OFDM/MIMO Master Class
Understanding the physical layer principles of WLAN, WiMAX and LTE

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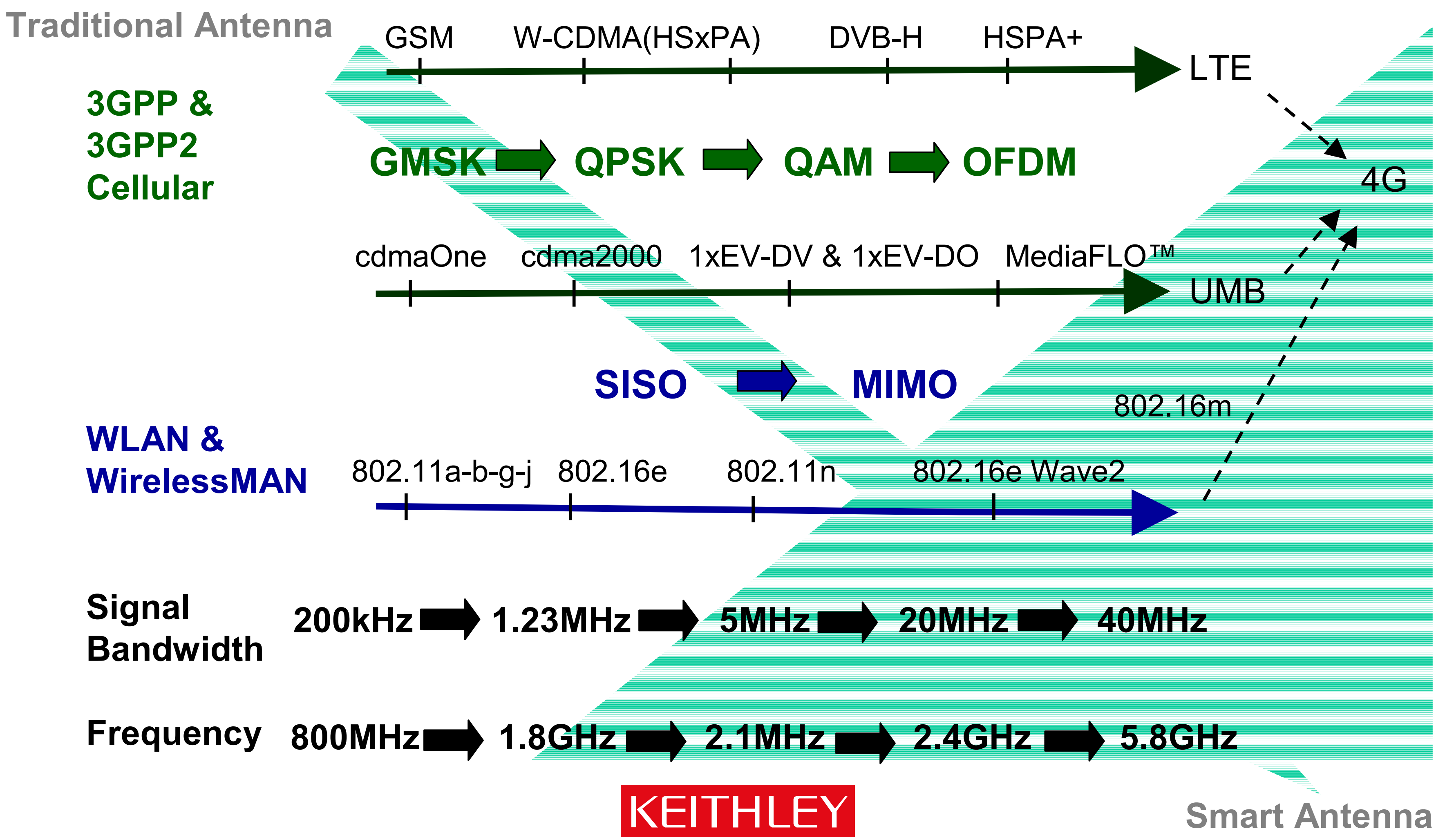
Agenda

- **The evolution of communications and an introduction to the test tools**
- **Part One – OFDM and SISO radio configurations**
  - The case for OFDM
  - OFDM Signal Structure, generic and WLAN.
  - Measurements
  - OFDM and OFDMA
  - Peak to average ratio considerations
  - WiMAX and LTE
- **Part Two – OFDM and MIMO radio configurations**
  - MIMO – Multiple Input Multiple Output Radio Topology
  - How it works.
  - Measurements
  - Channel Considerations
  - Smart Antenna Systems and Beam Forming Conclusion
- **Technology Overview and Test Equipment Summary**

The Evolution of RF Technology



Test tools we will use today

2800 VSA and 2900 VSG
SISO
Spectrum Analyzer, Signal Generator
GSM
CDMA
WLAN
WiMAX
LTE

2800 VSA, 2900 VSG + 2895
MIMO
WLAN
WiMAX
LTE

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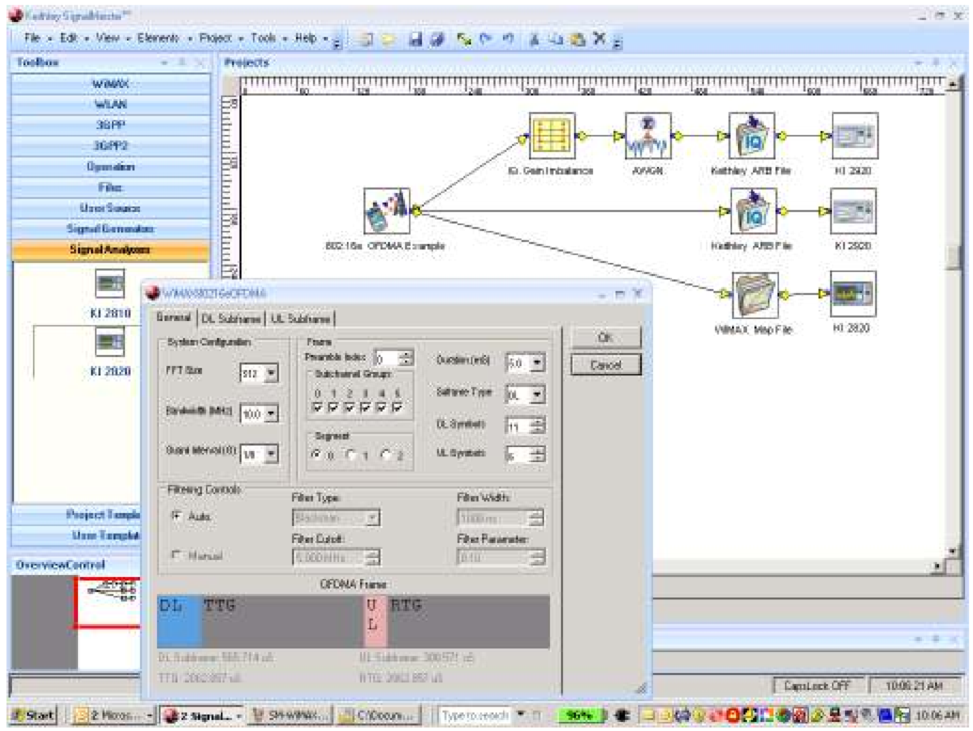
Keithley Simplifies Signal Creation and Analysis

- Introducing the industries only graphically based signal creation and analysis software – Signal Meister.
- Simplifies signal creation allowing users to create signals then optionally add distortion parameters quickly and easily
- Includes signal creation and analysis for 3GPP, 3GPP2, WiMAX, WLAN with MIMO configurations and channel distortion.
- Interfaces to the 2900/2800 series of Keithely vector signal generators and analyzers.



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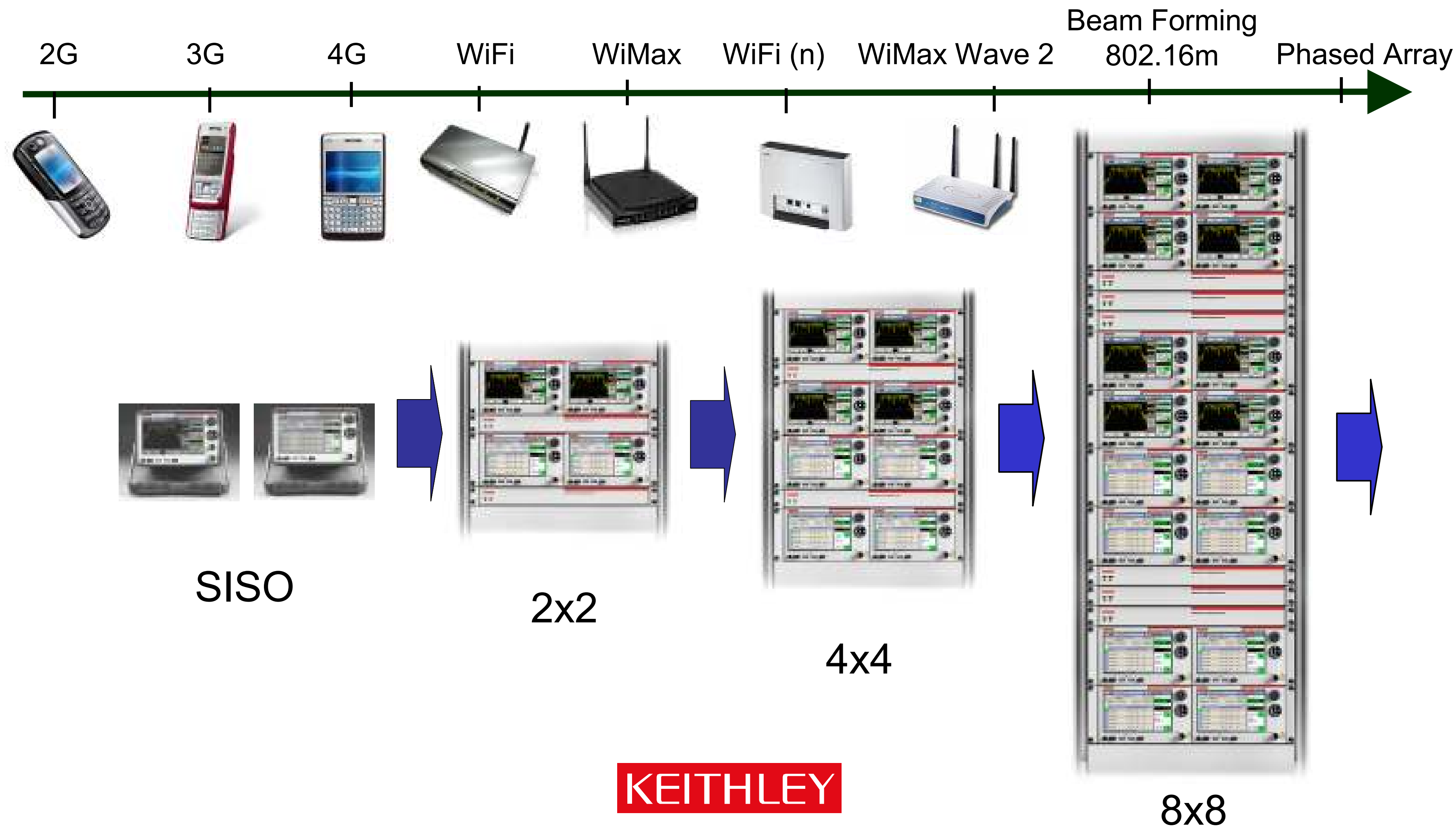
Technology Evolution



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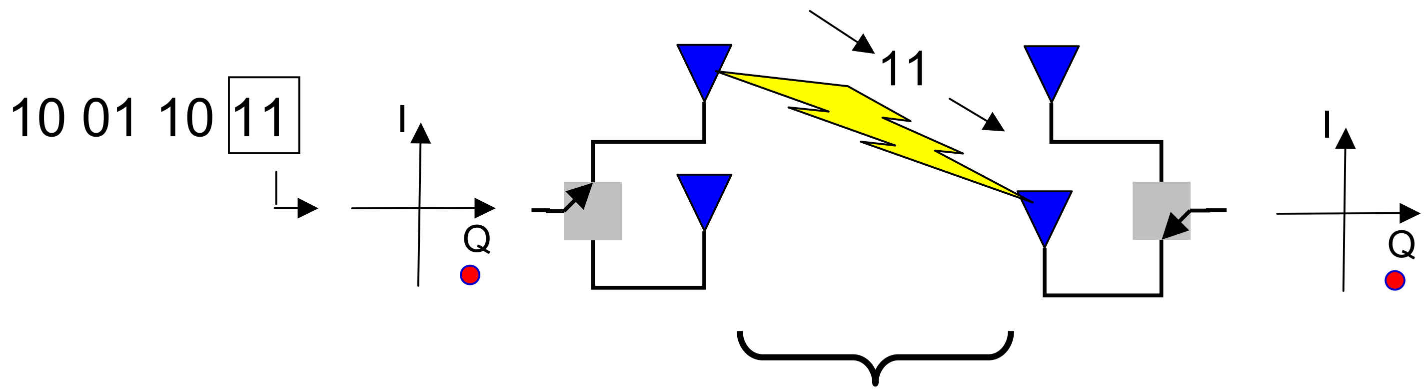
Traditional Serial Transmission using a SISO radio

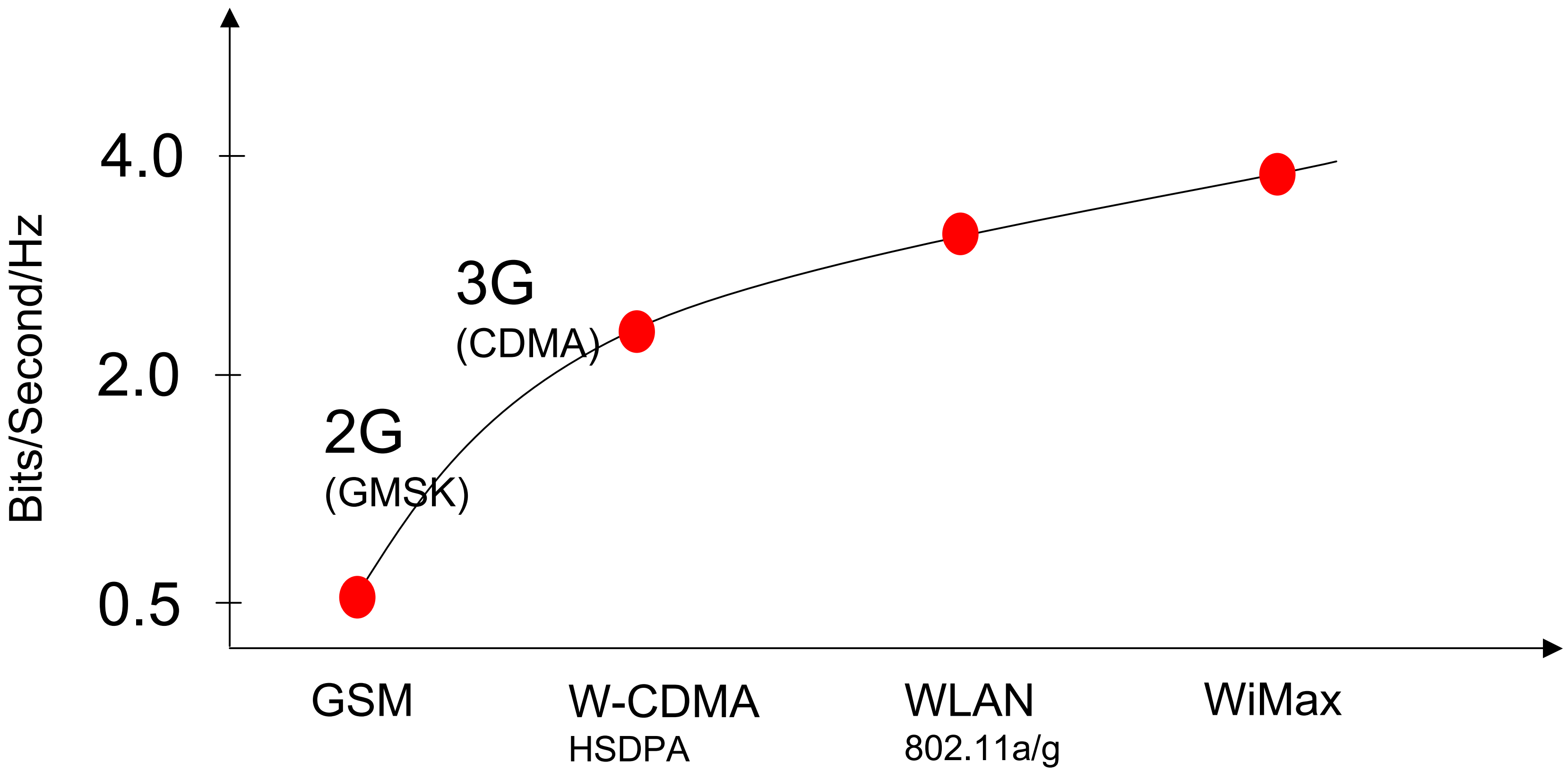


- Only one symbol is transmitted at a time
- One radio, only one antenna used at a time (e.g., 1 x 1)
- Antennas constantly switched for best signal path

Why use Orthogonal Frequency Division Multiplex?

- High spectral efficiency – provides more data services.
- Resiliency to RF interference – good performance in unregulated and regulated frequency bands
- Lower multi-path distortion – works in complex indoor environments as well as at speed in vehicles.

High Spectrally Efficiency – OFDM



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Why OFDM?

…Resiliency to RF interference.

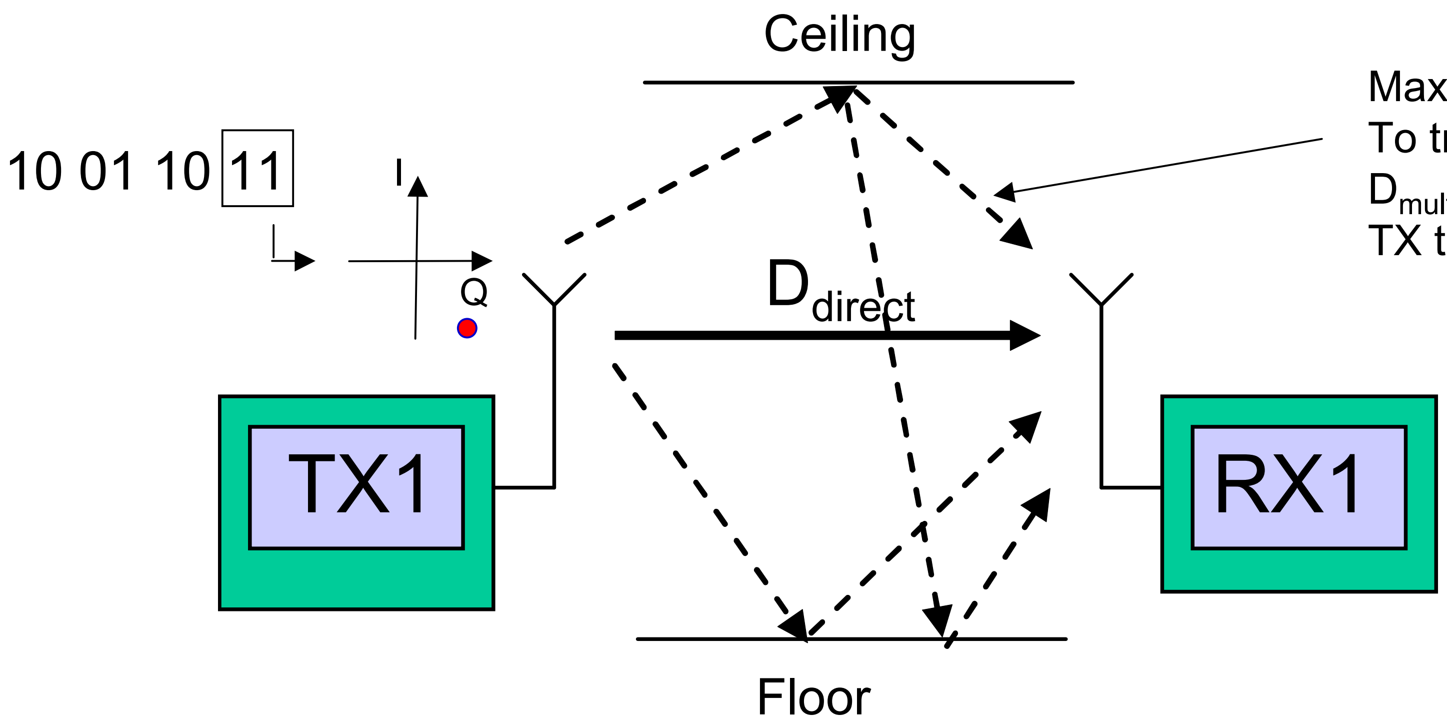
- **The ISM Band (Industrial Scientific and Medical) is a set of frequency ranges that are unregulated.**
- **Most popular consumer bands**
  - 915MHz Band (BW 26MHz)
  - 2.45GHz Band (BW 100MHz)
  - 5.8GHz Band (BW 100MHz)
- **Typical RF transmitters in the ISM band include…**
  - Analog Cordless Phones (900MHz)
  - Microwave Ovens (2.45 GHz)
  - Bluetooth Devices (2.45GHz)
  - Digital Cordless Phones (2.45GHz or 5.8GHz)
  - Wireless Lan (2.45GHz or 5.8GHz).

The Multi-Path Problem

Example: Bluetooth Transmitter & Receiver

Symbol Rate = 1MSymbols/s
Symbol Duration = 1/1E6 = 1us

Maximum Symbol Delay < 1us



Maximum time for signal
To travel D (Distance)
$D_{multipath} > D_{direct}$
TX to RX < 1us

Single Carrier – Single Symbol

- Bluetooth, GSM, CDMA and other communications standards use a single carrier to transmit a single symbol at a time.
- Data throughput is achieved by using a very fast symbol rate.

W-CDMA - 3.84 Msymbols/sec
Bluetooth – 1 Msymbols/sec

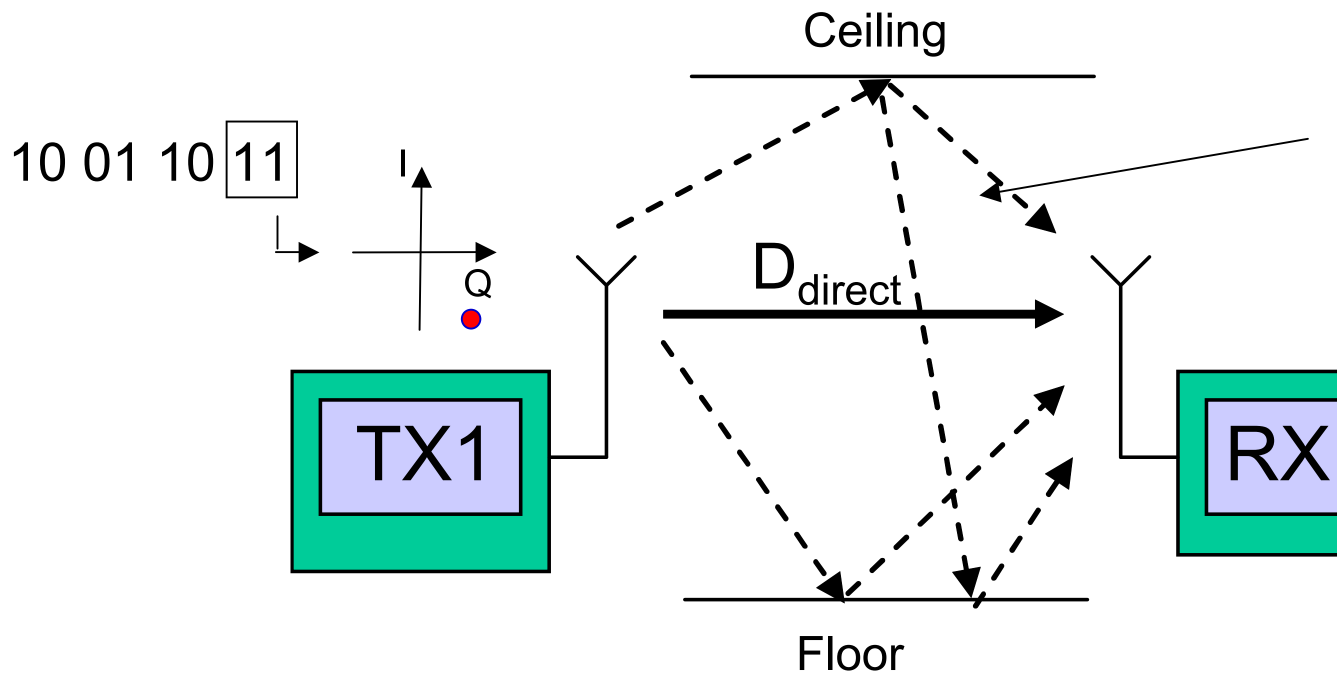
- A primary disadvantage is that fast symbol rates are more susceptible to Multi-path distortion.

Slow the symbol rate

Reduce the previous examples symbol rate by a third

Symbol Rate = 300kSymbols/s
Symbol Duration = 1/300 = 3.3us

Maximum Symbol Delay < 3.3us



Maximum time for signal
To travel D (Distance)
$D_{multipath} > D_{direct}$
TX to RX < 3.3us

But the data throughput is reduced!

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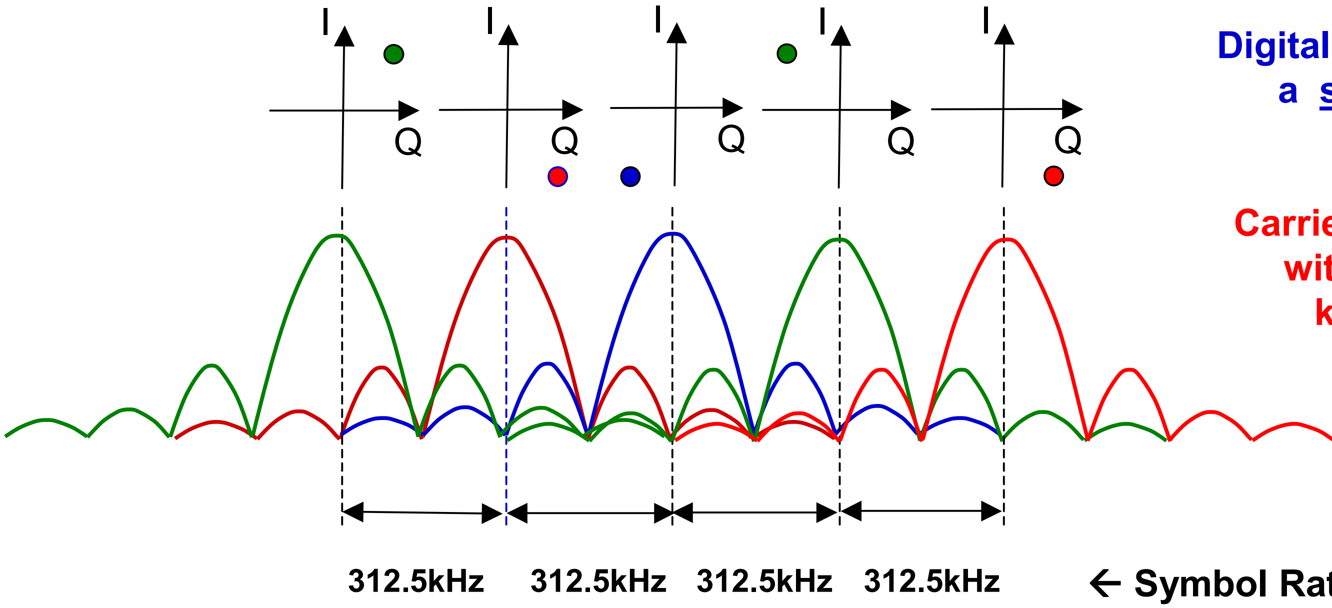
Improve the throughput - use more than one carrier!

802.11a-g WLAN example



Digital filtering creates a $\frac{\sin x}{x}$ spectra

Carrier spacing aligned with spectra nulls keeps carriers orthogonal

← Symbol Rate α Carrier Spacing

Low symbol rate per carrier * multiple carriers = high data rate

250 kbps symbol rate * 48 sub-carriers * 6 coded bits /sub-carrier * ¾ coding rate = 54 Mbps

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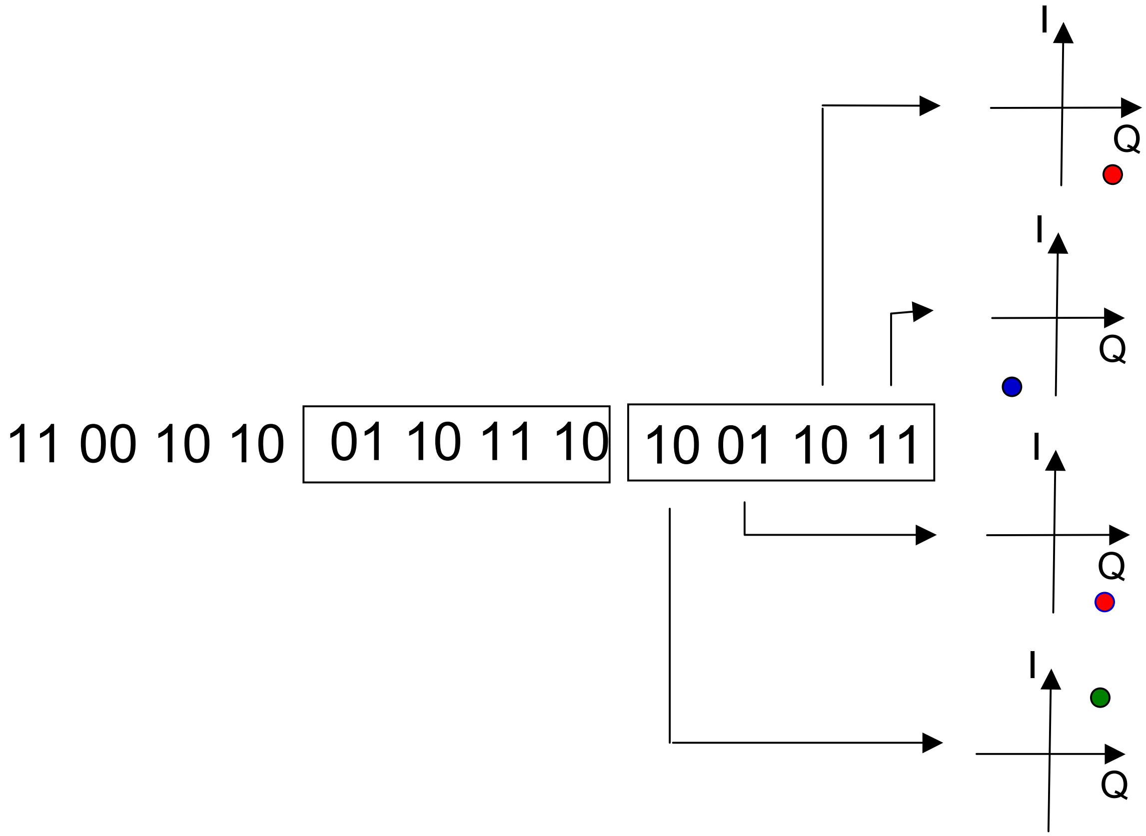
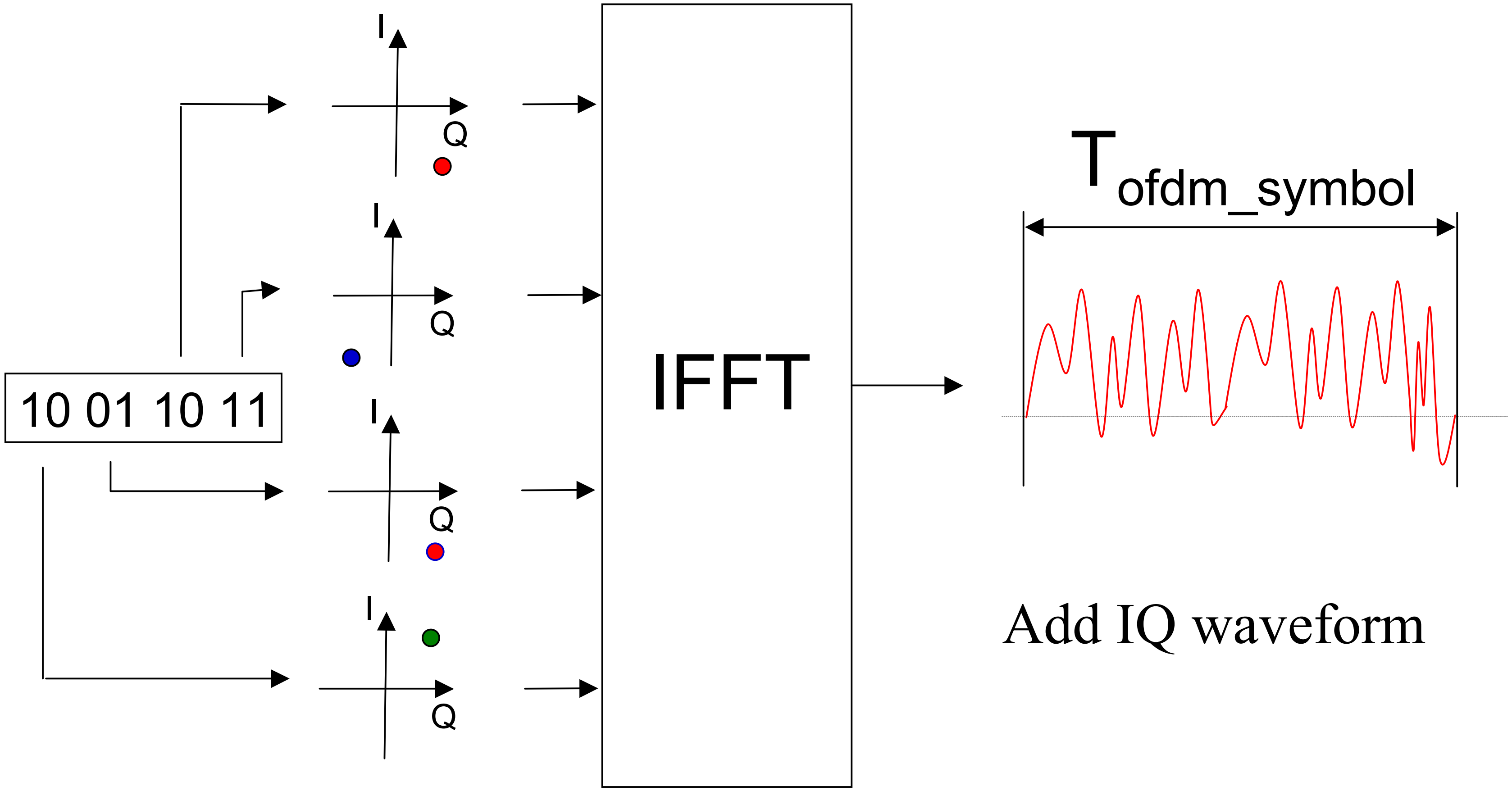
Parallel Symbols

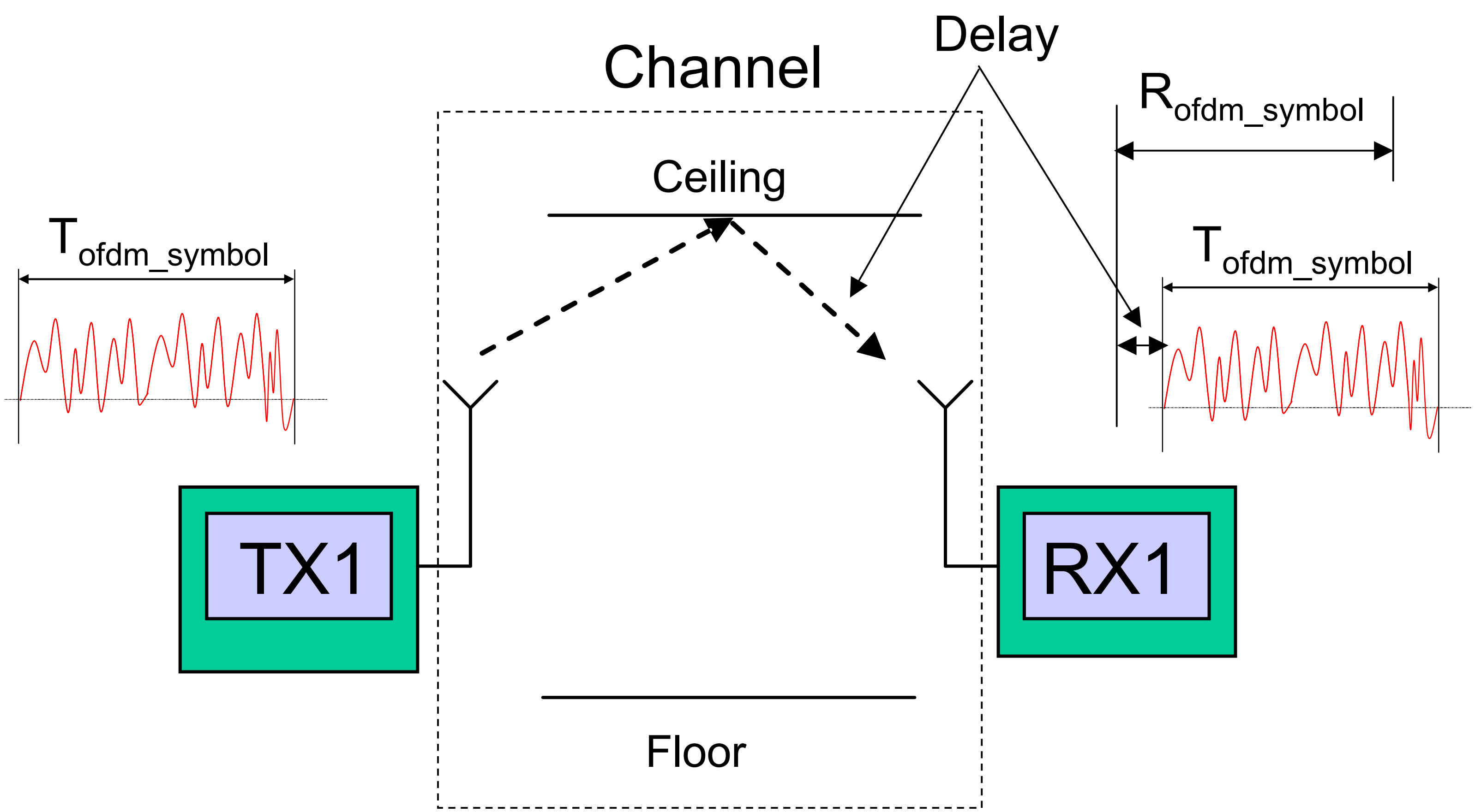


Parallel Symbols



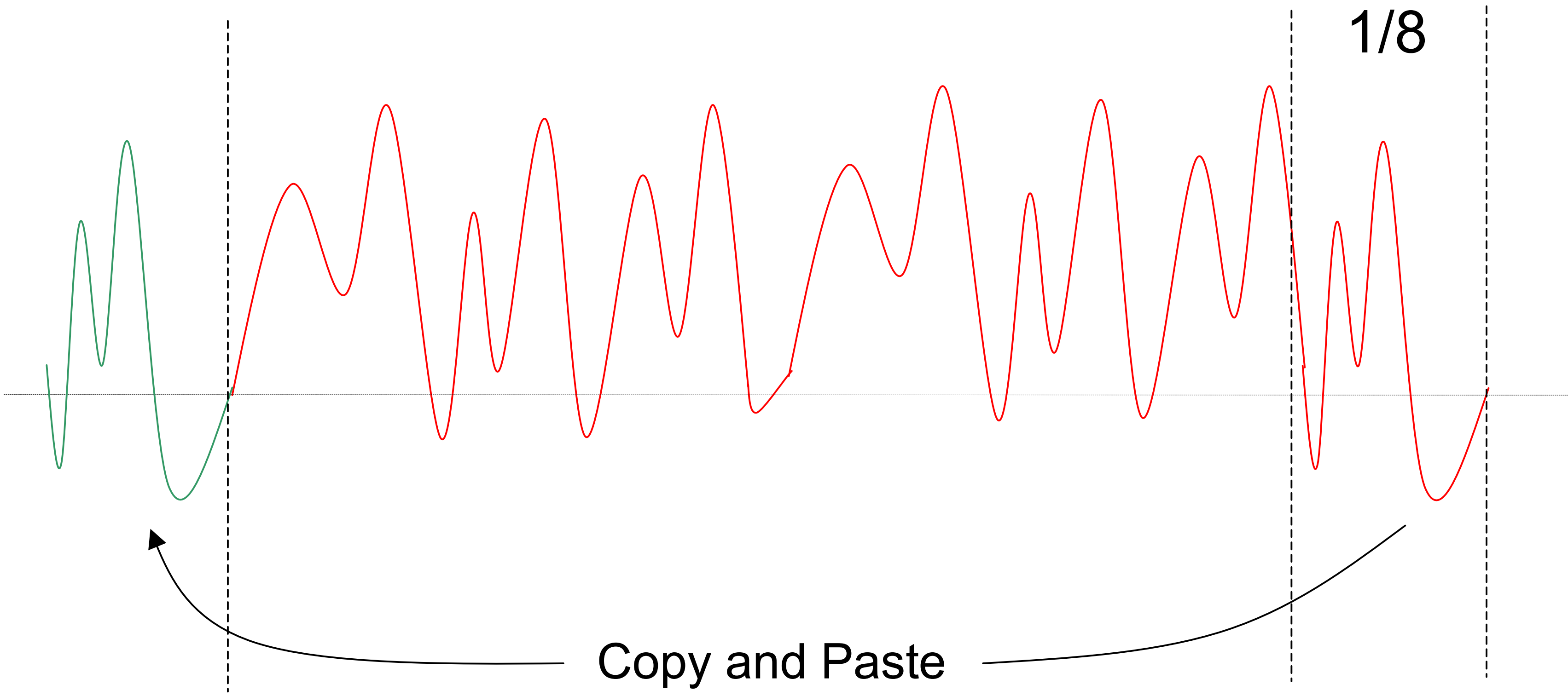
Add IQ waveform

Delays in the channel



The guard interval and cyclic prefix

Lengthen without discontinuity



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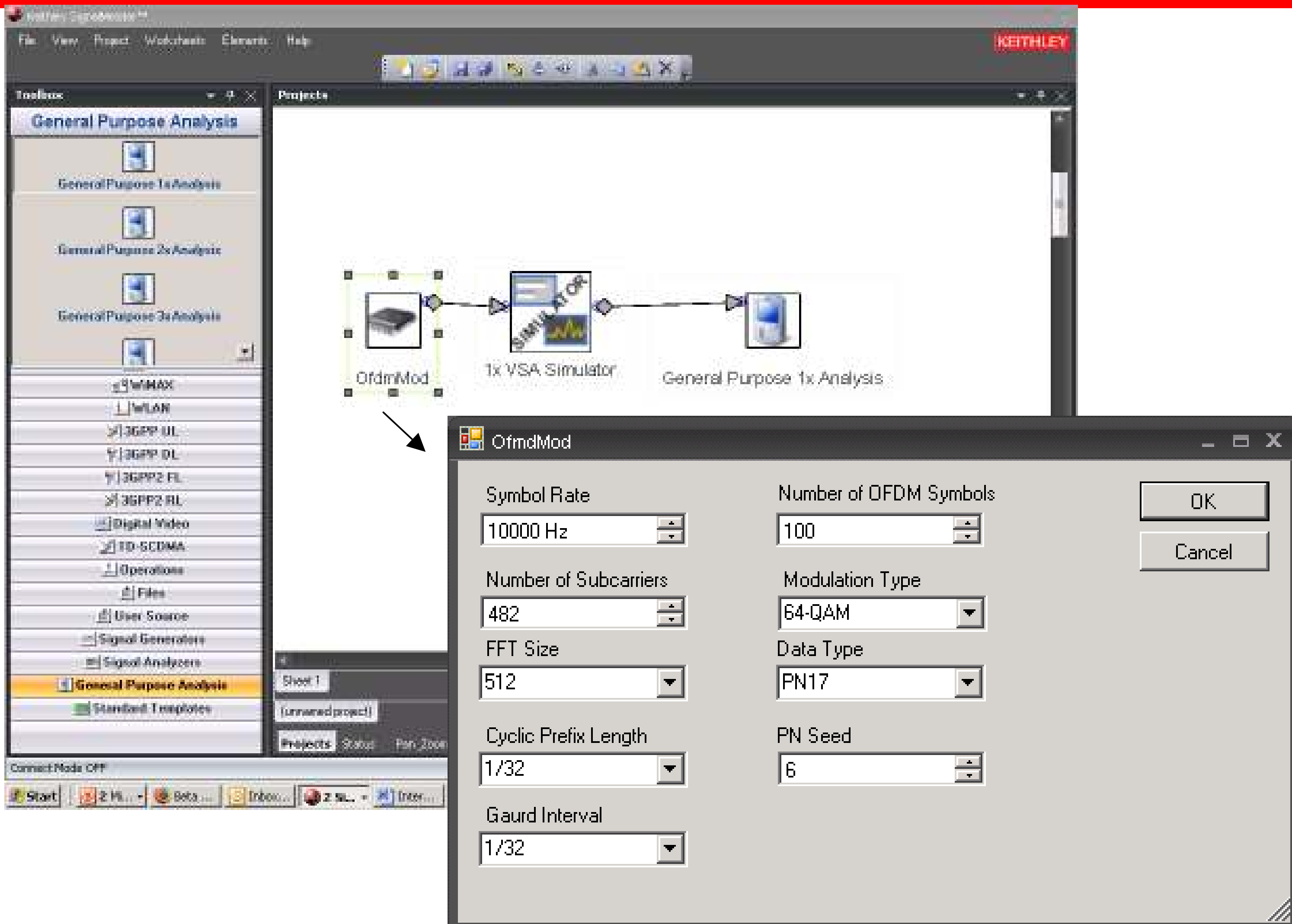
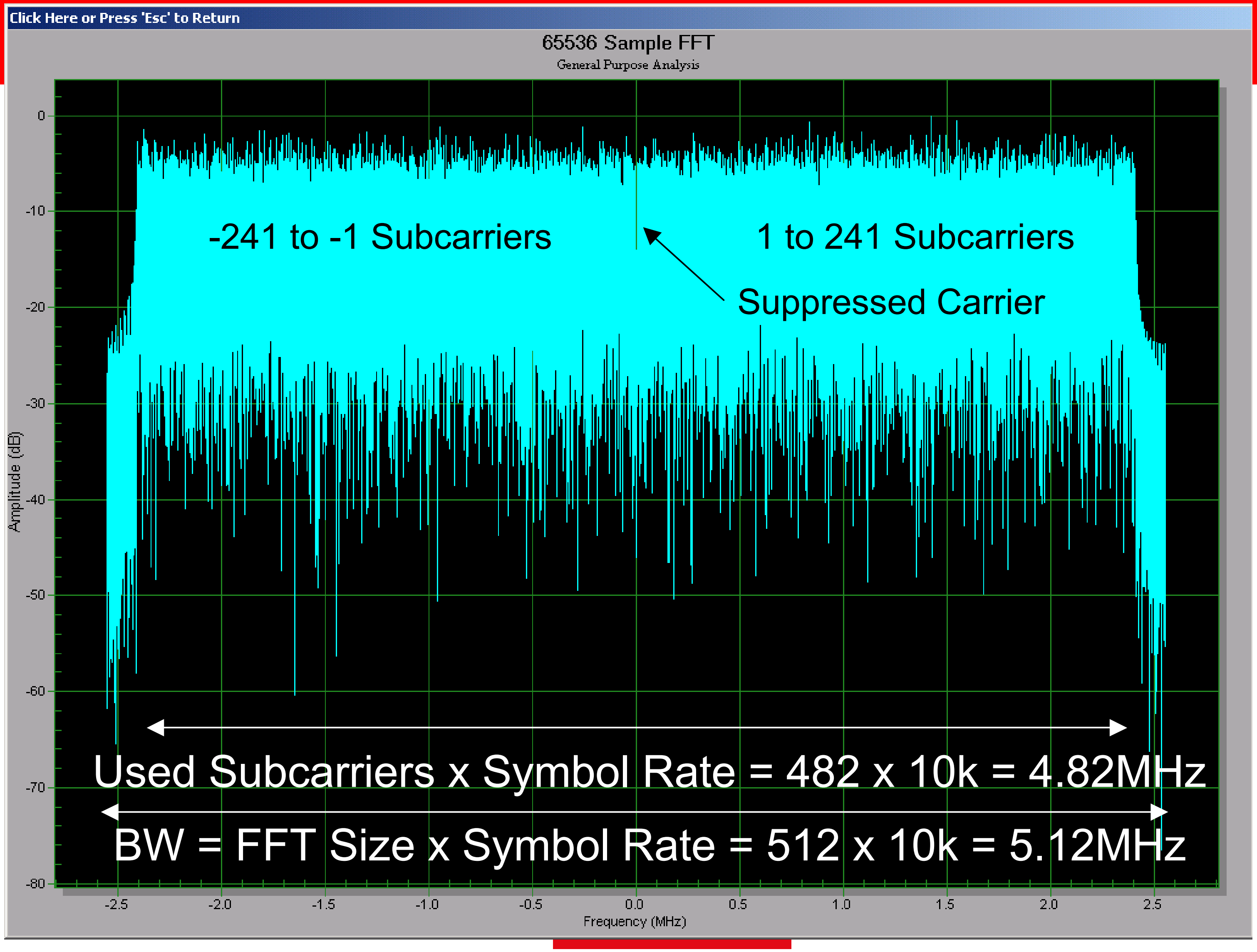
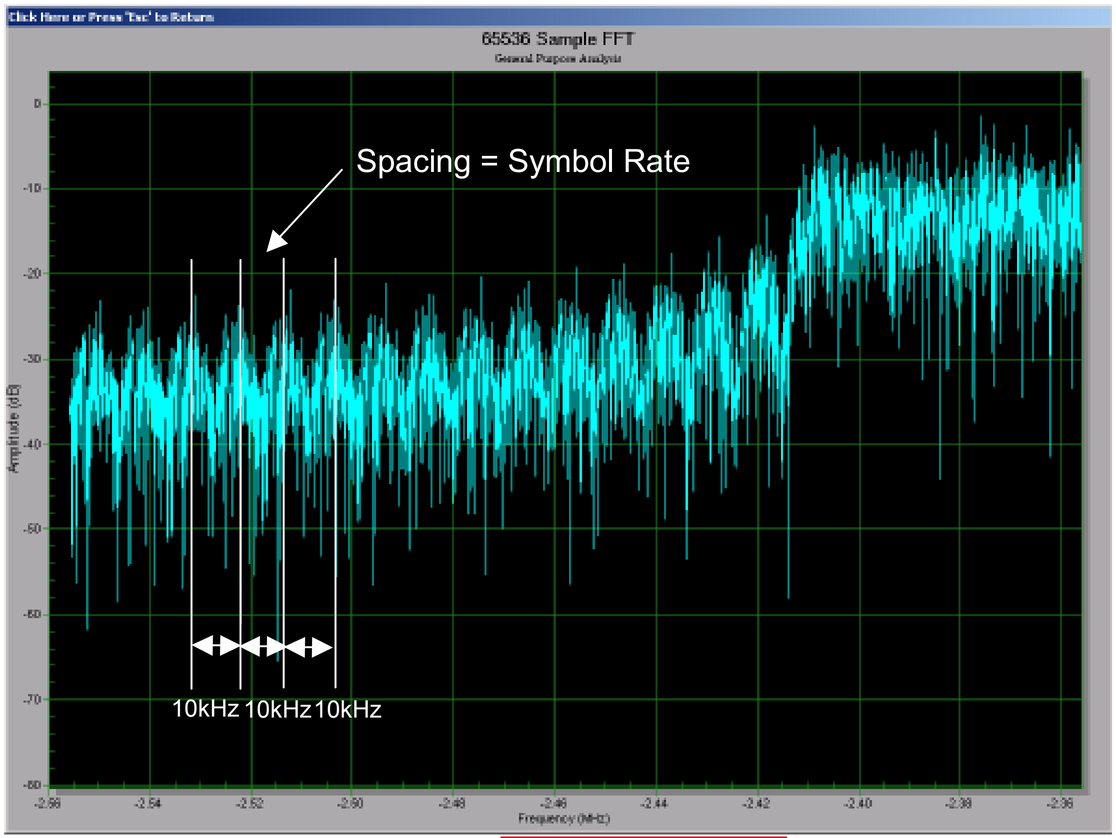
Building a simple OFDM signal



Examine the Signal in the Frequency Domain



Examine the Signal in the Frequency Domain



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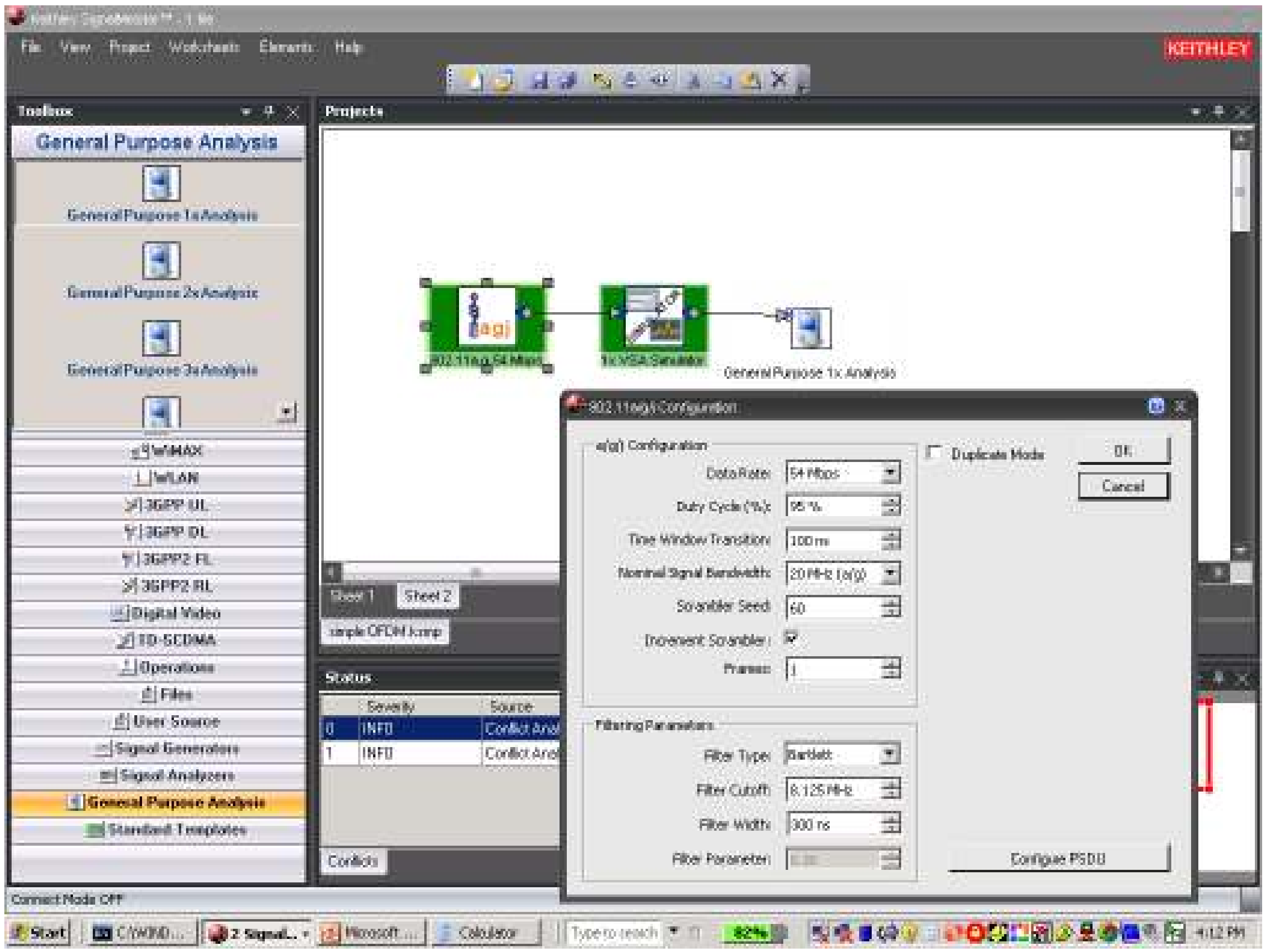
Example: WLAN (802.11a/g)

- Modulation Technique OFDM
- Bandwidth 16.25MHz
- Number of sub-carriers 52
- Sub-carrier numbering -26 to + 26
- Pilot sub-carriers -21, -7, +7 and +21 (BPSK)
- Sub-carrier BW 312.5kHz
- Packet Structure – Preamble – Header – Data Block
- SUB Carrier Modulation Types - BPSK, QPSK, 16-QAM or 64-QAM

WLAN Signal Generation



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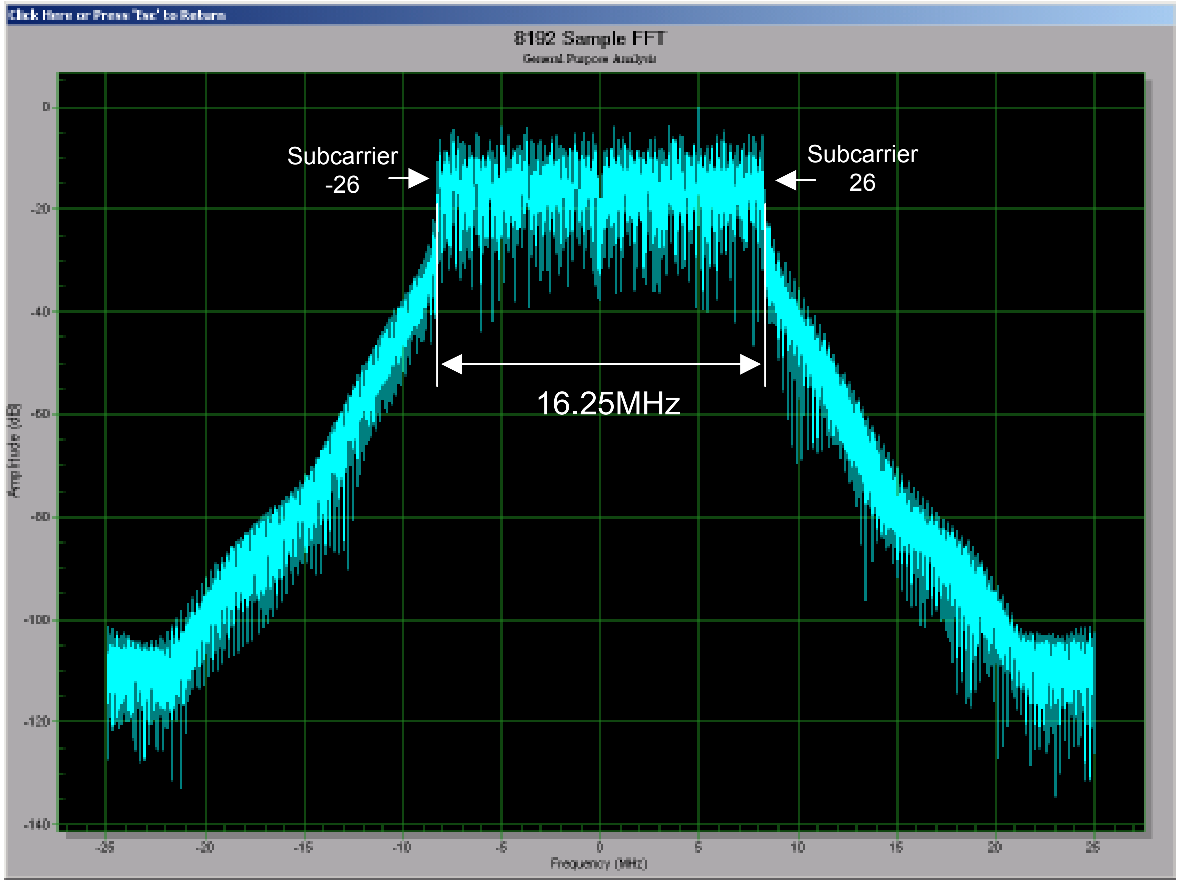
Frequency Domain 802.11g



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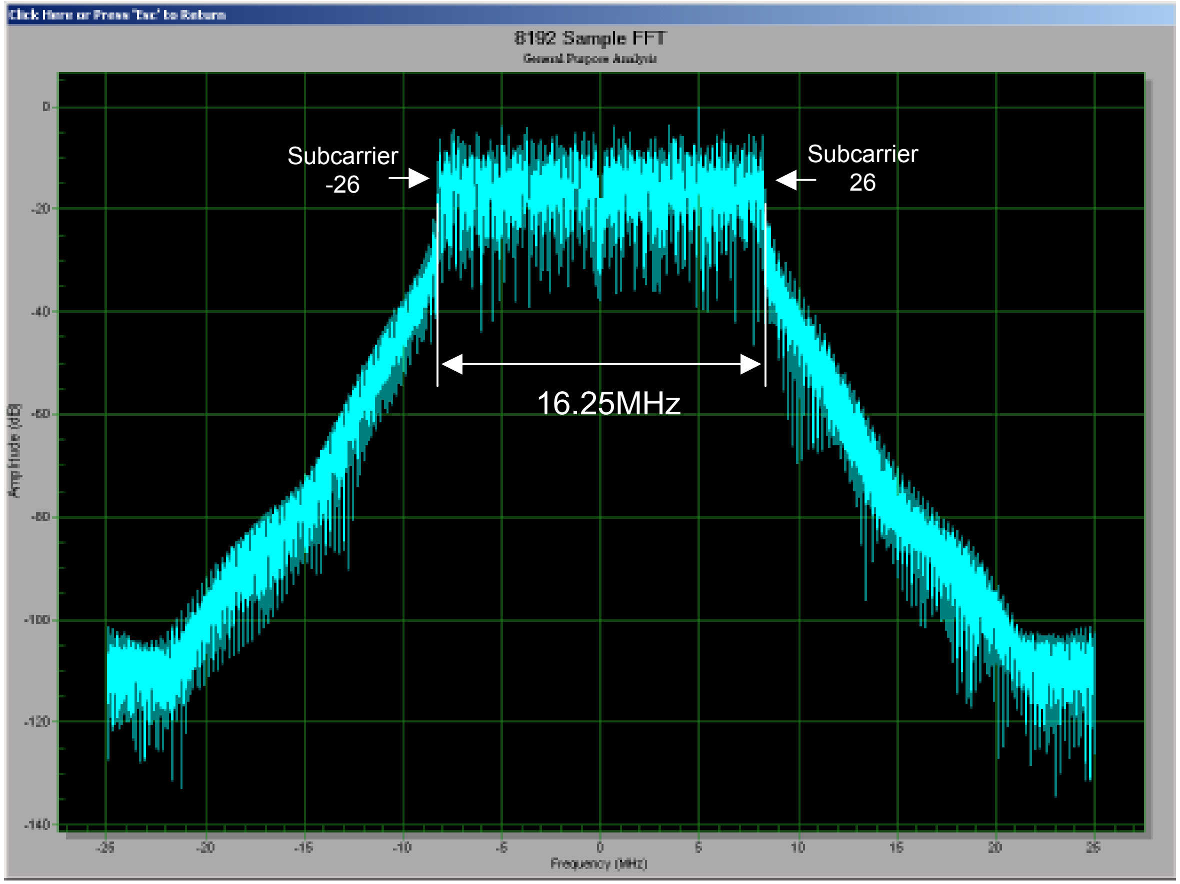
Frequency Domain 802.11g



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Key OFDM Measurements

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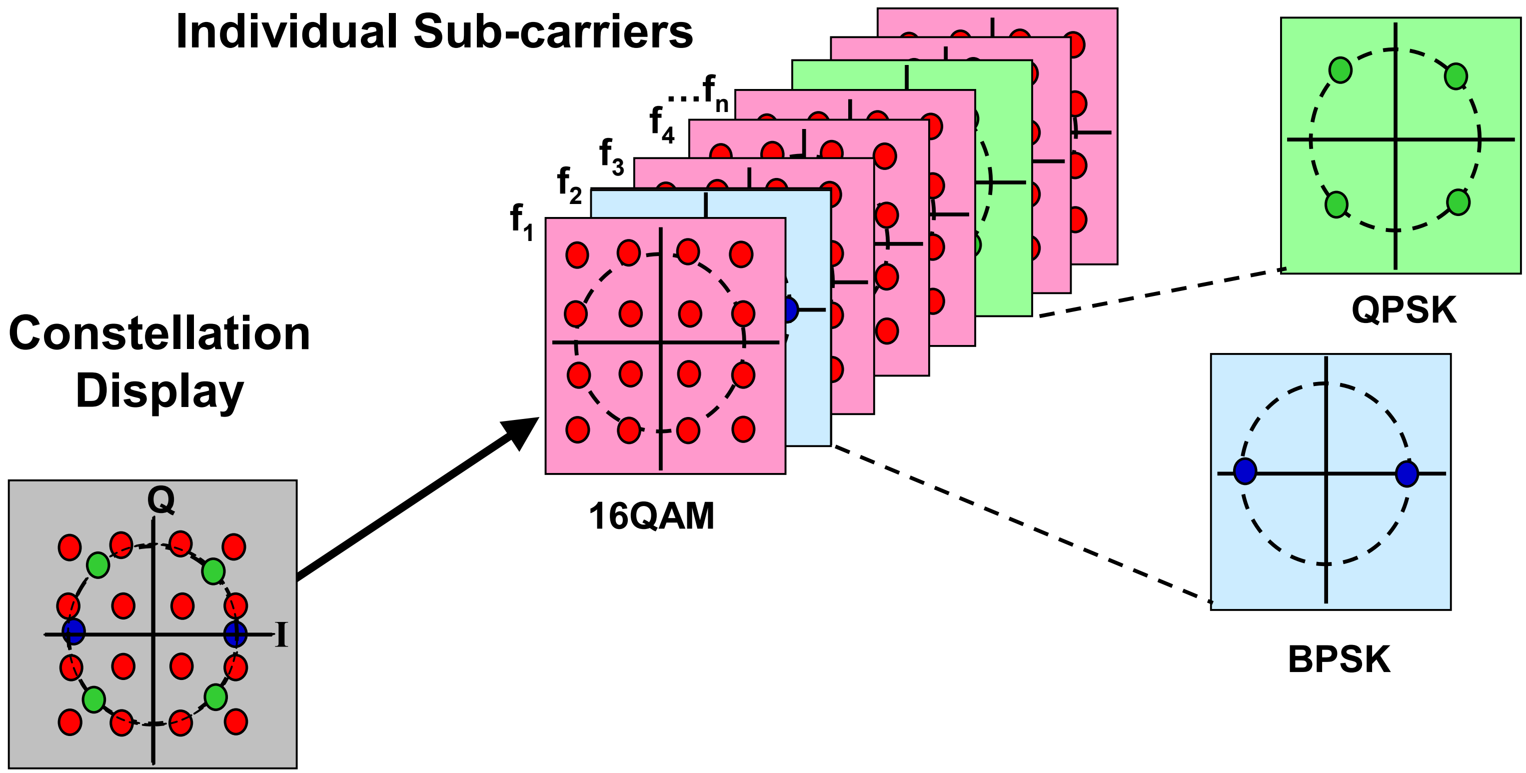
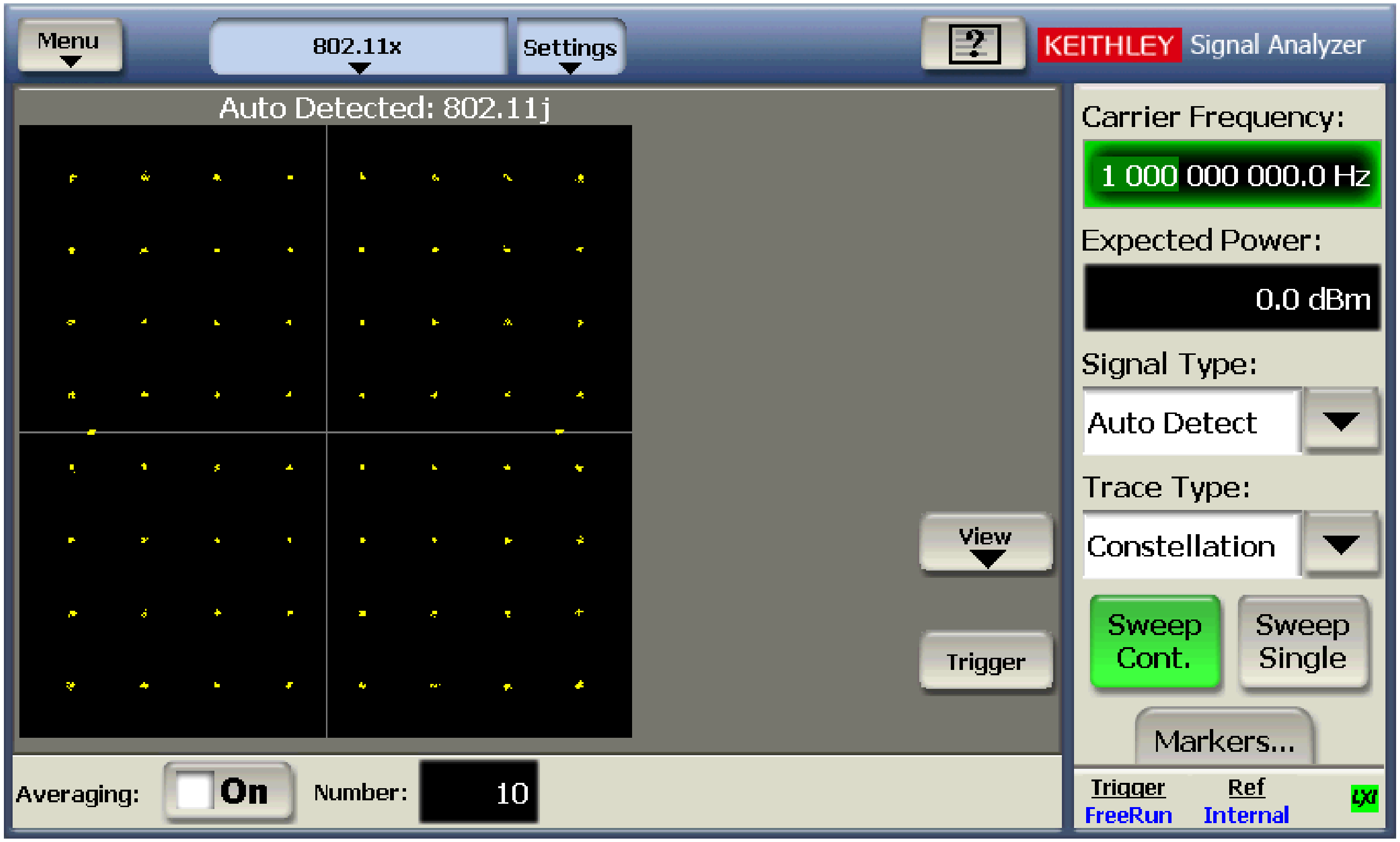
EVM - Constellation Display Is a Composite of all OFDM Sub-carriers



EVM
Error Vector Magnitude



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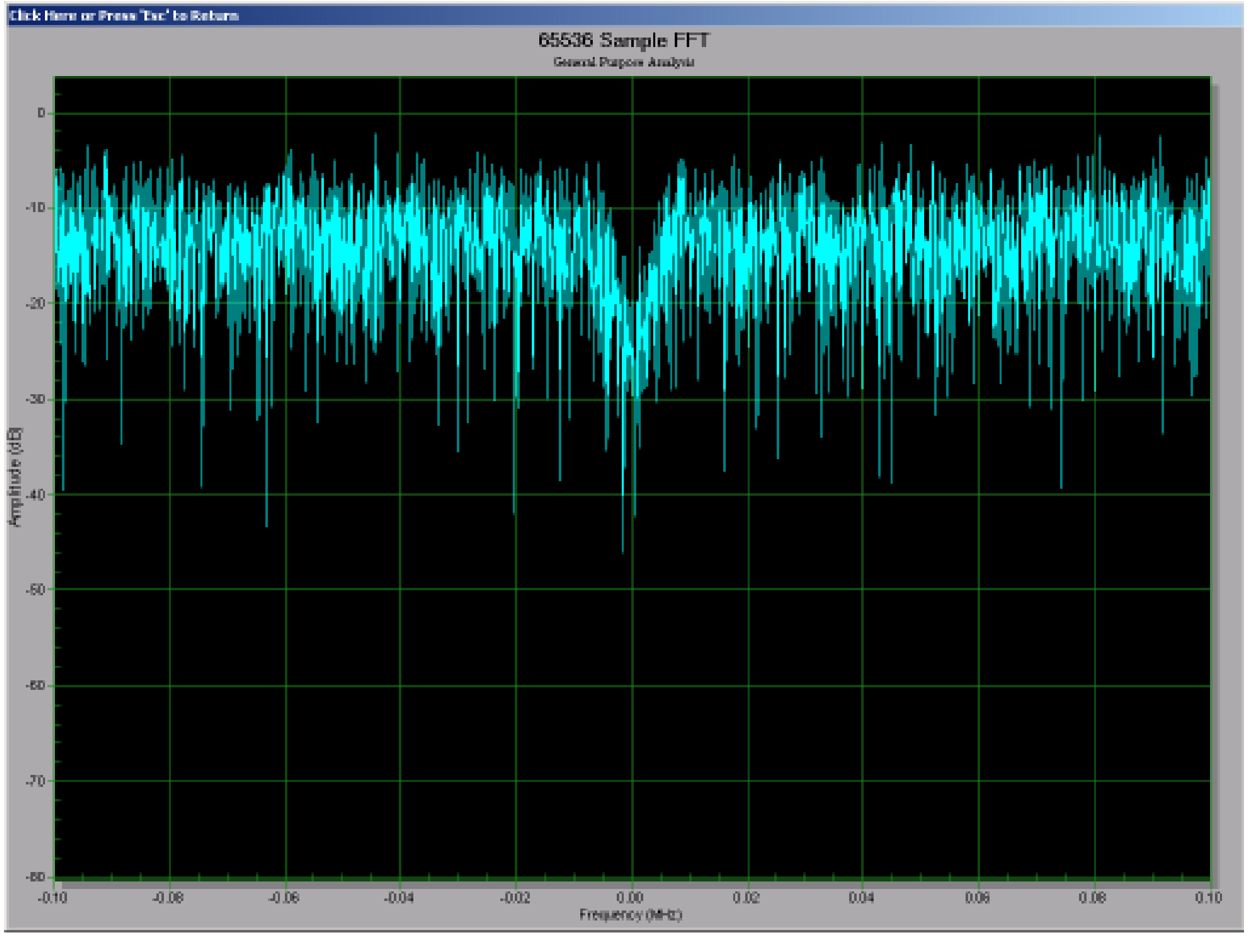
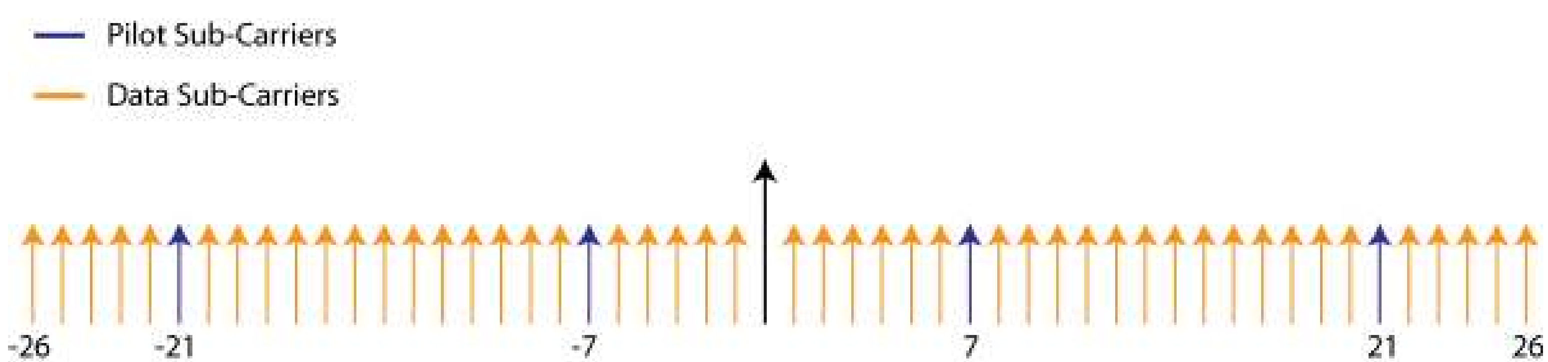
Carrier Feed Through

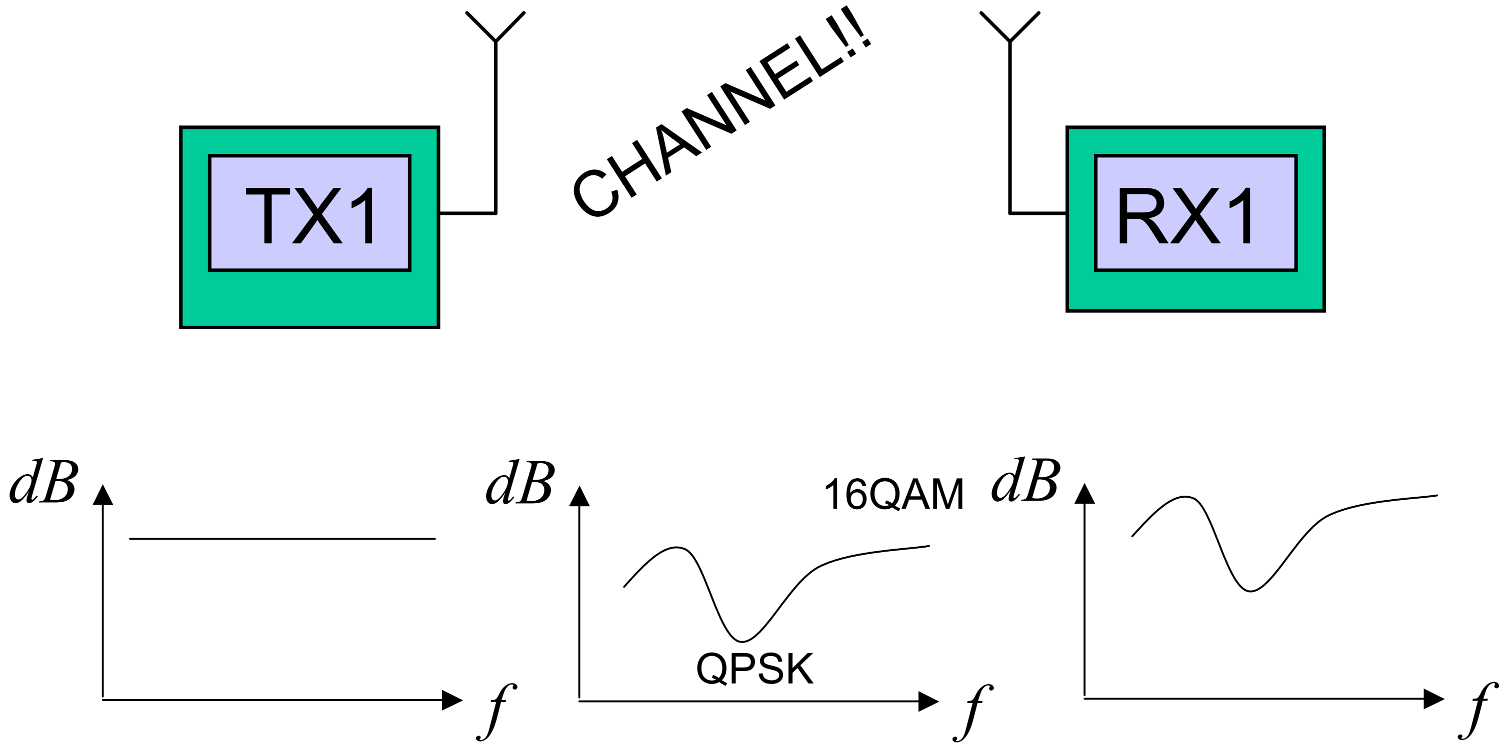


Pilot Carriers

- Not all of the sub-carriers are used to transmit data.
- Pilot sub-carriers are used to transmit training symbols throughout the duration of the packet.
- The receiver uses this information to correct for impairments such as phase variation, clock differences between transmitter and receiver, amplitude variation, and even assist in channel estimation.
- Pilots are transmitted using BPSK modulation.



Channel Flatness



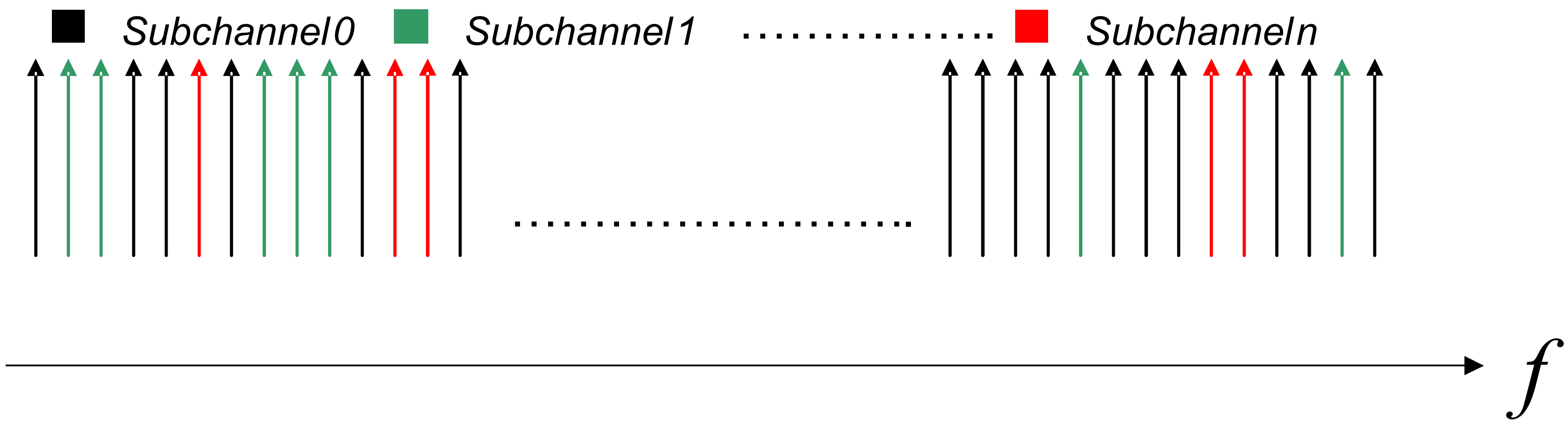
RX can equalize or
in a closed loop system
Send information back to TX.

OFDM to OFDMA

- **OFDM** used by WLAN and WiMAX Fixed (802.16d) as a modulation technique is not multi user – all sub-carriers in a channel are used to facilitate a single link.

- **OFDMA** used by WiMAX mobile (802.16e) and LTE (3GPP Release 8) assigning different number of sub-carriers to different users.

WiMAX (Mobile) sub-channels Frequency Domain



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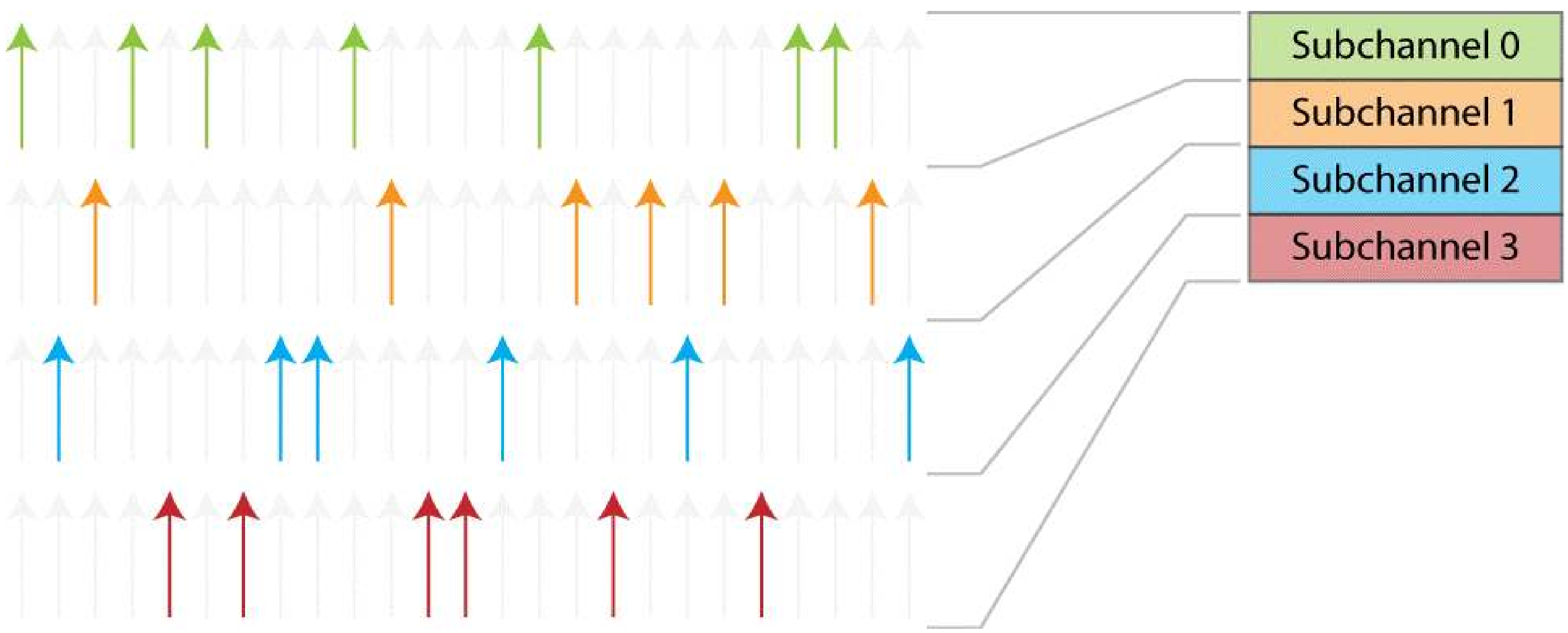
The Physical Channels are Different from the Logical Channels



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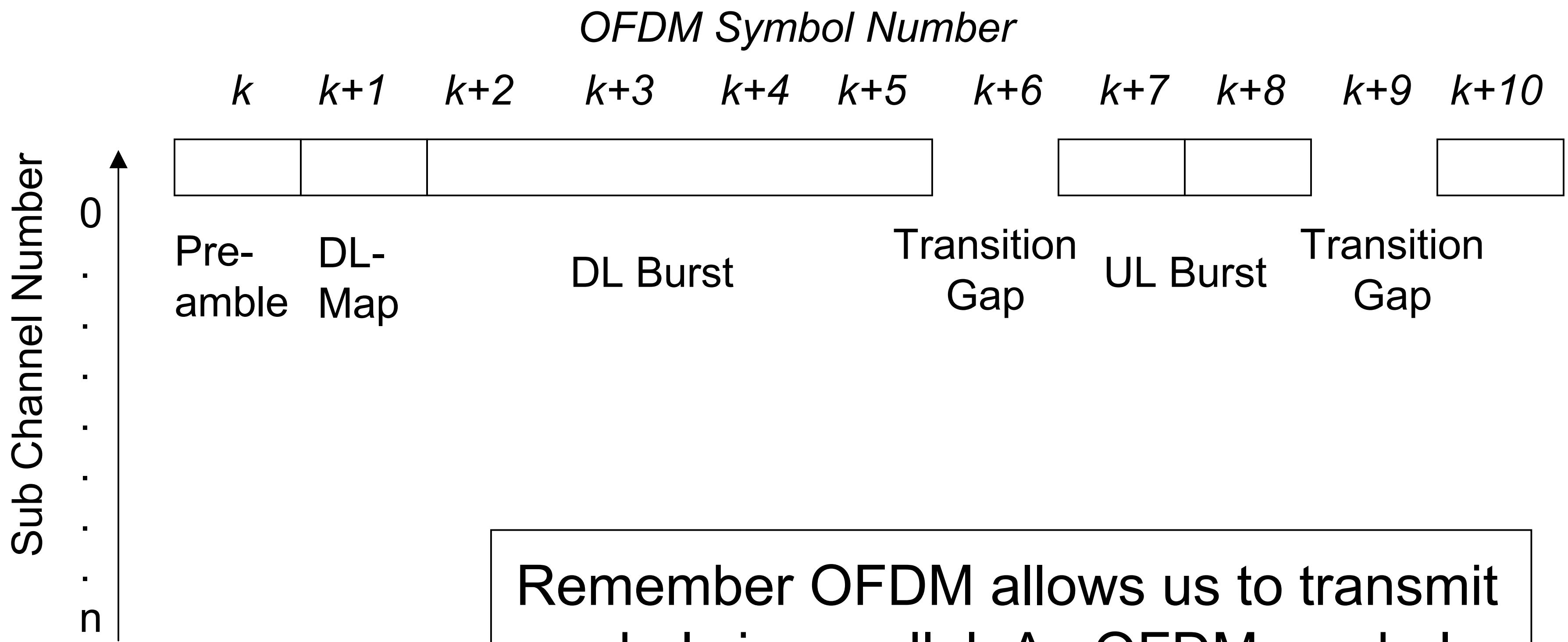
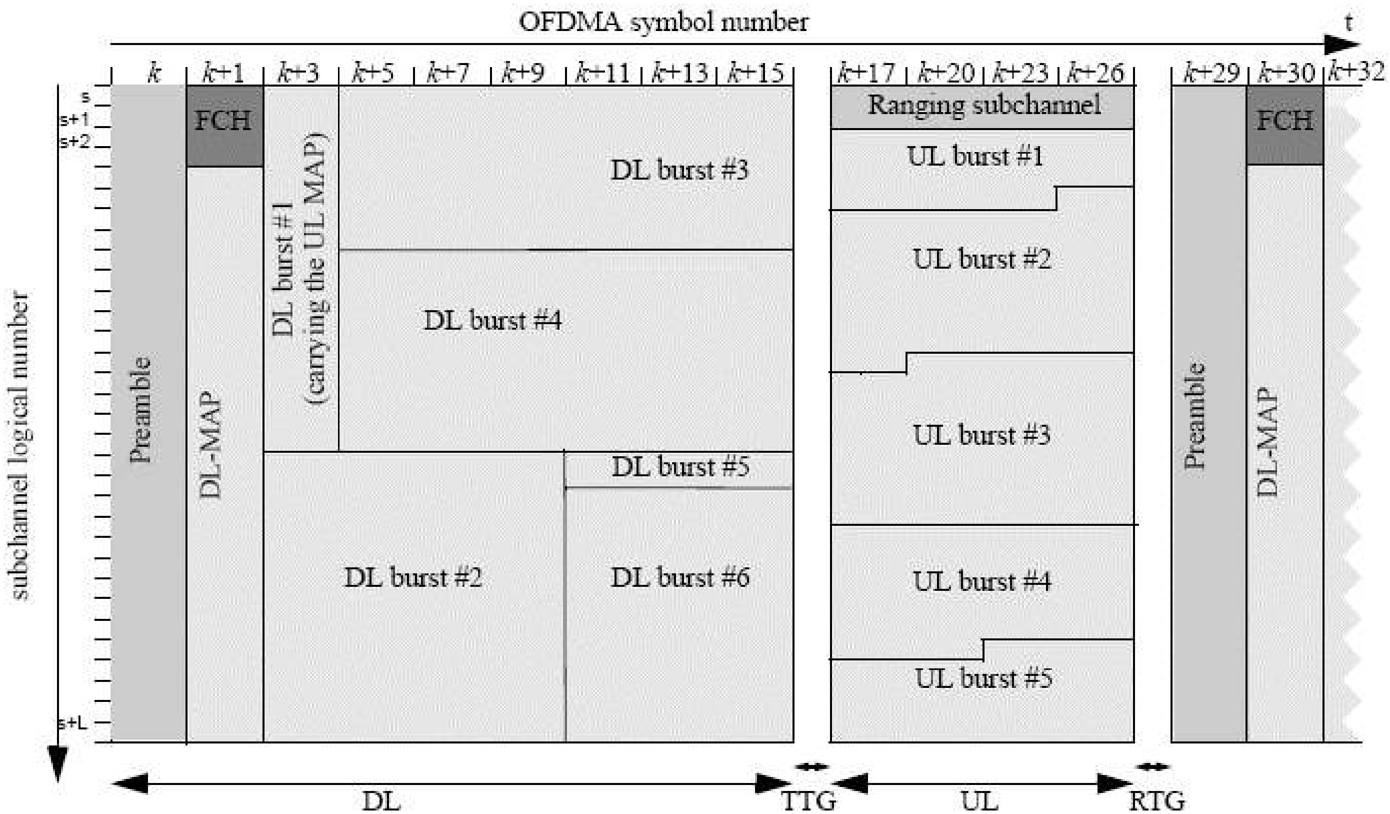
Symbol Transmission verses Time



Remember OFDM allows us to transmit symbols in parallel. An OFDM symbol period is a group of parallel symbols.

The WiMAX Symbol Map



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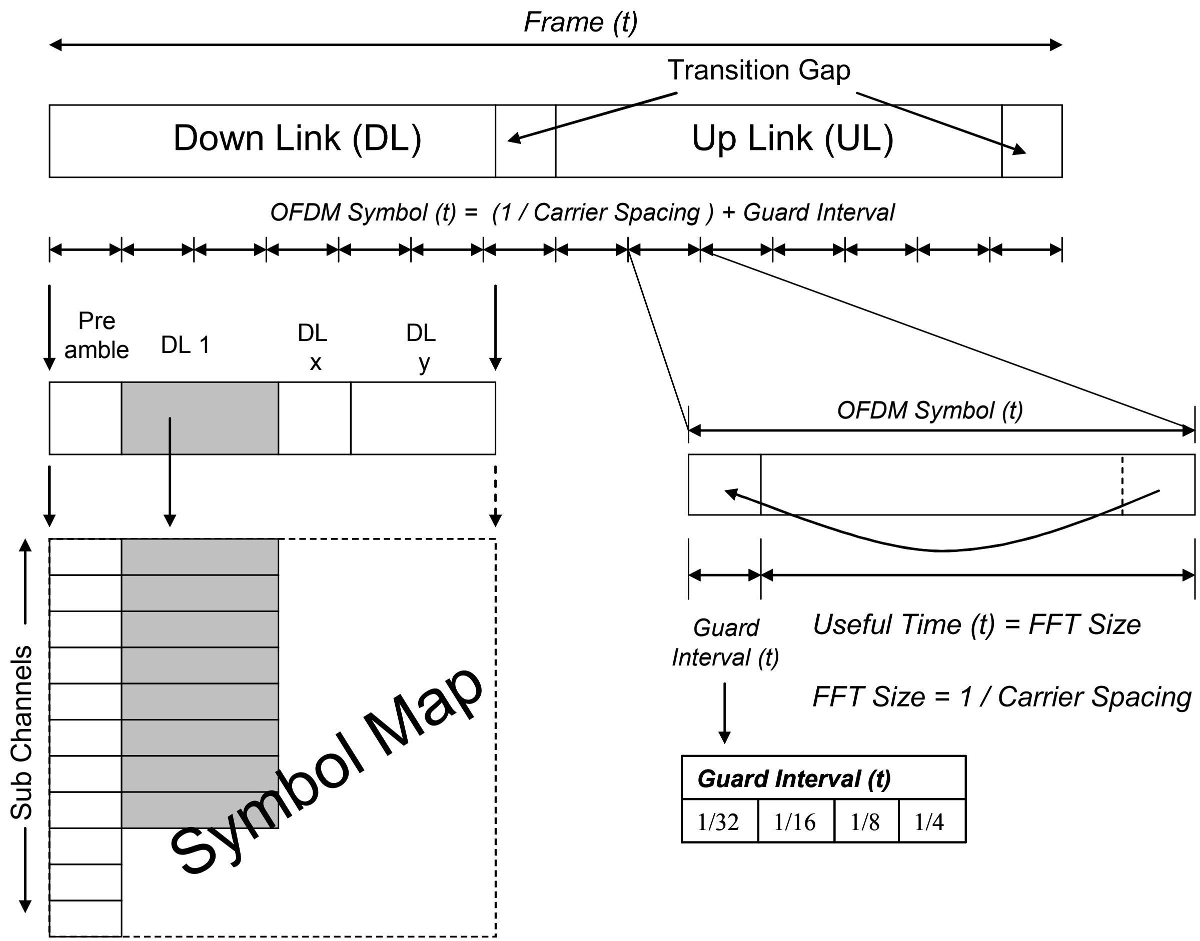
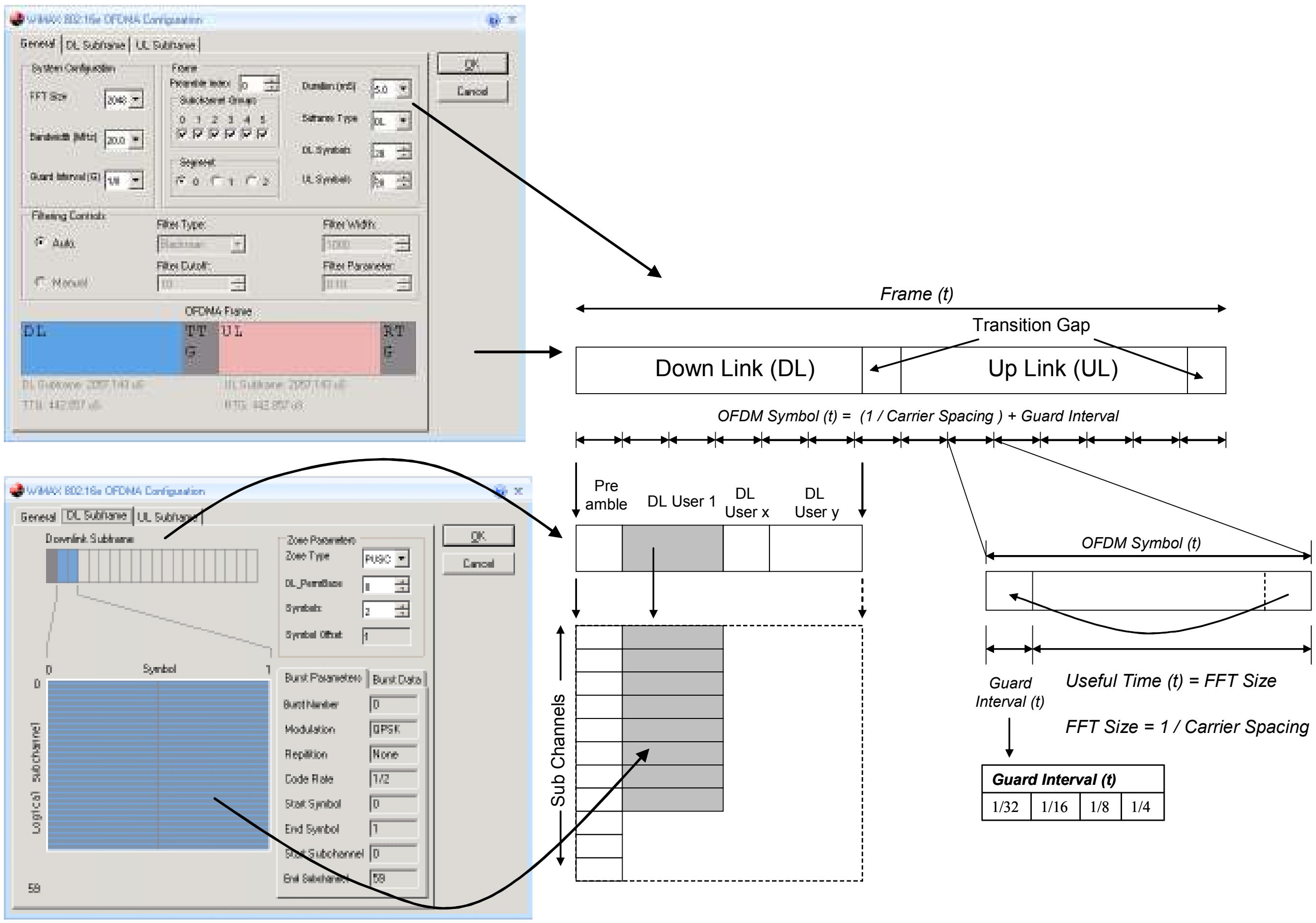
WiMAX putting it all together



Guard Interval (t)			
1/32	1/16	1/8	1/4

Creating a Signal



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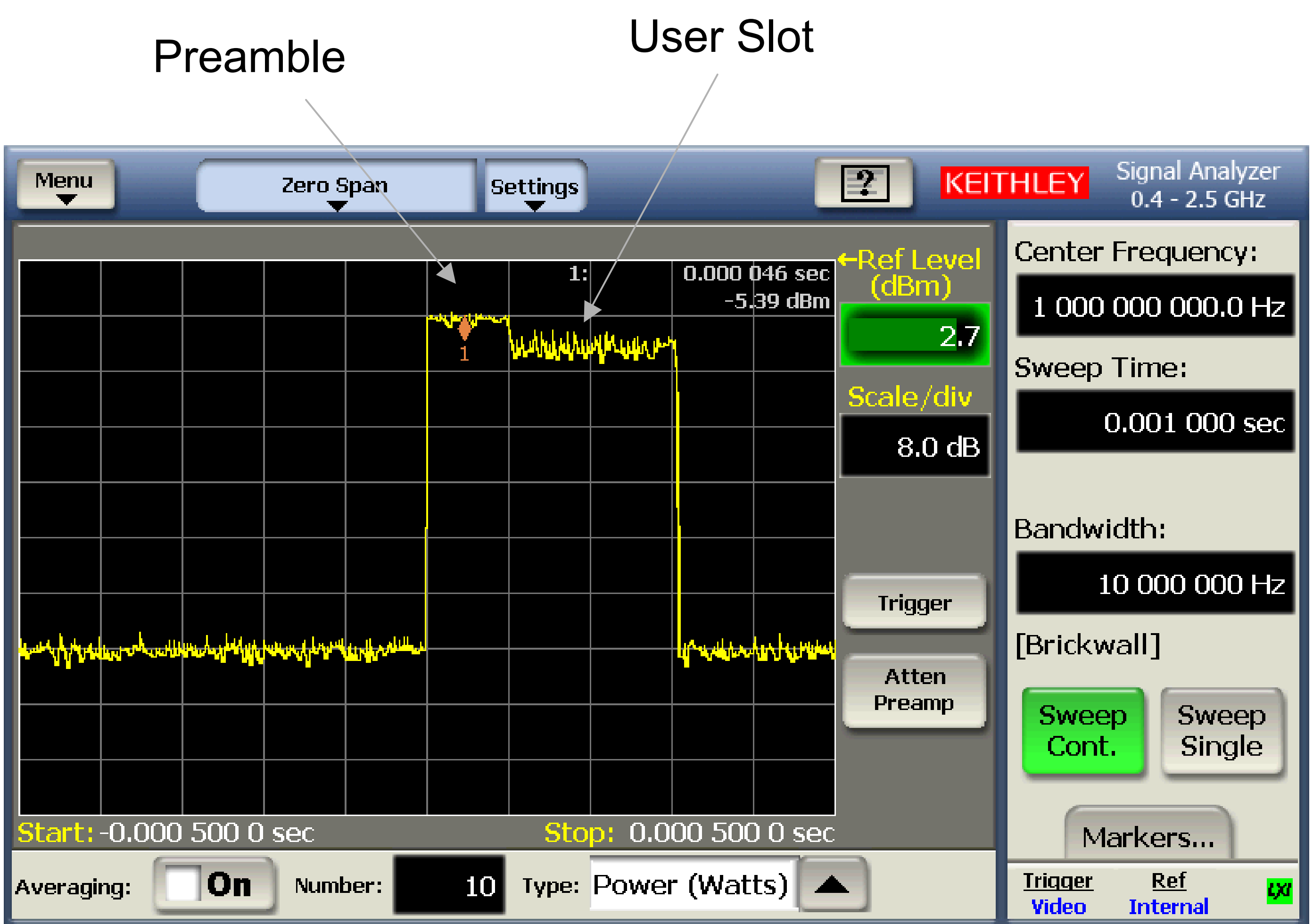
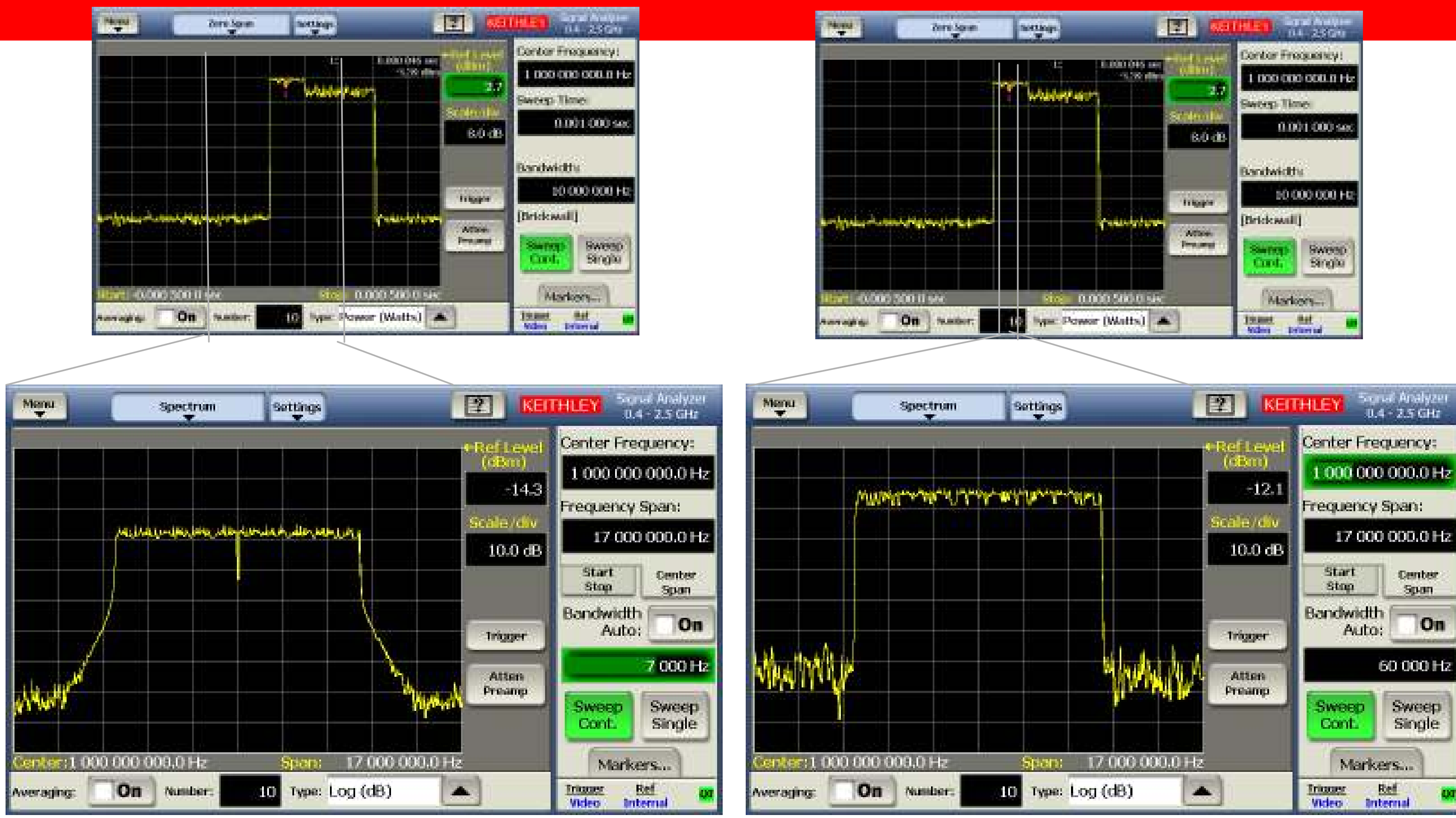
Time Domain Measurement

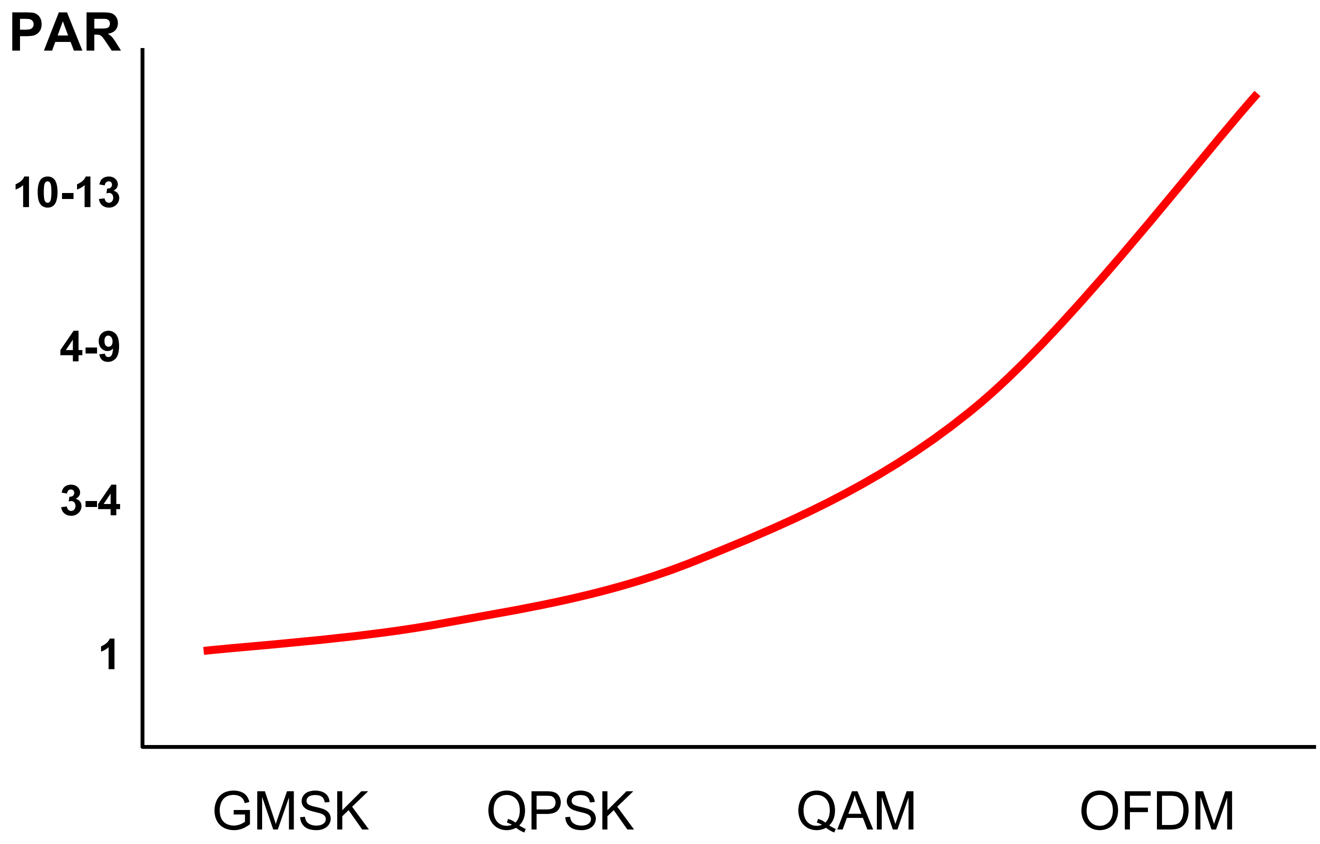


Frequency Domain Transient Effects



With Transients KEITHLEY Gated on Slot

Peak to Average Ratio for WiMAX and WLAN



Gain Compression Issues

- **Gain compression is illustrated graphically in figure 1.**

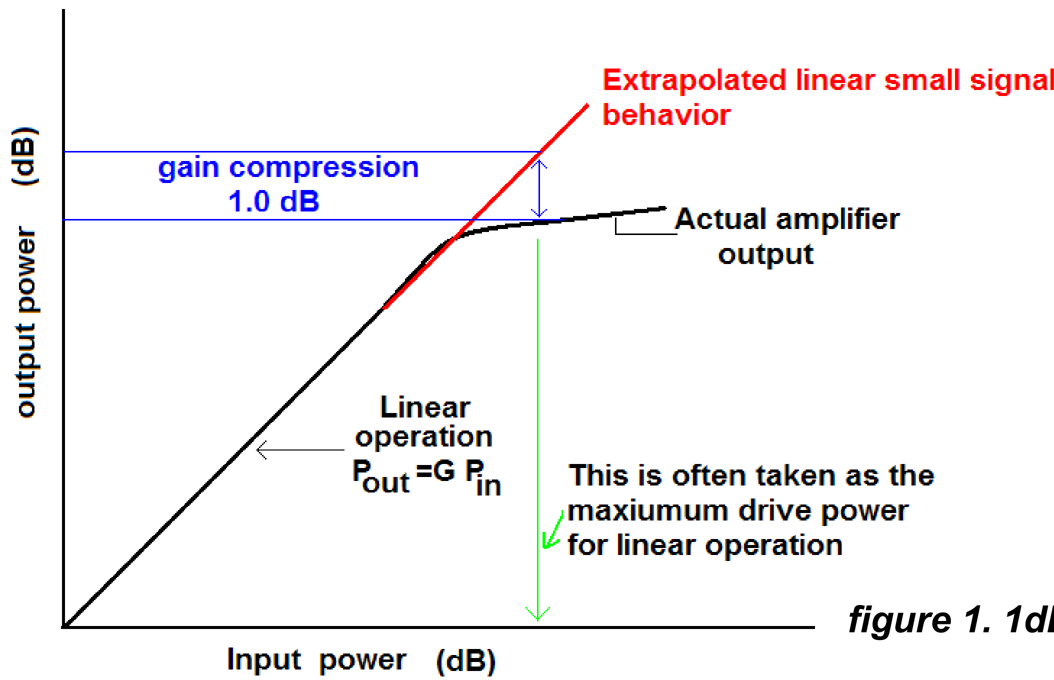
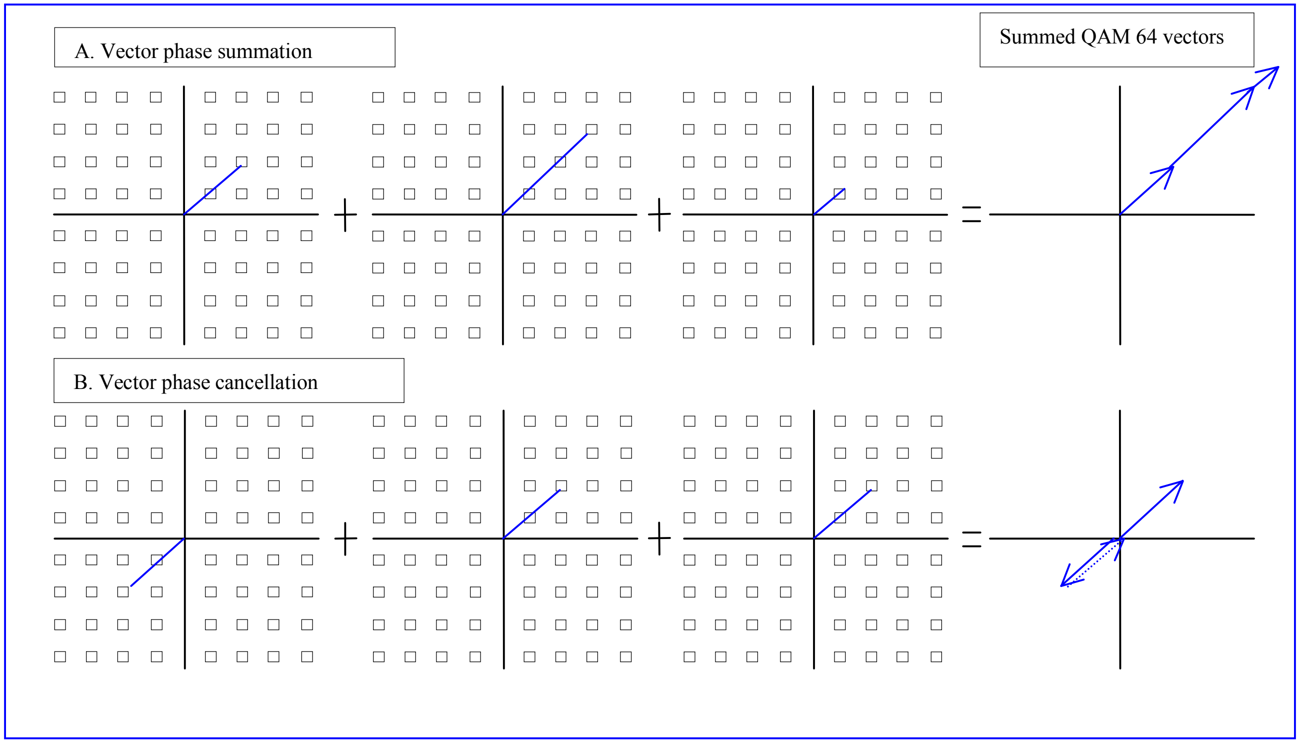


figure 1. 1dB Gain Compression

•The 1dB Gain Compression point is the input power level that causes the actual amplifier output level to be 1dB less than the extrapolated linear small signal behavior.

Random Phase Addition of Multi-carrier QAM 64 Waveforms

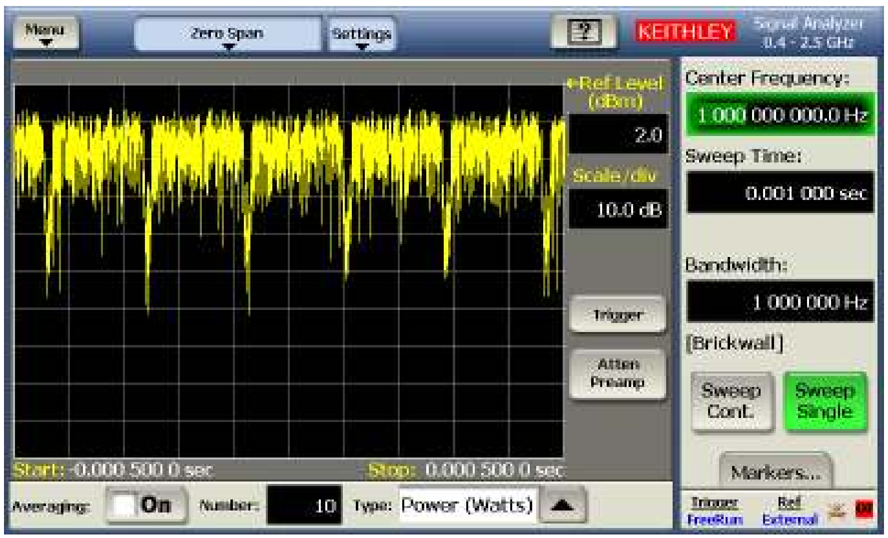
- Since each sub-carrier transmits their symbols in the same channel the instantaneous signal power due to random phases can add up constructively or they can cancel out.
- This means that the range of signal powers that the RF amplifier has to generate is widely varying and very dynamic. This is what creates the high peak to average ratio (PAR)



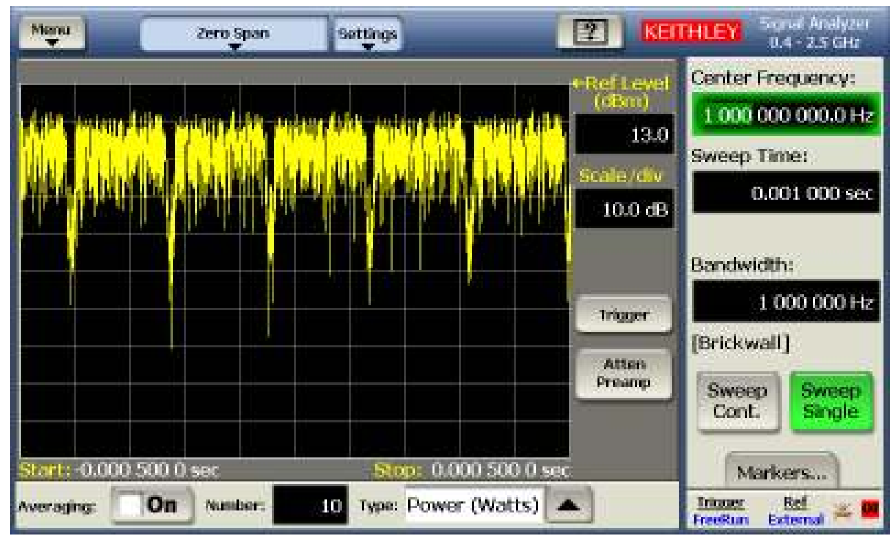
Effects of Gain Compression in OFDM Signals

•**Waveforms having a large PAR can severely stress an RF amplifier causing it to distort during peaks.**

•**The issue for measurement instrumentation is that it is not always easy to tell whether an amplifier is being stressed into compression because the signals are so noise like.**



802.11A 64QAM signal with 0% compression in zero span



802.11A 64QAM signal with 20% compression in zero span

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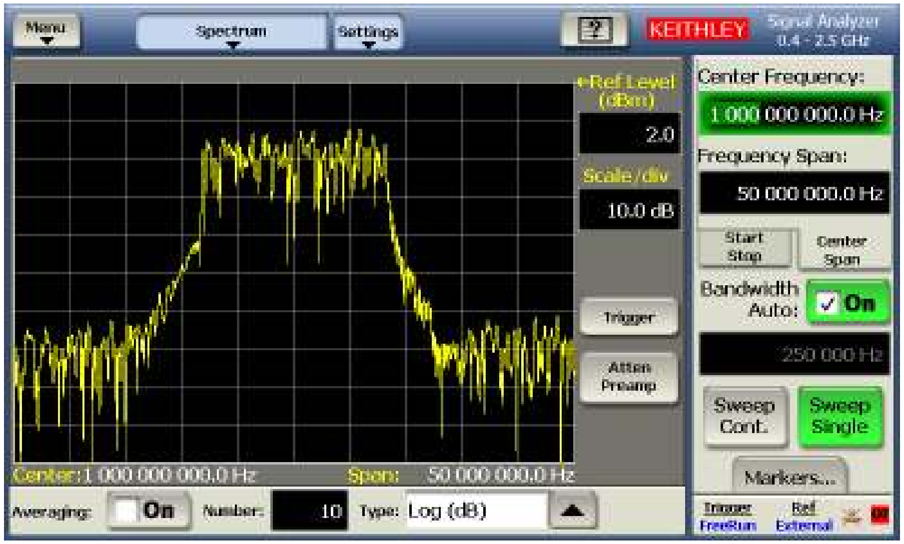
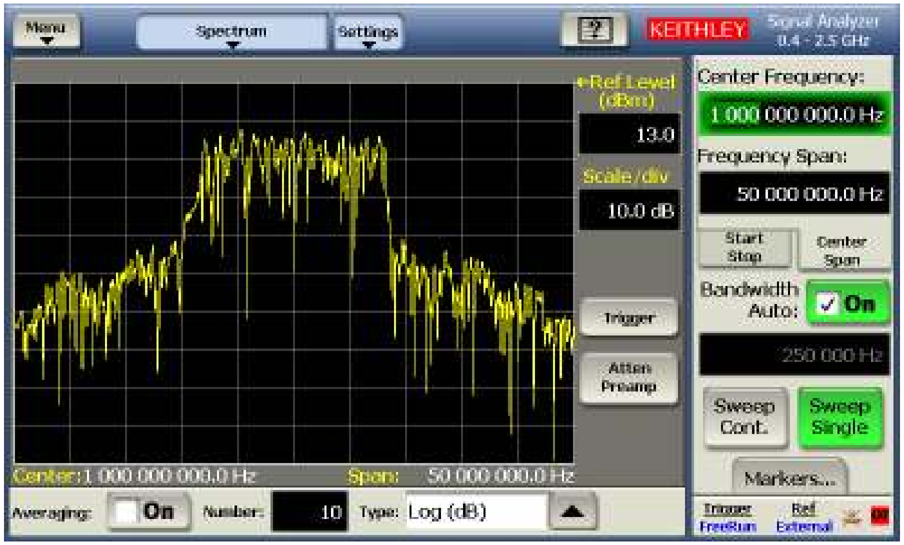
Effects of Gain Compression in OFDM Signals

• There are obvious degradations to the signal as viewed in the frequency domain as distortion increases, but it is difficult to derive a quantitive measure that would provide the designer feedback to optimize the circuit.



802.11A 64QAM signal with 0% compression



802.11A 64QAM signal with 20% compression

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Quantifying Gain Compression for OFDM Signals

•The noise like nature of OFDM signals means that in order to extract useful information from the signal a statistical description of the waveform's power levels is required.

•For these types of signals a complimentary cumulative distribution function (CCDF) is required.

•CCDF curves can specify completely the power characteristics of the signals that are transmitted in a communications channel.

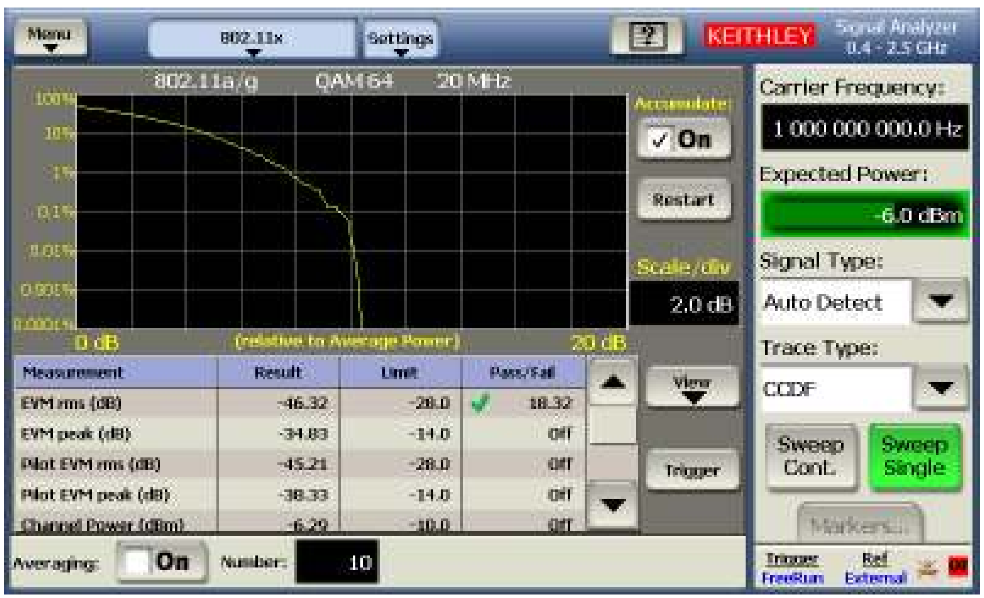

Figure 2. CCDF curve of 802.11A 64QAM signal - No Compression.

Notice the Y-axis is in percent and the x-axis is in dB relative to the average power.

This signal spends almost 1% of it's time at 8dB above the average power.

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Quantifying Gain Compression for OFDM Signals

- The addition of Gain Compression in this amplifier has affected the CCDF curve but not in any way that you could reliably indicate the level of gain compression.

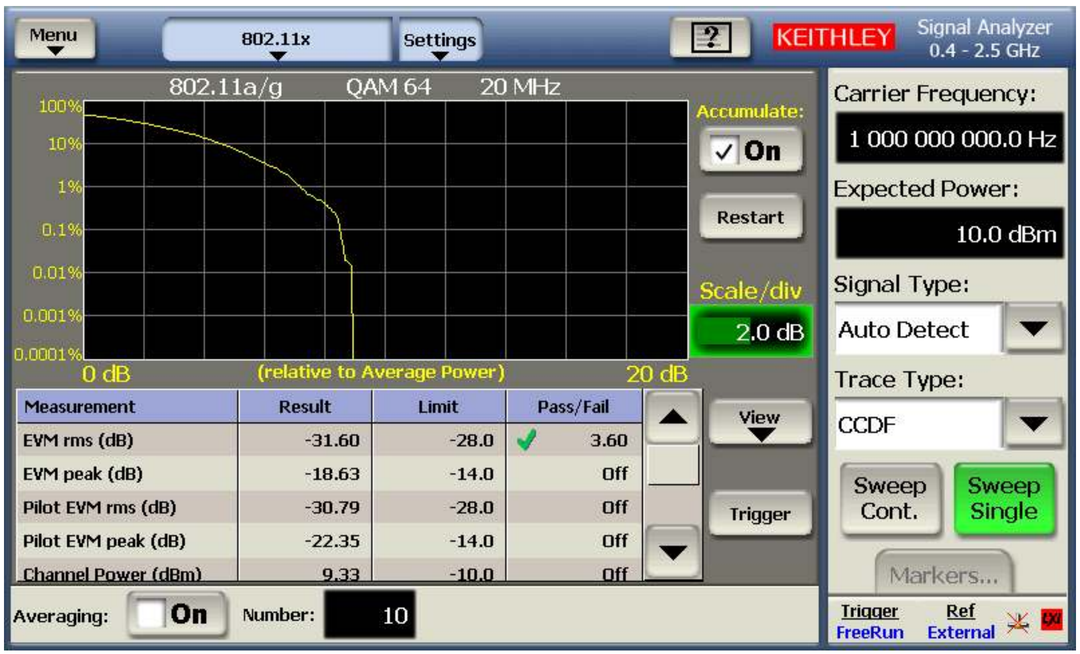

Figure 3. CCDF curve of 802.11A 64QAM signal – with 10% compression.

The compressed signal is noticeable on the CCDF curve but there can be no way to make a measurement of compression levels.

This signal spends almost 1% of it's time at 7.25dB above the average power.

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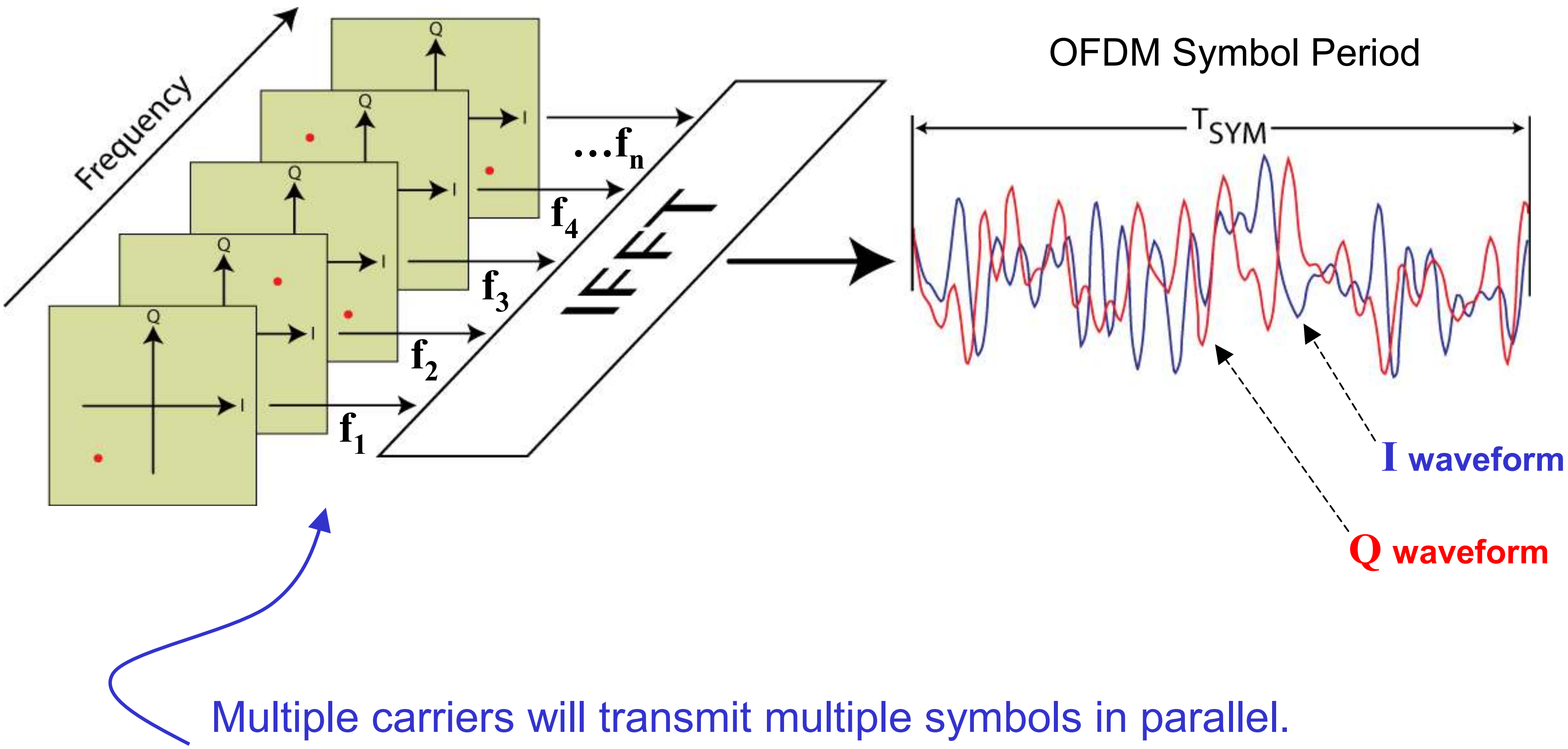
Symbol to Waveform

OFDM – Parallel Symbol Transmissions

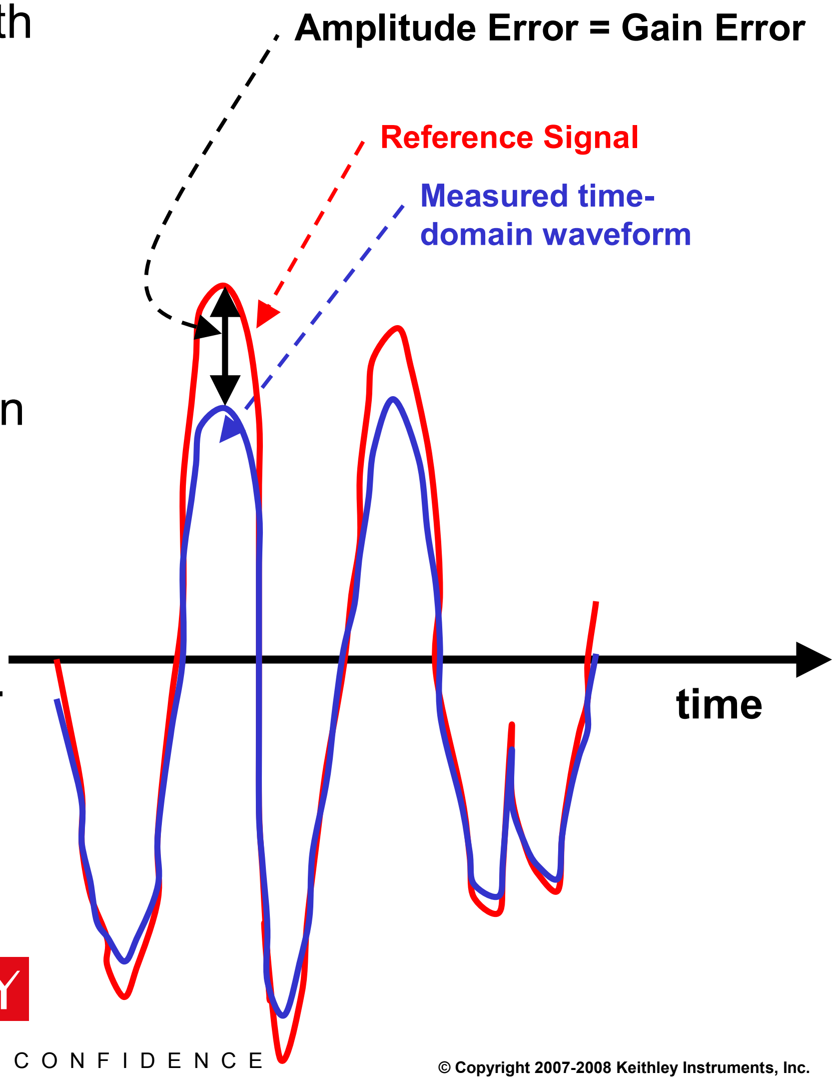


Multiple carriers will transmit multiple symbols in parallel.
Carriers may have different modulations – BPSK, QPSK… 64QAM.

Quantifying Gain Compression for OFDM Signals

- Compare the measured time-domain signal with a reference signal and plot the difference as a function of input magnitude.
- The reference signal is an ideal time-domain waveform, constructed from the demodulated symbol targets using an IFFT.
- Time domain errors are measured as a function of input magnitude.
- The linear gain error equates to the gain compression.
- Linear gain error is plotted relative to full scale. This gives % magnitude error as a function of input magnitude.

$$\frac{\text{Measured Magnitude} - \text{Reference Magnitude}}{\text{Full Scale Magnitude}}$$



Quantifying Gain Compression for OFDM Signals

- Keithley has developed a measurement technique that can easily and reliably discern the level of gain compression in RF amplifier DUT's employing OFDM signaling.

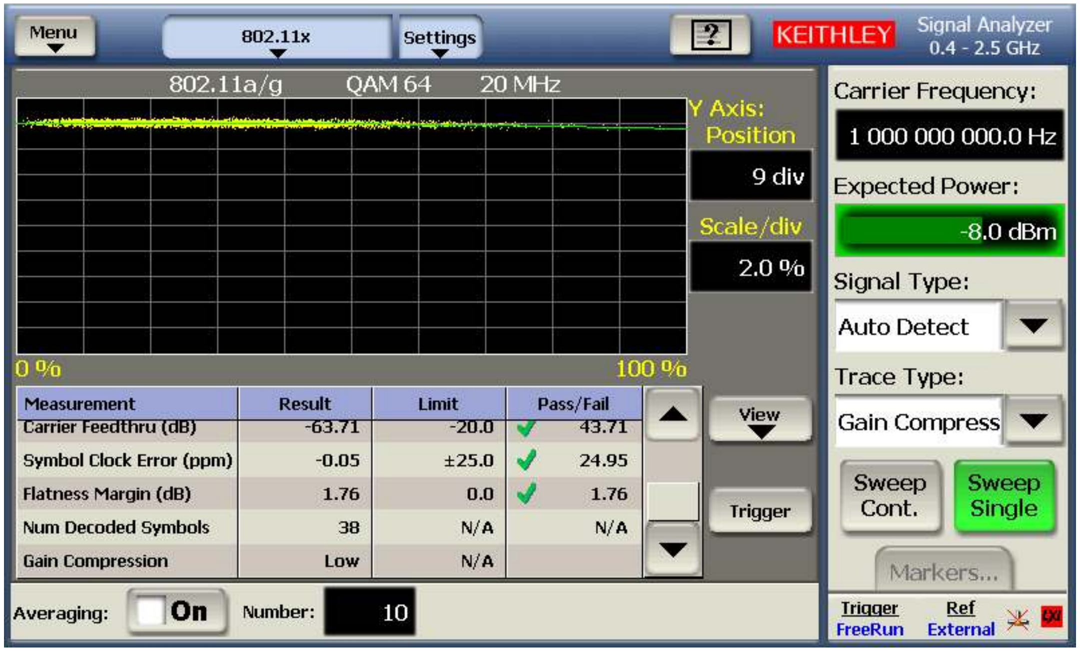


Figure 4. Keithley Gain Compression Measurement algorithm – No deliberate compression.

The Y-axis scale shows the level of amplitude error in percent %. The X-axis scale shows the full scale input power range in percent %

Axis are *Error in observed power level vs expected power level.*

Quantifying Gain Compression for OFDM Signals

- As the RF amplifiers input power is increased the OFDM signal begins to cause compression in the amplifiers output.

•*Optional example 2. Measuring Gain Compression on an RF amplifier transmitting OFDM signals*.

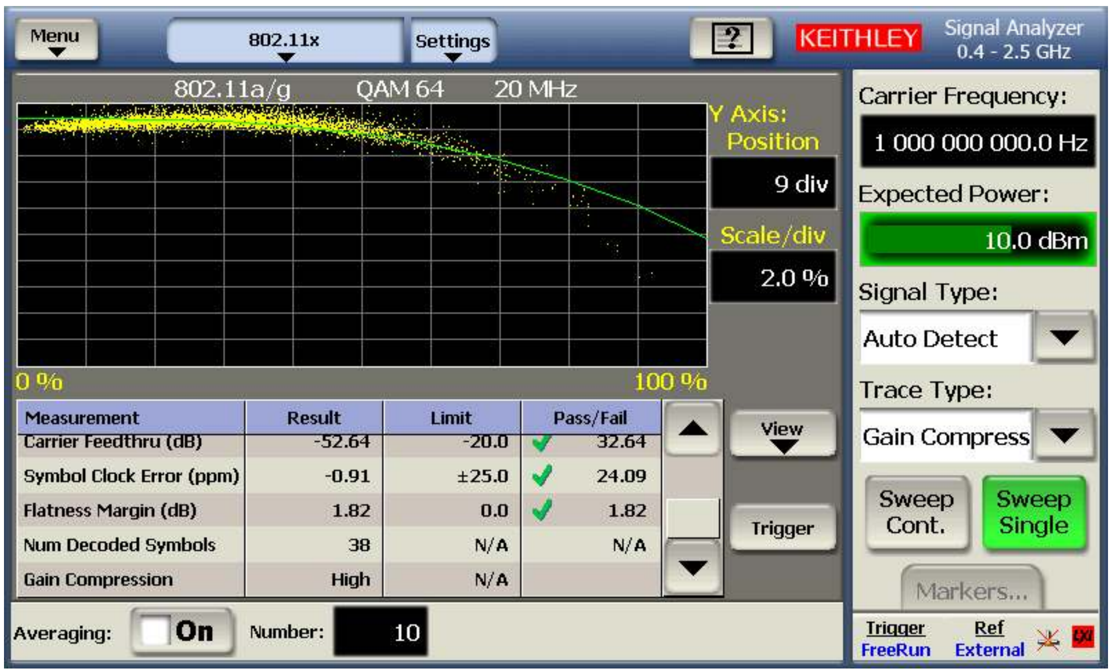


Figure 5. Keithley Gain Compression Measurement algorithm.

The Y-axis scale shows the level of linear gain error in percent %. The X-axis scale shows the full scale input power range in percent %

Notice that with 10% compression present there are larger errors in the measured values near the high power end of the response.

Axis are *Error in observed power level vs expected power level.*

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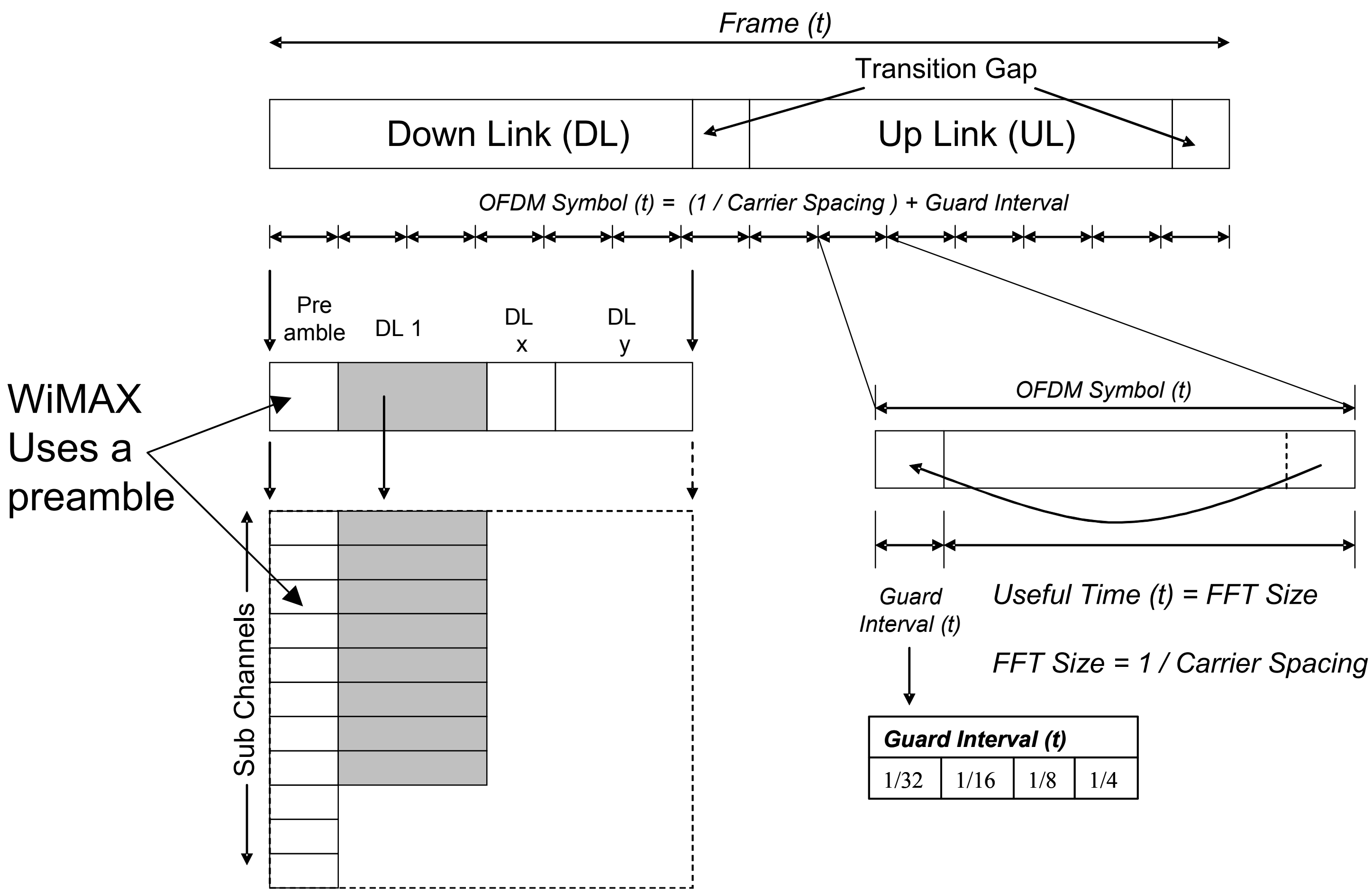
WiMAX and LTE

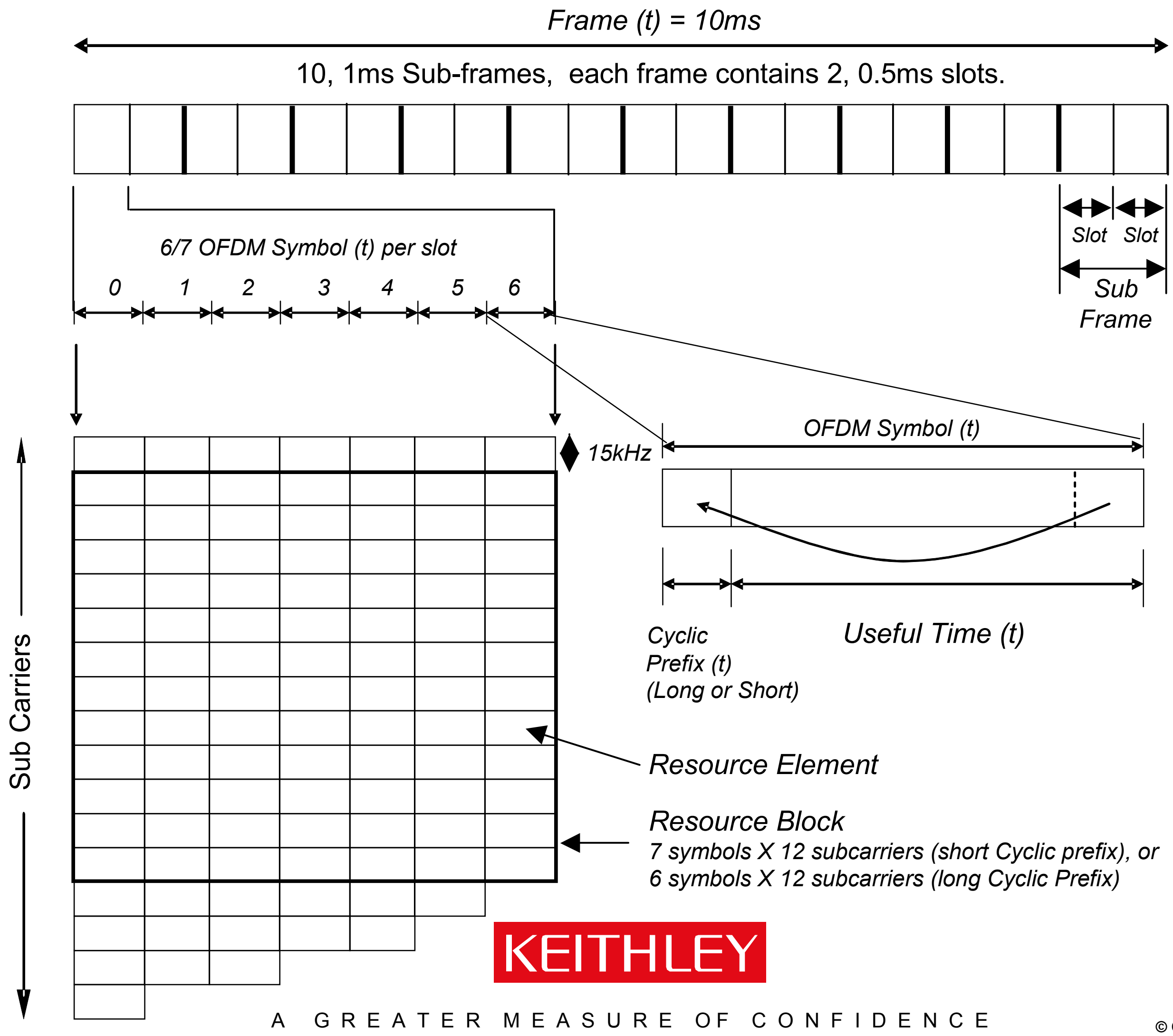
	WiMAX (802.16e)	LTE (Down Link)	LTE (Up Link)
Bandwidth	**Up to 20MHz**	**Up to 20MHz**	**Up to 20MHz**
Access scheme	**OFDMA**	**OFDMA**	**SC-FDMA**
Sub-carrier spacing	**10.94KHz**	**15kHz**	**60kHz (4x15khz)**
Modulation	**QPSK, 16QAM, 64QAM**	**QPSK, 16QAM, 64QAM**	**QPSK, 16QAM, 64QAM**
Duplex	**TDD**/FDD	**TDD**/FDD	**TDD**/FDD
MIMO	Up to 4	Up to 4	SISO

WiMAX TDD Frame Structure



Guard Interval (t)			
1/32	1/16	1/8	1/4

LTE FDD Frame Structure



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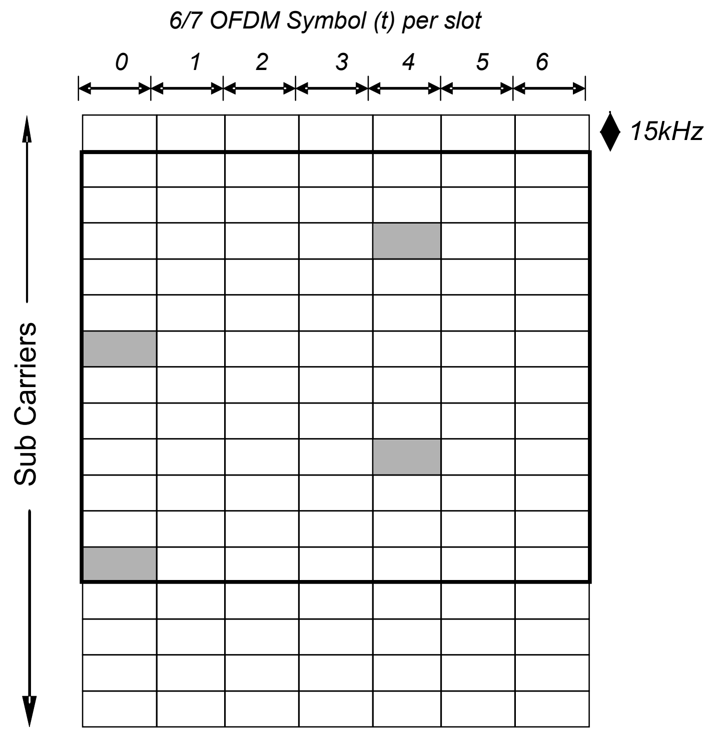
A GREATER MEASURE OF CONFIDENCE

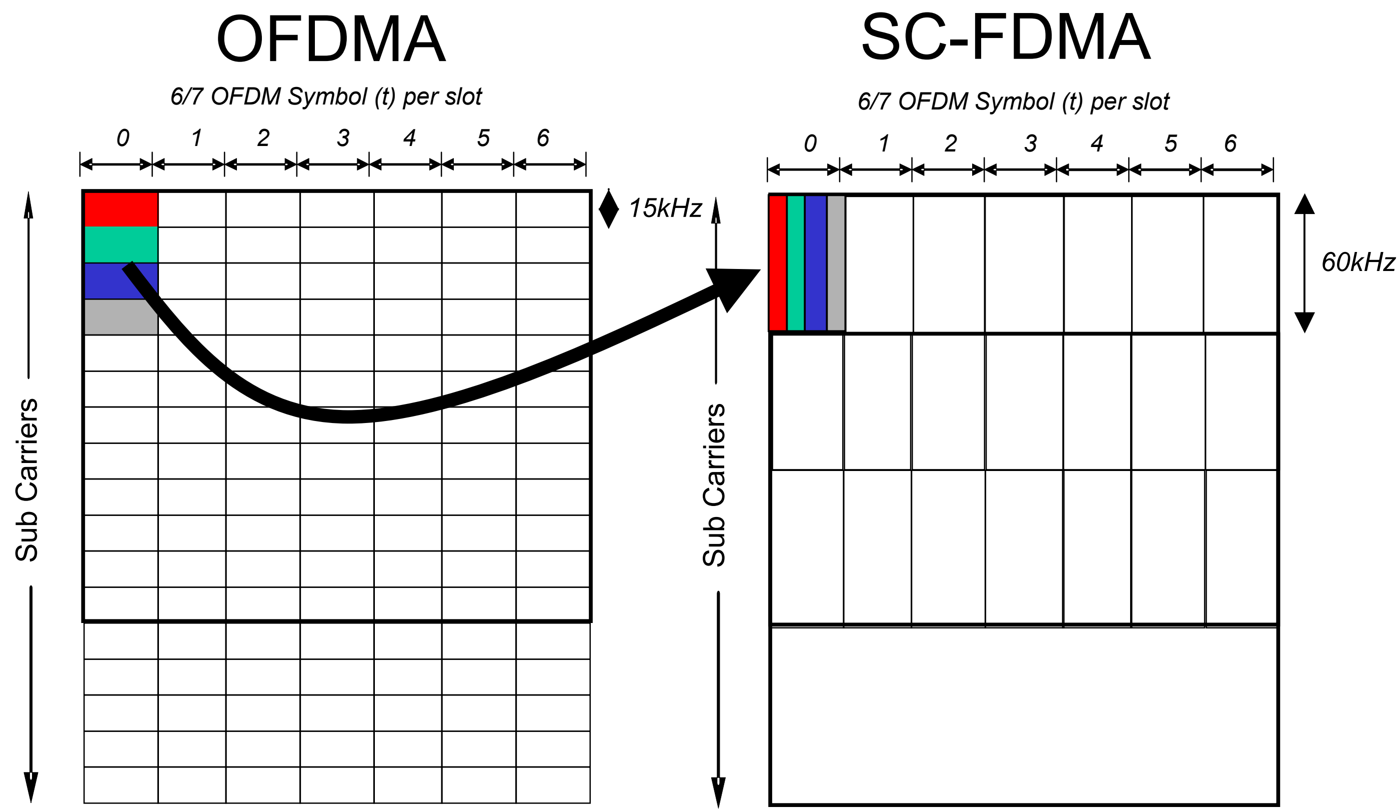
LTE, is not packet based



LTE is not a packet-oriented network, therefore does not employ preamble for carrier offset, channel estimation and timing synchronization. It uses reference signals transmitted during the first and fifth OFDM symbols of each slot when the short Cyclic prefix is used and during the first and fourth OFDM symbols when the long Cyclic Prefix is used.

LTE Up Link SC-FDMA

Single Carrier – Frequency Domain Multiple Access



In the baseband section SC-FDMA combines four subcarriers worth of symbols, then transmit them in a single symbol period using a carrier has four times the bandwidth.

WiMAX Up Link vs. LTE Up Link

- **Proponents of LTE state that SC-FDMA with a lower peak to average ratio can use a lower cost power amplifier, thus saving in cost and battery life.**

- **Proponents of WiMAX state that the increased baseband processing requirements for SC-FDMA requires a more expensive FPGA or ASIC that uses more power thus reducing battery life.**

Summary

- **Advantages**
  - Improved spectral efficiency
  - Good multipath performance
  - Resilient to interference
  - Complementary to MIMO transmission. (Part 2)
- **Disadvantages**
  - Increased baseband processing requirements.
  - High peak to average ratio.

Agenda

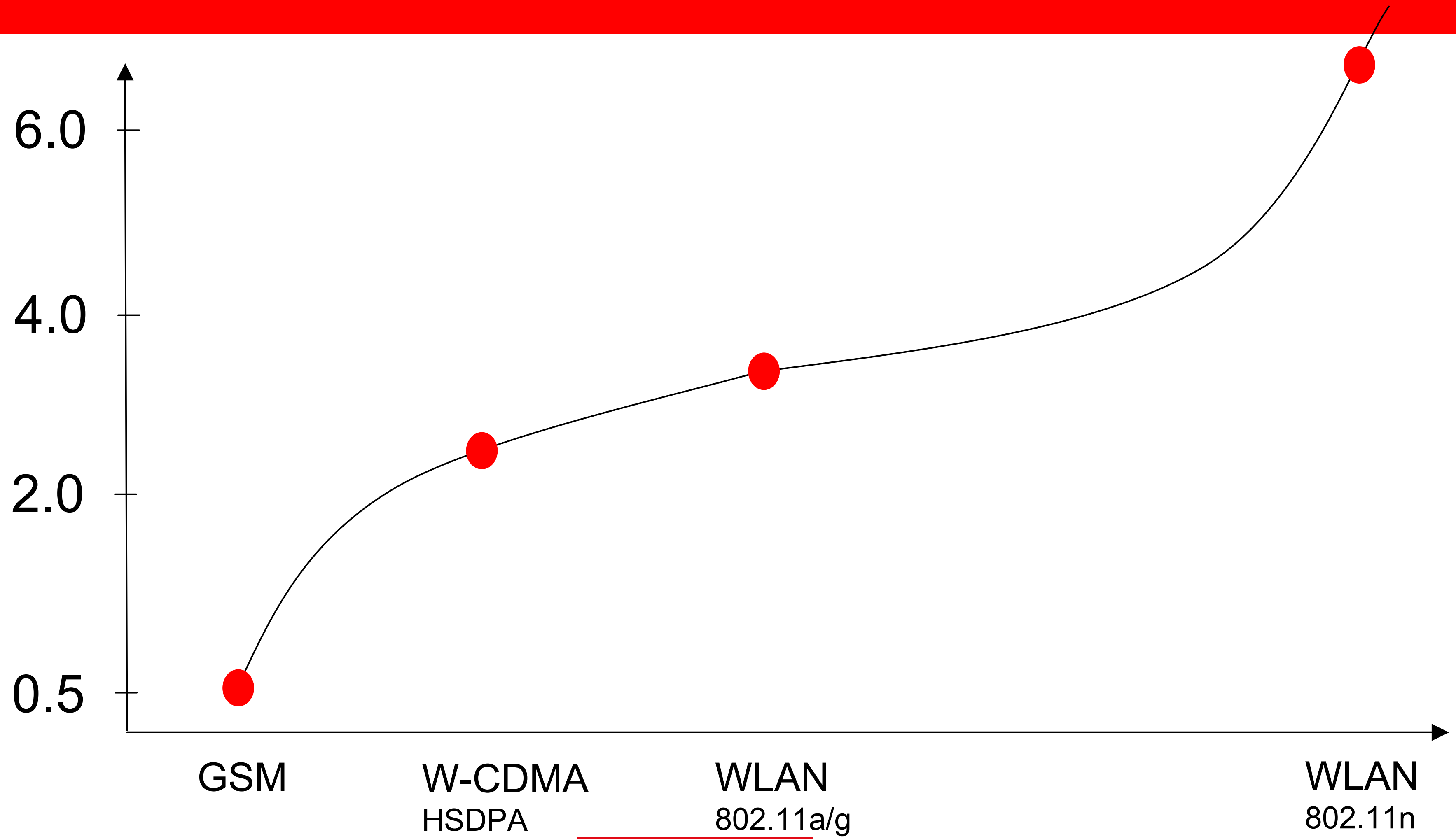
- **The evolution of communications and an introduction to the test tools**
- **Part One – OFDM and SISO radio configurations**
  - The case for OFDM
  - OFDM Signal Structure, generic and WLAN.
  - Measurements
  - OFDM and OFDMA
  - Peak to average ratio considerations
  - WiMAX and LTE
- **Part Two – OFDM and MIMO radio configurations**
  - MIMO – Multiple Input Multiple Output Radio Topology
  - How it works.
  - Measurements
  - Channel Considerations
  - Smart Antenna Systems and Beam Forming Considerations
- **Technology Overview and Test Equipment Summary**

OFDM/A to MIMO

- **MIMO based systems use multiple transmitters and receivers that are modulated with OFDM/A.**
- **WLAN (802.11n), WiMAX (802.16e) and LTE (3GPP Rel 8) all have MIMO configurations.**

Spectrally Efficiency – SISO - MIMO

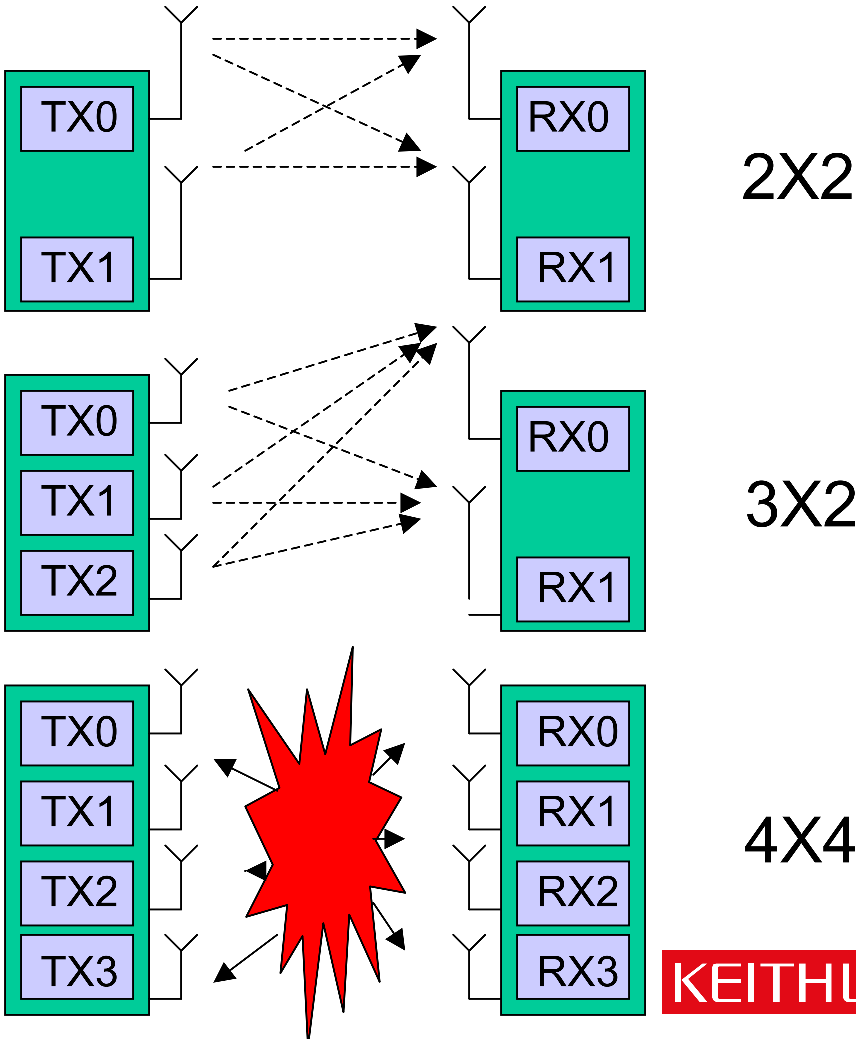
Bits/Second/Hz



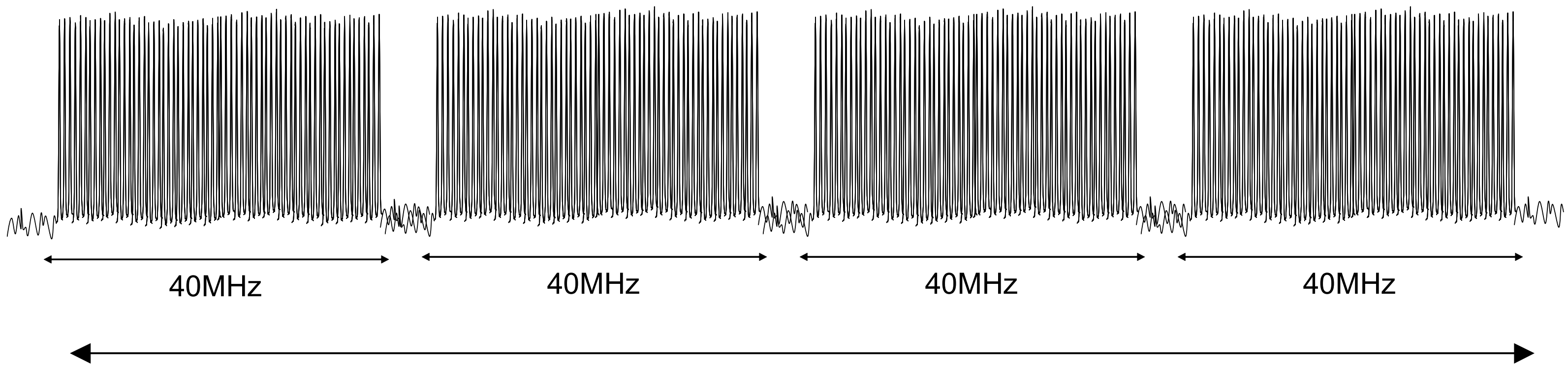
MIMO Configurations
Spatial Diversity, Spatial Multiplexing and Beam Forming

- Multiple replicas of the radio signal from different directions in space give rise to spatial *diversity*, which increases the reliability of the fading radio link.
- MIMO channels can support parallel data streams by transmitting and receiving on orthogonal spatial filters ("*spatial multiplexing*").
- *Beamforming*, the transmit and receive antenna patterns can be focused into a specific angular direction by the appropriate choice of complex baseband antenna weights. The more *correlated* the *antenna signals*, the better for beamforming.

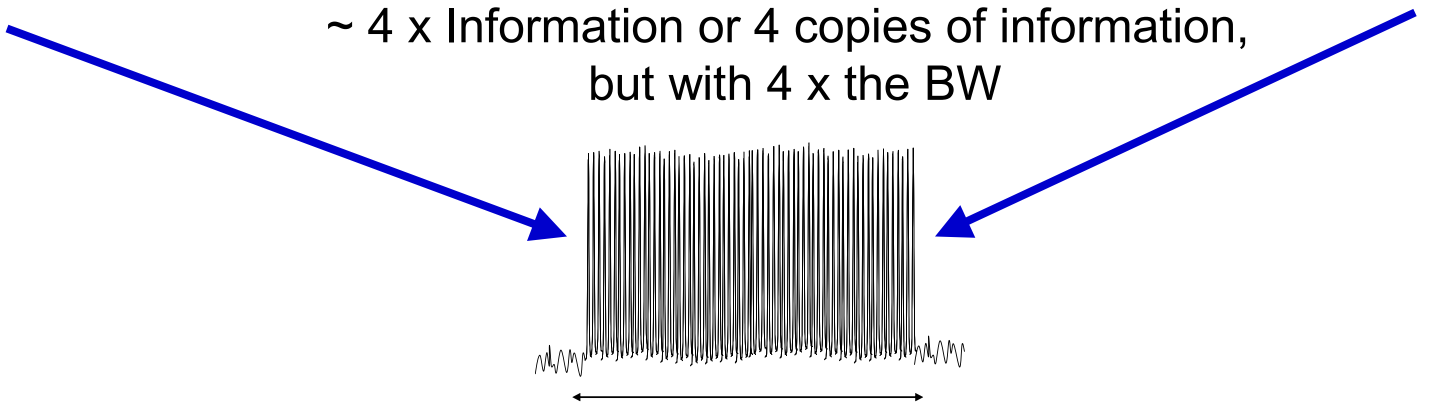
MIMO Radio Configuration



Why is MIMO different from standard OFDM?



~ 4 x Information or 4 copies of information,
but with 4 x the BW



~ 3.5 x Information, but with 1 x the BW

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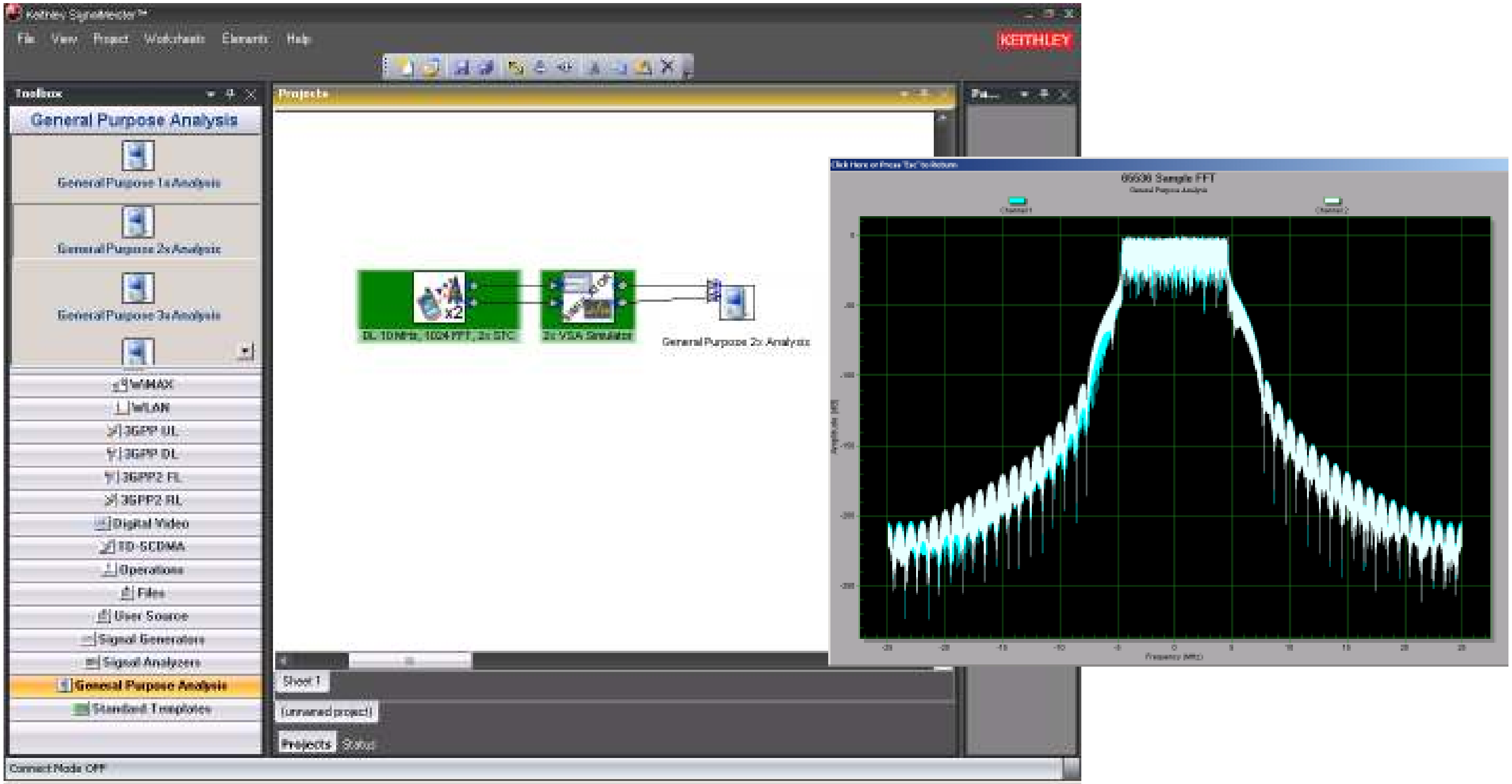
A GREATER MEASURE OF CONFIDENCE

Generate a 2x2 MIMO signal.

WiMAX Matrix A Space Time Coding



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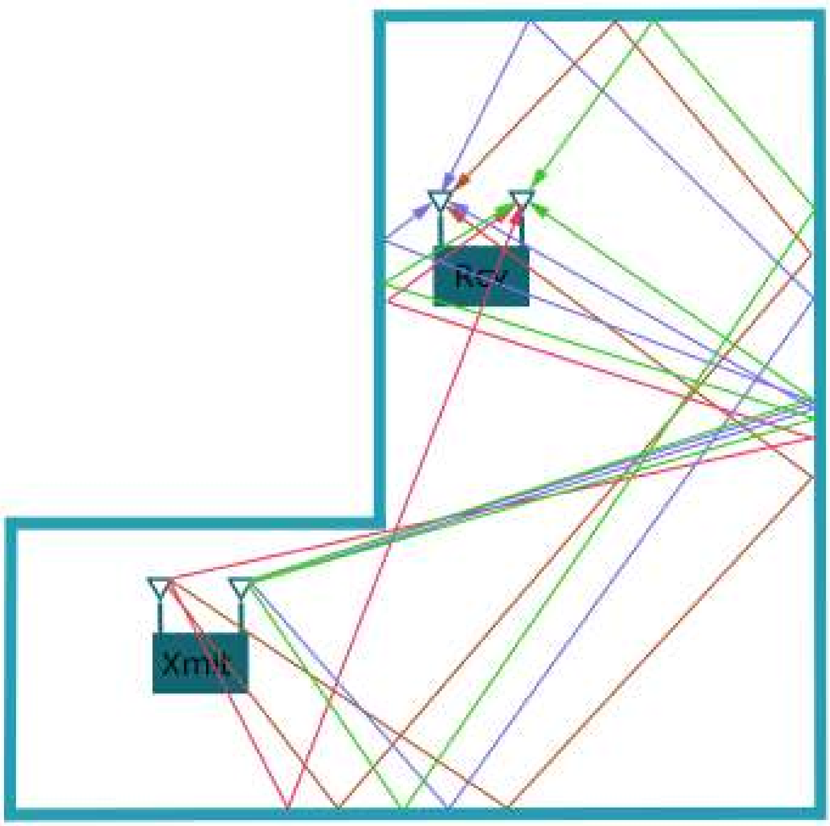
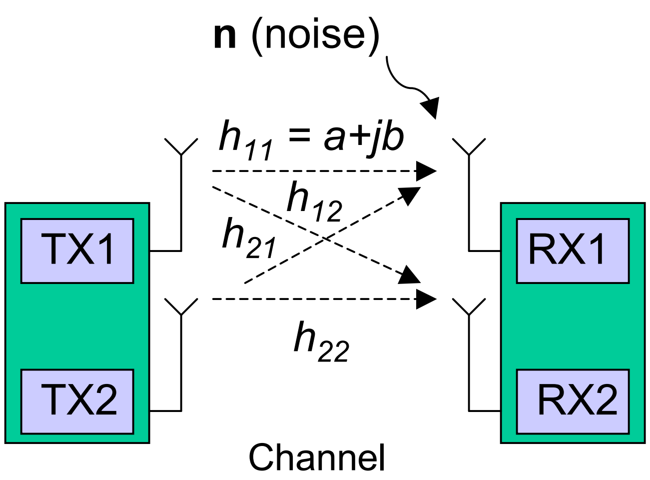
Solving for original stream symbols MIMO requires lots of paths!



If you have two unknown transmitted signals and two measurements at the receivers. If the two measurements are sufficiently independent, you can solve for the transmitted symbols!

Mathematically
Model the Channel

$$y = Hx + n$$



y = Receive Vector

x = Transmit Vector

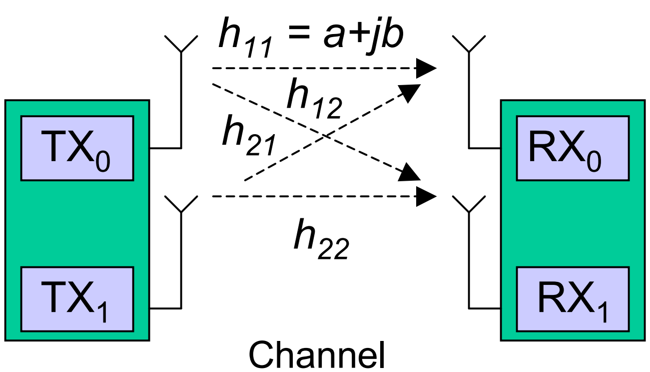
H = Channel Matrix

n = Noise Vector

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

Correct for channel effects

$$RX = H * TX + n$$



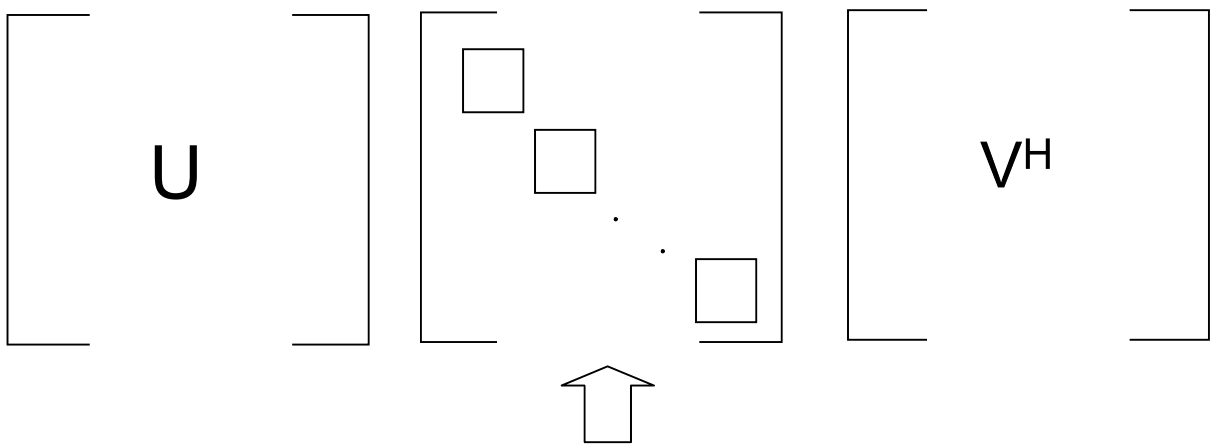
$$\underbrace{\begin{bmatrix} TX_0 \\ TX_1 \end{bmatrix}}_{\text{Data}} = \frac{\underbrace{\begin{bmatrix} RX_0 \\ RX_1 \end{bmatrix}}_{\text{Data}} - n}{\underbrace{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}}_{\text{Header}}}$$

Note this has the disadvantage of possible noise enhancement if |H| is small.

A Different Channel Model

$H=UDV^H$

Three matrices can represent the channel



D. Scaling matrix,
or singular values

The Details

•We could also express **H** as:

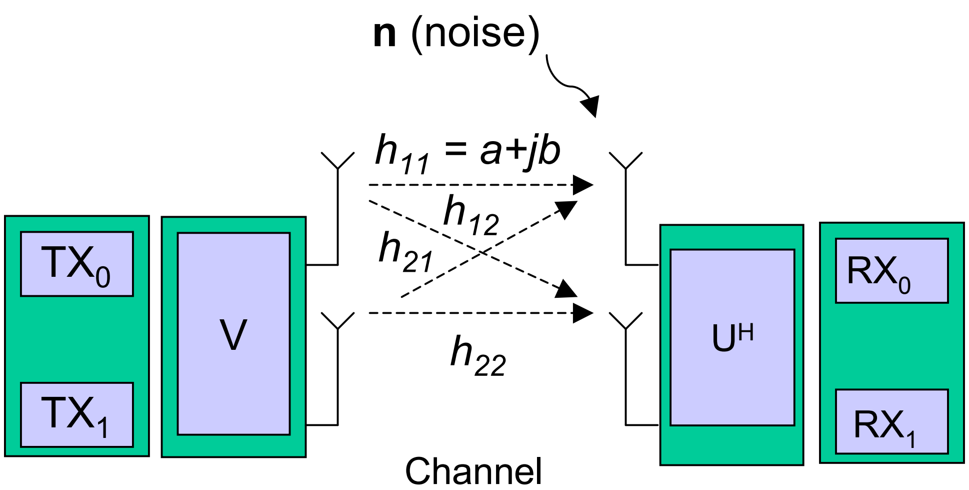
$$\mathbf{H} = \mathbf{U} \bullet \mathbf{D} \bullet \mathbf{V}^H = \begin{bmatrix} u_0 & u_1 & \cdots & u_{N-1} \end{bmatrix} \begin{bmatrix} \sigma_0 & 0 & 0 & 0 \\ 0 & \sigma_0 & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \sigma_{M-1} \end{bmatrix} \begin{bmatrix} \mathbf{V}_0^H \\ \mathbf{V}_1^H \\ \cdots \\ \mathbf{V}_{N-1}^H \end{bmatrix}$$

•We represent the **U** and **V** matrices as column vectors of their singular values for convenience.

•The factor **D,** is composed of the singular values of **H**

A more Complete Channel Model

$H=U.D.V^H$



$RX = U.D.V^H.TX + n$

→"Do the math" and

→$RX=D.TX+U^H.n$

D elements are singular values of H.
Also, |U| is unitary, so there is no noise enhancement.

WLAN Example

Number of Stream and Modulation type is determined by the MCS

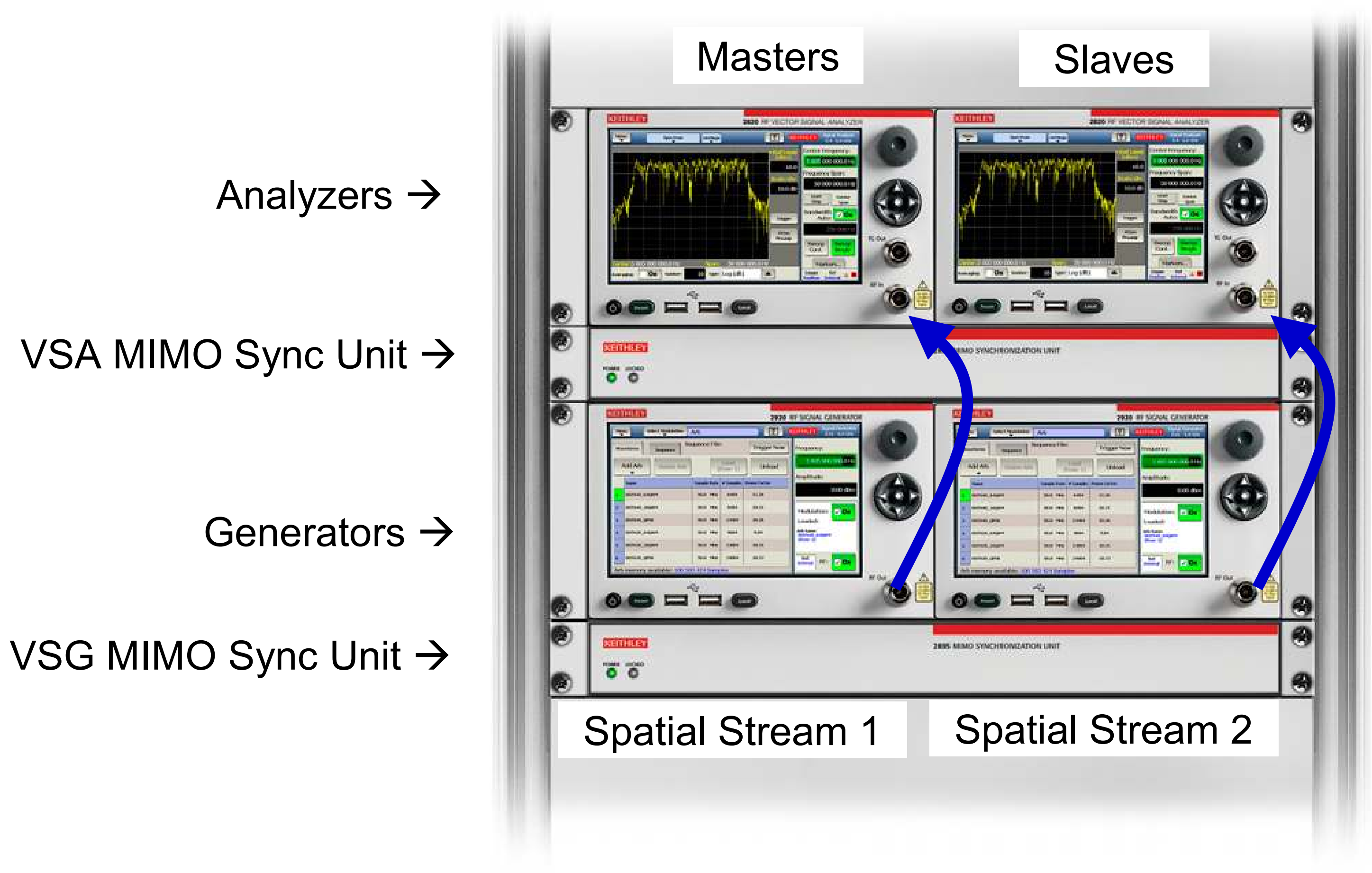
Selecting Modulation Coding Schemes (MCS)

- The table at right contains the specification of some of the 802.11n defined MCS
- This information is automatically encoded in the packet header of the 802.11n waveform, and automatically decoded by the WLAN analyzer program

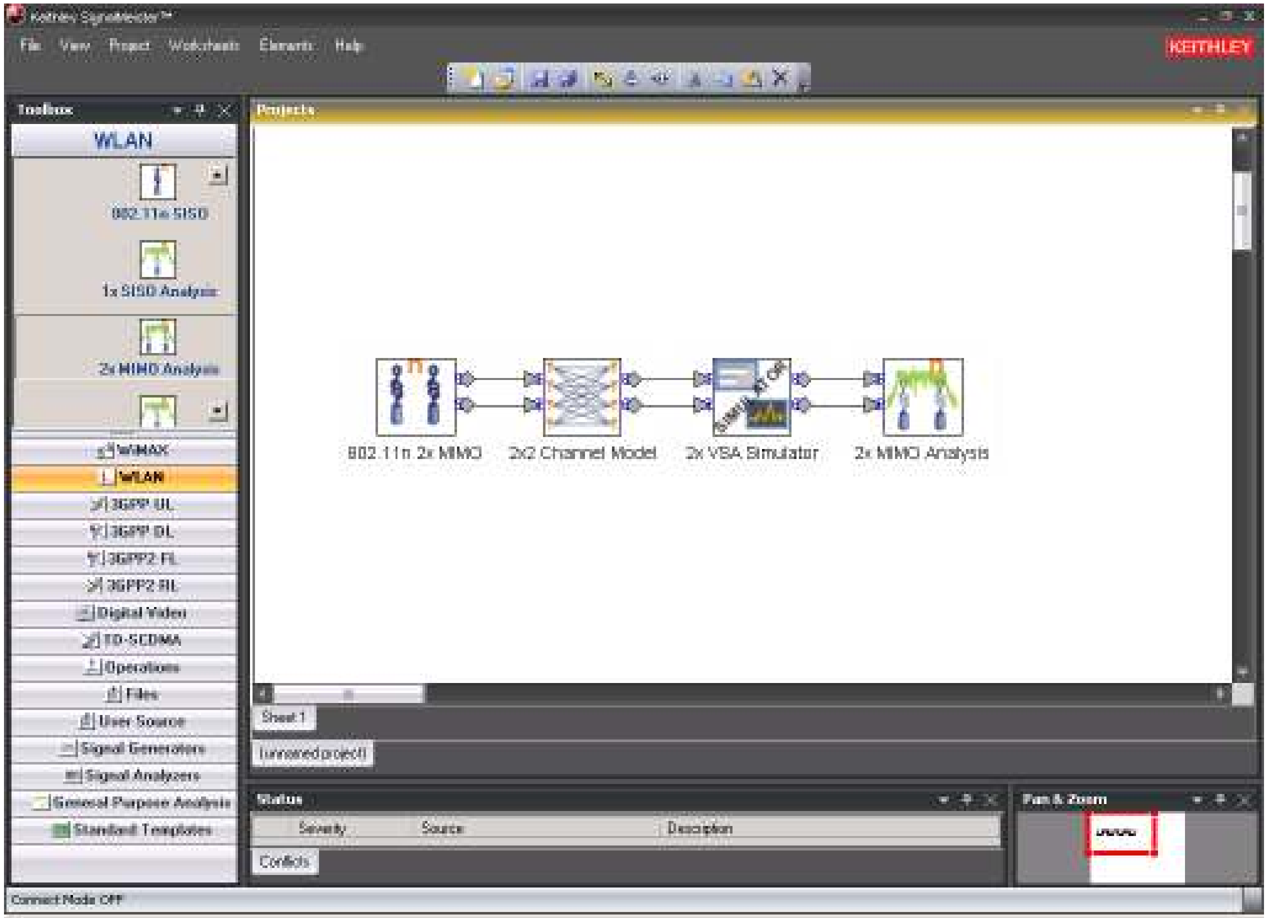
MCS Index	Modulation	Code rate	Spatial Streams	FEC coders	PHY rate 20 MHz	PHY rate 40 MHz
0	BPSK	½	1	1	6.5	13.5
1	QPSK	½	1	1	13	27
7	64-QAM	5/6	1	1	65	135
8	BPSK	½	2	1	13	27
14	64-QAM	¾	2	1	117	243
21	64-QAM	2/3	2	2	156	324
28	16-QAM	¾	4	2	156	324
31	64-QAM	5/6	4	2	260	540

For example a 2x2 BPSK can be analyzed by setting the MCS index to 8

2x2 MIMO Configuration



Generate a Signal



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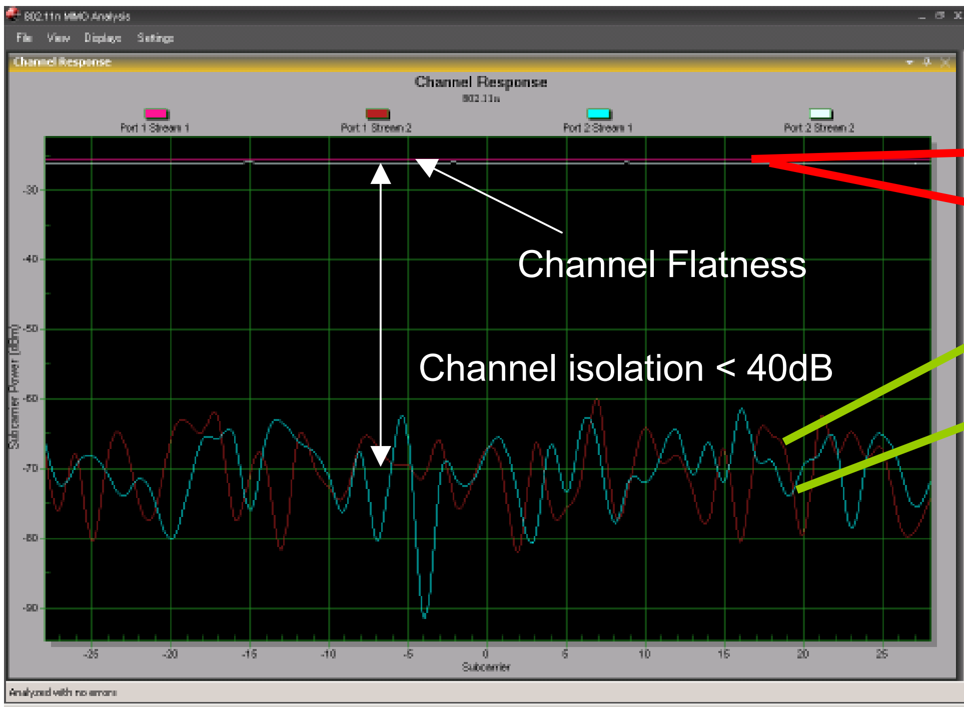
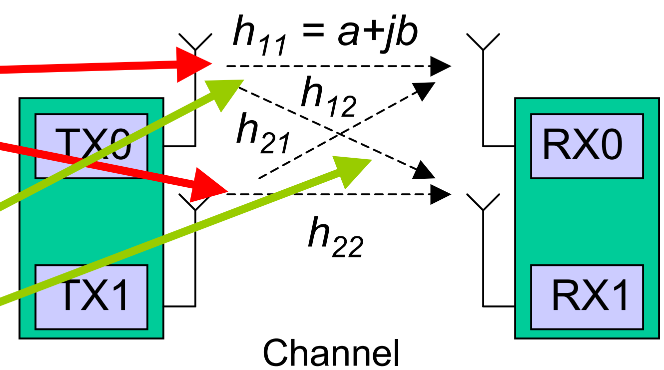
Test conditions require different channel conditions

Models Channel Behavior





In this example we use an RF cable to connect the TX to the RX. We see four plots TX0-RX0, TX1-RX1, TX0-RX1 and TX1-RX0

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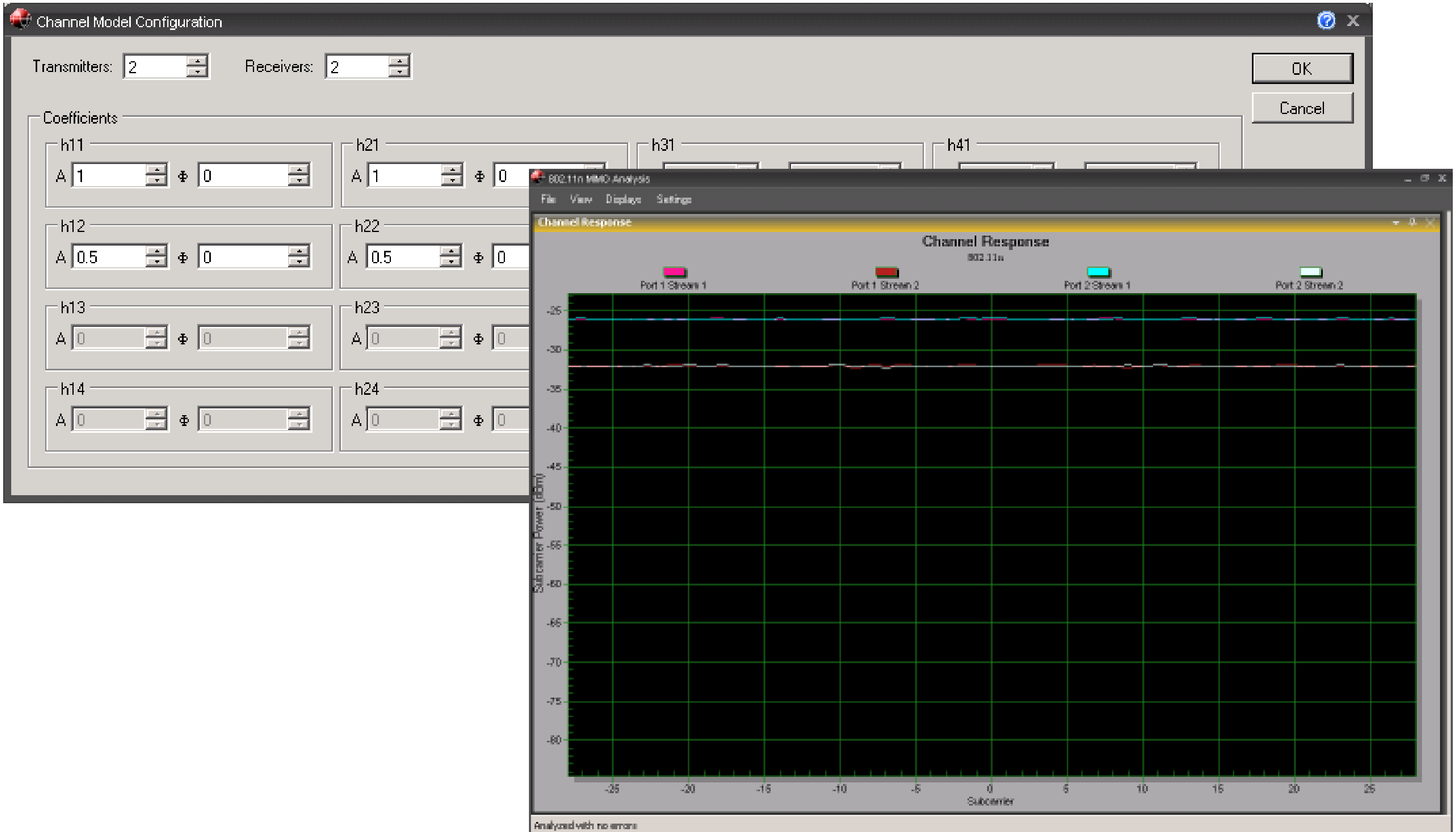
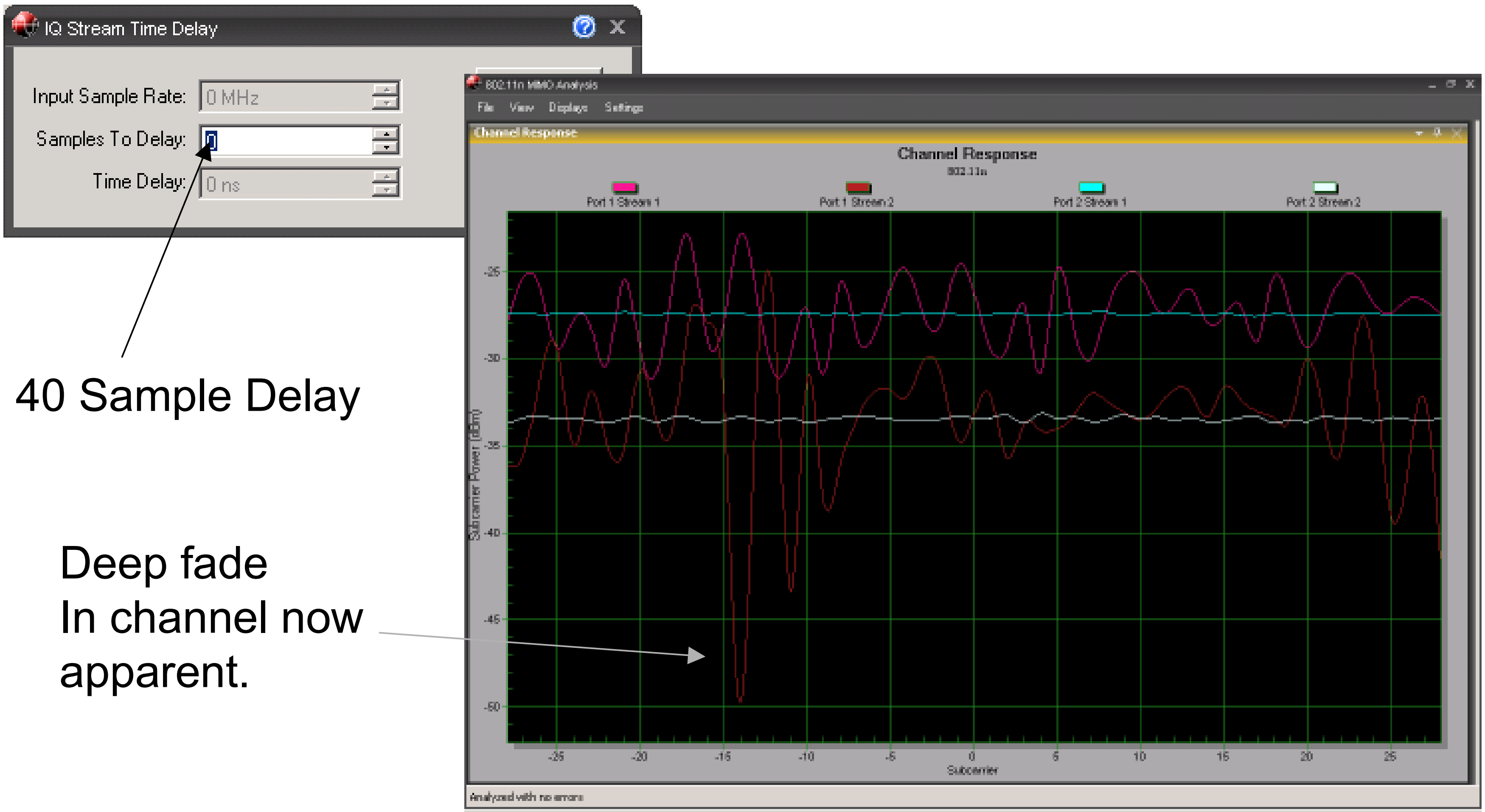
Examine different channel conditions
Magnitude only increase in cross components



Add delay to the equation



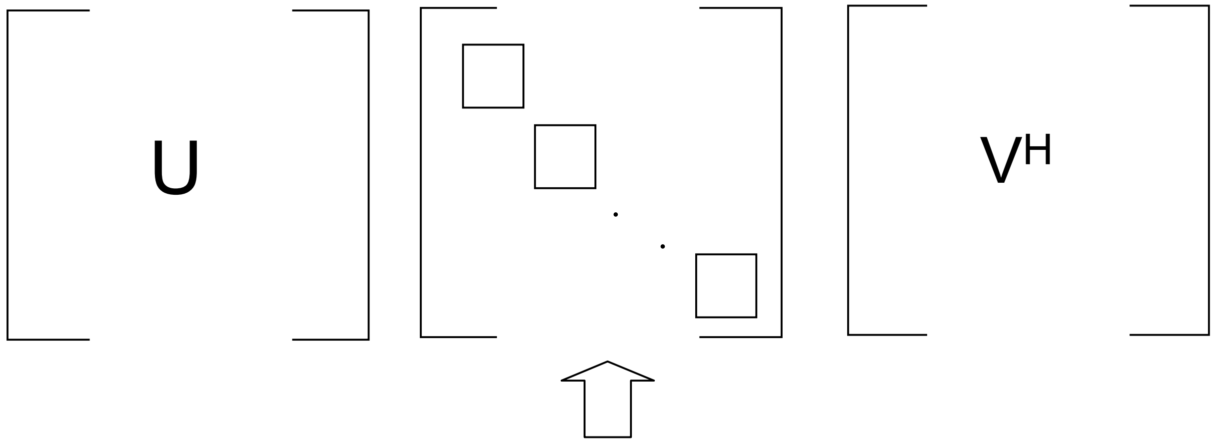
40 Sample Delay

Deep fade
In channel now
apparent.

Key Measurements
2: Channel Metrics - Singular Value Decomposition SVD

$$H=UDV^H$$

Three matrices can represent the channel

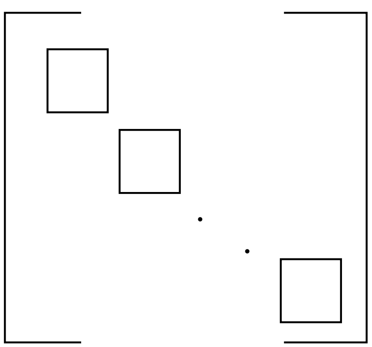


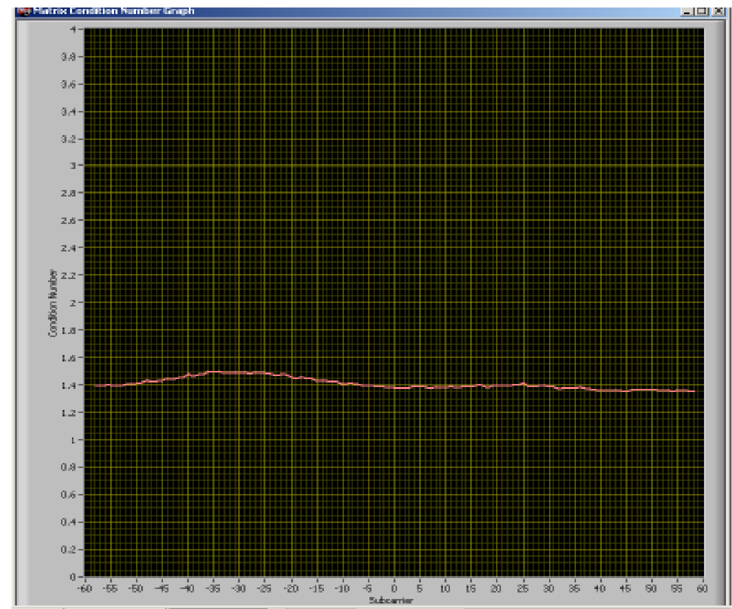
D. Scaling matrix,
or singular values

Key Measurements
2: Channel Metrics - Matrix Condition

The ratio of the highest singular value to the lowest is called the matrix condition.

If the received path was received with equal signal to noise, then the matrix condition would be unity. If the signal to noise ratio is very low on one of the paths, then the matrix condition would be high.





Scaling matrix,
or singular values

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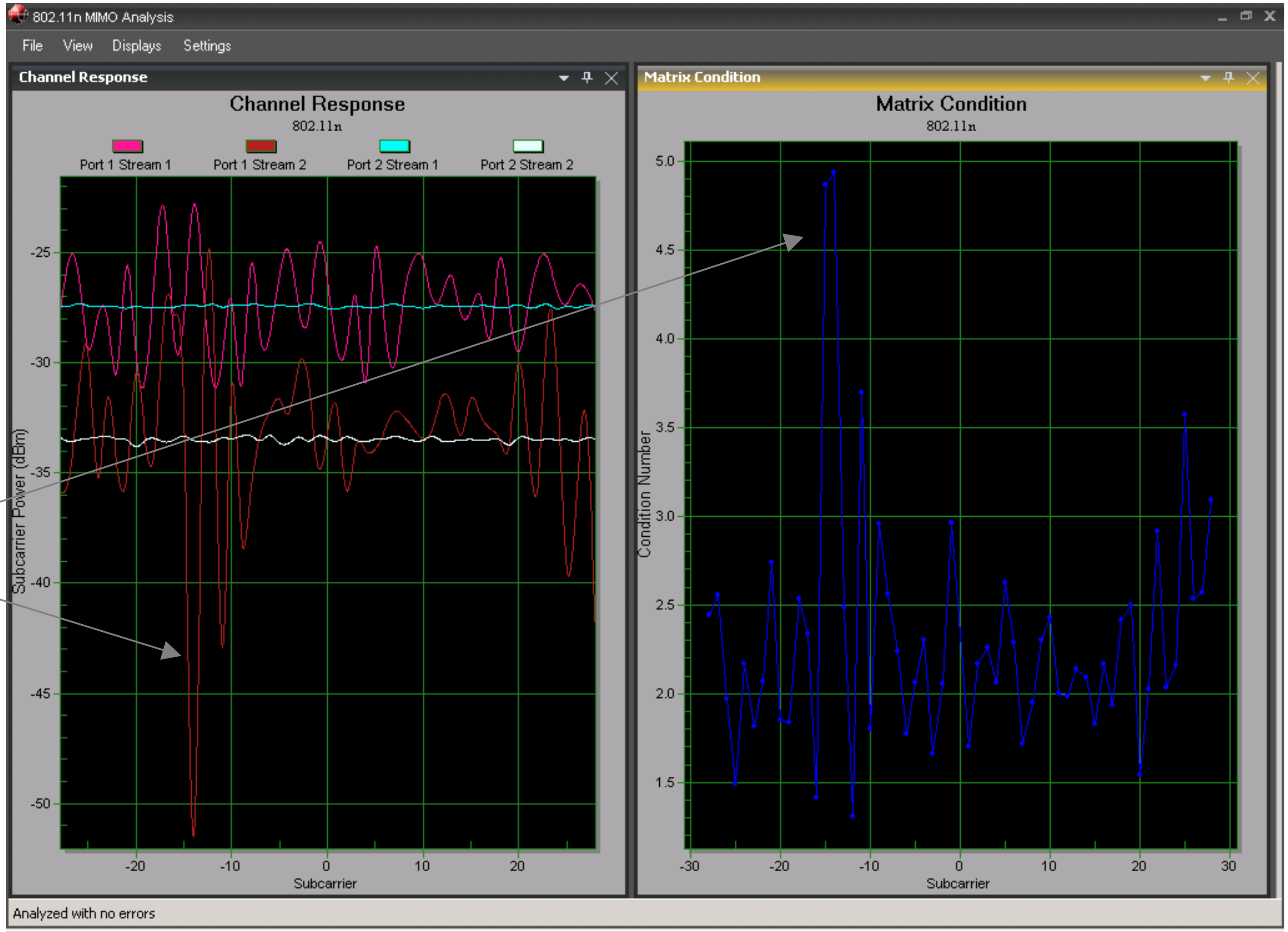
Matrix Condition

Note: Deep Fade Causes Low Signal to Noise, Creating a high matrix condition number.



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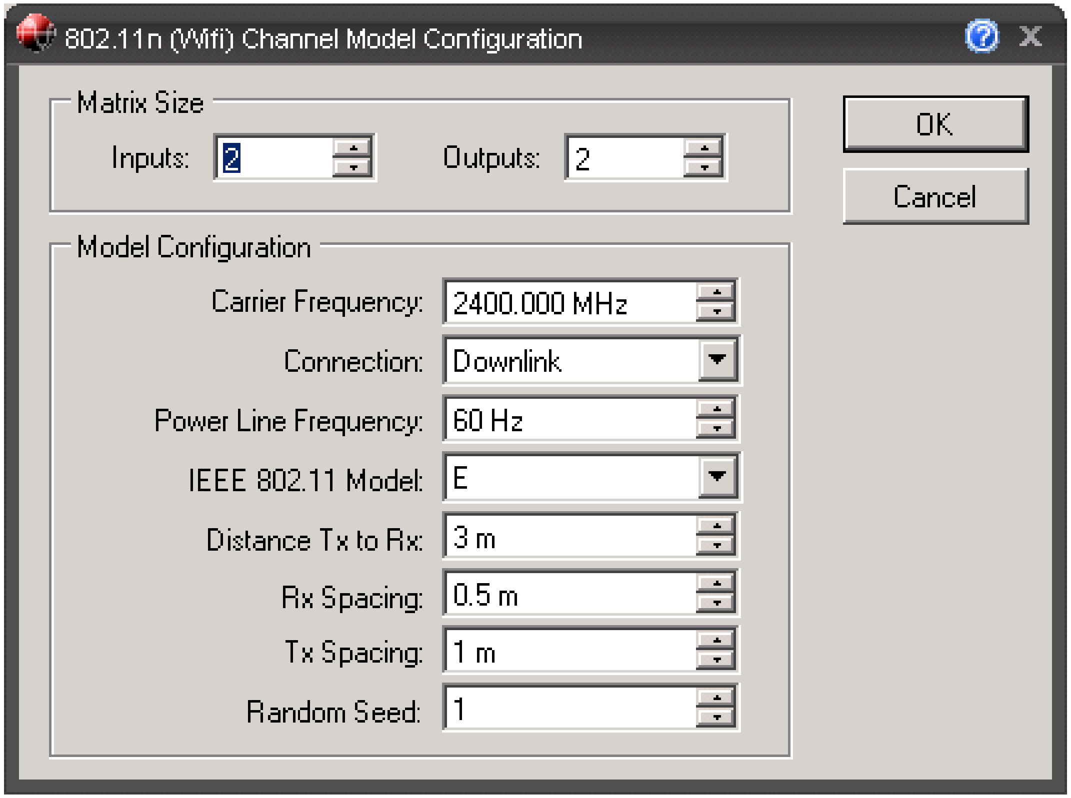
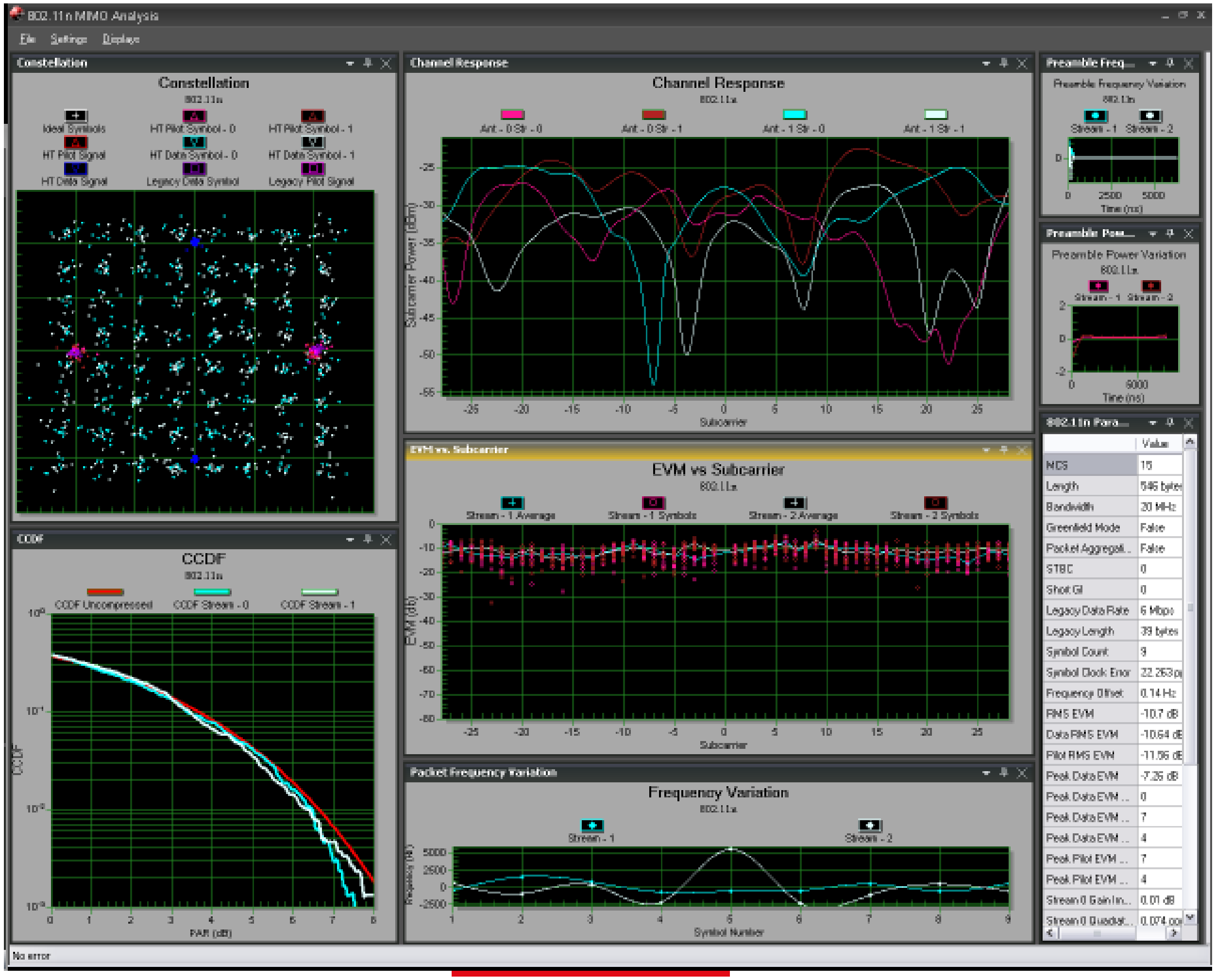
Channel Models



802.11n Analysis Display
2x2 MIMO Example with Channel Model E



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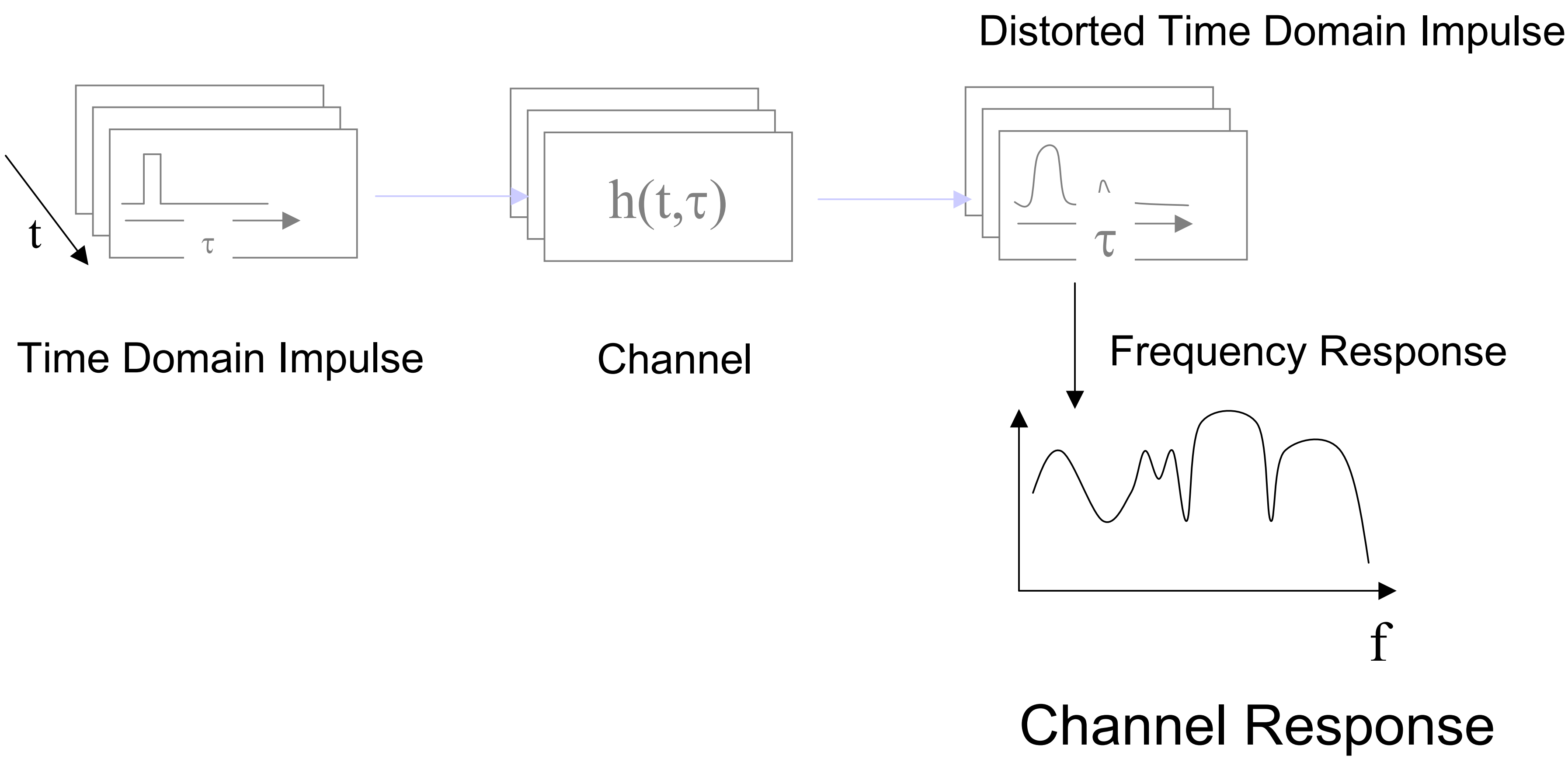
Understanding and Modeling the Channel
Sound the channel



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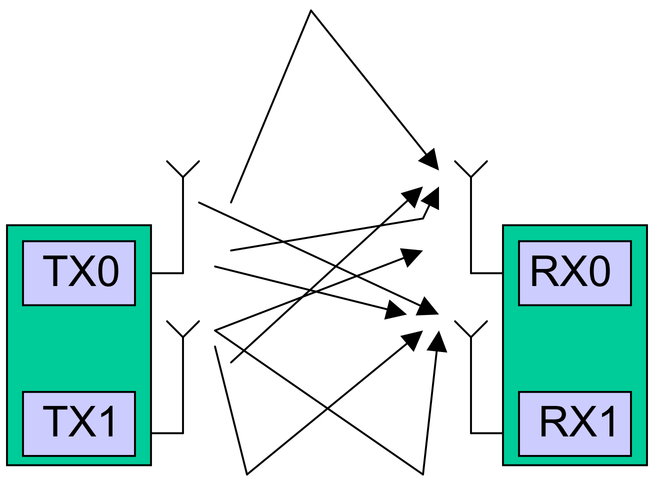
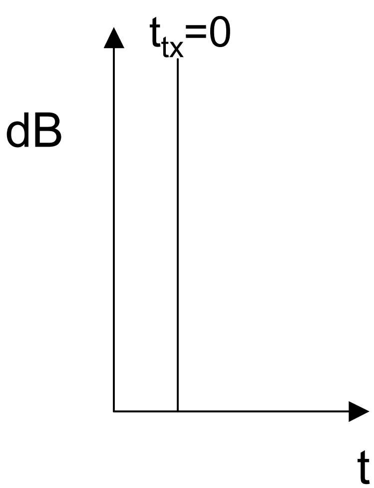
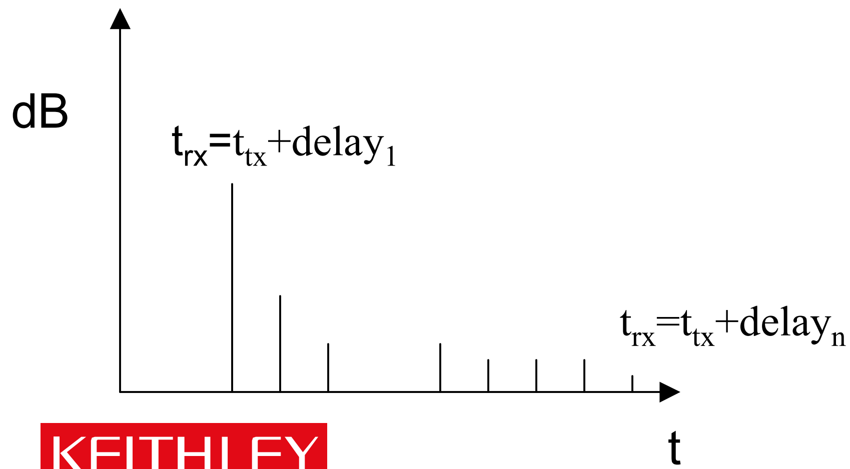
Model The Channel – Multi-path Represented by a Power Delay Profile



Because of multiple path reflections, the channel impulse response of a wireless channel looks likes a series of pulses. In practice the number of pulses that can be distinguished is very large, and depends on the time resolution of the communication or measurement system.





Static Channel Model Only

- **Sounding the channel with an impulse models the channel at single point in time does not account for mobility or environmental changes.**
- **A real time emulator such as the Azimuth Emulator would be used for this.**

Example of a channel emulator:
Azimuth Systems ACE 400WB
4x4 bidirectional unit
www.azimuthsystems.com

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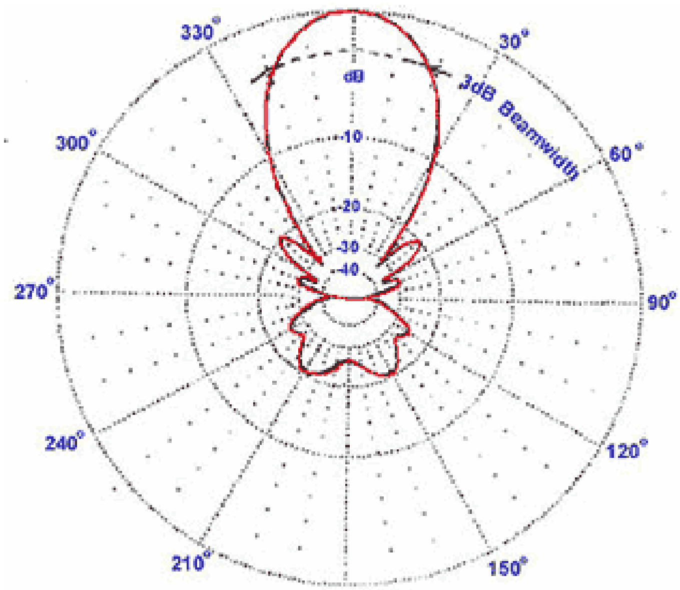
Smart Antenna Systems and Beam Forming



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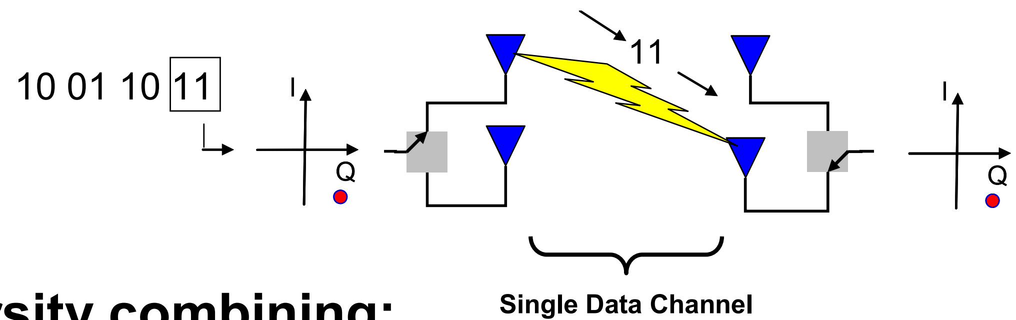
Antenna Systems

- **Diversity – most commonly used antenna system**
- **Sectorized – used by base stations**
- **Smart – Form a radiated RF beam, *beam forming*.**
  - Fixed
  - Adaptive

Diversity Systems (Time)

– **Switched/Selection diversity:**
  - The system continually switches between antennas so as always to use the element with the largest output.
  - No gain increase since only one antenna is used at a time.



– **Diversity combining:**
  - **This approach constructively sums the signals by correcting the phase error in two multi path signals effectively combining the power of both signals to produce gain.**

Diversity System (Space) MIMO based.

A single data stream is replicated and transmitted over multiple antennas.

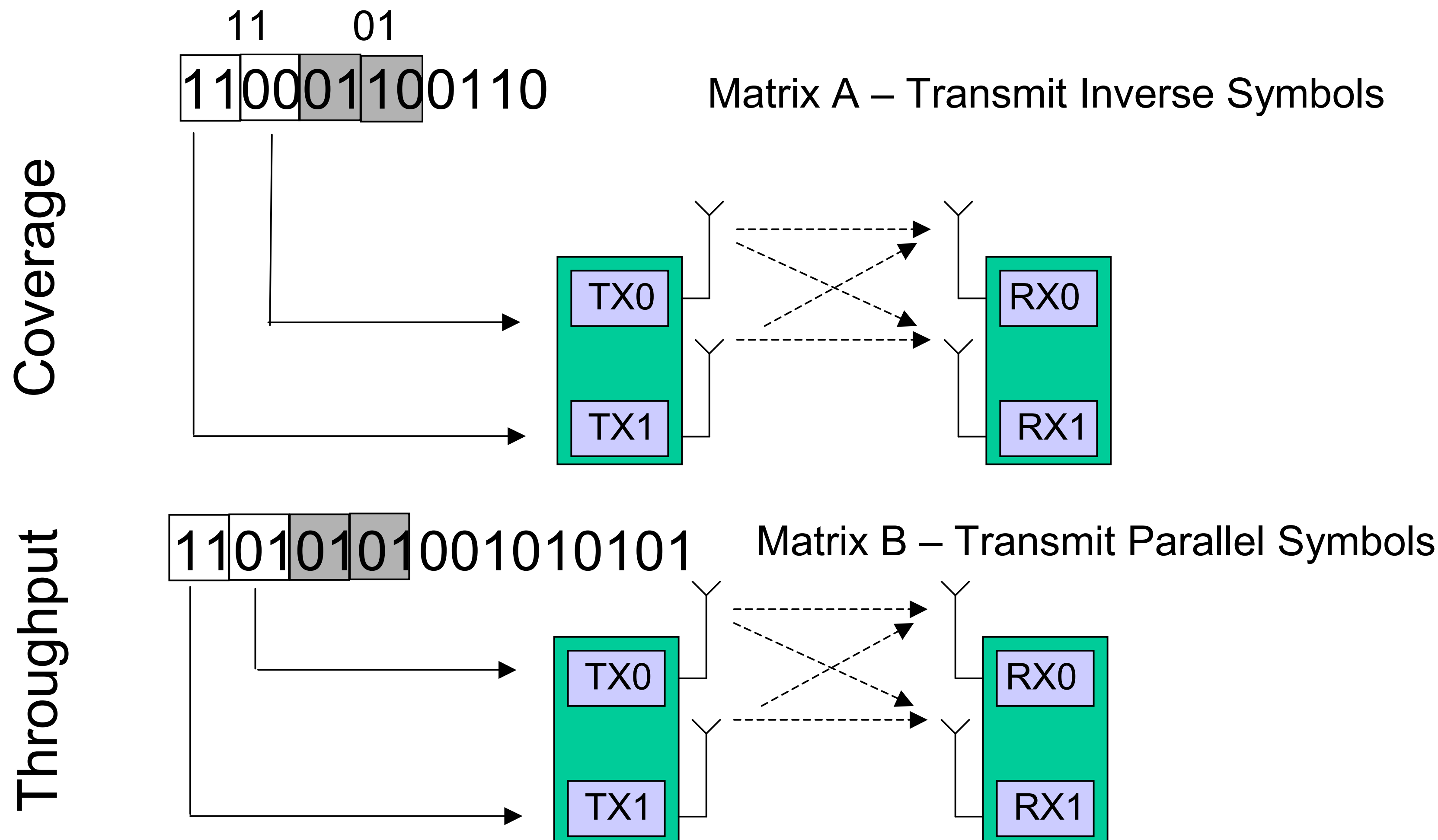
The redundant data streams are each encoded using a mathematical algorithm known as Space Time Block Codes.

Each transmitted signal is orthogonal to the rest reducing self-interference and improving the capability of the receiver to distinguish between the multiple signals.

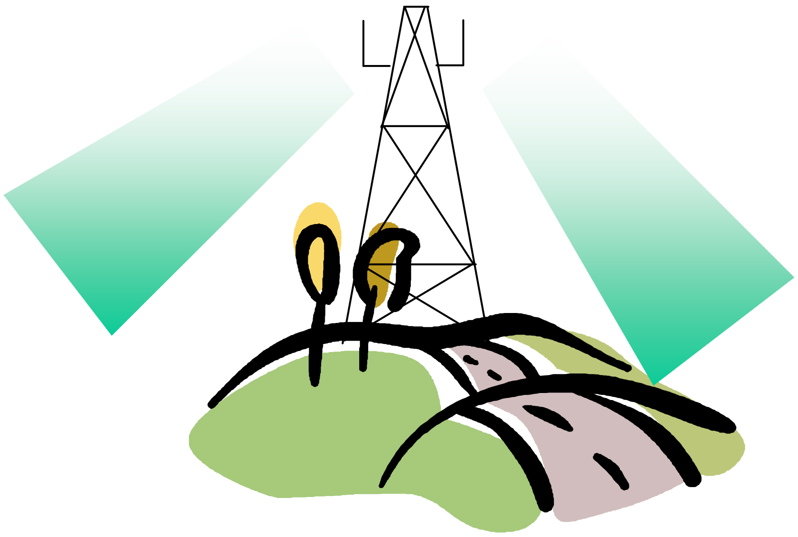
With the multiple transmissions of the coded data stream, there is increased opportunity for the receiver to identify a strong signal that is less adversely affected by the physical path.

The receiver additionally can use a diversity combining technique to combine the multiple signals for more robust reception.

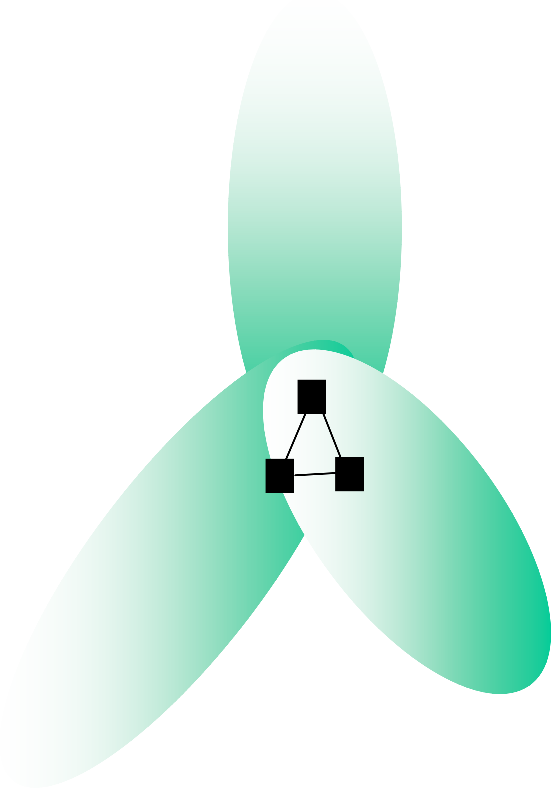
Spatial Diversity
WiMAX Matrix A STC vs Matrix B SMX



Sectorized antenna systems
Radiation Pattern



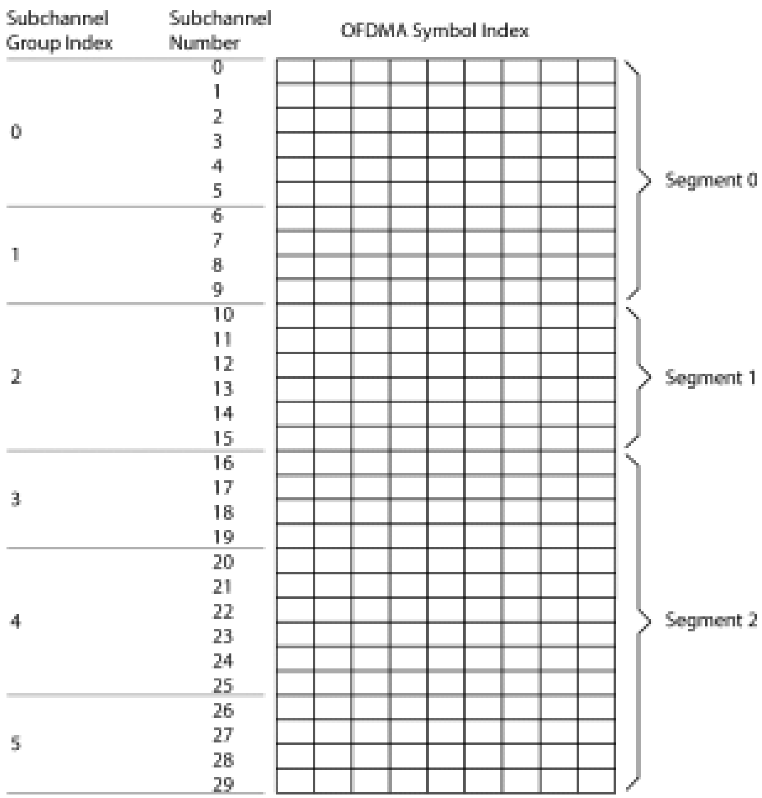
Side View



Top View

WiMAX and sectorized transmission.

- The Base Station may have multiple BS MACs.
- Each BS MAC may have a portion of the subchannel groups referred to as a segment.
- The functionality supports sectorized transmission.



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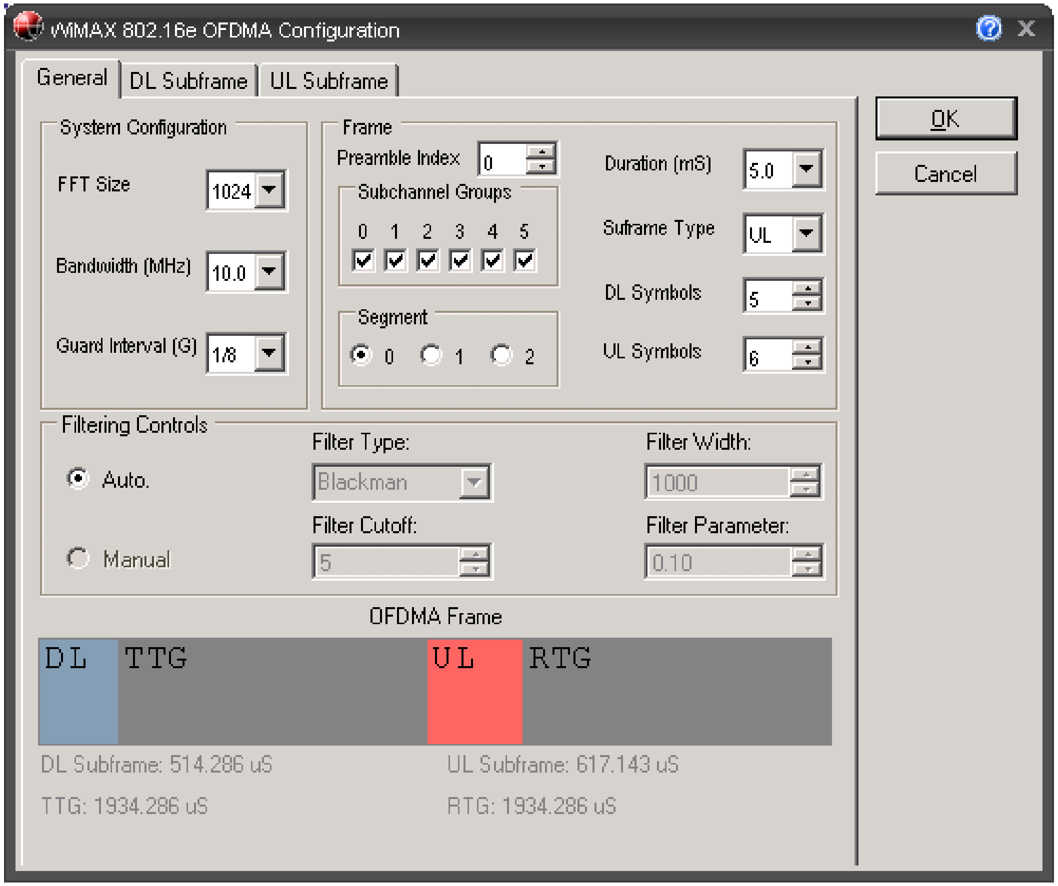
Configuring a Segment/Sector



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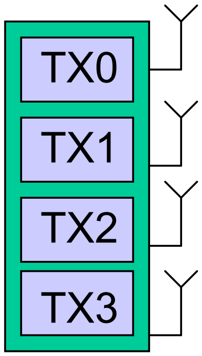
Smart Antenna Technology

- **How can an antenna be made more intelligent?**
  - Instead of having one transmitter you require multiple, the more the better!
  - The antenna becomes an antenna system that can be designed to shift signals before transmission at each of the successive elements so that the antenna has a composite effect.
  - When transmitting, a beam former controls the **phase** and relative **amplitude** of the signal at each transmitter, in order to create a pattern of constructive and destructive interference in the wave front. When receiving, information from different sensors is combined in such a way that the expected pattern of radiation is preferentially observed.



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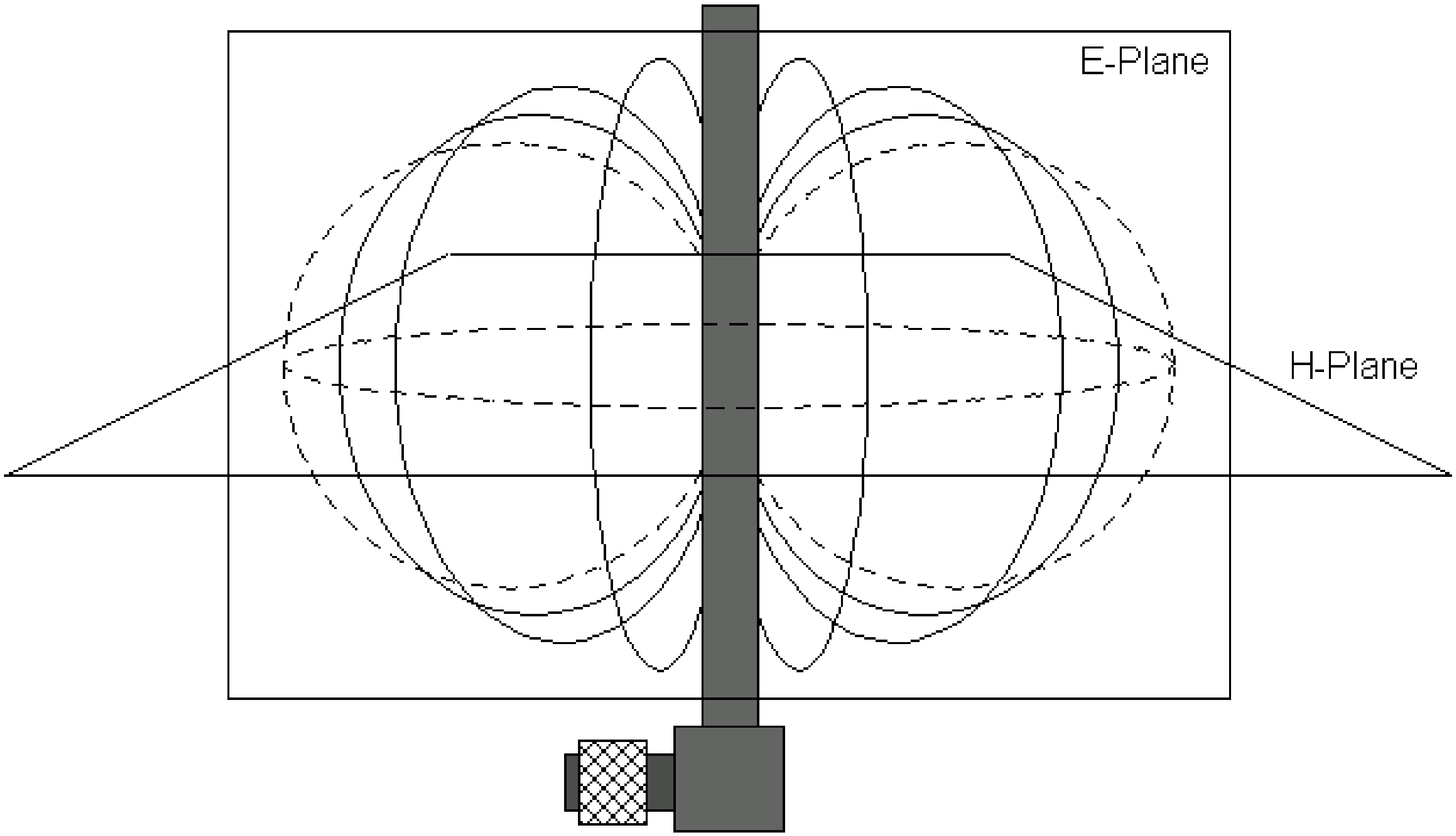
Beam Forming Benefits

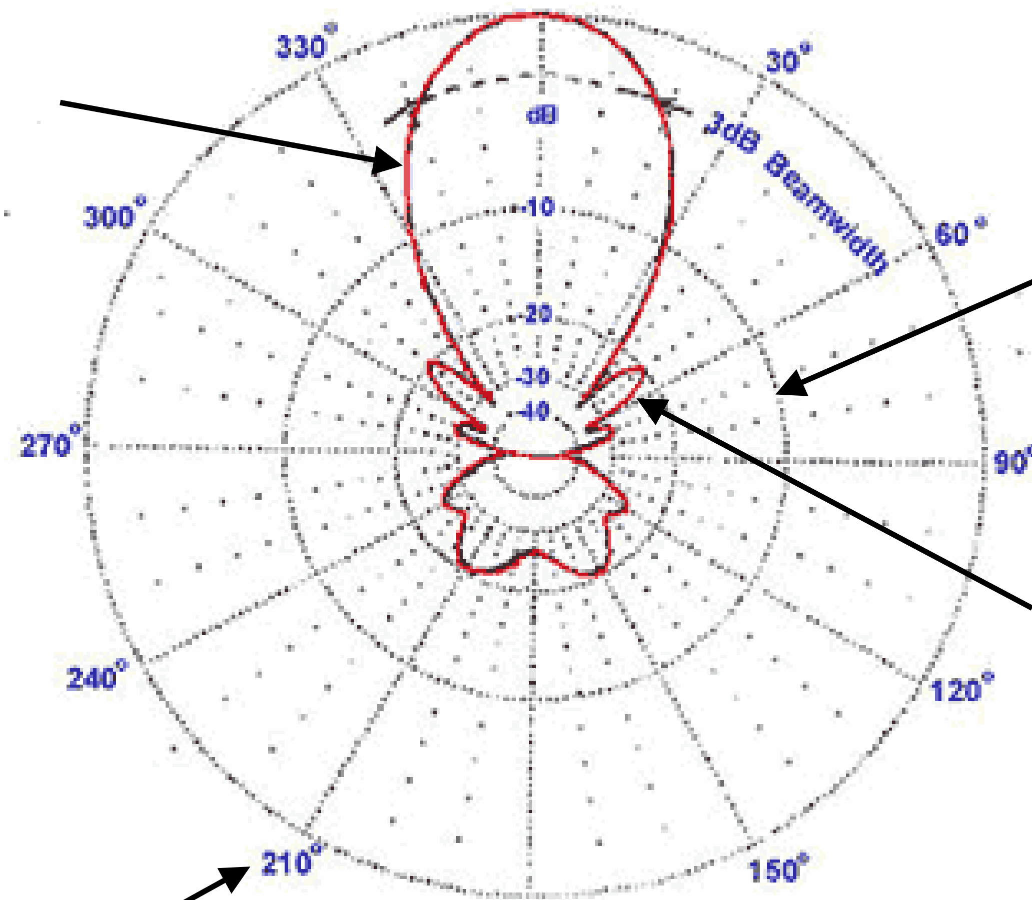
By controlling the directionality and shape of the radiated pattern increased range, capacity and the throughput of the transmission is achieved.

Antenna Radiation Pattern



Log Plot of Radiation Pattern Azimuth ("E" plane)

Main Lobe



dB from Maximum gain

Side Lobe (20dB down)

Degrees from Main Lobe axis

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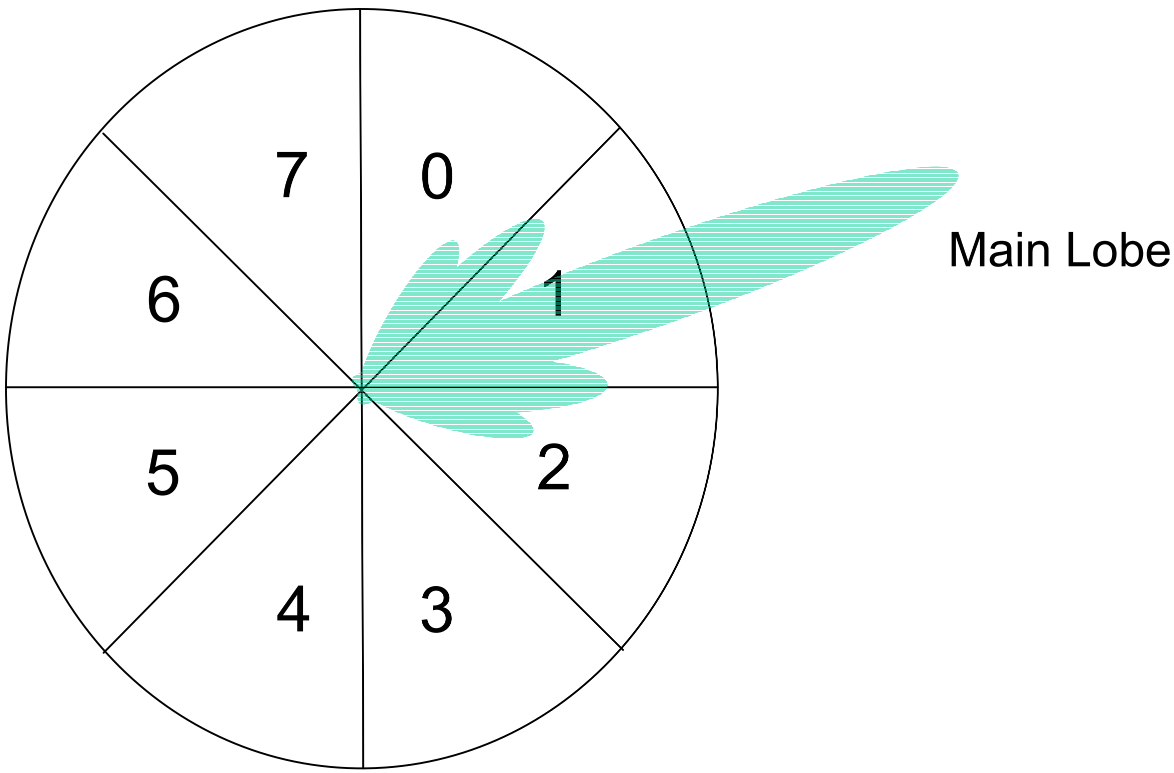
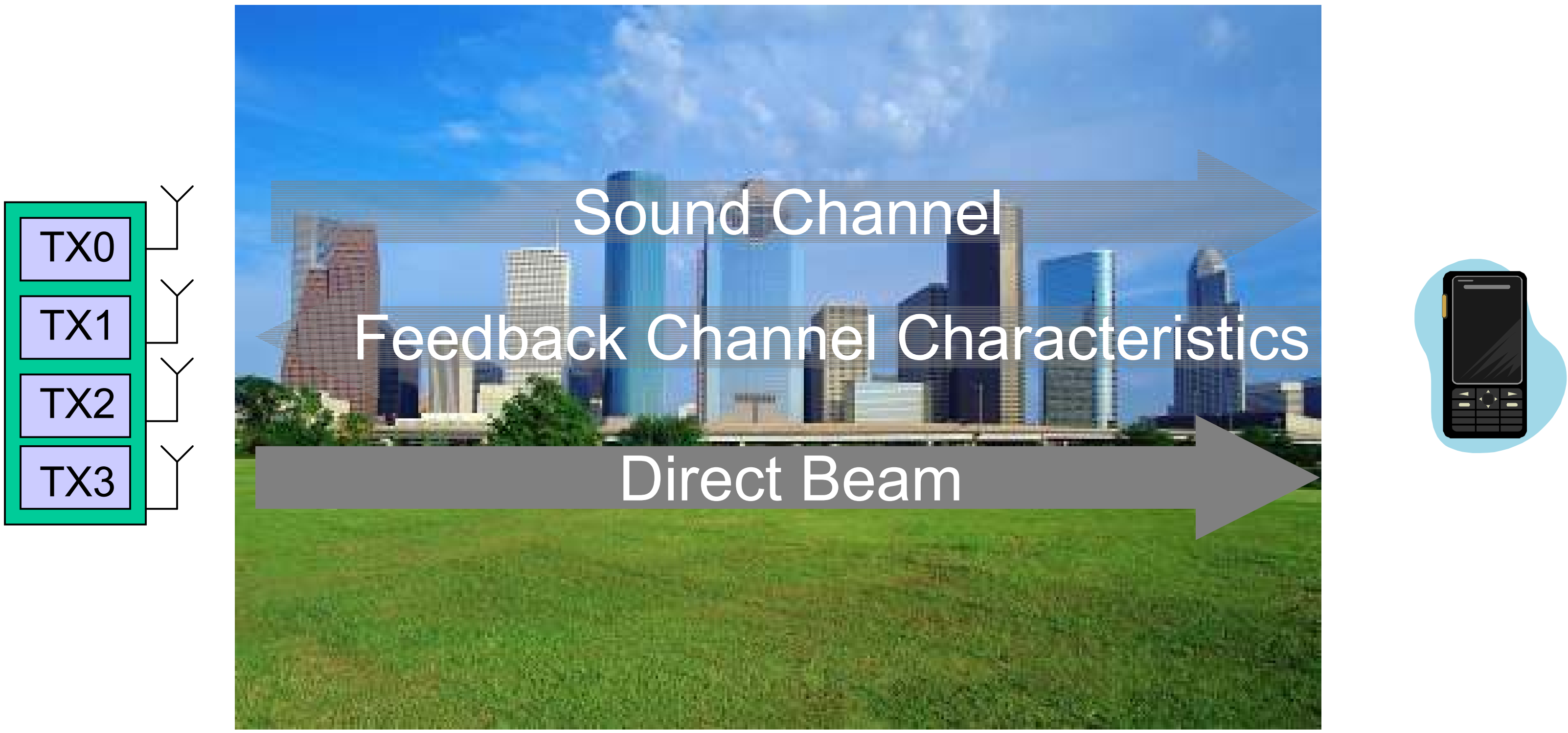
Fixed Beam Forming



The Adaptive Beam Forming Process
LTE Example - Closed Loop



Look up table approach

Antenna Correlation
High and Low

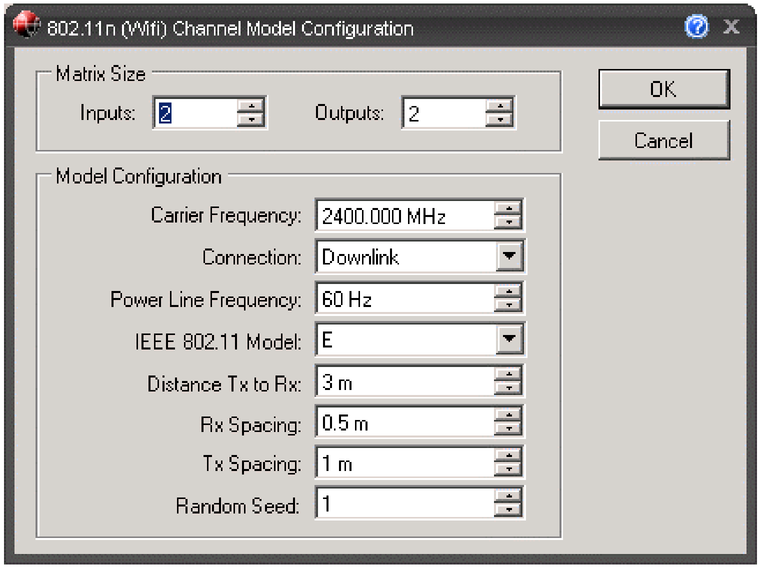
High - The distance between antennas is small (less than one wavelength).

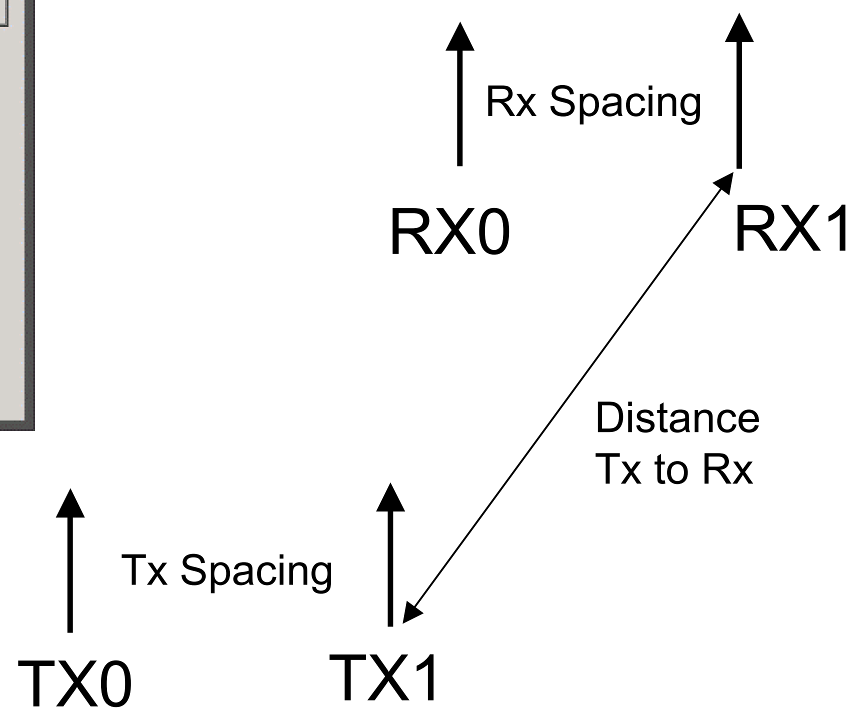
- Assume the same fade for each antenna (channel).
- The beam can be steered by phase shifts alone
- The beam tends to be wide

Low – The distance between antennas large (typically several wavelengths), or change polarization H vs. E.

- Assume different fading characteristics for each antenna (channel).
- Beam must be steered by phase shifts and magnitude changes via the beam steering vector.

Antenna Correlation High and Low





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Single layer Beam Forming

- **To maximize the signal at the receiver:**
  - Select a beam forming vector **V** such that

$$v_i = h_i^* / \text{sqrt}(\Sigma_{k=1}^{Nt} |h_k|^2)$$

  - This normalizes the signal to the complex conjugate of the channel so that total transmit power is unchanged.

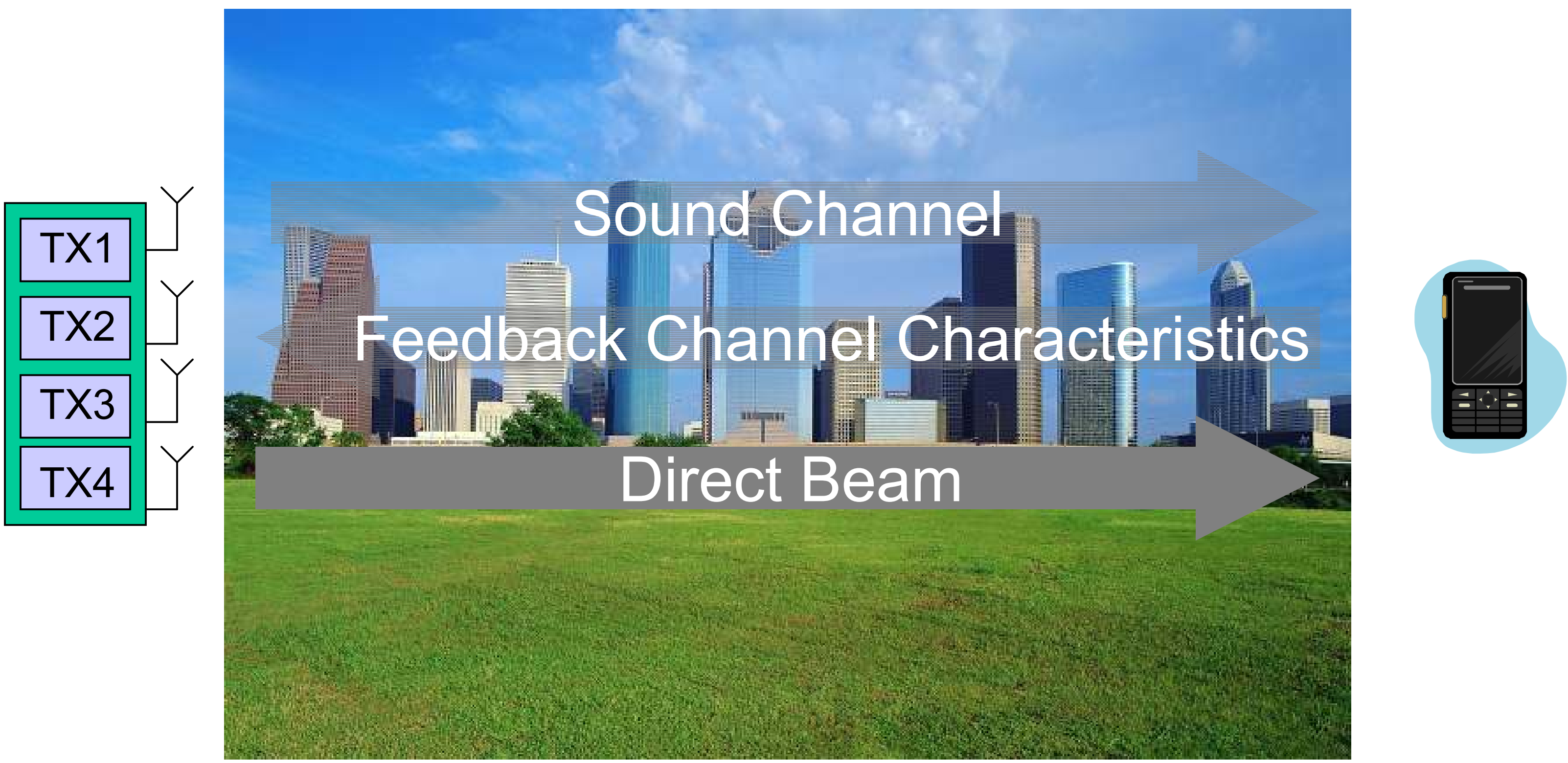
- **Observations:**
  - This technique phase rotates the transmit signals so received signals are time aligned.
  - In general, more power is allocated to antennas with good channel conditions. This maximizes capacity.
  - Overall transmit power is constant.

Single layer Beam Forming

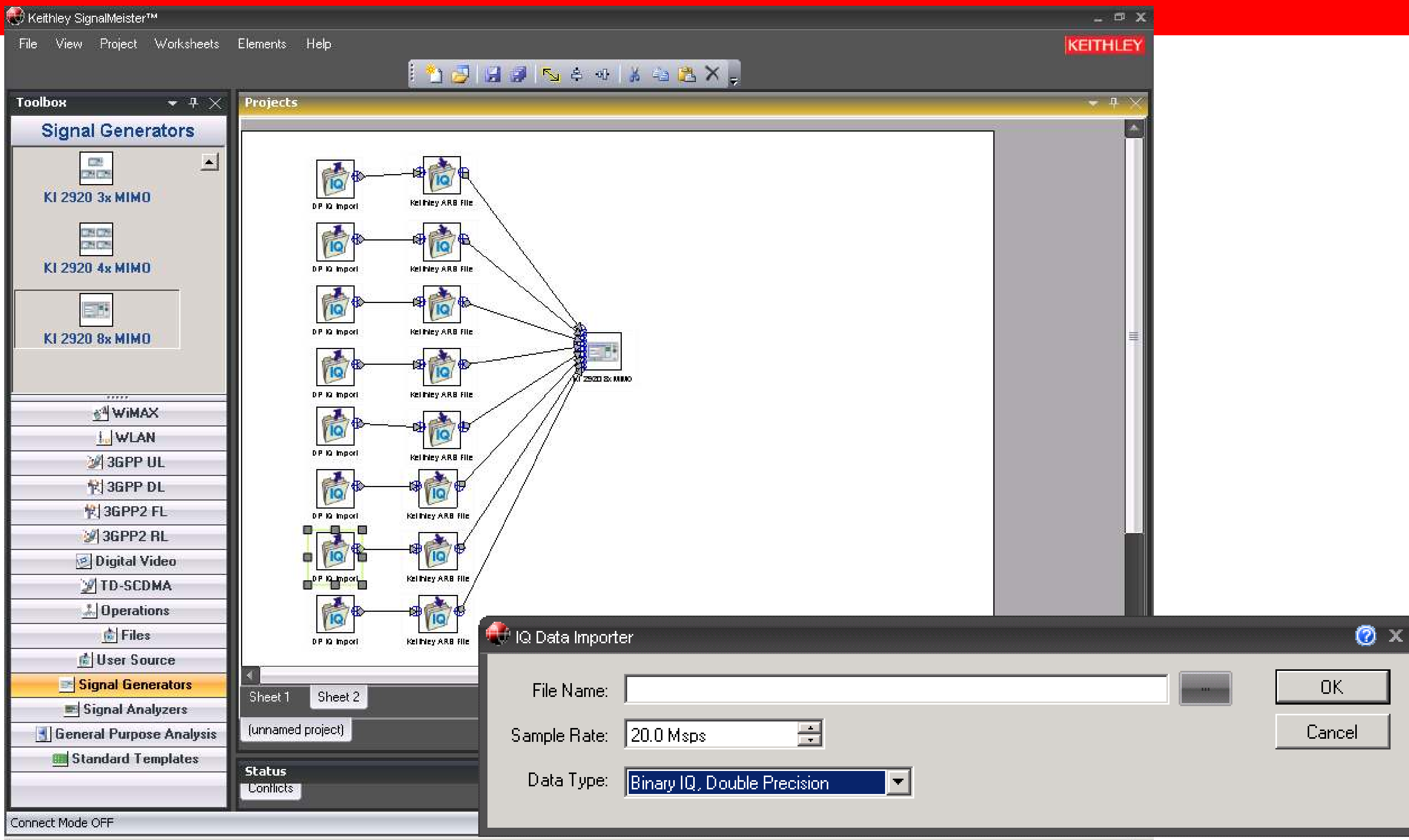
- **High correlation vs. Low Correlation beam forming observations:**
  - More knowledge of channel is needed for low correlation beam forming.
  - The beam forming vector must take the channel into account.
  - For FDD (Frequency Division Duplex), only the receiver knows the channel, so it must feedback channel information to the transmitter.
  - For TDD (Time Division Duplex) the up and down links share frequencies so the channel is known without feedback.

  - The above assumes channel gain is constant vs. frequency. If it's not then no single set of **B** coefficients are possible.
    - This can be resolved by using OFDM precoding weight based on each sub-carrier characteristic.

The Beam Forming Process
WiMAX Example - Closed Loop



Creating a Signal



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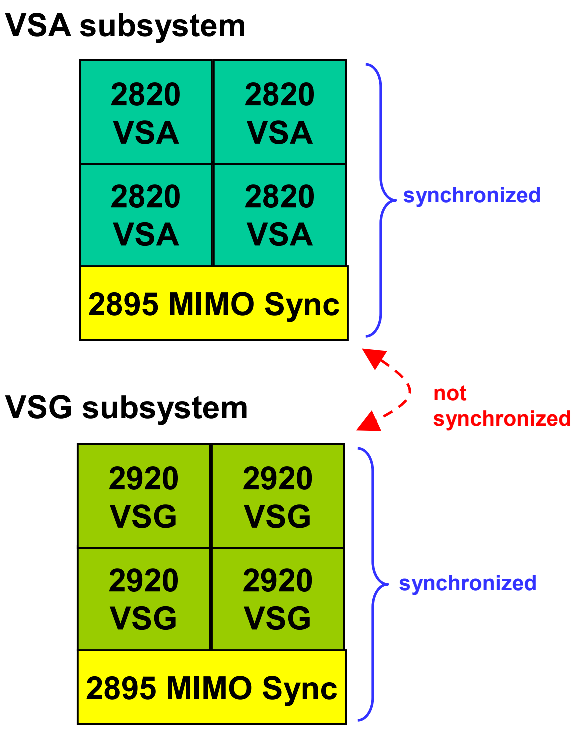
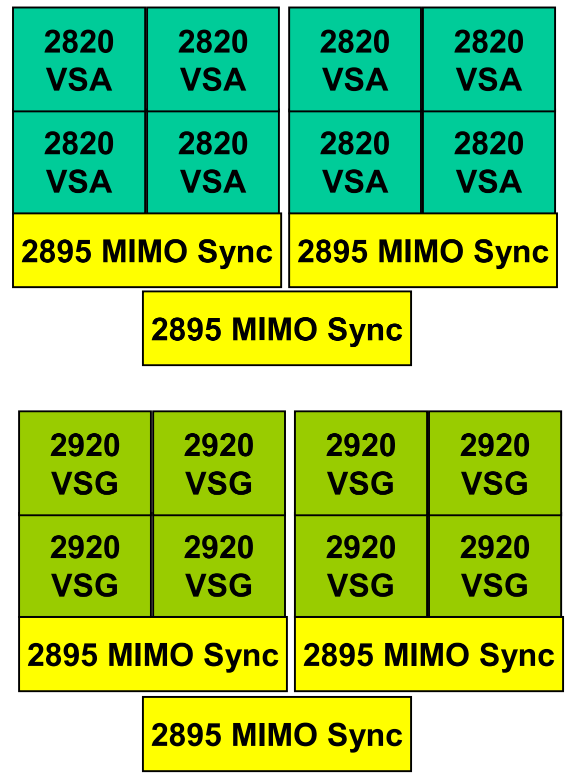
VSA and VSG Subsystem Configuration Groups…
…that are Synchronized Analyzers and Generators[1]

4x4 MIMO system
(or 2x2, 3x3, etc.)



8x8 MIMO system



1. Each VSA and VSG subsystem group is synchronized and cannot be separated. The VSA and VSG subsystems are separate and asynchronous from each other.

Scalable Solutions

SISO

GSM, W-CDMA,
WLAN, WiMAX

2x2 – 4x4
MIMO

WLAN, LTE, WiMAX

8x8
MIMO

Advanced Antenna
Research

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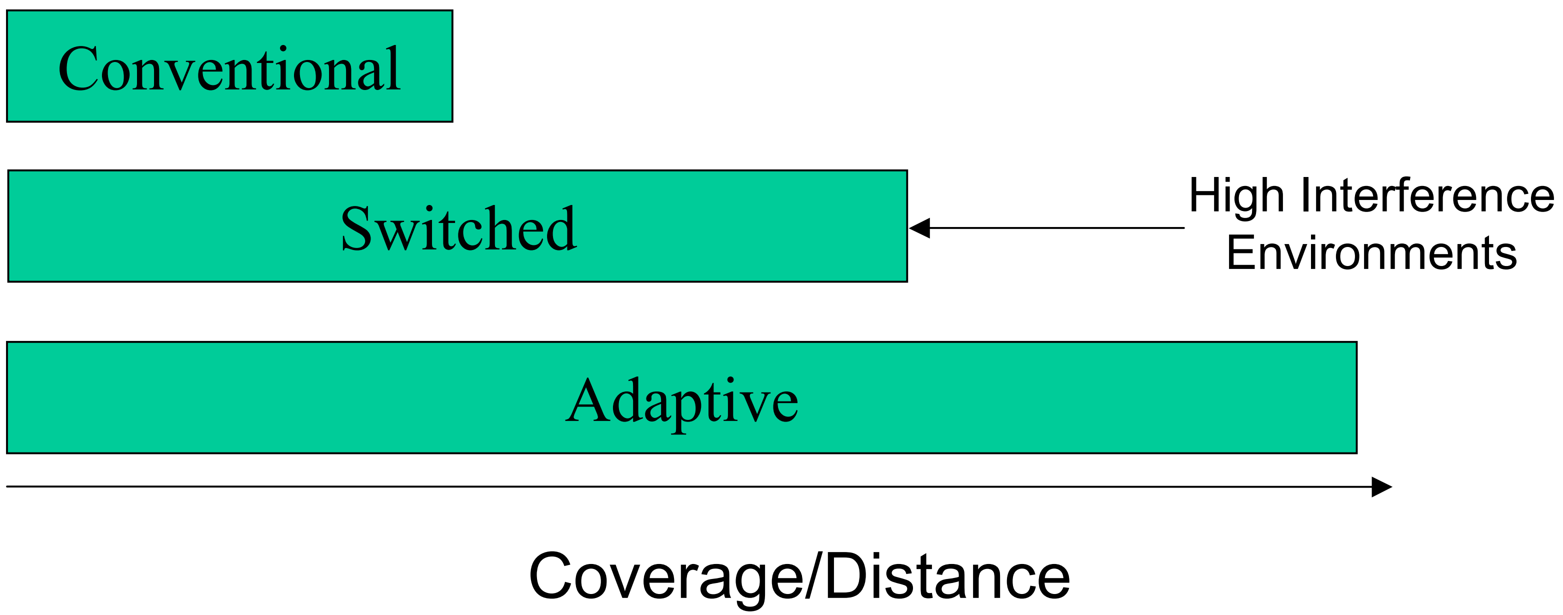
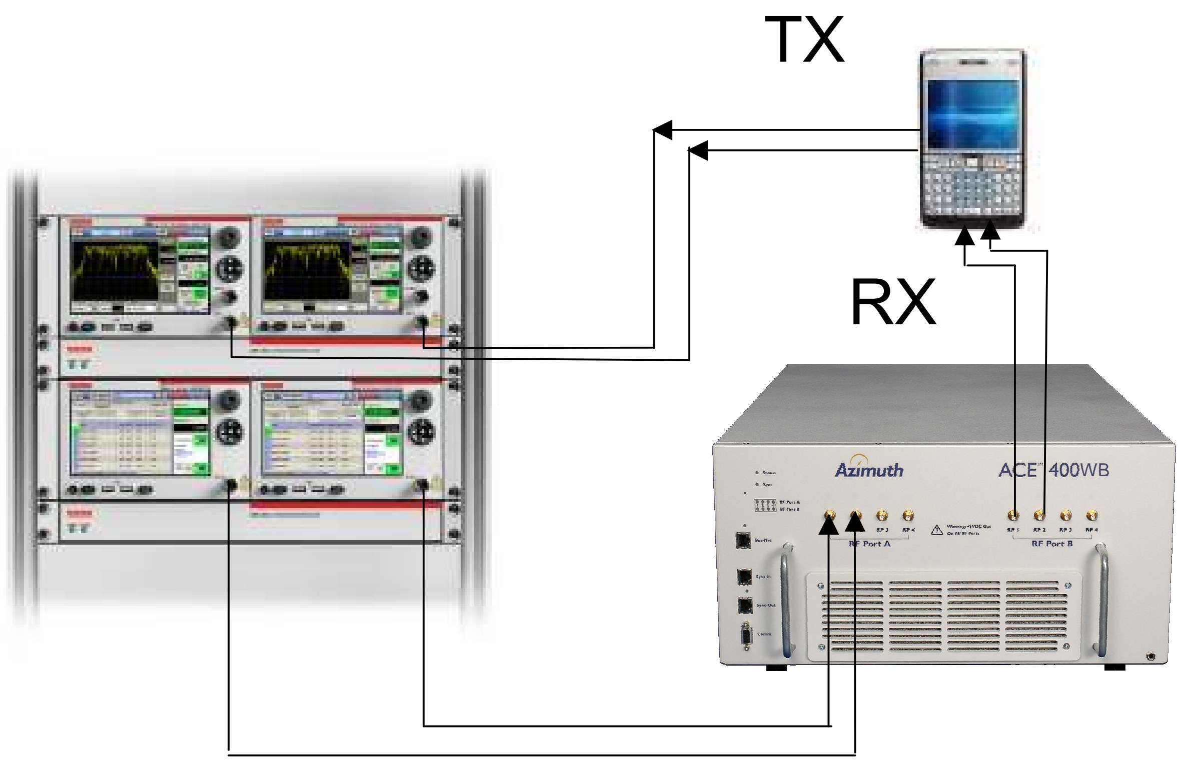
Beam Forming Summary



MIMO Conclusion

- **Allows for better throughput and coverage**
  - STC, Space Time Coding
  - SMX, Spatial Multiplexing
  - Beam forming
- **Requires knowledge of channel**
- **Requires higher levels of baseband processing**

Typical Test Setup 2x2



Throughput, Flexibility, and Ease of Use
Delivered in new wireless connectivity test capabilities

2800 VSA and 2900 VSG
SISO
GSM
CDMA
WLAN
WiMAX

2800 VSA, 2900 VSG + 2895
MIMO
WLAN
WiMAX
LTE

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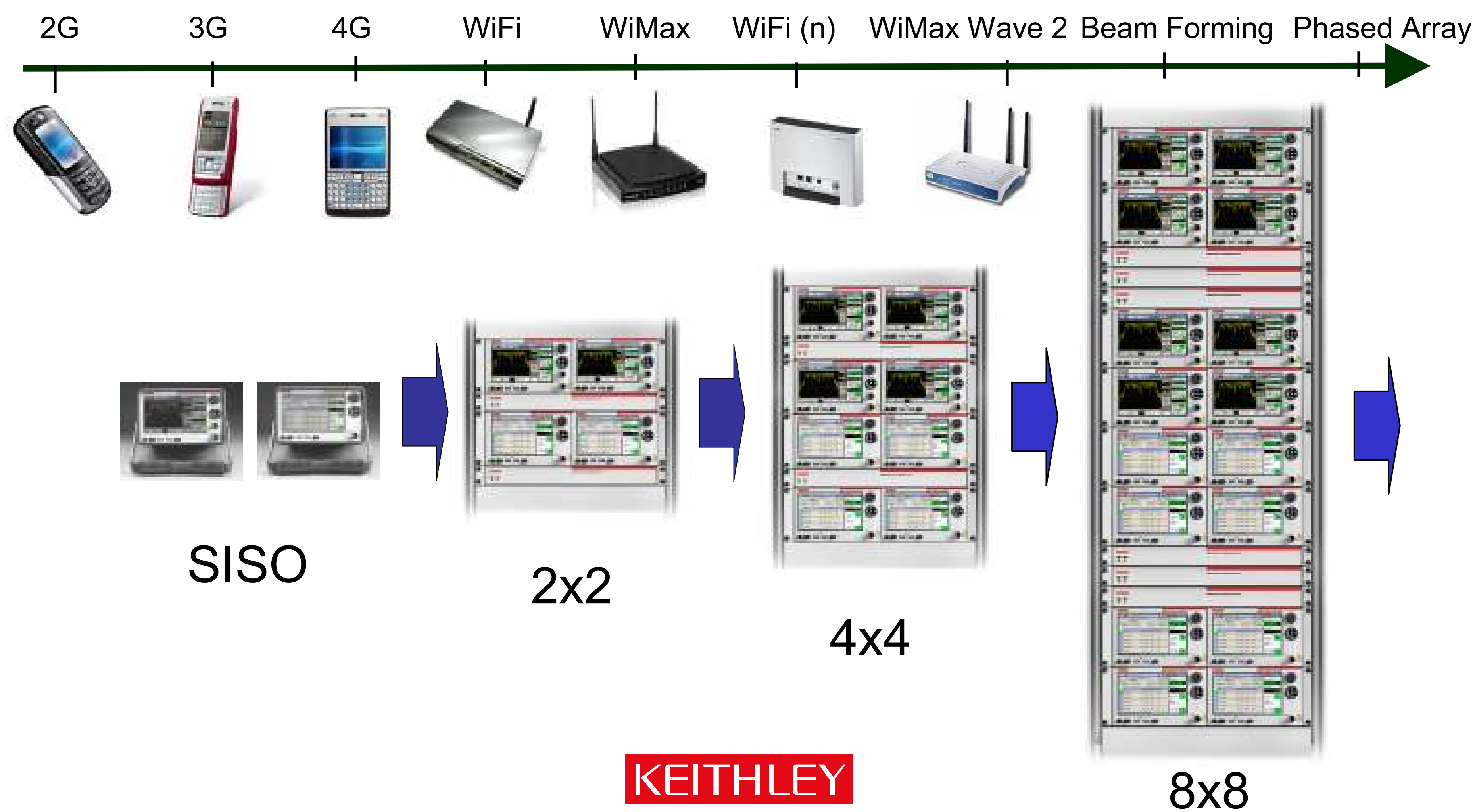
Technology Evolution



OFDM/MIMO Master Class
Understanding the physical layer principles of WLAN, WiMAX and LTE

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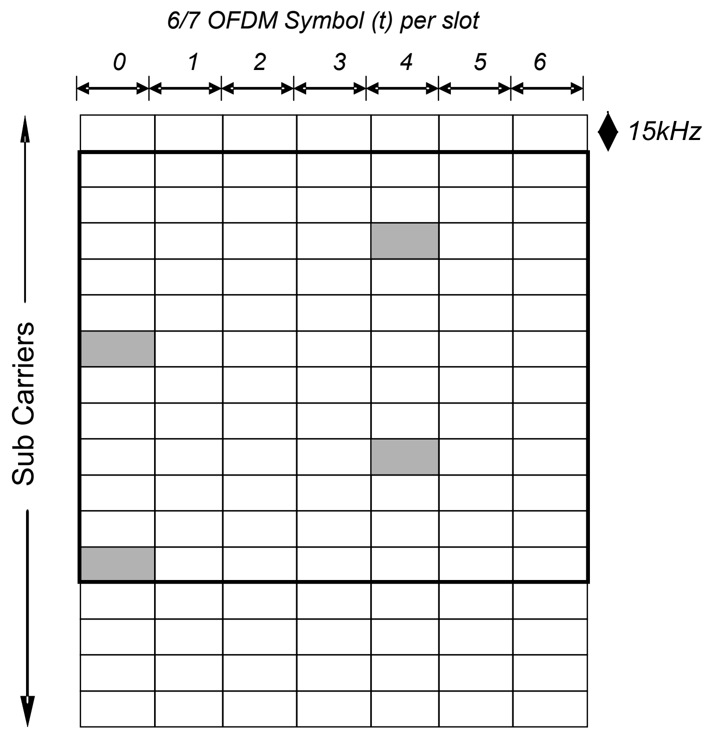
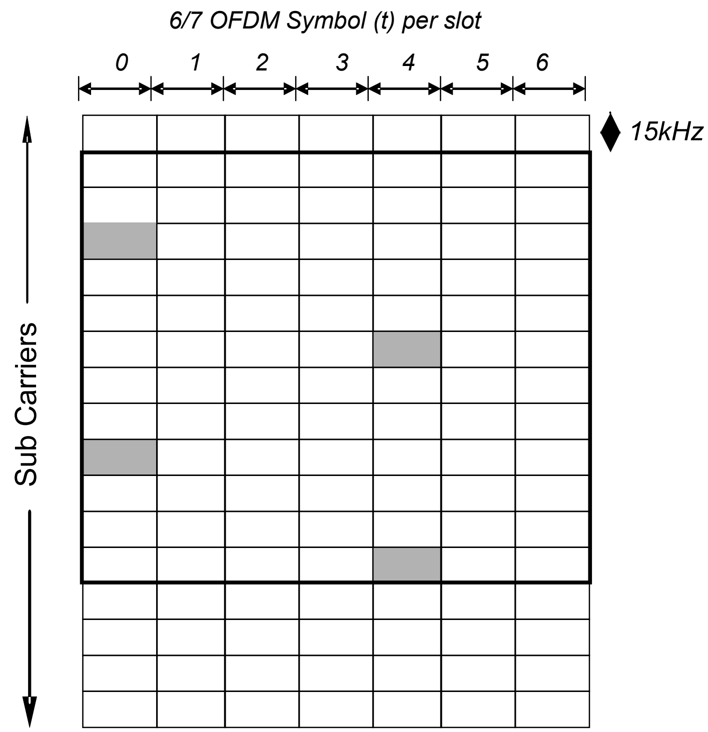
Back Up Slides

Time alignment LTE
2x2





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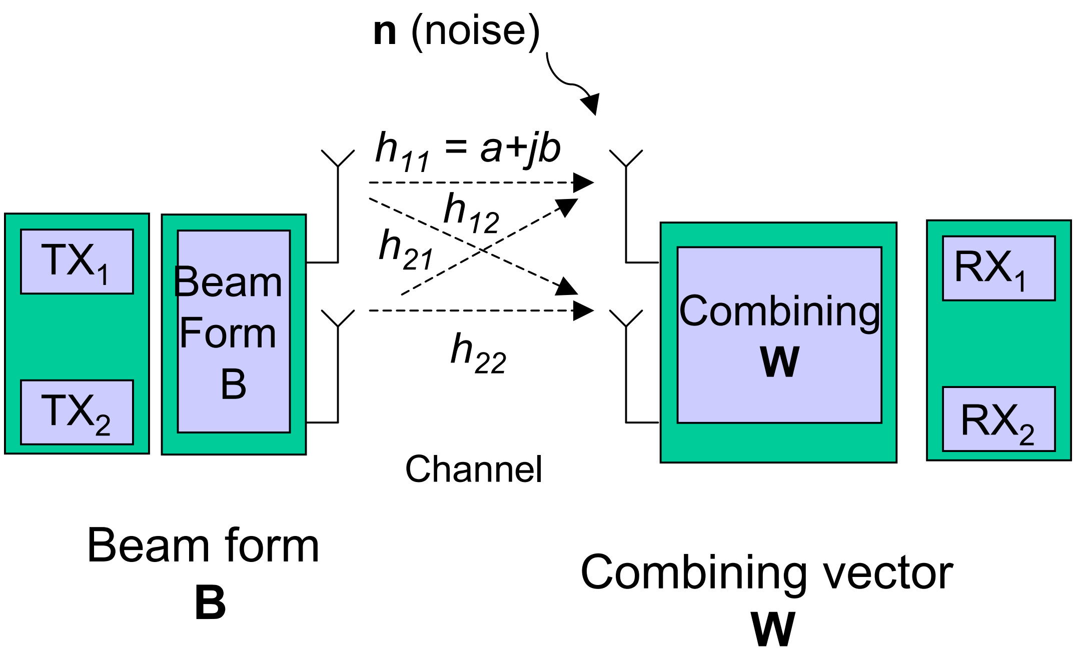
A more Complete Channel Model - leading to a more general solution



- The prior diagram suggests we should modify both the transmit and receive ends to maximize signal
- As shown with the diagram on the left, this is done with a beam forming matrix, B on the transmit side and a combining matrix W, on the receiver.
- Note:
  - If we only add W, we get noise enhancement.
  - If we only add B, the transmit power can be very high.

A bit more detail on "Do the math"

- Since we defined **H=U.D.V^H** Lets talk a bit more about that factorization.
  - We define $\mathbf{U}_{\mathbf{MxM}}$ and $\mathbf{V}_{\mathbf{NxN}}$ to be square, unitary matrices
  - In other words: $\mathbf{U}^{\mathbf{H}}.\mathbf{U} = \mathbf{V}^{\mathbf{H}}.\mathbf{V} = \mathbf{I}$. Where **I** is the identity matrix.
  - This also means, $\mathbf{U}^{\mathbf{H}} = \mathbf{U}^{\mathbf{-1}}$ and $\mathbf{V}^{\mathbf{H}} = \mathbf{V}^{\mathbf{-1}}$
  - **D** is the singular values matrix of size MxN whose elements appear in increasing order.
  - $\mathbf{V}^{\mathbf{H}}$ denotes Hermitian (transpose complex conjugate) ex;

$$a_{i,j} = \overline{a_{j,i}}$$

$$\mathbf{H} = \begin{bmatrix} 3 & 2-\mathrm{i} \\ 2+\mathrm{j} & 1 \end{bmatrix}$$

- The result, if **H** is complex, there is always a singular value decomposition with positive singular values.

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A bit more detail on "Do the math"

•Recall the decoded signal RX is what we want.

•Since we also defined $H=UDV^H$ we can rewrite the decoded signal equation as:

- $\mathbf{RX} = \mathbf{U^H}(\mathbf{H.V.Tx+n}) = \mathbf{U^H}(\mathbf{U.D.V^H})\mathbf{V.Tx+U^H.n}$

•Recall, $\mathbf{U^H.U} = \mathbf{V^H.V} = \mathbf{I}$. **I** is the identity matrix. So now,

- $\mathbf{RX} = \mathbf{D.TX} + \mathbf{U^H.n}$

•Result: no noise enhancement $|\mathbf{U^H}|=1$ and since **D** is diagonal, decoded signal is decoupled. In other words, we have orthogonality.