# Dual Channel MIMO Measurements for WiMAX™ Wave 2

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**In designing, troubleshooting and optimizing WiMAX Wave 2 systems, a variety of dual-channel measurements can provide essential insight into their operation and performance.**

| TYPE | Measure at | Matrix Decoder | OFDM Demod. | Equalizer Channel Freq. Response | MIMO Channel Freq. Response |
|---|---|---|---|---|---|
| A (STC) | Tx0 or Tx1 | OFF | Crosstalk Included | h0 * | h0 & h1 |
| A (STC) | Tx0 or Tx1 | ON | Crosstalk Removed | h0 or h1 | h0 & h1 |
| A (STC) | Rx | ON | Pre-encoded Matrix A Stream | h0 or h1 | h0 & h1 |
| B (MIMO) | Tx0 & Tx1 | OFF | Crosstalk Included | h00 or h11 * | h00, h01, h10 & h11 |
| B (MIMO) | Tx0 & Tx1 or Rx0 & Rx1 | ON | Matrix B Streams | h00, h01, h10 or h11 | h00, h01, h10 & h11 |

Frequency response based on pilots-only except when marked with * then based on preamble, pilots and/or data

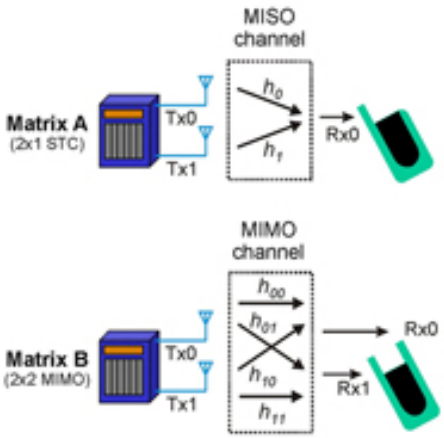
[1]

Table 1. Dual Channel MIMO Measurements for WiMAX Wave 2 Matrix A and Matrix B Configurations

The WiMAX™[1] Wave 2 specification currently supports multiple antenna operation for achieving improved system performance in both downlink (DL) and uplink (UL) transmissions. For example, systems using Multiple-Input Multiple-Output (MIMO) configurations can provide higher data rates with improved spectral efficiency when compared to traditional Single-Input Single-Output (SISO) implementations. Characterizing and troubleshooting these advanced WiMAX systems often requires a dual-channel signal analyzer with channel estimation capability, a “matrix decoder” and an OFDM demodulator.

**Matrix A and Matrix B Configurations**

Multiple antenna operation in a DL transmission of a WiMAX Wave 2 system may include Space-Time Coding (STC), defined as Matrix A, or MIMO, defined as Matrix B. Typical downlink configurations for the 2x1 STC and 2x2 MIMO are shown in Figure 1.




[2]

In Matrix A (STC) operation the channel can be modeled as two paths connecting the two transmitting antennas at the Base Station (BS) to a single receive antenna at the Mobile Station (MS). Each signal path can be represented by a unique channel coefficient or “hx”. Each coefficient represents a (presumed linear) combination of all paths between the respective transmit-to-receive antenna pair and may include channel-to-channel crosstalk created within the transmitter, along with numerous multipath signals present in the wireless channel. One technique for improving signal reception is by transmitting differently-coded versions of same signal from each antenna at different times at the same frequency. This spatial diversity technique is implemented in Matrix A configurations.

Alternately, Matrix B (MIMO) systems may achieve higher data rates and improved spectral efficiency by simultaneously transmitting different data streams from each antenna over the same frequency channel. For the Matrix B configuration shown in figure 1, the measured received signals in a noiseless system are:

$R_{x0} = h_{00}T_{x0} + h_{10}T_{x1}$ (1)

$R_{x1} = H_{01}T_{x0}+h_{11}T_{x1}$(2)

The Matrix B receiver, having knowledge of the four channel coefficients, can differentiate and recover the transmitted waveforms using the following simplified technique.

(3)$T_{x0} = B(H_{11}R_{x0} - h_{10}R_{x1}$

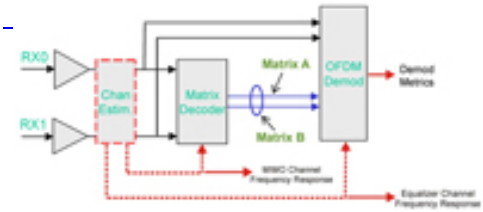
(4)$T_{x1} = B(-h_{01}R_{x0}+H_{00}R_{x1})$

(5)where B= 1 $H_{00}h_{11} - h_{10}h_{01}$

These equations may also be represented in matrix form as

(6)$[T_x]=[H]^{-1}[R_x]$

It is the function of a matrix decoder to perform the channel matrix [H] inversion and associated mathematical operations to recover the original transmitted data streams and pass this information to the demodulator. Note that matrix decoding operation is separate from, and performed prior to, the demodulation operation.

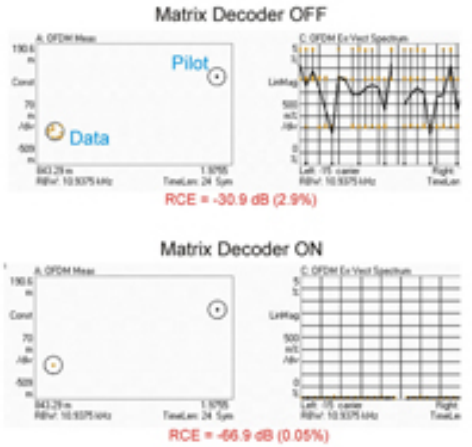



[3]

A practical WiMAX receiver may use eigen decomposition or MMSE techniques [1] for the actual data recovery when correlations exist between the channel coefficients. As mentioned, data recovery requires knowledge of the channel coefficients and their complex values are measured by the receiver or dual-channel signal analyzer using the unique pilot structure contained in the WiMAX OFDM waveform [2]. It is important to note that accurate matrix decoding depends on a degree of independence in channel coefficients, and this is further affected by the amount of noise in the channel. Correlated channel coefficients and/or noise result in reduced system performance as the channel matrix becomes “ill-conditioned” and difficult to accurately invert.

In the uplink, MIMO can be implemented with coordinated simultaneous transmissions from two separate MS (handsets) operating on the same frequency channel. This technique, referred to as Uplink Collaborative Spatial Multiplexing (UL-CSM), uses two or more receive antennas at the BS and a single antenna at each MS for 2x2 MIMO operation[2]. Note that in this configuration the MIMO operation is on the uplink only. DL-MIMO requires two antennas and receiver channels for each MS.

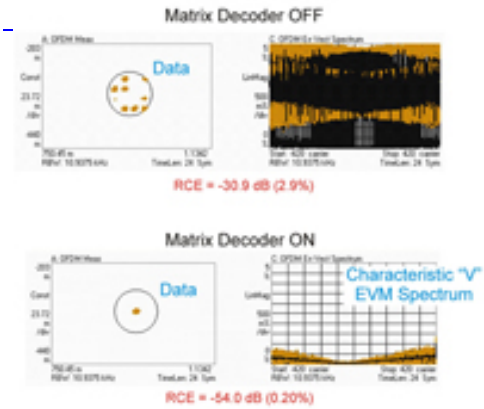
**Channel Estimation, Matrix Decoding and Demodulation**




[4]

Signal analysis and troubleshooting of Matrix A and Matrix B waveforms can be performed with Vector Signal Analyzers (VSAs) one or more inputs. A number of basic measurements, such as channel-to-channel crosstalk and timing within the STC or MIMO transmitter, can be made using a single-input analyzer connected directly to the selected transmitter output.[3] This single-input approach is useful when transmit signals are well-isolated (as with the direct connection described above) and would not require a matrix decoder for demodulation of the waveform. Some test procedures, such as the Radio Conformance Testing (RCT) defined in the WiMAX Wave 2 profile, specify single-channel measurement of transmitter signal quality in the presence of potential crosstalk and where the matrix decoder is not used. Unfortunately, during system optimization and troubleshooting, this type of basic measurement provides little insight into the root cause of many signal errors. In such cases, uncovering the contributions of different error sources often require measurement comparisons with and without a matrix decoder. For Matrix A systems, a single-channel VSA can be used for testing with and without the decoder. For Matrix B and UL-CSM systems, a dual-channel VSA is typically required to fully analyze these increasingly complex waveforms.

Figure 2 shows the measurement flow through a typical dual-channel VSA with WiMAX MIMO measurement capability, such as the Agilent 89600-series analyzer with option B7Y. For Matrix B configurations, MIMO signal analysis begins with estimating the complex channel coefficients using measurements made on a large number of known pilot subcarriers received from the two input signals, shown as Rx0 and Rx1 in the figure. These four channel coefficients, displayed as a function of subcarrier frequency, can be very useful as an analysis tool when optimizing and troubleshooting MIMO systems. The estimated channel coefficients are primarily used by the matrix decoder to recover the two independent data streams from the 2x2 MIMO signal. The matrix decoder is designed to reverse the channel effects and does not perform data demodulation. As shown in the figure, the recovered Matrix B data streams are then sent to the OFDM demodulator for further signal analysis.




[5]

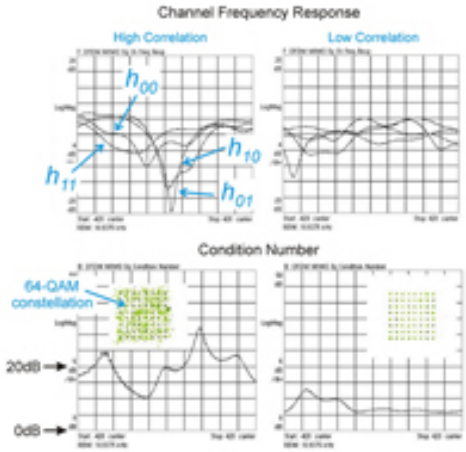
As previously discussed, when using direct connection to the transmitter ports, a matrix decoder may not be required for basic demodulation. Figure 2 also shows two measurement paths that bypass the matrix decoder. In this configuration, the channel characteristics are estimated using the information in the preamble, pilots

and/or associated data subcarriers. These channel responses may contain transmitter and channel crosstalk and are different from the MIMO channel coefficients which are derived from the embedded MIMO pilots. These channel responses are used to equalize (flatten the frequency response of) the waveforms as part of the demodulation process and may be very helpful when troubleshooting WiMAX waveforms. However these two measured channel responses do not contain enough channel information to perform the matrix decoder operation.

Matrix A signal analysis follows the same signal path through the VSA as a Matrix B configuration but only requires a single-channel analyzer. Table 1 shows a brief list of typical measurement configurations when testing Matrix A and Matrix B waveforms using a single and dual-input solution such as the Agilent 89600-series VSA. The table lists the effects of the matrix decoder on the OFDM demodulation results. The table also shows the displayed channel coefficients when selecting the Equalizer and MIMO Channel Frequency Response functions on the VSA.

**Uncovering Signal Impairments**

Example measurement results are shown in Figure 3 for a simulated pair of Matrix B waveforms using a dual-channel VSA. In this example, the influence of significant crosstalk between the transmitter channels is shown with and without the use of the matrix decoder. The left plots show a portion of the demodulated IQ constellation with one pilot and one data symbol point enlarged to show detail. With the matrix decoder off, shown in the upper left, there is a spreading in the data constellation as the other transmit channel couples into this measurement at a relative level of -29 dB. This high level of crosstalk results in a measured Relative Constellation Error (RCE) of 2.9%. The error from this crosstalk alone would be enough to fail the RCT requirement for a WiMAX Wave 2 waveform. Also shown in the upper right of this figure is the associated Error Vector Spectrum - the OFDM error plotted vs. subcarrier frequency. This measurement display is an excellent tool for troubleshooting timing errors in the system as will be shown in the next example.




[6]

The lower plots in Figure 3 show the measurement results with the matrix decoder active. The matrix decoder removes the effects of the crosstalk using the four (in the case of 2x2 MIMO) channel estimates. When the matrix decoder removes the

crosstalk the RCE improves to better than 0.05% and the error vector spectrum and data constellation reflect the difference. Note that the constellation points for the pilots are not affected by crosstalk or the matrix decoder. The pilots do not overlap in time and frequency, thus the pilot constellation points are not spread and the pilots can be used to measure the level of crosstalk between the two transmit channels.

While the matrix decoder is not used for RCT testing it is an excellent troubleshooting tool for measuring and removing the effects of crosstalk that could obscure additional signal impairments. For example, Figure 4 shows how the matrix decoder removes crosstalk to uncover a symbol timing error present in the system. As before, the upper plots show the constellation and error vector spectrum of a signal with a crosstalk level of 29 dB. Without the matrix decoder the error spectrum is dominated by the crosstalk, making it difficult to see the timing error in the waveform. With the matrix decoder enabled, the crosstalk is removed from the measurement and a timing error can easily be observed. In the measurement on the lower right the error spectrum now shows the familiar “V” pattern that is characteristic of a symbol timing error [4].

**Channel Frequency Response Measurements**

The equalizer and MIMO channel responses are other useful diagnostic tools for characterizing Matrix A and Matrix B waveforms. The magnitude and shape of these responses can provide an understanding into the quality of received waveforms prior to demodulation. For example, it is known that MIMO systems operating in rich multipath environments will generally experience low correlations between the channel coefficients, making better data recovery possible at the receiver. When the coefficients are highly correlated, the system performance rapidly degrades. Figure 5 shows the magnitude of the measured channel coefficients for two different MIMO channels, one with relatively high correlation (left) and the other with low correlation (right). Both measurements are made with the matrix decoder enabled. For the high correlation case the pairs of coefficients have a similar complex frequency response and it would be expected that the system performance would be reduced. As shown in the inset on the lower plot, the measured 64-QAM constellation shows a high degree of signal distortion. As a comparison, the measurement in the upper right shows the measured channel coefficients having low correlation. In this case, the coefficients have dissimilar frequency responses resulting in an improvement in the data recovery as shown by the measured constellation in the lower right of the figure.

**Condition Number**

Another useful troubleshooting tool is the “MIMO condition number” which is calculated from an eigen-decomposition of the channel matrix [H] and taking a ratio of the maximum singular value to the minimum singular value at each subcarrier. It is a measure of how ill-conditioned the matrix in the receiver is. The ratio is usually displayed on a log scale, and the ideal ratio of singular values for a well-conditioned matrix is 1, or 0 dB. As a general guide, when the condition number of the signal is larger than its signal/noise ratio, the matrix decoder will not be able to effectively separate the signals and demodulation performance will be poor. This is evident by the condition number response shown in the lower left plot of Figure 5. In this case,

the condition number is close or above a 20 dB value and the demodulated constellation is very poor. As a comparison, the plot on the right shows a condition number that is generally below 10dB and the associated constellation plot is greatly improved.

**Conclusion**

WiMAX Wave 2 systems using either Matrix A or Matrix B configurations can greatly improve system performance by taking advantage of the rich multipath characteristics of the wireless environment. In designing, troubleshooting, and optimizing these systems a variety of dual-channel measurements can provide essential insight into their operation and performance.

Ben Zarlingo has a BSEE from Colorado State University and has been with HP/Agilent for 28 years. His primary focus for the past dozen years has been emerging communications technologies and measurements using spectrum and vector signal analyzers.

**References**

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[2] Agilent Technologies, Webcast, “WiMAX Wave 2 Testing - MIMO & STC”, January 17, 2008, www.techonline.com

[3] “Matrix A and B re-measured; Single channel measurements for WiMAX™ Wave 2 reduce the need for multi-channel analysis” WiMAX Daily, June 18, 2008

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