Essentials of OFDM and MIMO

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This Presentation

Intuitive Explanation of OFDM and MIMO in Digital Communications

Non-Mathematical Approach to Explain How they Work

Measurement & Display Implications

How & Why OFDM & MIMO Often Used Together

Agenda

OFDM Signal Overview

- Fundamental characteristics
- Benefits of OFDM
- Creating OFDM
- OFDM measurements

MIMO & Other Smart Antenna Techniques Overview

- Benefits of MIMO
- How MIMO works
- MIMO and OFDM combined
- Single and multi-channel MIMO measurements
- Custom OFDM measurements and signal generation

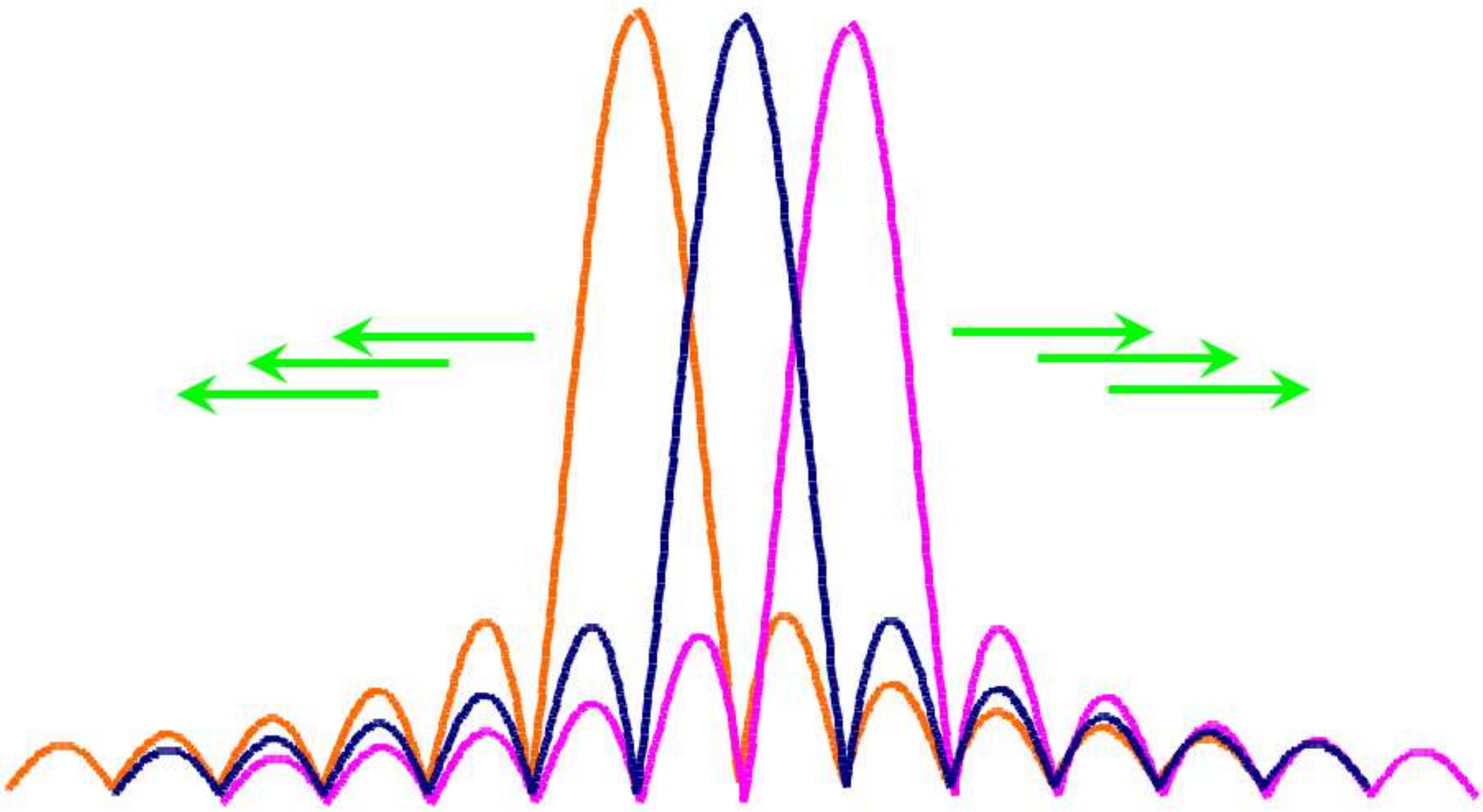
OFDM: Orthogonal Frequency-Division Multiplexing

OFDM is a modulation format that achieves:

- *high data throughput* by transmitting on hundreds or thousands of carriers simultaneously.
- *high spectral efficiency* by spacing the carriers very closely.
- *high data integrity* by transmitting at a relatively slow symbol rate.

Orthogonal Subcarriers

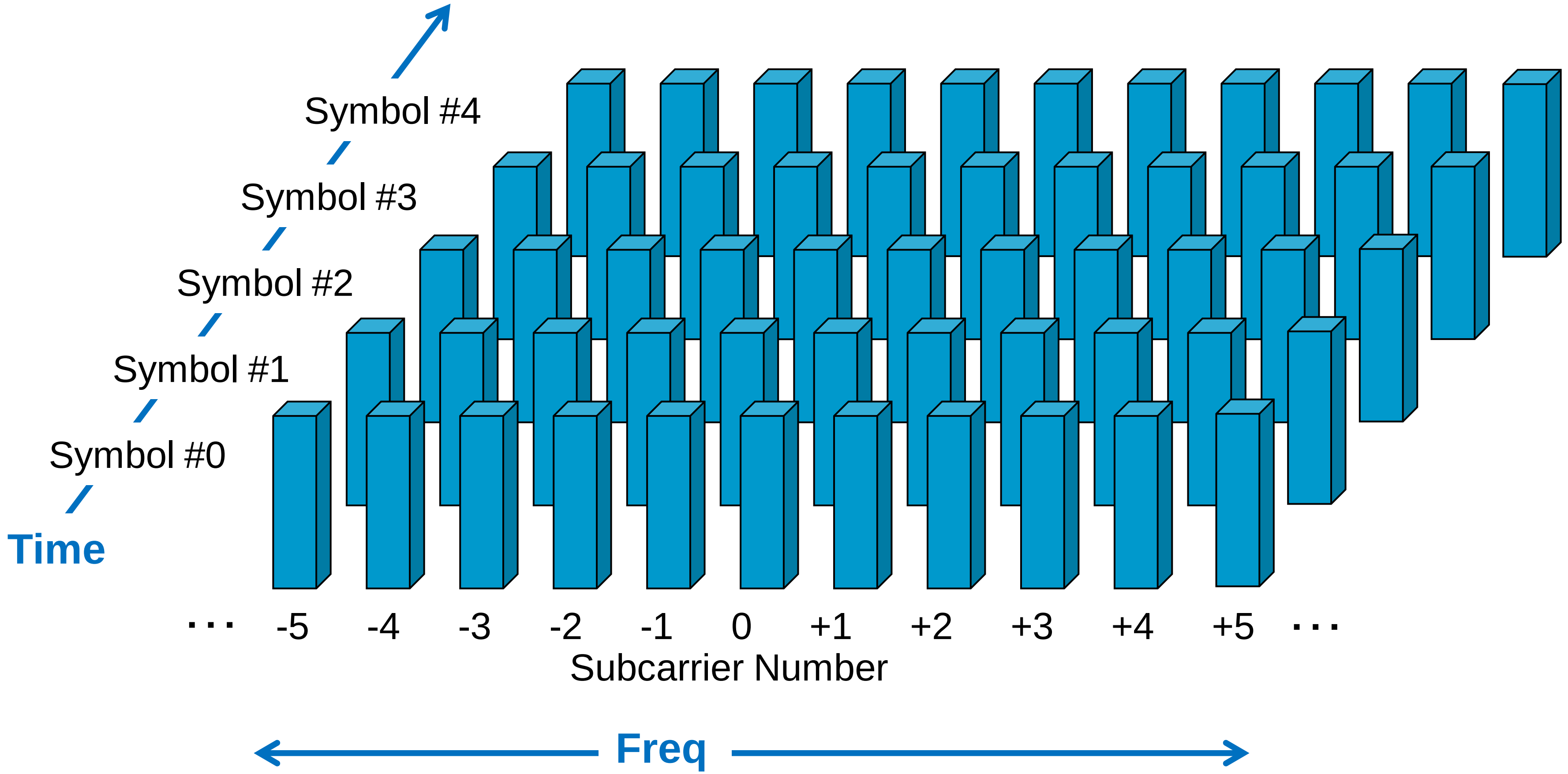
Overlapping Carriers But
No Inter-Carrier Interference (Ideally!)



Frequency domain analog of zero inter-symbol interference

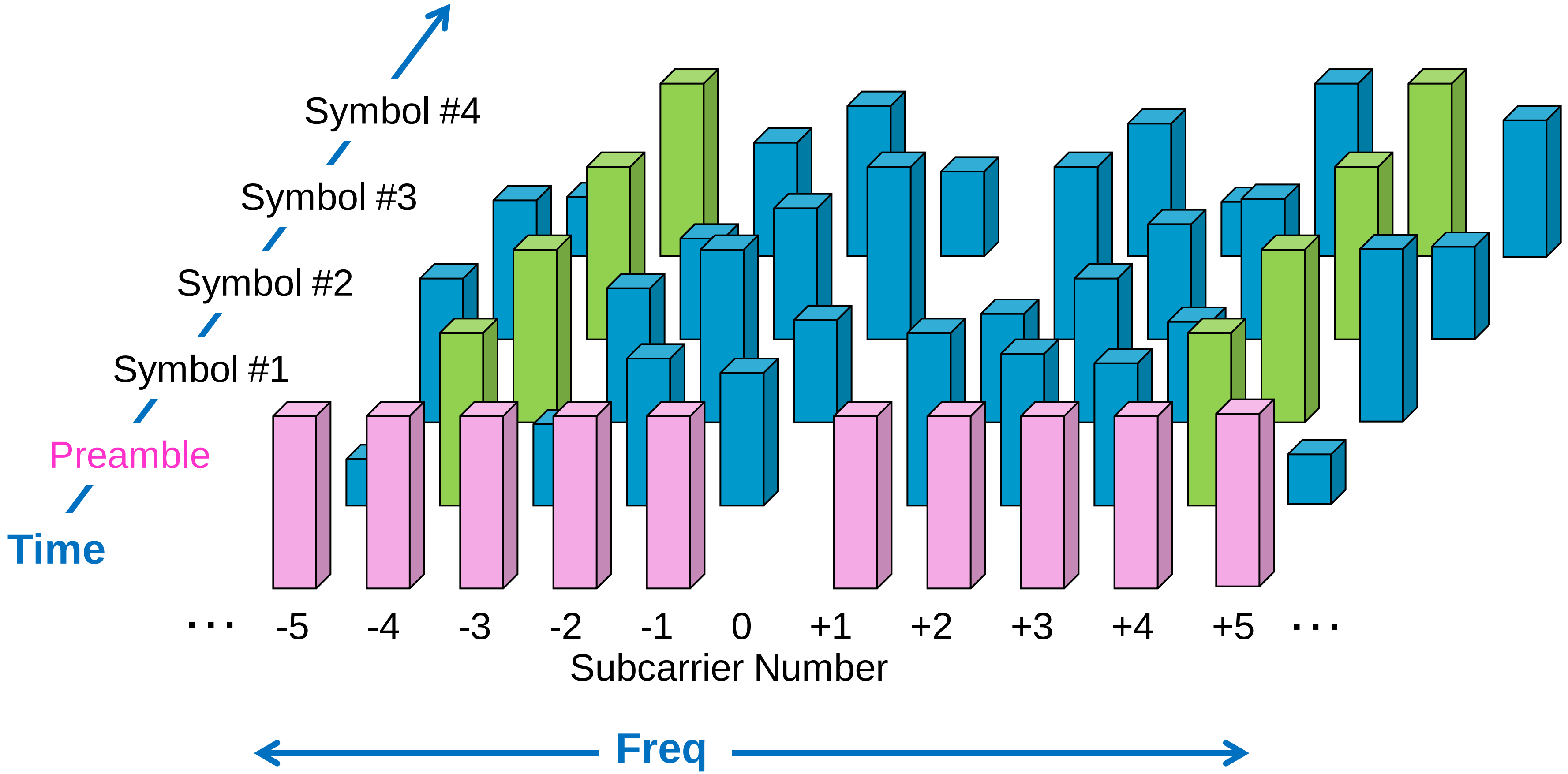
OFDM Symbols & Subcarriers

Simplified view

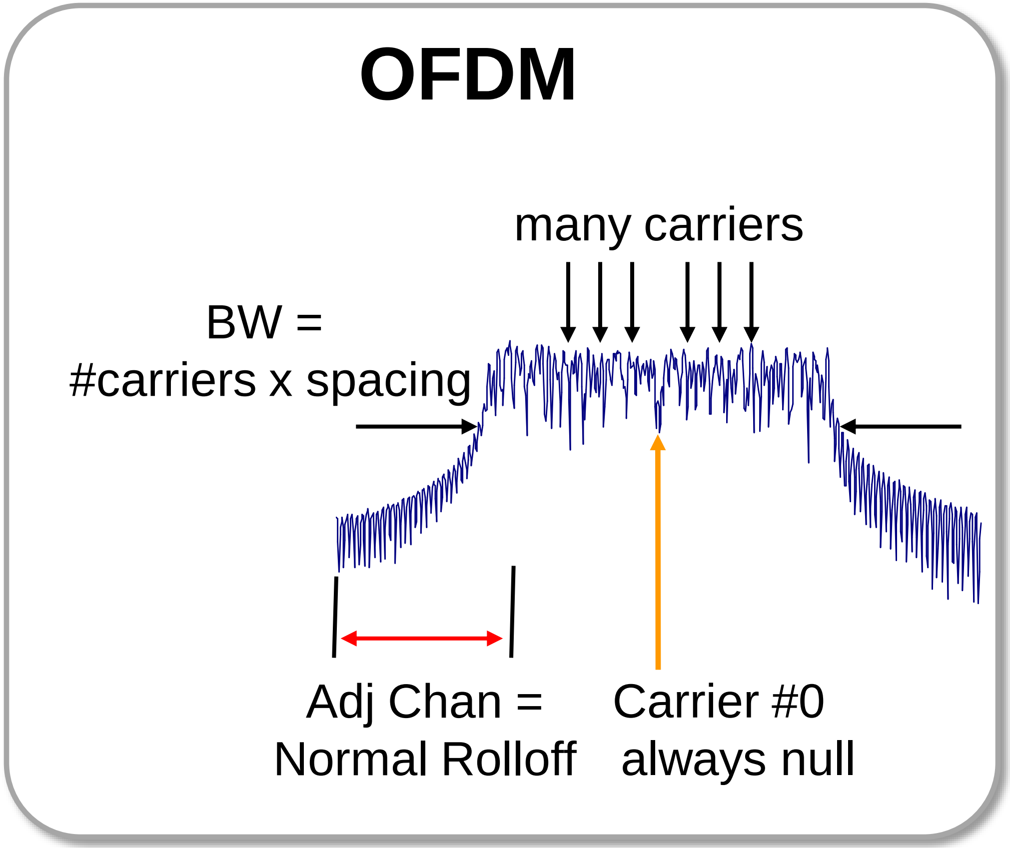


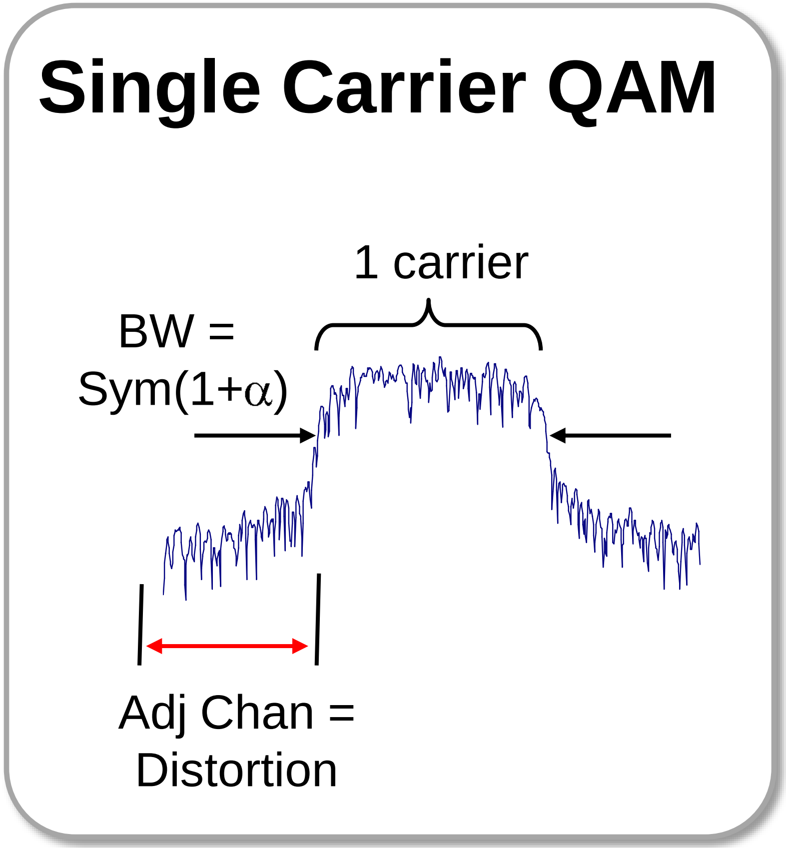
OFDM Symbols & Subcarriers

Real world view



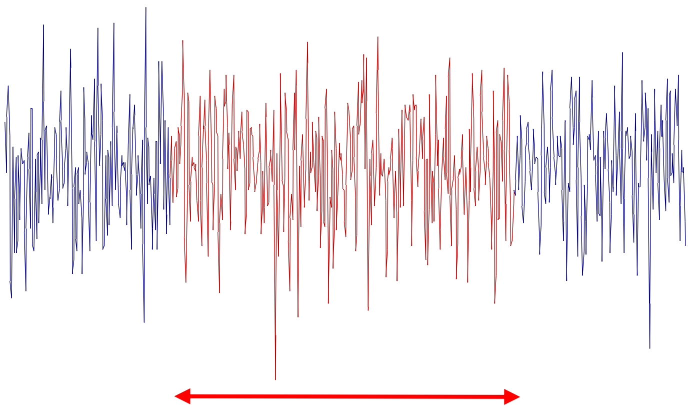
OFDM vs. Single Carrier Modulation
Frequency Domain View





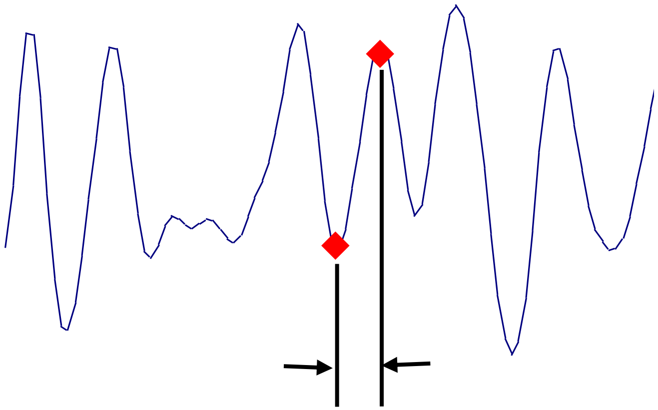
OFDM vs. Single Carrier Modulation
Time Domain View

802.11a OFDM



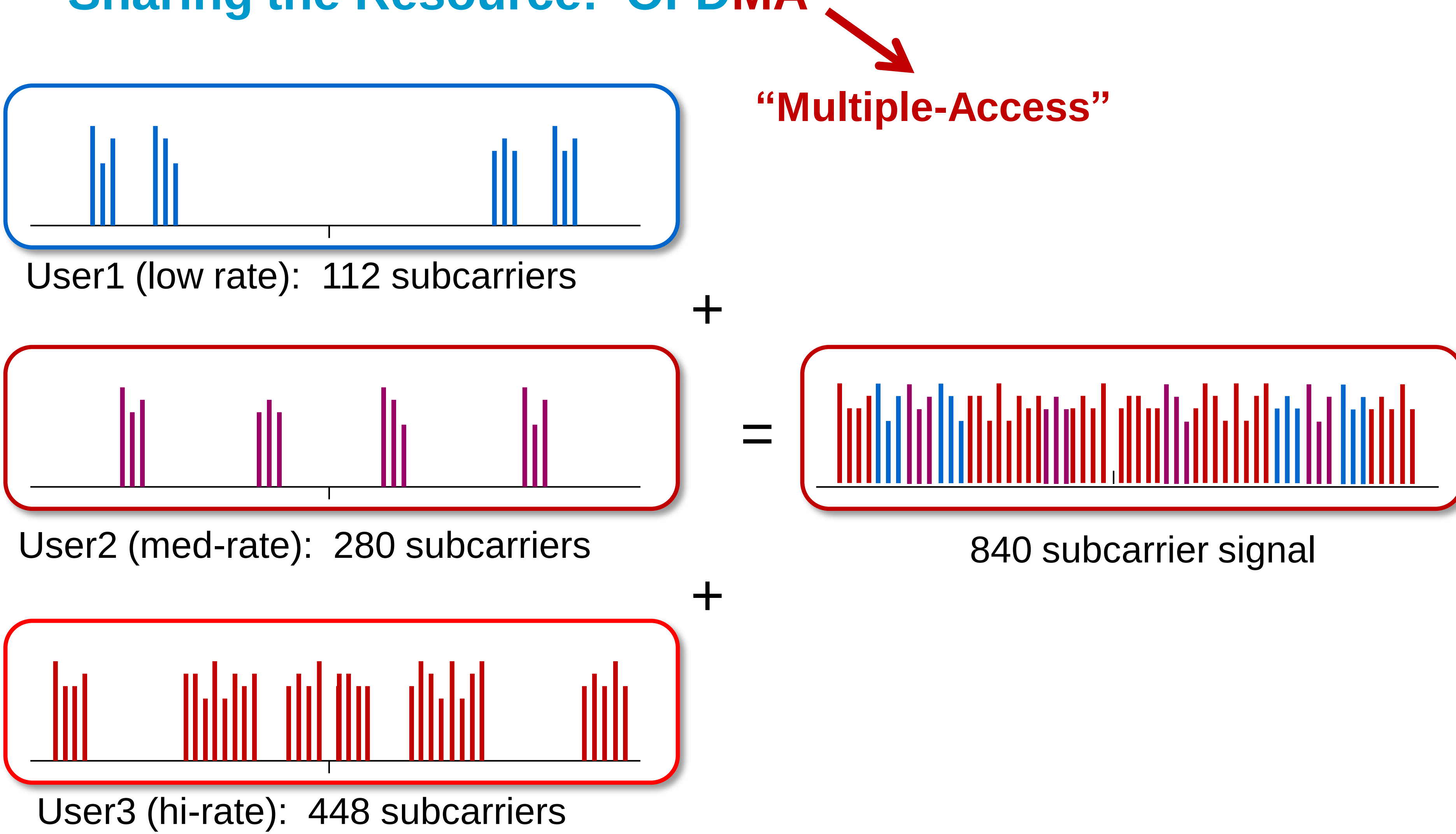
1 Sym = 64 Samples = 4.0 usec

Single Carrier 64QAM



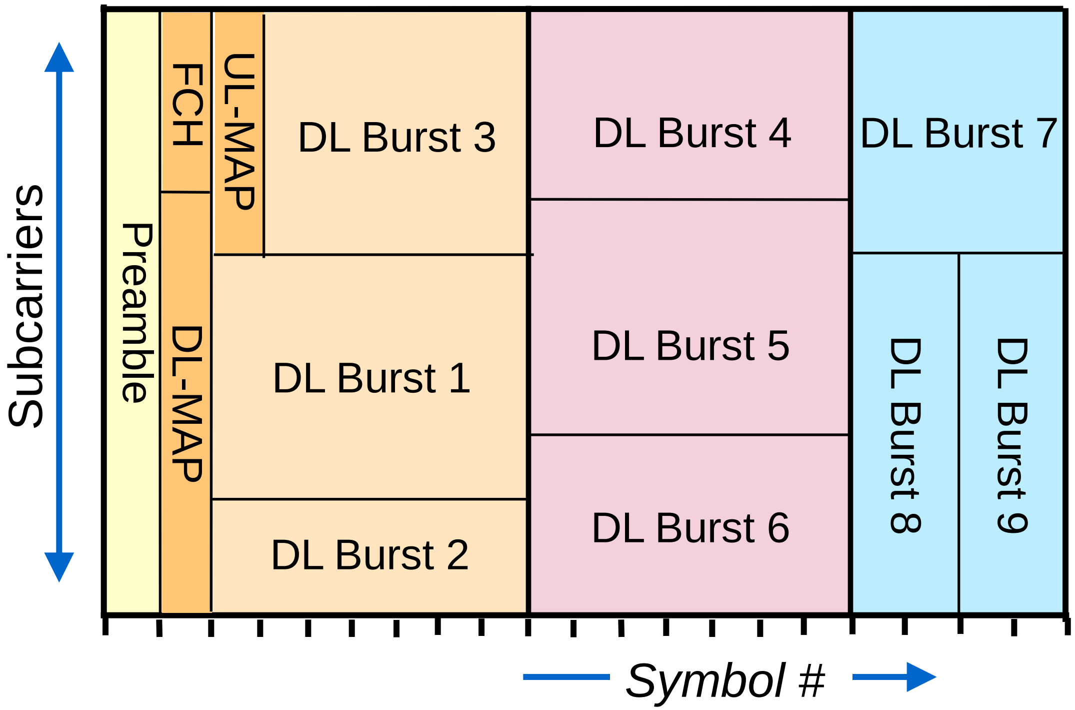
1 Sym = 1 Sample = .083 usec

Sharing the Resource: OFDMA



OFDMA Resource Map

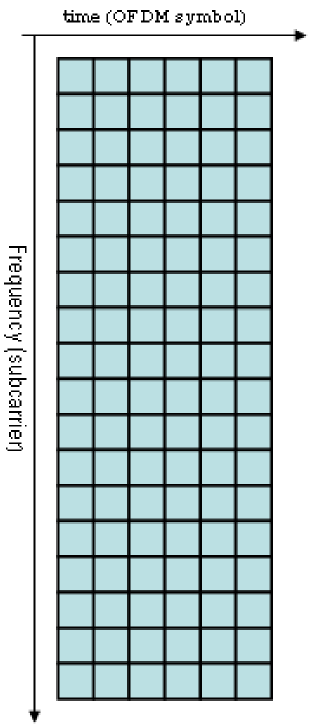
Example:
802.16e
Mobile WiMAX



- Shows allocation of subcarriers by time *and* frequency.
- Subcarriers are usually grouped into logical channels.
- Each channel can have different modulation, power level, coding, etc.

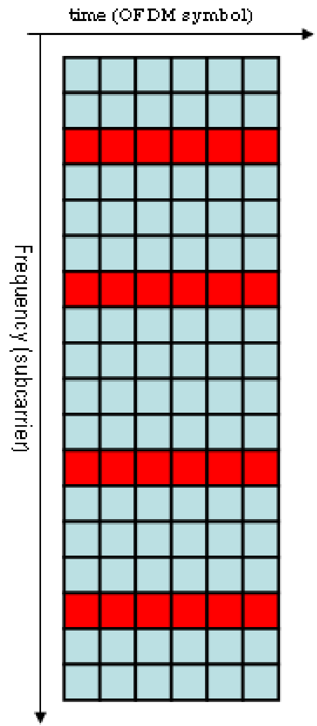
Pilot Structure

No pilot



Data subcarrier

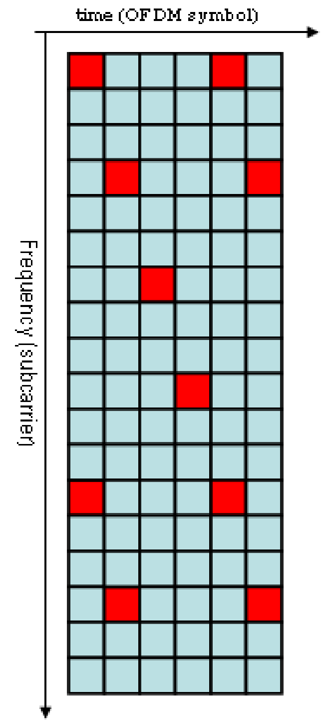
Continuous pilot



pilot subcarrier

Data subcarrier

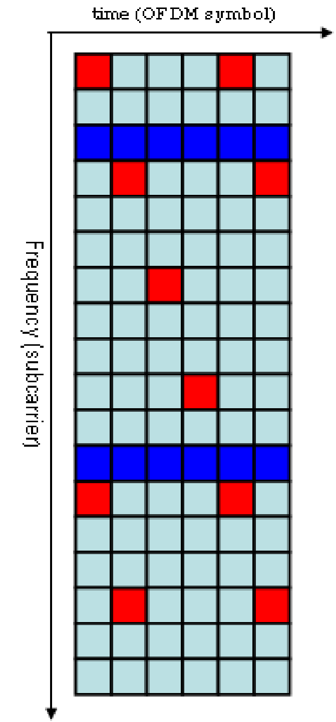
Scattered pilot



pilot subcarrier

Data subcarrier

Continuous pilot and scattered pilot

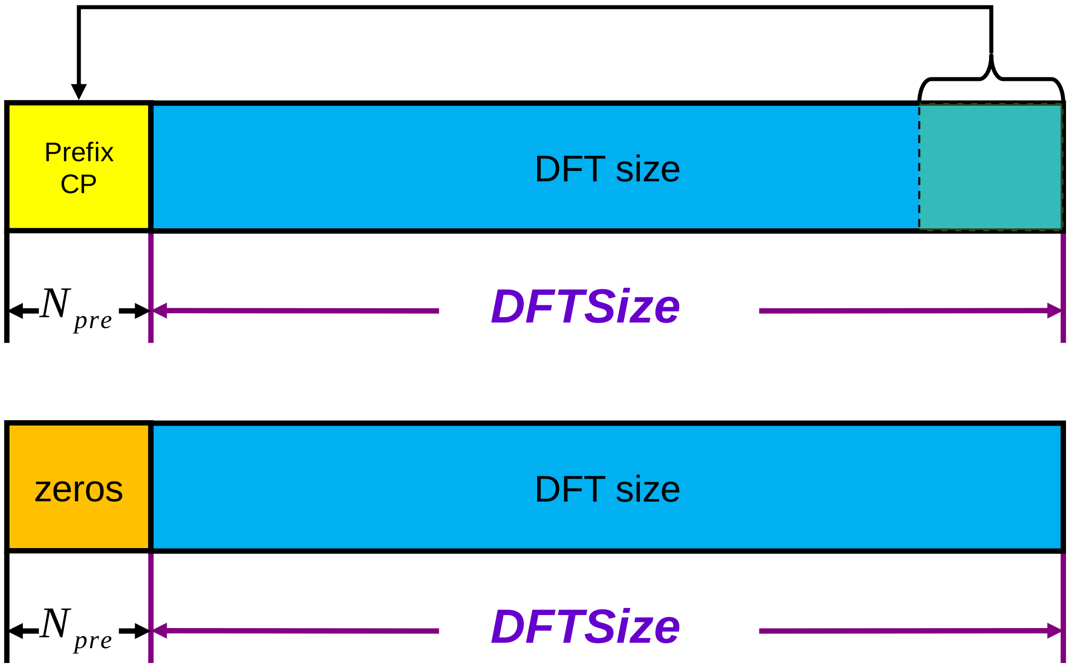


Scattered pilot subcarrier

Pilot Subcarrier

Data subcarrier

OFDM Symbol Structure: Extending Symbol Length

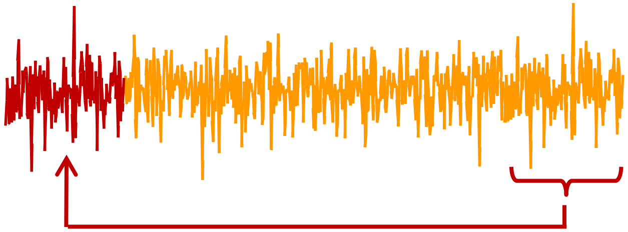


GuardIntervalType= CycleShift

GuardIntervalType= Zeros

$N_{pre} = DFTSize \times Gi$, where *Gi* is defined as the guard interval in parameter GuardInterval.

Summary: How OFDM Achieves its Goals



1.High throughput:

- An 800-subcarrier system with 64QAM mapped to each subcarrier can transmit 800 x 8 = 6400 bits per symbol.

2.Bandwidth efficiency:

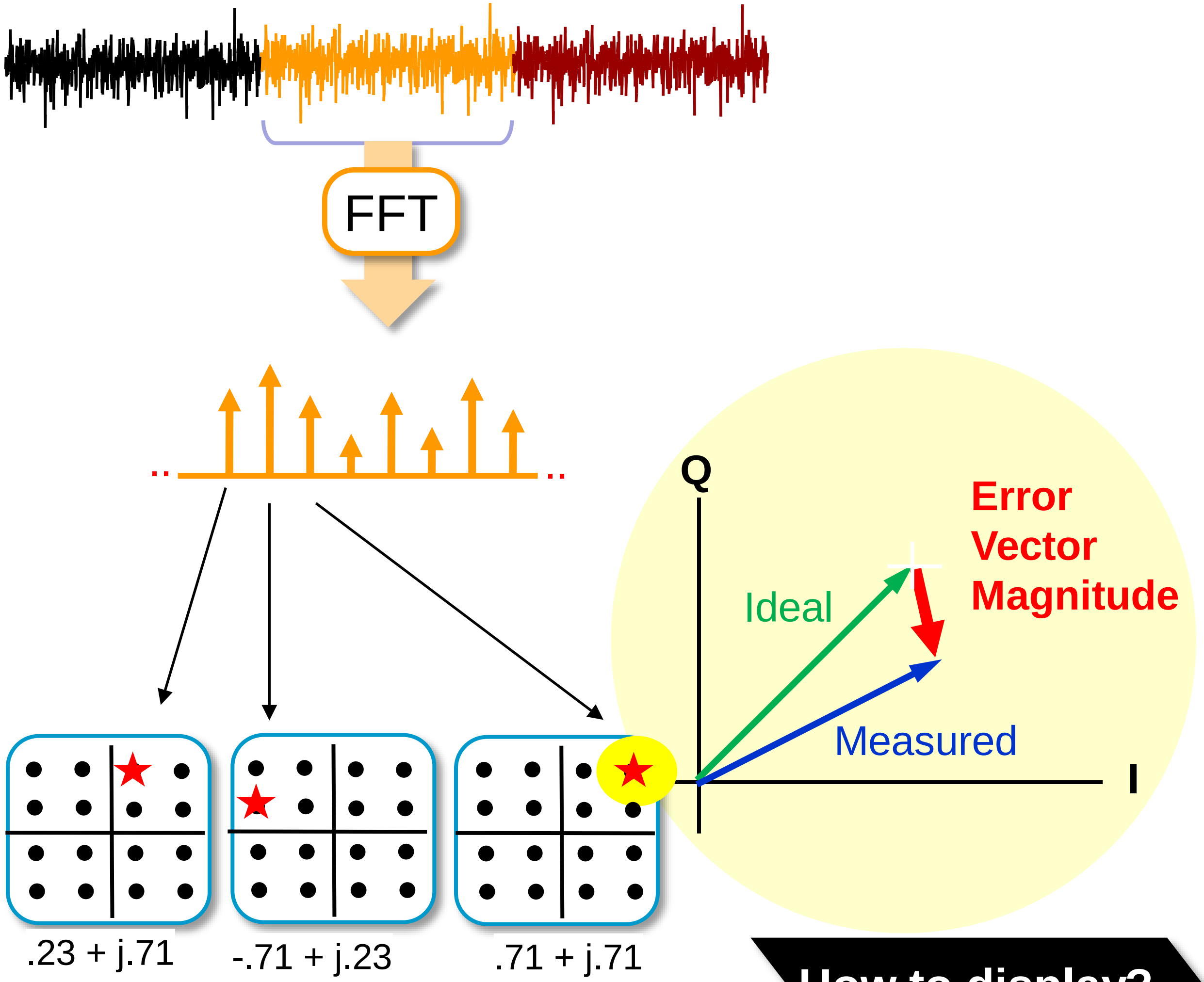
- With DSP techniques (FFT and IFFT), subcarrier spacing can be reduced to theoretical minimum, i.e. mathematically *orthogonal* (don't expect to see individual subcarriers!)

3.Data integrity: Multi-subcarrier symbol structure has advantages

- Symbol is long relative to most impulse noise.
- Single-freq interferer only disturbs 1-2 subcarriers, not entire signal.
- Built-in amplitude and phase references (pilots) allow signal to be re-synchronized and/or equalized for each symbol.
- Symbol can be *cyclically extended* for multipath immunity

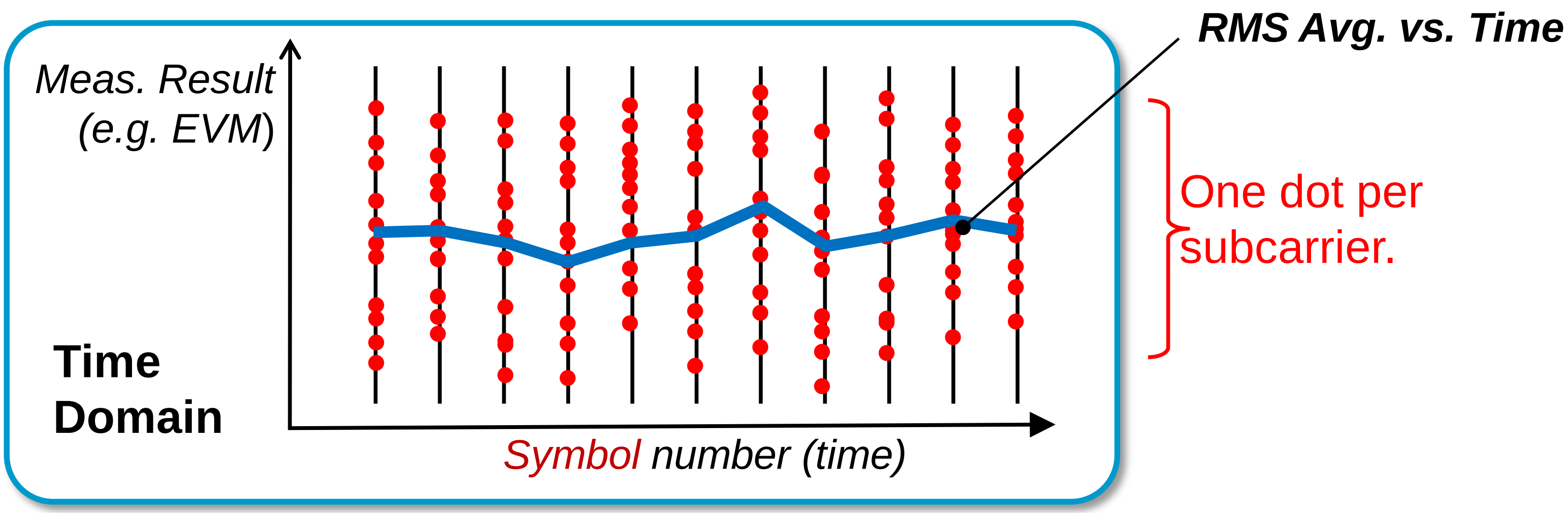
OFDM Signal Analysis

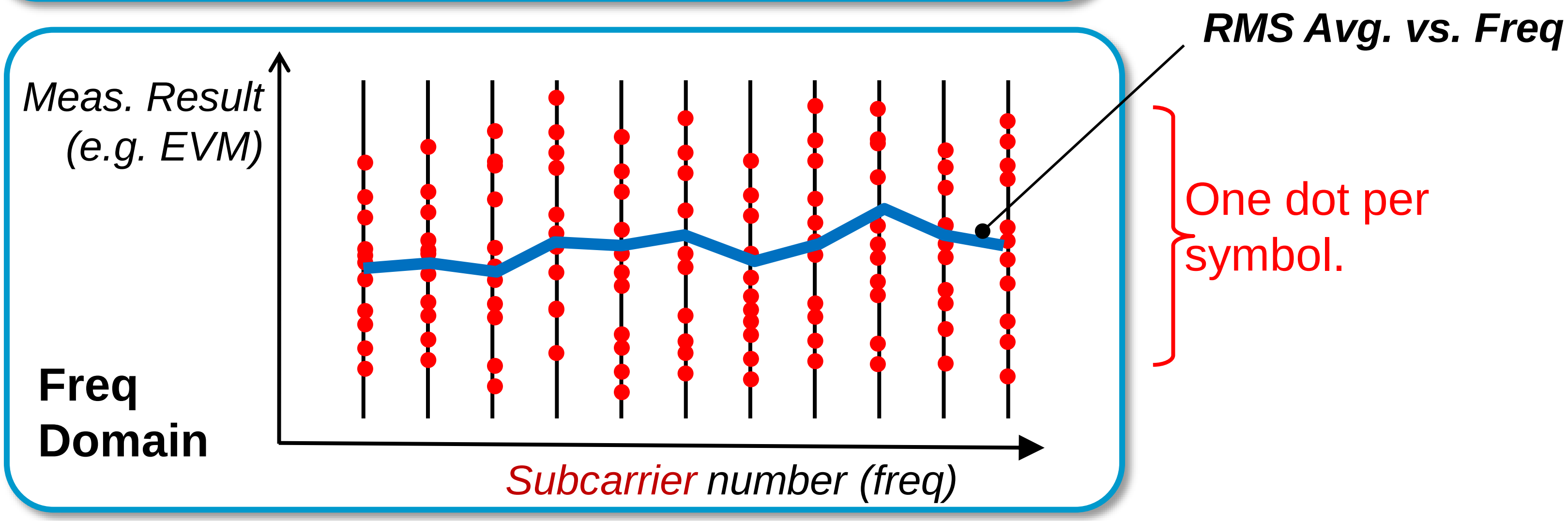
1. Isolate waveform for 1 symbol; synchronize in Freq, Time, Phase
2. Perform FFT
3. Map subcarrier I-Q values back to QAM constellations
4. Compute standard constellation metrics (EVM, SNR, etc.) for each subcarrier in each symbol



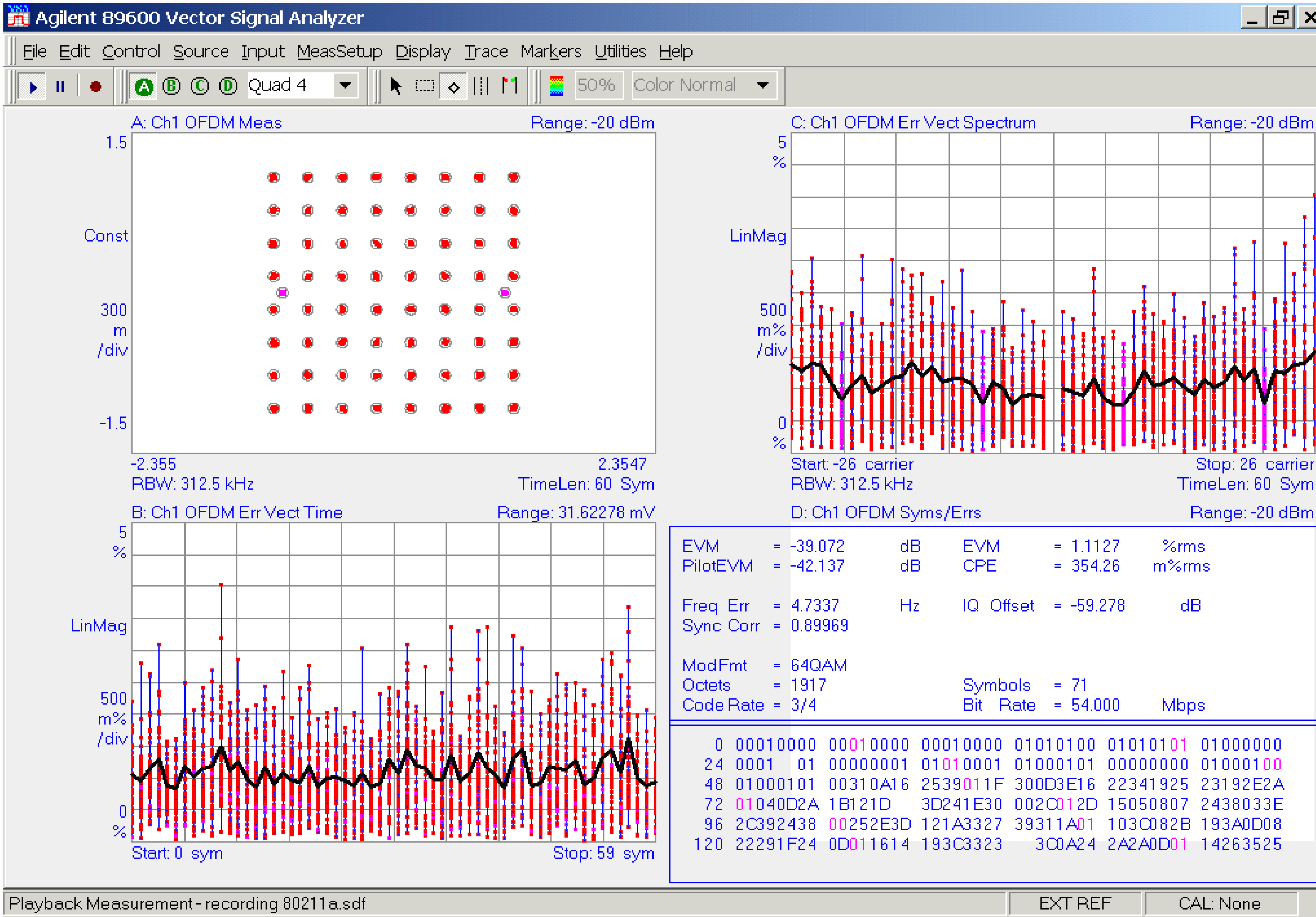
How to display?

How to Display OFDM Signals





Measuring Modulation Quality

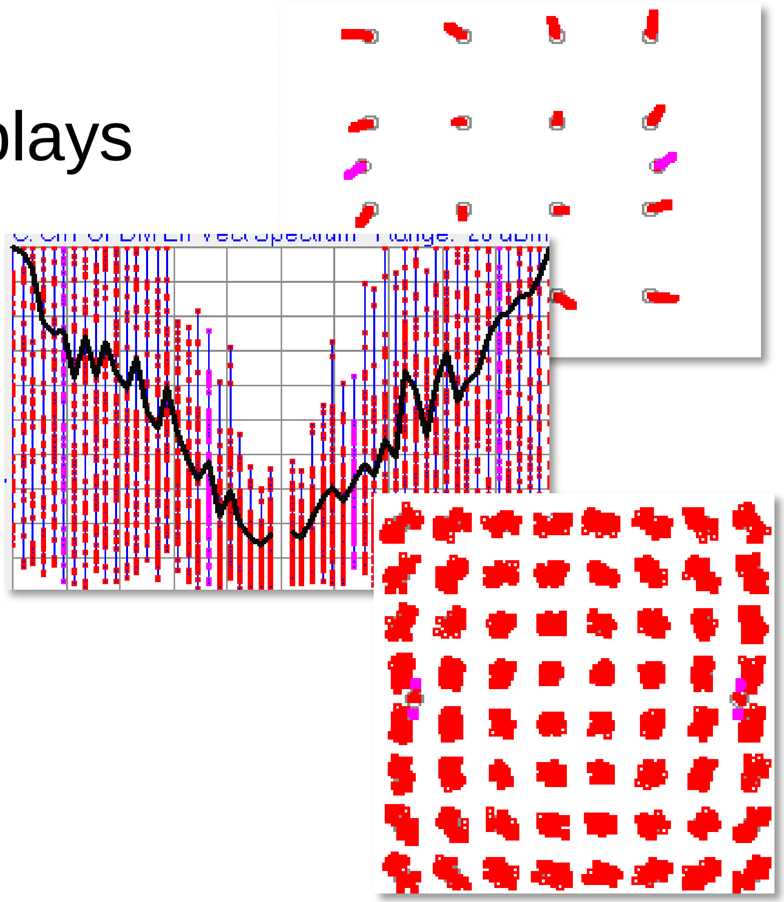


Measurement & Display Examples

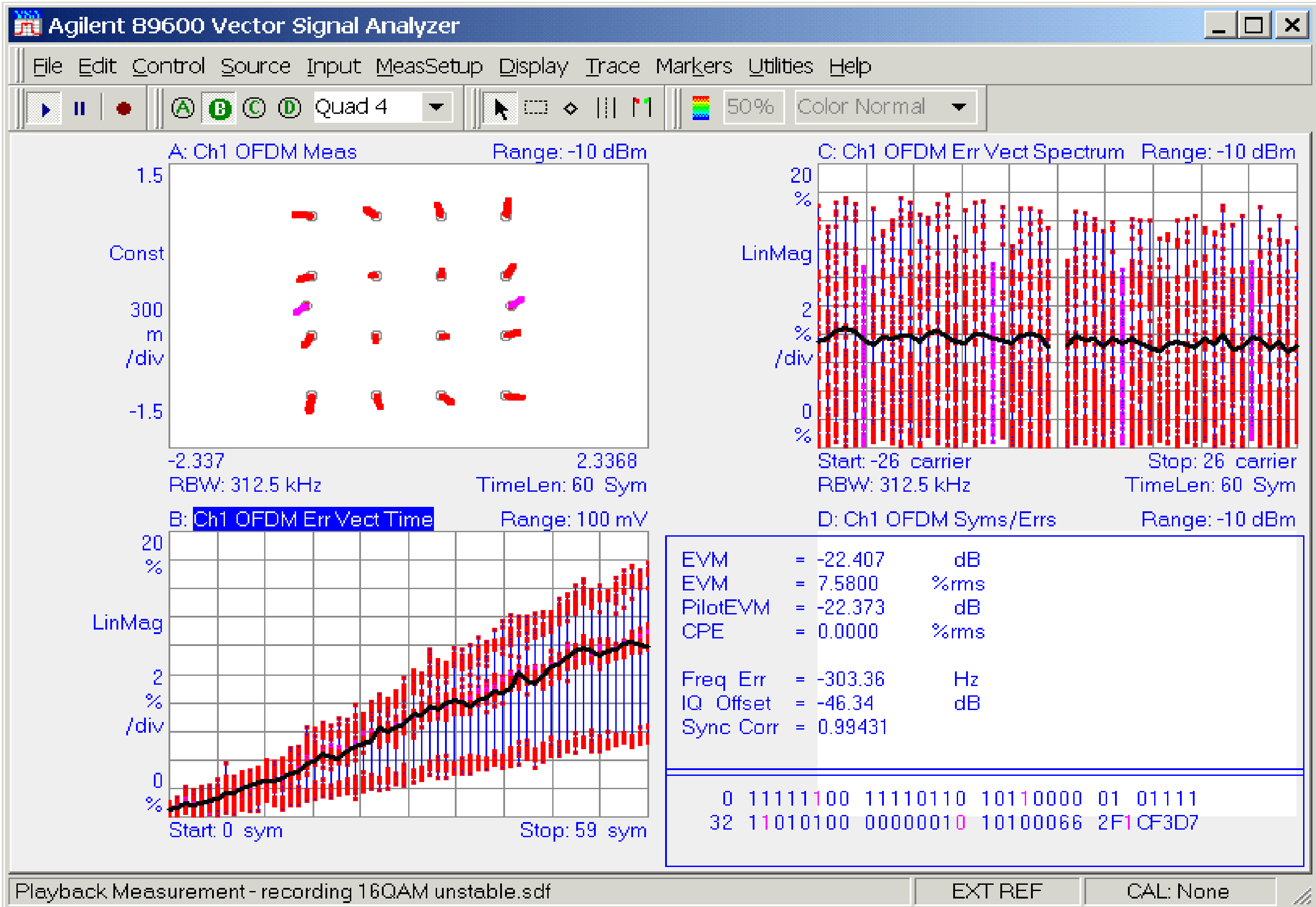
Amplitude & Phase Drift

- Typical measurements & displays
- Effect of pilot tracking

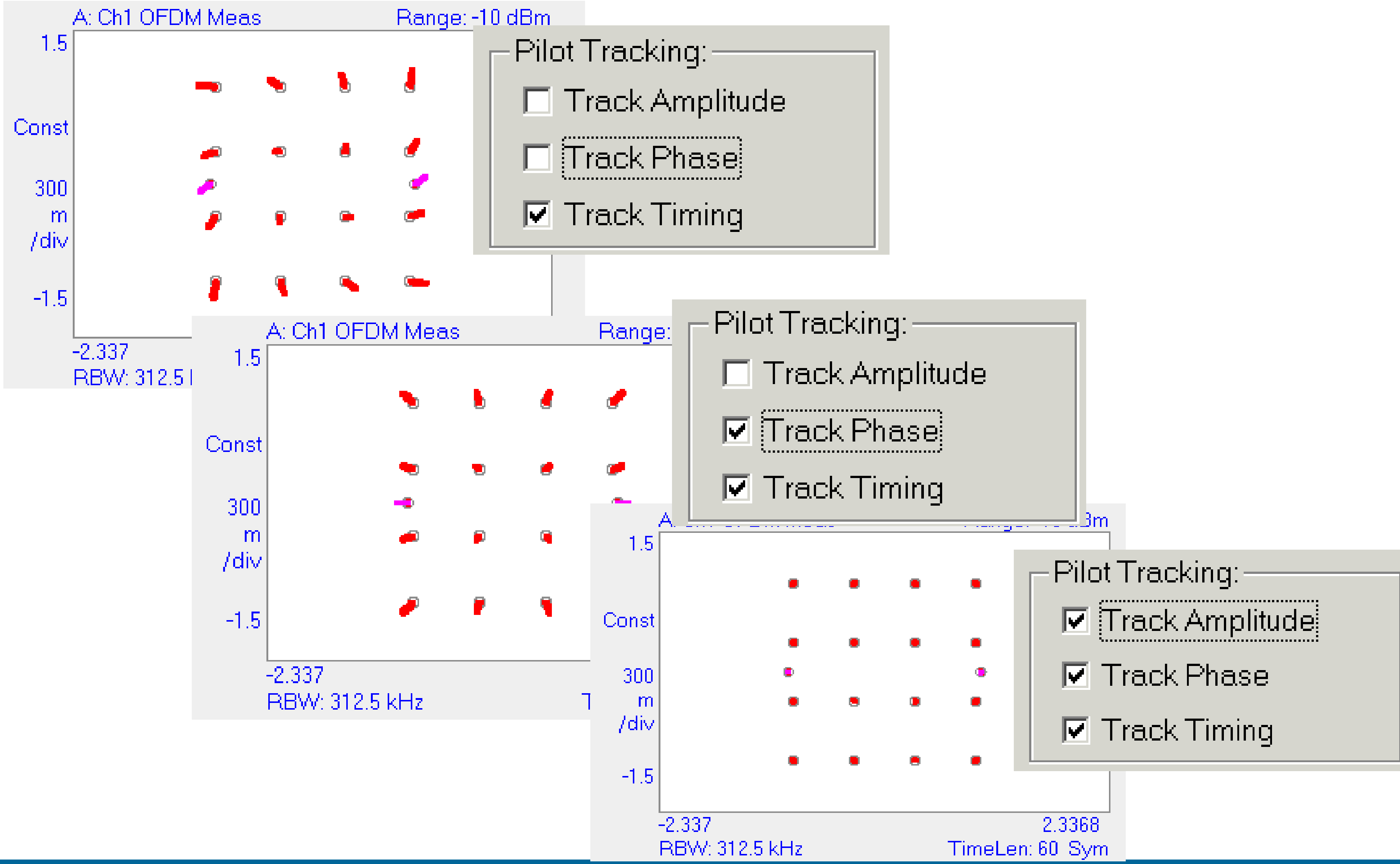
Combining Vector & Demodulation Displays



OFDM Impairments Example
Amplitude & Phase Drift



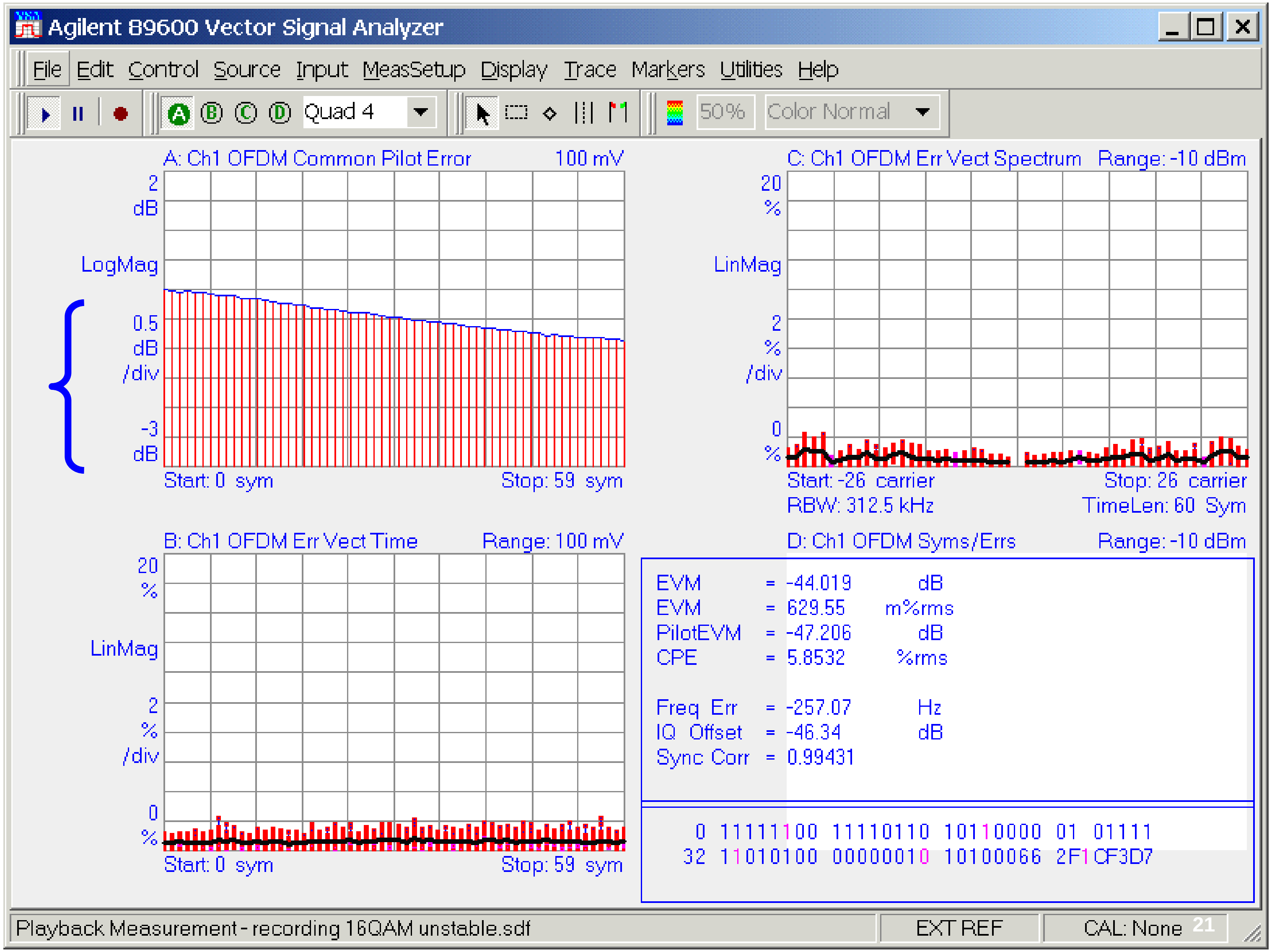
Pilot Tracking Compensates for or Hides Impairments



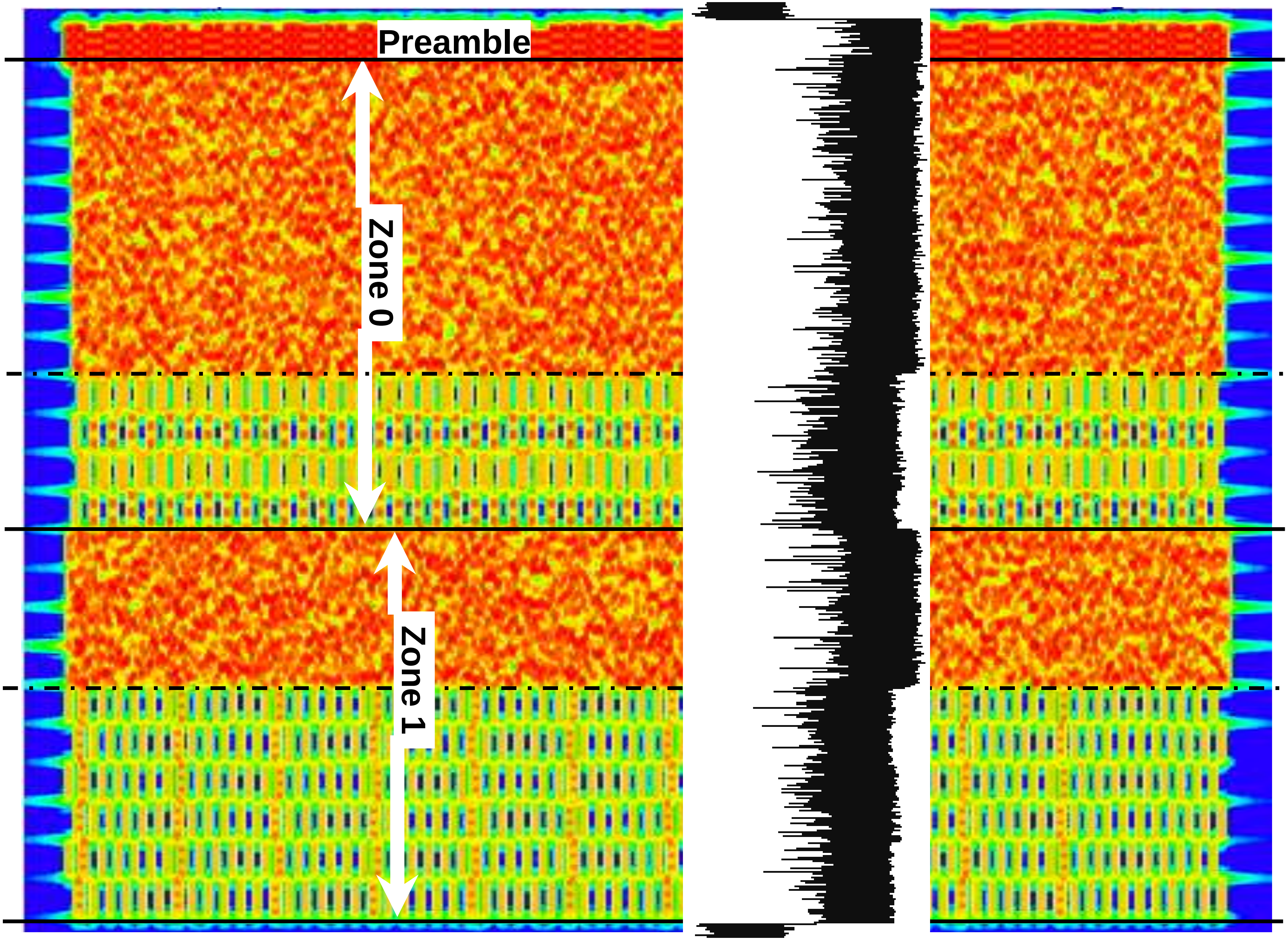
Common Pilot Error Display Shows the Defect Removed

~1 dB ampl. droop in 240 uSec

EVM looks fine with pilot tracking ON.



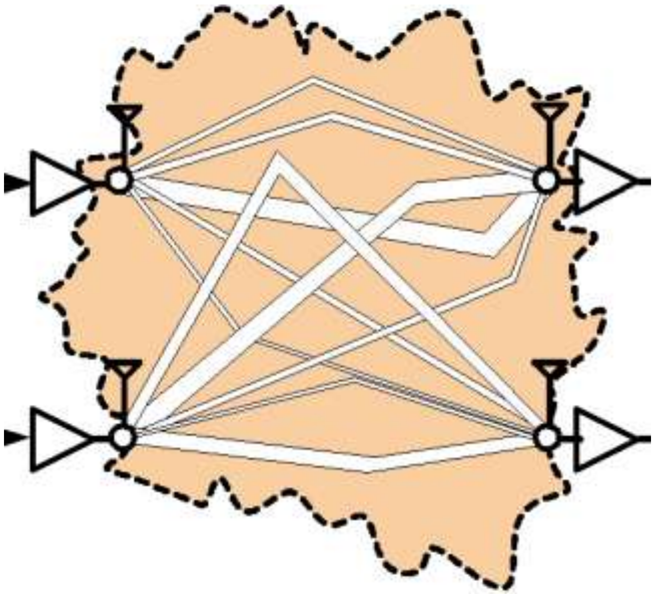
OFDMA--Spectrogram & Power Envelope



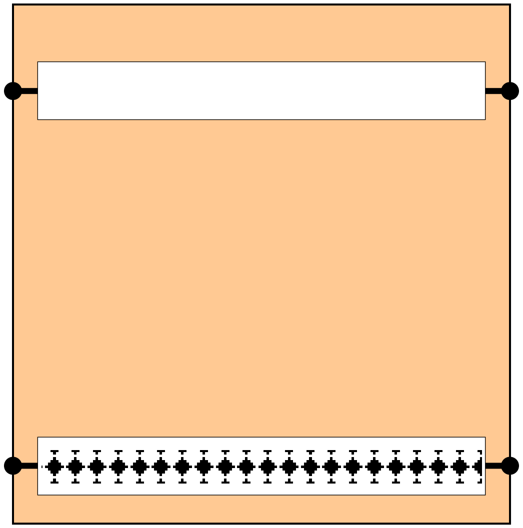
MIMO Overview

MIMO is the Science of Getting From

THIS to **THIS**



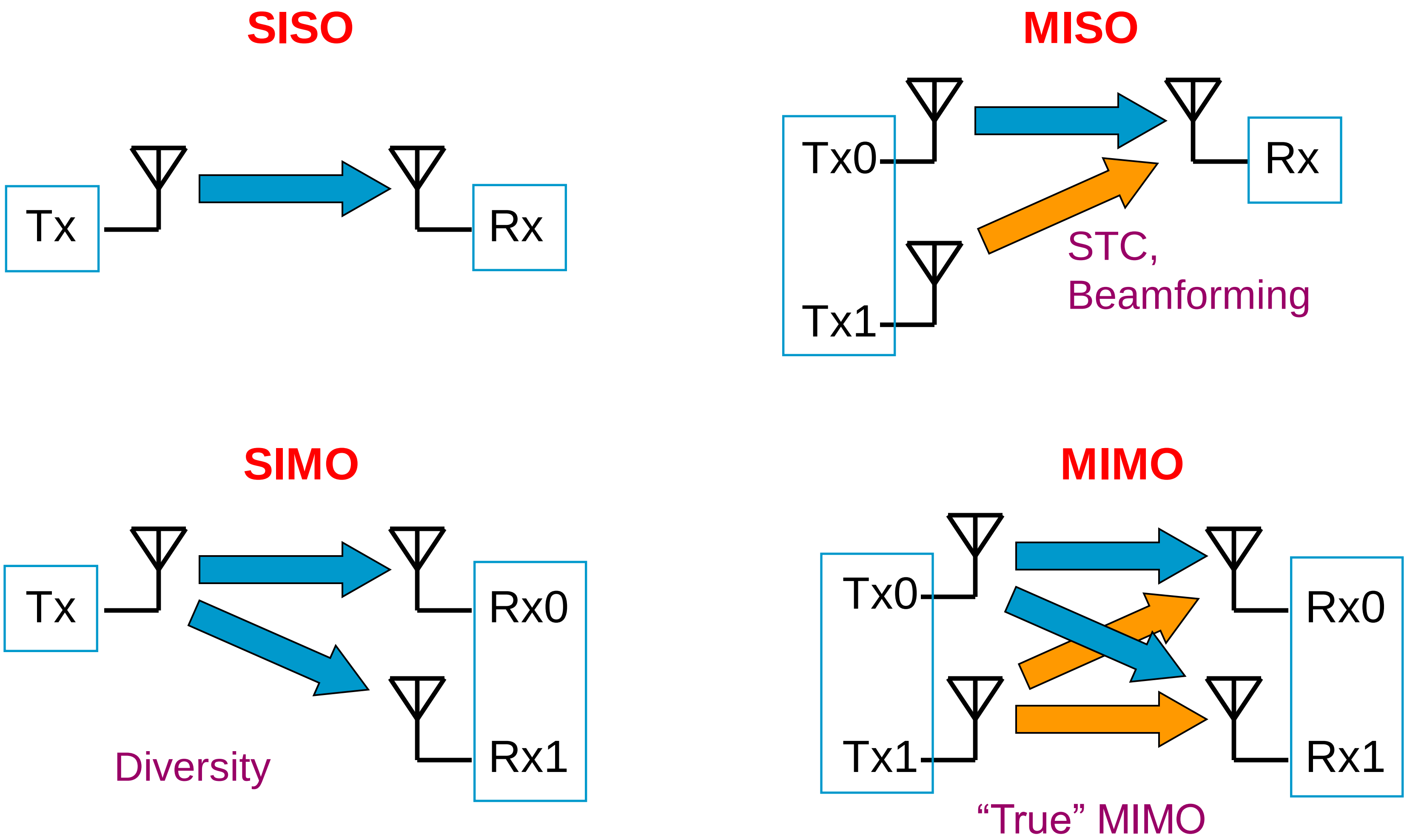
The "channel"



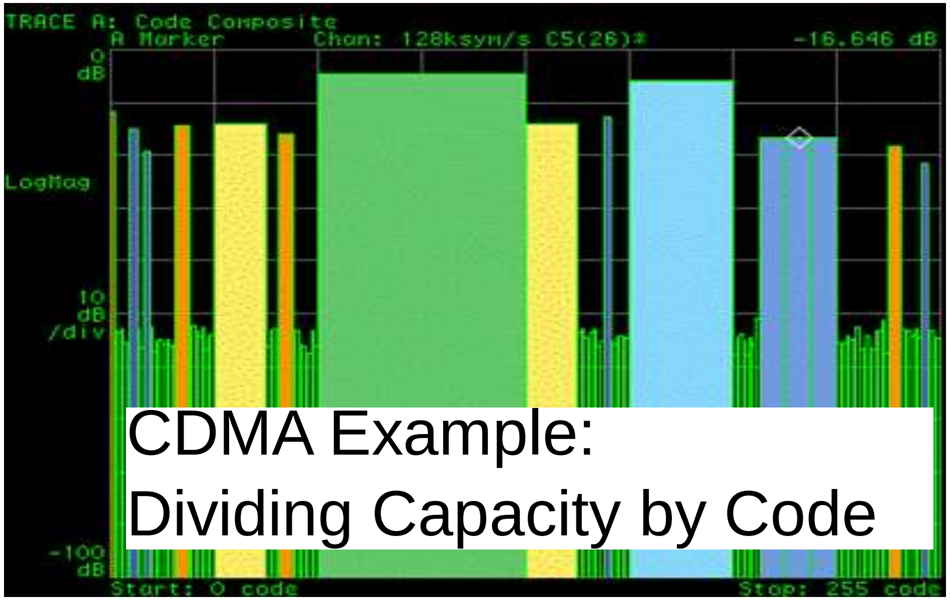
Increased capacity from a given spectrum occupancy

System & Antenna Configurations, Terms

"Input" and "Output" Refer to the Transmission Channel



Why MIMO?



CDMA Example:
Dividing Capacity by Code

MIMO is a Capacity Enhancement Scheme

- Evading Shannon's limit!
- Can Trade Capacity for more range or ??

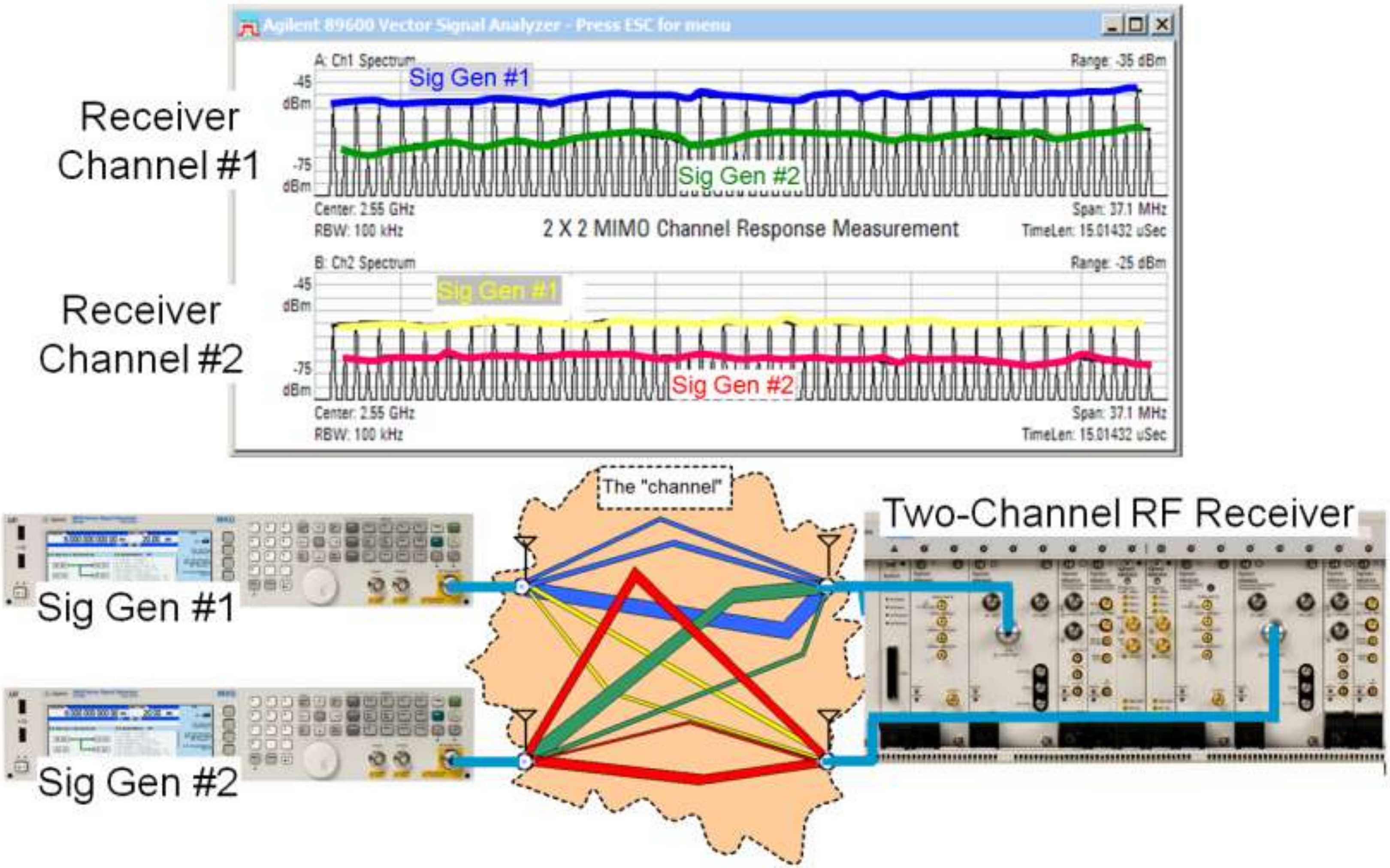
CDMA, OFDM, etc. are Multiplexing Schemes

- Dividing capacity among users, frequencies
- Better operation in impaired conditions
- "Shannon Limit" still applies!

DEMONSTRATION: Live 2x2 Channel

Two sources generate multi-tone signals with 1 MHz spacing, offset by 500Khz to identify each source at receiver (2-ch. VSA) antennas

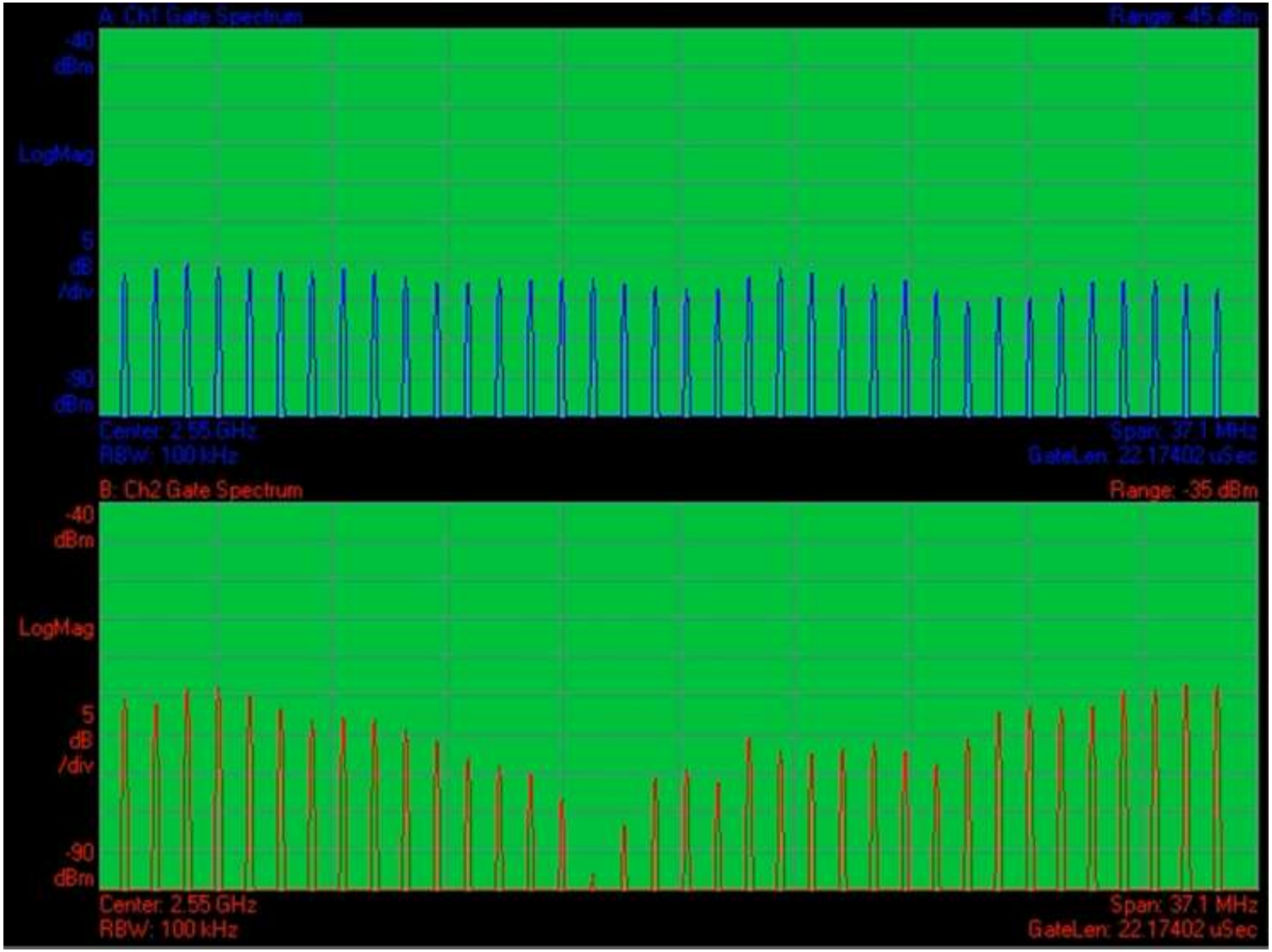
Movements in the environment near the antennas show how the four independent radio paths (color coded) can be identified



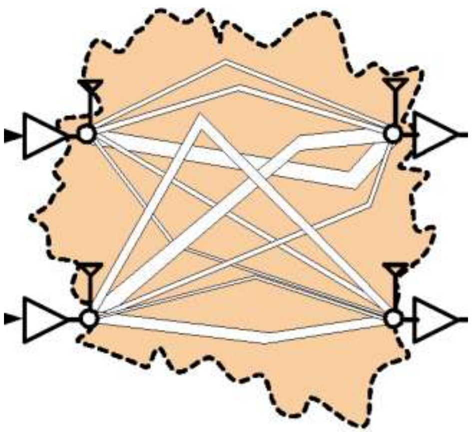
Frequency Response Example

Antenna 1:
5 dB Ripple

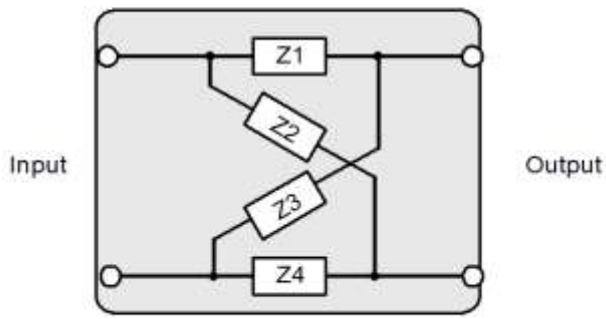
Antenna 2:
25 dB Null



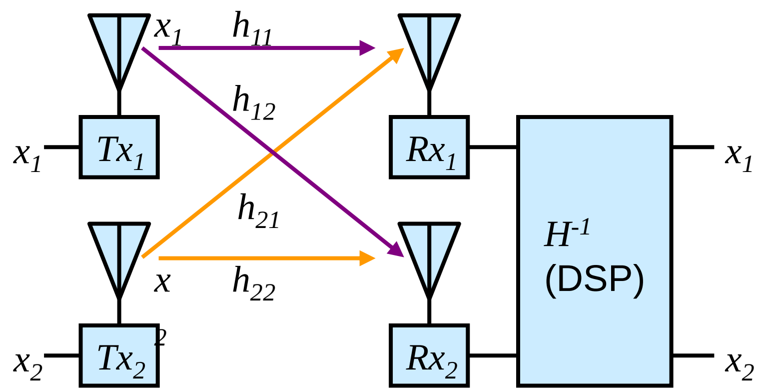
MIMO exposed (The 2 x 2 Instance)



The real channel (complicated)



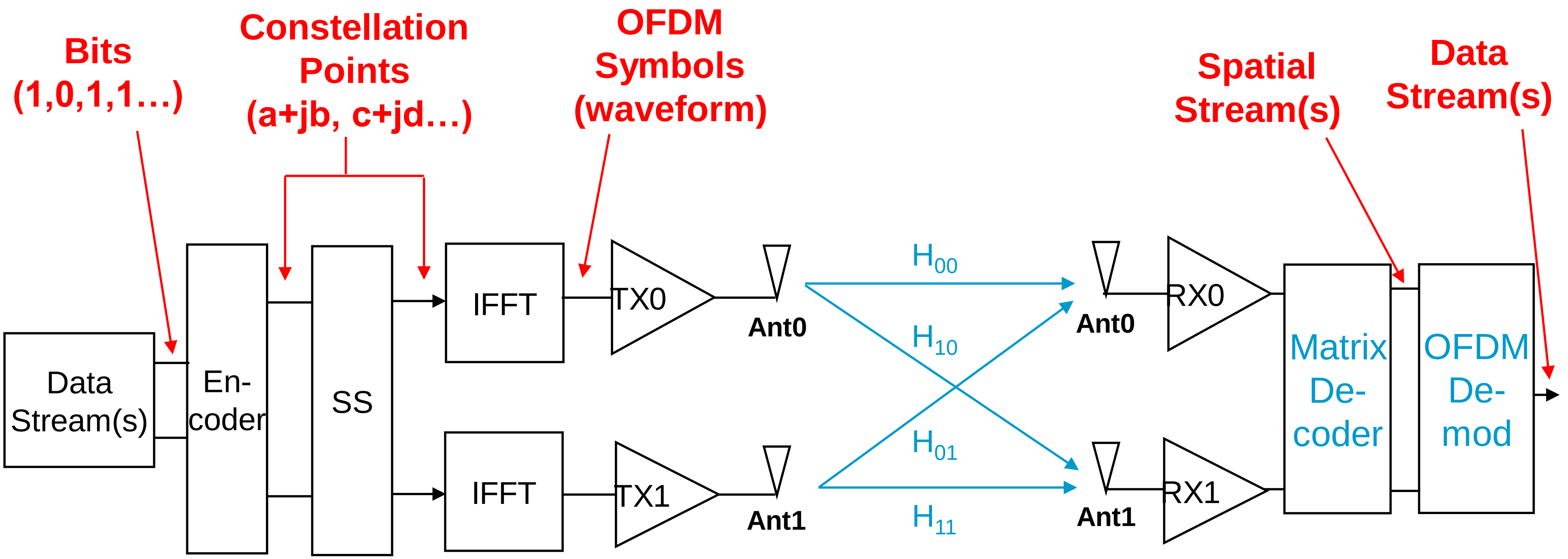
The channel for one OFDM sub-carrier during the course of a packet



Solving the equations

MIMO – Data & Spatial Streams, Channels

2x2 Example



Spatial Streams (aka Layers) *relate to the original data payload.*

TX Chains (aka Antennas) *relate to the actual transmitted signals.*

Channel Matrix *Individual freq response curves for each TX-RX path.*

MIMO Measurement Types

All the Basics, Plus More, Including Linked Channels

All Traditional Spectrum, Network, Power, Timing

Basic Modulation Quality

Isolation/Coupling/Crosstalk

Frequency Responses (multiple)

General Modulation Impairments

Proper MIMO Operation, Signal Content

MIMO Signal Separation

Optimization: Cost, signal quality, size, power consumption, complexity, antenna configuration

Analysis Approaches

Switch Off One Channel

- Simple, generally less expensive
- Use established equipment, approaches
- Results with limited applicability

Single-Input Measurements of 2 - 4 Transmitters

- Transmitters combined deliberately or incidentally
- Some signals can be separated by frequency or time
- No Matrix decoder

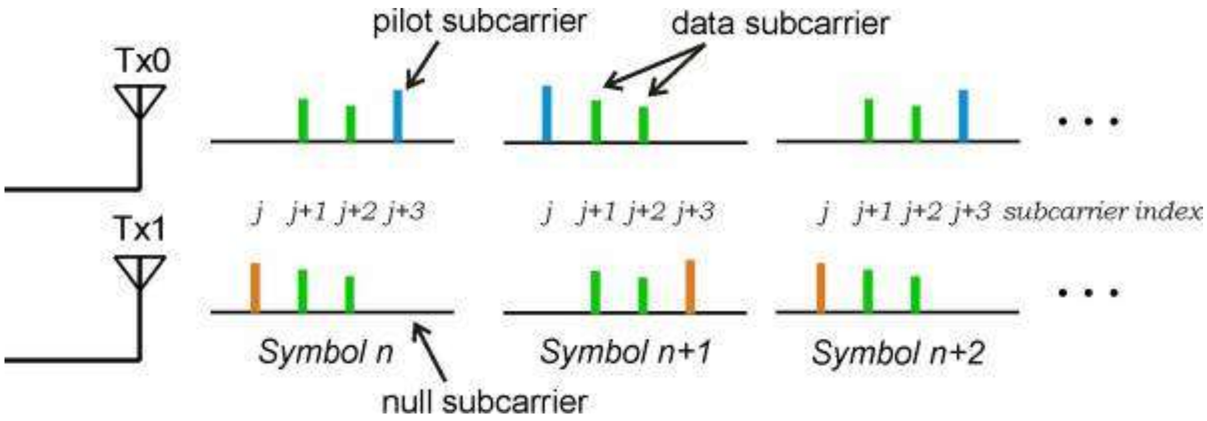
Multi-Channel Measurements, Two or More

- Signal processing to restore 40+ dB measurements
- Measure cross-channel parameters and how they vary with configuration changes

MIMO Signal Recovery:
Measuring Matrix Coefficients

Recovering the channel coefficients

(WiMAX Wave 2 example)



In WiMAX and LTE, more subcarriers are allocated as pilots

Pilot location changes from symbol to symbol

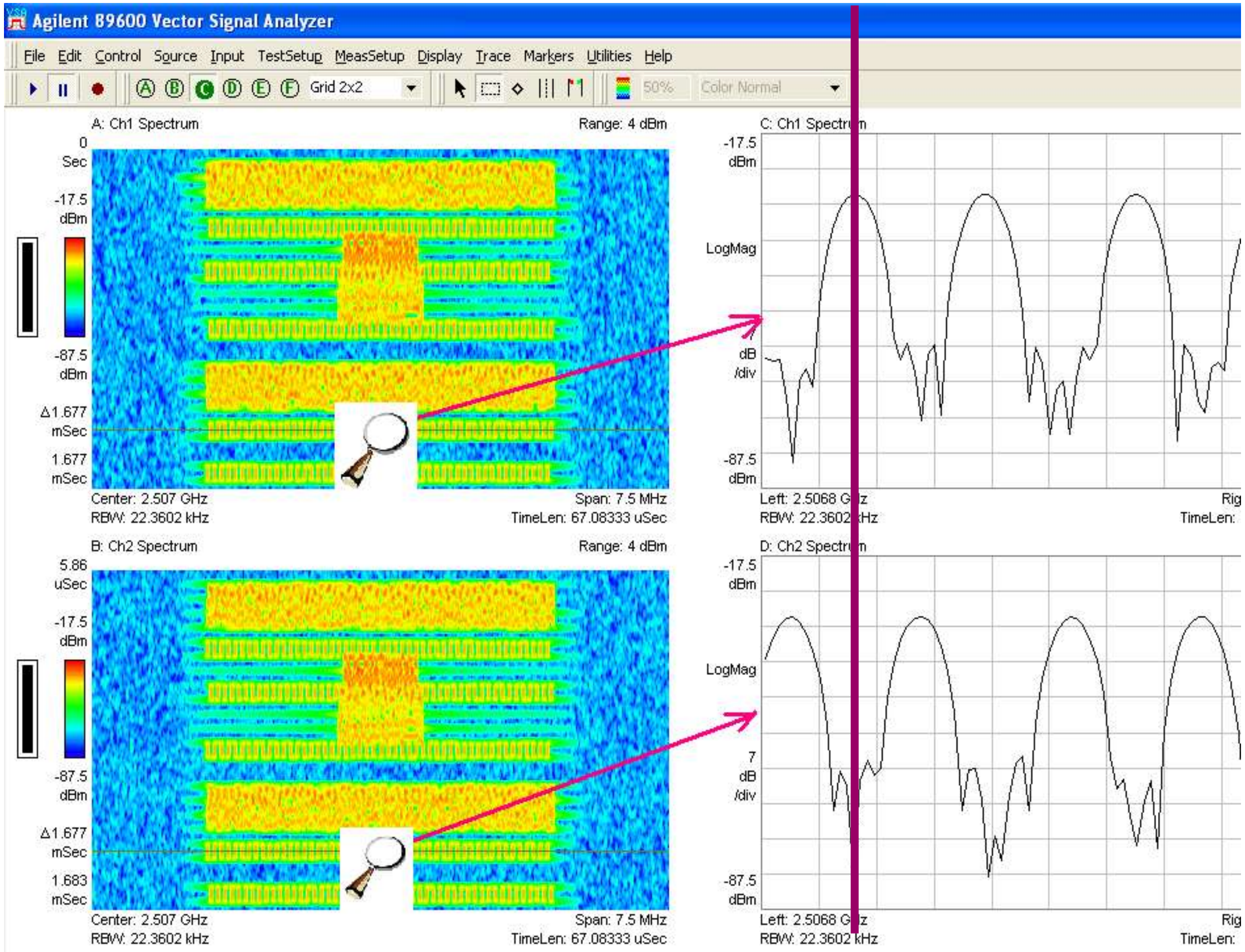
Pilot power is boosted to ensure errors from recovering the training signal do not dominate the demodulator performance

MIMO Signal Recovery – Spectrum View

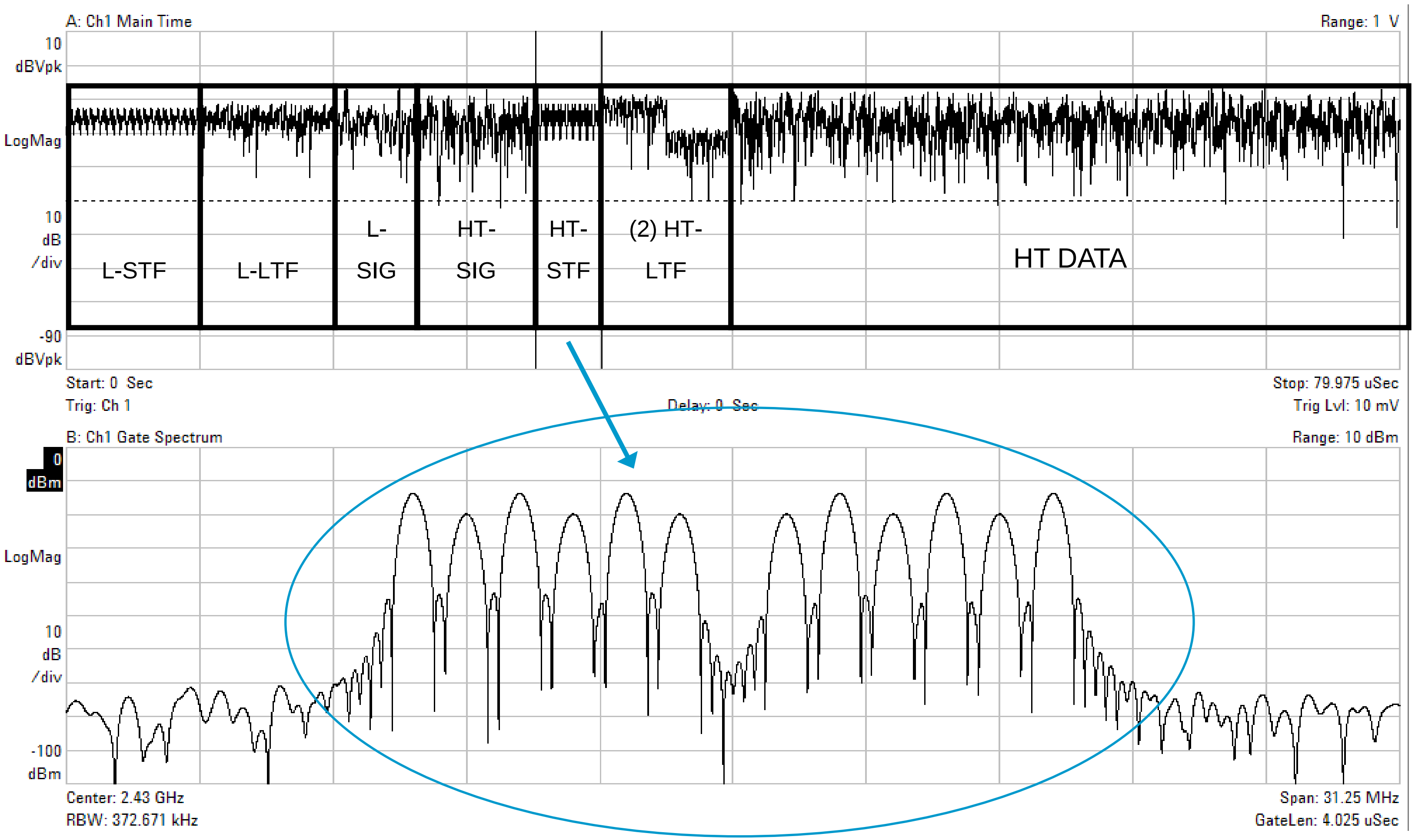
The traces in this LTE signal show how the Reference Signals (pilots) are on different frequencies at any instant in time

Spectrograms on left show spectrum versus time (time is vertical axis)

Unlike 802.16 OFDMA, the LTE RS (pilots) not present on all symbols



Frequency vs. Power in Burst: 802.11n (draft ver.)

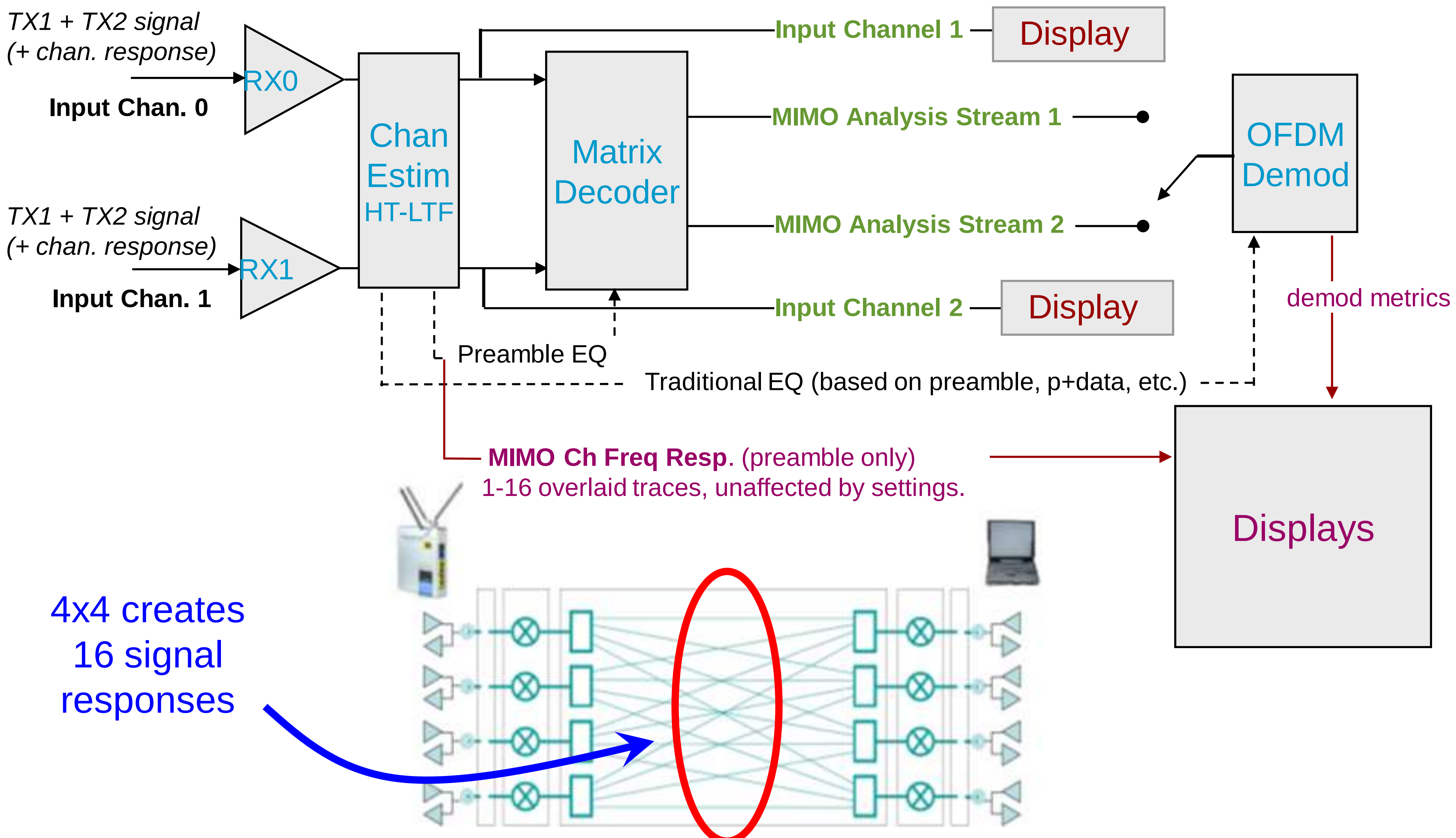


Channel Training Varies with Technology

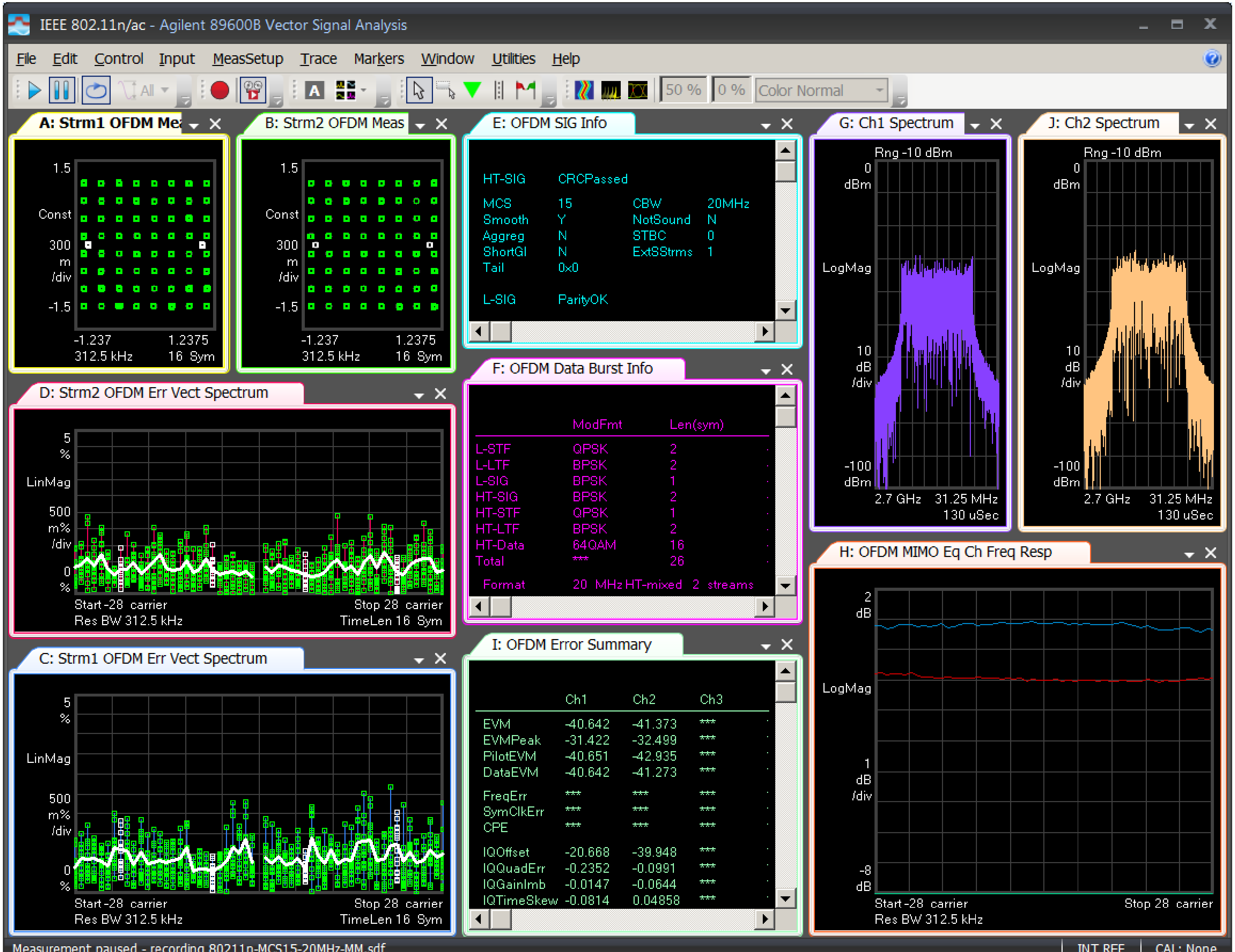
3GPP LTE	WiMAX	11n Wireless LAN
Reference signals (pilots) use different subcarriers for each transmitter The QPSK Reference signals are transmitted every 3rd or 4th symbol, mixed with data	BPSK Pilot subcarriers use different frequencies. Their positions vary symbol by symbol within a subframe, but 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		

VSA MIMO Signal Analysis

Conceptual Model--Only 2x2 shown for clarity



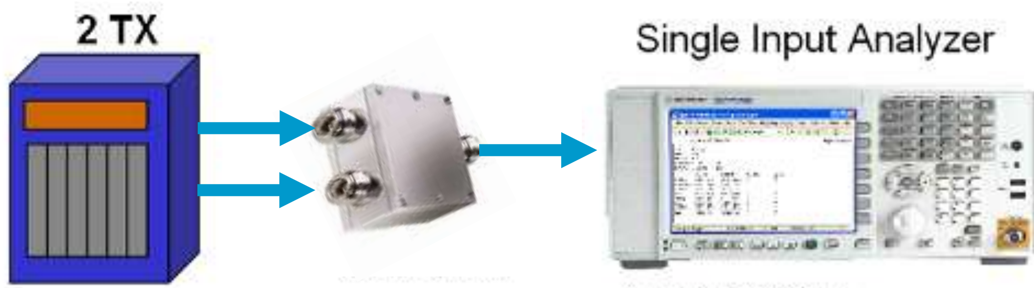
Demodulation Results: Const, Time, Spectrum, Tabular



Some Cross Channel Measurements Can Be Made With a Single Input Analyzer

Applies to LTE, WiMAX

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



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

Cable calibration may still be required

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

Demodulation Results

Detected Signal Content

A: OFDM Data Burst Info

	ModFmt	Len(sym)	Pwr(dBm)
HT-GF-STF	QPSK	2	-3.1148
HT-LTF	BPSK	2	-2.756
HT-SIG	BPSK	2	-3.0975
HT-LTF	BPSK	4	-2.6783
HT-Data	16QAM	6	-2.7525
Total	***	16	-2.8196

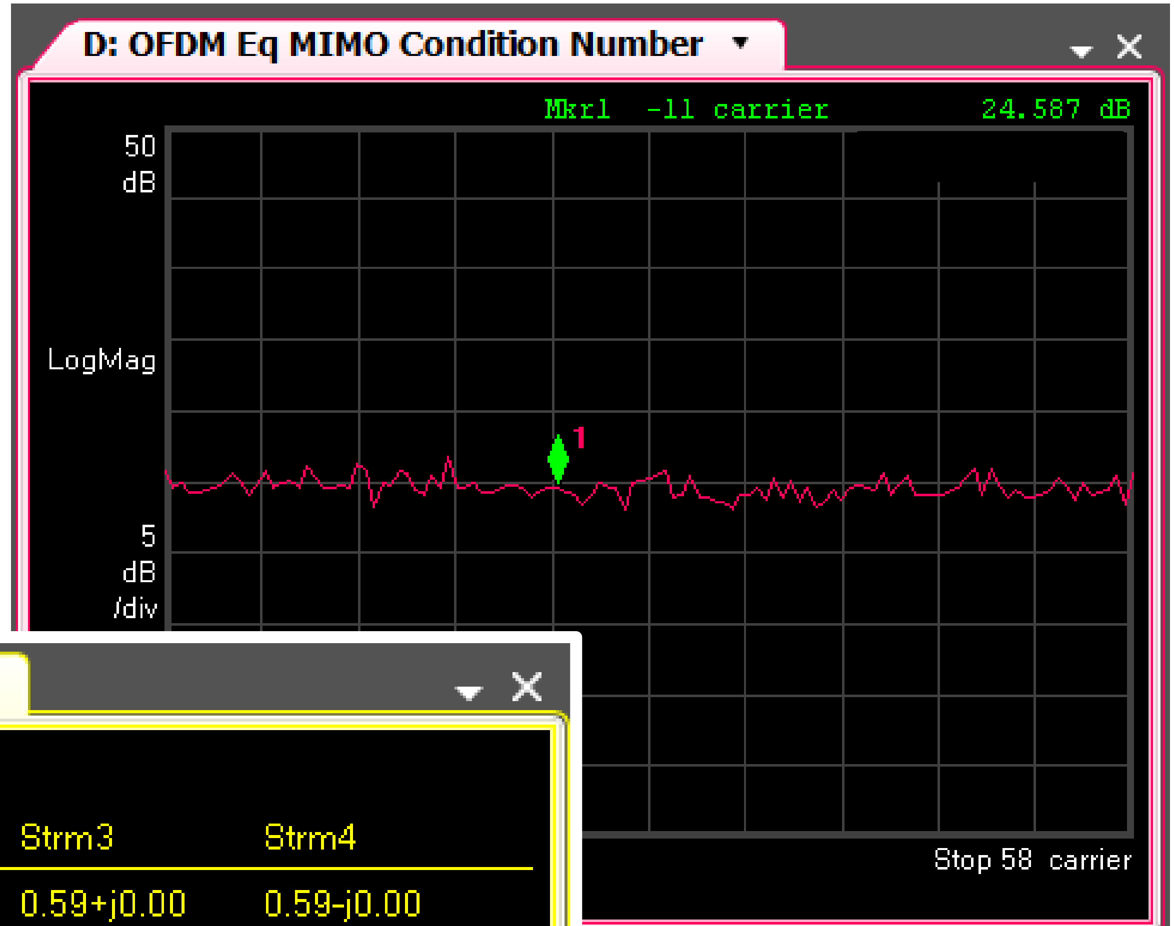
Format	40 MHz HT-greenfield	4	streams
VHT-SIG-A	None		
HT-SIG	CRCPassed		
L-SIG	None		

Measurements by Transmitter

D: OFDM Error Summary

	Ch1	Ch2	Ch3	Ch4	Avg	
EVM	-20.855	-20.763	-21.131	-10.137	-15.185	dB
EVMPeak	-4.7174	-4.9049	-4.0954	-3.2614	-3.2614	dB
PilotEVM	-25.676	-26.001	-27.093	-10.922	-16.573	dB
DataEVM	-20.696	-20.597	-20.955	-10.097	-15.12	dB
FreqErr	***	***	***	***	-791.60	Hz
SymClkErr	***	***	***	***	2.8796	ppm
CPE	***	***	***	***	4.1472	%rms
IQOffset	-44.877	-25.688	-46.057	-16.073	-21.634	dB
IQQuadErr	-0.8018	-0.6562	-0.0792	-0.3657	-0.4757	deg
IQGainImb	-0.2473	-0.3508	-0.2401	-0.2545	-0.27312	dB
IQTimeSkew	-0.0605	0.10948	-0.1924	-0.1005	-0.06101	ns
CrossPwr	0.01077	-0.0177	0.00722	-0.0013	-0.00026	dB
SyncCorr	0.30061	0.30061	0.30061	0.30061	0.30061	

4x4 Channel Matrix & Condition Number



A: OFDM MIMO Chan Matrix

	Strm1	Strm2	Strm3	Strm4
Ch1	0.59+j0.00	0.59+j0.00	0.59+j0.00	0.59-j0.00
Ch2	-0.50+j0.25	0.50-j0.26	-0.50+j0.25	0.50-j0.26
Ch3	0.52-j0.26	0.26+j0.52	-0.52+j0.26	-0.26-j0.52
Ch4	-0.01+j0.03	0.03+j0.01	0.01-j0.03	-0.04-j0.01

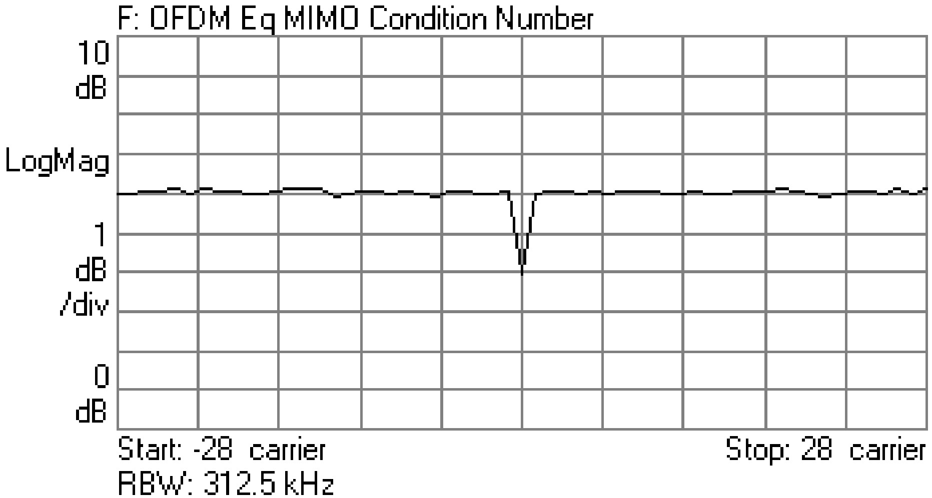
MIMO Condition Number

What it is:

a) A way to see if your MIMO system is functioning correctly

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

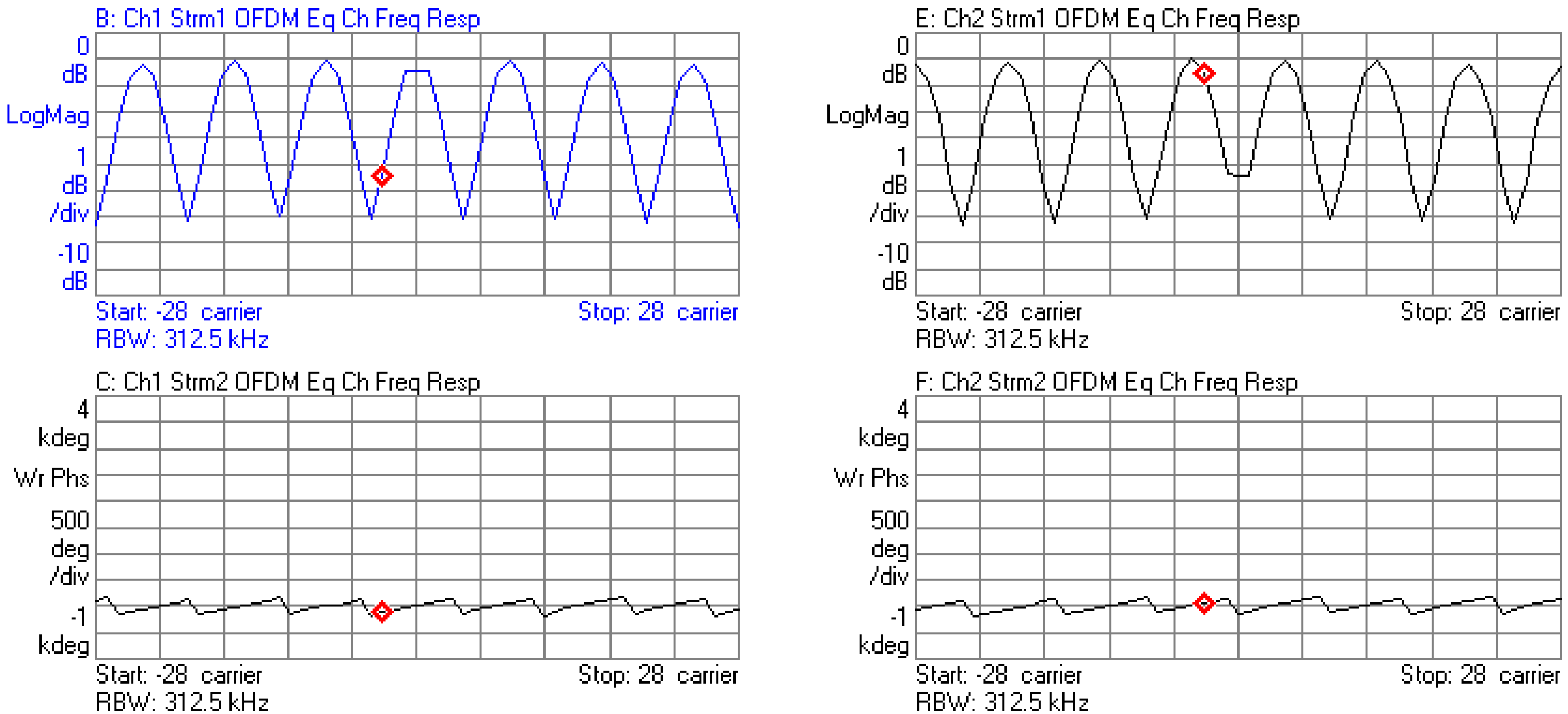
How you calculate it: Find the *singular values* of the channel matrix, and take the ratio of the highest / lowest



Matrix condition number

Ratio of max/min singular values of a matrix. Value always ≥1 (or ≥ 0 dB). If this value is greater than signal SNR it is likely the MIMO separation of data streams will not work correctly.

Frequency Response by Channel & Stream



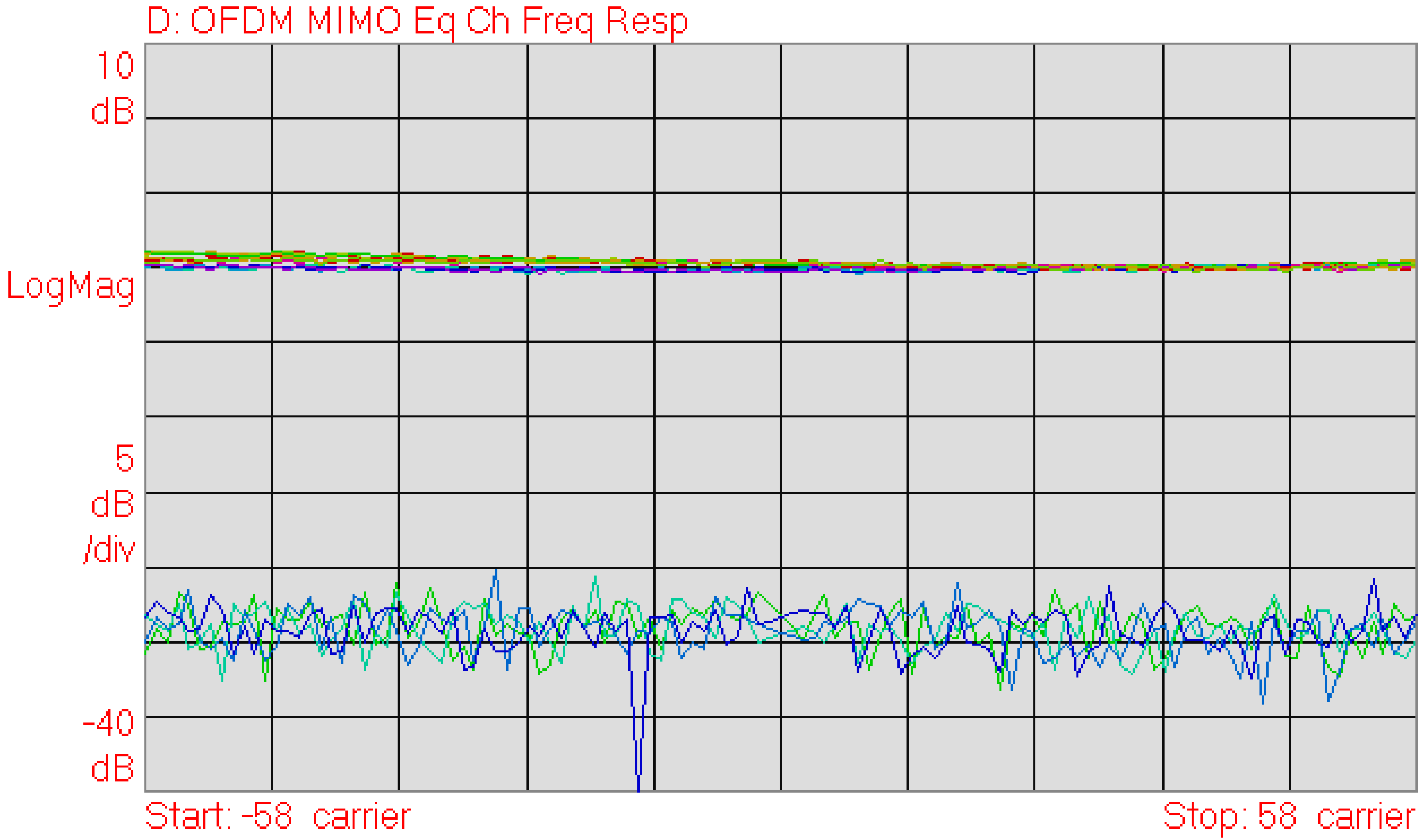
Trace B	Marker:	-3 carrier	-5.445 dB
Trace C	Marker:	-3 carrier	-103.1045 deg
Trace E	Marker:	-3 carrier	-1.524 dB
Trace F	Marker:	-3 carrier	49.1482 deg

Channel frequency responses

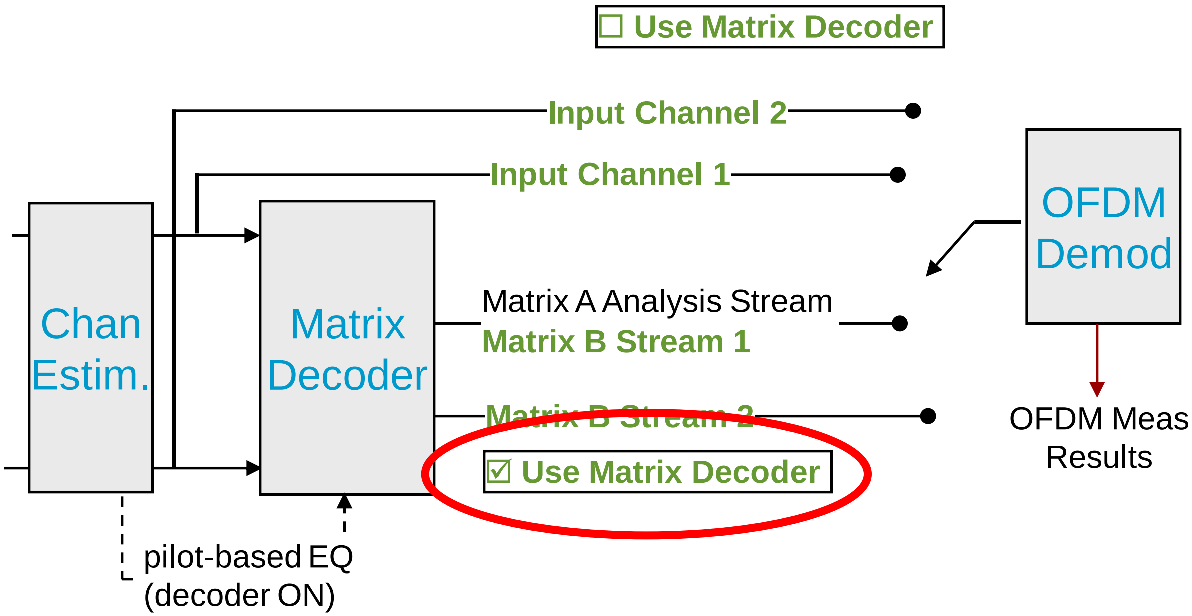
Shows the transfer functions (mag & phase) for each channel. Available for all data streams.

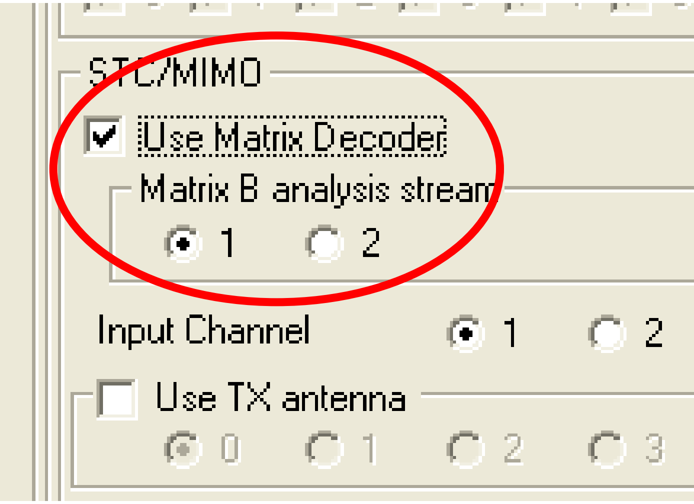
MIMO 4x4 Frequency Response

802.11n Example: One Weak Channel



Matrix Decoder & Crosstalk





Measurements Made Without Matrix Decoder

- Effects of crosstalk are included in measurement
- Crosstalk degrades EVM
- Error due to crosstalk can hide other errors

Measure Both Ways to Understand Error Contribution of Crosstalk

Signal Analysis Solutions, Comparisons

Standards-Based and Proprietary OFDM

Vector Signal Analysis Software

Spectrum/Signal Analyzers

Digital Oscilloscopes

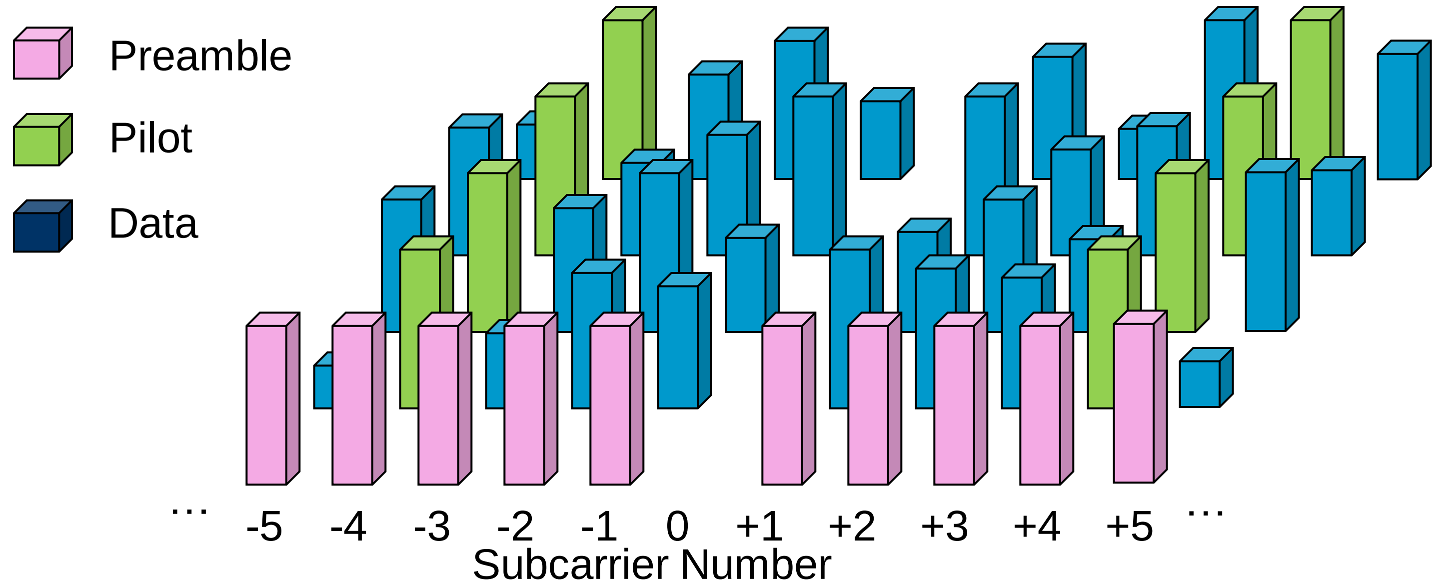
Modular PXI

Logic Analyzers

Design & Simulation Software

- Agilent SystemVue or ADS
- MATLAB

Analyzing Proprietary OFDM signals



Demodulator needs to know

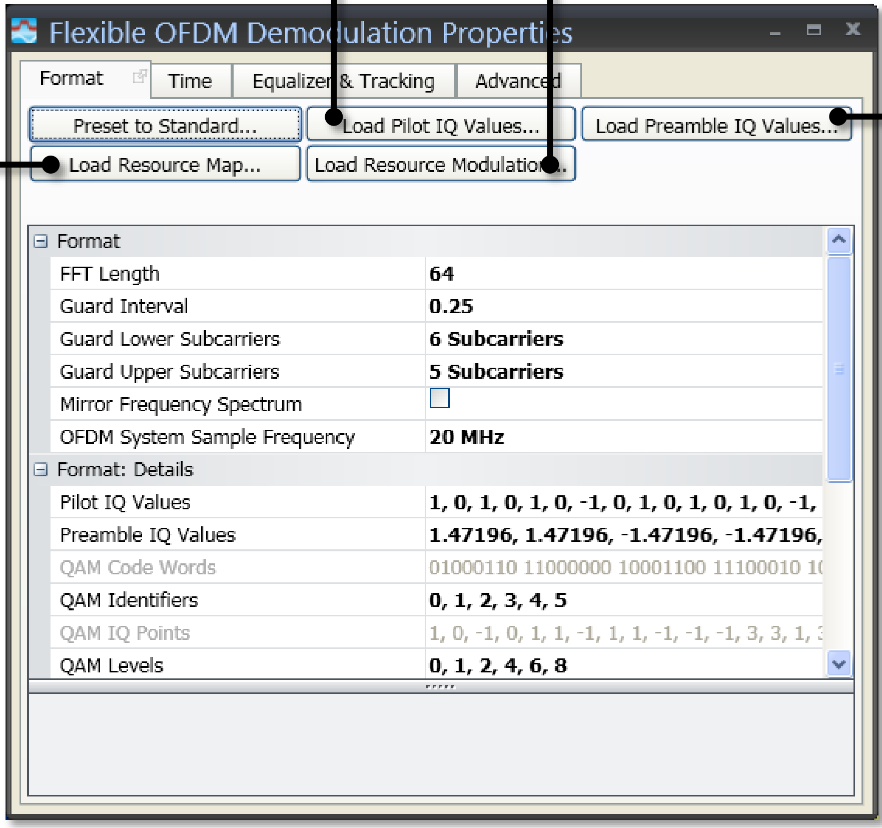
– basic time, freq and FFT parameters.
– which subcarriers are pilots?
– which subcarriers are preambles?
– what are the expected I-Q values for each preamble and pilot subcarrier?
– what is the expected modulation format for each data subcarrier?

Analyzing Proprietary OFDM Signals (cont)

Load Config File:
Pilot IQ Values

Load Config File:
Subcarrier Modulation

Load Config File:
Subcarrier Types



Load Config File:
Preamble IQ Values

Basic FFT Parameters

Configuration Files for Analyzing Custom OFDM

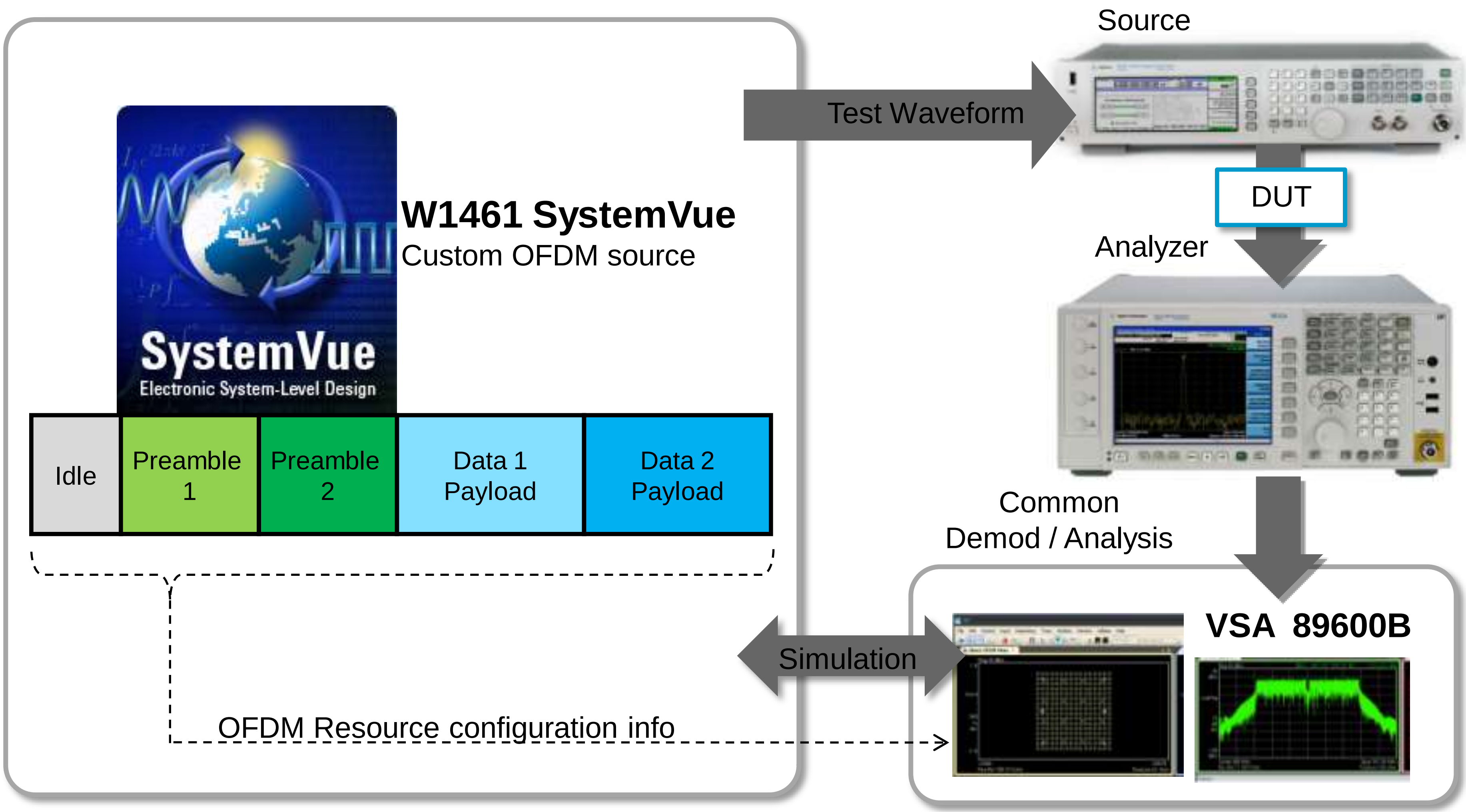
Configuration Files

- **Resource Modulation.txt** – Describes modulation format for each subcarrier.
- **Preamble I-Q.txt** – expected IQ value for each preamble subcarrier.
- **Pilot I-Q.txt** – expected IQ value for each pilot.

Features to simplify configuration

- **Auto-detect pilot I-Q –** can eliminate Pilot I-Q file
- **Auto-detect data subcarrier modulation format –** simplify Resource Mod file
- **Loop continuously through last N symbols –** shorter config files
- **Modulation format table** – modify all data subcarrier modulation formats simultaneously, by changing one value in table.

Custom OFDM for Simulation or Hardware Test



Measurements & Number of Inputs

	Number of measurement inputs required		
Measurement objective	1	2	> 2
SISO & MISO errors due to phase noise, timing errors and amplitude clipping	Y		
Spectrum Mask, Harmonics and Spurious	Y		
RF Phase and Baseband Timing Alignment, using pilot-based measurements	Using a power combiner.	No combiner needed but errors from second analyzer input will contribute to result	
Cross Channel Isolation. Using RS-based measurement	Y	Similar measurements to single input. Can connect to two transmitters at the same time	
Interference, Grounding, Transient settling	Y		
Transmit Diversity Space Time Coding (Specific channels)	Y		
MIMO Spatial Multiplexing (with unwanted coupling) and coding verification	Individual (Direct Mapped) streams	Y	If > 2 streams

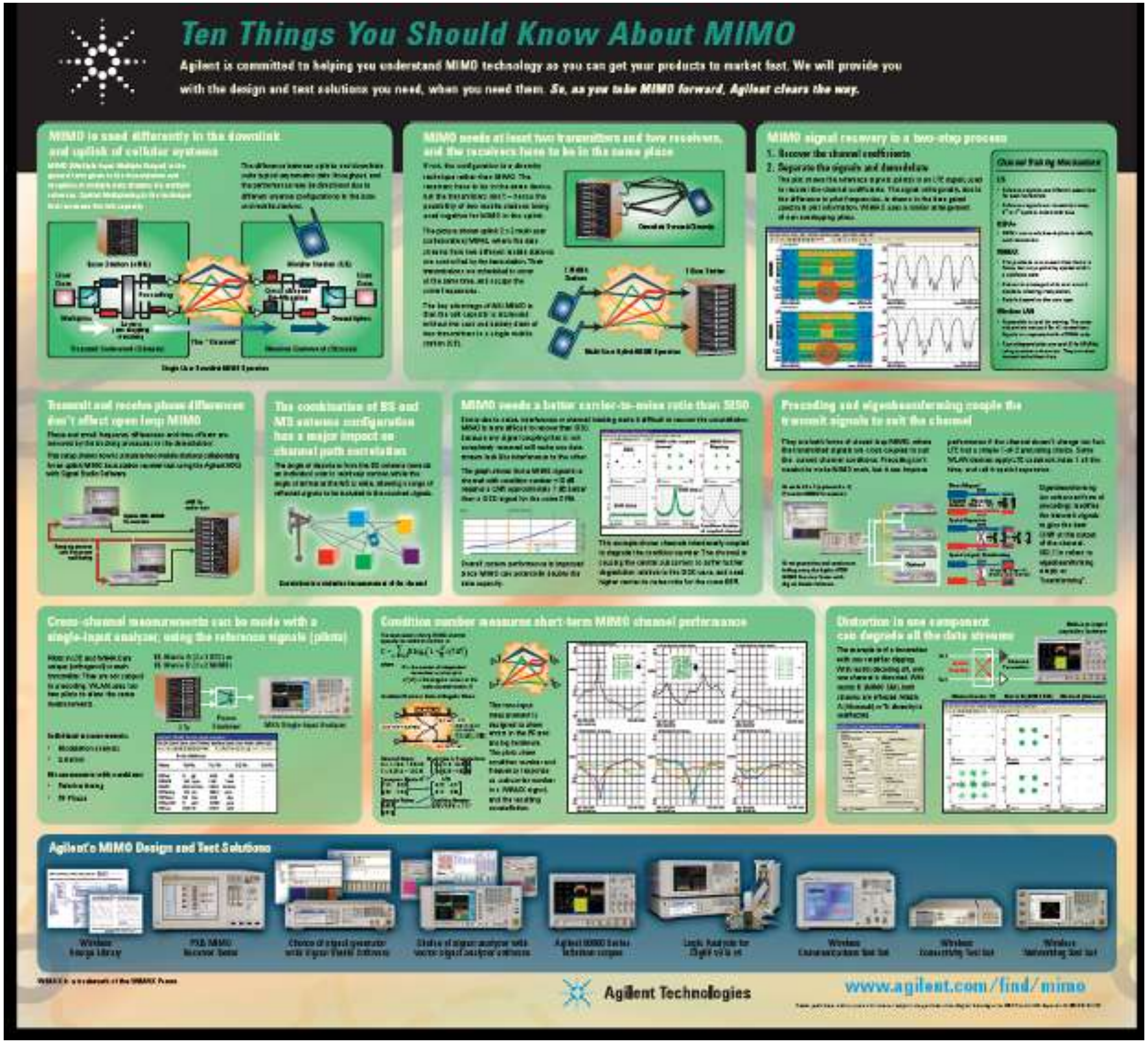
Test Types & Number of Sources

Issue	1 Channel	2 Channels
Input Sensitivity (BER or PER) due to noise floor, phase noise, RF signal Interference	Y	
Signal Path response matching Amplifier characterization	Y	
Interference, Grounding, Transient settling, dynamic performance, e.g. AGC operation	Y	Y
Cross Channel Isolation	(Y)	Y
MIMO operation and Interoperability Full Channel model Testing		Y

Poster, Webcast– Useful MIMO Information

At Agilent.com Search:

“Ten Things You Should Know about MIMO”



For More Information

More Information on OFDM, Flexible OFDM

- App note "Making Custom OFDM Measurements" http://cp.literature.agilent.com/litweb/pdf/5990-6824EN.pdf
- App note: http://cp.literature.agilent.com/litweb/pdf/5990-6998EN.pdf

For more information about Agilent SystemVue

- OFDM demonstration: http://www.youtube.com/watch?v=IFtCuKKi8Jw
- SystemVue for OFDM: http://www.agilent.com/find/eesof-systemvue-ofdm

For more information about Agilent VSA

- http://www.agilent.com/find/89600B

For more information about MIMO

- www.agilent.com/find/mimo
- Webcast slides: Ten Things You Should Know About MIMO http://www.home.agilent.com/upload/cmc_upload/All/MIMO-10-Things-Webcast-Oct08.pdf
- Poster: Ten Things You Should Know About MIMO http://cp.literature.agilent.com/litweb/pdf/5989-9618EN.pdf
- Webcast slides: MIMO RF Measurements: Choosing and Using Tools http://www.home.agilent.com/upload/cmc_upload/All/MIMO-Choosing-Using-Tools-webcast-Jan-2009.pdf
- 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