing the signal-to-interference-plus-noise power ratio (SINR). Figure 7 shows the measured EVMs of channels 1 and 2. It is clear that the EVM degrades as the interference signal level increases from 60 to 75 dB. The channel 1 EVM degraded from 34% to 43%, which is 26.4% increase in the RMS EVM. Similarly, the channel 2 RMS EVM degraded from 17% to 66%, which is a 288.23% increase in the RMS EVM. Additionally, the channel 1 RMS EVM had a higher standard deviation than the channel 2 RMS EVM standard deviation.

Figure 8 shows the two-channel BER in the metal enclosure in the presence of MIMO interference. We can see the two-channel BER degrades as we increase the interference level using B210 USRP. The measured BERs are presented for the two Tx gain values (8 dB and 10 dB) of the main communication link. The typical BER values increase from $10^{-8}$ to $10^{-1}$ as we increase the interfering USRP gain.

![Figures 6 and 7 showing the 2 × 2 MIMO BER and EVM measurement setup in the presence of the MIMO interference.](image-url)
Figure 7. Measured EVM of channel 1 and channel 2 in the presence of different levels of MIMO interference. Tx gain of the USRP is 10 dB.

Figure 8. Measured BER of USRP channel 1 and USRP channel 2 in the presence of different MIMO interference levels.

4.4. Near-Field MIMO BER and EVM Measurements in Empty and Loaded Enclosures

In the previous section, BER and EVM were measured in the presence of interference in an empty metal enclosure. Here, the BER performance was checked in an empty enclosure when the enclosure was loaded with losses in the RF absorber cones. Here, the BER performance of the near-field MIMO communication link was measured as a function of transmit gain, enclosure losses, and interference level. Figure 9 shows the measured BER of channel 1 and channel 2 in an empty metal enclosure at different interference gain values. It can be seen that there were BER values at lower Tx gain values as the interference was dominant at these values for all MIMO interference values. For the interferer Tx gain values, the BER of the two channels remained consistent, i.e., channel 2 had a higher BER.
than channel 1. The BER of both channels started to degrade as the interference gain level increased. The BER curve for channel 1 flattened for a Tx gain of 70 dB.

Figure 9c,d shows the EVM measurement of SDR channel 1 and SDR channel 2. It can be seen that the EVM measurements of channel 1 and channel 2 for all Tx gain values at the interference gain of 55 dB were less than the EVM measurements of channel 1 and channel 2 at the interference gain of 60 dB. The channel 2 EVM degraded at a high interference B210 USRP gain of 60 dB. The channel 1 EVM degraded less than channel 2 at all Tx gain values. The channel 1 EVM at the Tx gain of 10 dB degraded from 20.7% to 30.2%, which is a 45.89% increase in the EVM. Figure 10 shows the BER values as channel 1 and channel 2 when the metal enclosure was loaded with ten RF absorber cones. It can be seen that the measured BER degraded with the increase in the MIMO interference power. However, it required a higher MIMO interference power to obtain the same BER values of channel 1 and channel 2. Figure 11 shows the EVM measurements of SDR channel 1 and SDR channel 2, when the empty chamber was loaded with ten pieces of RF absorbers and the AGC gain was set to 50. It can be seen that both SDR channels have comparatively stable EVM values. This is because of the absorption effect of the absorbers and stabilized signal at the AGC output. In the next experiment, the effect of change in the AGC gain is demonstrated on EVM measurements of two USRP channels. EVM measurements were recorded by keeping the same environment and USRP configuration parameters and only changing the AGC gain from 50 to 60 dB.

Figure 9. Measured MIMO BER of channel 1 and channel 2 in the presence of the MIMO interference when the metal enclosure was empty.
Figure 10. Measured MIMO BER of channel 1 and channel 2 in the presence of the MIMO interference when the metal enclosure was loaded with ten pieces of RF absorber cones.
Figure 11. Measured MIMO EVM of SDR channel 1 and SDR channel 2 in the presence of the MIMO interference when the metal enclosure was loaded with ten pieces of RF absorber cones. The Tx gain was swept from 2 to 10 dB. The AGC gain was set to 50 dB.

In Figure 11, the measured EVM values of SDR channel 2 at Tx gain of 2 dB for all the interference levels are 86.1%, 86.4%, 86.2%, 86.8%, 85.9%, and 85.7% respectively.

4.5. Findings and Limitations

The findings and the limitations of the detailed 2 × 2 MIMO prototype as well as the constraints on the RF measurements are as follows:

- BER reduces with the increase in the Tx gain of the USRP or an increase in the Rx gain of the USRP.
- EVM reduces with the increase in the Tx gain of the USRP or an increase in the Rx gain of the USRP, except for some Tx-Rx gain combinations where the Tx amplifier of the USRP is overdriven.
- The EVM of the digital communication link is time-varying in a time-varying environment. For the fixed Tx-Rx gain combination, the EVM is time-varying when the stirrer is moving.
• For the fixed Tx-Rx gain combination, the EVM and BER degrade in the presence of the interference, and further degrade when the magnitude of interference increases. We have the following limitations:
• There is a software limitation in creating the feedback loop for a closed-loop MIMO system. This is extremely challenging in Simulink. It can be conducted by shifting the baseband signal processing blocks directly to the FPGA of the USRP.
• The testbed can be extended to a multi-user setting after conducting adjustments in the Simulink model and by using more X310 USRPs and an appropriate number of antennas.
• The testbed in its current form has the limitation of leveraging the maximum sampling rates of the USRPs. Increasing the sampling rates or increasing the number of USRPs shall increase the risk of a higher number of underflows and overflows in the system. We do not have consistent links in the presence of underflows and overflows. This is a limiting factor in understanding the link.

5. Conclusions and Future Work

In this work, we have shown a 2 × 2 near-field MIMO measurement setup and performed two-channel BER and EVM measurements in a metal enclosure. Near-field MIMO BER and EVM measurements were performed in the MIMO mode using USRP in different configurations. We checked the two-channel BER and EVM measurements in a stationary environment in a metal enclosure and discovered that BER and EVM measured as functions of the USRP Tx gain. In this configuration, we noticed BER and EVM improvements as the USRP Tx gain increased. In the second configuration, we performed BER and EVM measurements in dynamic channel conditions when the mode stirrer moved continuously. In this scenario, we noticed that the BER and EVM measurements were functions of the frequency offset and dynamic channel conditions. We present the mean EVM and standard deviations of near-field EVM measurements. The two-channel EVM and BER values changed dynamically as the stirrer performed movement. In the third scenario, we measured near-field MIMO BER and EVM measurements in the presence of the MIMO interference. In this scenario, we observed that BER and EVM degraded as the Tx gain of the interference generated by B210 USRP increased.

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Abbreviations

The following abbreviations are used in this manuscript:

AGC automatic gain control
BER bit error rate
EVM error vector magnitude
GPU graphical processing unit
LOS line of sight
MCS modulation and coding scheme
MIMO multiple input multiple output
OTA over-the-air
Rx receiver
SDR software-defined radio
SINR signal-to-noise plus interference ratio
Tx transmitter
WNoC wireless network on chip
USRP Universal Software Radio Peripheral
UWB ultra-wideband

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