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Agilent Technologies

What You Should Know About MIMO Operation and Measurement

By: PETER CAIN

Wireless Solution Planner, Agilent Technologies

peter_cain@agilent.com

MIMO techniques are becoming a popular combination with OFDM radio formats because they offer the possibility of increased spectral efficiency. The first commercially available MIMO system was in WLAN, but the interest has spread to cellular formats including WiMAX and LTE. Each format has adopted slightly different techniques and terminology, sometimes making it a little difficult to be sure what is being discussed.

MIMO systems also introduce a new dimension in test - that of the cross coupling of signals between hardware transmit and receive paths. This gives rise to new performance measurement techniques to augment the single channel tests that remain the starting point.

A selection from Agilent's "Ten Things You Should Know About MIMO" are presented in this paper, with the intention of giving the user an overview of the operation of MIMO technology and test methodology. Each item uses an example to highlight the impact on the radio system or associated test. A poster that summarizes all ten points is available from Agilent on request (order information can be found at the end of this paper).

The distinction between MIMO spatial multiplexing and diversity

The term "Multi-Input Multi-Output" can sometimes be applied to other multi-antenna techniques, such as transmit and receive diversity, which do not directly increase the spectral efficiency of the radio link. In practice, diversity techniques will be just as important as the spatial multiplexing that does fundamentally increase capacity, and the two methods will often be combined. This explains why we will see base stations with four antennas, even though the mobile only has two.

Referring to *figure 1*, the key to spatial multiplexing is the simultaneous transmission of separate portions of the incoming user data. It is inevitable there will be some cross coupling as the signals

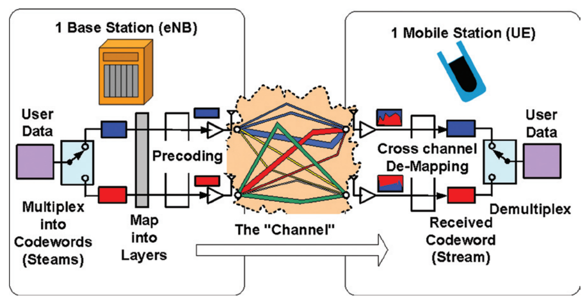


Figure 1 *Cellular style asymmetric MIMO operation.*

travel through the radio channel, which includes the antennas. The art of MIMO is to avoid the transmissions simply being interference to each other. Doing this means you have to know how the radiated signals are coupled, which requires there to be as many receivers as transmitters. This leads to the first item we should know.

Spatial multiplexing requires at least two transmitters and at least two receivers. The receivers need to be in the same place.

The receivers need to be in the same place because it is the combination of the information they recover about coupling that is used to separate the data streams, or what are called codewords in 3GPP LTE.

For measurements which post-process the signals, the constraint of the receiver hardware being in the same place is removed because the measurement software, like the Agilent 89600 VSA, can combine IQ data from multiple inputs and then perform the signal separation and analysis. Another special measurement case is where the signals are connected to the analyzer with cables and never coupled, i.e. direct mapped. It is then possible to recover each codeword (stream) by connecting a single input analyzer to each transmitter in turn.

If the signal being tested remains substantially constant from frame to frame, it is also possible to capture individual signals with a single switched input. An example of equipment using this technique for WLAN is the Agilent N4011A MIMO Multi-Port Adapter.

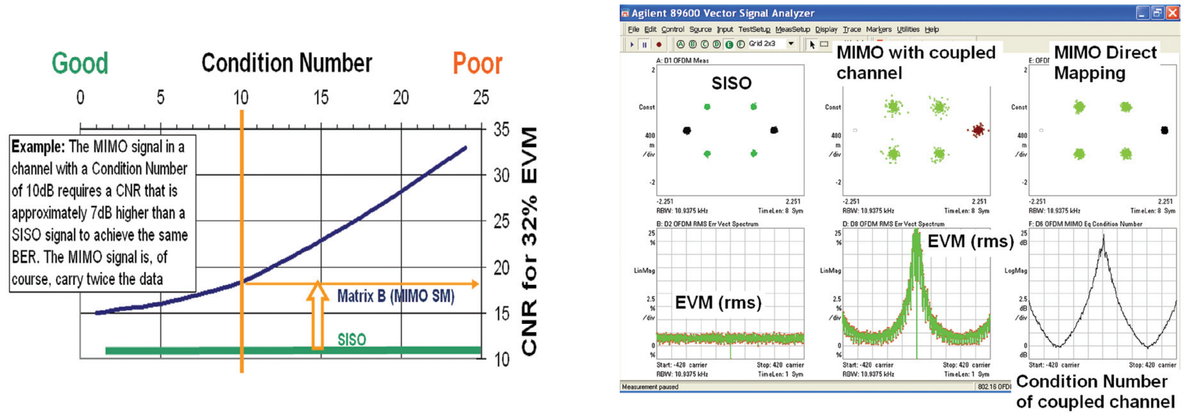


Figure 5 *Results demonstrating MIMO needs a better CNR than SISO.*

excess errors in the receivers' channel estimation due to insufficient processing resolution will cause receiver performance to degrade faster than expected. A further step in testing is to add a delay in the coupling, which introduces a phase variation proportionate to the OFDMA subcarrier.

The EVM trace in the Agilent 89600 VSA display of *figure 5* shows a V-shape indicating a time delay in an OFDM signal. In this example, the signal amplitude was first adjusted to ensure there was measurement noise, resulting in a raised level of EVM (RCE). The match between the increase in EVM and the worsening condition number is clearly seen in the bottom, center and right traces.

Distortion in one component degrades all coupled codewords (streams).

In a direct-mapped configuration, where the measurement is made on individual transmitter outputs, distortion from an analog component such as an amplifier or mixer will only affect the data codeword (stream) it is carrying. If however the data signal is precoded, such as with codebook 1 or 2 in LTE, the codewords share analog components and are affected by distortion in any of them.

To create the measurements in *figure 6*, a MIMO signal was subject to the 1,1,1,-1 precoding known as codebook 1 in LTE, or spatial expansion in WLAN. The gain of one of the receiver amplifiers was set to clip the ADC.

The left-hand column shows the individual signals before the coupling was removed. One of the curious MIMO measurement effects due to correlated interference can be seen. QPSK appears as a 3*3 constellation. It is called the "constellation of constellations". Despite this, it's clear the lower signal is suffering some distortion not seen on the upper signal.

In the center column, the signals have been separated so both are QPSK, but note how both are suffering some of the distortion previously only seen on one half. Finally, the right-hand column is a transmit diversity signal fed through a system where one transmitter was distorted. The point to note is that neither signal appears distorted; indicating that only measuring fully decoded diversity signals can mask physical hardware problems.

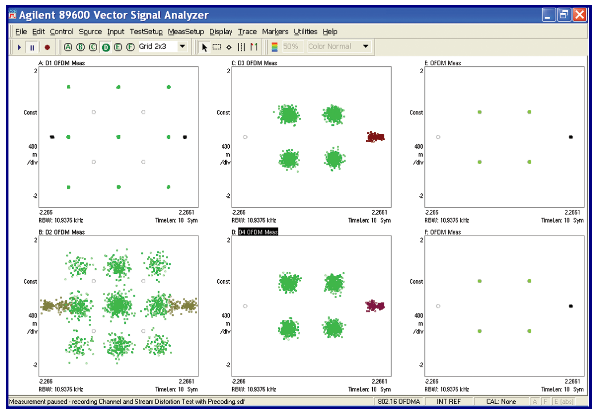


Figure 6 *In the left-hand column, distortion in one channel component is seen to only affect the lower trace. The spatially multiplexed signal in the center shows both streams impaired. The right-hand trace shows how the impairment is hidden when diversity, rather than spatial multiplexing, is applied.*

Summary

MIMO is an exciting addition to the transmission methods available to the radio engineer. This article has provided information relating to the key aspects of MIMO operation and measurement – showing how Agilent's design and test solutions help you ensure your receivers and transmitters are operating correctly.

Useful Resources from Agilent

To order your free copy of Agilent's new MIMO Poster "Ten Things You Should Know about MIMO" please visit **www.agilent.com/find/mimo-mwj**.

To view archives of Agilent's MIMO webcasts, please visit **www.agilent.com/find/webcasts**.

For more information on Agilent's suite of MIMO design and test solutions, please visit **www.agilent.com/find/mimo**.

5989-9618EN October 2008

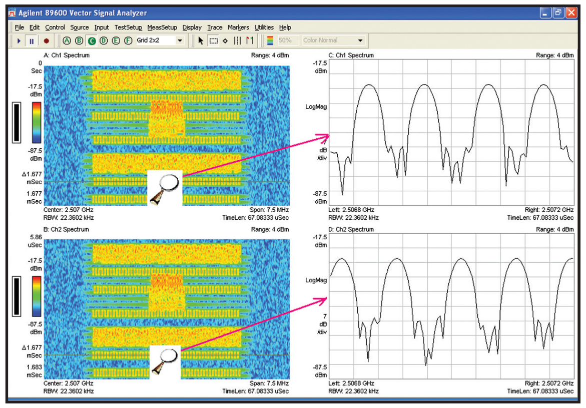


Figure 2 *The distinct MIMO channel training subcarriers in LTE.*

MIMO techniques are applied differently in the downlink and uplink of a cellular radio system.

In WLAN, the radio link is designed to allow symmetric operation. Figure 1 shows how this model has changed for cellular use, where the internet-led data downloading model results in the downlink being designed to have higher capacity than the uplink.

WiMAX and LTE base stations will have at least two transmitters. A number of designs have four or more transmitters, allowing the combination of MIMO and transmit diversity or phased array beamforming. All mobiles capable of supporting MIMO will have two receivers. The benefit of receive diversity is sufficient to mean mobiles would probably have two receivers even if MIMO is not initially implemented.

Figure 1 also shows the terms associated with the multiplexing of the incoming data signal into streams and layers. The incoming user data is separated into codewords (streams). If spatial multiplexing and diversity are being used in combination, there is a further step of mapping the codewords to layers, shown in the grey box. In this figure, direct mapping is shown, where no intentional cross coupling takes place before transmission.

In WLAN and WiMAX the incoming user data is multiplexed into streams which have the same modulation format (QPSK, 16QAM etc), but in LTE it is possible to have different modulation applied to each codeword. This points us to another of the MIMO fundamentals relating to the distinct difference between channel and data recovery.

MIMO signal recovery is a two-stage process.

Prior to demodulating the individual streams, the signals which were coupled as they travel through the channel have to be separated. To do this, the receivers look for channel training information which is unique to each transmitter. The generic term for a method using a special training mechanism is "non-blind".

In WiMAX and LTE this part of the signal can be made clearly visible. Channel estimation subcarriers are split among the different transmitters, so that no transmitter is using the same frequency at any one time. 802.11n originally considered this method, but settled on the use of orthogonal codes to distinguish the transmitters.

Figure 2 shows the spectrograms of two signals measured directly from LTE transmitters, and the zoomed-in spectral component for one of the training symbols. The LTE reference signal (RS) subcarriers can clearly be seen to be using different frequencies. Unlike the WiMAX pilots, the RS is only transmitted every 3rd or 4th symbol. The power level of all the subcarriers is the same, and their phase and timing relationship is known, which means it is possible to create a vector representation of the channel. This in turn provides the coefficients required to separate the data streams.

Phase differences don't affect open loop MIMO.

Open loop MIMO means the transmit signals are direct mapped. No feedback from the channel is used to couple (precode) the MIMO aspect of the signals.

Another way of saying this is that phase only matters when you couple different signals twice, which is most easily explained using the coupling of two CW signals on different frequencies. The first time they are combined there may or may not be a known phase relationship between them. It doesn't matter; the amplitude and phase of the two components will not be affected. If, however, they are coupled again, part of each signal will be common, and they will sum as vectors. The result will be changes in both amplitude and phase dependant on the combination of the original phase and the coupling factor. Complete cancellation could be one result.

This simple vector addition example explains why open loop MIMO, where the transmit signals have not been coupled, are not affected by the phase of the transmitted or received signals. The signals are only coupled once - in the channel. It also explains why uplink MIMO operation using two physically separated mobiles can work. Incidentally, precoding cannot be applied in this case, both because the input data is only available separately in each mobile, and also because the phase between mobiles cannot be controlled.

Figure 3 shows a test configuration for UL multi-user, MU, (collaborative) MIMO. The dashed line indicates the process that would take place in a real system, where the base station controls the transmission timing and power of each mobile such that the signals arrive aligned at the base station receiver. The mobiles themselves tune their frequency to match the base-station reference. In a test configuration, cables can be used and timing, power and frequency offsets can be applied with other impairments to ensure the receiver algorithms are sufficiently robust.

Cross-channel measurements can be made using a single input analyzer.

Most engineers will start with single input measurements because they are simple and provide much of the basic information about how well the components in the radio are working using available equipment. The presence of the subcarriers used for MIMO channel training in LTE and WiMAX allows a significant extension to what can be done with a single input analyzer.

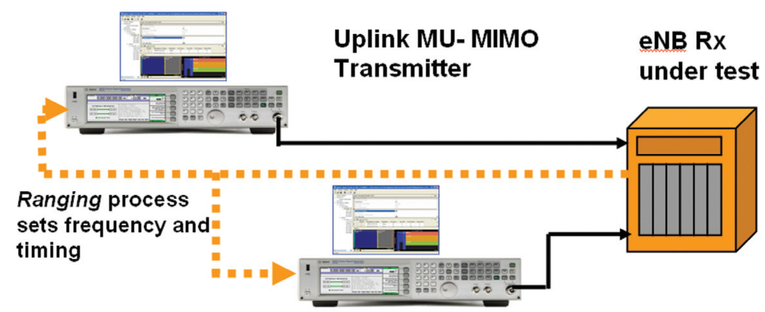
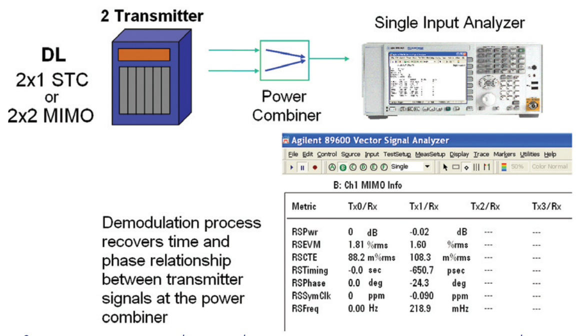


Figure 3 *Operation of multi-user (collaborative) MIMO in the uplink relies on the system working with only approximate power, frequency and timing alignment. The Agilent MXG with signal studio software–based test configuration shown here allows these parameters to be varied individually.*

As part of the measurement demodulation process, the isolation between channels can easily be measured. This assumes the signals have not been coupled in the transmitter. In LTE, the reference signal is not precoded, so even when precoding is applied it does not affect the measurement. For WLAN and WiMAX, direct mapping should be used.

Signals using transmit diversity only require a single receiver, so they can be fully analyzed with one input. Even MIMO signals that are direct mapped can be individually analyzed, although it will not be possible to remove any unwanted coupling. The single input analyzer should be connected to each transmitter output in turn, and the analysis configured for the appropriate codeword (stream).

The most precise RF phase and timing measurements can be made with a single input analyzer. If a power combiner is used to feed multiple inputs into the single input analyzer, as shown in *figure 4*, relative timing and RF phase measurements may be made by demodulating the signals and comparing the symbol alignment. This method entirely removes any effect of additional equipment, and can offer sub-nanosecond and degree-measurement resolution.



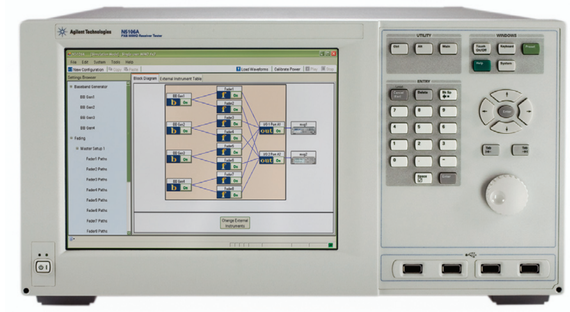
Metric	Tx0/Rx	Tx1/Rx	Tx2/Rx	Tx3/Rx
RSPwr	0 dB	-0.02 dB	---	---
RSEVM	1.81 %rms	1.60 %rms	---	---
RSCTE	88.2 m%rms	108.3 m%rms	---	---
RSTiming	-0.0 sec	-650.7 psec	---	---
RSPhase	0.0 deg	-24.3 deg	---	---
RSSymClk	0 ppm	-0.090 ppm	---	---
RSFreq	0.00 Hz	218.9 mHz	---	---

Figure 4 *Cross-channel measurements using a single-input MXA spectrum analyzer and power combiner include RF frequency and phase*

Antenna configuration has a major impact on the channel-path correlation.

After the receiver has been proven with static channels, fading according to different pedestrian and vehicular speed profiles can be added, using equipment such as Agilent's new PXB MIMO Receiver Tester. As noted earlier, the channel includes the antennas at both transmitter and receiver. There has been a lot of effort to model how changes in the antenna configuration affect the path correlation.

For certification, a subset of the possible antenna configurations is chosen, but during design or more thorough performance comparisons, it is important to assess performance using a much wider range of scenarios. The Agilent PXB MIMO Receiver Tester provides the flexibility needed to do this, calculating the correlation factors as it does so.



Agilent's N5106A PXB MIMO Receiver Tester

MIMO needs a better carrier-to-noise ratio than SISO.

MIMO offers improved spectral efficiency over SISO because, under the right circumstances, the channel capacity increases linearly with the number of transmit-receive pairs. But it doesn't come entirely for free. When comparing the performance of SISO and MIMO, the first step is to give the total transmitted signals equal power. With a direct mapped MIMO signal, this equates to requiring the carrier-(signal) -to-noise ratio, CNR, for each MIMO transmitter signal to be at least 3dB better for the same demodulation performance. This represents the point on the left hand axis in the graph of *figure 5*.

By introducing cross coupling, moving left to right in the graph, we can see how the CNR has to further improve as the condition number of the MIMO channel gets higher. The matrix condition number is a standard mathematical concept that indicates the potential increase in capacity for a particular MIMO channel. The poster associated with this article provides more details on how it is calculated.

In-phase (0°) coupling is a starting point for testing a MIMO receiver, as the step beyond single channel sensitivity testing. It will verify how well the channel recovery operates when the training signal has noise. For example, when a lot of coupling is applied,