From October 2009 *High Frequency Electronics*

Precoding and Spatially Multiplexed MIMO in 3GPP Long-Term Evolution

By Randall T. Becker
Agilent Technologies

This article examines the basic theory of precoding in a MIMO system, compares this with non-precoded MIMO, and describes methods for measuring system performance

Multiple Input Multiple Output (MIMO) technology has been shown to provide higher data rates with increased spectral efficiency [1, 2]. The performance of a MIMO system is directly related to the received signal-to-interference-and-noise ratio (SINR) and the correlation properties that are characteristic of the multipath channel and antenna configuration [3]. Although the wireless channel can deliver low SINR at some of the MIMO receive antennas, it is possible to improve system performance with the application of beamforming at the transmitter. Though often used together, it is important to differentiate here that beamforming is a signal processing technique, which is very different from beam steering where the direction of the main lobe of radiation is changed. Beamforming lends itself well to MIMO applications.The 3GPP Long Term Evolution (LTE) specification [4] includes several transmit beamforming techniques that may optimize system performance under various channel conditions. One technique, referred to as precoding, is designed to increase and/or equalize the received SINR across the multiple receive antennas.

MIMO and Precoding

A standard 2 × 2 MIMO spatial multiplexing scheme, shown in Figure 1a, assumes the wireless channel will provide four separate connections between transmit and receive antennas. Each channel connection, shown as an arrow in the figure, represents a unique combination of all transmission paths including the direct Line of Sight (LOS) path, should one exist, and the numerous multipaths created by reflection, scattering and diffraction from the surrounding environment. Depending on the resulting channel conditions, the MIMO system may not be able to properly recover the transmitted data streams (layers) if the SINR is too low at any of the receive antennas. With the addition of precoding, as shown in Figure 1b, the transmitter,

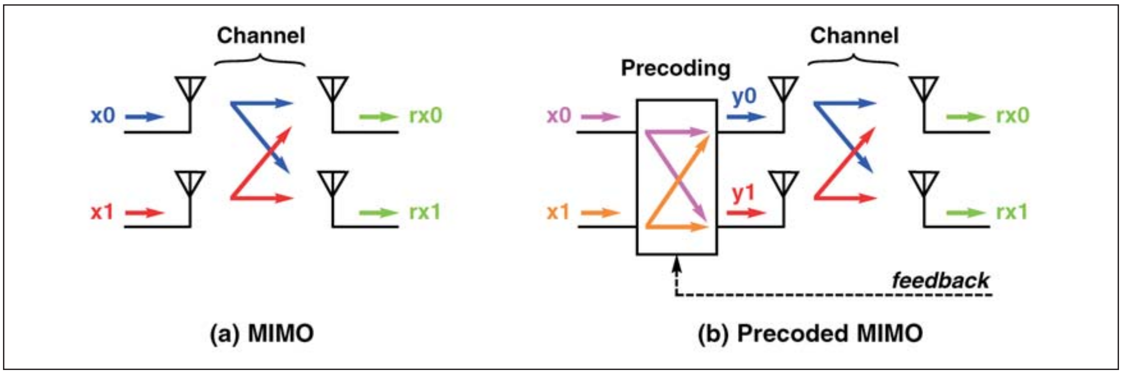

Figure 1 · Simplified block diagram showing the difference between (a) MIMO without precoding and (b) MIMO with precoding.

having knowledge of the current channel conditions, can effectively combine the layers before transmission with the goal of equalizing the signal reception across the multiple receive antennas. Precoding schemes have been specified for spatially-multiplexed and transmit-diversity applications [4]. This paper will examine precoding in spatially-multiplexed MIMO systems.

Precoding is based on transmit beamforming concepts with the provision of allowing multiple beams to be simultaneously transmitted in the MIMO system. The LTE specification defines a set of complex weighting matrices for combining the layers before transmission using up to 4 × 4 antenna configurations [4]. For a 2 × 2 configuration, the weighting matrix, W, is multiplied by the input layers to generate the precoded signals to be transmitted.

$$\begin{bmatrix} y^{(0)}(i) \\ y^{(1)}(i) \end{bmatrix} = W(i) \begin{bmatrix} x^{(0)}(i) \\ x^{(1)}(i) \end{bmatrix}$$

Here, $x^{(q)}(i)$ are the input layers prior to precoding ($q = 0, 1$) and $y^{(q)}(i)$ are the precoded signals applied to each transmit antenna. The simplest precoding matrix maps each layer to a single antenna dedicated to transmitting that layer, without any coupling to other antennas. In this case, the weighting matrix, defined with codebook index 0, becomes

$$W(i) = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

resulting in the following transmitted data as

$$y^{(0)}(i) = \frac{1}{\sqrt{2}} x^{(0)}(i)$$
$$y^{(1)}(i) = \frac{1}{\sqrt{2}} x^{(1)}(i)$$

A second precoding matrix, defined with codebook index 1, provides a linear combination of the sums and differences of the two input layers respectively. The weighting matrix for codebook 1 is

$$W(i) = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

resulting in the following transmitted data

$$y^{(0)}(i) = \frac{1}{2} x^{(0)}(i) + \frac{1}{2} x^{(1)}(i)$$
$$y^{(1)}(i) = \frac{1}{2} x^{(0)}(i) - \frac{1}{2} x^{(1)}(i)$$

This codebook selection allows a portion of each signal layer to be transmitted through each antenna, and depending on the channel conditions, providing some flexibility when attempting to improve and equalize the SINR at each MIMO receiver.

The LTE specification for precoding spatially multiplexed transmissions includes a total of four codebook matrices for two transmit antenna configurations and 16 codebook matrices for four transmit antenna systems. Proper selection of the optimal precoding matrix requires knowledge of the current channel conditions at the transmitter. The channel conditions are provided through feedback from the MIMO receiver creating a closed-loop system. For an LTE precoded downlink transmission, the mobile terminal or user equipment (UE) will measure the channel characteristics and determine the precoding matrix index (PMI), channel quality indicator (CQI) and/or Rank Index (RI). This information will be sent to the base station (eNB) which would modify the precoding codebook selection to improve overall system performance. As channel conditions may change rapidly over time, it is important for the system to avoid excessive delays when closing the feedback loop. Reduction of the signaling overhead and associated feedback delay is accomplished by restricting the number of codebook selections. Unfortunately, reducing the number of selections may also limit the number of possible adjustments thus reducing the effectiveness of precoding.

An LTE system design requires a thorough understanding of the tradeoffs between performance, precoding options and feedback constraints. A flexible measurement system can provide unique insight into the capability of precoding under a variety of simulated channel conditions including noise, interference and antenna/channel correlation.

Precoding Measurement Examples

There are a variety of measurement tools that are necessary when examining the performance of precoding and MIMO operating under diverse channel conditions. Figure 2 shows a typical 2 × 2 MIMO measurement setup consisting of a wireless channel emulator, signal sources and signal analyzers. The channel emulator, such as the Agilent N5106 PXB Receiver Tester, is used to create realistic multi-channel, multipath environments including the effects of antenna and spatial correlations [3]. Some commercial emulators have built-in baseband generators for generating complex waveforms using standards based or custom models developed in software tools such as Agilent Signal Studio, Agilent ADS and Agilent SystemVue. The outputs of the channel emulator are complex baseband waveforms representing the precoded MIMO signals modified by multipath, noise and/or interference. These baseband waveforms are then modulated onto RF carriers using the analog in-phase (I) and quadrature-phase (Q) inputs available on many RF vector signal generators. The baseband data can also be modulated onto RF carriers using digital I and Q inputs on signal generators such as the Agilent MXG series. This is the preferred method since it gives the best performance and also enables automatic power calibration of the system to be per-

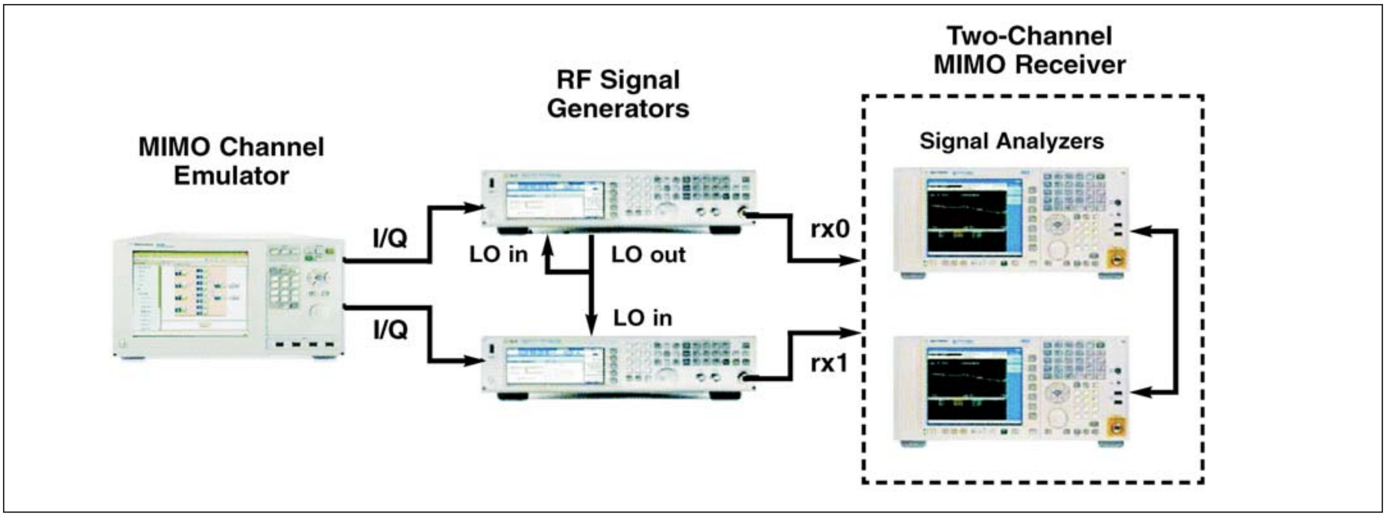

Figure 2 · Measurement setup for characterizing the performance of LTE precoding under various multipath and channel conditions as demonstrated using the N5106A PXB MIMO Receiver Tester, theN5182A MXG Vector Signal Generator and the N9020A MXA Signal Analyzer.

formed In the measurement system shown in Figure 2, the two RF signal generators are the inputs to a two-channel MIMO receiver. It is important to note that when using multiple signal generators to simulate a MIMO system, the generators require a stable phase relationship during test though the equipment is not required to be phase-locked. The term phase-locked is often referred to as "phase coherence" and describes a fixed phase condition between the RF outputs of two or more signal generators operating at a specified carrier frequency. A proper phase relationship is important for the precoding operation as signals from separate data layers are vectorially added before transmission based on known channel conditions. If the signal generators used to simulate multiple transmitters have an unknown and/or time-varying phase relationship, the received signals may include undesired phase offsets resulting in reduced performance in one or more of the recovered data streams. An example will be provided later in this article showing the relationship between signal generator phase offset and system performance. In a test system using two modern RF signal sources, such as the Agilent MXG signal generators, phase coherence is maintained by sharing the un-modulated local oscillator (LO) from one generator with the other as shown in Figure 2. In some test systems with multiple RF signal generators, such as in 4 × 4 and 2 × 4 configurations, a separate RF signal generator is recommended as a master local oscillator in order to provide enough drive level to the local oscillator inputs of the signal generators.

In the measurement example shown in Figure 2, the two-channel MIMO receiver is configured using two vector signal analyzers (VSA), such as Agilent MXA signal analyzers configured with Agilent 89600 VSA software. A similar configuration can be used to test the performance of an actual 2 × 2 MIMO receiver system by direct cable connection from the two signal generators to the inputs of the MIMO receiver. In this case, the channel emulator introduces multipath and channel impairments that would be found in a real-world environment. When testing a MIMO transmitter or eNB, the transmitter can be directly connected to the signal analyzer(s). Depending on the total number of measurement ports available on the test equipment, there are several possible configurations for connecting a MIMO transmitter to the signal analyzer(s). For, example, limited MIMO testing can be done with a single-input analyzer by using, a power combiner to add the multiple signals from the MIMO transmitters to the common port on the analyzer. In this case, since the transmitted downlink reference signals are orthogonal in frequency and/or time, the individual reference signals from each transmission antenna port can be analyzed for EVM characteristics and timing errors using the single-input analyzer. When two single-input analyzers are available for test, a two-channel MIMO transmitter can be directly cabled to the analyzers. In this case, the analyzers can recover the independent data from each codeword even for cases when precoding is applied such that each layer contains some combination of each independent codeword. This configuration is also useful for evaluating the effects of the propagation channel where cross talk and cross coupling of the channels will occur.

A measurement example of the potential system improvements that

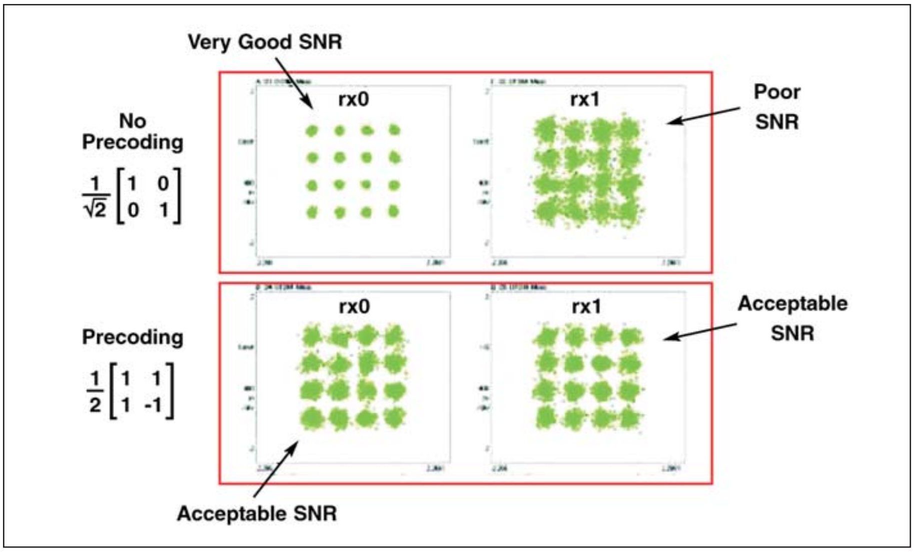

Figure 3 · Measured constellation with and without precoding made using the 89600 Series Vector Signal Analysis Software (6).

can be achieved using LTE precoding will now be shown using the basic 2 × 2 MIMO system described above. The channel emulator is configured to create a "static" multipath channel resulting in a high SINR for one received signal and a low SINR for the other. Figure 3 shows the measured constellations for the recovered two-channel MIMO signal without precoding (upper plots) and with precoding (lower plots). For the measurement without precoding, referenced with codebook index 0 in the LTE specification, the data layers are directly mapped to the two transmit antennas and transmitted through the emulated multipath channel resulting in one signal, rx0, being received with a relatively high SINR while the second received signal, rx1, is severely attenuated resulting in a very low SINR. The quality of the second signal and the large differences in SINR between the two make it difficult to properly decode this two-channel MIMO signal. With the application of precoding, using codebook index 1 for this example, the negative effects of the poor channel conditions may be partially removed as precoding attempts to equalize the measured SINR at each receiver. The results found in this measurement example, show an improvement in SINR for the poorer quality signal, rx1, and an acceptable reduction in SINR for the other, rx0. With the two receive channels properly equalized, the MIMO receiver can easily recover the original transmitted signals.

It was previously mentioned that phase coherence between RF signal generators is important for proper demodulation of the separate data layers. When a precoding index is selected to equalize receiver performance, it is assumed that the signal generators have a known phase offset. If the phase relationship between the generators changes, the performance in one data layer may degrade while the other may improve. As an example, continuing with the precoded measurement shown in Figure 3, the precoding index 1 was selected in order to equalize the performance between the two receivers and their associated constellations. In this case, the RF signal generators were phase coherent with a zero-degree offset. A figure-of-merit of the quality of the constellation is the Error Vector Magnitude (EVM). The EVM is a number, typically given as a percentage, quantifying how the received signal deviates from an ideal constellation. Low EVM values represent higher quality signals. For the precoded measurements shown in Figure 3, the EVM was approximately 13.5% at both receivers. If a phase offset is now introduced between the signal generators, the EVM will be reduced at one receiver and improved at the other. Figure 4 shows the EVM as a function of phase offset for each data stream in the 2 × 2 system described above. As shown in the figure, when the phase offset is zero-degrees, the codebook selection was properly chosen for the simulated wireless channel. As the phase offset increases, the EVM degrades for Stream 1 and improves for Stream 2. The opposite effect is observed when the phase offset is negative. The degradation in EVM between the two receivers results in a mismatch between selected codebook and the expected channel characteristics. If the phase offset is fixed, a different codebook selection may once again equalize the receiver performance. Unfortunately when using non-coherent signal generators, the time varying phase relationship will greatly affect the measured EVM results and system performance. To overcome this issue, phase coherent signal generators, as described in the measurement setup shown in Figure 2, will eliminate the time varying phase offset between the multiple generators.

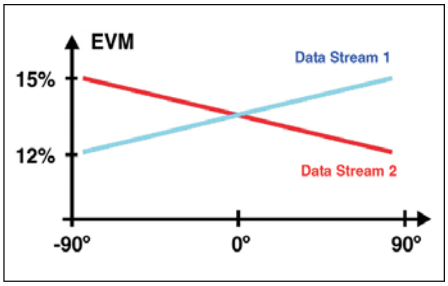

Figure 4 · Impact of phase offset on precoding accuracy.

System Implications when using Precoding—A second measurement example shows the effects of precoding when non-linear distortion is present in one of the transmitter channels. This measurement is made with the analyzers connected directly to the two outputs of a MIMO transmitter. It can be shown that distortion in one transmit channel or one receive channel will effect both recovered signals in a 2 × 2 precoded MIMO system. As shown in Figure 5, the 2 × 2 MIMO transmitter has non-linear distortion in the power amplifier of the upper channel, referenced here as Tx0. The upper transmit amplifier is deliberately set to saturate on the incoming waveform, y0. With precoding applied, a portion of each signal layer is combined and passed through the saturated amplifier. Examining both transmitter outputs using the VSA software, the undistorted channel, Tx1, shows a relatively clean frequency spectrum (lower left) while in comparison, the upper channel, Tx0, shows excessive spectral re-growth resulting from the power amplifier saturation (upper left). Another useful VSA measurement for examining the effects of amplifier compression is the complementary cumulative density function (CCDF). The CCDF displays the instantaneous power relative to the average power as a percentage of time [5]. If an amplifier is in compression, the measured output will have a lower peak value in comparison to an uncompressed signal. In this example, the CCDF shows a lower than expected peak-to-average ratio measurement (upper middle plot in Figure 5). As a reference, the CCDF curve for Gaussian noise is also plotted on the same graph and has a higher peak-to-average ratio.

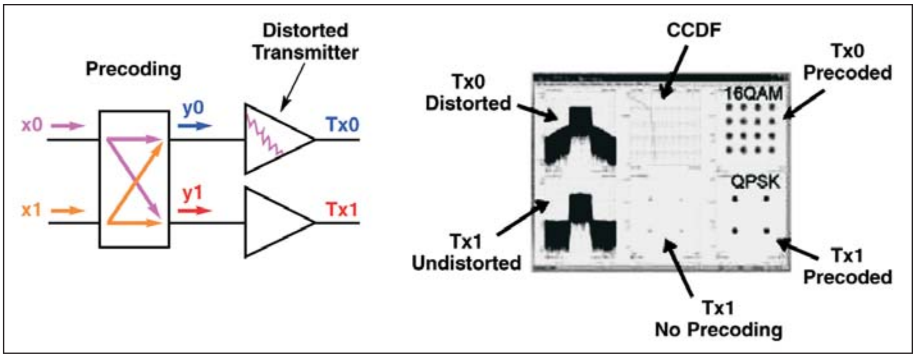

Figure 5 · Measured constellation of a precoded 2 × 2 MIMO signal with distortion in one transmit channel.

Figure 5 also shows the measured constellations of the recovered 2 × 2 precoded MIMO signal (right column). Here the upper right plot shows the measured 16QAM constellation for the Tx0 signal. The lower right plot shows the measured QPSK constellation for Tx1. With precoding applied, distortion is present in both constellations as a portion of each data layer is passed through the saturated amplifier. Without precoding, the measured constellation (middle lower plot) for Tx1 displays a relatively clean constellation as this layer is directly mapped to the output and does not pass through the saturated amplifier. As these measurements have shown, the key to optimizing and troubleshooting LTE components and systems relies on a flexible set of measurement tools capable of generating and analyzing realistic signals and multipath channels.

Conclusion

Precoding technologies in 3GPP LTE can greatly improve system performance when the multipath channel does not provide adequate SINR at one or more of the MIMO receivers. It was shown that a variety of measurements can provide very useful insight into the operation and performance of a precoded system under multipath and channel distortion.

References

1. Agilent Application Note: “3GPP Long Term Evolution: System Overview, Product Development, and Test Challenges,” Literature Number 5989-8139EN, May 2008.

2. Agilent Application Note 1509: “MIMO Wireless LAN PHY Layer (RF) Operation & Measurement,” Literature number 5989-3443EN, April, 2008.

3. Agilent Application Note: “MIMO Channel Modeling and Emulation Test Challenges, “Literature Number 5989-8973EN, Oct. 2008.

4. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation (Release 8), 3GPP TS 36.211 V8.4.0 (2008-09), 2008

5. Agilent Application Note: “Improving Methods for Measuring Distortion in Broadband Devices,” 5989-9880EN, Dec. 2008

6. Moray Rumney, editor, *LTE and the Evolution of 4G Wireless: Design and Measurement Challenges*, Agilent Technologies, 2009

Author Information

Randy Becker obtained his BSE in Electrical Engineering from Walla Walla College in 1997 and an MSEE from the University of Nebraska in 1999. At Hewlett-Packard/Agilent Technologies he has worked in a variety of technical marketing roles, starting as a marketing engineer in the Spectrum Analysis Division, then moving to the Signal Sources Division where he worked for 8 years. He is currently a senior application engineer in the Microwave and Communications Division supporting various cellular technologies with a focus in W-CDMA and LTE.