The challenges of testing MIMO

To meet the demand for higher data rates and better coverage of wireless networks without increasing bandwidth or acquiring expensive frequency bands, an emerging technology called multiple input, multiple output (MIMO) has appeared. MIMO is capable of significantly increasing wireless data throughput. Because this technology presents technical hurdles to chipset vendors, this article will focus on demystifying physical layer issues with MIMO and present ways of improving MIMO performance.

By Fan Liang

We are currently witnessing an unprecedented increase in the demand for higher speed and better coverage of wireless networks. To meet this enormous demand, one approach is to increase the channel bandwidth over which radio signals are transmitted. However, this approach is not practical because frequency spectrums are expensive and transmitter and channel bandwidths are determined by regulatory standards. Other ways to improve the throughput is to use more complex modulation schemes. This, however, increases the complexity of the radio system and, thus, the cost. This problem requires a better solution.

In the past two years, an emerging technology known as MIMO has been one of the most promising technologies to improve the performance of a wireless link. MIMO refers to a radio link with multiple transmitter antennas and receiver antennas. In wireless links, radio signals from the transmitter travel in space, reflect off objects and reach the receiver over multiple paths. Multipaths can cause interference and signal fading in conventional radios. MIMO takes advantage of multipaths by multiplexing those signals with advanced DSP algorithms to boost wireless bandwidth efficiency and range. Wireless systems using MIMO can significantly improve the spectral efficiency of a system. For example, a wireless local area network (WLAN) system using two transmit antennas to two receive antennas (2 x 2 MIMO) can boost the maximum raw data rate for 802.11a and 802.11g networks from 54 Mbps to more than 100 Mbps.

MIMO orthogonal frequency-division multiplexing (MIMO-OFDM) technology has been adopted by the IEEE 802.11 standards group as the foundation for a high throughput amendment to multimedia wireless fidelity (WiFi) applications. In addition, a consortium of chipset developers has formed task groups such as the TGnSync, WWiSE and, most recently, the Enhanced Wireless Consortium (EWC) are working together to create an IEEE 802.11n specification.

Recently, a number of new products based on MIMO technology were introduced in the market and have delivered significant improvements in data transfer speed and coverage area over products using standard 802.11a/b/g technology. Although currently more expensive, the cost of these MIMO-based devices is expected to drop to levels similar to 802.11 a/b/g devices as the technology gets widely deployed, increasing bandwidth and meeting more user expectations.

MIMO, as a new technology, poses great challenges for silicon chipset vendors, contract manufacturers and brand owners with respect to research and development and production test methods. This article focuses on the physical layer issues and challenges involved with testing MIMO devices. It aims to demystify these challenges as well as offer readers fast, accurate, scalable, and low-cost ways to identify impairments and help improve MIMO system performance.

How a MIMO system works

A standard 802.11a/b/g system uses one transmit antenna and one receive antenna in a radio link as shown in Figure 1. Radio signals from a transmitter traveling in space may reflect off multiple objects and arrive at the receiver through multiple paths. The receiver sees the vector combination of radio signals from these paths. Due to the phase delay difference over these paths, these signals sometimes add up in phase and, sometimes, when they are out of phase, they cancel each other out at the receiver. This causes the received signal strength to fluctuate constantly or fade and can significantly degrade the data throughput of the wireless system.

In wireless systems, radio signals from different users are typically separated by frequency, time or code. With beam-forming technology, also referred as smart antenna technology, each user can also be distinguished by their physical location in space.

Wireless systems use smart antenna technology to reduce the effect of multipath fading and to improve radio link quality and coverage. As shown in Figure 2, smart antenna technology uses adaptive antenna...
typically less than 4.

The different paths may be represented mathematically as:

$\mathbf{Rx} = \mathbf{h}_1 \mathbf{Tx}_1 + \mathbf{h}_2 \mathbf{Tx}_2 + \ldots + \mathbf{h}_n \mathbf{Tx}_n$

or, in matrix form as

$$\mathbf{Rx} = \mathbf{H} \mathbf{Tx}.$$

The $\mathbf{H}$ in equation (2) represents the transfer matrix of a MIMO channel.

In a traditional radio system, multipath signals decrease throughput as they cause co-channel interference. On the other hand, a MIMO system relies on this interference suppression to implement multi-datastream detection and then separate the individual transmitted streams. By carefully designing a MIMO packet and by using advanced digital signal processing (DSP) techniques in the MIMO decoder, we can recover the variously independent transmitted datastreams.

To recover the transmitted datastream $\mathbf{Tx}$ at the $\mathbf{Rx}$, the MIMO system decoder must first estimate the individual channel transfer coefficient $h_{ij}$ to determine the channel transfer matrix $\mathbf{H}$ during the MIMO preamble of the packet. Once the estimated $\mathbf{H}$ has been produced, the transmitted datastream $\mathbf{Tx}$ can be reconstructed by multiplying the vector $\mathbf{Rx}$ with the inverse of transfer matrix $\mathbf{H}^{-1}$. This is represented by

$$\mathbf{Tx} = \mathbf{H}^{-1} \mathbf{Rx}.$$

The process, in principle, is equivalent to solving a set of $N$ unknowns with $N$ linear equations. To ensure that the channel matrix is invertible, MIMO systems require an environment rich in multipath.

It is important to note that unlike traditional methods of increasing throughput by increasing bandwidth, MIMO systems can increase throughput without increasing bandwidth. This is accomplished in a MIMO system by exploiting the spatial dimensions and increasing the number of signal paths between the transmitters and the receivers.

Because each independent datastream is transmitted in parallel from separate antennas, the data throughput increases linearly with every pair of antennas added to the MIMO system. This means that by using a MIMO system, wireless network operators can increase their broadband services within the currently allocated spectrum without having to expand to more spectrums.

**Challenges and solutions to testing MIMO devices**

MIMO-OFDM technology brings significant performance improvements to wireless systems. However, it also brings many challenges to product development and testing due to the OFDM modulation and additional complexity of multiple radio architectures involved.

For the benefit of lower cost and higher-efficiency digital modulation, a zero intermediate frequency (ZIF) radio architecture with in-phase and quadrature (I/Q) modulation is often used in a MIMO system. In this type of architecture, the baseband signal is split into I, the in-phase component of the waveform, and Q, the quadrature-phase component of the waveform. On the transmitter side, the baseband I and Q components directly convert into radio frequency and feed the power amplifier and antenna for transmission. On the receiver side, the RF signal goes through the I/Q demodulator and converts directly to baseband I and Q components. Imbalances (amplitude, phase and group delay) between I and Q signal paths will directly affect modulation accuracy. In addition other impairments such as carrier frequency accuracy, phase noise, local oscillator (LO) leakage, spurious interference, and amplifier compression can affect the performance of a MIMO system. These are the imbalances and impairments we are most concerned with uncovering.

A MIMO packet consists of a legacy 802.11 a/g preamble field and a MIMO preamble field followed by the payload data. For each composite data packet received, the MIMO decoder must be able to estimate the channel transfer matrix $\mathbf{H}$ during the MIMO preamble of the packet. We assume that within the length of each MIMO signal packet, the characteristics of the communication link between the MIMO transmitters and receivers remain constant. The channel transfer matrix $\mathbf{H}$ determines the link characteristic. The quality of
the transmitted signal during the preamble has a significant impact on the accuracy of the channel transfer matrix \([H]\) estimation, and thus the quality of the MIMO system.

For the transmitters, the traditional impairments like I/Q mismatch, group delay and group delay variation, compression and phase noise will affect the system performance. There are many impairments that can affect transmitter performance such as variations in the baseband and radio-frequency integrated circuits (RFICs), component tolerance, impedance mismatching in the transmission line, components along the signal path, differences in the parasitic capacitances and inductances along the printed circuit board (PCB) traces for the I and Q signal path variations, spurious interference, non-linear effects of the amplifier, etc.

Error vector magnitude (EVM) defined as the vector difference between the ideal error-free decision points in a signal constellation and that of a measured signal, is a direct measure of the modulation accuracy and overall signal quality of the transmitter. EVM captures both amplitude error and phase error and reduces the many parameters that characterize distortions of a transmitted RF signal into a single one.

Parameters such as transmit EVM, symbol constellation diagram, transmitter power, transmitter spectral mask, and crosstalk between transmitters are all important measurements of the transmitted signal quality. They provide valuable information about the root cause of impairments during the phases of MIMO chip design, product development and design validation. Accurately measuring these parameters becomes even more important to designers of MIMO-OFDM-based systems due the complexity involved when multiple radios operate in the same frequency.

To measure and analyze the above parameters, designers and test engineers require a test instrument that combines a vector signal analyzer (VSA), spectrum analyzer, and a power meter. Figure 4 shows the block diagram of the IQnxn MIMO test system from LitePoint Corporation. The system, as shown, consists of two VSAs and two vector signal generators (VSGs). This test system is scalable and can be expanded to include more VSAs and VSGs to enable concurrent measurement of MIMO devices.

Figure 5 shows the measurement results of a device under test (DUT) with MIMO radio. The data rate transmitted from the DUT measures 108 Mbps total with a 54 Mbps datastream coming from each transmitter. The RF signal was sent through coax cables with 20 dB attenuators. The IQnxn MIMO system from LitePoint measured the following key parameters simultaneously in a single capture. Those measurements.

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provide detailed information about each individual transmitter. The transmitter spectral mask for both channels is shown at the top left and center window of the display. The blue trace is the power spectrum density. The red trace defines the spectrum mask as defined by the 802.11 standard. For each Tx channel in the MIMO system, the power spectrum measurement needs to stay below the spectrum mask limit in order to reduce adjacent-channel interference.

The time domain waveforms for both transmitters are shown at the top right window.

The channel estimation results are shown at the middle right window of the display. Channel 1 \([h_{11}]\) and channel 2 \([h_{21}]\) display the channel flatness and transmitter power balance of the OFDM signals. Channel 3 \([h_{22}]\) and channel 4 \([h_{12}]\) display isolation or leakage between channels.

Average EVM over each subcarrier for both channels is shown in the middle left window of the display. Notice that both EVM measurements are reasonably good over the 52 subcarriers except at the edge of channel 2 where EVM degrades due to group delay. Group delay imbalance between I and Q signal paths can adversely affect modulation accuracy and cause constellation distortion. Such an imbalance usually relates to the different trace lengths and dielectric constant of the PCB layer for the baseband I and Q signals. The difference in the I and Q signal paths inside an RFIC can also contribute to the imbalance. Group delay imbalance is frequency dependent, thus, affects each OFDM subcarrier differently. Typically, the end subcarrier will be affected the most.

The symbol constellation diagram combines with the corresponding system EVM measurement to give a good indication of signal quality. Sharp, well-defined points in the symbol constellation diagram represent good signal quality while distorted or smeared symbol constellation points represent poor signal quality. Designers can use a symbol constellation diagram as an easy way of qualitatively assessing and diagnosing adverse impacts such as I/Q imbalance, phase noise, and amplitude compression.

A symbol constellation diagram for both datastreams is shown in the lower part of the display (Figure 5). Each stream is transmitting 54 Mbps with OFDM and with a 64-quadrature amplitude modulation (QAM) constellation. The two green constellation points representing the four subcarriers carry binary phase shift keying (BPSK) modulated pilot tones. These pilots are used to create a continuous series of amplitude and phase references throughout the data frame. Demodulation is then performed relative to these pilot carriers and this allows for signal impairments to be corrected continuously throughout the burst. The 64 red constellation points represent 64-QAM symbol constellation measurements taken from each of the 48 OFDM data subcarriers and over many symbols. The constellation points of pilot tones are relatively well defined compared to constellation points of data subcarriers. I/Q amplitude mismatch results in the pilot tones separating mostly along the I axis, while I/Q phase mismatch results in the pilot tones separating mostly along the Q axis. Phase noise affects both modulation accuracy and EVM. Phase noise is usually introduced during frequency conversion when a baseband signal is mixed with a local oscillator (LO) to translate to RF frequency. The LO phase noise consists of contributions from three main sources in a frequency synthesizer: 1) the frequency stability of the reference crystal oscillator, 2) the frequency stability of the free-running voltage controlled oscillator (VCO) used by the phase locked loop (PLL), and 3) the loop bandwidth and the noise from the PLL used in the frequency synthesizer. The impact of phase noise can be seen as a circular distortion of the signal points around the center of the symbol constellation diagram.

At the bottom right of the display as shown in Figure 5, there is a window with numerical results of transmitter power, EVM, carrier frequency error, and phase noise.

Figure 5. Measurement results from a LitePoint IQnxn test system.

Figure 6. Composite MIMO measurement setup.
One of the important elements in a radio system is the RF power amplifier. To achieve maximum efficiency, the RF power amplifier is ideally operated close to its saturation point, but not above it. This fact directly affects product cost and quality since it requires a trade-off between power consumption and amplifier bias. The gain of the power amplifier is compressed when maximum, or peak power, exceeds the amplifier’s saturation point. When the amplifier operates into its saturation region, non-linearity of the amplifier can lead to many undesired effects such as harmonic distortion, intermodulation, spectral re-growth, cross modulation, and modulation inaccuracy.

A MIMO-OFDM radio generally requires a greater degree of power back-off from the power amplifier saturation point because of its high peak-to-average power ratio. The effect of amplifier compression can be seen in the symbol constellation diagram as constellation points are spread to the point where decision errors are likely.

On the production line, fast, accurate, and low-cost test methodologies are critical to lowering the overall cost of devices and to enable MIMO technology to gain widespread acceptance. Transmitter EVM testing along with transmitter power and transmitter spectrum mask testing of each of the transmitters can be used as a pass-fail metric for the system. Figure 6 is the block diagram of a MIMO test solution for mass production from LitePoint Corporation. The radio signals from two independent transmitters are combined through an RF combiner and fed into a single VSA and analyzed by proprietary DSP software.

Figure 7 shows the measurement results from a composite signal on a MIMO DUT. The data rate transmitted from the DUT measures 108 Mbps total with a 54 Mbps data stream from each transmitter. Notice that spectral mask, transmitter waveform, average EVM, frequency error, phase noise and symbol constellation are all shown as a composite measurement. Any defect or failure on any of the individual MIMO channels will result in a failure report in the composite measurement.

Channel estimation results for the individual MIMO channels are shown in the middle right window of the display. The graph provides information on the channel flatness of each channel and transmitted power balance between channels.

These proven, fast and accurate test methodologies greatly simplify MIMO system test in a production line, guard quality and increase test throughput.

Conclusion

MIMO-OFDM technology offers a promising way for next-generation wireless systems to enhance their channel capacity and robustness of the link. Accurate and fast measurements in the frequency, time and modulation domain can help greatly shorten the design cycle times and improve overall product quality and profitability. However, traditional test systems are not designed to handle the multiple simultaneous transmitters and receivers in a real MIMO system. Two test methods were investigated here. The first method proposed consisted of multiple synchronized VSAs and VSGs capable of simultaneously measuring all key parameters for system measurements involving multiple radios, simplifying a complex task to a straightforward one. This first test method proposed provided a fast, accurate, scalable, and affordable test solution for MIMO product development environments.

The second test method proposed involved a one-box MIMO test solution, which used the composite measurement approach to greatly simplify MIMO test procedures and improve test throughput on the manufacturing floor allowing for a fast and low-cost solution for mass production environments. The advantage of this method is that it can be used with existing test instruments such as the LitePoint IQflex.

ABOUT THE AUTHOR

Fan Liang is a senior member of the technical staff at LitePoint Corp. Liang has extensive experience in wireless networks, RF/microwave circuits and system design. He has worked with numerous wireless standards and has designed multiple 802.11 test systems for WLAN applications. He earned an M.S. degree from Xi’an Jiaotong University in Electrical Engineering with a focus on wireless communications. He may be reached at Fan.Liang@litepoint.com.