Agilent Technologies

Introduction to MIMO and Ten Things You Should Know

March 2009

The Full Agenda

System Operation

1:Cellular MIMO uses downlink and uplink differently

2: MIMO needs at least 2 transmitters and 2 receivers

3: MIMO signal recovery is a 2 step process

MIMO signal transmission and recovery

4: Transmit & receive phase differences don't affect open loop MIMO

5: BS and MS antenna configuration has a big impact on path correlation

6: MIMO needs a better SNR than SISO

7: Precoding and eigenbeamforming couple the signals to suit the channel

Single and Multiple input measurements

8: Cross channel measurements can be made with a single input analyzer

9: Condition number measures the short term channel performance

10: Distortion in one component can degrade both codewords

10 Things about MIMO: The Agenda

System Operation

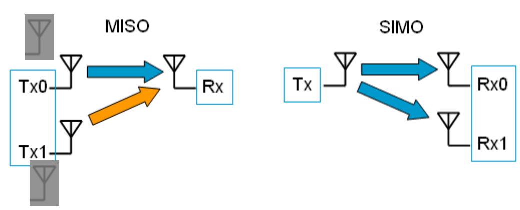
MIMO signal transmission and recovery

Single and Multiple input measurements

0: MIMO and Diversity – Different Objectives

Multiple Antennas can be used in a variety of ways:

- Beamforming
- Transmit Diversity
- Receive Diversity

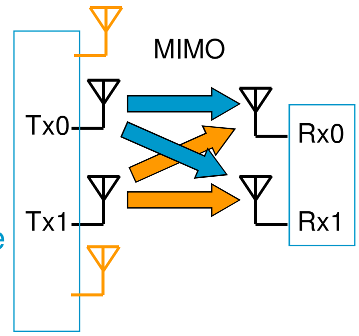


Diversity techniques protect against fading, and improve coverage

MIMO and Diversity

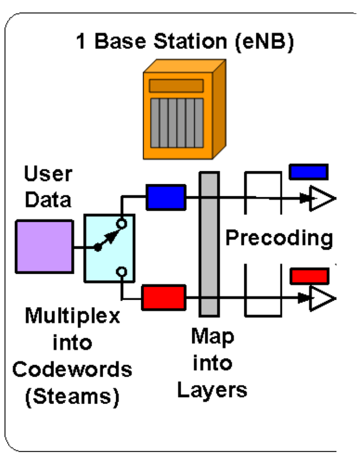
MIMO Spatial Multiplexing is the simultaneous use of the same frequencies to transmit different signals

Spatial multiplexing increases the spectral efficiency of the transmission, increasing capacity



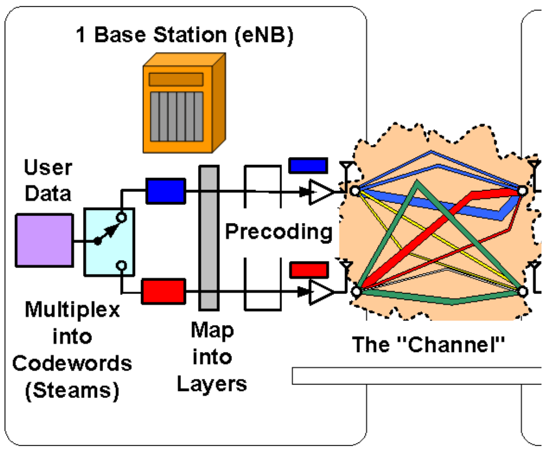
MIMO and diversity can be combined

1: MIMO is Used Differently in the Downlink and Uplink of a Cellular System



- In the Downlink, it's like WLAN, the whole MIMO transmission is given to a Single User (SU)
- The scheduler in the Base Station multiplexes user data traffic into codewords ("streams" in WiMAX)
- If there are more transmitters available than codewords, layer mapping is used

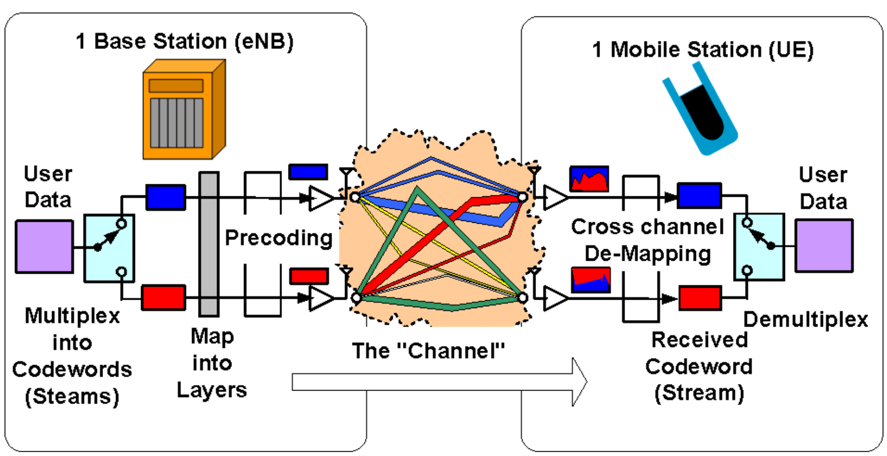
MIMO in the Downlink – Coupling in the Channel



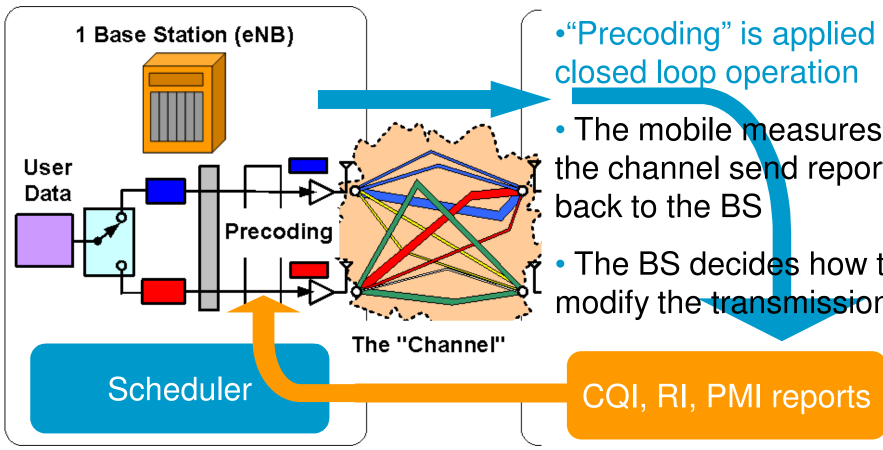
- The channel starts after precoding
- Unwanted coupling in the radio will introduce errors in precoding
- The antennas are a critical part of the channel

MIMO in the Downlink - Reception

A single mobile recovers the MIMO transmission



MIMO in the Downlink – Closed Loop



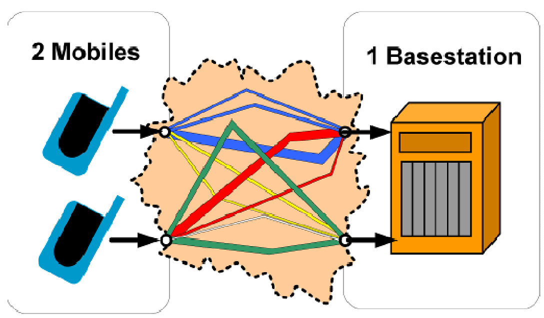
•"Precoding" is applied for closed loop operation

- The mobile measures the channel send reports back to the BS
- The BS decides how to modify the transmission

2: MIMO Operation Requires at Least Two Transmitters & Two Receivers

In cellular MIMO, two mobiles are used together in the Uplink to create the MIMO signal

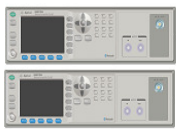
Known as "Collaborative" MIMO in WiMAX. "Multi-User MIMO" in LTE

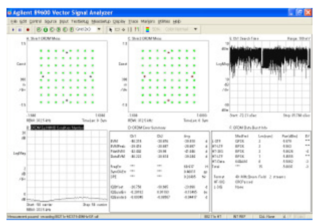


The receivers have to be in the same place - because both signals are used to calculate the amount of cross coupling

….at Least Two Transmitters & Two Receivers

For post processed measurements, the signal capture hardware does NOT have to be in the same unit





Measurement software gathers IQ information simultaneously from multiple receivers

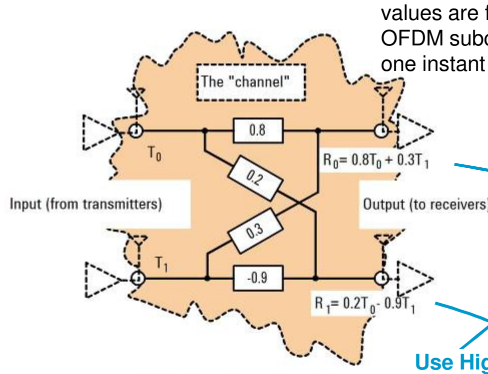
Measurement software gets data sequentially from a multiplexing switch

3: MIMO Signal Recovery is a Two Step Process

(Real only) examples values are for a single OFDM subcarrier at one instant in time

Step 1: Recover the channel coefficients

Need a robust signal format that uniquely identify each transmitter



Use High school simultaneous equations to express T_0, T_1 in terms of R_0, R_1

Calculate Input from Output:

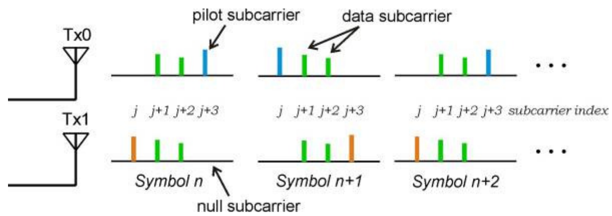
$T_0 = 1.15R_0 + 0.39R_1$

$T_1 = 0.26R_0 - 1.03R_1$

Step 2: Separate and demodulate the signals

MIMO Signal Recovery

Recovering the channel coefficients



In WiMAX and LTE, specific subcarriers are allocated as pilots

Their location is changed from symbol to symbol

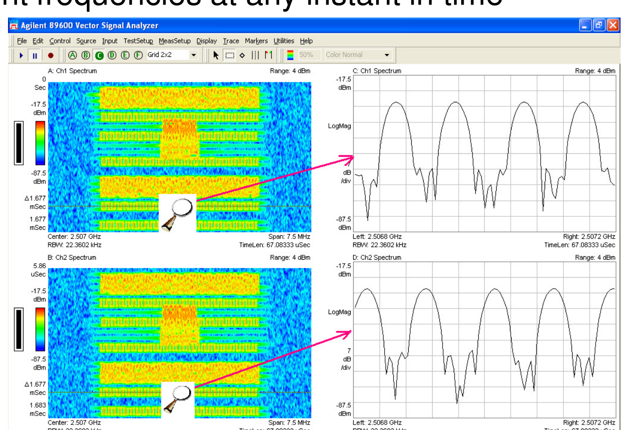
Their power can be boosted to ensure errors from recovering the training signal do not dominate demodulator performance

MIMO Signal Recovery – Spectrum View

The traces in this LTE signal show how the Reference Signals (pilots) are on different frequencies at any instant in time

The spectrograms on the left show spectrum versus time (vertical axis)

Unlike 802.16 OFDMA, the LTE RS is not present on all symbols



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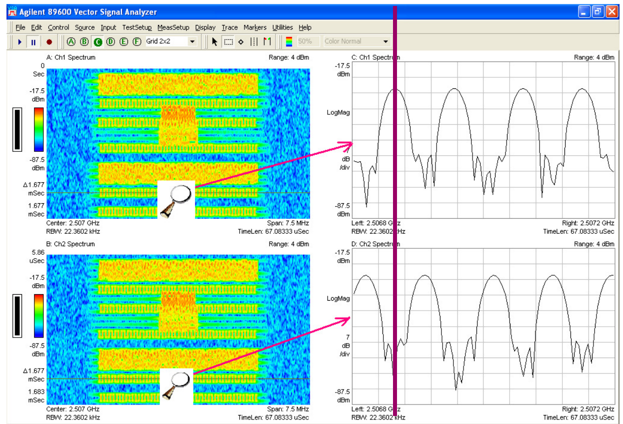


Channel Training Signals Vary with Technology

Summary Table

LTE	WiMAX	Wireless LAN
Reference signals (pilots) use different subcarriers for each transmitter **The QPSK Reference signals are transmitted every 3rd or 4th symbol, mixed with data**	**BPSK Pilot subcarriers use different frequencies. Their positions vary symbol by symbol within a subframe, but are constant from frame to frame.** **Subcarrier coverage builds over several symbols, allowing interpolation** **Details depend on the zone type (e.g. PUSC, AMC)**	**A preamble is used for training. The same subcarriers are used for all transmitters. Signals are separated by a CDMA code** **4 orthogonal QPSK pilots are used (6 for 40MHz), sharing the same subcarriers. They are never transmitted without data**
HSPA+ uses code channels on the Common Pilot Channel, CPICH, with unique symbol bit patterns having different locations in the OVSF code domain		

10 Things about MIMO The Agenda

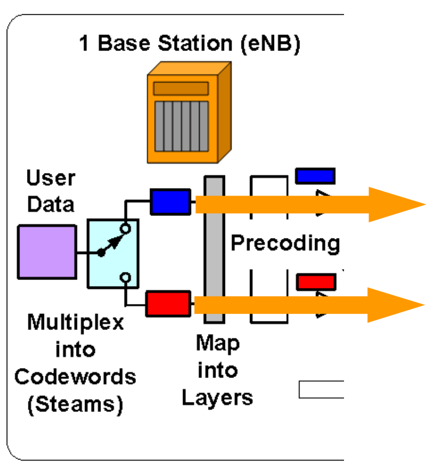
System Operation

MIMO signal transmission and recovery

Single and Multiple input measurements

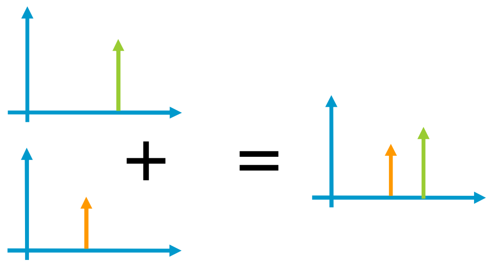
4: Transmit & Receive Phase Differences Don't Affect Open Loop MIMO

Open Loop MIMO implies direct mapping



Phase Differences

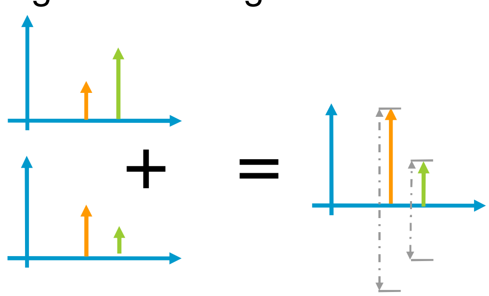
Phase only matters if you couple the same signals
Consider the case of an individual OFDM subcarrier (pilot)



Summing different signals the first time does not affect the individual components

Phase Differences

but summing common signals

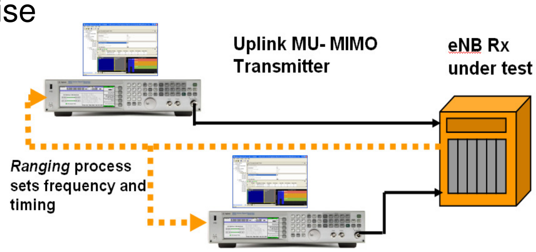


leads to vector addition

Application to Test Limits of Receiver Performance

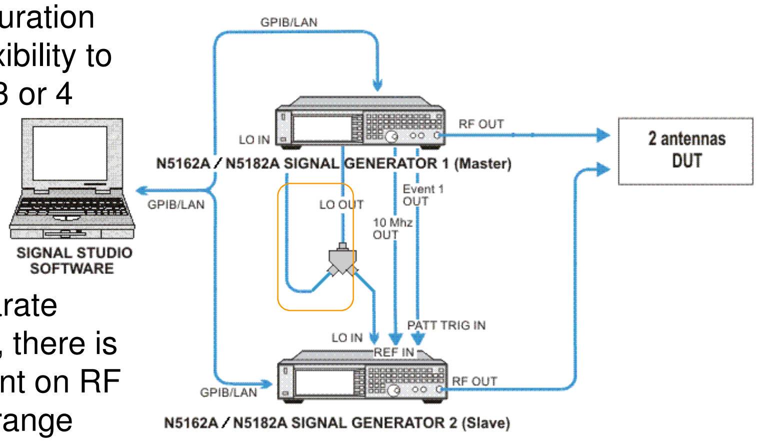
Combine the coded signal with controlled impairments using the signal generators

- Differences in amplitude
- Timing Offset
- Frequency offsets
- Phase Noise



N5182A Option 012: Phase Coherence

This configuration has the flexibility to expand to 3 or 4 generators



Using separate generators, there is no constraint on RF frequency range

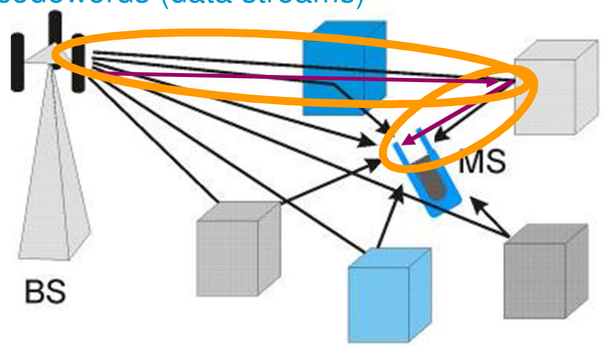
Timing synchronization is dealt with by instrument firmware

5: BS and MS Antenna Configuration Has a Big Impact on the Channel Path Correlation

Path correlation defines the coupling relationship between signals received at the antennas

It is important because it affects how easy or difficult it is to recover the individual codewords (data streams)

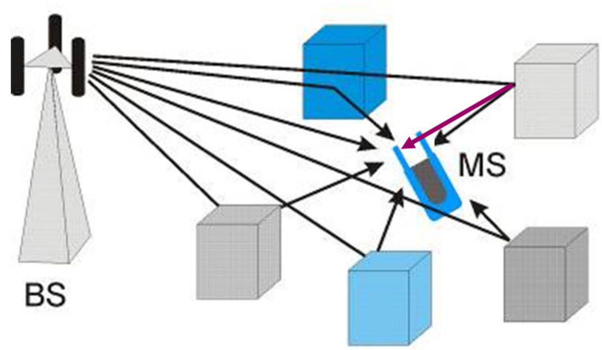
Each multipath item can have its own correlation factors

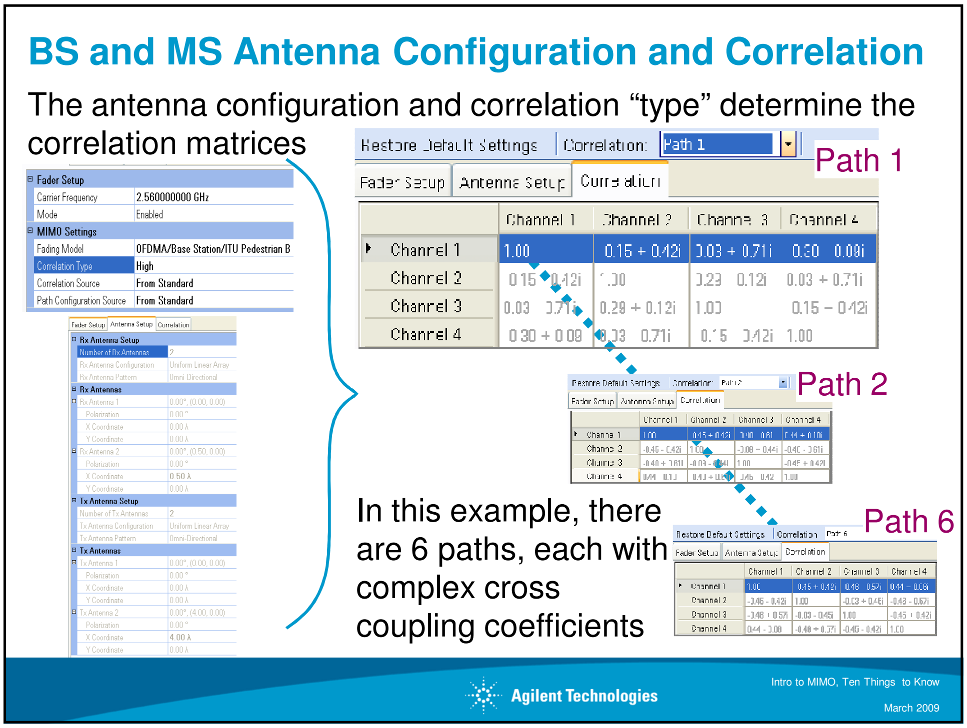


BS and MS Antenna Configuration Impact

Example: The angle of departure from the BS antennas is typically narrower than the angle of arrival at the MS

This gives the MS receivers the possibility of recovering different signals even if the antennas are closely spaced




BS and MS Antenna Configuration and Correlation
The antenna configuration and correlation "type" determine the correlation matrices
Path 1
Path 2
Path 6
In this example, there are 6 paths, each with complex cross coupling coefficients
Fader Setup
Carrier Frequency
2.560000000 GHz
Mode
Enabled
MIMO Settings
Fading Model
OFDMA/Base Station/ITU Pedestrian B
Correlation Type
High
Correlation Source
From Standard
Path Configuration Source
From Standard
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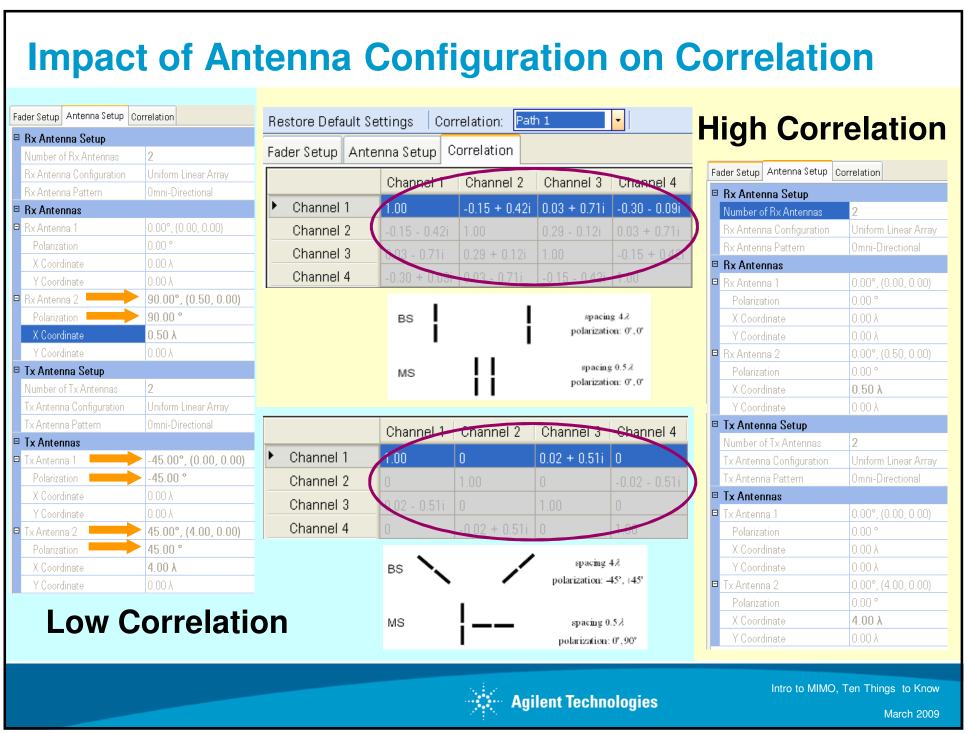
Impact of Antenna Configuration on Correlation
High Correlation
Low Correlation
Restore Default Settings
Correlation:
Path 1
Fader Setup
Antenna Setup
Correlation
Channel 1
Channel 2
Channel 3
Channel 4
BS
MS
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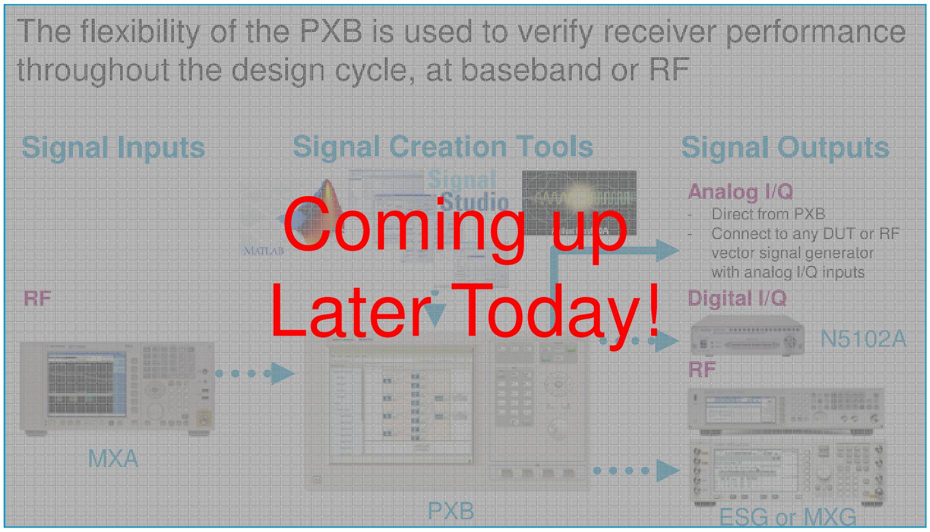
Simulating the Channel
N5106A PXB MIMO Receiver Tester



Channel Matrix Condition Number

What it is:

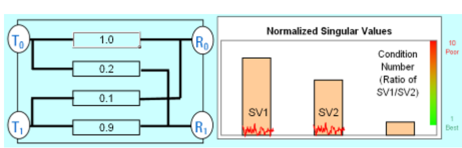
a) A way to check your MIMO system is functioning correctly

b) A short term indication of the SNR you need to recover a MIMO signal

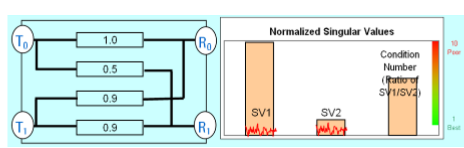
How you calculate it: Find the *singular values* of the channel matrix, and take the ratio of the highest / lowest

Simple examples:

A good channel

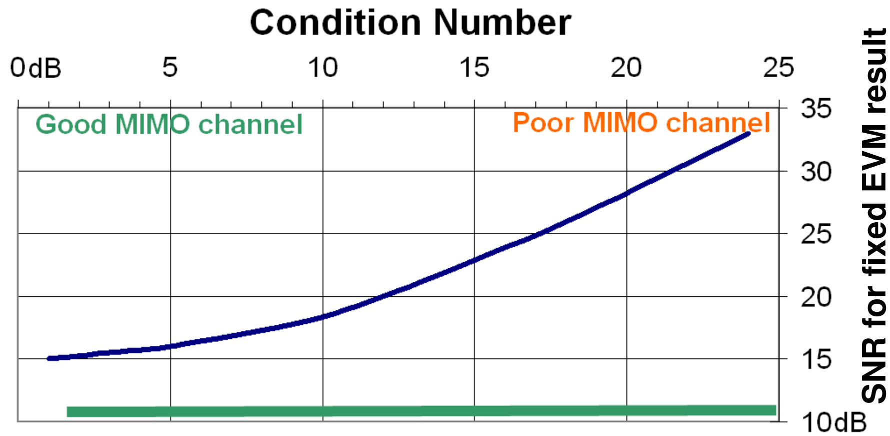


A poor channel



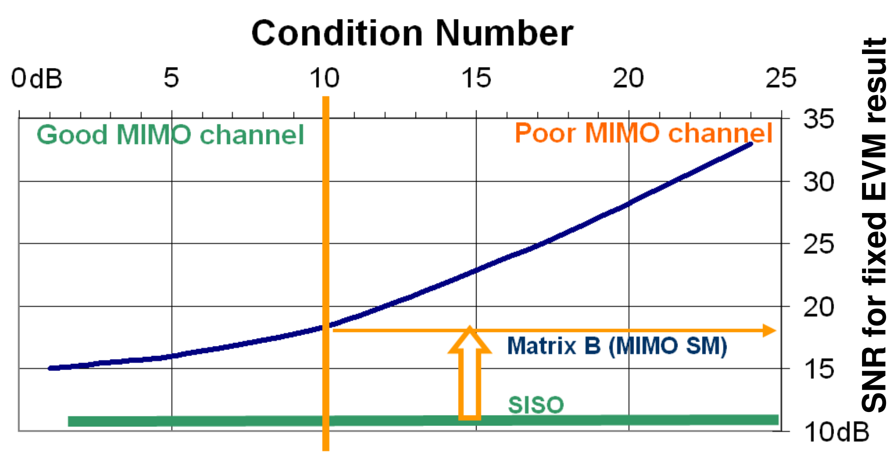
6: MIMO Needs Better Signal / Noise than SISO

Using a simple static channel, this graph shows how the SNR has to improve to maintain a constant performance as the condition number increases



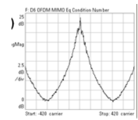
MIMO Needs Better SNR than SISO

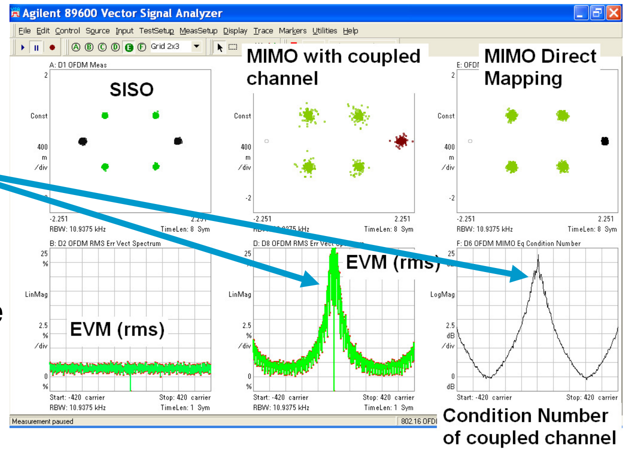
Example: Going from 0 to 10dB condition number means the SNR would have to be a further ~3dB better to maintain the same EVM



Example of MIMO versus SISO performance

Introduce a delay in a static channel to make the channel condition number vary with frequency



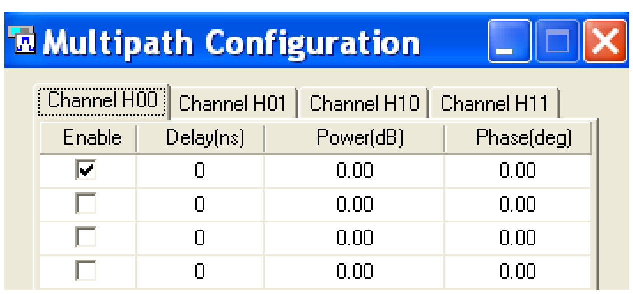


With a constant CNR, EVM gets worse as condition number increases

Would try not to use these frequencies for MIMO

Design a Static Channel Receiver Test

Add a static channel configuration in Signal Studio to give a known channel condition number



Enable	Delay(ns)	Power(dB)	Phase(deg)
☑	0	0.00	0.00
☐	0	0.00	0.00
☐	0	0.00	0.00
☐	0	0.00	0.00

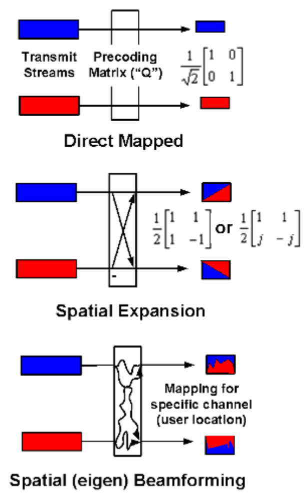
When noise is added, this provides a first step in confirming the receiver MIMO performance

7: Precoding and Eigenbeamforming Couple the Transmit Signals to Suit the Channel

Precoding can be very simple (LTE ***Codebook*** 0 is *Direct Mapped*)

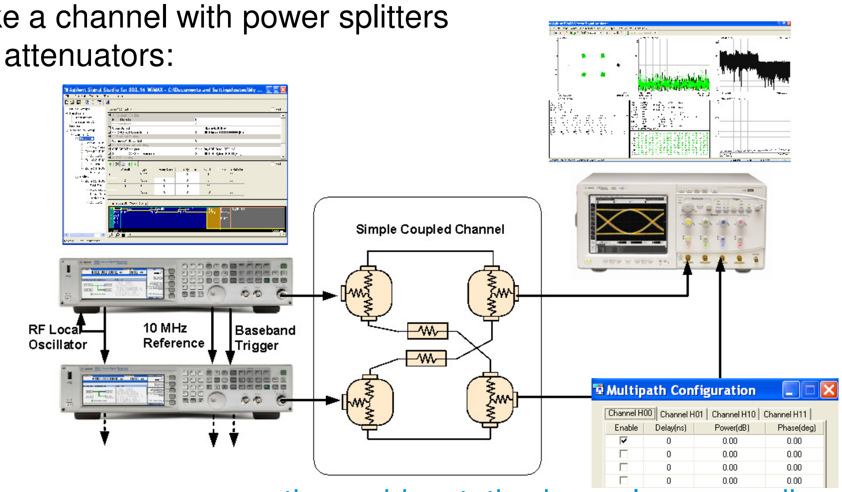
Some WLAN devices always apply Spatial Expansion

LTE does not precode the Reference Signal (pilots)



A Simple Example of Precoding Operation

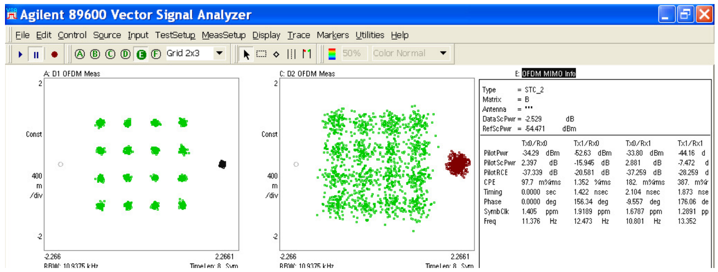
Make a channel with power splitters and attenuators:



………….then add a static channel as precoding

Precoding On a Static Channel

Channel Condition Number, $\mathbf{K}$ = 20dB. Receiver noise limited

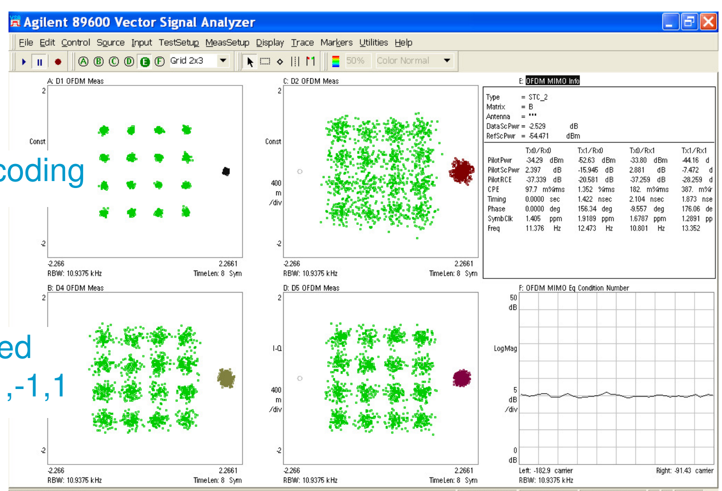


Without precoding, the SNR for one codeword is better than is needed, while the other is too low

Precoding Equalizes the Codeword Performance

No precoding

Precoded with 1,1,-1,1



10 Things The Agenda

System Operation

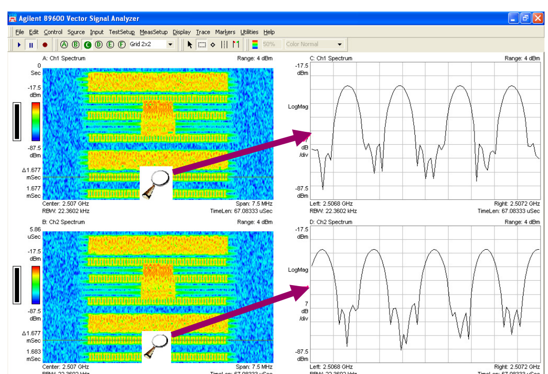
MIMO signal transmission and recovery

Single and Multiple input measurements

8: Cross Channel Measurements Can Be Made With a Single Input Analyzer

The Reference signals (pilots) uniquely identify each transmitter

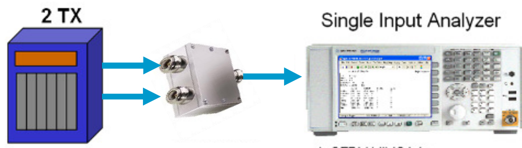
We use this to allow measurements on each separately



In LTE, the RS are not precoded. These measurements continue to work even when the signal is not direct mapped

Cross Channel Timing & Phase Measurement using a Power Combiner & Single Input

Using a power combiner removes ANY uncertainty due to timing jitter or calibration



A: OFDM MIMO Info

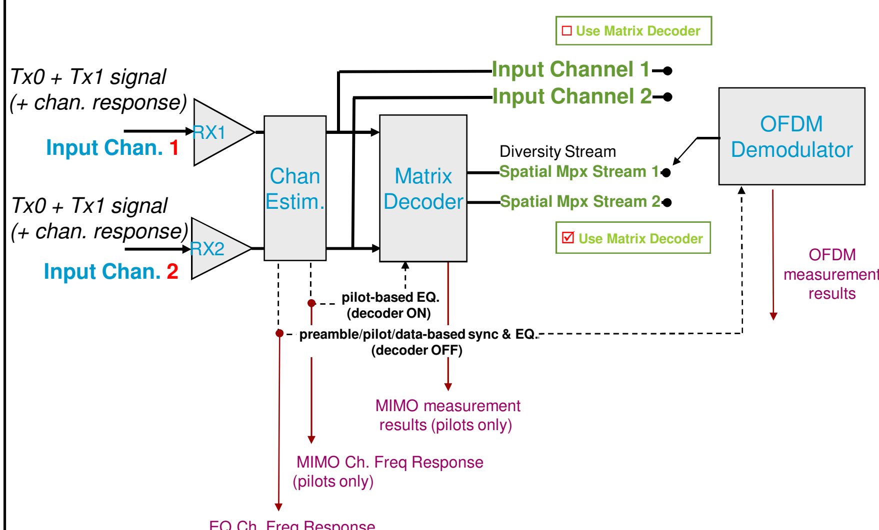
Type	= STC_2		
Matrix	= B		
Antenna	= 0		
DataScPwr	= -0.047	dB	
RefScPwr	= -46.702	dBm	

	Tx0/Rx0		Tx1/Rx0	
PilotPwr	-23.39	dBm	-65.72	dBm
PilotScPwr	5.528	dB	-36.8	dB
PilotRCE	-44.559	dB	0.672	dB
CPE	81.3	m%rms	92.09	%rms
Timing	0.0000	sec	-188.	nsec
Phase	0.0000	deg	77.528	deg
SymbClk	2.8036	ppm	-219.4	ppm
Freq	199.11	Hz	1.0076	kHz

The demodulation process recovers the time and phase relationship between the transmitters at the power combiner input

Cable calibration may still be required

89600 MIMO Demodulation Measurement Paths



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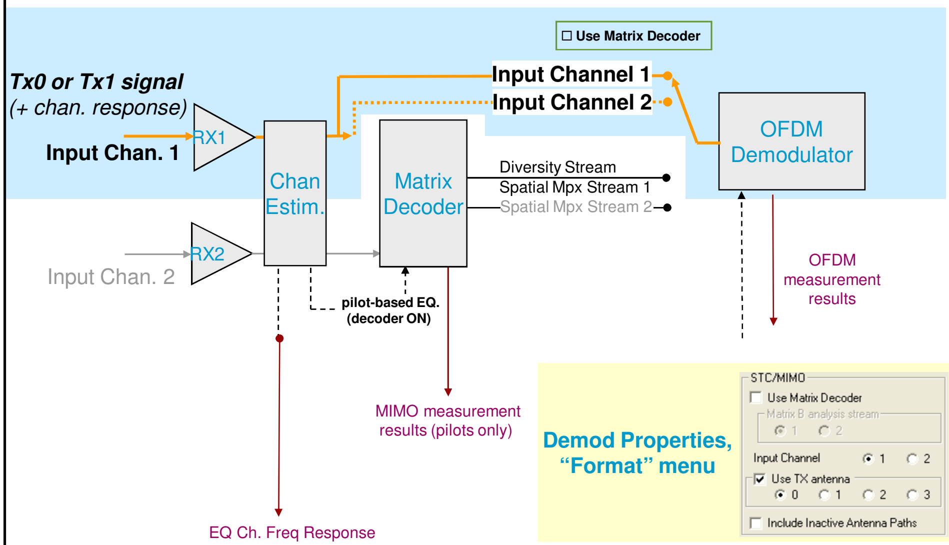
Direct Mapped Demod. with a Single Input Analyzer



9: Condition Number Measures the Short Term MIMO Channel Performance

$$C = \sum_{i=1 \text{ to } N} B.\log_2\left(1 + \frac{\rho}{N}\sigma_i^2(H)\right)$$

where

N = the number of independent transmitter-receiver pairs

$\sigma_i^2(H)$ = the singular values of the radio channel matrix, H

Condition Number = Ratio of Singular Values

How you calculate it:

Channel output

X = 1.15A + 0.39B

Y = 0.26A - 1.03B

Re-written in H matrix form

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} 1.15 & 0.39 \\ 0.26 & -1.03 \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix}$$

Transpose Matrix H^T

$$\begin{bmatrix} 1.15 & 0.26 \\ 0.39 & -1.03 \end{bmatrix}$$

H^TH

$$\begin{bmatrix} 0.73 & -0.11 \\ -0.11 & 0.85 \end{bmatrix}$$

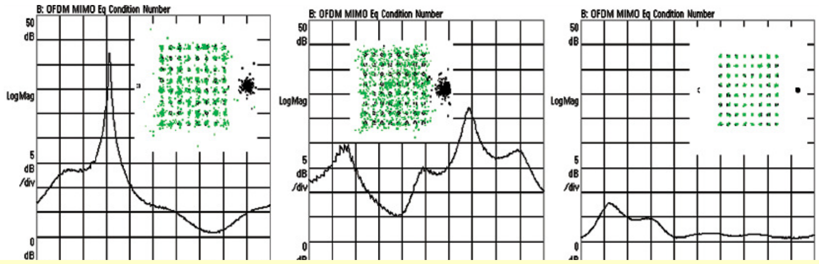
Singular Values

$$\begin{bmatrix} 0.957 \\ 0.815 \end{bmatrix}$$

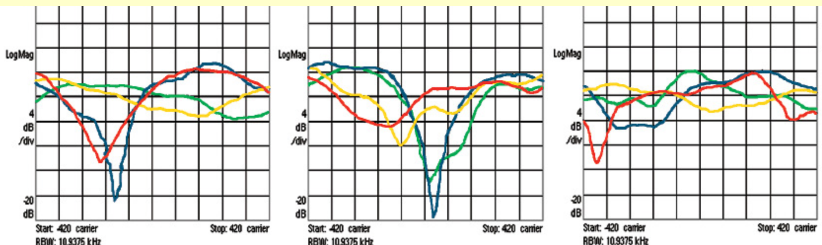
Condition Number

0.957 / 0.815 = 1.17

Ped. B Channel Condition number measurements

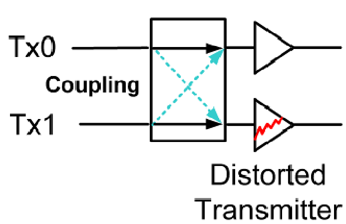


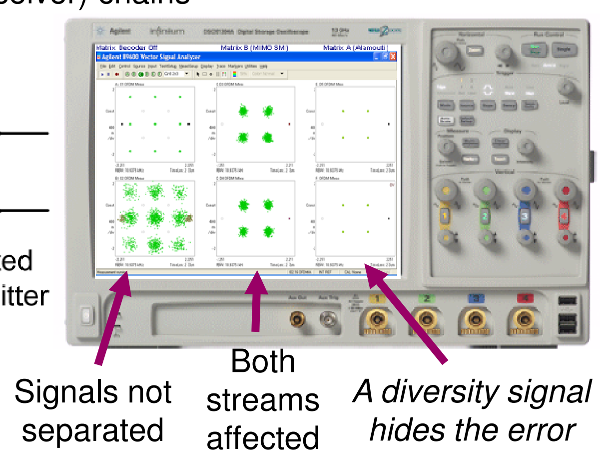
Three channel samples at different times during the fading profile
Lower overall condition number results in a tighter constellation



10: Distortion in One Component Can Degrade both Codewords

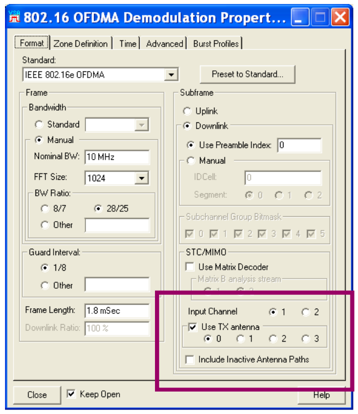
If the data streams are precoded, each signal passes through both transmitters (receiver) chains





One Component can Degrade both Codewords

We can use ***Input Channel*** selection to separate these problems



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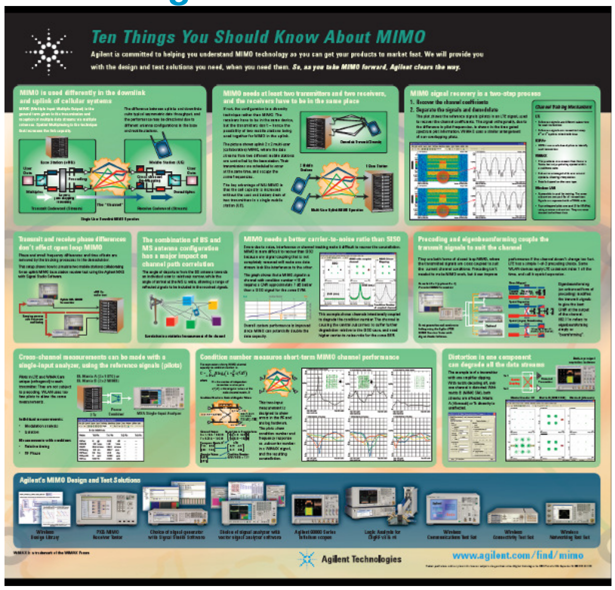
Poster – Ten Things You Should Know



Additional Resources

www.agilent.com/find/mimo

MIMO WLAN PHY layer Operation and Measurement AN1509
http://cp.literature.agilent.com/litweb/pdf/5989-3443EN.pdf

Video: “Single-channel measurements for WiMAX matrix A and B”
http://wireless.agilent.com/vcentral/viewvideo.aspx?vid=366

“WiMAX Wave 2 Testing - MIMO & STC” Agilent webcast 17 Jan 2008
http://www.techonline.com/learning/livewebinar/204203534