MIMO RFIC Test Architectures

Christopher D. Ziomek and Matthew T. Hunter
ZTEC Instruments, Inc. Albuquerque, New Mexico, USA

Abstract

This paper discusses the practical constraints of testing Radio Frequency Integrated Circuit (RFIC) devices in a Multiple-Input Multiple-Output (MIMO) topology. Techniques to optimize test equipment setup and operation for MIMO architectures are detailed. Because RFICs are tested at a device level, this paper focuses on MIMO compliance testing and characterization within a cabled RF environment without open-air antennas. The IEEE 802.11 WLAN protocol is used as an example to detail the theory, specific use cases, and test scenarios.

1. Introduction

The drive to increase wireless data rates within the limited radio frequency (RF) spectrum has led to radios with capabilities beyond a single-input single-output (SISO) topology. SISO radio devices use one transmitter and one receiver to send data over a single RF channel. Recently introduced wireless protocols have adopted Multiple-Input Multiple-Output (MIMO) topologies that use two or more transmitters and two or more receivers to send data simultaneously over the same RF bandwidth. For example, the IEEE 802.11n/ac WLAN and IEEE 802.16e WiMAX standards include MIMO functionality.

In this paper, we discuss MIMO RF topologies and the implications of MIMO on Radio Frequency Integrated Circuit (RFIC) test. Because MIMO topologies make use of multi-path signal transmission in a highly-scattered open-air environment, there are implications when testing MIMO RFIC devices in a cabled RF environment. This paper focuses on verification of MIMO RFIC performance using a cabled RF test topology. We use IEEE 802.11 WLAN to illustrate the details of MIMO test equipment setup and operation for a specific protocol.

2. Overview of MIMO

A MIMO RF system uses multiple transmitters and multiple receivers to send data simultaneously over a single RF band. For clarification, the input and output terminology are in reference to the RF channel. For example, the input (the SI or MI portion) is driven by the transmitter(s), and the output (the MO or SO portion) feeds the receiver(s). Figure 1 shows the four input-output topologies. In overview, the four topologies are used in different applications as follows:

- SISO is the most common transmission mode using a single transmitter and single receiver.
- SIMO or Receive Diversity is when a single transmitter feeds multiple receivers. Although there is no increase in data rate, the multiple receivers reduce multipath fading and enhance signal-to-noise ratio (SNR).
- MISO or Transmit Diversity is when multiple transmitters feed identical data to a single receiver. Similar to Receive Diversity, the duplicated transmitters reduce multipath fading.
- MIMO involves multiple transmitters sending unique data content to multiple receivers using spatial multiplexing. MIMO does increase data rates and requires better signal to noise than an equivalent SISO transmission.

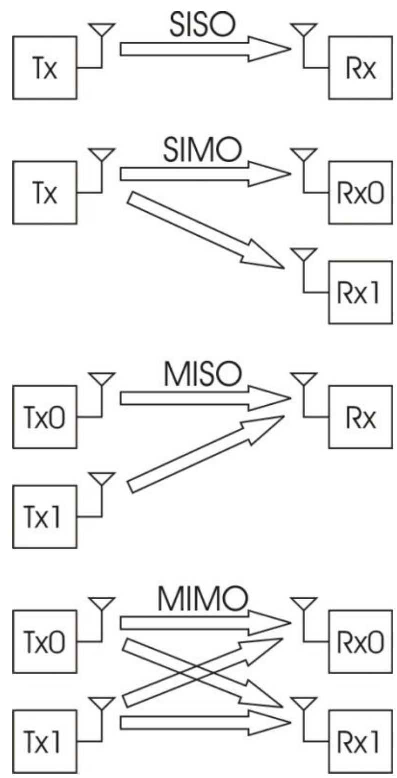

Figure 1) RF Transmission Topologies

Whereas multipath interference degrades a SISO channel by causing channel fading, MIMO topologies compensate for and benefit from multipath effects. In MIMO, phased sets of antennas take advantage of the differences in the spatial propagation paths to improve signal robustness or to send multiple data sets over a single frequency band. In general, having multiple antennas offer three potential use cases:

1. Diversity
2. Beam Forming
3. Space Division Multiplexing

2.1. Diversity

Diversity techniques are used in RF systems to improve signal quality and coverage. As noted above, diversity uses either SIMO or MISO configurations. In a diversity mode, duplicate data is sent in all data streams and there is no increase in data rate. Instead, the multiple receivers or multiple transmitters reduce multipath fading and enhance SNR.

Fading occurs when there are multiple transmission paths between a transmitter and receiver due to reflections and scattering in a wireless environment. The different transmission paths combine at the receiver to create a superposition of multiple copies of the original signal. The resulting constructive or destructive interference is defined as multipath fading. Fading can be overcome using multiple antennas at either the receiver or transmitter. If the antennas are separated by at least a half wavelength, a highly scattered multipath environment creates relatively independent paths to or from the different antennas [1].

In a SIMO receive diversity configuration, there are different methods used to combine the signals captured at the receive antennas. The three common receiver combining methods include:

- Selection Combining uses a switch to select the received signal with the greatest SNR.
- Equal Gain Combining uses an equally weighted combination of all received signals.
- Maximal Ratio Combining uses a weighted combination of the received signals based upon SNR. With this technique, SNR improves on average by a factor of N, where N is equal to the number of receivers.

In a MISO transmit diversity configuration, it has been shown that it is possible to get the same SNR improvement with two transmit antennas as can be achieved using Maximal Ratio Combining with two receive antennas [2]. Transmitting the identical signal simultaneously does have unwanted directionality effects caused by beamforming. Space Time Block Coding (STBC) is used to overcome the directionality effects by inserting a time delay into one of the transmission paths. The time delay for STBC is typically within the 50 ns to 200 ns range. STBC is prevalent in wireless systems because it is often more feasible to have multiple transmit antennas at the base station due to size and power constraints at the mobile device.

2.2. Beamforming

Beamforming is used to control the shape and directionality of transmitted or received signals. This technique combines elements in an antenna array such that signals at particular angles experience constructive interference and signals at other angles experience destructive interference. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity. This is useful to extend the range of an RF channel in a particular direction, while simultaneously avoiding signals from other directions.

2.3. Space Division Multiplexing

Space Division Multiplexing (SDM) is similar to diversity, but is used to achieve higher data rates instead of improved signal quality. In a highly scattered multipath wireless environment, SDM uses spatial multiplexing where different data streams are simultaneously transmitted and received over the same RF bandwidth. SDM requires a MIMO configuration with multiple antennas at both transmit and receive sides. Figure 2 shows an N x N MIMO configuration with signal path coefficients shown as h_{XY}. These signal path coefficients represent the magnitude and phase response of the signal path between each transmitter and each receiver. The definition of an SDM channel includes all of the simultaneous data transmissions on the set of MIMO antennas.

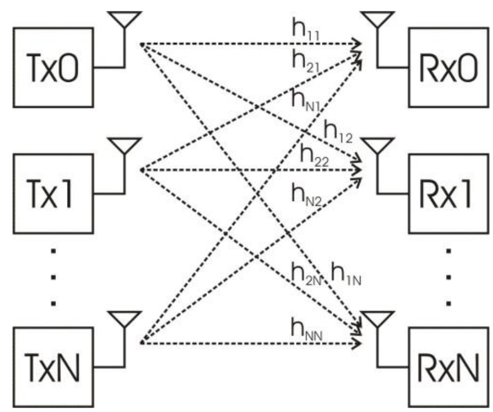

Figure 2) SDM Channel Using MIMO Topology

The best MIMO channels have strong, well-separated spatial propagation paths. Similar to diversity, antennas that are separated by at least one-half wavelength will provide good spatial separation.

In order for the receiver to recover and separate the individual data streams, an estimate of the MIMO channel response must be predetermined. Typically, channel estimation is accomplished during a training sequence where all transmitters generate a known training signal. Signal processing at the receivers is used to estimate the signal path responses to this known training signal. Mathematically, the MIMO channel can be represented as a matrix of signal path coefficients as shown in figure 3.

$$\begin{bmatrix} Rx0 \\ Rx1 \\ \vdots \\ RxN \end{bmatrix} = \begin{bmatrix} h_{11} & h_{21} & \cdots & h_{N1} \\ h_{12} & h_{22} & & h_{N2} \\ \vdots & & \ddots & \\ h_{1N} & h_{2N} & & h_{NN} \end{bmatrix} \begin{bmatrix} Tx0 \\ Tx1 \\ \vdots \\ TxN \end{bmatrix}$$

Figure 3) MIMO Channel Matrix

Using the inverse of the MIMO channel matrix (H) that is estimated during the training sequence, signal processing at the receivers can spatially demultiplex the original transmit data streams as:

$$T = H^{-1} R$$

where T, H and R are the matrices in figure 3 and H^{-1} is the matrix inverse of H.

The singular values of the MIMO channel matrix provide a measure of the strength and separation of the MIMO data streams. The best spatially separated MIMO data streams have large singular values that are approximately equal in magnitude. When this is the case, the MIMO channel has good spatial separation on the paths to/from the different antennas and robust SDM data transmission is possible.

3. WLAN MIMO Example

3.1. IEEE 802.11 WLAN Overview

The IEEE 802.11a/g/n/ac WLAN standards use orthogonal frequency-division multiplexing (OFDM) modulation. OFDM is a method of encoding digital data simultaneously on multiple subcarrier frequencies. Each subcarrier is used to transmit QAM or PSK encoded, unique digital data. The number of subcarriers varies by channel bandwidth and WLAN standard. For example, 802.11a contains 52 subcarriers in its 20 MHz channel bandwidth, and 802.11ac contains 484 subcarriers in its largest 160 MHz bandwidth.

In the time domain, WLAN signals are transmitted in frames, where each frame consists of training fields, signal fields and data as shown in Figure 4. The short training field (STF) and long training field (LTF) are used to synchronize and equalize the channel. The signal field (SIG) contains logical information used to decode the data transmission. The payload data is variable-length and the last four bytes contain a Cyclic Redundancy Check (CRC).

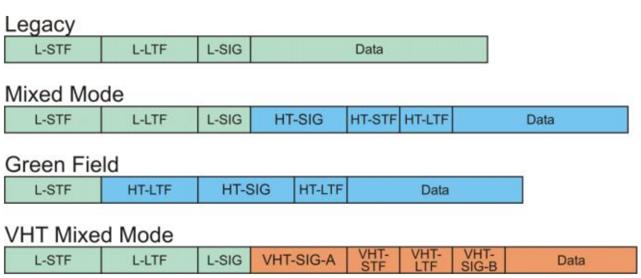

Figure 4) WLAN Frame Format

Figure 4 shows four different frame types for the various WLAN protocols. The Legacy fields (L-) are shown in green, the High Throughput fields (HT-) are shown in blue, and the Very High Throughput fields (VTH-) are shown in orange. IEEE 802.11a/g protocols use the Legacy fields only. IEEE 802.11n supports a Mixed Mode of both Legacy fields and High Throughput fields, and a Green Field mode that consists almost entirely of High Throughput fields. IEEE 802.11ac uses the Very High Throughput Mixed Mode.

3.2. MIMO in WLAN

MIMO was introduced in WLAN protocols with the 802.11n standard as a way to increase data rates without requiring more RF bandwidth. The newest IEEE 802.11ac WLAN standard, which is still in draft format, will achieve up to 6.93 Gbps using up to eight MIMO channels. Note that the legacy WLAN 802.11a/b/g protocols do not support MIMO. When transmitting a legacy protocol, an 802.11n/ac system with multiple antennas often uses STBC in a MISO configuration to improve channel integrity.

The OFDM modulation of WLAN simplifies the MIMO channel estimation requirements. The modulation bandwidth for each subcarrier is narrow enough to reduce the equalization coefficients to a single complex coefficient (e.g. amplitude and phase do not vary over the subcarrier bandwidth). Within 802.11n/ac systems, MIMO channel estimation is accomplished using MIMO training sequences based upon the HT and VHT training fields (STF and LTF) shown in figure 4.

4. WLAN Testing

The IEEE 802.11 WLAN specifications define a number of standardized compliance tests [3]. Much research has been done on test optimization for RF devices and systems in a SISO configuration [4].

4.1. Single Transmitter (SISO) Tests

Typically, a Vector Signal Analyzer (VSA) is used to perform standard compliance tests upon signals generated by a WLAN transmitter [5]. Standard transmitter tests include:

- Spectrum Mask
- Spectral Flatness
- Peak Power
- Center Frequency Error
- Symbol Clock Frequency Error
- Center Frequency Leakage
- Error Vector Magnitude (EVM)

In overview, WLAN protocol analysis software is used to analyze I/Q data captured by a VSA and return the various measurement results listed above. Figure 5 shows an example of this type of protocol analysis software tool.

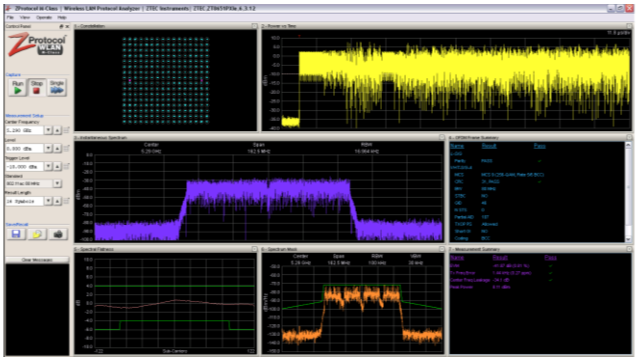

Figure 5) WLAN Analysis Software

EVM (also called relative constellation error) is often used as a comprehensive measure of transmitter performance [6]. EVM is a measure of how far the constellation points vary from their ideal locations and is degraded by any imperfection in the RF channel. The EVM thresholds for a WLAN transmitter for the various modulation coding schemes are shown in Figure 6.

Modulation	Coding Rate	Relative Constellation Error or EVM
BPSK	1/2	-5 dB (56.2%)
QPSK	1/2	-10 dB (31.6%)
QPSK	3/4	-13 dB (22.4%)
16-QAM	1/2	-16 dB (15.8%)
16-QAM	3/4	-19 dB (11.2%)
64-QAM	2/3	-22 dB (7.94%)
64-QAM	3/4	-25 dB (5.62%)
64-QAM	5/6	-27 dB (4.47%)
256-QAM	3/4	-30 dB (3.16%)
256-QAM	5/6	-32 dB (2.51%)

Figure 6) Transmitter EVM Specifications

4.2. MIMO Transmitter Tests

Testing MIMO transmitters is similar to testing a single transmitter with the added complexity of multiple channels. In addition to decoding MIMO-specific signal fields and training sequences, WLAN compliant testing for MIMO requires that composite EVM be calculated by averaging the individual EVM results for all spatial streams. In a composite EVM test, STBC is not used and consequently each transmitter simultaneously generates the same RF output signal. According to the specifications, each transmitter output port should be connected through a cable to a dedicated VSA input port. This test configuration returns individual and combined EVM performance, fulfilling the one additional MIMO test requirement of the IEEE 802.11 specifications [3]. In practice, verifying a MIMO design may require more sophisticated tests and test equipment setup. Additional RFIC design verification tests will be discussed in the next section.

4.3. Single Receiver (SISO) Tests

Typically, a Vector Signal Generator (VSG) is used to generate RF signals into a WLAN receiver for standard compliance testing. In overview, receiver tests verify the dynamic range and linearity of the receiver. Standard receiver tests include:

- Minimum Input Level Sensitivity
- Maximum Input Level
- Adjacent Channel Rejection (ACR)
- Non-Adjacent Channel Rejection
- Clear Channel Assessment (CCA) Sensitivity

The receiver Minimum Input Level Sensitivity defines the minimum input RF signal that meets a specified limit on packet error rate (PER). Successful demodulation requires a PER of less than 10%. The minimum sensitivity thresholds for a WLAN receiver for the various modulation coding schemes and modulation bandwidths are shown in Figure 7.

Modulation	Coding Rate	Minimum Sensitivity			
		20 MHz	40 MHz	80 MHz	160 MHz
BPSK	1/2	-82 dBm	-79 dBm	-76 dBm	-73 dBm
QPSK	1/2	-79 dBm	-76 dBm	-73 dBm	-70 dBm
QPSK	3/4	-77 dBm	-74 dBm	-71 dBm	-68 dBm
16-QAM	1/2	-74 dBm	-71 dBm	-68 dBm	-65 dBm
16-QAM	3/4	-70 dBm	-67 dBm	-64 dBm	-61 dBm
64-QAM	2/3	-66 dBm	-63 dBm	-60 dBm	-57 dBm
64-QAM	3/4	-65 dBm	-62 dBm	-59 dBm	-56 dBm
64-QAM	5/6	-64 dBm	-61 dBm	-58 dBm	-55 dBm
256-QAM	3/4	-59 dBm	-56 dBm	-53 dBm	-50 dBm
256-QAM	5/6	-57 dBm	-54 dBm	-51 dBm	-48 dBm

Figure 7) Receiver Minimum Sensitivity Specifications

4.4. MIMO Receiver Tests

The IEEE 802.11 specifications require MIMO receivers to be tested as multiple single receivers in parallel. For example, the Minimum Input Level Sensitivity defines the threshold as the average power per receive port for a MIMO system. This test configuration requires each receiver port to be connected through a cable to a dedicated VSG port.

Most MIMO receivers are tested for additional characteristics including cross-coupling between receivers. Receiver isolation is measured by applying a signal to one receiver and measuring the coupled response on all other MIMO receivers. Typically, the spectrum of the long training sequence is used for isolation measurements by acquiring data that is time-gated around the LTS symbols within the packets. Additional RFIC design verification tests will be discussed in the next section.

5. MIMO RFIC Design Verification

RFIC devices are production tested for compliance in a cabled RF environment with only one transmission path per RF port. Although this is adequate for production test, verification of operation or design performance in a true MIMO mode requires the simulation of the multipath transmission of a highly-scattered open-air environment. This section discusses additional design verification techniques.

5.1. Other Transmitter Tests

In addition to the parallel test configuration specified by the IEEE 802.11 WLAN standards, there are two other MIMO transmitter test configurations that use a single VSA. The additional combined VSA and switched VSA MIMO transmitter test configurations are shown in figure 8. Both configurations reduce test equipment costs, and both provide other advantages and disadvantages.

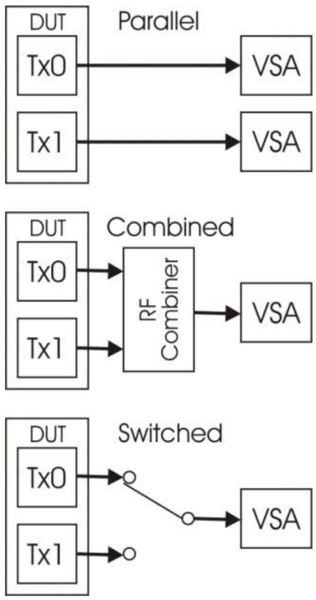

Figure 8) MIMO Transmitter Test Configurations

Combined VSA Tests

The combined VSA transmitter test configuration is a step closer to approximating an open-air environment where two transmitted signals are received by a single antenna. Note that the RF combiner must have very good isolation to prevent interaction between transmitters which causes intermodulation distortion. The combined transmitter configuration offers a different method to measure composite EVM performance. For example, one transmitter may create an in-band spurious signal that degrades the EVM of all other MIMO transmitters.

Also, a combined VSA configuration can be used to test some MIMO operational modes such as STBC where time-shifted data streams are received at a single VSA. Note that SDM cannot be tested with the combined VSA configuration because the two signals cannot be spatially separated.

Switched VSA Tests

The switched VSA transmitter test configuration uses multiple sequential VSA captures on a repeating waveform, and processes the sequential data as if it was transmitted simultaneously. The switched transmitter test configuration is very flexible and operational modes that utilize a multipath environment such as STBC demodulation and SDM demodulation can be simulated. The Device Under Test (DUT) must be capable of generating a sequential or repeating waveform that can be synchronized over multiple captures within the VSA. Results will be more susceptible to timing jitter and phase variations between captures. Also, due to the sequential captures, test time is longer than the parallel VSA or combined VSA configurations.

Interleaved Subcarrier Test

An additional test that can be performed using the standard parallel VSA transmitter test configuration is the interleaved subcarrier test. This test creates an interleaved set of subcarriers on two transmitters by offsetting the center frequency of one transmitter by one-half of the OFDM subcarrier spacing. For WLAN where subcarrier spacing is 312.5 kHz, the center frequency is offset by 156.25 kHz. In this test, each VSA captures a packet and separates out the long training sequence. Measuring the spectrum of the time gated LTS symbols will result in both desired and interfering subcarriers tones. This test provides a measure of transmitter-to-transmitter signal isolation.

5.2. Other Receiver Tests

In addition to the parallel VSG test configuration specified by the IEEE 802.11 WLAN standards, there is another MIMO receiver test configuration that uses of a single VSG. The split MIMO receiver test configuration is shown in figure 9. Similar to the single-VSA transmitter test configurations, the split receiver test configuration reduces test equipment costs and has other advantages and disadvantages.

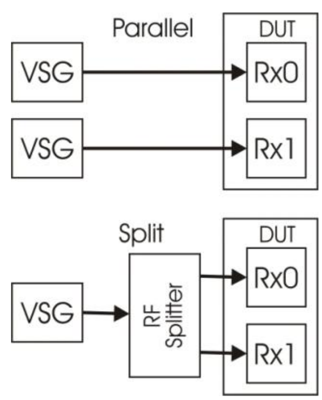

Figure 9) MIMO Receiver Test Configurations

Split VSG Tests

The split VSG configuration offers fast test times because all setup and testing is performed simultaneously. In the split VSG configuration, an identical signal applied to all receivers will provide an input sensitivity gain over a single receiver. Note that STBC and SDM cannot be tested with the split VSG configuration because the two signals are identical.

A split VSG testing technique based upon the emulation of the keyhole effect can assist with MIMO system design verification [7] [8]. Within this test, the split VSG configuration applies the identical signal to all receiver inputs and the MIMO channel matrix is estimated. An ideal MIMO receiver would result in a channel matrix of one dimension where all signal path coefficients are equal to either 0 or 1. A single dimension matrix indicates that the MIMO channel capacity is equal to that of a SISO system. In a test scenario, noise in the receiver or an imperfect channel estimate will create signal path coefficients not equal to the ideal coefficients of 0 or 1. The deviations from ideal provide a measure of receiver performance.

Channel Simulation

The VSG flexibility offers the ability to perform MIMO receiver testing in simulated multipath environments. The VSG uses an arbitrary waveform generator (AWG) to create any type of I/Q modulation waveforms. This allows the simulation of fading channels within the cabled RF connections. Other RF channel imperfections can also be simulated such as spurious signals, noise and distortion. This type of simulation offers a flexible and powerful design verification and characterization tool.

5.3. Multiple-Instrument Synchronization

One challenge of MIMO instrumentation setup is synchronization of the multiple instruments. Modular instruments such as PXI or PXIe are ideally suited to MIMO due to their easily integrated instrument-on-a-card architectures. A PXI/PXIe RF test set can be configured with multiple VSAs, multiple VSGs, or both. Figure 10 shows a modular PXIe test set with four synchronized ZT8651 VSAs for x4 MIMO transmitter testing.

Figure 10) PXIe MIMO Transmitter Test Set

Triggers and timebase clocks routed over the PXI/PXIe backplane enable time and phase synchronization between instruments for MIMO configurations. Figure 11 shows the trigger and clock routing requirements of a PXIe backplane. The backplane triggers allow all instruments to synchronize to and operate upon the same WLAN packet(s). A common timebase of either 10 MHz or 100 MHz is distributed over the PXI/PXIe backplane and enables phase synchronization between instruments. With the PXI/PXIe instruments locked to the same timebase, the relative phase between instruments can be adjusted in software.

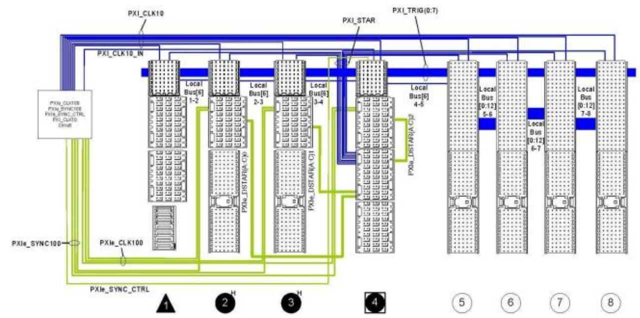

Figure 11) PXIe Backplane Trigger & Clock Routing

6. Conclusion

MIMO adds some complexity to wireless RFIC testing. In a cabled RF environment, the multipath effects that enable MIMO functionality are not present, and consequently other techniques must be used to characterize and verify design performance of RFIC devices. Fortunately, modern test equipment offers a number of techniques that can be used to test RFIC devices that will accurately quantify device performance and operation in a true MIMO environment.

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