

An Introduction to Orthogonal Frequency Division Multiplex Technology

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Commercial radio technology has reached an inflection point. The communications market and the underlying technology that provides voice and data services are evolving. Customers are always expecting higher wireless bandwidths and service providers want to sell high value services beyond voice. That's a market given; however, recently the cost of the digital signal processing technology required to deploy high bandwidth broadband wireless systems has dropped to a point where it can now be used in the variety of commercial communications devices—the phones, PDAs, and the laptops we have become so dependant on.

The technology of choice for this broadband connection is based on a modulation scheme called Orthogonal Frequency Division Multiplex.

Agenda

- **Part One – OFDM and SISO radio configurations**
 - Why use OFDM?
 - SISO – Single Input Single Output Radio Topology
 - Digital Modulation Overview
 - Multi-path Issues
 - OFDM and WLAN
 - OFDMA and WiMAX
 - Test Equipment Requirements
- **Part Two – OFDM and MIMO radio configurations**
 - MIMO – Multiple Input Multiple Output Radio Topology
 - MIMO and WLAN
 - MIMO and WiMAX
 - Test Equipment Requirements
- **Conclusion**
 - Technology Overview and Test Equipment Summary

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You'll find OFDM technology used in two types of radio configurations. We'll examine SISO—Single Input Single Output—in the first part of the seminar and MIMO—Multiple Input and Multiple Output—in part two. SISO means we have one transmitter and one receiver – the configuration that is used in all commercial communications devices today. We're going to explore why OFDM has many benefits over other radio technologies, and we'll examine a SISO radio and how OFDM technology can overcome multi-path problems. Finally, we'll look at two practical implementations of SISO OFDM in WLAN and WiMAX and examine their structure and, of course, how to measure them.

In the second part, we'll look at how OFDM technology is used in Multiple Input Multiple Output radio configurations, we'll look at a MIMO radio block diagram and see how it applies to WLAN as part of the 802.11n standard, and for WiMAX as part of the Wave 2 deployment.

Why 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

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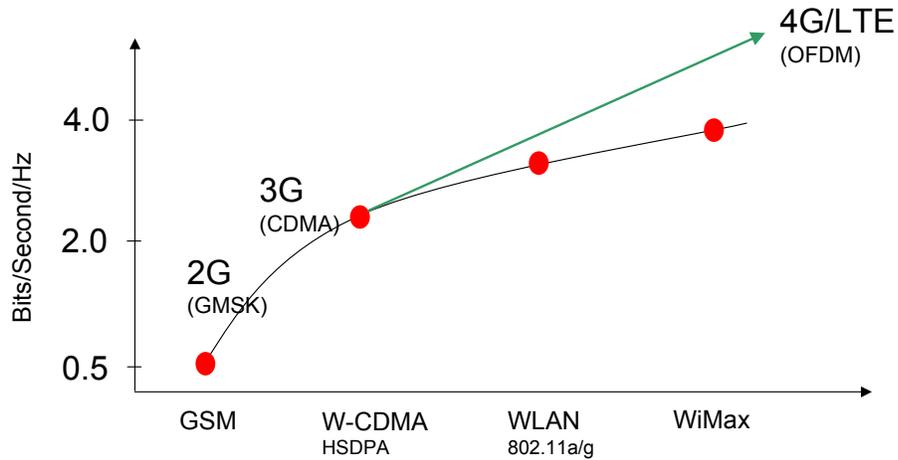
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OFDM is efficient. We'll examine how it compares to GSM and W-CDMA on the next slide. It's also very resistant to RF interference – this is important as WLAN is deployed in the unregulated ISM band. Finally, OFDM works really well in harsh multi-path environments.

Spectral Efficiency – OFDM



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This graph is a comparison of the spectral efficiency of the leading cellular technologies and how they compare to WLAN and WiMAX. Fourth Generation technology, often referred to as LTE, or the Long Term Evolution of wireless for cellular devices will use OFDM.

System Standards using OFDM

Wireless

- IEEE 802.11a, g, n (WiFi) Wireless LANs
- IEEE 802.15.3a Ultra Wideband (UWB) Wireless PAN
- IEEE 802.16d, e (WiMax), WiBro, and HiperMAN Wireless MANs
- IEEE 802.20 Mobile Broadband Wireless Access (MBWA)
- DVB (Digital Video Broadcast) terrestrial TV systems: DVB-T, DVB-H, T-DMB and ISDB-T
- DAB (Digital Audio Broadcast) systems: EUREKA 147, Digital Radio Mondiale, HD Radio, T-DMB and ISDB-TSB
- Flash-OFDM cellular systems
- 3GPP UMTS & 3GPP@ LTE (Long-Term Evolution), and 4G

Wireline

- ADSL and VDSL broadband access via POTS copper wiring
- MoCA (Multi-media over Coax Alliance) home networking
- PLC (Power Line Communication)

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Even today, OFDM is very pervasive. In addition to its use in Wireless LAN and WiMAX, it is used for digital video and digital radio transmissions.

Why OFDM? Resistance 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).**

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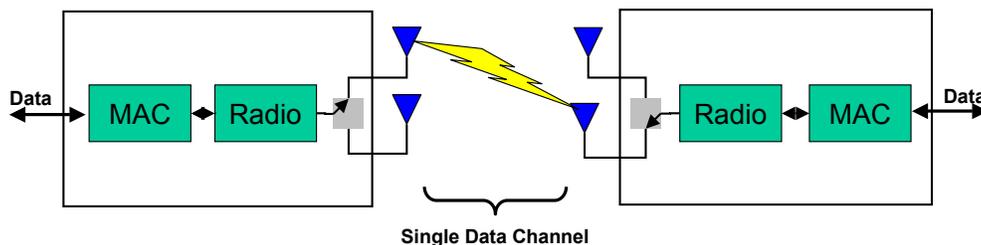
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A lot of the technologies I mentioned in the last slide are deployed in the unregulated Industrial Scientific Medical band. The ISM band is where many unregulated devices transmit – it includes everything from microwave ovens and cordless phones to broadband Wireless LANs.

What is SISO? Single-Input Single-Output

Traditional – SISO Architecture



- One radio, only one antenna used at a time (e.g., 1 x 1)
- Antennas constantly switched for best signal path
- Only one data “stream” and a single data channel

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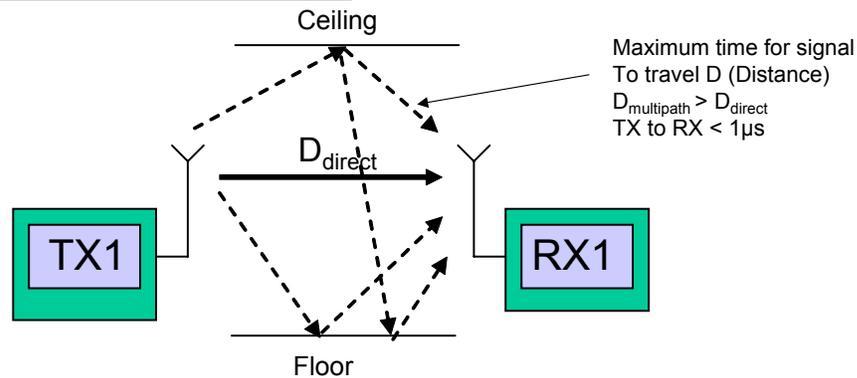
Here we can see a SISO radio. Look familiar? It has one transmitter and one receiver. This configuration is used in almost all radio products today. Sometimes we may have an extra antenna for diversity. However, we have a single up converter and down converter, single demodulator/modulator in the radio and a single data stream in the higher levels of the product’s communications stack.

The Multi-Path Problem

Example: Bluetooth Transmitter & Receiver

Symbol Rate = 1MSymbols/s
Symbol Duration = $1/1E6 = 1\mu\text{s}$

Maximum Symbol Delay < $1\mu\text{s}$



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Multi-path adds another layer of complexity to Error Vector Magnitude measurements. In this example, we can see the Bluetooth signal has a symbol rate of one mega symbol per second. That means that the receiver will expect a specific symbol within a window of one microsecond. If multi-path delays the signal by more than one microsecond, the receiver will receive the symbol in the next symbol period, causing a significant symbol error.

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 - 3.14Msamples/s

Bluetooth - 1Msamples/s

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

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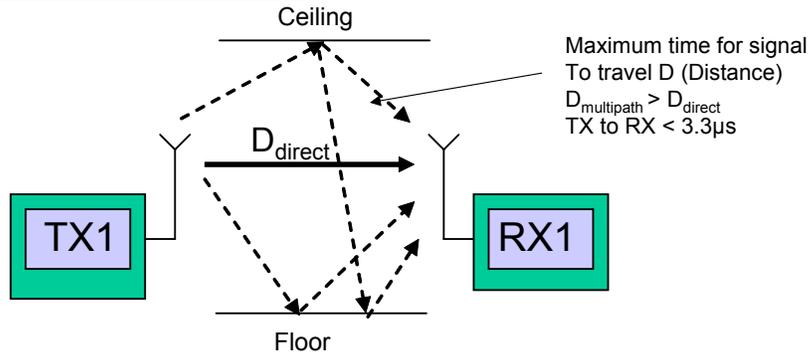
Most modern communications systems use a single carrier to transmit a single symbol at a time. Data throughput is achieved by increasing the symbol rate. However, as we demonstrated in the last example, the faster the symbol rate, the shorter the time the symbol ‘waits’ for the received symbol. High symbol rates work well if there is a direct path, such as used in line of site microwave links; however, most communications systems operate in environments where multiple signal paths can exist.

Slow the Symbol Rate

Reduce the Previous Example's Symbol Rate by a Third

Symbol Rate = 300kSymbols/s
Symbol Duration = $1/300 = 3.3\mu\text{s}$

Maximum Symbol Delay < $3.3\mu\text{s}$

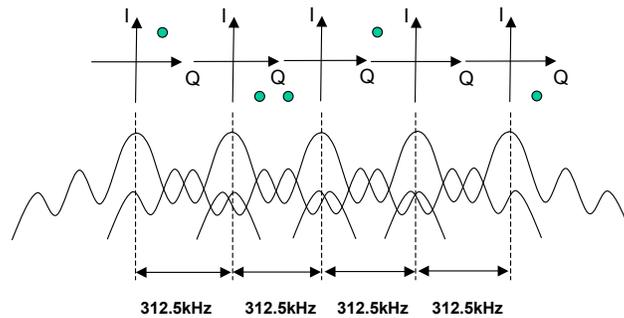


But now we have reduced the data throughput!



In this example, we've slowed the symbol rate by a third, thus improving the maximum time for the signal to travel. However, by using just a single carrier scheme, we've now reduced the data throughput.

Improve the throughput -
use more than one carrier!

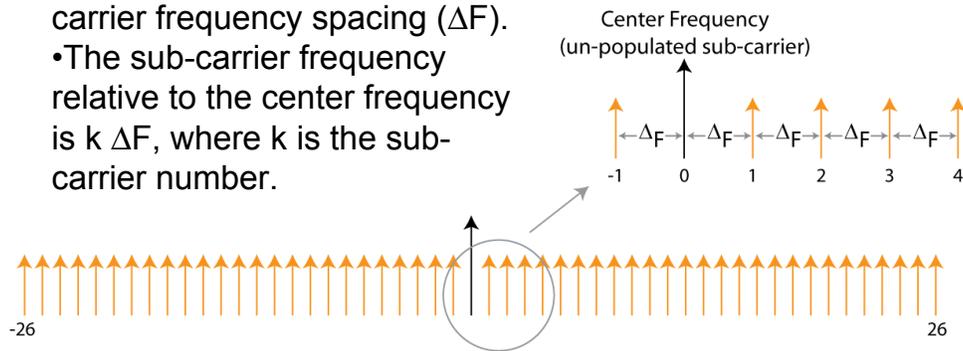


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Instead of transmitting a single symbol at a time, OFDM transmits multiple symbols simultaneously on a number of carriers. This is the Frequency Division Multiplex component. The sub-carriers are distributed in carefully chosen multiples of frequency so that they are “orthogonal,” so that the closely adjacent sub-carriers don’t interfere with each other.

Sub-carrier Spacing

- The sub-carriers are spaced at regular intervals called the sub-carrier frequency spacing (ΔF).
- The sub-carrier frequency relative to the center frequency is $k \Delta F$, where k is the sub-carrier number.



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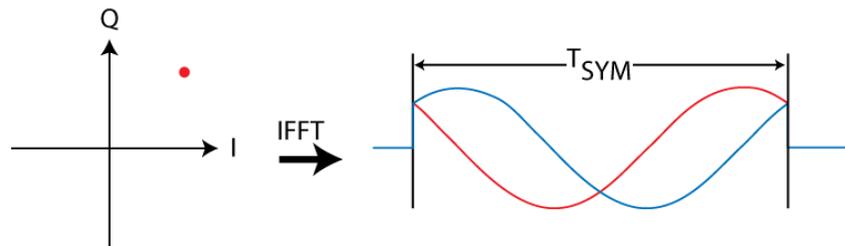
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Each carrier within the modulation scheme is referred to as a sub-carrier. The sub-carriers are spaced at regular intervals called the sub-carrier frequency spacing (ΔF). The sub-carrier frequency relative to the center frequency is $k \Delta F$ where k is the sub-carrier number.

Symbol to Waveform

Traditional – Serial Symbol Transmissions

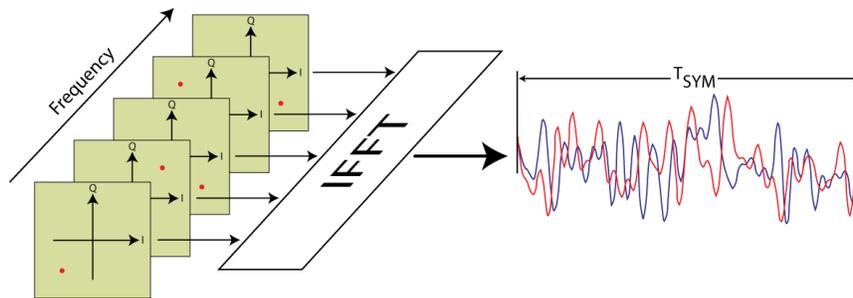
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In traditional systems, we transmit all symbols serially. We achieve data throughput by increasing the symbol rate. We have already learned that this method is not very tolerant of multi-path interference.

Inverse Fast Fourier Transform



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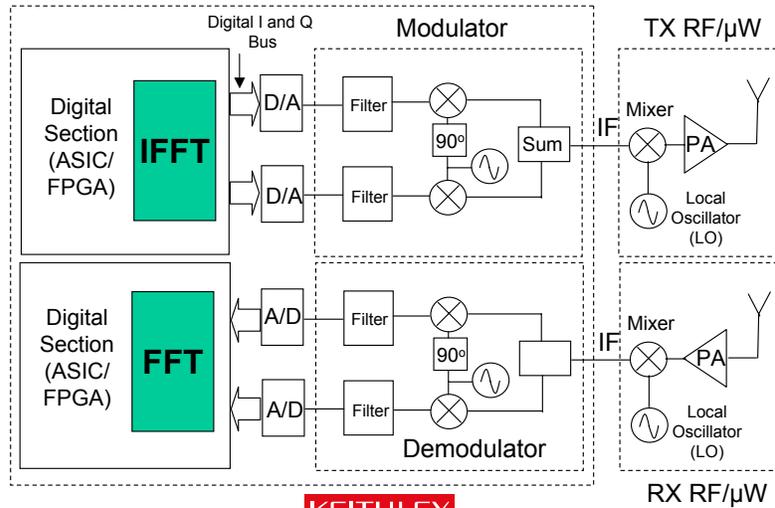
OFDM uses the Inverse Fast Fourier Transform as a tool. A fast stream of data is broken down into many slower parallel data streams, and fed into an IFFT to have those slower streams distributed over the bandwidth as individual “sub-carriers.” The lower data rate of each of the sub-carriers allows a guard band to be added to the symbols being sent so that the guard band time is long enough to prevent most multi-path reflections from causing any inter-symbol interference.

Fundamentally, the objective is to slow down the symbol rate, while maintaining a high data rate by using an Inverse FFT to facilitate the transmission of slow symbols in parallel rather than fast symbols in serial as discussed in the previous slide.

Each sub-carrier symbol contributes to the time domain waveform, but can be separated by the FFT at the receiver.

We call the time domain waveform consisting of all sub-carrier contributions over the symbol duration (T_{SYM}) an OFDM symbol.

The OFDM Radio



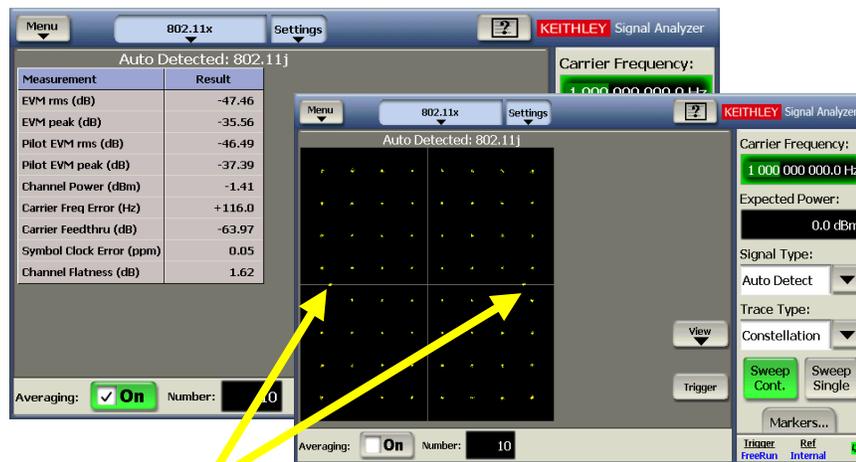
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This is a diagram of a complete OFDM radio. In the top transmitter section, the data that was broken down into many slower streams of data and then modulated flows into the IFFT, which converts those streams into different frequency components (sub-carriers) of the transmitted signal bandwidth. On the bottom, you can see the FFT that takes those individual sub-carriers and then (with the help of demodulation schemes) converts them back into those slower data streams. Those slower data streams are then reassembled into a single fast data stream.

Key Measurements: Constellation and EVM



Pilot Symbols

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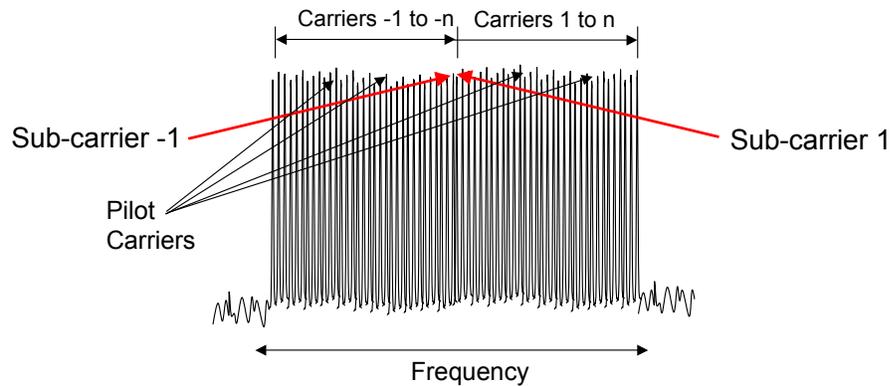
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Here are some of the key measurements that OFDM users commonly look at. EVM (Error Vector Magnitude) is one of the most frequently used measures of signal quality. Here, you can see the EVM measurement as part of a table of measurements that are made automatically by our signal analyzer. In the second plot, you can see a constellation diagram that is commonly used for observing the quality of the modulation, including the pilot symbols that act as part of the modulation alignment and calibration for the receiver.

Data and Pilot Carriers

- Used as reference for phase and amplitude to demodulate the data in the other sub-carriers.



This diagram shows how the sub-carriers in an OFDM signal are numbered. This also shows the “pilot carriers,” which are known signals that the receiver can use as reference points for leveling and equalizing that part of the bandwidth, to help compensate for signal path variations.

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 Bandwidth 312.5kHz**
- **Packet Structure – Preamble – Header – Data Block**
- **Sub-carrier Modulation Types - BPSK, QPSK, 16-QAM or 64-QAM**

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Let's now examine the characteristics of a WLAN signal. Within a 16.25MHz bandwidth there are 52 carriers spaced 312.5kHz apart. Carriers 7 and 21 are the pilots.

WLAN Summary

- **WLAN implies Wireless LAN compatible with one the IEEE 802.11 sub standards. It is what you have in your laptop.**
- **WiFi is an industry consortium that defines a required subset of 802.11 to ensure better operation between different vendors' equipment.**
- **EWC is an industry consortium that took the unfinished N standard, agreed upon a version, and is attempting to field solutions prior to 802.11n ratification.**

802.11	Means
a	54Mbps OFDM, 5.9 GHz Band, 20 MHz channels
b	11Mbps CCK, 2.4 GHz (Legacy, not OFDM)
g	What you can easily buy now – same as a , but at 2.4 GHz
j	Japanese version of g that uses half the sample rate.
n	<ul style="list-style-type: none"> • Not a finished standard yet. • Like g, but up to 600Mbps • OFDM • MIMO • 20 & 40 MHz channels

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WLAN is defined by the IEEE 802.11 standard. WiFi is an industry consortium that monitors interoperability. The original WLAN standard is 802.11b, which is not based on OFDM. A and g are the same; a works in the 5GHz ISM band and g works in the 2.4GHz ISM band. J is a slower symbol rate version of g for the Japanese market and n is based on MIMO technology, which we'll look at in the second part of this seminar.

WLAN OFDM — Test Equipment Requirements

- **Frequency Coverage up to 5.8GHz**
- **Modulation Bandwidth up to 16.25MHz**
- **802.11a/g Signal Creation and Analysis Capability**



Keithley Instruments' Model 2820 VSA and Model 2920 VSG have a frequency range of 6GHz and 40MHz bandwidth as standard.

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Test equipment for WLAN must have a frequency range up to about 6GHz and have the ability to modulate or demodulate OFDM signals with a bandwidth of up to 16.25MHz for all types apart from 802.11n, which has a maximum bandwidth of 40MHz.

OFDM to OFDMA

- **OFDM as a modulation technique is not multi user – all sub-carriers in a channel are used to facilitate a single link.**
- **OFDMA assigns different groups of sub-carriers to different users in a fashion similar to CDMA.**

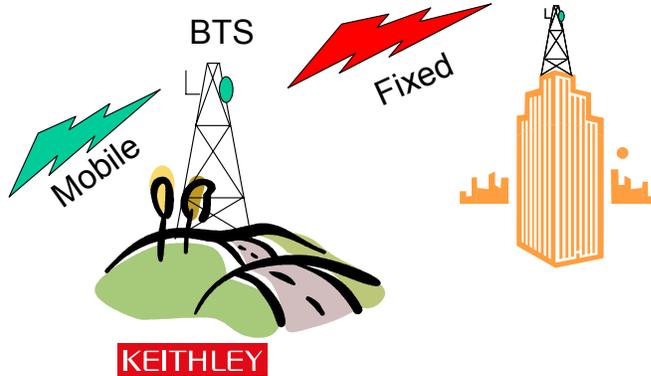
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So far we've looked only at OFDM. In OFDM, all the carriers are used to facilitate a single link. OFDMA or Orthogonal Frequency Division Multiple Access can assign different groups of sub-carriers to different users.

Wi-MAX 802.16d/e OFDMA

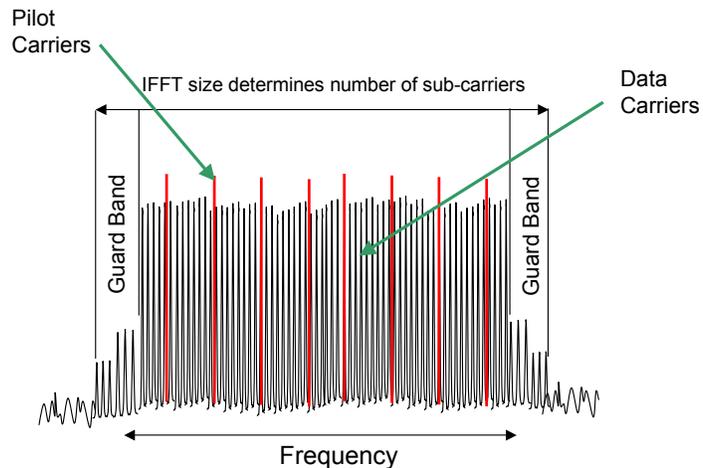
- **Worldwide Interoperability for Microwave Access**
- **Fixed – 802.16d, backhaul applications**
- **Mobile – 801.16e, enhanced data services mobile applications.**

WiMAX enhanced
Mobile Devices



WiMAX or Worldwide Interoperability for Microwave Access uses OFDMA. There are two major variations of WiMAX, fixed and mobile. Mobile facilitates the link between a mobile device and a call, while Fixed facilitates the backhaul link. They also don't need to be used together; fixed link could be used to link a number of buildings on a campus, for example.

RF Characteristics 802.16e Mobile

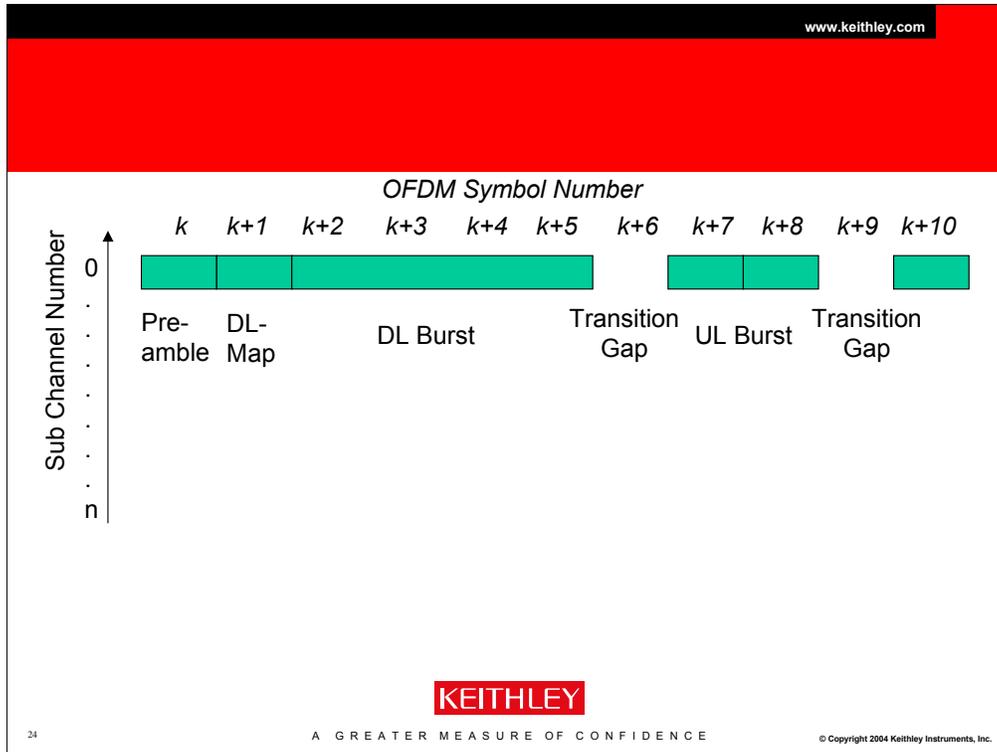


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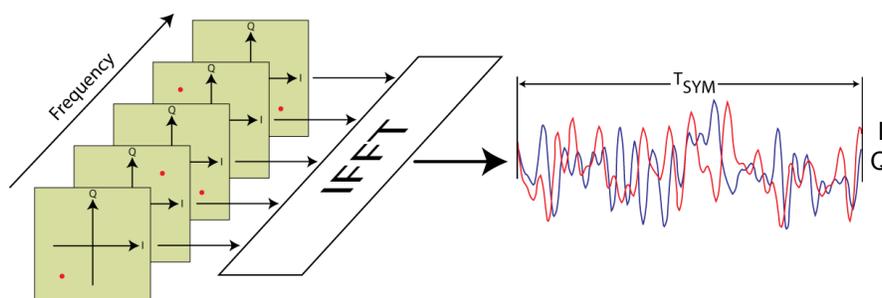
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A sub-carrier spacing of 10.94kHz implies that 128, 512, 1,024, and 2,048 FFTs are used when the channel bandwidths are 1.25MHz, 5MHz, 10MHz, and 20MHz, respectively.



Each time increment is referred to as an OFDMA symbol. In this drawing, a symbol is represented in the same way as with any digital communication system—transitioning from symbol to symbol at a specified symbol rate. Note, although we call this time increment the OFDM symbol, not just the symbol time. As with any digital radio, the symbols are structured in time (i.e., we begin with a preamble, then a down link map, some information we wish to receive [DL Burst, for now, we’ll consider a burst as some consecutive symbols]), a transition gap, then the uplink burst, followed by another transition gap before the cycle starts afresh. The 802.16e standard allows either the use of time division duplex or frequency division duplex between the up and the down link burst.

Figure One: Transmitting Multiple Symbols Simultaneously



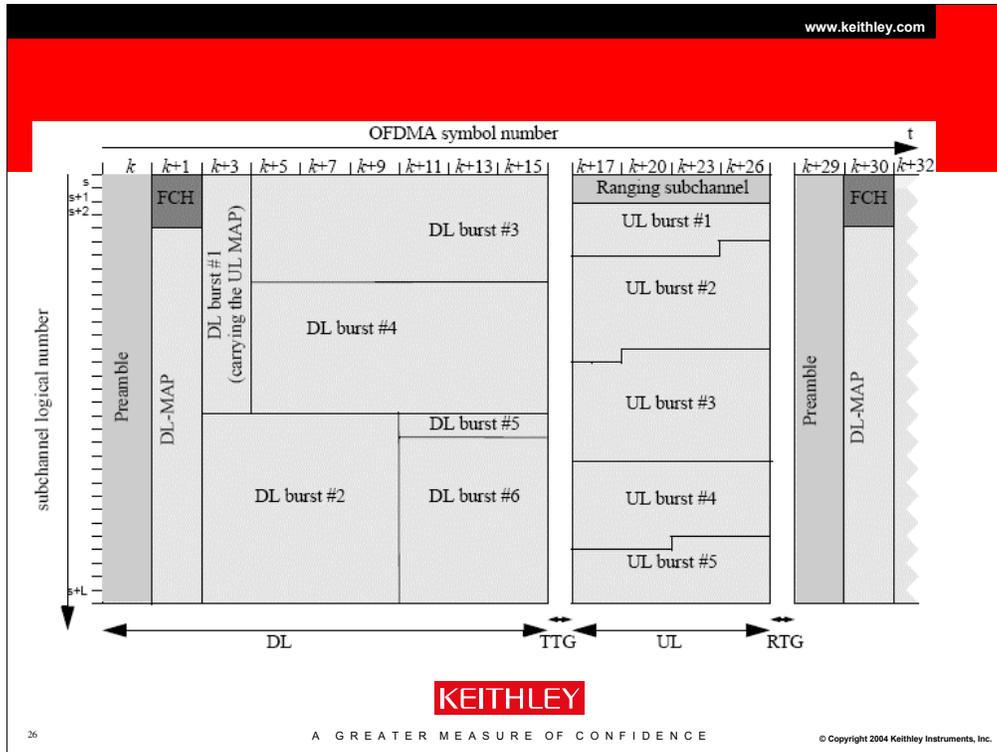
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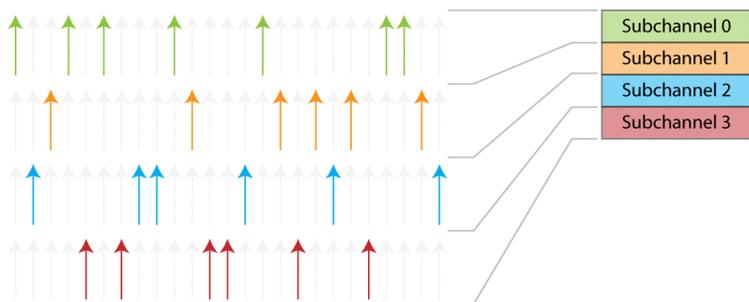
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As we said earlier, OFDM transmits many slow symbols in parallel using an inverse FFT. The larger the IFFT, the more symbols you transmit simultaneously using more carriers. Therefore, each ‘instance in time’ or ‘OFDMA Symbol time’ of the transmission has multiple symbols and each symbol can have differing types of data throughput, depending on the modulation type used to create the symbol. In Figure 1, each symbol was created using QPSK, although 16 or 64 QAM could be employed.

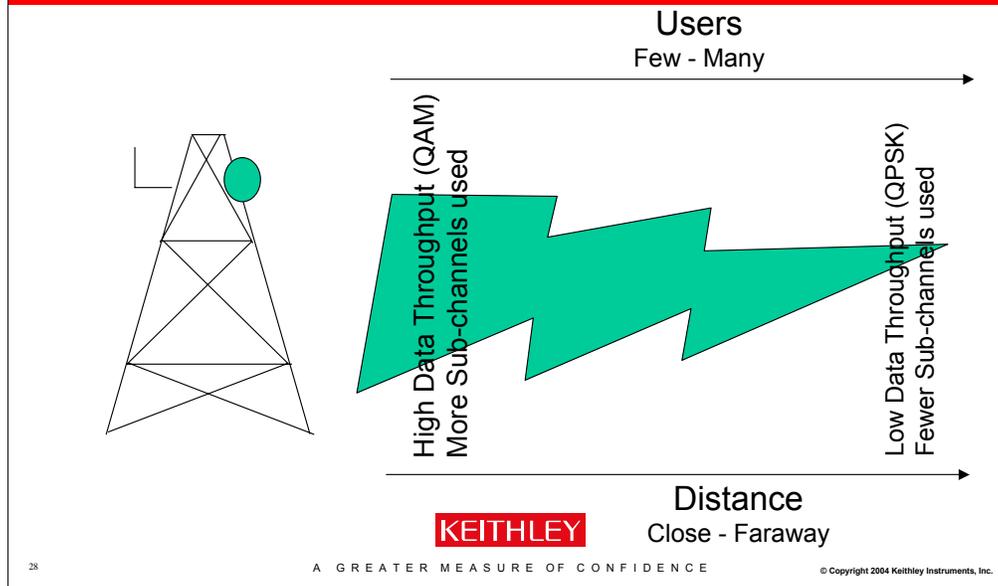


Therefore, in every OFDMA symbol period, we transmit multiple symbols in parallel. In fact, we can transmit between 128 and 2048 symbols per OFDM symbol period. The vertical axis is labeled ‘sub-channel number.’ The sub-channels are not actually physical channels, but groupings of our ‘parallel symbols’ that are transmitted every OFDM symbol period. How the 802.16e signal is constructed and behaves over time is defined in the symbol map. The symbol map is essentially a two by two matrix of symbols, the vertical are the parallel symbols, and the horizontal represents how these symbols behave over time.



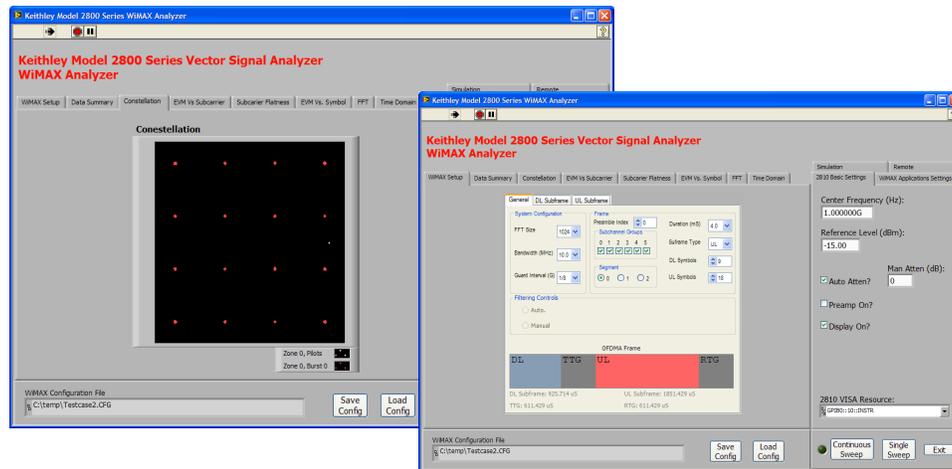
The next step is to construct the physical makeup of the signal. Each sub-channel is assigned an actual carrier in the frequency domain – the carriers don't have to be adjacent or even logically grouped. Each carrier is modulated with the appropriate modulation and the signal is transmitted.

Link Characteristics



WiMAX is a dynamic system. The amount of data transferred is a function of the modulation type and symbol rate on each set of sub-carriers. If the link quality is good, a high throughput modulation type is used, such as QAM and most of the bandwidth is consumed, thus limiting the number of users on the system. As the user moves further away from the base station, the signal quality declines and the ability to maintain a high throughput link diminishes. A lower throughput modulation scheme such as QPSK would then be employed. This of course does not require a large group of sub-carriers, so the system can support more users.

Measurements



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In this measurement, we can see a packet structure containing downlink and uplink data, DL and UL. Each is separated by a transition gap. The UL contains more data and would use a complex modulation format such as QAM. This what we have chosen to demodulate. We could also demodulate the DL portion, which is QPSK. We can even demodulate both and display a hybrid of the two modulation types in the constellation.

WiMax Summary

- This is metropolitan area networking – Internet to your home, office, or car.
- Implies one of the 802.16 standards
- Very similar in concept to 802.11, but the demands of multiple simultaneous users (possibly mobile) make the implementation much more complex.
- Uses scheduled transactions to ensure all paying users get access. You can get frozen out with WiFi.
- Stands for **Worldwide Interoperability for Microwave Access**

802.16	Means
802.16-2004 (aka 802.16d)	Fielded system for fixed-point access (to the home or office) <ul style="list-style-type: none"> • OFDMA (OFDM multiple access) • 2-11GHz (no regulatory approval above 5.9GHz) • Practical rate: 10 Mbps over 2km
802.16e-2005	The current version of the standard, upgraded to include mobile wireless. <ul style="list-style-type: none"> • SOFDMA (Scalable OFDM Multiple Access) • SOFDMA interoperates with OFDMA, but requires new equipment. • Adds MIMO

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We have two major type of WiMAX, d for fixed applications and e for mobile applications.

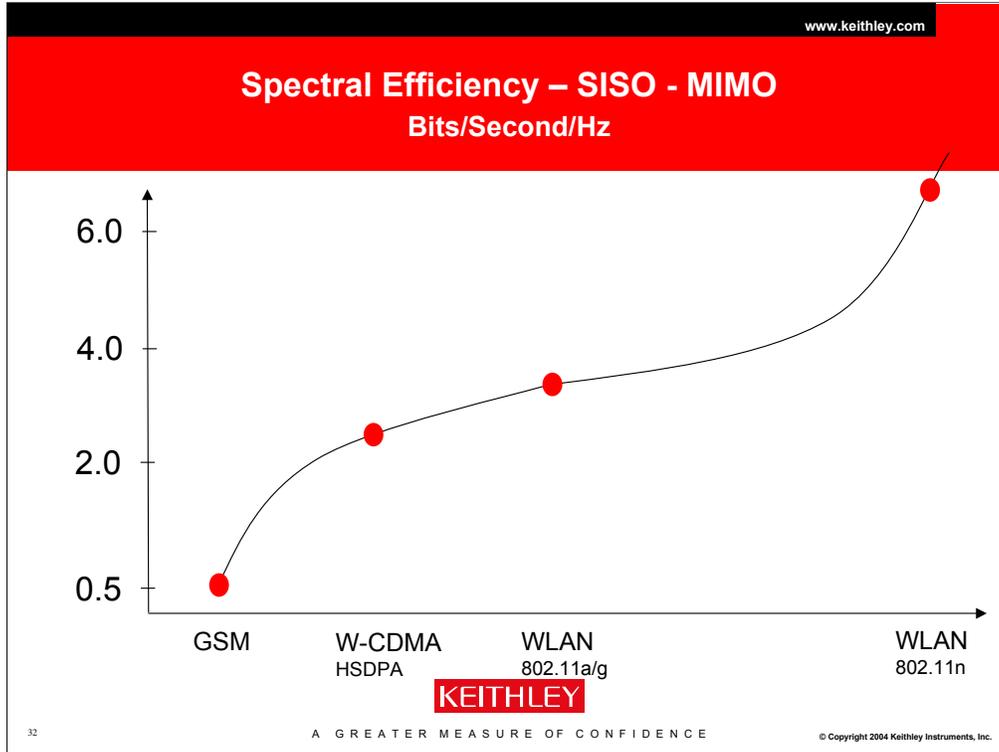
802.16 is similar to 802.11. The major difference is that 802.16 supports simultaneous users by using different combinations of sub-carriers and modulations types both to balance the load between users and to maintain a working link, even when signal conditions worsen.

OFDM/A to MIMO

- **MIMO uses multiple transmitters and receivers that are modulated with OFDM/A.**
- **Both WLAN (802.11n) and WiMAX (802.16e) have MIMO configurations.**

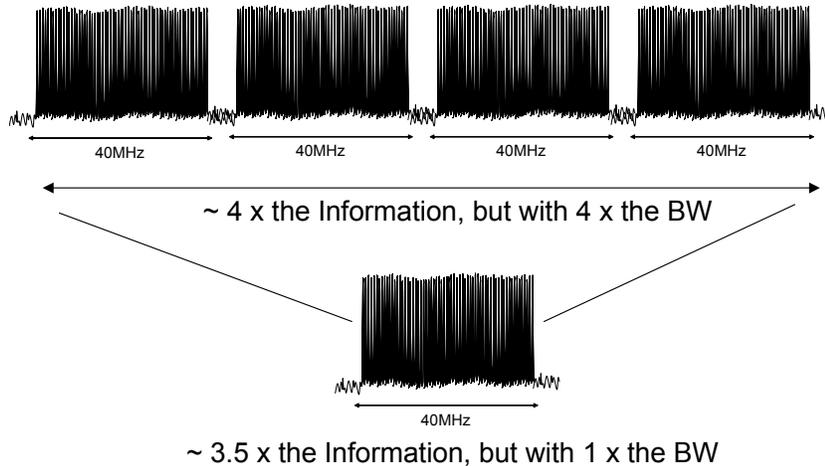
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Finally, we can enhance the performance of OFDM-based radios by employing Multiple Input Multiple Output technology. Both WLAN and WiMAX have MIMO-based variants.



MIMO takes spectral efficiency to a new level. But with that efficiency comes a higher level of complexity.

Why Is MIMO Different from Standard OFDM?



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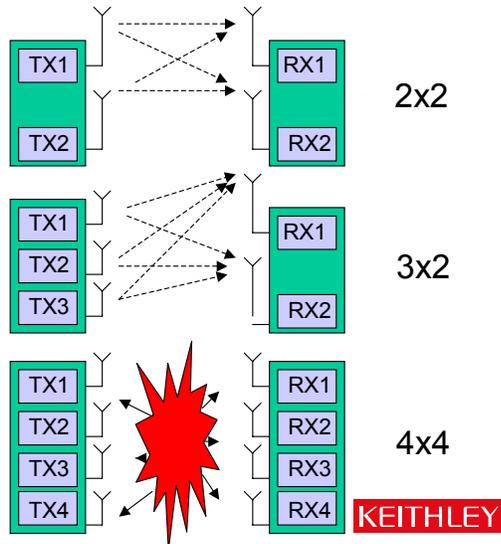
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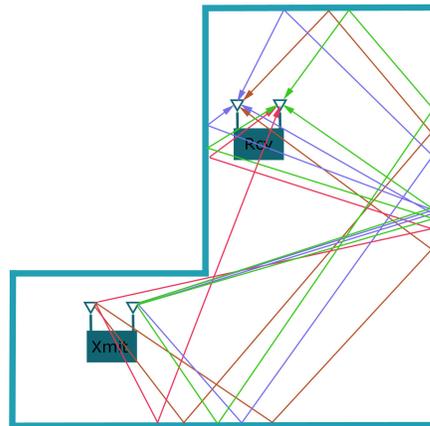
MIMO is four separate radio transmissions, each with a data stream. With 4 different radios, you'd get 4 times the bandwidth - if they all transmitted on separate frequencies. Of course, that wouldn't be very spectrally efficient. MIMO transmitters transmit multiple OFDM signals on the same channel. The challenge at the receivers is to be able to get back to four independent radio signals. Therefore, MIMO allows the same bandwidth to be used multiple times, allowing a higher spectral efficiency. You can see that when you compare the efficiency of 802.11a/g wireless LAN signals without MIMO to the 802.11n wireless LAN signals with MIMO.

MIMO Radio Configuration



Here are some typical MIMO configurations. A 2x2 system contains two transmitters and two receivers, a 4x4 has four transmitters and four receivers. Many commercial WLAN devices today employ a 3x configuration of 3 transmitters and 2 receivers.

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!

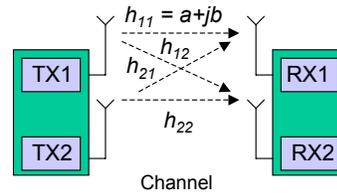
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For example, if a MIMO transmitter, transmits two signals on the same frequency, each signal takes a slightly different path to the receiver and each signal's characteristics diverge from the originally transmitted signals, mainly due to multi-path distortion. Two receivers receive a mixture of both the original signals. As the two receivers are independent, we can perform a simultaneous equation on the two received signals and solve for the transmitted symbols.

Mathematically Model the Channel

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

y = Receive Vector
x = Transmit Vector
H = Channel Matrix
n = Noise Vector

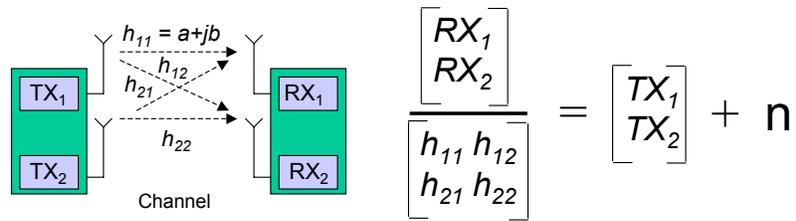


$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

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The transmitter transmits a known signal in the form of a header. The receiver then uses this to build a model of the channel, which is represented by H . When the data is transmitted, the receiver divides through by the channel model (H) to get as close as possible to the original vectors given the transmission error represented by the noise vector (n).

Correct for Channel Effects



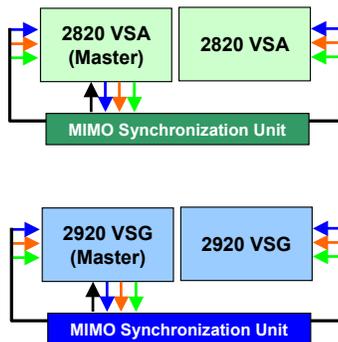
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Here, we see the full equation solving for the original symbols, with the added noise component. As each term contains an amplitude and phase component, it is important that the transmitters and receivers are phase and time aligned.

MIMO Instrument Requirements



Hardware

- All 28/2920 VSAs are identical standard units
- Flexibility to use 2820 VSAs as stand-alone generators
- User-definable instrument configuration setting
 - Stand-alone
 - MIMO Master
 - MIMO Slave

System

- Common LO and clock signals for all analyzers
- Master provides LO, 100MHz digital clock, and Trigger Sync to MIMO Synchronization Unit
- MIMO Sync. Unit distributes a common LO, common 100MHz clock, and synchronized Trigger to all units
- Signal sampling alignment within ± 1 nsec

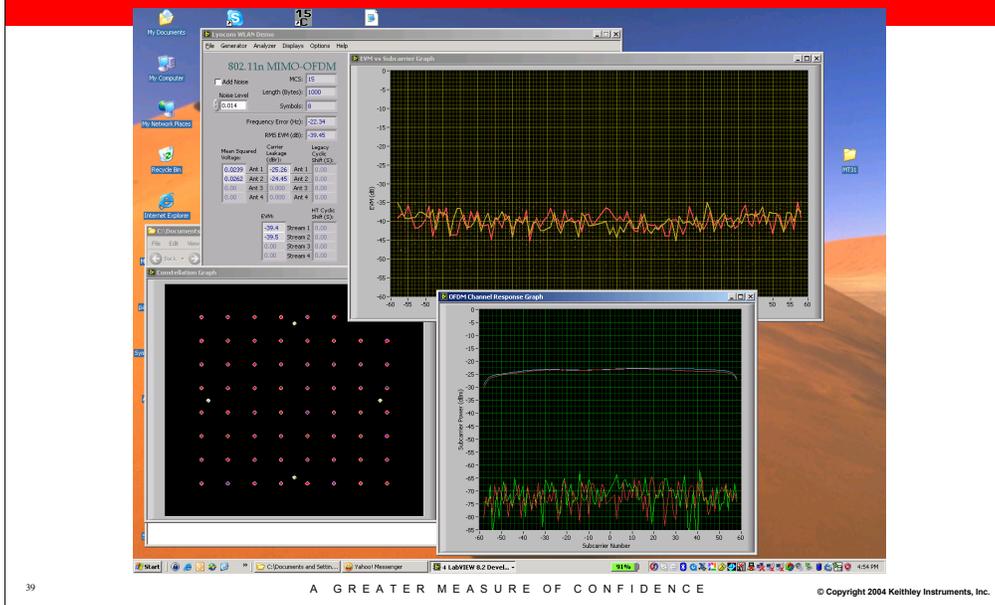
Form Factor

- 2820/2920: 3U high, $\frac{1}{2}$ -rack width
- MIMO Sync. Unit: 1U high, full-rack width

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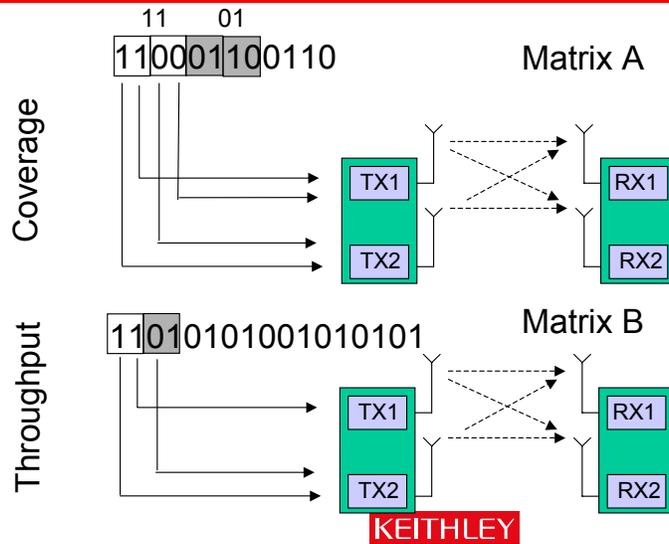
The Keithley MIMO system uses the Model 2895 MIMO Synchronization Unit to time and phase align standard vector signal generators and vector signal analyzers. A 2x2 can easily be achieved by using two Model 2920 Vector Signal Generators with the Keithley MIMO synchronization unit. Conversely, to independently receive MIMO signals, you need to synchronize two Model 2820 Vector Signal Analyzers. You can also synchronize 2x3, 3x2, 2x3, 2x4, 3x4 up to a maximum configuration of 4x4.

802.11n 2x2 Measurements



This slide shows three MIMO measurement on a two channel system. The upper measurement is EVM across the OFDM sub-carriers on each channel shown by the yellow and red plots. Underneath that we can see the channel frequency response of more than sixty sub-carriers. Finally, we see the constellation of a channel.

802.16e Matrix A and B Robust Symbols vs. More Symbols



In this simplified diagram, we can see the difference between Matrix A and B. A is optimized for coverage and B for throughput. For Matrix A, you transmit the same OFDM symbol on both transmitters. For Matrix B, you split the OFDM symbols into multiple streams, thus transmitting more symbols per OFDM symbol period. Matrix C, not shown in this slide, uses four transmitters and receivers and works much like Matrix B, with improved throughput.

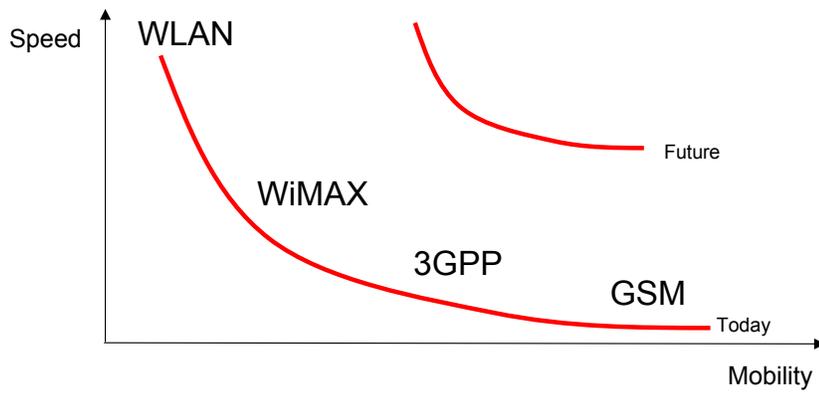
Conclusions



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The technology is moving at an unprecedented pace to provide high speed data everywhere. The primary mechanisms for this are OFDM modulation schemes combined with Multiple Input, Multiple Output radio configurations.

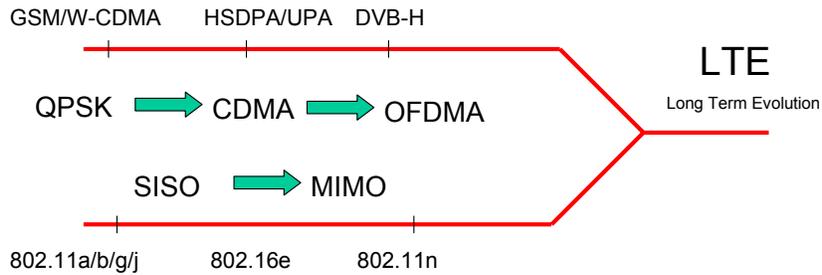
Speed vs. Mobility



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The WLAN and WiMAX standards provide a marked increase in data speed over traditional cellular-based communications technology. In the wireless future, both data rates and mobility will increase.

The Long Term Evolution of Wireless



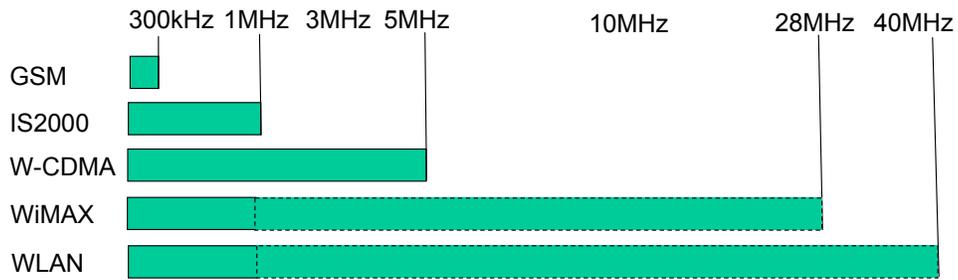
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Fourth-generation cellular systems or LTE (the Long Term Evolution) of cellular will be based on a combination of OFDM types of modulation and MIMO radio configurations. When choosing test equipment for testing today's radio standards, it's important to consider the evolution of wireless technology to ensure that your purchases are forward compatible.

Instrument Bandwidth Requirements



Keithley instruments have 40MHz BW as standard.

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One key consideration is bandwidth – WiMAX and WLAN have bandwidths that can exceed 25MHz. Keithley’s growing line of Wireless equipment has 40MHz of bandwidth as standard, creating a new price performance point in the marketplace.

Summary

- OFDM and SISO radio configurations
- OFDM and MIMO radio configurations
- OFDMA
- WLAN, WiMAX and the evolution to 4G

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