Advanced Measurement Techniques for OFDM- and MIMO-based Radio Systems:

Demystifying WLAN and WiMAX Testing

1st Revised Edition

A GREATER MEASURE OF CONFIDENCE

KEITHLEY

Keithley appreciates the assistance and diligence of the following, who contributed to and/or reviewed the content of this handbook: Mark Elo, Director RFI New Product Development; Robert Green, Senior Market Development Manager; Michael Millhaem, Principal RF Application Engineer; Dave Murray, RF Application Engineer; Steve Murray, Senior Industry Consultant; Douglas Olney, Senior DSP Engineer; and Carl Scharrer, Sales Account Manager.

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RF Measurement Notes

Orthogonal frequency division multiplexing (OFDM)

Orthogonal frequency division multiplexing (OFDM) is a form of digital modulation used in a wide array of communications systems. The following will explain what OFDM is, why it's important, where it's used, and what test instrumentation is required to measure it.

Perhaps we should first explain what is so special about OFDM. Three things stand out.

OFDM is spectrally efficient, carrying more data per unit of bandwidth than such services as GSM and W-CDMA. **Figure 1** shows 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 the Long Term Evolution (LTE) of wireless for cellular services, uses OFDM or OFDMA.

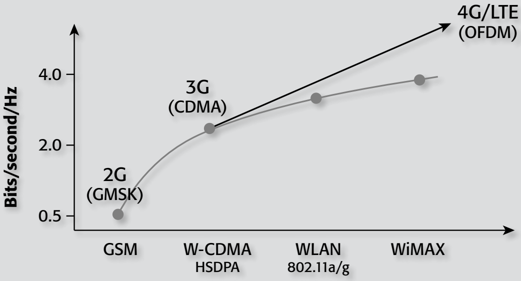


Figure 1. The spectral efficiency of the leading cellular technologies and how they compare to WLAN and WiMAX. Fourth Generation technology, often referred to as LTE, or the Long Term Evolution of wireless for cellular devices, will use OFDM.

OFDM tolerates environments with high RF interference. Some services that use OFDM — such as WLAN — operate in the unregulated ISM (Industrial Scientific Medical) bands, where they must co-exist with many unregulated devices, including analog cordless phones (900MHz), microwave ovens (2.45GHz), Bluetooth devices (2.45GHz), digital cordless phones (2.45GHz or 5.8GHz), and wireless LAN (2.45GHz or 5.8GHz).

Finally, OFDM works well in harsh multi-path environments, as we shall see.

The Multi-Path Problem

In traditional communication systems the more information you want to transmit, the more symbols you would send (higher data throughput is proportional to a higher symbol rate). **Figure 2** shows a Bluetooth signal with a symbol rate of 1M symbols per second. That means that the receiver will expect a specific symbol within a window

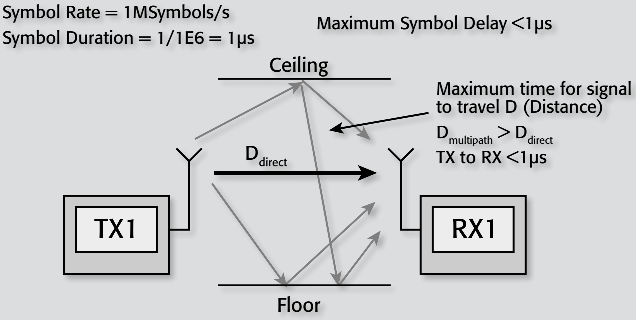


Figure 2. If the difference in path length between direct and reflected paths exceeds 1 microsecond, the receiver will receive the symbol in the next symbol period.

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.

The faster the data rate, the higher the chance that multi-path will cause Inter Symbol Interference (ISI). An obvious way to reduce the error rate would be to slow down the symbol rate; each symbol would last longer and be more resistant to multipath. Unfortunately, this reduces the data rate. What's needed is a way to slow down the symbol rate without slowing the data rate — a seemingly impossible task. The answer to the puzzle is OFDM.

OFDM transmits a large number of closely-spaced carrier waves, each modulated with a different signal. **Figure 3** shows that the individual I and Q input signals are translated into separate carriers. The symbol rate for each carrier is low, making it

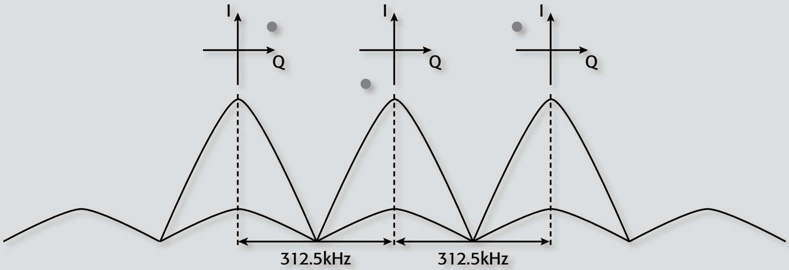


Figure 3. Instead of transmitting a single symbol at a time, OFDM transmits multiple symbols simultaneously on a number of carriers. This is the Frequency Division Multiplex component. The subcarriers are distributed in carefully chosen multiples of frequency so that they are "orthogonal" and the closely adjacent subcarriers don't interfere with each other.

resistant to multipath, but because there are so many carriers the overall data rate is high. Adjacent carriers are in phase quadrature with each other, which keeps crosstalk between them to a minimum without requiring a bank of narrow-band filters. Each transmission of a set of parallel symbols on multiple carriers is called an OFDM Symbol, which is represented in **Figure 5** by the time, T_{sym}.

Even with a slower symbol rate, multi-path still exists and provision for it is made with OFDM. In **Figure 5** we see that the parallel symbols passed through the IFFT create the time domain waveform of period T_{sym}. This signal is periodic – note that during the symbol period we see only one cycle of the signal, which means that we can make a copy of the last part of the wave form and attach it to the beginning without any discontinuity in the signal. This is a perfect way to increase the length of the signal in the time domain to allow for any time delays that will be encountered in the channel due to multi-path. Finally, as with any communications system, we apply a filter to smooth out the discontinuities caused by the signal changing every OFDM symbol period.

The OFDM Radio

As you can see, a lot of complex math is involved in this. Many conventional instruments lack the signal processing capability to perform these measurements quickly. As shown in **Figure 4**, Keithley's DSP enhanced architecture makes it possible to perform the analysis very quickly.

OFDM is simple in concept, even though its implementation is complex. Mathematically, it can be implemented by using an Inverse Fast Fourier Transform (IFFT) in the transmitter and conversely an FFT in the receiver. **Figure 5** shows the

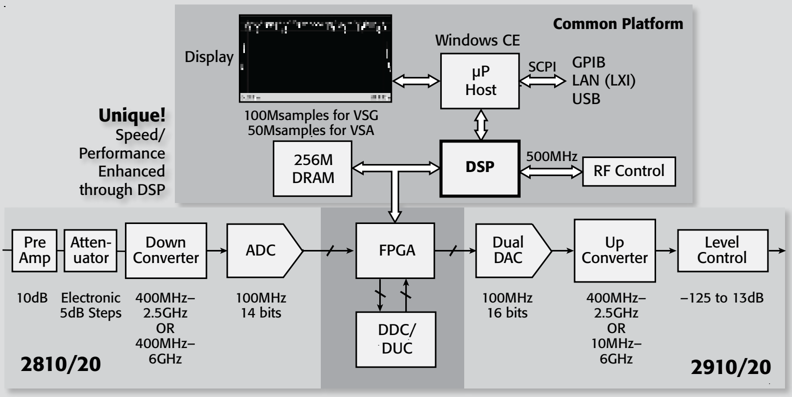


Figure 4. This block diagram shows the digital circuit in the Model 2810 Vector Signal Analyzer and the Model 2910 Vector Signal Generator.

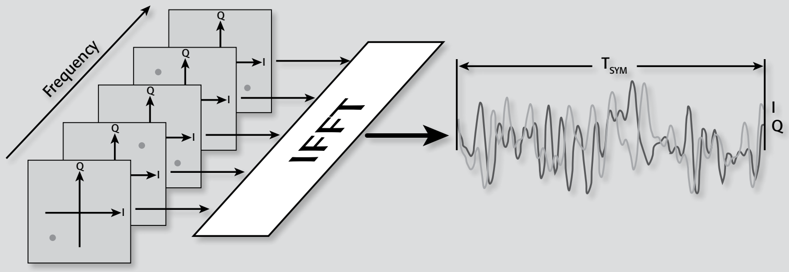


Figure 5. OFDM can be implemented by using an Inverse Fast Fourier Transform (IFFT) in the transmitter and conversely an FFT in the receiver. In the transmitter, the IFFT converts the parallel input signals into the two modulated sine waves in the output. It's as if the IFFT acts as a specialized multiplexer.

parallel symbols being converted to the two modulated sine waves in the output. It's as if the IFFT acts as a specialized multiplexer.

In order to keep things synchronized, an OFDM signal includes several subcarriers (**Figure 6**) designated as pilot carriers that are used as reference for phase and amplitude to synchronize the receiver as it demodulates the data in the other subcarriers.

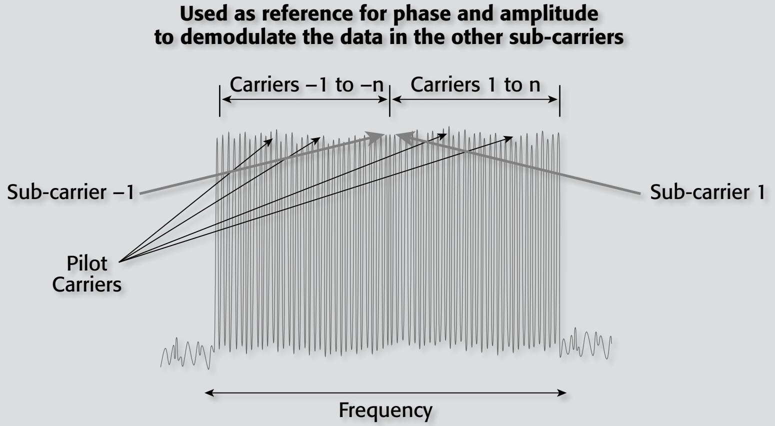
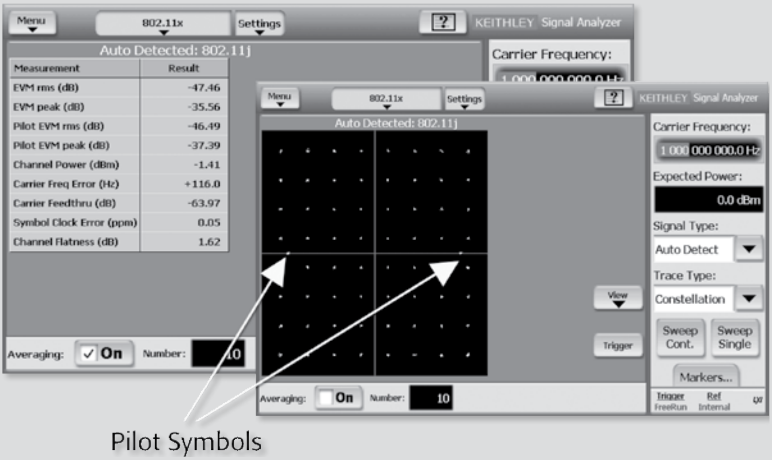


Figure 6. An OFDM signal includes several subcarriers designated as pilot carriers that are used as reference for phase and amplitude to synchronize the receiver as it demodulates the data in the other subcarriers.

Key Measurements: Constellation and EVM

Figure 7 shows the constellation of a WLAN signal conforming to the 802.11j standard. Note that even though the signal has been transmitted using many carriers, it is still essentially a QAM signal. There are also two extra symbols, representing the information modulated on the pilot carriers.



Auto Detected: 802.11j

Measurement	Result
EVM rms (dB)	-47.46
EVM peak (dB)	-35.56
Pilot EVM rms (dB)	-46.49
Pilot EVM peak (dB)	-37.39
Channel Power (dBm)	-1.41
Carrier Freq Error (Hz)	+116.0
Carrier Feedthru (dB)	-63.97
Symbol Clock Error (ppm)	0.05
Channel Flatness (dB)	1.62

Averaging: ☑ On Number: 10

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: 0.0 dBm

Signal Type: Auto Detect

Trace Type: Constellation

Averaging: ☐ On Number: 10

Figure 7. The constellation diagram of a WLAN signal conforming to the 802.11j standard. Note that even though the signal has been transmitted using many carriers, it is still essentially a QAM signal. There are also two extra symbols, representing the information modulated on the pilot carriers.

OFDM is very pervasive, as shown in **Table 1**.

Table 1: Communication services using OFDM

Wireless	Wireline
IEEE 802.11a, g, n (WiFi) Wireless LANs	ADSL and VDSL broadband access via POTS copper wiring
IEEE 802.15.3a Ultra Wideband (UWB) Wireless PAN	MoCA (Multi-media over Coax Alliance) home networking
IEEE 802.16d, e (WiMAX), WiBro, and HiperMAN Wireless MANs	PLC (Power Line Communication)
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	

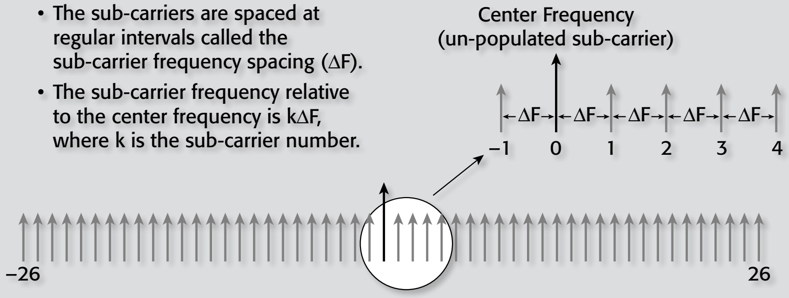
WLAN

WLAN is defined by the IEEE 802.11 standard, of which there are several variations, a through g, as shown in **Table 2**. Within a 16.25MHz bandwidth are 52 carriers (**Figure 8**), numbered –26 to +26, spaced 312.5kHz apart. Carriers 7 and 21 (–21, –7,

Table 2: WLAN Summary

802.11	Means
a	54Mbps OFDM, 5.9GHz band, 20MHz channels
b	11Mbps CCK, 2.4GHz (Legacy, not OFDM)
g	What you can easily buy now – same as a, but at 2.4GHz
j	Japanese version of g that uses half the sample rate
n	• Not a finished standard yet • Like g, but up to 600Mbps • OFDM • MIMO • 20 and 40MHz channels

+7, and +21) are the pilots. The packet structure is Preamble – Header – Data Block, and the subcarrier modulation types are BPSK, QPSK, 16-QAM, or 64-QAM.



- 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 kΔF, where k is the sub-carrier number.

Figure 8. Each carrier within the modulation scheme is referred to as a subcarrier. The subcarriers are spaced at regular intervals called the subcarrier frequency spacing (ΔF). The subcarrier frequency relative to the center frequency is kΔF where k is the subcarrier number.

The original WLAN standard is 802.11b, which is not based on OFDM; however, the rest (a, g, j, and n) are. 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 is covered in another white paper.

Several organizations are involved with WLAN: WiFi is an industry consortium that defines a required subset of 802.11 to ensure better operation between different vendors' equipment, while 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.

Test Equipment Requirements for WLAN

Test equipment for WLAN must have a frequency range up to about 6GHz and be able 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.

So far we've looked at OFDM. In OFDM all the carriers are used to facilitate a single link. OFDMA (Orthogonal Frequency Division Multiple Access) assigns different groups of subcarriers to different users in a similar fashion as in CDMA. OFDMA's best-known use is in mobile WiMAX.

WiMAX

WiMAX, or the Worldwide Interoperability for Microwave Access, is very similar in concept to 802.11, but the demands of multiple simultaneous users make the implementation much more complex.

There are two major variations of WiMAX: fixed and mobile. The mobile version, 802.16e-2005 (often called 802.16e), facilitates the link between mobile devices. It is OFDMA (Orthogonal Frequency Division Multiple Access) based. OFDMA allows multiple users to be assigned subgroups of carriers. Mobile WiMAX also employs SOFDMA (Scalable OFDM Multiple Access), which uses subsets of spectrum, called subcarriers, to be used when spectrum isn't available for the complete specified WiMAX bandwidth. 802.16e also adds MIMO (Multiple-Input Multiple-Output), called Wave 2, which is the subject of another white paper.

The fixed version of WiMAX, 802.16d (sometimes referred to as 802.16-2004) is primarily designed for back haul applications. It uses OFDM and its operation is similar to that of WLAN.

The differences are summarized in **Table 3**.

Table 3: Fixed and mobile WiMAX

802.16	Means
802.16-2004 (aka 802.16d)	Fielded system for fixed-point access (to the home or office)
	OFDMA (OFDM multiple access) 2–11GHz (no regulatory approval above 5.9GHz) Practical rate: 10Mbps over 2km
802.16e-2005	The current version of the standard, upgraded to include mobile wireless
	SOFDMA (Scalable OFDM Multiple Access) SOFDMA interoperates with OFDMA, but requires new equipment Adds MIMO

Mobile WiMAX is based on an OFDMA physical layer. It uses both frequency division multiplex and time division multiplex. Groups of subcarriers (**Figure 9**) represent individual data streams. Each group of subcarriers also has a frame structure.

Time division characteristics are shown in **Figure 10**. The frame structure equates to a packet. There is a timing gap between the uplink and downlink called the transition gap.

Mobile WiMAX is a dynamic system. The amount of data transferred is a function of the modulation type and symbol rate on each set of subcarriers. If the link quality is good, a high throughput modulation type such as QAM is used, and most of the bandwidth is consumed, thus limiting the number of users on the system. As the user

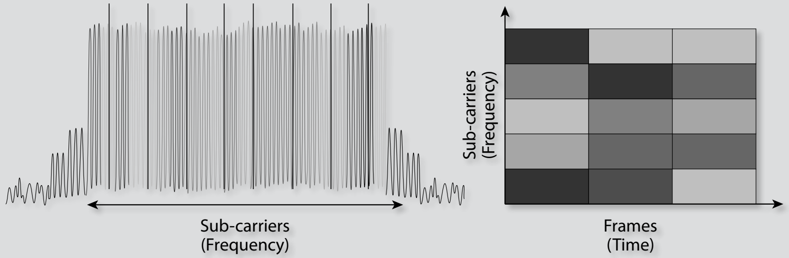


Figure 9. Mobile WiMAX uses both frequency division multiplex and time division multiplex. Groups of subcarriers represent individual data streams. Each group of subcarriers also has a frame structure.

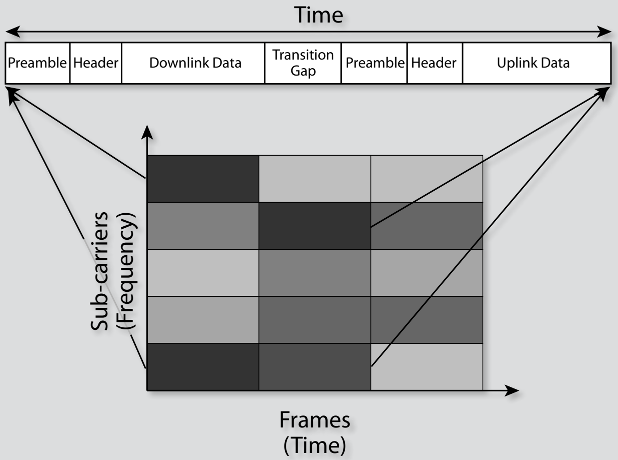
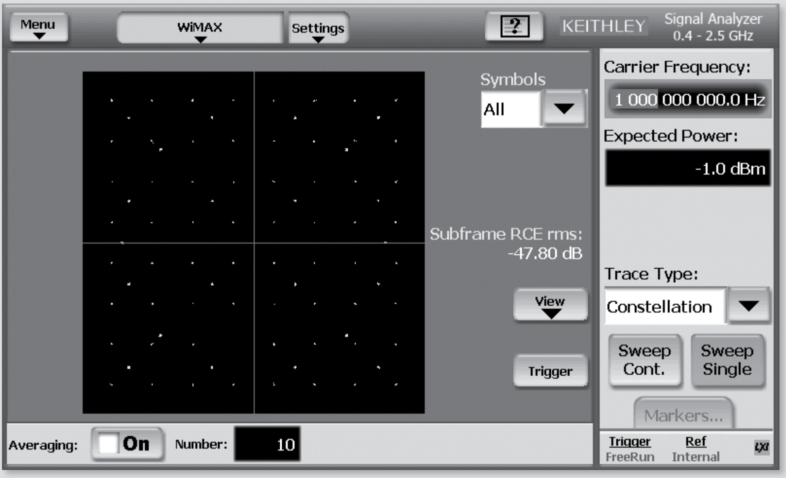


Figure 10. Time division characteristics. The frame structure equates to a packet. There is a timing gap between the uplink and downlink called the transition gap.

moves further away from the base station, the signal quality decreases, and with it the ability to maintain a high throughput. A lower throughput modulation scheme such as QPSK would then be employed. This, of course, does not require a large group of subcarriers, so the system can support more users.

Figure 11 shows two WiMAX measurements that the Keithley Model 2820 can perform. We can see a packet structure containing downlink and uplink data, DL and UL, each separated by a transition gap. The UL contains more data and would use a complex modulation format such as QAM. This is what we have chosen to demodulate, although



Symbols: All

Subframe RCE rms: -47.80 dB

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: -1.0 dBm

Trace Type: Constellation

Averaging: On

Number: 10

Trigger: FreeRun

Ref: Internal

Figure 11. In this WiMAX measurement, we see a packet structure containing downlink and uplink data, DL and UL, each separated by a transition gap. The UL contains more data and would use a complex modulation format such as QAM. This is what we have chosen to demodulate, although 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.

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Conclusions

In terms of speed versus mobility, the WLAN and WiMAX standards provide a marked increase in data speed over traditional cellular based communications technology.

The future of wireless and of fourth generation cellular systems, such as LTE or UMB, will be based on a combination of OFDM types of modulation and MIMO radio configurations (**Figure 12**). When choosing test equipment for testing today's radio standards, it's important to consider the evolution of wireless technology and to ensure that your purchases are forward compatible

One key consideration for instrumentation is bandwidth; WiMAX and WLAN have bandwidths that can exceed 25MHz. The Keithley range of wireless equipment has 40MHz of bandwidth as standard, creating a new price performance point in the marketplace.

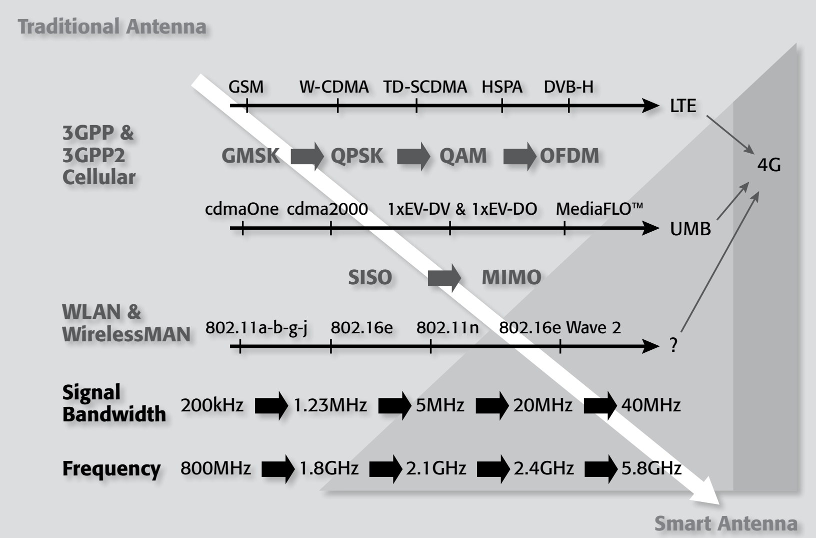


Figure 12. The long term evolution (LTE) of wireless and of fourth generation cellular systems will be based on a combination of OFDM types of modulation and MIMO radio configurations. When choosing test equipment for testing today's radio standards, it's important to consider the evolution of wireless technology and to ensure that your purchases are forward compatible.

MIMO: The future of wireless. Test challenges for WiMAX, HSPA+, and LTE

The communications market and the underlying technology that provides voice and data services are evolving to provide higher data rates in the same frequency spectrum to ever more users. New communications standards are using Multiple-Input, Multiple-Output (MIMO) techniques to maximize throughput and coverage while preserving bandwidth. The following examines the MIMO transmission scheme used by standards such as 802.16e mobile WiMAX Wave 2, HSPA+, and LTE. It covers MIMO signal generation, modulation quality measurements, channel emulation, and beam forming concepts that enable engineers to effectively design products based on multiple radio/antenna technology.

Introduction

MIMO takes spectral efficiency to a new level. It can offer higher rates of data throughput or improved coverage depending on the transmission technique used. But with this efficiency a higher level of complexity is employed. In concept, though, it is simple—MIMO employs more radio carriers to transmit more information. Spectral efficiency is gained by transmitting all the signals on the same channel occupying the same bandwidth. For example, a 2×2 MIMO radio has two transmitters and two receivers, a 4×4 radio has four transmitters and four receivers.

Currently, many MIMO systems use a 2×2 configuration; however, all market indicators suggest that higher configurations are on the way. Even today W-LAN, WiMAX, and LTE have 4×4 configuration proposals.

Beam forming research today is based around developing higher configurations of radios within devices to truly maximize the amount of services that can be delivered to a customer. 8×8 radio and even 16×16 radio configurations are leading the way in commercial broadband radio research.

MIMO Concepts

MIMO works on the principle of accurately modeling the transmission channel to decompose the multiple received symbols back into single data streams. Taking WLAN 802.11n as an example (**Figure 1**), the transmitter sends a known signal in the form of a header. The receivers then use this to build a model of the channel, which is represented by H. When data is transmitted, the receiver divides through by the channel model (H) to get as close to the original vectors, given the transmission error represented by the noise vector (n).

While the concept of modeling the channel applies to all MIMO systems, the method varies from standard to standard. For example, 802.11n WLAN transmits the header information on both TX1 and TX2, while WiMAX 802.16e Wave 2 transmits the header

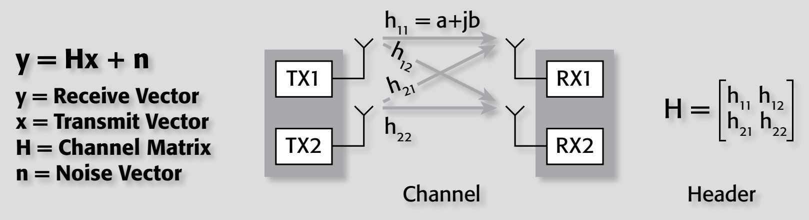


Figure 1. Understanding the transmission channel

only on the first transmitter. The elements of matrix H (h11 and h22) are the actual amplitude and phase vectors of the transmitted signals.

MIMO systems have three types of configurations: spatial multiplexing, spatial diversity, and beam forming. With spatial multiplexing, you transmit multiple sets of symbols to increase the throughput. Spatial diversity is a redundancy technique where you essentially transmit the same symbols multiple times to improve the coverage. Beam forming allows you to adjust the phase and amplitude weights of each antenna or transmitter to direct a beam of RF radiation at a specific user within a specific geographic area, which improves both throughput and coverage.

Measurement System Time Alignment

The channel distorts the signal in many ways. For example, reflections off surrounding objects can cause multiple instances of the signal to arrive at the transmitter at different times (multi-path). Multi-path introduces amplitude degradation and time and phase delays. Conceptually, the more channel distortion added to a signal through processes such as multi-path, the more likely the receiver algorithms can resolve for the originally transmitted signals. If the transmitter or the receiver adds amplitude, time, and phase errors, the channel will not be accurately modeled and the symbols will not be resolved effectively.

For effective, accurate MIMO measurements, the measurement equipment including sources (transmitters) and analyzers (receivers) need to be phase, time, and frequency aligned. In some cases the reference frequencies and the D/A and A/D sample rates are locked in order to minimize their contribution to the channel. However, if the system is required for beam forming, then the local oscillators must be phase aligned. Ideally, a phase error of less than a degree and a nanosecond of timing alignment will yield an accurate result.

System Performance

Understanding how the MIMO system behaves overall is the first indicator of performance. Performance can be modeled in a number of ways, for example: the quality of the modulation, how the channel performs, or how each stream performs.

Modulation Quality Metrics: As with most traditional digital transmission systems, the key modulation quality measurement is the actual received symbol vector (symbol phase and amplitude distortion) compared to what the receiver expected. The most common measure is EVM (Error Vector Magnitude), but other variants exist across standards, such as the Relative Constellation Error (RCE). For a MIMO system, overall EVM is still a good measurement; an RMS EVM can be calculated to give an overall indication of modulation quality across transmitters.

Constellation Diagram: The constellation diagram gives a pictorial representation of the quality of received signals. Depending on the configuration of the MIMO system, there can be multiple constellation diagrams. A 2x2 system will have two constellations representing both resolved spatial streams (h11 and h22). A 4x4 system would have four constellations. As with a traditional digital system, the same qualitative measurements can be derived from the constellation, including phase error, noise, and IQ balance.

Channel Response: The channel response is a key indicator of the spatial stream's behavior. In **Figure 2**, two transmitters are connected directly with coaxial cables to the receiver. The two straight lines represent h11 and h22, while the noise like signals show h21 and h12. This test setup uses coaxial cables to minimize cross talk between spatial streams; thus h21 and h12 are noise like.

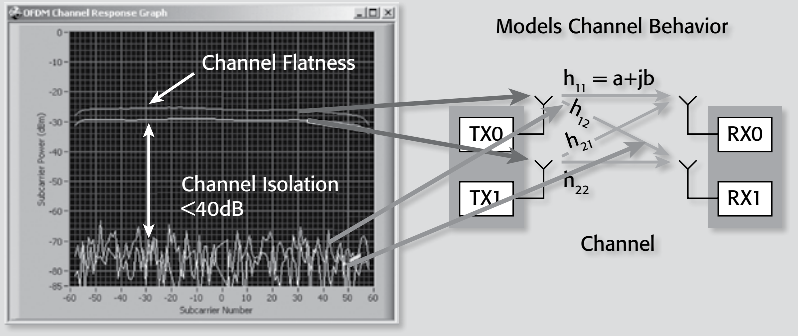


Figure 2. Channel response

Using antennas (or for a more quantitative measure, a channel emulator), an accurate model of the channel can be derived. This helps the transmitter designer understand how robust the transmission is under varying channel conditions using the calibrated receiver as the reference. The receiver can also be tested in the same way using different channel models to stress the receiver. These signals can be generated by applying the appropriate channel distortion to a standard waveform using an arbitrary waveform generator or by using a real-time channel emulator.

As the performance of a MIMO system is dependant on the behavior of the channel, the transmitter and receiver must be tested using a multitude of channel models from both predefined standards and user defined models to ensure the design maintains performance across a multitude of environments. **Figure 3** shows a typical setup. The Vector Signal Analyzer (VSA) and Vector Signal Generator (VSG) can be substituted by the transmitter or receiver depending on whether the device under test is the transmitter or receiver.

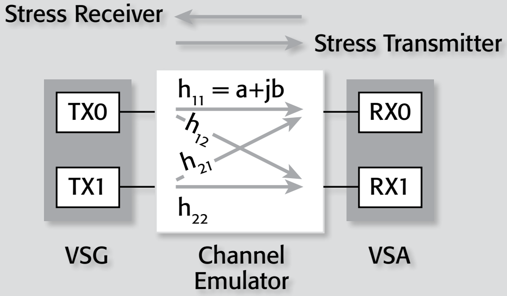


Figure 3. Measurement setup using a channel emulator

Matrix Condition and Singular Values: Earlier, the channel was briefly discussed and represented by the matrix H (**Figure 1**). This can be represented by two rotation operations (TX and RX) and a scaling operation. This process is called the Singular Value Decomposition (SVD). The scaling matrix in the SVD represents what is known as the singular values. 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. This can provide an indication of the receiver's dynamic range since the amplitude of one path might be high (the scaling vector is close to one) and the amplitude of another path might be very low (the scaling vector is a very small number).

Like EVM, the matrix condition number is a good indicator of transmitter performance. It is essentially a measure of how orthogonal each spatial stream is. For example, if you connect the VSAs to the transmitter using cables, the matrix condition should be close to unity (0dB). If it isn't then the transmitter could be creating some interstream interference. This could be due to a mathematical error in the DSP or a problem in the RF section. As the matrix condition is the ratio of the largest to the smallest singular value, you could check the singular value per stream by selecting the singular values measurement. A common measurement approach is to monitor the matrix condition number until there is an unusually large value and then switch to monitoring the actual singular values to understand the matrix solution.

Stream Performance

Individually transmitted stream performance can be analyzed in two major ways. The first method is the instantaneous quality of the signal, for example, the power or EVM of each stream. The second method is analysis over time or frequency, such as EVM over time or frequency.

Measurements Over Time: Measuring EVM, amplitude, or frequency error over a time period helps identify problems associated with each radio's behavior over time. For example, a glitch in one radio's transmitter FPGA could cause a periodic error in the EVM.

With parallel symbol transmission schemes based on orthogonal frequency division multiplexing (OFDM), the time increments are usually referred to as the OFDM symbol period. This is because each time increment can contain many thousands of symbols. For example, WiMAX (802.16e) can transmit between 128 to 2048 symbols per OFDM symbol period. In **Figure 3** the vertical axis is labelled Subchannel Logical Number. The subchannels are not actually physical channels, but groupings of 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, as shown in **Figure 4**. The symbol map is essentially a 2×2 matrix of symbols, with the vertical axis representing the parallel symbols and the horizontal axis representing how these symbols behave over time.

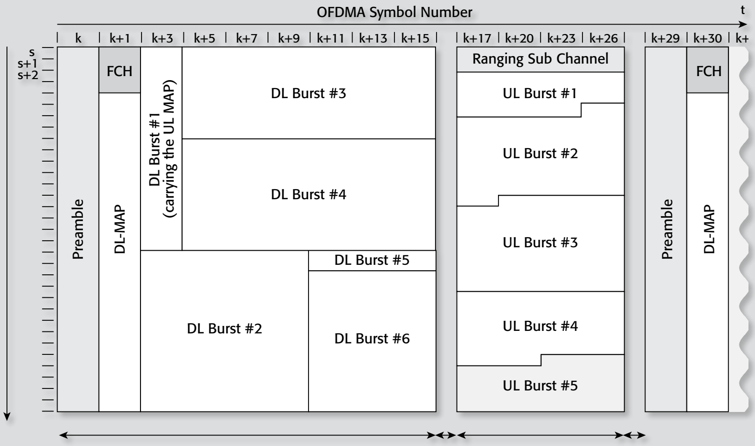


Figure 4. An OFDM symbol map from WiMAX

Modulation Quality Frequency: Measuring EVM or amplitude over frequency will help identify in-band problems such as low level spurious interference that can be generated by a clock within the radio.

Beam Forming

One of the key benefits of MIMO and one of its key original uses is the ability to align RF energy to specific users through the process know as beam forming. Many of the standards for commercial systems have provisions for MIMO beam forming, which is sometimes called closed loop MIMO. Beam forming has the benefit of delivering more capacity to users, but increases the complexity of the device as an array of transmitters, receivers, and antennas are required to control the direction and shape of a radiated signal. The direction and shape are a function on the channel environment. Techniques such as channel sounding are used to model the channel, from which the correct phase and amplitude of the beam can be established.

Test equipment must have the ability to control the phase and amplitude of each source in order to build the required RF radiated patterns based on the calculated knowledge of the channel.

Conclusions

MIMO represents one of the most important shifts in commercial radio technology since the move from analog to digital transmission techniques a number of years ago. All the next generation standards, including WiMAX, HSPA+, and LTE are MIMO based systems, presenting many new challenges for commercial communication equipment designers. As users demand more and more services and more reliable connections, MIMO systems will evolve to encompass techniques such as beam forming and increasing the number of transmitters, receivers, and antennas in a device.

Measurement techniques for OFDM and MIMO based systems

Introduction

OFDM and MIMO transmission techniques are becoming the preferred method for high data rate mobile technologies. Systems such as WLAN, WiMAX, and LTE all use OFDM modulation techniques with MIMO radio architecture. This will present many new challenges for the engineer who needs to validate the quality of a design or end product.

OFDM is based on many closely spaced carriers (some systems use thousands) that all can be modulated differently. Test challenges range from being able to demodulate all the signals at the same time quickly to understanding the effects of high peak to average ratios (a subject discussed elsewhere in this handbook).

MIMO uses multiple antennas to transmit and receive different signals. It relies on multi-path fading and channel modeling to help resolve the signal back to the originally transmitted symbols. Some of the key test challenges for MIMO are the ability to transmit and receive multiple signals with very good timing alignment and the least cross channel interference with the radios.

This following first discusses OFDM generation and measurement and then goes on to explore the challenges associated with moving from SISO OFDM to MIMO OFDM. We will then look at both SISO and MIMO OFDM with respect to WLAN, WiMAX, and LTE.

Test Equipment Considerations

Test instrumentation should support current needs and have an easy upgrade path to measure the next generation of signals. For example, for SISO OFDM does the test equipment have enough bandwidth to measure signals in excess of 20MHz and enough processing power to demodulate thousands of carriers simultaneously? Then, can it be easily configured as both a SISO tester and a MIMO tester? Modern instrumentation, such as Keithley's 2820 VSA (Vector Signal Analyzer) and 2920 VSG (Vector Signal Generator) tend to use SDR (Software Defined Radio) architecture. These instruments are essentially broadband receivers and transmitters with a wide dynamic range that are based on a DSP (Digital Signal Processing) architecture. They can be configured to test different radio technologies by simply changing the software or be reconfigured to test MIMO systems by synchronizing multiple instruments.

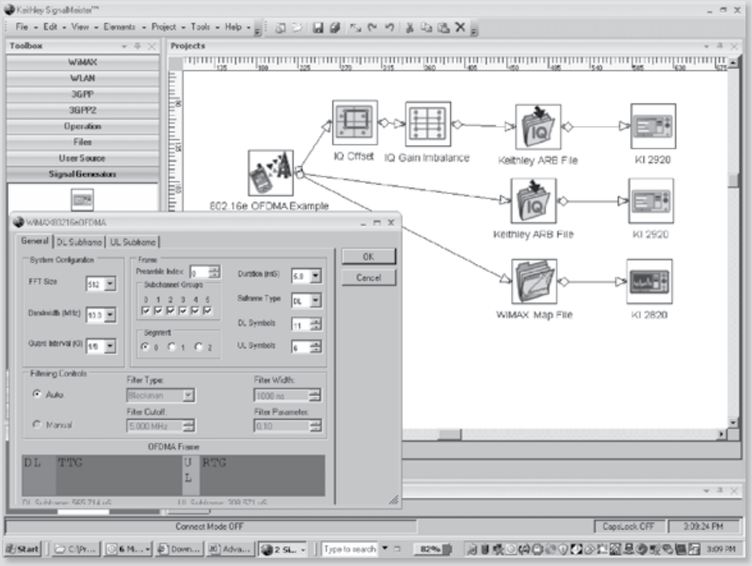
An option to consider is the software packages that accompany the test equipment. Ideally, the software should support waveform generation of all the key digital communications standards and make the creation of complex communications waveforms a simple task. Depending on the complexity of your tests, you may need some customizable features and/or the ability to save projects and create templates.

Keithley's signal generation suite, SignalMeister™ (**Figure 1**), offers all this and it also provides a toolbox of measurements, impairments, and direct I/O for installing and running files automatically on Keithley's VSGs and VSAs.

Finally, consideration for non **OFDM/MIMO** measurements must be made—**that technology** is still with us. LTE, or the Long Term Evolution of mobile devices, documented by 3GPP as Release 8, is the next generation of cellular technology based on OFDM and MIMO. However, the handsets that it will be deployed in will still use GSM and W-CDMA functionality, so test equipment must have a strong forward looking path as well as being capable of supporting today's test standards.

SISO Measurements of OFDM Signals

Currently most commercial radio systems available today such as GSM and W-CDMA employ a SISO radio architecture, which in most cases, only transmits a single stream of



System Configuration
FFT Size: 512
Bandwidth (MHz): 10.0
Guard Interval (G): 1/8

Frame
Preamble Index: 0
Subchannel Groups: 0 ☑ 1 ☑ 2 ☑ 3 ☑ 4 ☑ 5 ☑
Segment: ● 0 ○ 1 ○ 2
Duration (mS): 5.0
Subframe Type: DL
DL Symbols: 11
UL Symbols: 6

Filtering Controls: ● Auto ○ Manual
Filter Type: Blackman
Filter Width: 1000 ns
Filter Cutoff: 5.000 MHz
Filter Parameter: 0.10

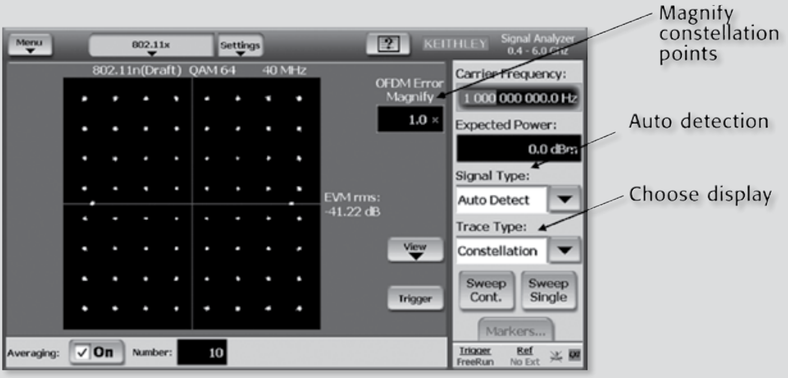
Figure 1. Creating WiMAX signals using SignalMeister. In the example, the WiMAX library is used to create an SISO 802.16e signal. By clicking on the library element, the specification of the WiMAX signal can be changed. The library element is then connected to an IQ Offset and IQ Gain Imbalance element. This distorted signal is then fed to ARB file element, which then feed an actual instrument as indicated by the Keithley 2920 element. The WiMAX library is also directly connected to an ARB and Instrument element, allowing generation of an undistorted signal in parallel. Finally, by connecting the library to a WiMAX Map File element, the configuration of the WiMAX signal can be downloaded to the Keithley 2820 VSA to enable the demodulation of the signal.

data. However, OFDM modulation differs from its predecessors as it transmits symbols in a parallel fashion on many carriers as opposed to transmitting symbols in serial on a single carrier. What we learn in the following section is that largely the measurements we make are still the same (such as EVM); however, the results will be over many carriers, not just one.

Measuring SISO OFDM Signals

Constellation diagram

Digital communication employs the concept of a constellation diagram (**Figure 2**) that shows the position of all the demodulated measurement signals in vector space. Generally, the demodulated data is overlaid on top of the ideal constellation points. Any magnitude or phase errors caused by the communications channel will show as a dot offset from the ideal position in the constellation. When there are many decoded symbols, the vector errors tend to make a "smudge" around each ideal constellation point. In general, the larger the smudge, the greater the EVM. Keithley's VSAs can perform a localized zoom into the ideal constellation points allowing us to see the EVM errors more clearly. They also provide an Auto Detect mode that can display the type of signal just above the constellation diagram. Along with the constellation, the RF input signal can be broken down and viewed in a number of different ways.



802.11n(Draft) QAM 64 40 MHz

OFDM Error Magnify: 1.0 ×

EVM rms: -41.22 dB

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: 0.0 dBm

Signal Type: Auto Detect

Trace Type: Constellation

Averaging: ☑ On

Number: 10

Magnify constellation points

Auto detection

Choose display

Figure 2. 802.11a/b/j/n constellation and EVM

EVM

As well as instantaneous measurement results, it is important to analyze metrics such as EVM over both time and frequency. For example, measuring power or EVM across a packet allows us to see effects caused by amplifier heating or if the transmitter is generating a clock spur. Also, by measuring EVM over frequency we can also get an indication of any in-band interference in the transmitter such as sampling clock harmonics.

Spectral Mask

Finally, for conformance, the signal must fit within the appropriate spectral mask defined by the standard. All the measurements examined so far will effect how a signal performs in the frequency domain.

MIMO OFDM Measurement Techniques

MIMO works on the principle of accurately modelling the transmission channel to decompose the multiple received symbols back into single data streams. Taking WLAN 802.11n as an example (**Figure 3**) the transmitter emits a known signal in the form of a header. The receiver then uses this to build a model of the channel, which is representing 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).

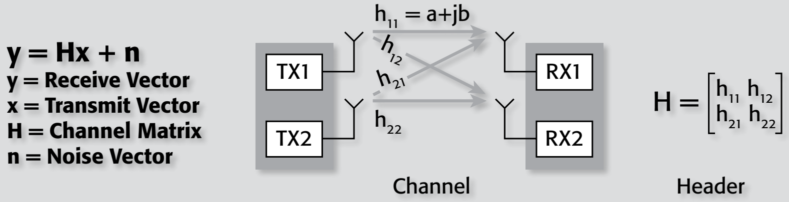


Figure 3. MIMO requires a model of the channel

MCS (Modulation Coding Scheme)

WLAN MIMO signals are defined by the MCS (Modulation Coding Scheme) index. This information is automatically encoded in the packet header of the 802.11n waveform and automatically decoded by the WLAN analyzer program. **Table 1** shows the characteristics of some MCSs. The following are examples that illustrate how to read the table:

- MCS 31 defines a four spatial stream configuration with each stream using 64 QAM as the modulation type.
- A 2×2 BPSK can be analyzed by setting the MCS index to 8 in the chipset or device.

Example Test System Setup

Figure 4 shows a MIMO measurement system comprised of two Series 2800 VGAs and two Series 2900 VSGs. The Model 2895 MIMO synchronization unit locks the instruments together and provides the MIMO system with precise and stable synchronization. As MIMO relies predominantly on channel effects, especially multipath, to resolve for the originally transmitted signals, timing alignment between the instruments is key in terms of phase, sample rate, and arbitrary waveform playback

Table 1. Specifications of some 802.11n defined MCSs

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

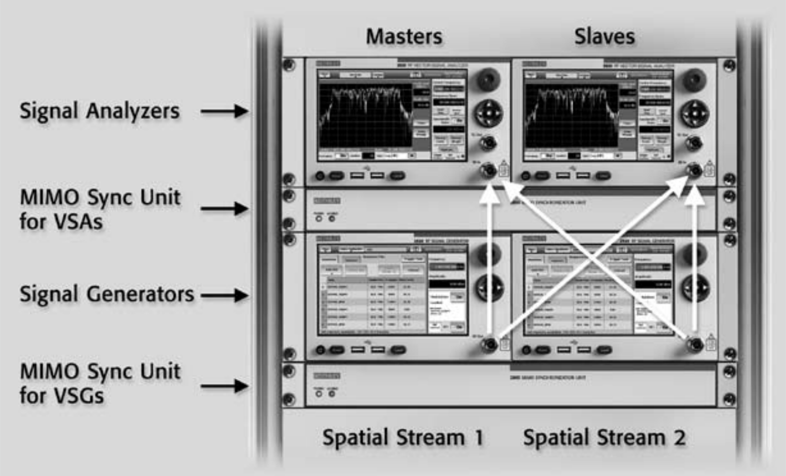


Figure 4. A 2×2 MIMO configuration

of each instrument. For this measurement example, each VSA and VSG transmits and receives a spatial stream. A Model 2895 MIMO synchronization unit can sync up to four 2800s or four 2900s, which will be demonstrated in the next section.

Key Measurements of MIMO OFDM Signals

As with SISO measurements we'll want to measure the performance of each stream over time and frequency. We can also get an indication of overall system performance with measurements such as the composite RMS EVM, matrix condition, and channel response. To analyze individual spatial stream behavior (each transmitter's performance), we should also measure subcarrier flatness, EVM, and power measurements over time and frequency.

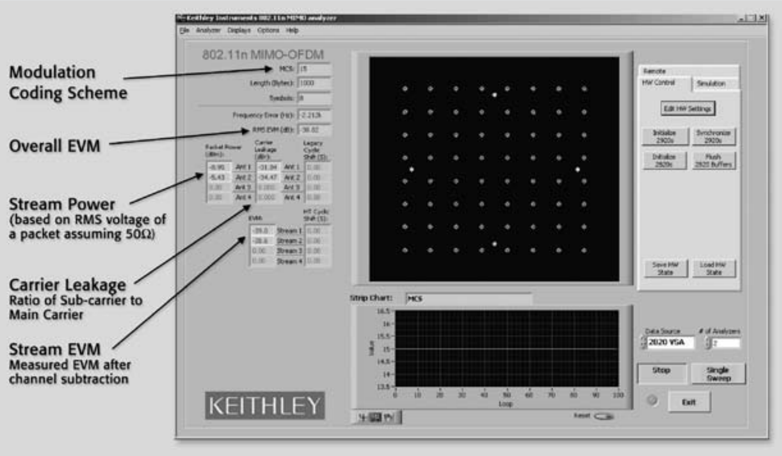


Figure 5. Default measurement screen

On the main screen (**Figure 5**) there should be a number of measurements. First the demodulator automatically detects the MCS. In this case it is 15, which is a 2×2 MIMO configuration. The screen also shows the overall frequency error and the RMS EVM of the combined streams. It can then measure and display: each stream's power, how much a carrier is suppressed, and the EVM of each stream.

The main screen also shows a constellation diagram. By clicking the mouse on Displays at the top of the screen, another 12 measurement display options become available. You can view each measurement individually or by pressing Options, Display Options—view multiple measurements in floating windows.

The following discusses six key measurements for MIMO OFDM signals:

1. EVM
2. Channel metrics
3. 2×2 channel response
4. 2×2 sub carrier flatness
5. Measurements over time
6. Measurements over time and frequency

EVM

In the constellation diagram of **Figure 5**, each subcarrier is displayed as a constellation point. Symbols from one stream are represented by one color and symbols from the other stream are represented by another. The pilots are shown in yet another color.

Constellation diagrams were discussed in detail in the section titled SISO Measurements of OFDM Signals.

Channel Metrics

Like EVM, the matrix condition number is a good indicator of transmitter performance. It helps to determine the amount of stream cross talk the transmitter introduces and the ability of the receiver to use lower amplitude streams in the presence of high amplitude streams.

Earlier the channel was briefly discussed and represented by the matrix H. This can be represented by two rotation operations (Tx and Rx) and a scaling operation. This process is called the SVD (Singular Value Decomposition).

The scaling matrix in the SVD represents what is known as the singular values. 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. This can give an indication of the receiver's dynamic range as the amplitude of one path may be high (the scaling vector is close to one) and the amplitude of another path very low (the scaling vector is a very small number).

2×2 Channel Response

For the example in **Figure 6**, we used an RF cable to connect the Tx to the Rx. We see four plots with each plot showing the magnitude of the signal paths (h11, h22, etc). As we are using a coaxial connection in this example, the h21 and h12 components are minimal. If antennas where used or we created some channel distortion in SignalMeister™, we would see the frequency response in the channel of all the components. This is an extremely useful tool to help you visualize the different channel conditions that could stress your receivers' design.

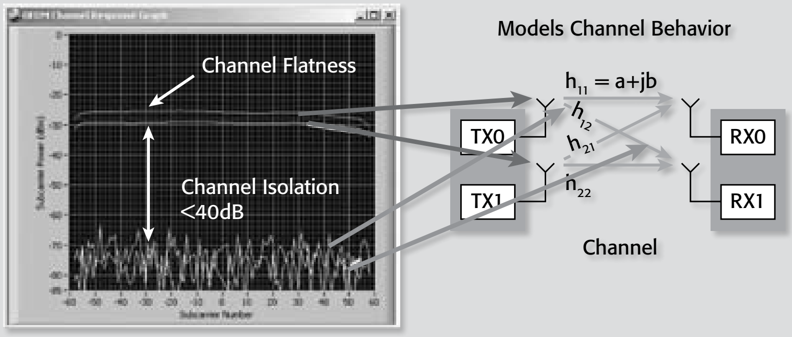


Figure 6. Channel behavior

2×2 Sub Carrier Flatness

The flatness of the received carriers shows if there are any frequency response problems associated with the transmitters. This is useful to detect if any of the transmitters' filters are band limiting or attenuating the signal in any way.

Measurements over Time

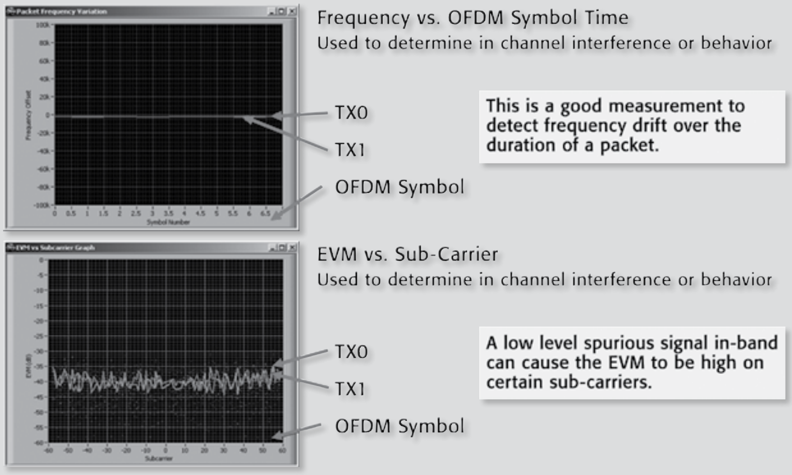
Measuring EVM over time helps identify problems associated with the radio's behavior over time. For example, a glitch in the radio's FPGA may cause a periodic error in the EVM. Measuring EVM over frequency can help to identify in-band problems such as low level spurious interference that could be generated by a clock within the radio as we previously discussed.

Measurements over Time and Frequency

Frequency vs. OFDM symbol time is good for detecting frequency drift that may be occurring on one of the radios. Power vs. OFDM symbol time is useful for analyzing the amplitude of each stream over time, which tells you if the power is remaining constant over time. See **Figure 7**.

Summary

Even though OFDM systems employ parallel symbol transmission techniques as opposed to the serial techniques used in traditional radio systems, many of the measurements remain the same. We still look at the constellation diagram to determine the health of a system and use EVM to quantify the quality of the transmission. The same holds true for MIMO-based systems as well, except now we can have up to four



Frequency vs. OFDM Symbol Time
Used to determine in channel interference or behavior

This is a good measurement to detect frequency drift over the duration of a packet.

EVM vs. Sub-Carrier
Used to determine in channel interference or behavior

A low level spurious signal in-band can cause the EVM to be high on certain sub-carriers.

Figure 7. Measurements over time and frequency

constellations to look at if there are four transmitters in the system. The key difference for MIMO is an understanding of how the radio behaves under different channel conditions. Having the ability to view the channels' characteristics and also analyze the scaling vectors or singular values provides design engineers the tools they need to validate the MIMO radio system using the most demanding channel conditions.

Measuring power amplifier gain compression with OFDM signals

Organizations responsible for communication standards are working to increase data rates to support new, multi-media mobile applications. Many of the approaches to increase data rates use OFDM modulation. Some of the advantages OFDM offers include resistance to multi-path fading and higher data rates in mobile applications.

The primary disadvantage to OFDM is an increased peak to average power ratio (PAR). The class AB amplifier is best able to cope with the high signal PAR in OFDM devices. (For this discussion, let's assume that for any given signal, an amplifier can be designed to maintain linearity over the required signal range.) While the class AB amplifier can maintain linearity over a wide signal range, its cost is proportional to the range over which linearity is to be maintained. The AB amplifier is also very power inefficient. For a mobile device, both cost and power efficiency are of utmost importance since the "per unit" cost must be low and the device is powered by a battery. Designers of these products need to find the ideal balance of performance, cost, and power efficiency. As we will see, with the typical arsenal of tools usually available to the designer, this can be a daunting task. To aid in the measurement and characterization of devices using OFDM technology, Keithley has introduced a new technique that makes the measurement of gain compression (linearity) in an OFDM device a far simpler prospect.

The following discusses how gain compression is traditionally measured in continuous wave (CW) and analog modulation waveforms. It then describes Keithley's solution for measuring gain compression in RF amplifiers designed for 802.11x waveforms.

Gain Compression in CW and Analog Modulation Waveforms

When an amplifier is operating in its linear region (**Figure 1**), for every 1dB increase in input there is a corresponding 1dB increase in output, indicating a constant gain. As the output power of the amplifier increases, eventually there will come a point when the amplifier will operate in a non-linear fashion; where the increase in output power will be less than the corresponding increase in input power. This non-linear region is where gain compression occurs and the amplifier begins to distort. When an amplifier distorts, the amplifier output generates signals other than the desired amplified input signals, such as harmonics and inter-modulation products. These undesired signals are related mathematically to the input signal.

After gain compression begins, the output power reduces with each corresponding increase in input power. When the output power is reduced by 1dB with respect to what is predicted by the extrapolated linear behavior (dashed line), then we say that the gain compression of the amplifier is 1dB.

As the output power continues to increase, a point will eventually be reached where the output power will no longer increase with any corresponding increase in input

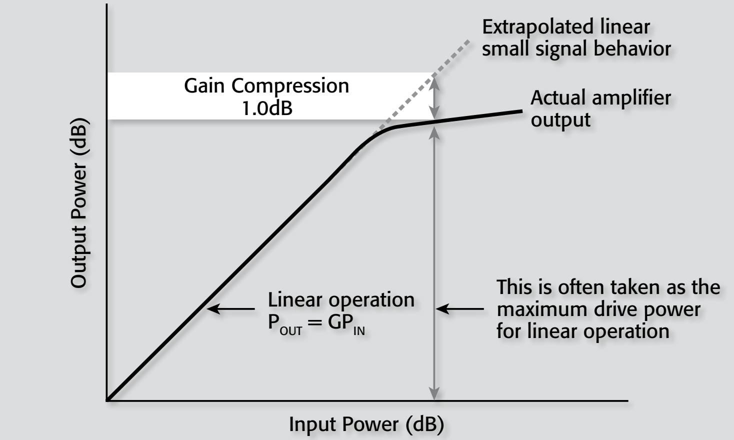


Figure 1. 1dB gain compression

power; the inter-modulation products overwhelm the amplifier by causing the undesired signal output levels to increase faster than the desired output signal levels. At this point the amplifier is saturated. However, sometime before this point is reached, the amplifier ceased to work adequately as an amplifier.

Gain compression is defined as a deviation from an idealized linearly extrapolated line (the dashed line in **Figure 1**). During an amplifier's linear operation, a unit increase in input power (in dB) results in a unit increase in output power (dB) + gain (dB). During non-linear operation (gain compression), the input power (dB) = output power (dB) – gain (dB). These equations are for small signals. (A small signal is an amplifier input level that does not cause distortion at the output of the amplifier, which also means that the amplifier is operating in its linear range.)

Gain Compression in OFDM Signals

Orthogonal frequency division multiplexing (OFDM) is a multi-carrier modulation technique. It splits a high-rate data stream into a number of low-rate streams that are transmitted simultaneously over subcarriers. In OFDM we increase the robustness of the communications channel by deliberately reducing the symbol rate on each subcarrier. By reducing the symbol rate (increasing the time the symbol is present at the receiver and increasing the guard interval between symbols) we reduce the impact of the same signal coming to the receiver along a different path (multipath) to a simple gain and phase offset at each carrier. These path delays are small relative to the symbol duration, so the receiver has an easier time decoding what was transmitted. Normally, this would reduce the overall data rate in proportion to the symbol rate. In OFDM, however, we take this

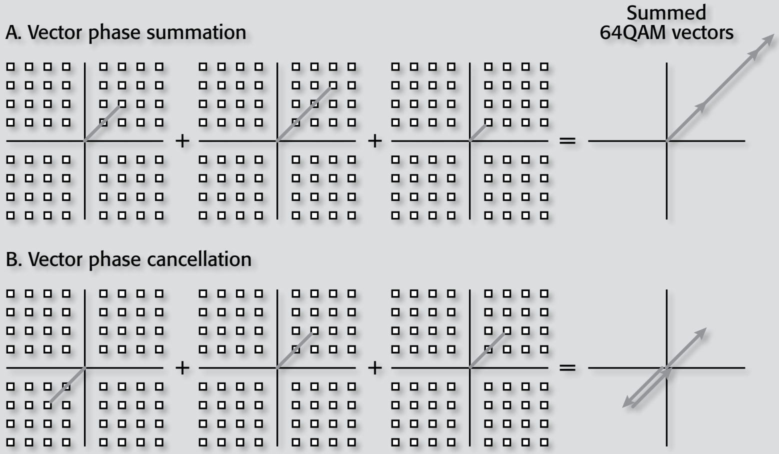
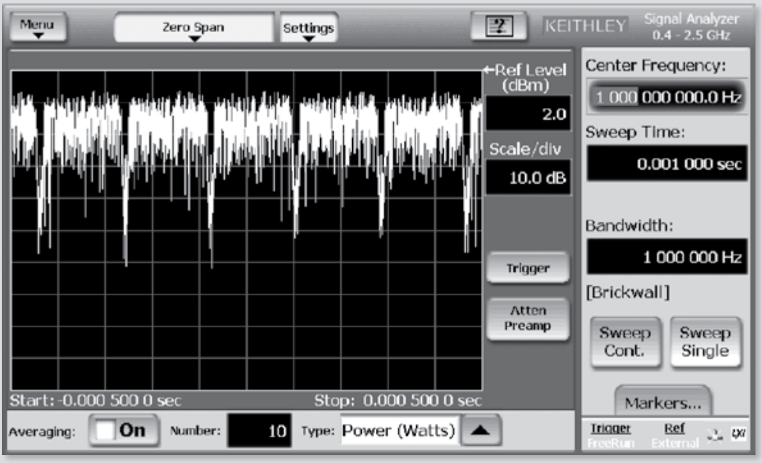


Figure 2. This graphical representation shows how the random phases of OFDM subcarrier signals can produce instantaneous power levels that cause an amplifier to compress momentarily and create distortion and, ultimately, symbol errors.

reduced rate bit stream and convert the transmitter sequence into many parallel streams of the same low rate, modulate them onto subcarriers, and transmit them all at once as a composite RF signal stream. These modulated subcarriers are orthogonal, so they don't interfere with each other. At the receiver, the composite RF stream is decoded in parallel too. So, while the data rate of an individual subcarrier was reduced, because we sent multiple parallel carriers at the same time; the overall data rate is high.

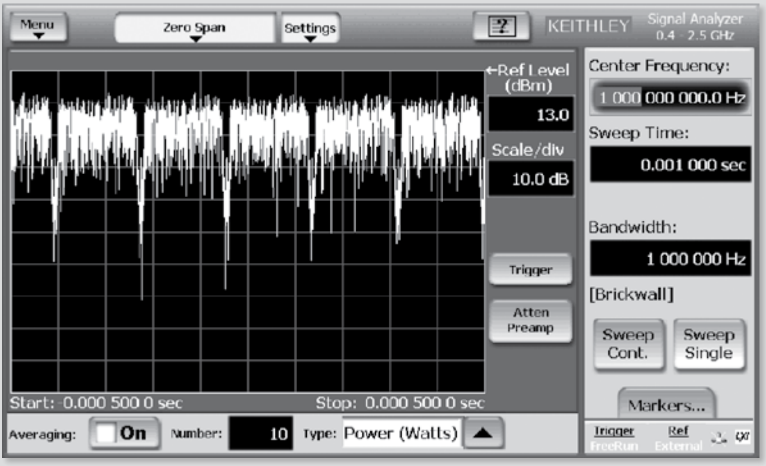
This type of digital modulation scheme creates a time-domain waveform that looks very noise like. Multi-carrier waveforms like those used in OFDM schemes have a high peak to average ratio (PAR). Signals having a high PAR ratio can cause an amplifier to compress unpredictably during transmission. This is because each of the modulated subcarriers has a random phase relationship with respect to each other and all subcarriers transmit their symbols in the same channel. The instantaneous signal power due to random phases can add up constructively or they can cancel out (as shown in **Figure 2**), which creates the high PAR and indicates that the range of signal powers that an RF amplifier must generate be widely varying and very dynamic.

RF power amplifiers need to be designed to work with signals having a large PAR because waveforms with a large PAR can severely stress an RF amplifier and can cause it to distort during signal peaks. Manufacturers must test their amplifiers with specific digitally modulated waveforms to ensure that they meet the specifications laid out by the various standards.



Ref Level (dBm) 2.0
Scale/div 10.0 dB
Center Frequency: 1 000 000 000.0 Hz
Sweep Time: 0.001 000 sec
Bandwidth: 1 000 000 Hz
[Brickwall]
Start: -0.000 500 0 sec
Stop: 0.000 500 0 sec
Averaging: On
Number: 10
Type: Power (Watts)
Trigger FreeRun
Ref External

Figure 3a. 802.11A 64QAM signal with 0% compression in zero span

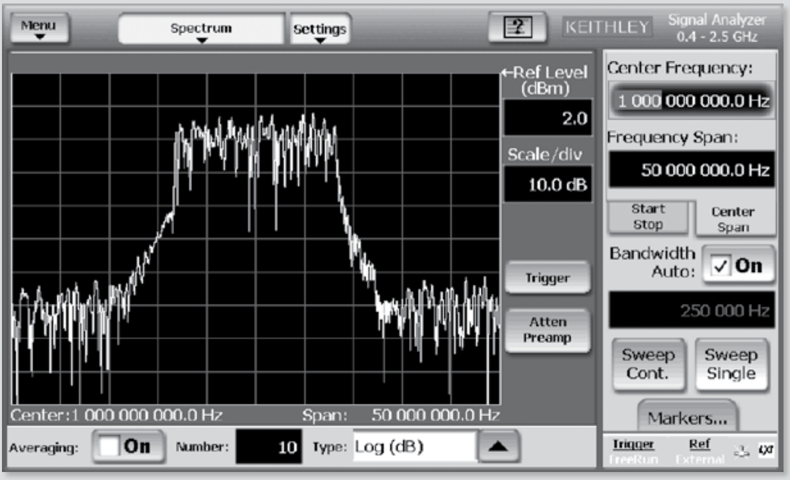


Ref Level (dBm) 13.0
Scale/div 10.0 dB
Center Frequency: 1 000 000 000.0 Hz
Sweep Time: 0.001 000 sec
Bandwidth: 1 000 000 Hz
[Brickwall]
Start: -0.000 500 0 sec
Stop: 0.000 500 0 sec
Averaging: On
Number: 10
Type: Power (Watts)
Trigger FreeRun
Ref External

Figure 3b. 802.11A 64QAM signal with 20% compression in zero span

Detecting Gain Compression in OFDM Signals

OFDM signals are very dynamic and due to their noise-like nature, it is not always clear whether an amplifier is being stressed into compression, which can make compression problems hard to detect. For example, while differences clearly exist in the signal characteristics of the compressed and uncompressed OFDM signals shown in **Figures 3a** and **3b**, it is not obvious that gain compression is present in the time domain.



Ref Level (dBm) 2.0

Scale/div 10.0 dB

Center Frequency: 1 000 000 000.0 Hz

Frequency Span: 50 000 000.0 Hz

Bandwidth Auto: ☑ On

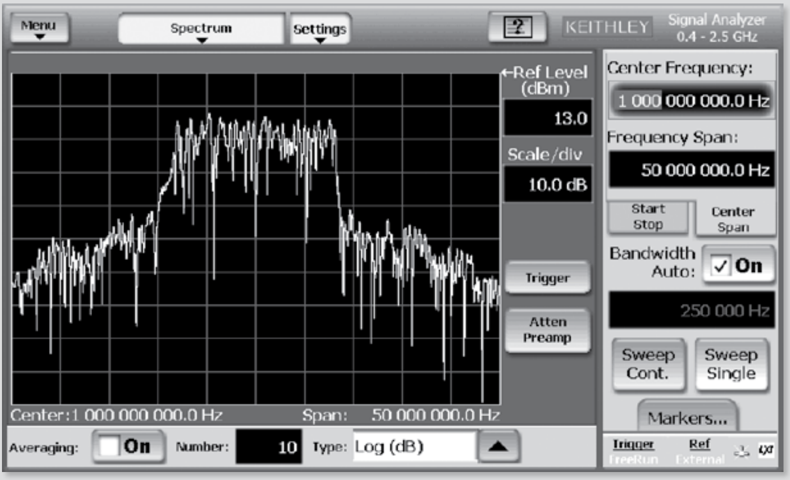
250 000 Hz

Center:1 000 000 000.0 Hz Span: 50 000 000.0 Hz

Averaging: ☐ On Number: 10 Type: Log (dB)

Trigger FreeRun Ref External

Figure 4a. 802.11A 64QAM signal with 0% compression



Ref Level (dBm) 13.0

Scale/div 10.0 dB

Center Frequency: 1 000 000 000.0 Hz

Frequency Span: 50 000 000.0 Hz

Bandwidth Auto: ☑ On

250 000 Hz

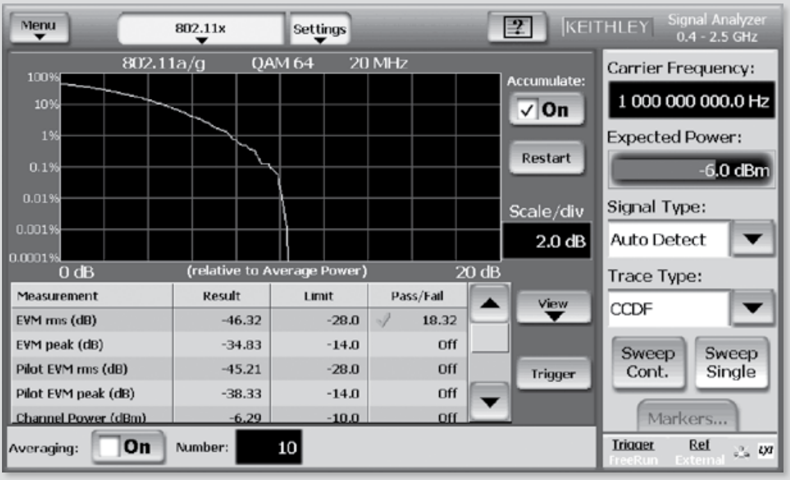
Center:1 000 000 000.0 Hz Span: 50 000 000.0 Hz

Averaging: ☐ On Number: 10 Type: Log (dB)

Trigger FreeRun Ref External

Figure 4b. 802.11A 64QAM signal with 20% compression

The differences in the signal characteristics for both a compressed and uncompressed OFDM signal in the frequency domain are more apparent as distortion increases, as shown in **Figures 4a** and **4b**. In this comparison, the signal to distortion ratio has degraded; however, it is difficult to derive a quantitative measure that would provide the designer feedback to optimize the circuit.



Accumulate: ☑ On

Scale/div: 2.0 dB

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: -6.0 dBm

Signal Type: Auto Detect

Trace Type: CCDF

Measurement	Result	Limit	Pass/Fail
EVM rms (dB)	-46.32	-28.0	✓ 18.32
EVM peak (dB)	-34.83	-14.0	Off
Pilot EVM rms (dB)	-45.21	-28.0	Off
Pilot EVM peak (dB)	-38.33	-14.0	Off
Channel Power (dBm)	-6.29	-10.0	Off

Averaging: ☐ On

Number: 10

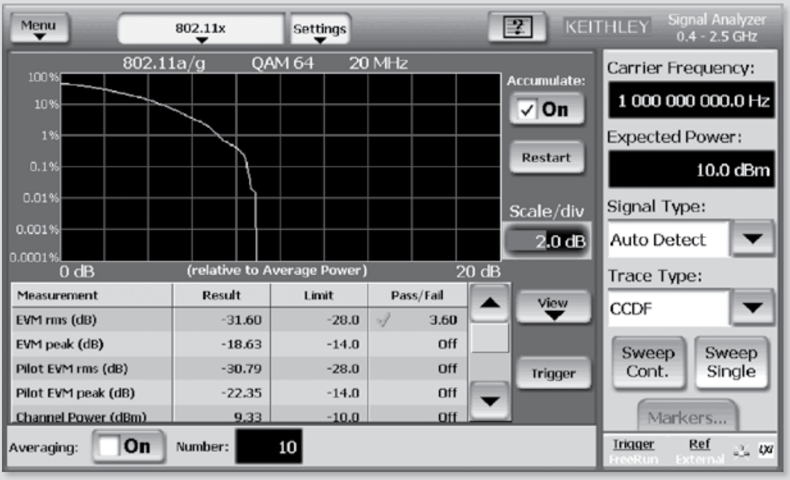
Figure 5. CCDF curve of an 802.11A 64QAM signal with no compression. This signal spends almost 1% of its time at 8dB above the average power. (Notice the Y-axis is the probability, in percent, of observing a signal power larger than a given x value, and the X-axis is in dB relative to the average power.)

In order to extract useful information from a signal with the noise-like nature of OFDM signals, a statistical description of the waveform's power levels is required, such as a complimentary cumulative distribution function (CCDF). For example, the CCDF curve in **Figure 5** shows how much time a signal spent above a given power level. The power level is expressed in dB relative to the average power. A CCDF curve is useful for describing how dynamic a signal is. The curve can also specify the power characteristics of signals transmitted in a communications channel.

Figure 6 illustrates that the addition of gain compression in this amplifier has affected the CCDF curve, but not in any way that the level of gain compression can be reliably indicated. When the gain compression is so high that the amplifier is fully saturated, the CCDF curve can show that severe gain compression is present by the distortion of the curve. For severely compressed signals, the shape of the curve flattens out noticeably. However, when low to moderate levels of gain compression are present, the changes in the curve are much harder to discern.

Measuring Gain Compression in OFDM Signals

Keithley has developed a measurement technique that can reliably, quickly, and easily measure the level of gain compression in an RF amplifier transmitting an OFDM signal. The technique requires the use of a Model 2810 or 2820 RF vector signal analyzer. This technique measures the error in the observed power level versus the expected power



Accumulate: ☑ On

Scale/div: 2.0 dB

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: 10.0 dBm

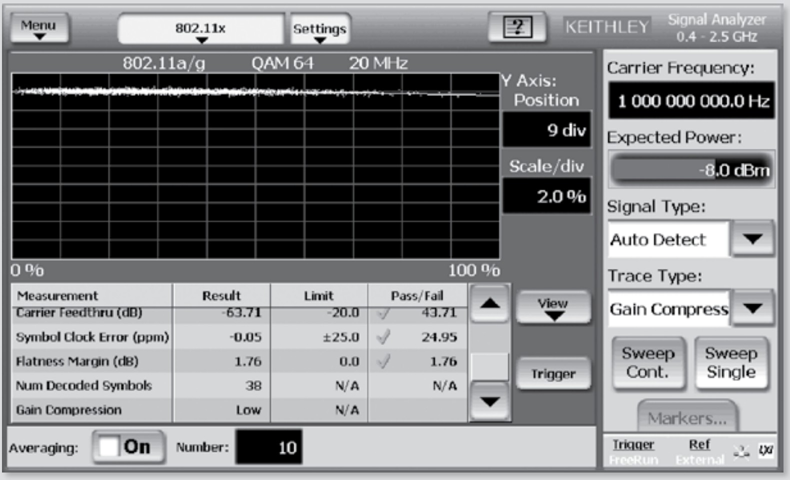
Signal Type: Auto Detect

Trace Type: CCDF

Measurement	Result	Limit	Pass/Fail
EVM rms (dB)	-31.60	-28.0	✓ 3.60
EVM peak (dB)	-18.63	-14.0	Off
Pilot EVM rms (dB)	-30.79	-28.0	Off
Pilot EVM peak (dB)	-22.35	-14.0	Off
Channel Power (dBm)	9.33	-10.0	Off

Averaging: ☐ On Number: 10

Figure 6. CCDF curve of an 802.11A 64QAM signal with 10% compression. The compressed signal is noticeable on the CCDF curve, but there is no way to make a measurement of compression levels. This signal spends almost 1% of its time at 7.25dB above the average power.



Y Axis: Position: 9 div

Scale/div: 2.0 %

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: -8.0 dBm

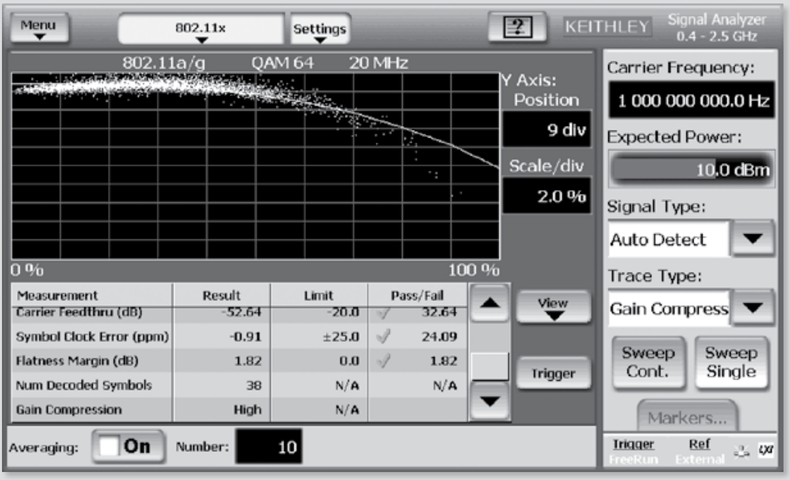
Signal Type: Auto Detect

Trace Type: Gain Compress

Measurement	Result	Limit	Pass/Fail
Carrier Feedthru (dB)	-63.71	-20.0	✓ 43.71
Symbol Clock Error (ppm)	-0.05	±25.0	✓ 24.95
Flatness Margin (dB)	1.76	0.0	✓ 1.76
Num Decoded Symbols	38	N/A	N/A
Gain Compression	Low	N/A	

Averaging: ☐ On Number: 10

Figure 7. Keithley Gain Compression Measurement algorithm of an OFDM signal with no deliberate compression. The Y-axis scale shows the level of linear gain error in percent (%) of full scale. The X-axis scale shows the full scale input power range in percent (%) of full scale.



Y Axis: Position: 9 div

Scale/div: 2.0 %

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: 10.0 dBm

Signal Type: Auto Detect

Trace Type: Gain Compress

Measurement	Result	Limit	Pass/Fail	
Carrier Feedthru (dB)	-52.64	-20.0	✓	32.64
Symbol Clock Error (ppm)	-0.91	±25.0	✓	24.09
Flatness Margin (dB)	1.82	0.0	✓	1.82
Num Decoded Symbols	38	N/A		N/A
Gain Compression	High	N/A		

Averaging: On

Number: 10

Figure 8. Keithley Gain Compression Measurement algorithm of an OFDM signal with compression. 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 (%).

level and is illustrated in **Figure 7**. The Y-axis displays the level of linear gain error in percent (actual linear gain divided by the expected linear gain for a non-compressed signal). The X-axis shows the full scale input power range in percent. This is analogous to the gain compression definition model shown in **Figure 1**. The individual dots displayed over the gain compression curve are measured power values over time. Notice that with little or no compression present, there are measured values near the high power end of the response displaying minimal errors.

As the RF amplifier's input power is increased, the OFDM signal begins to cause compression in the amplifier's output, as shown in **Figure 8**. Notice that with this relatively high compression level, there are larger gain errors in the higher power end of the response. The dots represent samples in the time domain. Notice how few there are at the high power end of the response. Compression of these measured sample values will lead to these values being decoded at lower power levels, causing increased EVM (error vector magnitude) and bit errors.

Quantifying Gain Compression for OFDM Signals

To quantify the gain compression of an OFDM signal, compare the measured time domain signal with a reference signal and plot the difference as a function of magnitude, as shown in **Figure 9**. The reference signal is an ideal time-domain waveform, constructed from the demodulated symbol targets using an IFFT (inverse fast Fourier transform).

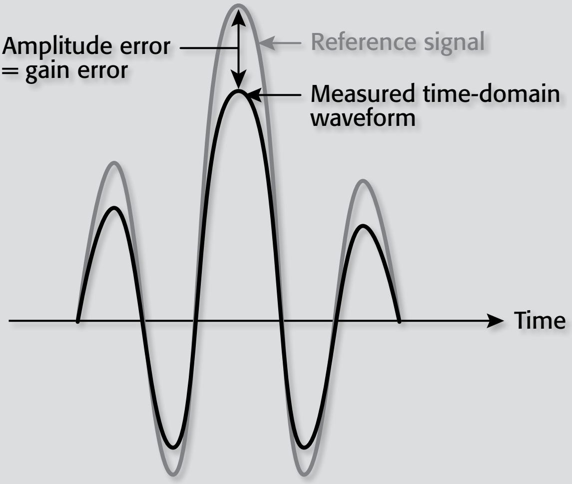


Figure 9. Gain Error = (Observed Magnitude – Reference Magnitude)/Full Scale Magnitude

Time domain errors are measured as a function of input magnitude. The linear error equates to gain compression. This is analogous to the difference in reference signal versus the actual measured signal. The linear gain is plotted relative to full scale. This gives % magnitude error as a function of input magnitude.

The diagram in **Figure 9** is related to the gain compression plot (**Figure 1**). The slope of the extrapolated linear signal behavior curve in **Figure 1** is represented by the reference signal in **Figure 9**. The actual amplifier output curve in **Figure 1** is represented by the measured time-domain waveform in **Figure 9**. It is easier to look at **Figure 9** and imagine that as the amplifier input power is increased and begins to cause gain compression, the level of the measured time-domain waveform will reduce relative to the reference signal, thus increasing the amplitude error.

Understanding the perils of spectrum analyzer power averaging

Introduction

Averaging is a common technique for reducing the measurement uncertainty inherent in all measurements. Performing the same measurement a number of times and calculating the average of the measured values can often reduce the randomness of an experimental result. Many (if not most) instruments attempt to simplify the measurement process by performing averaging automatically. Rather than returning 100 noisy measurements, the instrument is responsible for taking all 100 measurements, calculating their average, and returning just the average. Averaging is so common and conceptually simple that one might assume there's little room for debate on the correct way to average. However, recent experience has demonstrated that power averaging in spectrum analyzers isn't necessarily straightforward. The following discussion explores the issues associated with power averaging in order to help readers avoid making the same mistaken assumptions the author did. The conclusions presented here are the results of an experiment that involved correlating the power measurements of two spectrum analyzers from different vendors. However, the issues discussed are generic in the sense that they apply to any spectrum analyzer power measurement with some form of post-detection averaging.

Incorrect Assumption #1: *To find the average power of a Zero-Span trace or a portion of the trace, average the RMS power.*

Averaging is so natural to engineers that it hardly seems to merit presenting the mathematical formula for calculating it. Nonetheless, to get everyone on the same page, let's refer to Eq. (1). M_{AVE} is the average of a series of individual measurements taken over N trials of an experiment, where each of those measurements is denoted as M_i:

$$M_{AVE} = \frac{1}{N}\sum_i M_i \tag{1}$$

In this instance, the task was to verify that instrument "A" correlated with instrument "B" to within some level of accuracy (say ±1dB). All measurements were performed in Zero-Span (ZS) mode. The fact that ZS was used is largely irrelevant to the problems with averaging; the same types of averaging issues occur in traditional frequency domain spectrum analysis. However, both vendors used the ZS technique for the measurements, in this case, Adjacent Channel Power Ratio (ACPR) measurements. This is typical of modern digital-IF analyzers, where the instrument performs multiple power measurements at varying offsets from the center frequency without re-tuning the analyzer. For those unfamiliar with ZS, it is a common spectrum analyzer technique for measuring power at a specific frequency. Put simply, ZS is a time-domain measurement that shows the variation of the signal's power envelope vs. time. In ZS mode, the analyzer is not sweeping frequency, but is instead tuned for a specific center frequency. The analyzer then measures the instantaneous detected voltage for a user-specified sweep time, and the equivalent power of this voltage "trace" is calculated and displayed vs. time. (In analog spectrum analyzers, the envelope of the signal is the output of the detector diode, while modern "digital-IF" spectrum analyzers digitize the baseband signal directly and calculate the envelope mathematically.)

Figure 1 shows a real ZS measurement of pulsed GSM signal. The curve represents the actual GSM pulse envelope. Note that the measurement performed here is the "Occupied RF Spectrum (ORFS) due to Modulation," which is simply an ACPR measurement. Note that the "squiggles" at the top of the burst are due to the resolution bandwidth and video bandwidth settings, both 30kHz per the GSM ORFS Mod specification. If these settings were widened, the trace would start to look much more like a rectangular pulse.

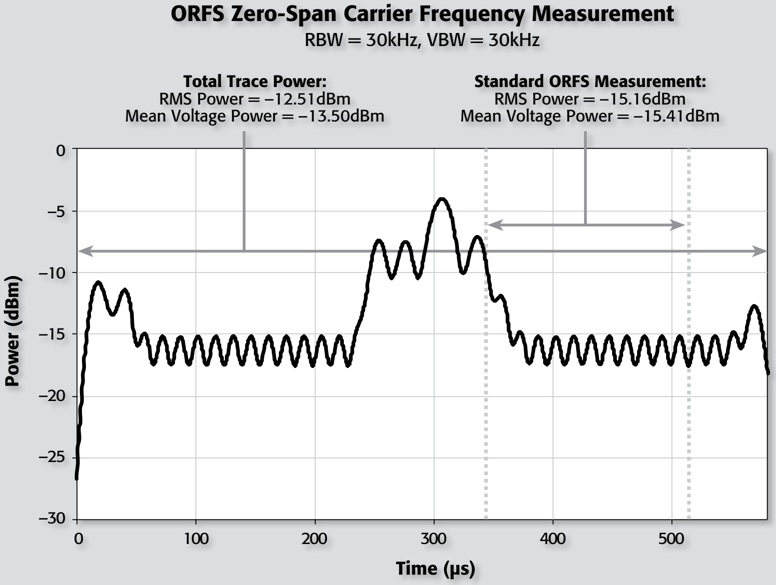


Figure 1. Zero-span trace of a pulsed GSM signal

It's possible to calculate a number of useful results from the trace, such as the maximum peak power, minimum power, and average power. Finding the trace maximum power and minimum power is pretty straightforward, at least conceptually—simply have the analyzer do a maximum peak and minimum peak search on the entire trace and return the results. How can one find the average power between the dashed lines? As a side note, the GSM ORFS Mod test requires that the average power be calculated over a limited portion of the burst—this is the region between the dashed lines.

The obvious way to calculate the average power is average across all points between the dashed lines. Eq. (2) accomplishes this, where N is the number of trace points between the dashed lines, and $P_{\text{ith point}}$ is power in the ith point.

$$P_{AVE} = \frac{1}{N}\sum_{i} P_{\text{ith point}} \tag{2}$$

Eq. (2) is completely intuitive. Moreover, it seems like the "correct" way to calculate power. Unfortunately, instrument manufacturers don't always agree. One of the instruments averaged powers as in Eq. (2), while the other instrument first converted each power point to a voltage, took the *average of all of these voltages*, then used the average voltage to calculate the average power. Eq. (3) shows the calculation.

$$P_{AVE}' = \frac{\left(\frac{1}{N}\sum_{i} V_{\text{ith point}}\right)^2}{50\,\Omega} \tag{3}$$

Proving that one instrument was using Eq. (2) and the other was using Eq. (3) was not a trivial exercise, because the difference between the two reported average powers wasn't that large. It was necessary to pull *multiple* traces out of both instruments and calculate the average every conceivable way until good fits were found. In the example in **Figure 1**, the difference between the "true" average power (subsequently referred to as the RMS power) and the average *voltage* power is 0.25dB (RMS power is 0.25dB greater). Given that two different instruments were being compared, this could have been written off as a simple measurement difference (error) between the two instruments. While 0.25dB may not seem like much, when the requirement is for ~1dB of correlation (or just plain accuracy), 0.25dB becomes significant. This is particularly true at low signal levels, where the noise power becomes a significant portion of the total measured signal. Note that if the difference in powers over the whole burst is examined, the delta widens to ~1dB (again, RMS power is higher than average voltage power). In this case, the difference is equal to the level of accuracy one is trying to obtain.

The average voltage power represents the "mean-square***d***" power [Eq. (3)], while the RMS power is, obviously, the "mean-square" power [Eq. (2)]. From elementary statistics, it can be shown that the mean-square minus the mean-squared is equal to the variance. What this implies, and what is probably obvious, is that the amplitude variation (amplitude variance) will directly contribute to the difference in reported powers. Finally, note that the mean-square power will *always* be greater than or equal to the mean-squared power (RMS power ≥ average voltage power).

Incorrect Assumption #2: *Average power is always calculated by averaging in Watts (linear).*

To continue with this example, assume that the average powers are themselves noisy. To remove some of the measurement noise, one may decide to apply an additional average: take multiple traces, compute each trace's average power, then average the powers across all traces (average of the averages). This is a common measurement requirement, particularly for low-level signals (in the case of the GSM ORFS Mod measurement, the standard dictates that the power results are to be averaged over 200 bursts). Eq. (4) shows the required calculation. To reiterate, each individual trace power ($P_{\text{Trace i}}$) is a *single number* calculated with Eq. (2) or Eq. (3) (either RMS power or average voltage power).

$$P_{\text{AVE}} = \frac{1}{N_{\text{Traces}}} \sum_{i} P_{\text{Trace i}} \tag{4}$$

It's reasonable to assume that the average will be computed with the $P_{\text{Trace i}}$ values in *Watts* (referred to as linear averaging). However, many analyzers offer the ability to average *logarithmically*. In this case, the "dBm"s are averaged. If, for example, given trace power averages of 1dBm and 3dBm, the linear average would be:

(1.25mW + 2mW) / 2 = 1.62mW = 2.11dBm.

On the other hand, the log average would be:

(1dBm + 3dBm) / 2 = 2.0dBm.

Log averaging the numbers introduces an error of 0.11dB.

In addition to the fact that averaging "dBm"s isn't really correct, there is a more subtle issue—for **repetitive** signals, linear and log averaging will produce the same result; thus, log averaging a repetitive signal introduces *no error*. Note that a repetitive signal is defined as a signal that has the same power vs. time trace for every sweep. The fact that a repetitive signal would give the same results regardless of the averaging type (linear or log) might not be intuitive, because taking the log of a number is a non-linear operation. However, it is trivial to demonstrate this fact. Starting with the equation for the log average, one has:

$$P_{\text{AVE, dBm}} = \frac{1}{N_{\text{Traces}}} \sum_{i} P_{\text{Trace i, dBm}} \tag{5}$$

The signal is repetitive, so $P_{\text{Trace i, dBm}}$ is the same value for all i. It's possible to drop the summation sign and rewrite Eq. (5) as:

$$
\begin{aligned}
P_{\text{AVE, dBm}} &= \left(\frac{1}{N}\right) N \cdot P_{\text{Trace, dBm}} \\
&= P_{\text{Trace, dBm}} \\
&= 10 \log\left(P_{\text{Trace, mW}}\right)
\end{aligned} \tag{6}
$$

So, regardless of the units used for P_{Trace} (mW or dBm), linear and log averaging will both produce the same result, provided the N values are identical. As a side note, it can also be shown that, in general, the log average will be equal to 10 times the log of the geometric mean of the linear trace powers:

$$
\begin{aligned}
P_{\text{AVE, dBm}} &= \frac{1}{N_{\text{Traces}}} \sum_i P_{\text{Trace i, dBm}} \\
&= \frac{1}{N_{\text{Traces}}} \sum_i 10 \log\left(P_{\text{Trace i, mW}}\right) \\
&= \frac{1}{N_{\text{Traces}}} \left(10 \log\left(P_{\text{Trace 1, mW}}\right) + 10 \log\left(P_{\text{Trace 2, mW}}\right) + \ldots + 10 \log\left(P_{\text{Trace N, mW}}\right)\right) \\
&= \frac{1}{N_{\text{Traces}}} \left(10 \log\left(P_{\text{Trace 1, mW}} \cdot P_{\text{Trace 2, mW}} \cdot \ldots \cdot P_{\text{Trace N, mW}}\right)\right) \\
&= \frac{1}{N_{\text{Traces}}} \left(10 \log\left(\prod_i P_{\text{Trace i, mW}}\right)\right) \\
&= 10 \log\left(\left(\prod_i P_{\text{Trace i, mW}}\right)^{\frac{1}{N_{\text{Traces}}}}\right)
\end{aligned} \tag{7}
$$

The fact that non-repetitive signals could produce different results is worth remembering, particularly because real-world operation conditions can differ from lab test conditions. Laboratory test signals are typically repetitive, given that they are often generated from an Arbitrary Waveform Generator (ARB). The ARB just plays back the same waveform over and over again, so it's repetitive by definition. Real-world signals are not, because they typically contain useful information that is changing in real time. Provided there isn't a large difference in the average power from trace to trace, the differences between log and linear averaging are small.

Let's now look at a real example that shows how a non-repetitive signal affects both the *per-trace* power average (either RMS or average voltage) and the power average taken across a number of traces (either linear or log). **Figure 2** is a plot of two traces of an EDGE burst with a constantly changing payload (pseudo-random sequence, PN15). The middle portion of the signal is repetitive; this is the GSM/EDGE Training Sequence, which is constant from burst to burst. However, the data portions on either side of the Training Sequence are changing from burst to burst. **Table 1** shows the results of calculating the RMS power (mean-square) and average voltage power (mean-squared) on 20 bursts, looking over the second data portion of the burst. Also, the linear and log average of all the bursts has been calculated.

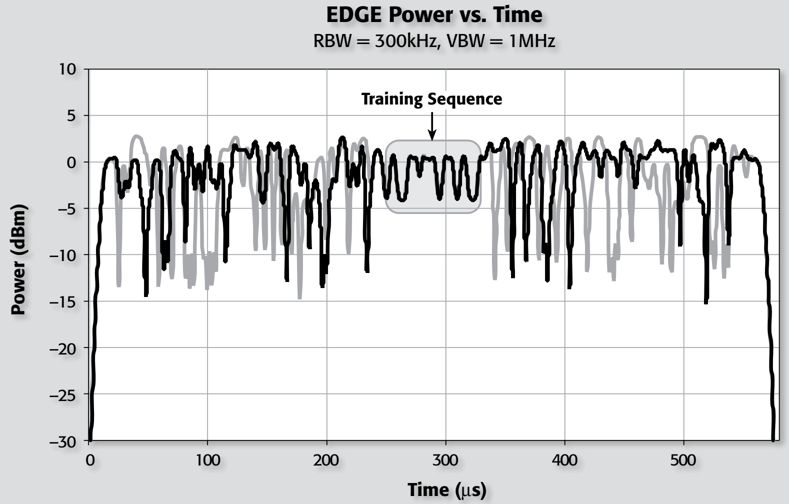


Figure 2. Non-repetitive EDGE signal

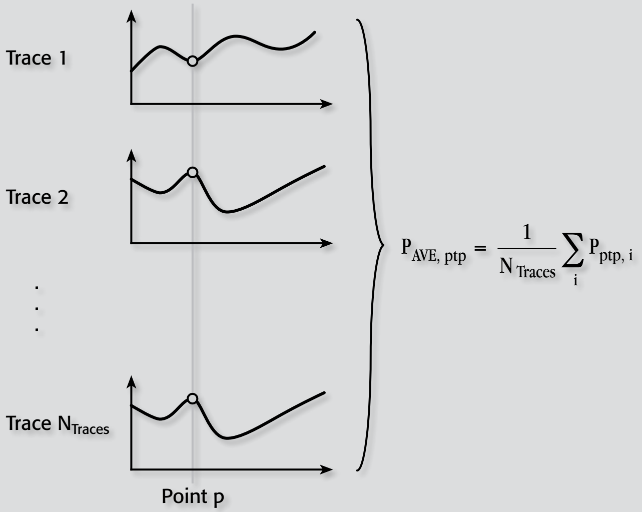
First, note that if one takes the "average of the average trace powers" for *either* RMS power *or* average voltage power, the difference (delta) between the linear and log average of all trace powers is very small for both RMS power and average voltage power (deltas of 0.02dB and 0.03dB respectively). That's because the average power values for all traces are reasonably close, in the sense that there isn't a large peak-to-peak swing across the averages. On the other hand, the differences between the RMS power and average voltage powers are significant if one looks at each trace *individually*—always at least 0.5dB, and approaching 0.75dB. What is more important, however, is that the difference is changing on a *trace-by-trace* basis. Again, the portion of the burst under examination is non-repetitive. The nice thing about repetitive signals is that, even though there will be a difference between RMS and voltage average power, the difference will be constant (if one were to measure power across the Training Sequence portion of the burst, this is exactly what would be found). For the current signal, however, the max to min difference is ~0.4dB. When one looks back at **Figure 2**, the large deltas aren't very surprising. This signal in particular has ~10dB of amplitude swing, and the larger the amplitude swing is, the larger the difference between RMS and average voltage power will be. Incidentally, this is not a contrived "worst-case" signal. The EDGE specification allows for even more amplitude swing, which will obviously increase the size of the difference.

Table 1. Results of calculating the RMS power (mean-square) and average voltage power (mean-squared) on 20 bursts

Trace #	Trace RMS Power (dBm)	Trace RMS Power (mW)	Trace Average Voltage Power (dBm)	Trace Average Voltage Power (mW)	Trace RMS – Ave Voltage Delta (dB)
1	−1.01	0.793	−1.65	0.684	0.64
2	−0.11	0.975	−0.74	0.843	0.63
3	−0.54	0.883	−1.05	0.785	0.51
4	−0.37	0.918	−0.91	0.811	0.54
5	−1.10	0.776	−1.81	0.659	0.71
6	−0.31	0.931	−0.77	0.838	0.46
7	−0.98	0.798	−1.69	0.678	0.71
8	−0.25	0.944	−0.78	0.836	0.53
9	−0.41	0.910	−1.04	0.787	0.63
10	−0.20	1.047	−0.12	0.973	0.32
11	−1.52	0.705	−2.15	0.610	0.63
12	−1.31	0.740	−1.86	0.652	0.55
13	−0.12	0.973	−0.64	0.863	0.52
14	−0.97	0.800	−1.68	0.679	0.71
15	−1.11	0.774	−1.73	0.671	0.62
16	−1.13	0.771	−1.72	0.673	0.59
17	−0.70	0.851	−1.23	0.753	0.53
18	−0.98	0.798	−1.69	0.678	0.71
19	−0.51	0.889	−1.04	0.787	0.53
20	−0.12	0.973	−0.64	0.863	0.52
Linear Average of All RMS Trace Powers (dBm)	−0.64		Linear Average of All Average Voltage Trace Powers (dBm)	−1.21	
Log Average of All RMS Trace Powers (dBm)	−0.67		Linear Average of All Average Voltage Trace Powers (dBm)	−1.25	
RMS Lin – Log Delta (dB)	**0.02**		**Average Voltage Lin – Log Delta (dB)**	**0.03**	

> **Incorrect Assumption #3:** *Trace averaging is always performed by calculating a single "summary" number for each trace, then averaging across these summary numbers.*

Up to this point, two forms of averaging have been discussed: single trace averaging, where all or a portion of a signal is averaged to come up with single number (RMS or average voltage power), and multiple trace averaging, where the results of performing single trace averaging on each trace are themselves averaged together (average of averages). There is another type of spectrum analyzer power averaging that should be addressed, which, for lack of a better term, can be called point-to-point averaging. Here, multiple traces are collected, and each trace point is averaged against the corresponding points in all other traces. **Figure 3** is a graphical representation of how this works.



$$P_{AVE,\,ptp} = \frac{1}{N_{Traces}} \sum_i P_{ptp,\,i}$$

Figure 3. Point-to-point averaging

Again, each point is averaged with all of the points that occur at the same *x* value, resulting in an “average” trace. For this discussion, *x* will be time, but it could be frequency, and the same results would apply. As before, the points can be averaged either linearly or logarithmically. Once the averaging is complete, an additional average can be applied to the whole trace or part of it. If the waveform is repetitive, linear and log averaging will give the same average trace, because for each and every trace, a given point will have the same power. What happens when the waveform is not repetitive? **Figure 4** shows the average traces for both linear and log power averaging taken over 20 bursts of an EDGE signal with varying payload data. There is certainly a difference between the two traces, and it’s obvious that the log averaged trace has less power than the linear averaged trace. **Figure 5** shows the *difference* between the two traces at every point. Note that, as expected, the Training Sequence portion of the burst shows no difference between linear and log averaging (again, the Training Sequence is repetitive from burst to burst).

The difference arises from the way that log averaging exaggerates power swings. This is best illustrated by a simple example: assume one is measuring power at a specific point in time (or a specific frequency) over N bursts. The power is oscillating between two levels, for example, 0dBm and –10dBm; 50% of the power readings give 0dBm, and 50% give –10dBm. So, the peak-to-peak swing is, obviously, 10dB. What is the average power across the N bursts? Calculating the log answer is trivial: –5dBm. To calculate the linear average, one converts 0dBm and –10dBm to Watts, finds the average, and then

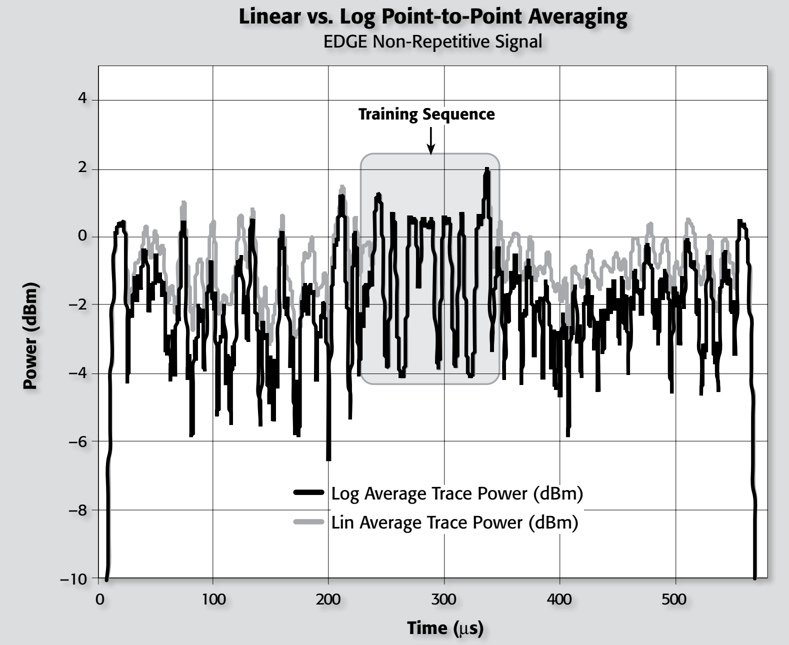


Figure 4. Linear vs. log point-to-point averaging

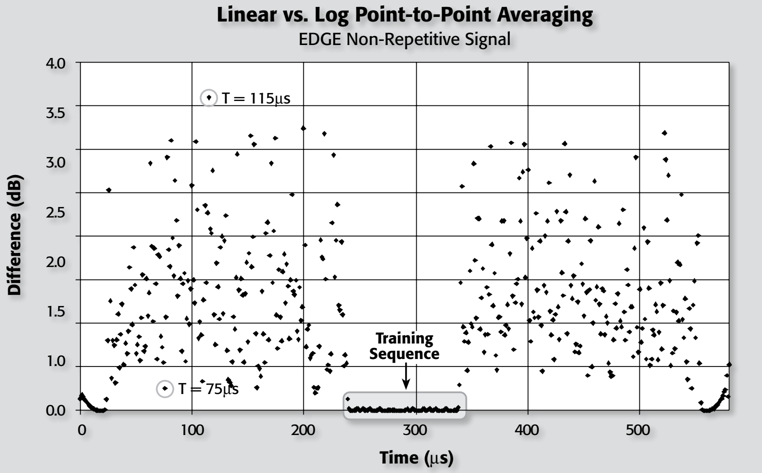


Figure 5. Linear vs. log delta

converts this number back into dBm units. The average power in Watts is 0.55mW, or –2.6dBm. Using log averaging introduces an error of 2.4dB.

To generalize the calculation, it's known that an *x*dB change is equal to a change of 10(*x*/10) in linear power. Therefore, it's possible to write the following equation, again assuming that 50% of the points are at one level M_{hi}, and the other are ΔdB down from that level:

$$\begin{aligned}
P_{\text{LinAve, dBm}} &= 10\log\left(\frac{M_{hi}+M_{hi}\cdot 10^{-\Delta/10}}{2}\right)\\
&= 10\log\left(\frac{M_{hi}\left(1+10^{-\Delta/10}\right)}{2}\right)\\
&= 10\log\left(M_{hi}\left(\frac{1+10^{-\Delta/10}}{2}\right)\right)\\
&= 10\log\left(M_{hi}\right)+10\log\left(\frac{1+10^{-\Delta/10}}{2}\right)
\end{aligned} \tag{8}$$

Note that, as Δ goes to infinity, $10\log\left(\frac{1+10^{-\Delta/10}}{2}\right)$ goes to –3dB. This means that, in the case of equal numbers of two different power levels, the resulting average linear power will be *at most* 3dB less than the higher power. It's possible to further generalize the result for an arbitrary ratio:

$$P_{\text{LinAve, dBm}} = 10\log\left(M_{hi}\right) + 10\log\left[r + (1-r)\cdot 10^{-\Delta/10}\right] \tag{9}$$

In Eq. (9), r is the ratio of the number of occurrences of the higher power (M_{hi}) to the total number of measurements (correspondingly, 1 – r is the ratio of the number of occurrences of the lower power to the total number of measurements). Note that when Δ goes to infinity, the resulting average power will be *at most* less than the higher power.

It's also possible to write the equation for the log average as:

$$\begin{aligned}
P_{\text{LogAve, dBm}} &= 10\log\left(M_{hi}\right)\cdot r + (1-r)\left(10\log\left(M_{hi}\right) - \Delta\right)\\
&= 10\log\left(M_{hi}\right) + \quad (r_{\Delta} - 1)
\end{aligned} \tag{10}$$

If Eq. (10) is subtracted from Eq. (9), the result is an expression for the difference between linear averaging and log averaging (this is the error introduced by log averaging):

$$P_{\text{Lin–Log, dB}} = 10\log\left[r + (1-r)\cdot 10^{-\Delta/10}\right] - \Delta(r-1) \tag{11}$$

Figure 6 plots Eq. (11) vs. Δ for various values of r (Eq. 11). The plot was limited to a Δ of 20dB because this is likely to be at the upper end of common Crest Factors. (Crest Factor is often referred to as the "peak-to-average" power ratio.)

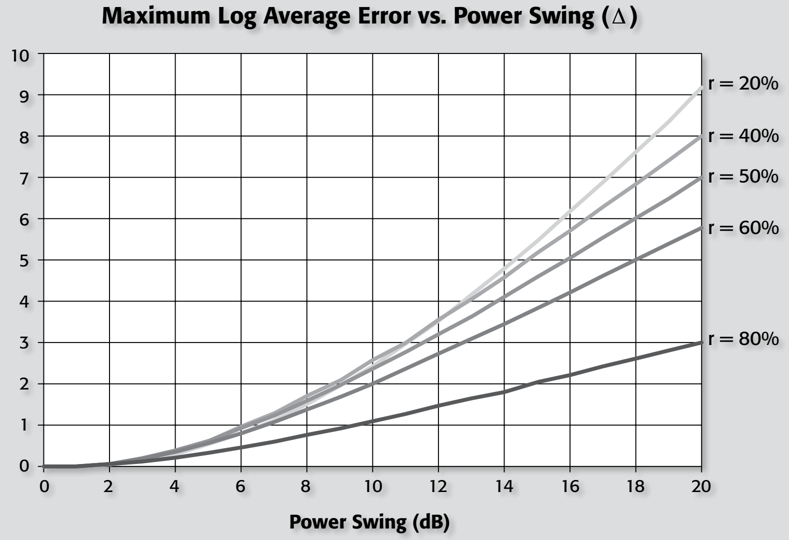


Figure 6. Maximum log average error vs. power swing

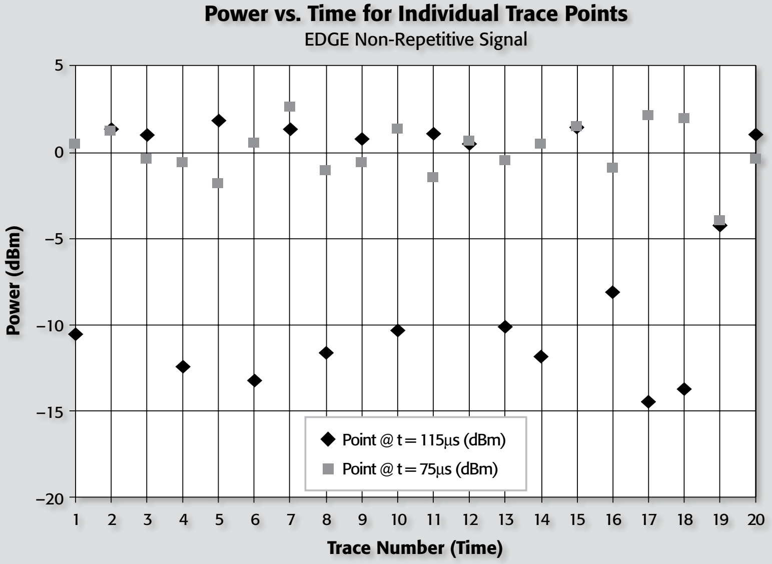


Figure 7. Power vs. time for individual trace points

As a sanity check, it would be helpful to look at a few points in some real data (refer back to **Figure 5**). Here, two points in time are highlighted, one with a relatively large power difference (more than 3.5dB at T = 115μs) and the other with a much smaller difference (~0.25dB at T = 75μs). From the previous discussion, it would be reasonable to expect the corresponding power vs. time plot for those points to look considerably different; the point with the high error should show quite a bit of power swing, while the low error point should show a smaller power swing. This is, in fact, the case, as seen in **Figure 7**. Here, the trace corresponding to the point at T = 115μs has ~15dB max amplitude swing, while the trace for the point at T = 75μs has ~5dB of swing. If one assumes that the high and low values occur equally (i.e., r = 0.5), then the trace for T = 115μs should have a maximum error of ~4.5dB, and the trace for T = 75μs should have a maximum error of ~0.5dB (see **Figure 6** and Eq. [11]). These values are greater than the measured 3.5dB and 0.25dB, but it's important to recall that the plot in **Figure 6** shows worst-case numbers (it assumes just two power levels, with equal numbers of each). One would expect the error to be smaller, since it's obvious there are more than two values (i.e., there isn't just a "high power" and a "low power").

Conclusion

In summary, engineers should keep in mind that spectrum analyzers don't always adhere to the "correct" way of calculating average power. Furthermore, the size of the potential errors introduced depends on the characteristics of the signal being analyzed. In particular, remember that it's important to:

- Understand the way the spectrum analyzer is calculating average power: RMS, voltage average, etc.
- Be aware that power isn't always averaged in linear units (Watts). Log averaging is also a possibility (averaging the "dBm"s).
- Repetitive signals can be misleading. The result may be either a static error (error is always the same and constant, for example, RMS vs. average voltage) or no error (linear vs. log averaging). Likewise, non-repetitive (or real-world) signals will have time-varying errors that depend on the signal swing.

As this discussion has illustrated, differences in averaging techniques can certainly lead to 1.0dB or more of error. The best way to understand how a particular spectrum analyzer calculates power averages is to pull a few traces out of the box and determine if manual calculations produce the same results as the analyzer does. While this can be a little tedious, it's well worth the effort if the application has reasonably tight accuracy requirements.

WiMAX: Understanding its signal structure and performing meaningful measurements

This application note is designed for engineers and scientists working on mobile WiMAX (802.16e-2005 OFDMA) products, either at the chip or product level. It assumes the reader has some knowledge of digital communication techniques, quadrature modulation techniques, and TDD (Time Division Duplexing) techniques and a basic understanding of OFDM concepts.

WiMAX is a very versatile modulation scheme, but with versatility comes complexity. This application note steps you through:

- The WiMAX physical layer,
- Generating signals based on differing signal layer parameters, including the addition of distortion, and
- Measuring and interpreting signals so you can use the results to improve the performance of your WiMAX device or end user product.

WiMAX Physical Layer Overview

The easiest way to understand WiMAX is to consider its behavior over time. For the TDD scheme, one downlink transmission (called the downlink subframe) is followed by one uplink transmission (called the uplink subframe). For FDD systems, the downlink subframes and downlink subframes are transmitted on two different frequencies permitting simultaneous transmission. The total time of the uplink and/or downlink subframes in addition to the transmitter transition gaps where not transmission occurs is called the frame as shown in **Figure 1**. The uplink and downlink subframes can be further broken into smaller time increments called an OFDM symbol

Before OFDM, digital modulation techniques such as GSM and W-CDMA transmitted a single symbol at a time. To increase the throughput of these older techniques that used serial transmission schemes, you could increase the symbol rate—A process that is very susceptible to channel effects at high symbol rates. OFDM actually slows the symbol rate down to reduce the channel effects, but transmits many symbols simultaneously on a number of closely spaced carriers called subcarriers.

The advantages of using OFDM goes well beyond its immunity to channel effects for mobile WiMAX. Using OFDM in combination with the high level of timing and frequency synchronization imposed by mobile WiMAX permits multiple radios to transmit at the same time within the same bandwidth. This is possible considering the individual OFDM subcarriers are orthogonal to each other and therefore do not interfere. Considering we have many subcarries that may be used at any given time, we can allocate one set of subcarriers to one user and another set of subcarriers for another user.

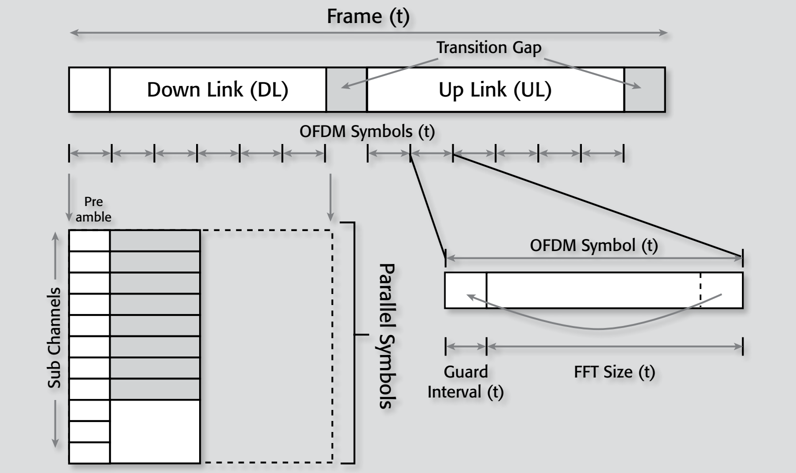


Figure 1. Creating a Mobile WiMAX signal

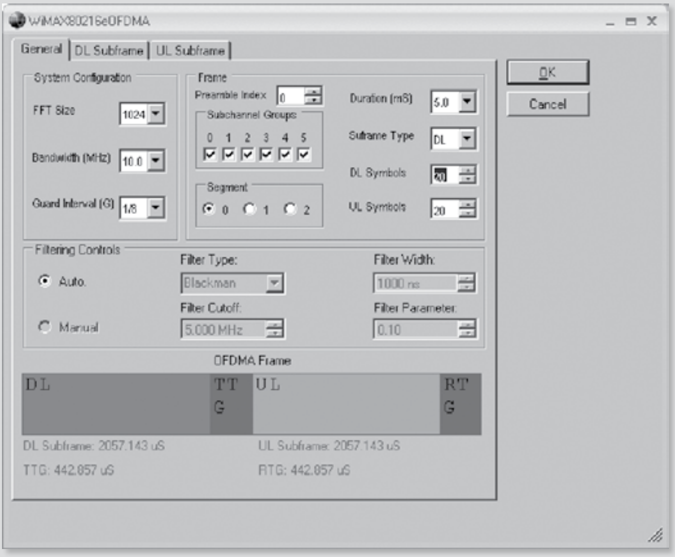
WiMAX groups subcarriers into sets called subchannels. The subcarriers within a subchannel are not necessarily adjacent and are frequently spaced across the entire signal bandwidth, but it is assured each subcarrier is assigned to only one subchannel. Considering the subchannels as the vertical access and the OFDM symbols as the horizontal axis as shown in **Figure 1**, we can create a map which depicts how data is allocated. The allocation of a certain region of the subchannel – OFDM symbol map is a burst. A burst may contain information for a specific user or information intended for all users.

Creating a WiMAX OFDM Signal

Using the Keithley SignalMeister™ Signal Creation Software, let's create a single QPSK burst occupying two OFDM symbols.

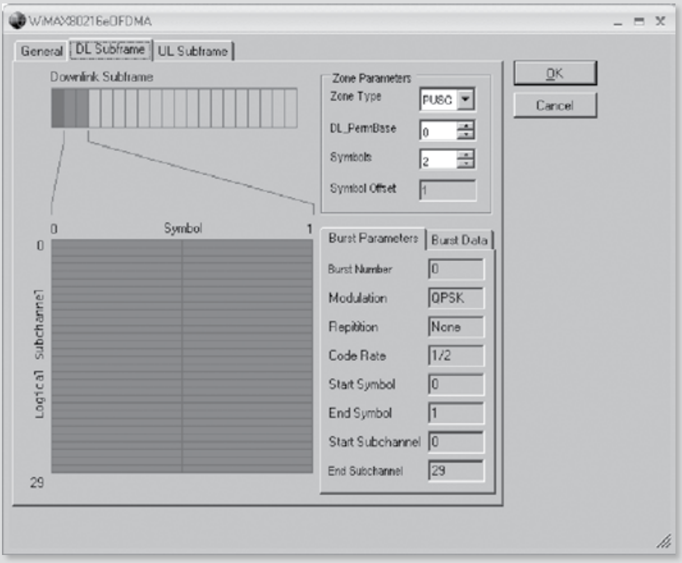
In the SignalMeister main screen, select the WiMAX example signal generation element from the left pane and move it to the main editing area. Double click on the icon and you will be presented with the WiMAX OFDMA signal setup screen (**Figure 2a**). This screen allows you to specify general system parameters such as the FFT (Fast Fourier Transform) size and the bandwidth the signal will occupy. In this example, we are using a 1024 point FFT and a 10MHz bandwidth. The bandwidth of the signal specifies the fundamental sample rate of the signal. The sample rate is equal to the bandwidth times the sampling factor (n). n is either 8/7 or 28/25 and depends on the bandwidth.

Table 1 shows the n for a sample of the possible bandwidths and specifies that n for a 10MHz bandwidth is 1.12 (28/25). Multiply n (1.12) by the channel bandwidth (10MHz) to



FFT Size: 1024
Bandwidth (MHz): 10.0
Guard Interval (G): 1/8
Preamble Index: 0
Subchannel Groups: 0 ☑ 1 ☑ 2 ☑ 3 ☑ 4 ☑ 5 ☑
Segment: ● 0 ○ 1 ○ 2
Duration (mS): 5.0
Subframe Type: DL
DL Symbols: 30
UL Symbols: 20
● Auto. ○ Manual
Filter Type: Blackman
Filter Cutoff: 5.000 MHz
Filter Width: 1000 ns
Filter Parameter: 0.10
DL Subframe: 2057.143 uS
TTG: 442.857 uS
UL Subframe: 2057.143 uS
RTG: 442.857 uS

Figure 2a. WiMAX OFDM signal setup screen



Zone Type: PUSC
DL_PermBase: 0
Symbols: 2
Symbol Offset: 1
Burst Number: 0
Modulation: QPSK
Repitition: None
Code Rate: 1/2
Start Symbol: 0
End Symbol: 1
Start Subchannel: 0
End Subchannel: 29

Figure 2b. Downlink Subframe screen

Figure 2. Configuring a WiMAX signal in SignalMeister

find the sample rate (11.2 Msps). The subcarrier spacing can then be calculated by dividing the sample rate by the FFT size of 1024. This yields a subcarrier spacing of 10.9375kHz.

Table 1. Over-Sampling Rate

Bandwidth	Sampling Rate
1.25MHz	28/25
5MHz	28/25
3.5MHz	8/7
5MHz	28/25
10MHz	28/25
20MHz	28/25

Without the channel effects caused by multi-path, we would simply make the OFDM symbol period equal to the number of samples to make one complete FFT period. That would be approximately 91.4μs in this case (1024/11.2Msps). Due to multi-path, a guard interval is insterted which extends the OFDM symbol by duplicating a portion of the end of the original FFT period at the beginning of the OFDM symbol. In our example, we select a 1/8 Guard Interval. Since the FFT period (or useful portion of the symbol) is periodic, we copy the last 1/8 of the useful symbol period and paste it to the front without creating a discontinuity. This process adds 11.425μs (91.4μs/8) to the length of our symbol, which gives an overall symbol time of 102.9μs. This is the OFDM symbol duration.

We have specified 20 OFDM symbol periods for the uplink and downlink.subframes Select the Downlink Subframe tab to see the 20 OFDM symbol periods (**Figure 2b**). For the downlink, the first OFDM symbol is used for the pre-amble, leaving 19 OFDM symbol periods for the zone allocations . In this example, the Zone Type was set to PUSC (Partial Usage of Subcarriers) with two OFDM symbols representing.

Table 2. Number of subchannel allocations per FFT size

FFT Size	PUSC Subchannels (downlink/uplink)	FUSC Subchannels (downlink only)
128	3/4	2
512	15/17	8
1024	30/35	16
2048	60/92	32

In **Figure 1**, we have a burst occupying two OFDM symbols on the horizontal axis as well as a number of subchannels on the vertical axis. In **Table 2**, we see that the number of subchannels is dependent on FFT size.

Notice that in **Figure 2b** we are using QPSK. WiMAX uses an Adaptive Modulation and Coding (AMC) scheme to dynamically change the modulation type based on channel conditions. This allows us to choose the best modulation scheme for our single burst occupying two OFDM symbols. If the signal-to-noise ratio is addequate, then 64QAM could be used rather than QPSK or 16 QAM.

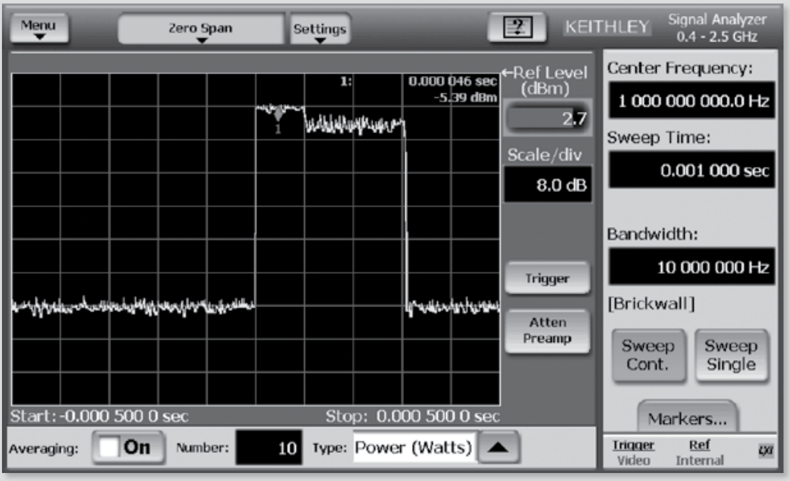
Analyzing a WiMAX OFDM Signal

Frequency and Time Measurements

Now that we have defined the signal, we can download it to a Series 2900 Vector Signal Generator (VSG) and begin to analyze its behavior using a Series 2800 Vector Signal Analyzer (VSA). **Figure 3** shows a time domain representation of the signal. From the discussion above, we know that our OFDM symbol period is 102.9μs and that the first symbol period is the preamble and the next two symbols are our DL User 1.

The Sweep Time sets the X-axis time base. Each vertical grid line is set to 100μs, so we can see approximately one symbol between two consecutive grid lines. To trigger a signal, set the video Trigger to a value that provides a stable signal. This allows us to easily see that the first part of the signal is the pre-amble, corresponding to the 102.9μs OFDM symbol period, and that the signal after the pre-amble and within the following two grid lines is the two OFDM symbols that represent our downlink user. By setting the correct bandwidth, 10MHz in this case, and changing the Detector Type to Power Average (using the Settings tab) we can use the cursor to make accurate measurements of the average power in the pre-amble and the power of the user data OFDM symbols. As Series 2800 instrumentation have touch screens, the position of the cursor can be changed by simply moving your finger across the screen. (It should also be noted that Series 2800 VSAs are optimized for measuring the power of digitally modulated signals.)

In **Figure 3**, the Sweep Time is set to 1000μs, or roughly 10 OFDM symbol periods (one symbol between two consecutive grid lines). The Series 2800 Trigger point is defined as the screen's center, so we can see that the start point is 500μs before the



1: 0.000 046 sec -5.39 dBm

Ref Level (dBm) 2.7

Scale/div 8.0 dB

Center Frequency: 1 000 000 000.0 Hz

Sweep Time: 0.001 000 sec

Bandwidth: 10 000 000 Hz

[Brickwall]

Start: -0.000 500 0 sec

Stop: 0.000 500 0 sec

Averaging: ☐ On

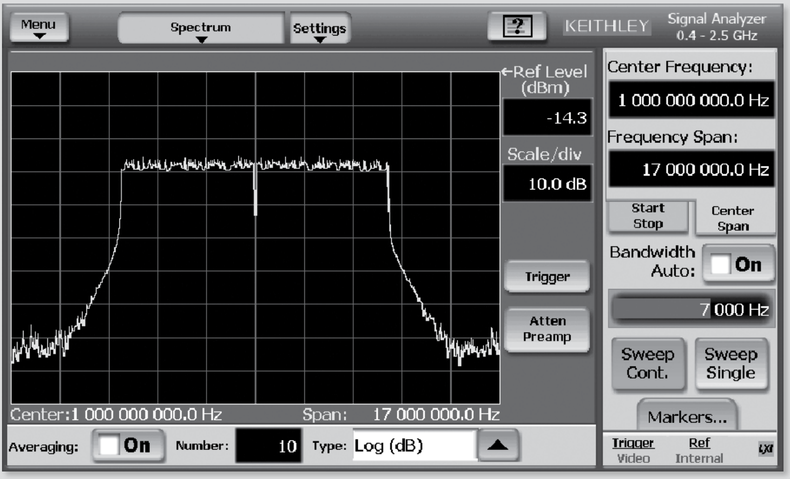
Number: 10

Type: Power (Watts)

Trigger Video

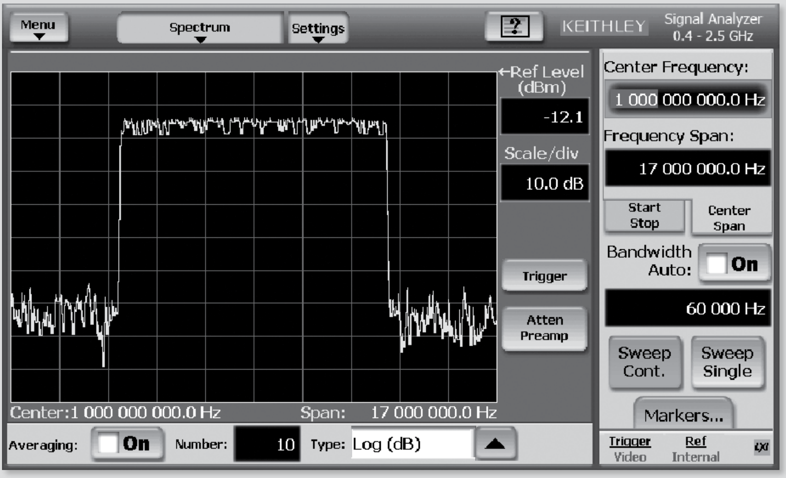
Ref Internal

Figure 3. A generated WiMAX signal in the time domain



←Ref Level (dBm): -14.3
Scale/div: 10.0 dB
Center Frequency: 1 000 000 000.0 Hz
Frequency Span: 17 000 000.0 Hz
Bandwidth Auto: ☐ On
7 000 Hz
Center:1 000 000 000.0 Hz
Span: 17 000 000.0 Hz
Averaging: ☐ On
Number: 10
Type: Log (dB)
Trigger: Video
Ref: Internal

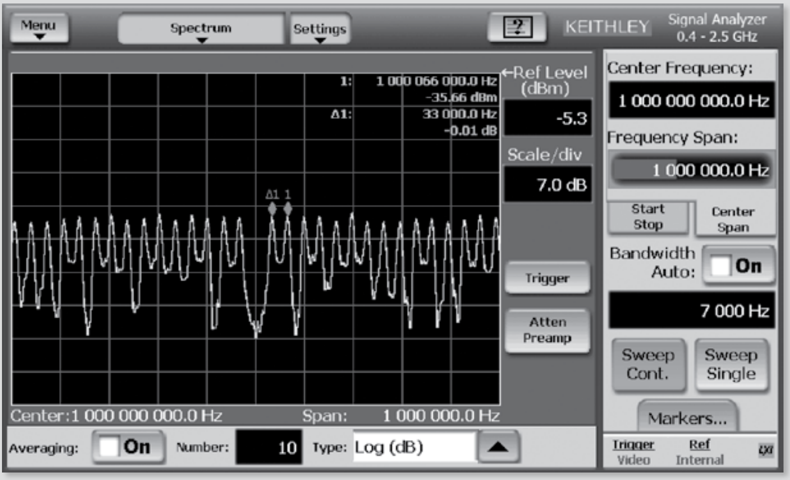
Figure 4a. Spectral spread due to the burst



←Ref Level (dBm): -12.1
Scale/div: 10.0 dB
Center Frequency: 1 000 000 000.0 Hz
Frequency Span: 17 000 000.0 Hz
Bandwidth Auto: ☐ On
60 000 Hz
Center:1 000 000 000.0 Hz
Span: 17 000 000.0 Hz
Averaging: ☐ On
Number: 10
Type: Log (dB)
Trigger: Video
Ref: Internal

Figure 4b. Spectral spread due to modulation

trigger, shown by the number –500μs, and the stop point is +500μs after the trigger point. If we now switch to the spectrum display (**Figure 4**) we see the WiMAX signal correctly triggered. **Figure 4a** shows the spectral characteristics of the signal. (Note we are still observing the Power Average of the signal.) The spectral spread of the signal is caused by both the burst and modulation components of the signal.



1: 1 000 066 000.0 Hz -35.66 dBm
Δ1: 33 000.0 Hz -0.01 dB
Ref Level (dBm) -5.3
Scale/div 7.0 dB
Center Frequency: 1 000 000 000.0 Hz
Frequency Span: 1 000 000.0 Hz
Bandwidth Auto: ☐ On
7 000 Hz
Center:1 000 000 000.0 Hz Span: 1 000 000.0 Hz
Averaging: ☐ On Number: 10 Type: Log (dB)
Trigger Video Ref Internal

Figure 5. OFDM carriers

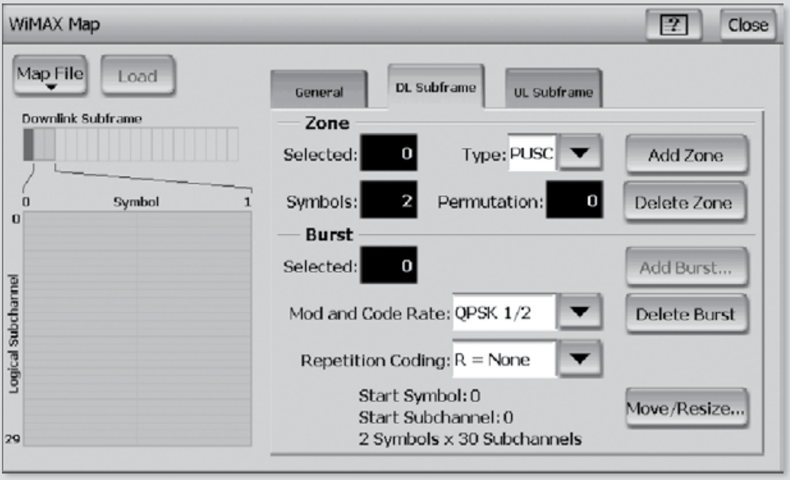
The acquisition time of the signal is approximately 3/bandwidth, so for this measurement we are acquiring 3/7kHz or 400μs seconds. That equates to a window starting 200μs before the trigger point and 200μs after, which in this setup encompasses the rising edge of the signal. By changing the bandwidth to 60kHz, the acquisition time is now plus and minus 25μs of the center trigger point, giving an overall trigger time of 50μs (approximately one half of an OFDM symbol). By setting the trigger delay to 25μs, we can see the spectral spread due to the pre-amble data, demonstrated in **Figure 4b**.

If we now set our bandwidth back to 7kHz and set the span to 1MHz, we can resolve some of the individual OFDM carriers. This is shown in **Figure 5**. In this case we see every third OFDM subcarrier, denoted by the 33kHz carrier spacing and the suppressed CW (continuous wave) in the center of the screen.

Demodulating and Measuring a Signal at the Transmitter

RCE and EVM

In many digital modulation schemes EVM (Error Vector Magnitude) is a fundamental measure of quality. It is a measure of the difference between the measured vector positions relative to the expected positions, and it is reported as a percentage. RCE (Relative Constellation Error) was chosen as the modulation quality metric for WiMAX, and like EVM is the difference between the measured vector positions relative to the expected vector positions. It is reported in dBs rather than percent.



Zone

Selected: 0

Type: PUSC

Symbols: 2

Permutation: 0

Burst

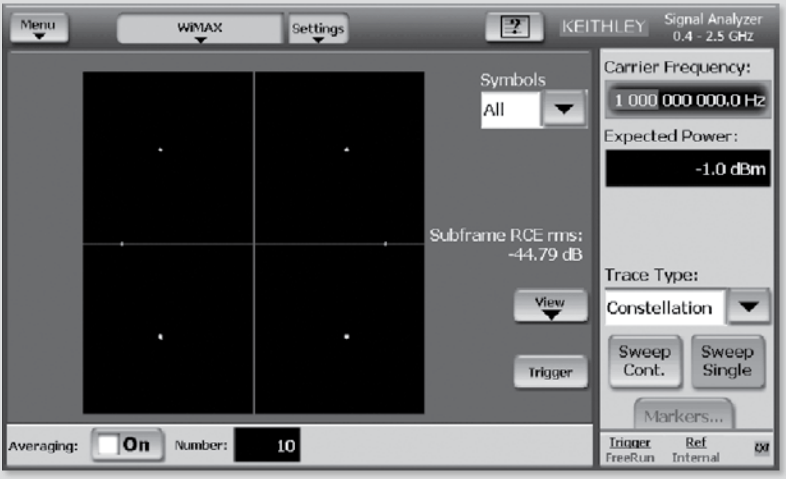
Selected: 0

Mod and Code Rate: QPSK 1/2

Repetition Coding: R = None

Start Symbol: 0
Start Subchannel: 0
2 Symbols x 30 Subchannels

Figure 6a. WiMAX map with QPSK modulation over the entire burst



Symbols: All

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: -1.0 dBm

Subframe RCE rms: -44.79 dB

Trace Type: Constellation

Averaging: On

Number: 10

Trigger: FreeRun

Ref: Internal

Figure 6b. Demodulated WiMAX signal

Configuring the VSA with a WiMAX Map File

In order to demodulate a signal and measure RCE, the receiver most know the configuration of the downlink signal. This can be done in two ways. The first method is to create and download to the Series 2800 VSA a WiMAX map file at the same time you create and download the corresponding signal file to the Series 2900 VSG. The second method is to define your own WiMAX map file in the WiMAX setup screen of the Series

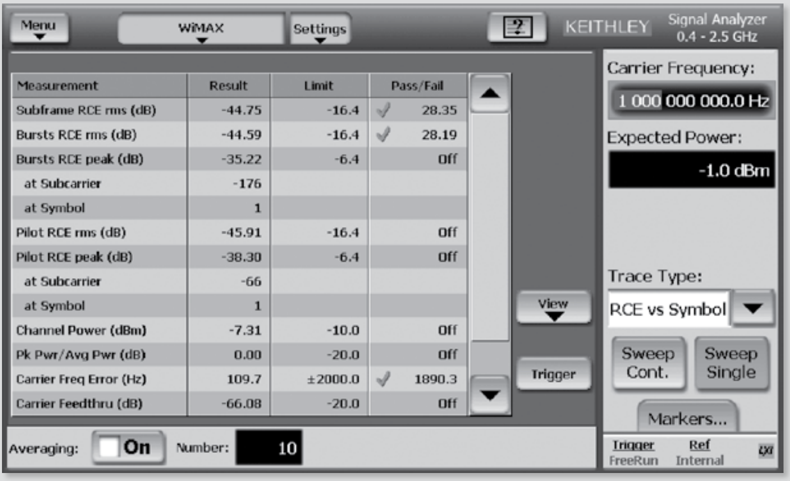
2800 as shown in **Figure 6a**. This can be edited using the instrument's touch screen. **Figure 6b** shows the demodulated signal.

The constellation of the QPSK signal is the user downlink data. The points that make up the square in **Figure 6b** are QPSK. The outerlying points on the horizontal line are the constellation of the BPSK pilot symbols. Pilot carriers are used for receiver synchronization.

Viewing Measurement Data

Series 2800 VSAs can display measurement data in a number of ways. By selecting the View, you can see a pictorial representation or a graph view of the measurement data. In our example, these are a constellation diagram (**Figure 6b**) or a list of all the measurement results in table format (**Figure 7**). In **Figure 7**, notice that a limit can be set for each parameter as well as a Pass/Fail indicator.

The constellation diagram and RCE measurements provide a clear idea of the instantaneous performance of the transmission. Using the Trace Type selector shown in **Figure 6b**, we can observe in the frequency domain the flatness of the signal and the RCE measurement over the subcarrier. In the time domain, we can measure RCE over the OFDM symbol and also monitor how RCE changes over longer periods of time using the RCE history display.



Measurement	Result	Limit	Pass/Fail
Subframe RCE rms (dB)	-44.75	-16.4	✓ 28.35
Bursts RCE rms (dB)	-44.59	-16.4	✓ 28.19
Bursts RCE peak (dB)	-35.22	-6.4	Off
at Subcarrier	-176		
at Symbol	1		
Pilot RCE rms (dB)	-45.91	-16.4	Off
Pilot RCE peak (dB)	-38.30	-6.4	Off
at Subcarrier	-66		
at Symbol	1		
Channel Power (dBm)	-7.31	-10.0	Off
Pk Pwr/Avg Pwr (dB)	0.00	-20.0	Off
Carrier Freq Error (Hz)	109.7	±2000.0	✓ 1890.3
Carrier Feedthru (dB)	-66.08	-20.0	Off

Carrier Frequency: 1 000 000 000.0 Hz

Expected Power: -1.0 dBm

Trace Type: RCE vs Symbol

Averaging: ☐ On Number: 10

Trigger FreeRun Ref Internal

Figure 7. Measurement results in table format

More Complex Signals

So far we have only analyzed a QPSK signal. This type of modulation format is used when the signal conditions are poor since it works robustly in limited signal-to-noise ratio conditions. The drawback is that you can only transmit two data bits per symbol. If the signal or channel conditions are good, then the WiMAX system can choose a higher modulation type that requires good signal-to-noise ratios such as 16QAM or 64QAM.

In our original example, we had a Zone with one downlink burst consuming a period of two OFDM symbols. The subchannels, ultimately the subcarriers, were modulated with QPSK. Keeping the same Zone type (a two OFDM symbol time) we shall now add three downlink bursts consuming an equal amount of subchannels each. One burst modulates its subcarriers with QPSK, the second uses 16QAM, and the third uses 64QAM. **Figure 8a** shows the setup and **Figure 8b** shows the demodulated signal.

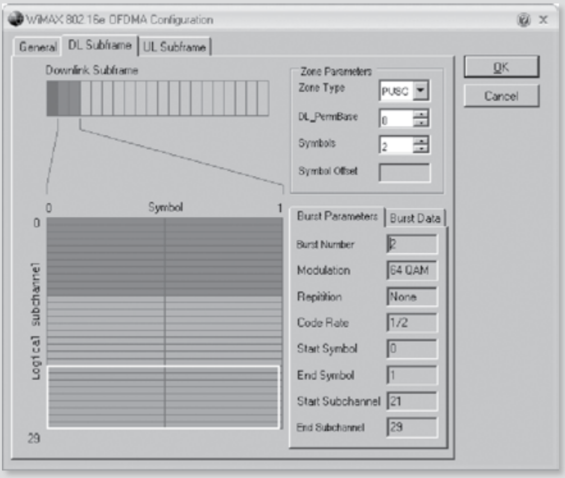
Stressing the transmitter with this type of signal is important since each modulation format can behave differently. Because 64QAM requires the highest signal-to-noise ratio (this can be seen in the constellation diagram by the outermost symbols), it deteriorates more than the QPSK element (which is represented by vectors located near the center of the diagram). Frequency selective attenuation in the channel will cause the WiMAX transmitter to choose which carriers are modulated with 64QAM or QPSK.

If we now change the view to RCE vs. Subcarrier, we can see the RCE performance of each of the active subcarriers. Referring to **Table 3**, we can examine the relationship between FFT sizes (the total number of subcarriers) vs. the active subcarriers for the downlink. Note that the active subcarriers contain both pilots and data transmitting subcarriers.

Table 3. FFT size and how each subcarrier is utilized

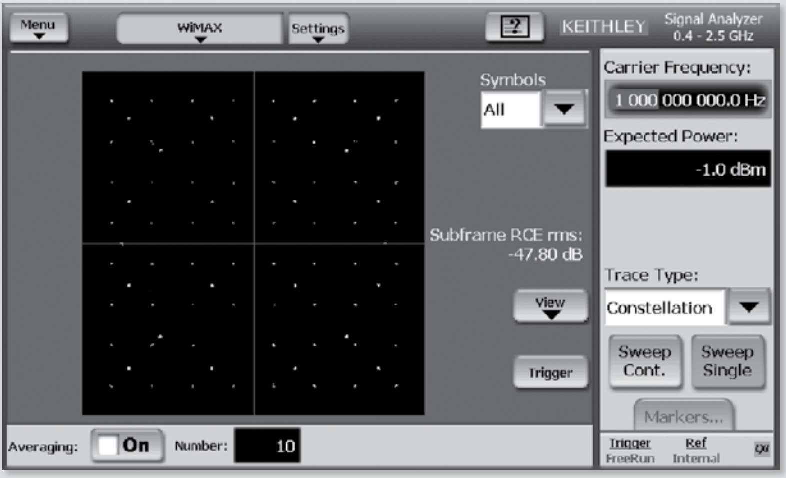
Bandwidth	FFT Size	Guard	Pilot	Data	Active
5MHz	512	92	60	360	420
10MHz	1024	184	120	720	840
20MHz	2048	368	240	1440	1680

Activating the cursor allows us to measure the RCE of each of the subcarriers. The generated signal has a bandwidth of 10MHz using a 1024 point FFT. **Table 3** tells us that 840 carriers from the original 1024 are used to transmit this signal. Each subcarrier within an OFDM system is numbered outward from the center carrier. Subcarriers below the main carrier in frequency have a negative number, and subcarriers above the main carrier have a positive number. The 840 carriers used to transmit the signal will be numbered from 0 to –420 and 0 to +420. This can be verified by changing the Trace Type from Constellation to RCE vs. Subcarrier, as shown in **Figure 9**. Entering a cursor position of 420 or –420 moves the cursor to the outermost subcarriers.



Zone Type: PUSC
DL_PermBase: 0
Symbols: 2
Symbol Offset:
Burst Number: 2
Modulation: 64 QAM
Repitition: None
Code Rate: 1/2
Start Symbol: 0
End Symbol: 1
Start Subchannel: 21
End Subchannel: 29

Figure 8a. A single zone with three user bursts

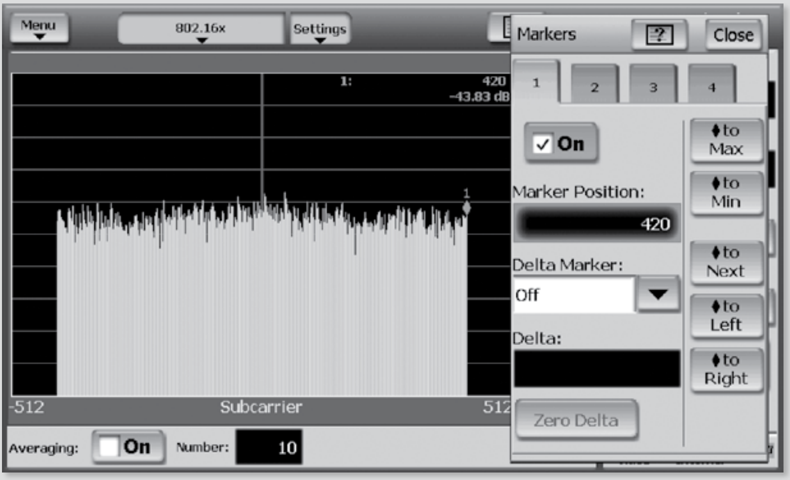


Symbols: All
Carrier Frequency: 1 000 000 000.0 Hz
Expected Power: -1.0 dBm
Subframe RCE rms: -47.80 dB
Trace Type: Constellation
Averaging: On
Number: 10
Trigger: FreeRun
Ref: Internal

Figure 8b. Demodulating the three bursts

Receiver Measurements

Validating the sensitivity of the receiver is a key performance indicator, especially with respect to the Received Signal Strength Indicator (RSSI) metric. Measuring the sensitivity of the device requires some kind of feedback from the chipset in terms of the packet errors (PER) or bit errors (BER), or the test equipment must be able to facilitate



☑ On

Marker Position: 420

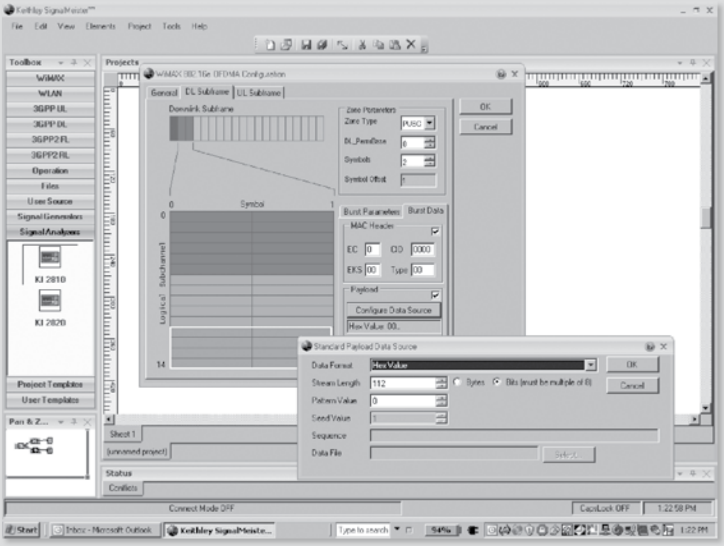
Delta Marker: Off

Averaging: ☐ On

Number: 10

Figure 9. RCE vs. subcarrier

a loop-back bit or packet-error measurements. **Figure 10** shows how to configure the MAC header and payload to facilitate Packet or Bit Error Rate Measurements.



Zone Type: PUSC

DL_PermBase: 0

Symbols: 2

Symbol Offset: 1

EC: 0 CID: 0000

EKS: 00 Type: 00

Hex Value: 00...

Data Format: Hex Value

Stream Length: 112 ○ Bytes ● Bits (must be multiple of 8)

Pattern Value: 0

Seed Value: 1

Sequence:

Data File:

Figure 10. Modifying the MAC header and payload data

Understanding WiMAX 802.16e Mobile

Imaging taking every radio transmission concept you know and making it part of a single standard. Welcome to 802.16e mobile WiMAX. The following discusses the WiMAX signal structure and its many elements, ranging from TDMA, OFDMA (orthogonal frequency division multiple access), and MIMO.

Like GSM, 802.16e can have a time division component—the purpose of which is to differentiate the uplink from the downlink signals. That's the easy part.

It also uses OFDM to ensure fast data rates, but by keeping the symbol rate slow per carrier, it can be more resilient to multi path effects. An OFDM signal in the frequency domain can have hundreds of carriers transmitting symbols in parallel, but unlike 802.11b/g, 802.16e (mobile WiMAX) uses different groups of these carriers to facilitate different links between multiple users.

Multiple users are facilitated by allocating groups of subcarrier symbols in the time domain to different users; these are called bursts. A burst can have different types of modulation, depending on the link quality and number of users trying to use the link. Groups of bursts are mapped to different channels, or more properly termed as subchannels. A subchannel can then be a group of subcarries within the OFDM spectrum. The subcarriers within a subchannel are not necessarily adjacent and can change from one OFDM symbol to the next. Groups of subcarriers are called segments. Segments are useful when the base station has multiple sectors, ensuring that each antenna only transmits or receives unique groups of subcarriers.

Finally, the Wave 2 variant or evolution uses MIMO configurations to improve coverage and throughput. Matrix A and B configurations use a 2×2 radio for coverage and throughput respectively. Matrix C further improves throughput by using a 4×4 radio.

Which Domain?

In mathematics, the best way to analyze and understand any complex problem is to convert it into a domain that makes analysis relatively simple. Unfortunately for 802.16e, we need to traverse many domains to be able to say, "I really understand how it works."

The Time Domain

Figure 1 represents part of an 802.16e signal over time. 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 that we call this time increment the OFDM symbol, not just the symbol time. As with any digital radio, the symbols are structured in time:

- We begin with a preamble, then
- A downlink map,

- Some information we wish to receive (DL Burst, for now we'll consider a burst as some consecutive symbols),
- A transition gap,
- The information we wish to transmit through the uplink burst, and
- Another transition gap before the cycle starts afresh.

802.16e can use either time division duplexing or frequency division duplexing between the uplink and the downlink bursts. But wait, the preamble is just a single symbol in length, so a receiver can't do much with that, can it?

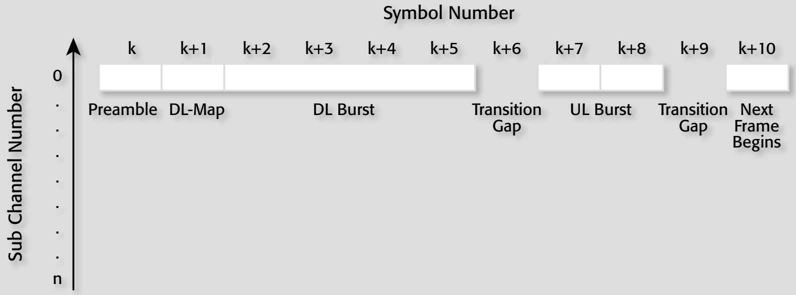


Figure 1. An example 802.16e signal over time

The Symbol Domain—Symbol Subchannel vs. Symbol Time

A fundamental concept of OFDM is to employ an inverse FFT to transmit many slow symbols in parallel. The larger the IFFT size, the more symbols you transmit simultaneously using more carriers. Therefore each instance in time or OFDMA symbol period 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 WiMAX does employ an adaptive modulation scheme so 16QAM or 64QAM could be used depending on the link quality and number of subscribers.

Therefore, in every OFDM symbol period, we transmit multiple symbols in parallel. In fact, we can transmit between 128 to 2048 symbols per OFDM symbol period. How the 802.16e signal is constructed and behaves over time is defined in the symbol map (**Figure 2**). The symbol map is essentially a two by two matrix of symbols; the vertical are the parallel symbols (the vertical axis is labeled Subchannel Logical Number in **Figure 2**) and the horizontal axis represents how these symbols behave over time. The subchannels are not actually physical channels, but groupings of parallel symbols that are transmitted every OFDM symbol period.

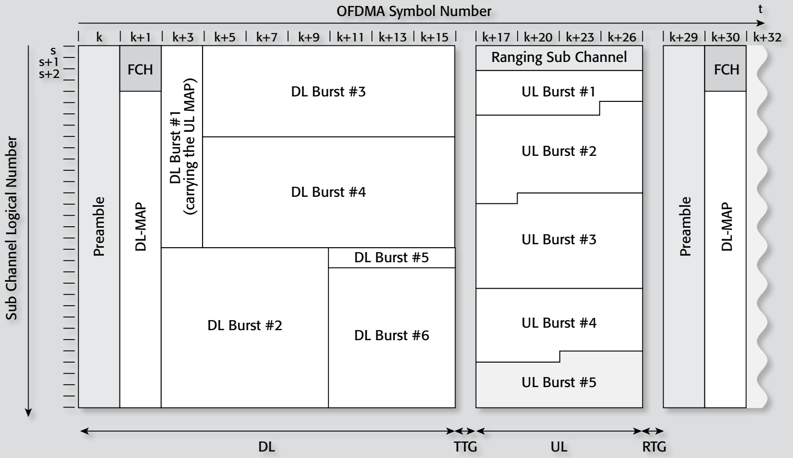


Figure 2. Example symbol map (where: FCH is Frame Control Header, RTG is Receive/Transmit Transition Gap, and TTG is Transmit/Receive Transition Gap)

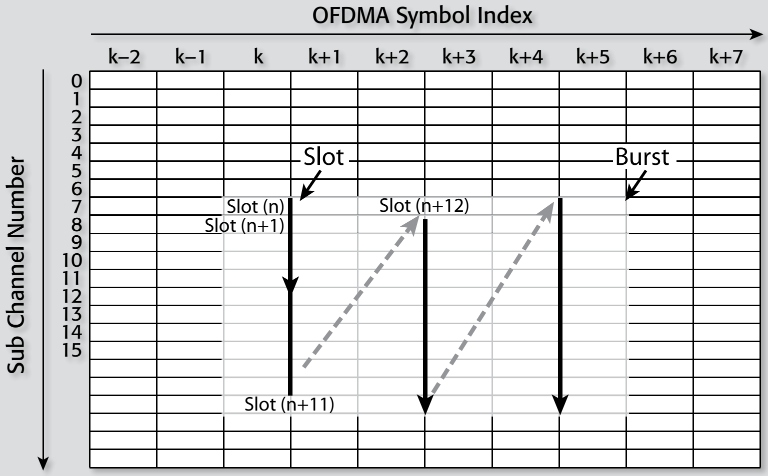


Figure 3. Bursts are made out of multiple slots

An instance of a single symbol allocated to a specific subchannel is called a slot. In **Figure 1** we can see that the preamble is represented by one symbol allocated to subchannel zero. This is a minimal definition of a slot. A slot can be between one and three symbols, but always uses a single subchannel. Data is transmitted in bursts;

bursts contain an integer number of slots and correspond to a contiguous section of the subchannel symbol map. You can see how the bursts are made out of multiple slots in **Figure 3**.

The Frequency Domain

The OFDM symbol period on the X-axis of the symbol map (**Figure 2**) is constant, regardless of the size of FFT used for the parallel symbols making up the subchannels. What this means in the physical frequency domain is that the subcarrier spacing is fixed at 10.94kHz. For example, if a 128 point FFT (or 128 parallel symbols) is employed, the channel bandwidth will be 1.25MHz and, conversely, a 1024 point FFT (or 1024 parallel symbols) yields a bandwidth of 10MHz. The ability to change the number of parallel symbols in this way and in turn the bandwidth of the actual physical signal is called SOFDM or Scalable OFDM.

As I mentioned earlier, the subchannels are not in fact physical channels. They are mapped to physical channels (**Figure 4**) by using two main schemes, diversity and contiguous. The Diversity scheme assigns physical subcarriers in a pseudo random fashion. This scheme can be used in two ways: FUSC, or Fully Used Subcarrier, (available for downlink only) and PUSC, Partial Used Subcarrier. The first uses all the available carriers, the second allocates a subset. The Contiguous subcarriers scheme in WiMAX is called band adaptive modulation and coding (AMC). This scheme allocates subchannels to users based on their frequency response.

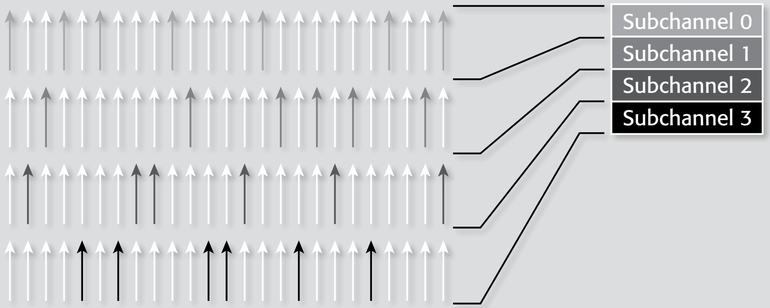


Figure 4. Subchannels are mapped to physical channels

The Diversity scheme has benefits in mobile applications as it provides frequency diversity and inter-cell interference averaging. The Contiguous scheme improves the system's capacity, however, it is less robust in high mobility applications.

The Spatial Domain

MIMO (Multiple Input, Multiple Output) adds yet another dimension to mobile WiMAX. Often referred to as smart antenna technology, MIMO involves more than multiple antennas; it requires multiple radio transmitters and receivers as well. In a traditional radio configuration, SISO (Single Input, Single Output), multiple radios transmitting simultaneously require some form of multiplexing, either in frequency, time, or code, in the case of CDMA. In a MIMO configuration, spatial multiplexing is employed. This simply means that all radios transmit on the same frequency, occupying the same bandwidth. This gives a number of benefits; you can multiplex the symbols across all the radios and improve your throughput, or you can transmit the same symbols on all the radios and improve the signal to noise ratio.

Mobile WiMAX has provision for both of these configurations. Looking at a two stream system (two transmitters and two receivers), the Matrix A configuration uses a redundancy technique and transmits the inverse of each symbol on the second transmitter. This technique improves the coverage. The Matrix B configuration improves throughput by transmitting different symbols on each stream.

One of the key benefits of MIMO and one of its key original uses is the ability to align RF energy to specific users through the process know as beam forming. Many of the standards for commercial systems including WiMAX have provisions for MIMO beam forming or closed loop MIMO. Beam forming has the benefit of delivering more capacity to users, but increases the complexity of the device since an array of transmitters, receivers, and antennas are required to control the direction and shape of the radiated signal. The direction and shape are a function of the channel environment. Techniques such as channel sounding are used to mathematically model the channel, then the correct phase and amplitude of the beam can be established.

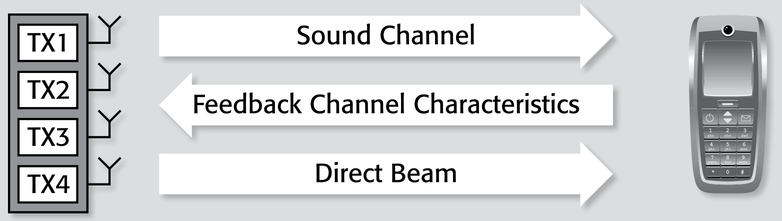


Figure 5. A closed loop MIMO system

Mobile WiMAX uses two techniques for beam forming—statistical Eigen Beam Forming (EBF) and Maximum Ratio Transmission (MRT). The first is good when the user is moving, because it can quickly build a channel model then form the beam. The second builds a very accurate channel model, thus improving throughput and coverage; however, the disadvantage of the system is that it has a longer processing time, making it unpractical for users who are moving.

Conclusion

This paper has discussed some of the key elements of WiMAX, ranging from TDMA, OFDM, and MIMO, including bean forming. As you can see, WiMAX is probably the most flexible radio architecture introduced to the market so far. It has provisions for not only many types of service but also due to its scalability the ability to work in many different types of environment, where, for example, broad spectrum is not available. As the market and technology move forward, we will see many more systems based on similar concepts such as the next generation of cellular communications, often referred to as LTE or the Long Term Evolution of cellular.

Spectrum and vector analysis

There are many analyzers available in the market today. Some are very specialized, and others offer more generic radio measurement capability; some are called spectrum analyzers, and others are called signal analyzers. All measure and display frequency vs. amplitude and most demodulate the signal displaying metrics such as EVM.

Understanding Performance

What is meant by performance? The choice of mixers, LOs amplifiers, A/D converters, IF FPGA/ASIC, and microprocessor all contribute to cost and performance. For example, a single loop local oscillator design may be very cost effective, however, it may introduce enough phase noise distortion to render the measurements useless. Or a low cost microprocessor may seem attractive from a cost perspective, however, if the analyzer uses this microprocessor for complex signal demodulation, then the spectrum analyzer will execute the measurement at a very slow pace.

Here are innovative ways to provide performance while keeping cost and, ultimately, price under control:

- **To sweep or not to sweep:** Many traditional analyzer manufactures still use a sweeping architecture. While this is good for μWave and mmWave spectrum analysis, many new innovative RF analyzer suppliers forgo this traditional sweep system and create a similar—in most cases better—measurement using signal processing techniques. The Keithley Series 2800 Vector Signal Analyzers are great examples of this.
- **Measurement speed:** When thinking about buying an analyzer, a good question to ask is how is the measurement data processed? Some instruments use multiple processors to get a fast result, while others leave the main processor for general instrument housekeeping and use an FPGA or ASIC to execute the measurement. Some just have a single microprocessor to do all the work. Obviously, while the latter is the most cost effective for the supplier, ultimately, as modulation schemes such as OFDM become more complex, using a single microprocessor is not a sustainable speed advantage. The Keithley Series 2800 provides the industry's highest performance measurement infrastructure, using a unique high speed architecture based on an FPGA-based IQ measurement engine.

Frequency Range

One of the largest contributors to instrument price is the frequency range. Many analyzers have frequency breaks around 2.5GHz, 6GHz, 13GHz, and 26GHz. High performance instrumentation can often go up to 50GHz. If you are working on cellular products or products that operate in the ISM band, such as 802.11b/g wireless LAN devices, often the most cost effective analyzer would be one with an upper frequency range of less than 3GHz or 6GHz.

CW Measurements

Let's take a look at the simple spectral situation illustrated in **Figure 1**. Here we have two signals: a CW, or carrier wave, and a smaller interfering signal. The carrier wave has a number of components. It has amplitude, frequency, phase noise, and broadband noise. The amplitude is the spectral energy emitted by your device at a specific frequency. The phase noise, represented by the skirt of the signal, tells you how stable or spectrally pure your signal is. Usually the local oscillator in your product contributes to the phase noise of the signal. To the left we see an unwanted signal, or a spurious signal. This signal may be due to a large transmitter close by or it could be generated by some other part of your system; for example, it could be derived from the sample clock.

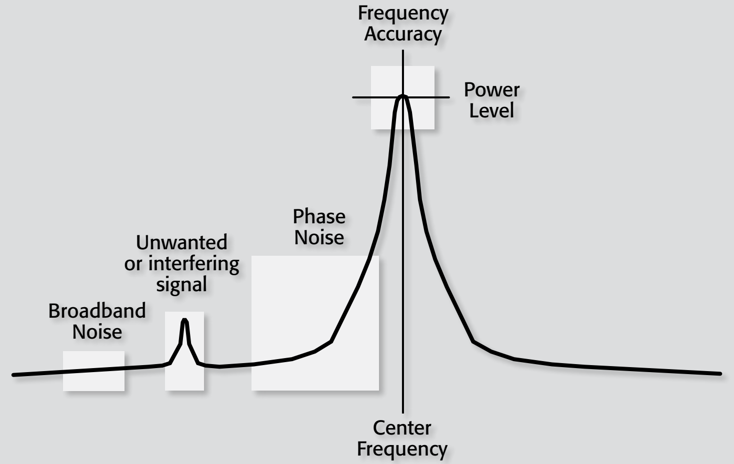


Figure 1. Basic signal characteristics

Amplitude Measurements

Originally, spectrum analyzers where not designed for absolute amplitude measurements. Over the years, advanced calibration techniques have constantly improved analyzers' ability to measure power. However, many analyzers in the market today are still primarily designed to measure the power of a CW signal using a marker, which is not a reliable method for determining the power of a digitally modulated signal. Some analyzers use a conversion technique to change a Gaussian filter based marker measurement to that of a broadband power measurement. Instruments like the Keithley Series 2800 have been designed from the ground up to measure digital signal power and have definable filters such as RRC and Brickwall so the power measured by the marker is correct.

Noise Measurements and Low Level Signals

When measuring noise and/or low level signals, make sure that your analyzer has a pre-amp. Also, again take a look at the analyzer's measurement architecture. Analyzing low level signals often means you'll want to set a very narrow span. When you compare the speed performance in narrow spans across a number of analyzers, you'll notice swept based analyzers slow down considerably, while analyzers that employ digital signal processing techniques don't suffer this type of degradation. Finally, you'll want to express your noise measurement result in terms of noise density within a certain bandwidth. Unlike other analyzers that define the resolution bandwidth as the 3dB point on a Gaussian shaped filter, the Keithley Series 2800 can specify its filters as noise bandwidths, making it very easy to perform this type of measurement. Also, with enhanced DSP sweeps, 1Hz filter measurements can be performed with relatively fast sweep times.

Intermodulation Measurements

This type of measurement determines the distortion a device or system may create when stressed under specific signal conditions. Looking at **Figure 2**, we can see we are stimulating our device with two CW carriers, or tones. The tones are causing the device to generate distortion that can easily be seen in the frequency domain as the two distortion products, left and right of the input tones. As the analyzer is also a receiver with active components in its signal path, there is a risk that the analyzer can also generate this type of distortion, invalidating the measurement. One easy check to verify the signal's integrity is to increase the attenuation setting of the analyzer. If the signal reduces in amplitude as you increase the attenuation, then the products are generated by the analyzer. If changing the attenuation has no effect on the products,

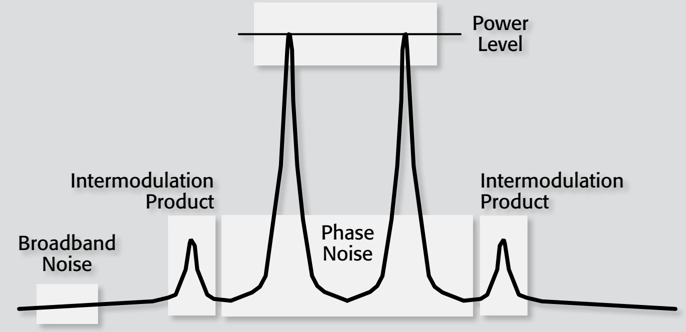


Figure 2. Two tones (non-linear amplifier distortion)

then the measurement is valid. When you increase the attenuator value, you will notice that the noise floor increases by the same amount of dBs. This is so the amplitude of the carrier remains constant with different levels of attenuation. The increase in noise floor, however, could mean that the noise could mask the intermodulation product.

To get the best measurement performance, fine attenuator steps are important. Coarse attenuation steps can move the noise floor by 10dBs, quickly masking the signals that you want to measure.

The ability to measure small signals in the presence of large signals is a key use of any type of spectrum analysis instrument – this performance attribute is defined as the dynamic range of an instrument. Dynamic range is often expressed as a combination of the analyzer's third order intermodulation performance (the two tone measurement we discussed above), the instrument's noise floor performance, and its phase noise. It is often quite difficult to directly compare the dynamic range of an instrument, as different manufactures can optimize the instrument for noise floor performance or distortion performance. An easy way to relatively compare the dynamic range of multiple analyzers is to examine the W-CMDA adjacent channel power. This measurement takes into account all of the above parameters. When measuring an OFDM signal, be aware that simple two tone intermodulation measurements will not help you understand how your amplifier performs. Signals with varying peak-to-average ratios or crest factors need to be used to adequately stress the device under test.

Modulated Signals

So far, we've only looked at carrier wave (CW) signals. Modulated signals present a whole new challenge, especially when they have a high peak-to-average ratio. When measuring modulated signals, you need to ensure that your spectrum/signal analyzer has the ability to not only measure the spectrum of the signal, but also the ability to differentiate between the peak and average power of symbols and the ability to measure the quality of the modulation.

Figure 3 shows a typical digitally modulated signal in the frequency domain. This signal uses a modulation scheme that does not have a constant power envelope, so its amplitude varies over time. A key measurement an analyzer must be able to perform is the average power of this type of signal. This is usually specified over a defined bandwidth. The intermodulation and phase noise distortion manifest itself in the skirts of the signal. The adjacent channel power feature of the analyzer helps quantify the intermodulation and phase noise performance of the device under test.

The ability to demodulate the signal and express the quality of the signal in terms of a metric such as EVM (error vector magnitude) is a key requirement for modern analyzers. Key analyzer performance characteristics that enable this type of measurement are the instruments digitizing bandwidth and its corresponding frequency and phase response. For example, the Keithley Series 2800 has the ability to capture and digitize signals up

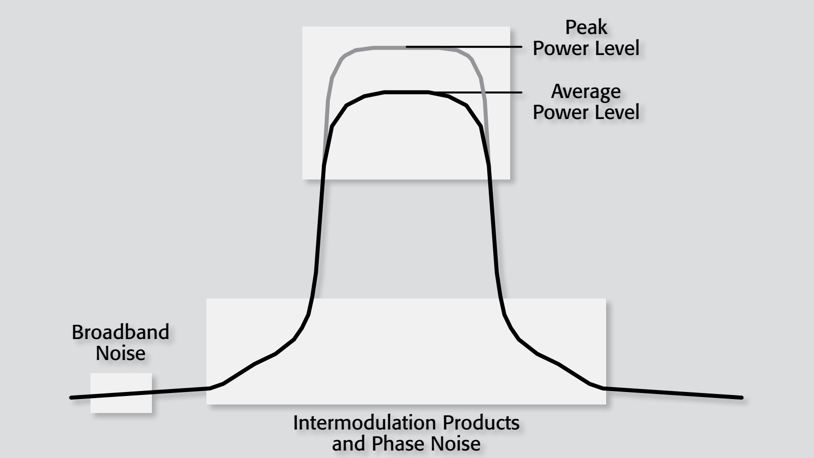


Figure 3. Modulated signal

to a maximum bandwidth of 40MHz. For popular modulations schemes such as GSM, W-CDMA, WLAN, or WiMAX demodulation and quality metrics are often built into the analyzer. However, your choice of analyzer needs to adapt to evolving communications technologies. **Figure 4** shows how a Series 2800 can be used as a calibrated IQ acquisition engine. In this measurement setup, a Series 2800 is capturing a signal from the device under test and storing it as calibrated IQ pairs in its 50 megasample memory. You can then export this record from the instrument and import it in to any commercial analysis package, such as MATLAB.

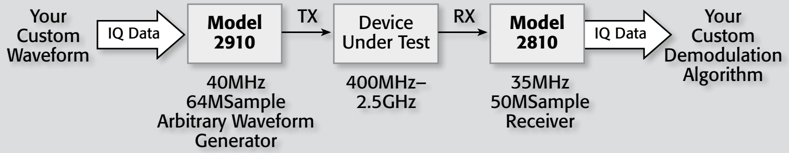


Figure 4. Model 2810 as a calibrated IQ acquisition engine

Analyzer Connectivity

Most modern analyzers are LXI-C compliant. LXI (LAN eXtension for Instrumentation) is a standard that defines instrument connectivity over LAN. There are three versions of the LXI standard: A, B, and C. C means you can control the instrument over LAN, and it contains a web server for remote operation. For example, if you are sharing measurement information across global teams, you simply type the IP address for the analyzer into your web browser, and the analyzer's display appears in your web browser. B and A are still evolving. They are super sets of C that provide more advanced measurement triggering functionality.

Of course, today most of your instruments are still controlled through the GPIB interface. When choosing an analyzer, ensure that it has the connectivity for your legacy test needs using GPIB and is set for the future with at least LXI class C compliance.

With the advent of LAN enabled instruments, Internet security and safety are becoming key issues, especially across large enterprise systems. For example, if an instrument is based on Windows® XP, it has all the characteristics of a PC. You'll need to talk with your IT Department to put it on the network, and it is susceptible to viruses and attacks just like any other PC. Some instrument manufacturers have chosen Linux for this reason, although this in turn reduces the instruments' connectivity to Microsoft® based tools. The Keithley Series 2800 uses Windows CE, which is a good compromise between operating systems, offering both connectivity and safety.

Summary

Signals are changing at a rapid rate. At one time most devices could be characterized with a simple CW stimulus. Today with complex modulation schemes such as OFDM presenting devices with very large peak to average ratios, signal analyzers need to measure a signal's power and the quality of the signal's modulation as well as the compression characteristics being observed.

Also, with radio architectures moving from SISO (Single Input, Single Output) to MIMO (Multiple Input, Multiple Output) topologies, a simple upgrade path is needed that will enable instruments to meet the new measurement challenges presented by this technology shift.

Software-defined radio: the next wave in RF test instrumentation?

Test equipment manufacturers are constantly challenged to develop new solutions for testing their customers' latest devices, but they've traditionally developed specialized hardware to meet this challenge. The communications market is still more challenging due to the rapid development of new standards, which often require new stimulus and measurement capabilities. To keep pace, test vendors must find new approaches that reduce instrument development times and allow instruments to adapt to new requirements. Software-defined radio is one technique that can help.

Software-Defined Radio (SDR) can be defined as a radio communication system that uses software to modulate and demodulate radio signals. Economics is the driving force behind the growing use of SDR. These systems can achieve high flexibility at a lower cost than traditional analog designs. **Figure 1** illustrates an SDR system.

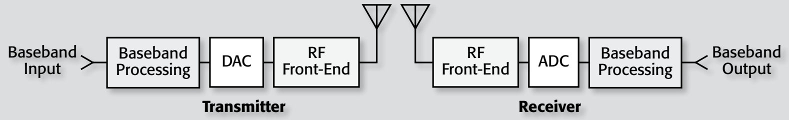


Figure 1. Software-defined radio system

In the purest sense, digital-to-analog (D/A) and analog-to-digital (A/D) conversion would occur at the carrier frequency and no analog up- and down-conversion would be required. Today's SDR applications typically have at least one analog up- and down-conversion stage. Clearly, the A/D and D/A converters are key elements of an SDR system. The speed and resolution of the converters will determine how much analog frequency conversion is required. Converters need sufficient resolution (bits) to produce or capture the modulation data adequately, and more complex modulation formats will require converters with even greater resolution. The speed of the converters will limit the maximum signal frequency that can be created or sampled. Converter technology continues to advance, providing higher combinations of resolution and frequency.

Digital signal processing is another key element of SDR because it performs several functions traditionally performed with analog circuitry, including frequency conversion, modulation, demodulation, and filtering. Digital signal processing also allows better performance than analog designs by supporting functions such as waveform pre-distortion and decimation. Pre-distortion of transmitted waveforms takes into account the known non-linearity of the analog circuitry and modifies the baseband waveform to compensate for it, producing a better quality modulated signal.

Three basic approaches can be used to implement digital signal processing. The first approach is to do all the signal processing in software using generic computing resources, such as those provided in PCs. The second approach is to define a logic circuit to perform the signal processing, then program that circuit into a field programmable gate array (FPGA). The third approach is to use programmable hardware devices designed to implement the functions required for digital signal processing. These devices include digital signal processors (DSP) and digital up-conversion (DUC) and digital down-conversion (DDC) devices.

All three approaches can fulfill the primary objective of SDR: providing a highly flexible system. However, to control costs, the other primary objective of SDR, it's important to consider both development and per-unit costs. The cost of the solutions will vary, influenced largely by the system's real-time bandwidth requirements. Wider bandwidths will require more processing power, driving up costs. However, for a moderate level of performance, the FPGA approach will likely be the most expensive solution, while the DSP system will likely be the least expensive.

Frequency generation is a key element of any communications system. Direct digital synthesis (DDS) is a technique for using a D/A converter to create sine waves at very precise frequencies. Direct digital synthesis allows for very fast frequency switching at a low cost. Advancements in semiconductor technology have led to rapid progress in DDS technology as well. Today's DDS devices can produce sine waves with frequencies of several hundred megahertz with microhertz frequency resolution.

SDR approaches are increasingly popular for applications that demand economical flexibility, such as military communications systems and multi-function cellular base stations. These applications tend to share the following characteristics:

- Moderate to high flexibility requirements
- Low to moderate volumes
- Moderate to high complexity

Test instrumentation shares many characteristics with the other applications that employ SDR techniques. Test instrumentation tends to be very complex because of the level of performance required to measure leading-edge systems with a reasonable margin. Test instrument volumes can be considered low to medium when compared with high volume items like cell phones or base stations. Flexibility continues to be an important characteristic in test instrumentation, especially in the area of communications.

The key technical and economic requirements in test instrumentation related to communications include wide modulation and demodulation bandwidth, wide dynamic range, and fast throughput.

Digital communication systems have changed rapidly in recent years, particularly in the area of modulation formats. New standards mean that test instruments like signal sources must be able to generate new modulation waveforms and signal analyzers must be able to demodulate and analyze them. Key performance parameters tend to vary from standard to standard, so new analysis routines are often required.

These changes have created a demand for test instruments that can be upgraded quickly and easily to add new modulation standards rather than forcing their owners to replace them. While upgradeability is obviously desirable from a cost standpoint, it's equally desirable from a time-to-market perspective. Communication system and device manufacturers can't afford to wait for the next generation of test equipment to be developed. Communications standards also change frequently during development, which can require modifications to signal generation and analysis routines.

These requirements make SDR a very desirable approach for test instrumentation. The same cost and performance tradeoffs that apply to generic SDR applications apply to test instruments. The first SDR test instruments used either the software processing or the FPGA approach. Advances in digital signal processing devices like DSPs and DDC/DUCs provide the power to make that approach viable for test instruments. This approach can provide the best balance of cost and performance for test equipment.

Test instruments employing SDR techniques offer advantages to both equipment manufacturers and their customers:

- Easy upgradeability to new communication standards. Signal generation and analysis are largely performed by routines programmed into the digital signal processor. When new standards emerge, it's easy to create new DSP programs for the new functions and distribute them to the owners of existing instruments via firmware upgrades.
- Improved throughput due to faster frequency switching and signal analysis. Wide bandwidth A/D converters and fast DSP devices can process large FFTs very efficiently. For example, a DSP-based analyzer can provide measurement times several orders of magnitude faster than traditional spectrum analyzers, under conditions of wide spans and narrow resolution bandwidths. Direct digital synthesis provides significantly faster frequency switching than traditional approaches allow. Fast frequency switching will improve the throughput of both signal generators and signal analyzers.
- Faster time to market for test instruments. Test equipment manufacturers can leverage the capability of leading-edge, commercially available signal processing devices and achieve instrument-level performance from them. This reduces the amount of development required for test instruments dramatically. Also, the basic digital design can be shared across a range of instruments, further reducing development costs. For example, **Figure 2** shows the digital architecture used in Keithley Instruments' Model 2810

Vector Signal Analyzer and Model 2910 Vector Signal Generator. Both instruments share the same digital processing design.

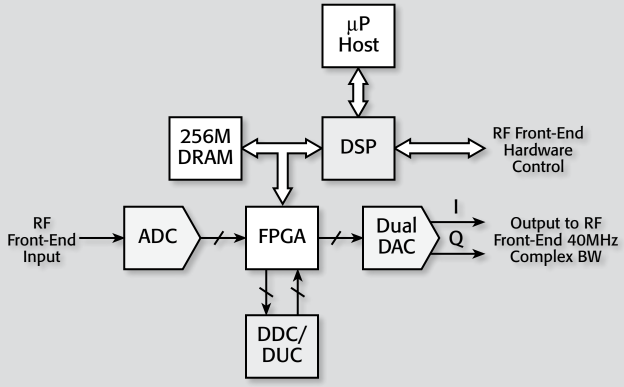


Figure 2. Digital architecture of the Model 2810 Vector Signal Analyzer and Model 2910 Vector Signal Generator

Communication standards are likely to continue evolving. At the same time, test cost pressures from communication system and device manufacturers will keep forcing test equipment vendors to provide cost-effective instruments that offer continuing performance value. Together, SDR techniques and high end signal processing devices provide test equipment manufacturers with invaluable tools to meet these requirements.

Communicating with a Series 2800 Vector Signal Analyzer and a Series 2900 Vector Signal Generator from MATLAB®

For engineers developing and analyzing RF waveforms in MATLAB, a Series 2800 Vector Signal Analyzer (VSA) and a Series 2900 Vector Signal Generator (VSG) are powerful companions. The following describes how to use these industry leading instruments as a cost effective RF front end to MATLAB—generating the data using an ARB (arbitrary waveform) file on the VSG and analyzing the data by extracting the I/Q time record from the VSA for analysis in MATLAB.

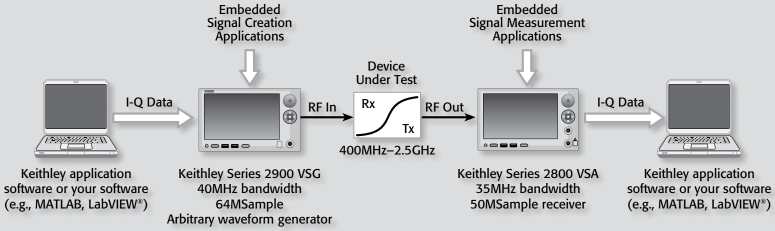


Figure 1. Communicating with a Series 2800 vector signal analyzer and a Series 2900 vector signal generator

There are three choices for connecting MATLAB code to instruments. You can use a GPIB card with the MATLAB instrument control library to communicate over GPIB. You can use socket communications from the MATLAB instrument control library. The third choice is to write a LabVIEW® wrapper around MATLAB using LabVIEW's instrument control capability.

Introduction

The following describes how to connect MATLAB to Keithley's Series 2800 and 2900 RF instruments. Because the details of the connection will vary depending on how the connection is made, the paper is divided according to connection type:

- GPIB: Use a GPIB card and the MATLAB instrument control library. This is the best way to get up and running quickly. The bus transfer speed isn't as high as a LAN, but there are fewer setup issues.
- LAN: Use the socket controls in the MATLAB instrument control library. This setup is more complex, but does not require GPIB hardware.
- LabVIEW: Use the LabVIEW/MATLAB script interface. If you already have LabVIEW instrument control available to you, the MATLAB script interface in LabVIEW 8.2 is an effective method of adding instrument control and

graphical interfaces. LabVIEW can connect to the instruments using GPIB, LAN, or USB.

Connecting to MATLAB using GPIB

In order to do this, you will need MATLAB 7.0 or later and the MATLAB instrument control library (available at additional cost from MathWorks). In addition, you will need a GPIB card installed on your computer, plus a GPIB cable to connect to the instrument. GPIB has been the industry standard for instrument control for several decades and is very reliable. If you want to get a working connection in the least amount of time, I recommend GPIB.

Establishing a connection to an instrument through GPIB from within MATLAB requires that you know:

- The GPIB address of the instrument (usually 10 for a Series 2800 instrument and 12 for a Series 2900)
- The name of the GPIB card within the computer (usually GPIB0)
- The manufacturer of the GPIB card (National Instruments is used in this example)

MATLAB uses the concept of single session—once it connects to an instrument, the information is shared with all the routines that need to communicate with that instrument. As such, to talk to the instrument, you first look up a session using the instrfind() function, which returns a reference to an instrument object that may already be connected to the instrument. If it is not, be prepared to create a session with all the correct parameters. In order to ensure robust operation, the code below also checks for unusual conditions, such as multiple open sessions and a session that has been created but is not open.

```
% Build the VISA ID string to pass into instrfind and visa call.
interface='GPIB0';
GPIBAddr='12';
visaID=[interface '::' num2str(GPIBAddr) '::0::INSTR'];
% Grab existing if already open
obj1 = instrfind('Type', 'visa-GPIB', 'RsrcName', visaID, 'Tag', '');

% Create the VISA-GPIB object if it does not exist
% otherwise use the object that was found.
if isempty(obj1)
    obj1 = visa('ni', visaID);
    % Set properties
    obj1.InputBufferSize=500000;
    obj1.OutputBufferSize=500000;
    obj1.ByteOrder='littleEndian';
    % Connect to instrument object, obj1.
    fopen(obj1);
end

% it is possible to have two sessions on same address.  Use first
if length(obj1) > 1
```

```
    obj1 = obj1(1);
end

% make sure session is open
if strcmp(obj1.status, 'closed') == 1
    fopen(obj1);
end
```

At this point, obj1 can be passed to fprintf, fscanf, fwrite, and fread to communicate with the instrument. For example, to read the identifier string:

```
fprintf(obj1, '*IDN? ');
idString=fscanf(obj1, '%s');
```

When you are finished with the session, you have the option of closing the session. This is optional in GPIB. It is mentioned here because you must close a LAN session for reliable operation, so for consistent coding you might choose to close GPIB as well:

```
fclose(obj1);
```

Sending an ARB File to a Series 2900 VSG

The MATLAB script below accepts a complex array of data that we wish to play back in an RF signal generator. The data is the baseband time description of our waveform. The instrument will upconvert the waveform on an RF carrier. The script assumes that the data is in iqdata and that the sample rate (in Hz) is in sampleRate. Some things to note:

- A Series 2900 supports up to 50Msample rates.
- Series 2900 firmware versions before 2.0 only support the sample rates of 50, 25, 10, 6.25, 5, 2.5, 1.25 … MHz. Firmware after 2.0 will automatically resample the data as it is read in.
- It is up to you to ensure a smooth transition as the ARB waveform wraps around at the end of the waveform and starts back at the beginning.
- The script below scales the waveform so the peak is at the full scale of the A/D converter. For some waveforms, it may be necessary to back off slightly to avoid distortion.
- The script below calculates the RMS power of the waveform. If your waveform is pulsed, you need to modify the calculation to only calculate RMS power during the active part of the pulse. The RMS power is used to provide calibrated output power from the RF source.

The script below assumes that: a file name such as mywaveform.arb is in the variable filename, the complex data is in iqdata, and the sample rate is in sampleRate, in Hz. The data is formatted as 16-bit integers, real interleaved with imaginary, and a header is created. The data is transferred to the instrument as an ARB file, and the ARB file is loaded and played back. If there is already an ARB file loaded with the same name, it is deleted.

```
% Scale the floating point values so unity full scale
% becomes full scale on a 16 bit signed DAC
iqdata = iqdata/max(abs(iqdata))* (2^15);

% Split out the real and imag parts, convert to
% integer, then interleave
realData = int16(real(iqdata));
imagData  = int16(imag(iqdata));
outData = [ realData' imagData' ]';
outData = outData(:);

% calculate the power factor.  If the waveform is pulsed, modify this
step to
% calculate only over the active part of the burst
powerFactor = -10 *log10(mean(iqdata.*conj(iqdata)));

% Send the initial command
numBytes = length(iqdata)*4 + 16;
lenStr = num2str(numBytes);
numChars = length(lenStr);
numCharsStr = num2str(numChars);

obj1.EOIMode = 'off';
obj1.EOSMode = 'none';
fwrite(obj1,['MMEM:DATA \ArbWaveform\User\'
fileName ', #' numCharsStr lenStr ] );


% Write the 16 byte header
fwrite(obj1, [sampleRate, powerFactor, 0, 0], 'float32');

% Write the arb waveform out, careful not to exceed the buffer size
bufSize = obj1.OutputBufferSize;
bufSize = 4*floor(bufSize/4);  % force to an integer number of 4 byte
words
numLeft = length(outData);
numToWrite = bufSize/2;
writeIdx = 0:(numToWrite-1);
curIdx = 1;

while (numLeft > numToWrite)

    fwrite(obj1, outData(curIdx + writeIdx), 'int16');
    curIdx = curIdx + numToWrite;
    numLeft = numLeft - numToWrite;
end

% Write out last little bit
fwrite(obj1, outData(curIdx:length(outData)), 'int16');

% Write a trailing new line
obj1.EOIMode= 'on';
obj1.EOSMode= 'read&write';
fwrite(obj1, char(13));

% Look to see if name already used as loaded waveform.  If
% so, delete that waveform to avoid table pollution
fprintf(obj1,':RAD:ARB:LIST?');
```

```
tableStrings = fscanf(obj1,'%s');
allWords='';
remainder = tableStrings;
while (any(remainder))
    [chopped,remainder]=strtok(remainder,',');
    allWords = strvcat(allWords, chopped);
end

if length(allWords) > 2
    % table isn't empty, process it
    celldata=cellstr(allWords);
    table = reshape(celldata',4,[])';

    [numRows, numCols] = size(table);
    relativeRow = 0;
    for cnt=1:numRows
        relativeRow = relativeRow + 1;
        if (strcmp(upper(char(table(cnt,2))),upper(nameInTable))==1)
            % We have a match!  Delete it
            fprintf(obj1,'RAD:ARB:STATE OFF; :RAD:ARB:DEL %i',relativeRow);
            relativeRow = relativeRow - 1;
        end
    end
end

% Now load the file
fprintf(obj1,':RAD:ARB:OPEN %s\n',nameInTable);
fprintf(obj1,':RAD:ARB:PLAY %s\n',nameInTable);

% close the session
fclose(obj1);
```

Acquiring and Reading Back I/Q Data using a Series 2800 VSA

A Series 2800 VSA provides a special command to acquire a block of data and transfer the complex I/Q pairs out of the instrument, the logical companion to an ARB file in a Series 2900 VSG. First, configure the instrument for a zero span measurement with the desired settings such as bandwidth, sweep time, filter type, and trigger parameters. This can be done either from the front panel or using remote commands. (In general, setting bandwidth to the signal bandwidth with the flat filter shape are the settings to use.) Then, put the instrument in single sweep mode and issue the :MEAS:IQ? command. The instrument will acquire a block of data and respond first with the sample rate in Hz as an ASCII string, then with a binary block transfer of the I/Q data. The data is in 16-bit signed integers, interleaved real and imaginary. The instrument chooses the sample rate based on the bandwidth, filter type, and sweep time. The sample rate is at least 5/4 the bandwidth and can be considerably more. Because the data is scaled to fit in the 16-bit integers, it is not calibrated for absolute power.

Assuming that a valid session to a Series 2800 (typically at GPIB address 10) has been established, the MATLAB script below issues the :MEAS:IQ? command and returns the I/Q data in iqdata. Full scale is 2^{15}, so the values will be large integers. This script also reads a calibration factor thate converts the measured values to power in dBm. The calibration factor is returned in dB, so it must be converted to linear and scaled by 2^{15}

before being applied to the data. Note that this script is simpler than the ARB script because it assumes the whole trace transfer will fit into a single buffer, as set by obj1. InputBufferSize. You may need to increase this buffer size. If you change the buffer size in your script, issue instrreset to close the existing session, so it can be reopened with the correct parameters.

Before running this script, make sure the instrument is in single sweep mode. If you are using video or external triggering, make sure that a valid trigger will occur or the instrument will indefinitely wait for the trigger, although the GPIB session will time out. To recover, press local on the instrument and issue instrreset on MATLAB.

```
% Now lets read the trace back!
fwrite(obj1,':MEAS:IQ?');       % trigger meas, read result back

% The first value that comes back is a 32 bit float with sample rate.
% read character by character until we find the comma
a=fscanf(obj1,'%c',1);
b=a;
while a~=','
    a=fscanf(obj1,'%c',1);
    b = [ b a ];
end

sampleRate = sscanf(b,'%f');

% Start the binary trace transfer.  It starts with a header that
% tells us the size of the transfer (even though we already know
% the number of points).
header=fread(obj1,2,'uchar');   % first two bytes are '#5', where 5 is
number of
                                % BCD digits following, the BCD number
                                % being the number of bytes in the
transfer
numChar=header(2)-double('0');  % dig out the number of BCD digits
lenString=fread(obj1,numChar,'uchar');  % get the BCD digits
numBytes=sscanf(char(lenString),'%i');  % convert to number of bytes
numValues=numBytes/2;                    % each value is 2 bytes
dataArray=fread(obj1,numValues,'int16');  % read back interleaved IQ
iqdata=dataArray(1:2:numValues)+j*dataArray(2:2:numValues);  %split to
real/imag

% read trailing newline
a=fscanf(obj1,'%c',1);

% Read and apply the calibration factor
fwrite(handle2810,':MEAS:IQ:CFAC?');
calFactor_dB = fscanf(handle2810,'%f');
calFactor = 10^(calFactor_dB/20) * ( 2^15);
iqdata = iqdata / calFactor;
```

Connecting MATLAB using a LAN

Connecting to instruments using a LAN is similar to using GPIB. Communication is achieved through the socket object in the MATLAB instrument control library. Large block transfers are faster over a LAN; however, a LAN setup is a little more complex.

In order to open a session to the instrument, you need to know its IP address. This can be found by selecting the Menu button, then Utilities, then Ethernet Settings. In the example below, we assume the IP address has been entered as a string in ipAddr, as in ipAddr='196.129.0.100';

```
if exist('obj1') ~= 1
    obj1 = tcpip(ipAddr,5025);
end

if strcmp(obj1.status,'open')==0
    obj1.OutputBufferSize = 1e6;
    obj1.InputBufferSize = 1e6;
    obj1.ByteOrder='littleEndian';
    fopen(obj1);
end
```

At this point, obj1 can be passed to fprintf, fscanf, fwrite, and fread to communicate with the instrument. For example, to read the identifier string:

```
fprintf(obj1, ' *IDN? ');
idString=fscanf(obj1, '%s');
```

When you are finished with the session, it is recommended that you close the LAN session for reliable operation:

```
fclose(obj1);
```

Sending an ARB File to a Series 2900 VSG

This example is very similar to the GPIB example, but there is no need to control the EOIMode and EOSMode (they aren't present in socket communications).

```
% Scale the floating point values so unity full scale
% becomes full scale on a 16 bit signed DAC
iqdata = iqdata/max(abs(iqdata))* (2^15);

% Split out the real and imag parts, convert to
% integer, then interleave
realData = int16(real(iqdata));
imagData  = int16(imag(iqdata));
outData = [ realData' imagData' ]';
outData = outData(:);

% calculate the power factor.  If the waveform is pulsed, modify this
step to
% calculate only over the active part of the burst
powerFactor = -10 *log10(mean(iqdata.*conj(iqdata)));

% Send the initial command
numBytes = length(iqdata)*4 + 16;
lenStr = num2str(numBytes);
numChars = length(lenStr);
numCharsStr = num2str(numChars);

fwrite(obj1,['MMEM:DATA \ArbWaveform\User\'
```

```
fileName ', #' numCharsStr lenStr ] );


% Write the 16 byte header
fwrite(obj1, [sampleRate, powerFactor, 0, 0], 'float32');

% Write the arb waveform out, careful not to exceed the buffer size
bufSize = obj1.OutputBufferSize;
bufSize = 4*floor(bufSize/4);  % force to an integer number of 4 byte
words
numLeft = length(outData);
numToWrite = bufSize/2;
writeIdx = 0:(numToWrite-1);
curIdx = 1;

while (numLeft > numToWrite)

    fwrite(obj1, outData(curIdx + writeIdx), 'int16');
    curIdx = curIdx + numToWrite;
    numLeft = numLeft - numToWrite;
end

% Write out last little bit
fwrite(obj1, outData(curIdx:length(outData)), 'int16');

% Write a trailing new line
fwrite(obj1, char(13));

% Look to see if name already used as loaded waveform.  If
% so, delete that waveform to avoid table pollution
fprintf(obj1,':RAD:ARB:LIST?');
tableStrings = fscanf(obj1,'%s');
allWords='';
remainder = tableStrings;
while (any(remainder))
    [chopped,remainder]=strtok(remainder,',');
    allWords = strvcat(allWords, chopped);
end

if length(allWords) > 2
    % table isn't empty, process it
    celldata=cellstr(allWords);
    table = reshape(celldata',4,[])';

    [numRows, numCols] = size(table);
    relativeRow = 0;
    for cnt=1:numRows
        relativeRow = relativeRow + 1;
        if (strcmp(upper(char(table(cnt,2))),upper(nameInTable))==1)
            % We have a match!  Delete it
            fprintf(obj1,'RAD:ARB:STATE OFF; :RAD:ARB:DEL %i',relativeRow);
            relativeRow = relativeRow - 1;
        end
    end
end

% Now load the file
fprintf(obj1,':RAD:ARB:OPEN %s\n',nameInTable);
fprintf(obj1,':RAD:ARB:PLAY %s\n',nameInTable);

% close the session
fclose(obj1);
```

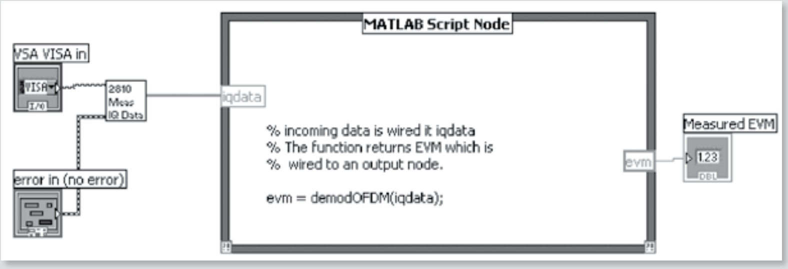
Acquiring and Reading Back Data using a Series 2800 VSA

In this case, the code for reading back a trace is identical whether you are using a socket or GPIB. Once the socket is open and in obj1, the same script shown in the GPIB section can be used.

Connecting MATLAB to an Instrument using LabVIEW

If you have LabVIEW, you can use the MATLAB scripting capability (in version 8.2 or higher) to call your MATLAB script. This has the benefit of relieving your MATLAB code of having to interface to an instrument.

Suppose, for example, you had a VI (virtual instrument) called MeasIQ2810 that transferred the I/Q data out of a Series 2800 and made it available as a complex array. Now suppose you have a MATLAB function called demodOFDM() that takes a complex array as a pass parameter. The LabVIEW VI to call your script is shown in **Figure 2**. In LabVIEW, you place a script object on the block diagram. Inside, you put a call to your measurement script. Input parameters are wired on the left, output on the right.



```
% incoming data is wired it iqdata
% The function returns EVM which is
%  wired to an output node.

evm = demodOFDM(iqdata);
```

Figure 2. Connecting MATLAB to an instrument using LabVIEW

Measure phase locked loops with a spectrum analyzer

The frequency settling time of a phase locked loop (PLL) is a critical specification for many RF circuits. There are various techniques for measuring both the amplitude and frequency settling time of a PLL, but using a general purpose Vector Signal Analyzer (VSA) is one of the more attractive methods for several reasons:

- It is a piece of test equipment that most RF labs already own.
- It provides relatively low-cost spectrum analyzer functions.
- The techniques employed can be accomplished with any VSA that allows the transfer of complex IQ time domain samples to a PC.
- A wide variety of phase locked loops can be measured, as long as a TTL trigger can be derived at or near the start of phase lock tuning.
- 10Hz resolution is easily achieved.

The specific technique described in this discussion resulted from a Keithley development project on an RF synthesizer. To avoid a major expenditure for a high-end spectrum analyzer or specialized test equipment with limited application, other solutions were investigated. After some thought, the development team recognized that a tuned instrument with a fast digitizer could be used to measure frequency settling time. An evaluation of existing equipment revealed that a VSA had the appropriate features, and a technique was quickly developed to measure both amplitude and frequency settling.

Other Alternatives Considered

There are three basic techniques to detect frequency as a function of time. Frequency counters measure the length of time between zero crossing, discriminators convert a frequency change into a power change, and VSAs directly measure frequency versus time for signals within their acquisition bandwidth.

Prior to the advent of high-speed digitizers, the preferred technique for measuring frequency versus time was to use an instrument that timed the zero crossings of the waveform. Most RF frequency counters employ this technique, and more advanced instruments log data versus time. Frequency vs. time instruments called modulation domain analyzers are now largely obsolete, and most have been replaced by VSA-based equipment.

The lowest cost approach to measuring frequency vs. time is to run the signal through a device that has a roughly linear magnitude slope vs. frequency, causing the frequency variation to turn into an amplitude variation. This can be as simple as the partial-cutoff region of a bandpass or lowpass filter. The power at the output of the filter/discriminator is then measured using either a spectrum analyzer or a power sensor.

While inexpensive, this approach makes accuracy difficult to maintain, as amplitude variations in the signal can be confused with frequency variation, and it is difficult to resolve fine-grain variations on the order of 10Hz, which we want for PLL settling time measurements.

Another possibility is to use a fast sampler or sampling oscilloscope to capture the signal. However, this technique does not have the dynamic range typically required to measure down to 10Hz.

The preferred approach for modern solutions is to use a VSA. This instrument uses an RF downconverter followed by a fast digitizer, which feeds a digital IQ detector. The solution can be as simple as a standard VSA, plus external software to process the trace. More complex solutions include real time spectrum analyzers and signal source analyzers. These instruments may provide more features and allow more types of measurements, but at significantly higher cost. Unless these features and functions are necessary for other applications, their cost is excessive for the basic task of measuring when a synthesizer frequency has settled.

Measurement Theory for VSA Solutions

When first faced with measuring frequency, many engineers will acquire a time record and use progressively larger Fast Fourier Transforms (FFTs) to get increasingly finer resolution in the frequency domain. This works well when dealing with a modulated carrier that has rich frequency content, but can be frustrating for measuring the frequency trajectory of an unmodulated carrier. For an unmodulated carrier, the main concern is the dominant frequency at a given instant in time. In that case, FFT calculations return a lot of unneeded information and cause a trade off in time resolution as longer FFTs are used to get better frequency resolution.

This was the case in Keithley's development of an RF synthesizer that uses a PLL to generate carrier frequencies. Therefore, development engineers began to consider the fundamental definition of frequency – the rate of change of phase. In effect, this says that you can estimate frequency as often as you can make a phase measurement. The resolution of the frequency estimate is limited only by the noise in the measurement. Still, caution must be exercised. The instantaneous frequency estimated from the derivative of phase can only be interpreted as the carrier frequency when there is a single carrier present, without any modulation other than the tuning of that carrier. Other signals present in the measurement bandwidth will cause the measured phase to vary wildly.

In the case of a PLL, when measuring its voltage controlled oscillator (VCO) tuning, the single carrier assumption generally holds true. Unless the VCO breaks out into spurious oscillations, the derivative of the phase is the frequency estimate you want.

The measurement methodology is to set the VSA to the expected ending frequency, trigger the VSA at the start of tune for the synthesizer under test, and log an IQ time record long enough to cover the settling time. Eventually, the signal falls within the IF bandwidth of the VSA, and we can calculate phase versus time. From that we calculate frequency versus time. At the same time, we also have the magnitude versus time.

To measure phase versus time, an IQ detector multiplies the IF signal, $s(t) = I(t) + jQ(t)$, with a cosine to get the real part and with a sine to get the imaginary part. A filter follows the multiplication to turn it into convolution and to remove spurious frequency components. The phase Θ_i is computed as $\tan^{-1}[Q(t)/I(t)]$. An IQ detector is inherently band limited, and the magnitude and phase flatness across frequency is a key consideration. The best solutions use a digital IQ detector with perfectly matched channels and well-behaved filters.

To convert phase to frequency, we approximate the derivative with a time difference. One approach would be to subtract adjacent samples. Unfortunately, that introduces a half-sample delay in the data. To avoid a time shift, it is better to subtract two samples that are equidistant from the current sample, subtracting the value N samples before the current sample from the value N samples after the current sample. If the phase samples are in an array Θ_i, then the frequency estimate is computed using:

$$F \cong \frac{\Theta_{i+N} - \Theta_{i-n}}{2\pi \cdot (2N)\Delta t},$$

where Δt is the sampling interval, the inverse of the sampling rate.

It is necessary to use unwrapped phase samples for this estimate[1], and it is also necessary that the incoming signal not progress more than 180° in between samples. In general, having a detector bandwidth that is below the Nyquist bandwidth ensures the second criteria.

By using samples equidistant before and after the current sample, there is no effective time delay. The quantity $(2N)$ is known as the aperture, denoting the separation between the phase samples. It is important to note that we divide by the aperture, which means that we can trade noise for time resolution with a simple post-processing operation.

The measurement bandwidth is set by the IQ detection filter and is an important consideration because frequency resolution is limited by noise, causing us to want smaller bandwidths. At the same time, filter bandwidth limits the frequency deviation we can see, and filter ringing can dominate the time response. In addition to bandwidth, the filter shape is important because its frequency shape affects the magnitude response, and its impulse response can show up as ringing on both the frequency and amplitude response.

---

[1] In general, a sinusoidal function of time can be characterized with its argument expressed as a general angle $\phi(t)$ that changes in time, i.e., $x(t) = A\cos(\phi(t))$, and the time-derivative of that unwrapped angle, $\phi'(t)$, is the **instantaneous frequency** of that sinusoid at any given time t. The angle $\phi(t)$ is said to be **unwrapped** if it is continuous everywhere except at places where the absolute value of the jump discontinuity is less than π radians.

A good rule of thumb is to use a bandwidth about 1000 times larger than the desired frequency resolution. For example, to measure settling down to 100Hz, use a 100kHz bandwidth. When measuring large deviations, use a flat top filter to capture as much information as possible. When measuring the final settling with high precision, use a Gaussian filter to avoid ringing. **Figure 1** shows the ringing due to a flat top filter at 10kHz bandwidth (around 10Hz resolution) as compared to a Gaussian filter.

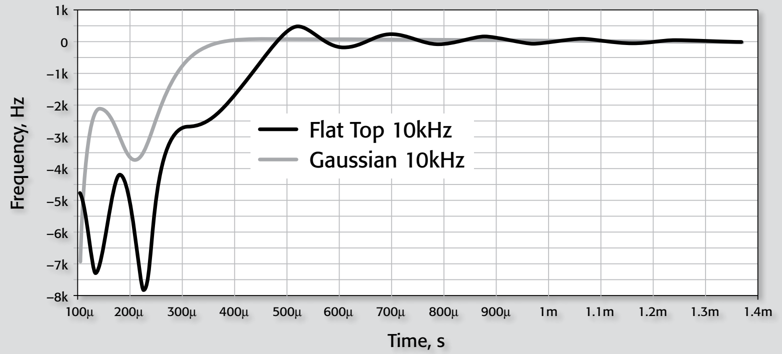


Figure 1. Frequency ringing comparison of flat top and Gaussian filters with 10kHz bandwidth

Time accuracy is also important in this measurement, which means paying attention to trigger accuracy. We need a trigger signal to start the VSA acquisition. If there is any ambiguity in the relationship between the start trigger and the actual start-of-tune of the VCO, the measurement accuracy is reduced. It is best if the control module that starts the synthesizer tuning also generates the start-of-tune trigger. It is sometimes possible to derive a valid trigger from existing signals in the system, such as existing control lines and synchronization signals.

Finally, it is important that the digital acquisition system be calibrated for accurate trigger time. Because of pipeline delays in the digital processing system, the next sample available after a trigger event will have taken place sometime before the trigger event. Most commercial VSAs calibrate the time axis so that the correct sample at the trigger instant is identified.

Example Measurement Data

In this example, an RF synthesizer was programmed to hop between 1142MHz and 998MHz. A Keithley Model 2810 VSA was used for the settling time measurements. It was tuned to 998MHz and used a 35MHz flat top filter. The synthesizer triggered the VSA at the time the VCO started tuning from 1142MHz to 998MHz. **Figure 2** shows that the signal comes within the measurement bandwidth about 33 microseconds after the VCO begins tuning, The VCO frequency overshoots that 998MHz target by about 8MHz, but the PLL brings the frequency in until there is lock-on at about 220 microseconds after start-of-tune. The VCO amplitude (**Figure 3**) settles much earlier – after about 70 microseconds.

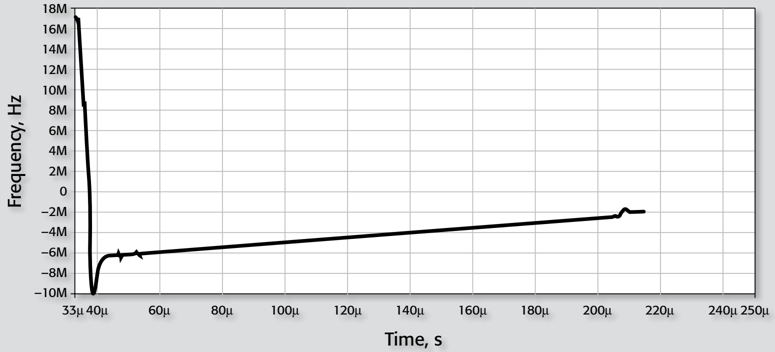


Figure 2. Difference frequency trajectory and lock-on (zero difference) for an RF synthesizer's PLL using the VSA measurement technique described in the text

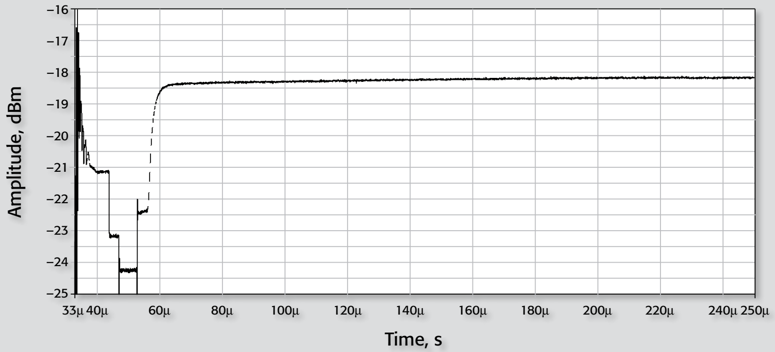


Figure 3. Amplitude trajectory and lock-on for the signal in Figure 2

This measurement was made by placing the VSA in zero span mode at 998MHz. The receive filter was configured as a 35MHz flat top filter. The sweep time was 300 microseconds. The trigger was configured for external trigger (from the synthesizer), with a trigger delay of 170 microseconds. Data were collected using the **:MEAS:IQ?** SCPI command, which acquires the data and transfers it to the host computer in a binary format. The post-processing software used an aperture of 900 nanoseconds when computing the frequency trajectory.

Figure 4 shows approximately the final 200Hz of settling time for a synthesizer that was tuned from 1214.39011MHz to 998MHz using a 100kHz Gaussian filter. As before, data were processed externally to calculate frequency trajectory. This figure shows that the VSA technique can easily resolve frequency features as small as10Hz.

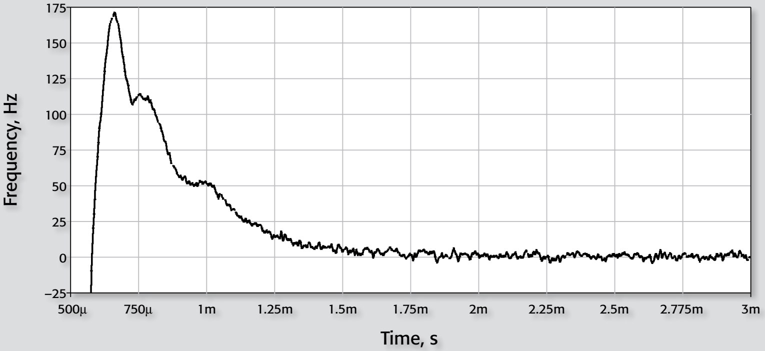


Figure 4. Final portion of frequency settling curve for a PLL tuned from 1214.39011MHz to 998MHz. Note the resolution of 10Hz or better.

To simplify the measurement setup, we now build in the ability to command the synthesizer to hop between two frequencies every few milliseconds, and provide a TTL trigger at the start of tune.

Conclusion

What started as an effort to preserve capital budget quickly became a preferred method for measurement of frequency settling time. The litmus test was when we realized we could resolve 10Hz differences in output frequency on samples less than 100 microseconds apart. That is significantly better than the old engineering rule that says you have to measure over a 0.1 second period to resolve a 10Hz frequency difference. This methodology has a number of advantages:

- Ability to zoom out and measure the last few MHz of the trajectory with high time resolution.
- Ability to zoom in and resolve around 10Hz for the final settling.
- Ability to trade time resolution for noise on the frequency trace by adjusting the aperture of the phase-to-frequency derivative.
- Valid amplitude trajectory once signal is within IF bandwidth.
- If a VSA is not already owned, it is relatively economical to acquire (about $20,000 for a Keithley Model 2810), compared to a high-end spectrum analyzer.

Keithley Model 2810 VSA with Spectrum Analyzer Capabilities Fits a Wide Variety of Applications

The Keithley Model 2810 VSA is optimized for automated production testing of wireless devices and transmitter circuits, but is also well suited for a wide variety of product R&D applications, such as the frequency settling measurements described in this article. It features automatic and manual measurements at speeds up to three times faster than competitive instruments in production testing, takes up half the space, and costs half as much.

These features are combined with complex signal analysis capability and unprecedented ease of use with a touchscreen GUI. In addition to decomposing a waveform into constituent frequencies, the Model 2810 can also decompose digitally modulated signals into their I and Q phase components.

This performance is made possible with an advanced software-defined radio architecture and a 500MHz digital signal processor, enabling fast data acquisition and processing. Its speed allows engineers and scientists to significantly reduce the time it takes to acquire large sets of data needed for efficient product development. For example, the Model 2810 can perform a 200MHz span sweep using a narrow resolution bandwidth of 100Hz in approximately 15 seconds. A conventional spectrum analyzer takes 1000 times longer.

The Model 2810's exceptionally wide signal acquisition – greater than 30MHz of 3dB measurement bandwidth with 20MHz of flatness within 1dB – allows the capture of wide bandwidth signals in one acquisition. This performance exceeds what is possible with conventional spectrum analyzers and is better than most VSAs in the $30,000 and under price range.

References

Agilent Application Note AN 1275, "Automatic Frequency Settling Time Measurement Speeds Time-to-Market for RF Designs," available at http://cp.literature.agilent.com/litweb/pdf/5964-4335E.pdf.

Configuring an optimal RF/microwave switch system

Introduction

Given the explosive growth of the communications industry, a tremendous amount of testing is being performed on the various components that make up different communications systems. These components range from active components such as Radio Frequency Integrated Circuits (RFICs) and Microwave Monolithic Integrated Circuits (MMICs) to space communication systems. While the testing requirements and procedures for these components differ widely, all are tested at very high frequencies, typically at gigahertz or higher. The main components in a typical test system may include DC bias, DC measurement, RF power meter, network analyzer, etc. Automating the test process and improving test efficiency demands integrating RF/microwave and low frequency switching systems into the test system.

The purpose of a switch is to route signals from measurement instruments to the Device Under Test (DUT). With the help of a switch, an instrument can measure multiple DUTs with increased efficiency. Multiple tests with different instruments can be run on the same DUT or multiple instruments can test multiple DUTs. With the help of a switch system, the test process can also be automated. For example, in the typical DUT (in this example, mobile phone) lifetime test illustrated in **Figure 1**, the DUT can be stressed at an elevated level for a specified period, then its electrical characteristics can be measured.

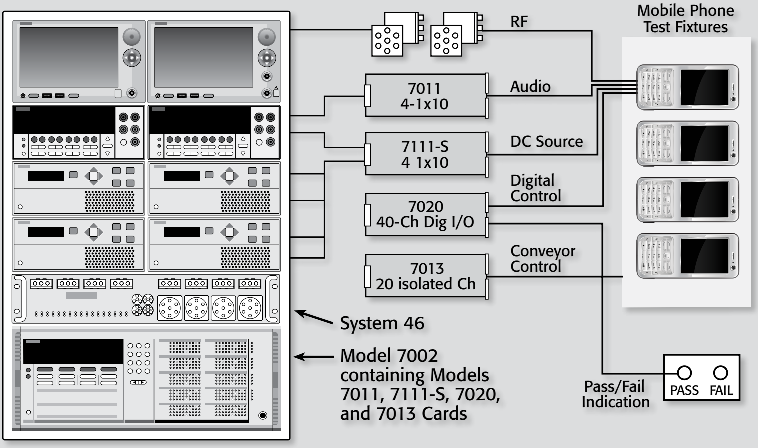


Figure 1. In a typical lifetime test, the DUT (in this case, a mobile telephone) can be stressed at an elevated level for a specified period, then its electrical characteristics can be measured.

The DUT can be stressed even further and the electrical characteristics can be measured again. Automated switching allows this process to be performed very efficiently.

The following briefly discusses several important aspects of configuring a high frequency switch system, including the system configurations and the critical switch specifications.

Configuring a Switch System

Switch systems can be very simple or quite elaborate. For example, a Single Pole Double Throw (SPDT) switch can be used to route signals to two different DUTs. It can be expanded further into a "multiplexer" configuration so that a single instrument can be routed to many different DUTs. Multiple instruments can be routed to multiple DUTs. In this case, the switch system is known either as a Multiplexer-Demultiplexer or a blocking matrix—only one signal path is active at any given time. **Figure 2** shows the application of an SPDT and a 1×16 multiplexer.

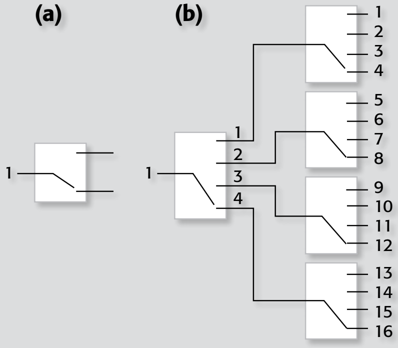


Figure 2. A single-pole, double-throw (SPDT) switch can be used to route signals to two different DUTs (a). It can be expanded further into a "multiplexer" configuration, so that a single instrument can be routed to many different DUTs (b).

To improve testing flexibility, a switch system can connect multiple instruments to multiple DUTs. This is the "blocking" configuration. Any instrument can be connected to only one output at a time. **Figure 3** shows a 4×4 blocking switch system.

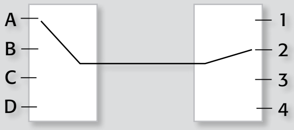


Figure 3. For improved flexibility, a series of switches can be arranged in a blocking matrix to connect multiple instruments to multiple DUTs.

In order to switch any signal to any DUT at any time, a “non-blocking” configuration (sometimes called a switch matrix) can be used. While this switch configuration has the highest flexibility, it is also the most expensive. **Figure 4** shows a 4×4 non-blocking switch configuration and **Figure 5** shows an expanded 4×6 switch configuration.

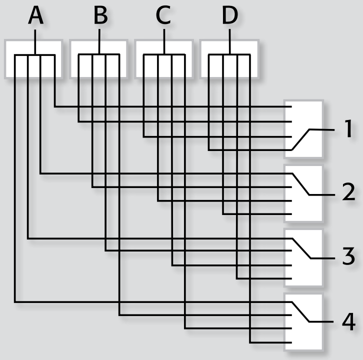


Figure 4. 4×4 non-blocking switch. A non-blocking matrix makes it possible to switch any signal to any DUT at any time. While this configuration has the highest flexibility, it is also the most expensive.

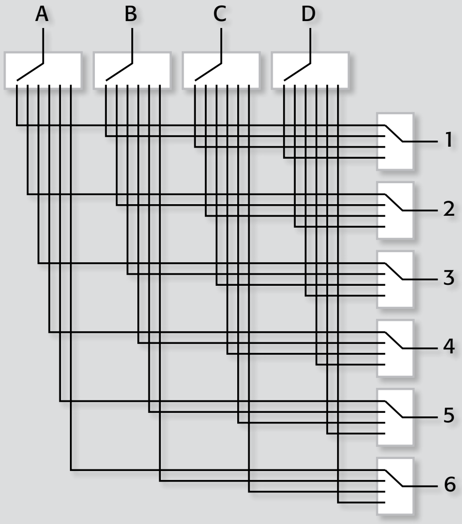


Figure 5. 4×6 non-blocking switch

Critical Switch Specifications

The use of a switch will inevitably degrade the performance of the measurement system, so it is important to consider several critical parameters that may affect system performance significantly. Two types of specifications are very important when configuring a switch: electrical and mechanical. These switches are complex to design and manufacture, so they tend to be significantly more expensive than lower frequency switch systems. During the design phase, the costs and benefits are often weighed against each other to achieve an optimal solution. The following section will briefly discuss some specifications that are critical to RF/microwave switch systems.

Electrical Specifications

Impedance Matching: The switch is positioned between the measurement instruments and the DUT, so it's critical to match the impedance levels of all three system elements. For optimal signal transfer, the impedance of the source has to be equal to that of the switch and the DUT. In RF testing, different impedance levels are used to achieve different purposes. The most commonly used impedance level is 50Ω. For better power transfer, the impedance could be lowered to 30Ω. To provide less RF signal attenuation, the typical impedance used is 75Ω. Whichever impedance level is required, matching them properly will ensure overall system integrity.

Insertion Loss: Any component added to the signal path will cause some degree of loss. The amount of loss is especially severe at higher or resonant frequencies. When signal level is low or noise is high, insertion loss is particularly important. The insertion loss is reflected as a decrease in the available power on the DUT as compared to the test instrument source value. Normally, it is specified as the ratio of output power over the input power in dB at a certain frequency or over a frequency range.

$$\text{Insertion Loss (dB)} = -10 \log(P_{out}/P_{in})$$

where P_{out} = the output power (in W) and P_{in} = the input power (in W).

Path Isolation: At higher frequencies, signals traveling on different paths can interfere with each other due to capacitive coupling between the paths or through electromagnetic radiation. This is especially severe when signal paths are not properly shielded or de-coupled from each other. Sometimes, this is referred to as "crosstalk." Crosstalk is particularly problematic when a weak signal is physically adjacent to a very strong signal. When maintaining signal path isolation is critical, additional isolation measures should be used.

Voltage Standing Wave Ratio (VSWR): Any component added to the high frequency signal path will not only cause insertion loss, but will also cause an increase in the standing wave in the signal path. This standing wave is formed by the interference of the transmitting electromagnetic wave with the reflected wave. This interference is often the result of mismatched impedances in different parts of the system or connecting points in the system, such as connectors. VSWR is specified as the ratio of the standing wave's highest voltage amplitude to the lowest voltage amplitude in the signal. VSWR is often also expressed as Return Loss:

Return Loss (dB) = –20 log[(VSWR–1)/(VSWR+1)]

Figure 6 shows an example circuit with a VSWR of 1.50:1. This is equivalent to a return loss of 14dB. As a result, with 50W forward power, reflected power would be 2W.

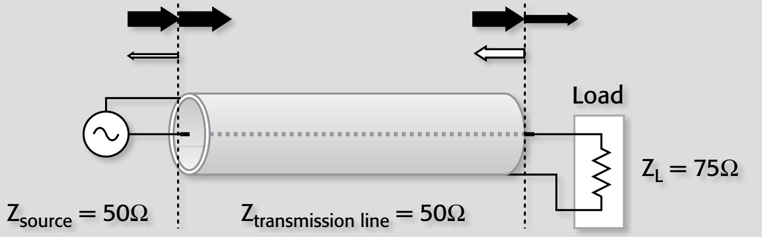


Figure 6. The impedance mismatch between the load and the cable results in a VSWR of 1.50:1, or a return loss of 14dB. For 50W forward power, 2W of power is reflected back to the source.

Signal Filter: Signal filters can be useful in a number of circumstances, such as when spurious noise is inadvertently added to the signal as it travels through the switch. They can also be helpful if the original signal frequency does not fit the DUT testing frequency. In these cases, filters can be added to the switch to modify the signal frequency bandwidth or spurious signals at unwanted frequencies can be eliminated from the signal to the DUT.

Phase Distortion: As a test system expands in size, signals from the same source may travel to the DUT via different paths of different lengths. This specification is often referred to as propagation delay. For a given conducting medium, the delay is proportional to the length of the signal path. Different signal path lengths will cause the signal phase to shift. This phase shift may cause erroneous measurement results. Therefore, techniques to ensure same phase or path length can be used to compensate for such effects.

Reliability and Repeatability: Obviously, the reliability of the switch is a major concern when designing a switch system. Typically, a switch relay should provide a lifetime of at least one million closures; many relays offer rated lifetimes of five million closures.

The repeatability of the switch performance is an equally important issue. Repeatability is the measure of the changes in the insertion loss or phase change from repeated use of the switch system. In RF measurement, it is not easy to eliminate the effects from the cycle-to-cycle change in the switch relay closure.

Mechanical Specifications

Physical Form Factor: The test system specifications, available rack space, and the potential need to have the switches located close to the devices-under-test will dictate the physical enclosure design of the switch system.

If space is critical and the switching bandwidth needed is below 3.5GHz, then PC board, RF relay cards such as the Model 7711 2GHz, dual 1×4 50Ω multiplexer card and the Model 7712 3.5GHz, dual 1×4 50Ω multiplexer card can address the system requirements. These cards slide into the Model 2700 mainframe to provide a microwave switch system in a compact, half-rack, 2U-high package. The disadvantage of PC board RF relays is that they have limited bandwidth, higher insertion loss, and lower isolation than coaxial, electromechanical relays. When more bandwidth is needed, the System 46 Microwave Switch System uses coaxial relays packed into a 2U-high, full rack enclosure. The S46 can have multiplexer systems as large as 1×18 and non-blocking matrices as large as 2×6.

Medium to large switch systems can use either the Model 7001 two-slot mainframe or the Model 7002 10-slot mainframe. In addition, these mainframes permit remote location of the microwave switches if such a configuration is needed. Not only do these mainframes support microwave switch configurations of substantial size, but they also permit the integration of low frequency switching and control. Thus one switch system can be designed to provide all of a test system's switching requirements.

Connectors and Cables: Many different types of connectors and cables can be used in RF/Microwave switch systems. The signal frequency, system impedance, power rating, and test fixture/handler compatibility, etc. should all be taken into consideration when choosing connectors and cables.

LED Visual Feedback: Switch mainframes that provide an LED display to indicate the open/closed status of the switch relays are very useful during system setup and troubleshooting.

Considerations When Specifying an RF/Microwave Switch System

Besides electrical and mechanical specifications for an RF/microwave switch system, several other factors need to be considered carefully. These factors can easily degrade the system performance even when the best parts are used.

Termination: At high frequencies, all signals must be properly terminated or the electromagnetic wave will be reflected from the terminating point. This, in turn, can cause an increase in VSWR. It may even cause damage in the source if the reflected portion is large enough. Typically, the coaxial cables used are terminated at 50Ω. For other types of communication systems, signals may terminate at 75Ω.

Bandwidth: Most switch system users would like to have as wide and as flat a bandwidth switch as possible. However, wide bandwidth switches are costly. If it is not absolutely needed, a narrow band switch can achieve the same objectives at a significantly lower cost. Another factor to consider is that when a higher frequency is used, the bandwidth will depend on the type of connectors and cables used. More expensive types of connectors and cables are typically needed to ensure adequate system performance.

Power Transmission: Another important consideration is the system's ability to transfer RF power from instrument to DUT. Due to insertion loss, the signal may require amplification. In some applications, it may be necessary to reduce the signal power to the DUT. The use of either an amplifier or attenuator may be needed to ensure that the accurate level of power is transmitted through the switch.

Conclusion

We have briefly discussed some typical applications of switching in communication testing. When specifying a switch system, the first step is to consider the system configuration. In order to achieve an optimal, yet cost-effective system, system designers must weigh a variety of electrical and mechanical parameters. Understanding these parameters makes it possible to make informed tradeoffs between switch flexibility and system cost.

Managing RF signals in test systems

Minimizing reflections and signal losses in test systems associated with the design, characterization, and production of RF products can be a complex challenge. In addition to issues such as cable and interconnect quality, engineers must consider conductor length, physical layout, and other aspects of system design that have little effect on DC circuits, yet are fundamental to the satisfactory operation of high frequency RF systems. Understanding and dealing with the mechanisms of impedance matching and signal loss are crucial in designing test systems for wireless products.

Basic Electrical Properties

Several electrical properties must be considered when developing an RF test system. The main parameters include system bandwidth, insertion loss, isolation, power-handling capability, and voltage standing wave ratio (VSWR).

Power losses primarily are a function of the resistive and impedance mismatch losses through a circuit path. Mismatch usually is the largest contributor to power measurement uncertainty and can be calculated from the magnitudes of the reflection coefficients of the source and load as:

$$\text{Uncertainty} = 20 \log (1 \pm \Gamma_S \Gamma_L)\text{dB} \tag{1}$$

where Γ_S = the reflection coefficient of the source, and Γ_L = the reflection coefficient of the load.

RF sources, loads, and signal paths all have characteristic impedances that must be perfectly matched or energy will be reflected back through the system. Mismatch is quantified as either return loss or VSWR.

$$\text{Return Loss} = 20 \log \left(\frac{1}{\Gamma}\right) \text{dB} \tag{2}$$

$$\text{VSWR} = \frac{1 + \Gamma}{1 - \Gamma} \tag{3}$$

The reflection coefficient can be determined from the Return Loss by:

$$\Gamma = \frac{1}{10^{\left(\frac{\text{Return Loss}}{20}\right)}} \tag{4}$$

Similarly, the reflection coefficient can be calculated from the VSWR by:

$$\Gamma = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} \tag{5}$$

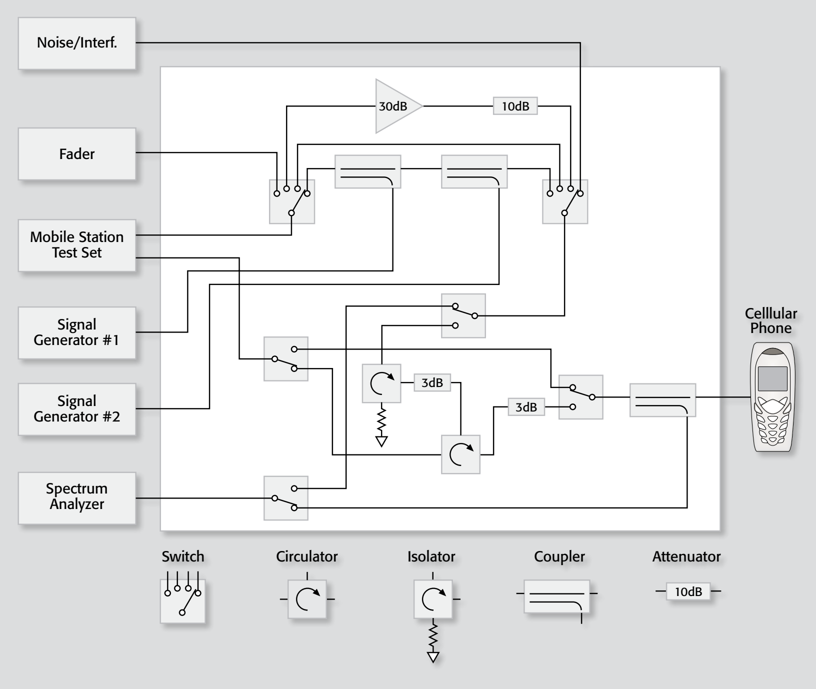


Figure 1. Signal conditioning/switching system example

RF Signal Conditioning and Switching Application Example

Test systems often must simulate actual application environments using complex signal paths that contain switches, other passive components, and active components. Characterizing how well a cellular phone can reject multipath interference, noise, and other RF signals is one example of such a production test.

Simulating the mechanism of multipath interference in a test system is a complex procedure, because it requires that noise and time-delayed signals reach the phone under test with appropriate power levels and phase relationships. **Figure 1** shows a typical signal conditioning/switching system for testing mobile phones.

For mobile phone receiver testing, the output of the mobile station test set can be switched through two types of paths:

- A path through instrumentation that simulates multipath fading and noise interference.
- Paths than can switch in gain to simulate varying distances between the mobile phone and the base station.

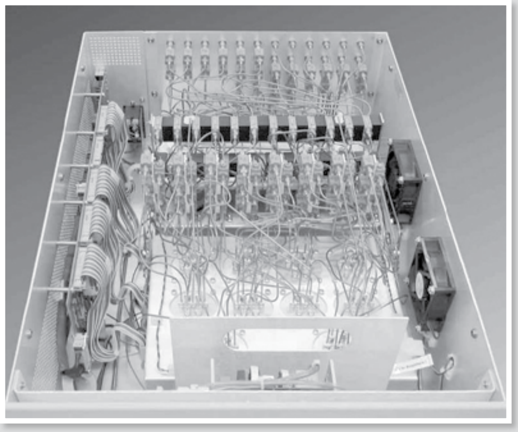


Figure 2. Typical switching system

For phone transmission testing, the output of the phone is directed to the mobile station test set through either an attenuated or unattenuated path. For monitoring purposes, the output of the phone or the input to the phone can be connected to a spectrum analyzer.

Figure 2 shows the control and signal path cabling associated with this type of system. Electromechanical switches are located in the foreground. Signal paths extend to the rear panel through banks of isolators, divider/combiners, and additional isolators. Ribbon cables are used for control.

Understanding and Managing Power Loss

Before attempting to perform any meaningful testing or calibration, it's critical to quantify the power losses through the RF test system. Some first-time users of RF test systems may expect that such systems will have negligible effects on RF signals, implying perfect matching, zero insertion loss, and insensitivity to frequency-dependent effects.

However, switches, circulators, isolators, couplers, and attenuators present many avenues for slight impedance mismatches and power loss. **Table 1** lists typical specifications for these components at 2GHz. In general, matching and VSWR become worse as frequency increases.

- Switches are used to route signals to different parts of a system. Typical switch types include electromechanical and solid state. Generally, switch performance is judged in terms of bandwidth, insertion loss, isolation, and VSWR.

Table 1. Typical system component characteristics at 2GHz

Device	Parameter	Value
Electromechanical Switches	VSWR (max.)	1.2:1
	Insertion Loss (max. dB)	0.2
	Isolation (min. dB)	80
Directional Couplers	VSWR (max.)	1.15:1
	Insertion Loss (max. dB)	0.1
	Coupling (max. dB)	10 ±1
	Directivity (min. dB)	10
Two-Way Power Divider/Combiner	VSWR (max.)	1.3:1
	Insertion Loss (max. dB)	0.4
	Isolation (min. dB)	22
	Amplititude Bal. (max. dB)	0.2
	Phase Bal. (min. dB)	3
Isolators	VSWR (max.)	1.25:1
	Insertion Loss (max. dB)	0.4
	Isolation (min. dB)	20
Terminations and Attenuators	VSWR (max.)	1.2:1
	Attenuation (dB) (attenuators only)	3 ±0.3
10″ Length SMA Cable	VSWR (max.)	1.10:1
	Insertion Loss (max. dB)	0.23

Electromechanical switches typically offer wider bandwidth, lower insertion loss, and lower VSWR specifications than solid-state switches. However, electromechanical switches have a shorter life cycle—typically 2 million switching cycles as opposed to 10 million for solid-state switches. Electromechanical switches also require switching times on the order of 25ms, as compared to 25ns for solid state switches.

- Directional couplers extract a specific amount of RF energy from a wave traveling in one direction through a transmission line. Directivity is the difference between the coupled port's output with power flowing in the forward direction and its output with power flowing in the reverse direction.

  Often, the insertion loss specification of a coupler does not include the loss represented by coupled power. This power loss also must be included when estimating total system insertion loss.

  For example, the insertion loss of a directional coupler might be rated at 0.1dB maximum, but the insertion loss from the coupling of 10dB of the power theoretically would be 0.46dB. As a result, 0.56dB of insertion loss would have to be budgeted for the coupler.

- N-way strip line power dividers/combiners divide an input into n separate paths or combine n inputs into one output with a specified amount of isolation between inputs. These devices are band limited. Often, the insertion loss specification of dividers/combiners does not include the split loss. The insertion loss from the power division usually has to be added to the insertion loss specification.

A typical two-way divider might have an insertion loss specification of 0.4dB. The insertion loss that results from dividing the power in half is 3dB. As a result, 3.4dB of insertion loss would have to be budgeted for this power divider when dividing the power and only 0.4dB when combining the power.

- A circulator is a multiport device that allows power to travel sequentially from one port to the next port. Each port can be used as an input or output. In an ideal four-port circulator, for example, power input at port 1 would appear only at port 2, power input at port 2 would appear only at port 3, and power input to port 3 would appear only at port 4.
- An isolator is a circulator containing a terminated port. If a four-port circulator had port 4 terminated, power could be injected in ports 4, 1, or 2 and would appear at the next port. Power input to port 3 would be dissipated by the termination on port 4.
- A termination is an RF device that, ideally, completely absorbs all RF energy flowing into it and reflects no energy back to the transmission line. This implies a VSWR = 1.0:1.
- An attenuator, ideally, also reflects no energy, but it reduces the RF power in the path by a specified amount and passes the remainder to an output port. Attenuators can be fixed or adjustable.
- Interconnecting cables sometimes are ignored when designing an RF test system, but they can be a critical element in system performance. In addition to electrical parameters such as characteristic impedance and insulation properties, physical attributes such as diameter, length, conductor and shielding design, and plating can strongly affect bandwidth, loss, and VSWR and the suitability of a given cable in RF applications. Generally, larger diameter cables offer lower insertion loss and higher power handling capability but decreased bandwidth and flexibility as compared to smaller diameter cables.

Quantifying the Performance of a System

Estimating system VSWR requires that sources of reflected power be identified and consideration be given to the effects on reflected power of components in the signal path. **Figure 3** shows a simple RF path consisting of a combiner, an isolator, an attenuator, and cables.

Table 2 lists specifications for the components in **Figure 3**. The reflection coefficients in the table have been determined using Equation 5.

Table 2. Characteristics of components in Figure 3 @ 2GHz

Component	VSWR	Reflection Coefficient (Γ)	Insertion Loss	Isolation
Cable	1.10:1 max.	0.048	0.40 dB max.	
Combiner	1.30:1 max.	0.130	0.40 dB max.	22 dB min.
Isolator	1.25:1 max.	0.111	0.40 dB max.	20 dB min.
Attenuator	1.20:1 max.	0.091	3 ± 0.3 dB	

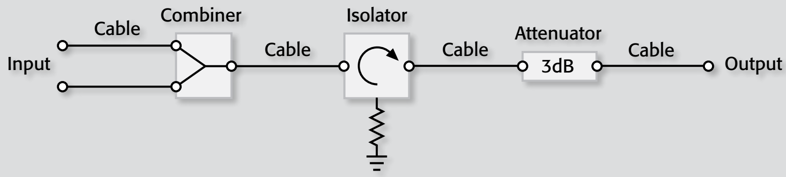


Figure 3. RF circuit-path example

Table 3. Input VSWR estimate

Step 1. Return Loss $= 20 \log \left(\frac{1}{0.048}\right) + 2 \cdot 3 = 32.375$	Convert reflection coefficient of cable to return loss and lower the return loss by twice the value of the attenuator.
Step 2. $\Gamma = \frac{1}{10^{\left(\frac{32.375}{20}\right)}} = 0.024$	Calculate the reflection coefficient corresponding to the above return loss.
Step 3. $\sqrt{0.024^2 + 0.091^2 + 0.048^2} = 0.106$	RMS sum of reduced cable reflection coefficient with coefficients of attenuator and another cable.
Repeat Step 1 using $\Gamma = 0.106$.	Convert this reflection coefficient representing two cables and the attenuator to a return loss, 39.494dB.
Repeat Step 2 using Return Loss = 39.494dB.	Find the reflection coefficient corresponding to the combined return loss.
Repeat Step 3 to include three cables, the attenuator, and the isolator.	The equivalent reflection coefficient is 0.121.
Repeat Steps 1, 2, and 3 to arrive at an overall reflection coefficient = 0.163.	
Use Equation 3 to determine the VSWR = 1.389.	

To estimate the VSWR at the input of a system, start at the output port. The reflection coefficients of the components in the path are root summed squared to yield the estimate of VSWR at the input port. In this case, VSWR can be calculated to be 1.389:1. The steps taken to arrive at this conclusion are detailed in **Table 3**.

The best case input-to-output insertion loss would be no worse than the summation of the individual components' insertion loss specifications. In this case, that would be four cables at 0.4dB each, the combiner at 0.4dB, the isolator at 0.4dB, and the highest value of attenuation of 3.3dB, adding up to a maximum of 5.7dB of insertion loss through the system.

The worst case output-to-input isolation can be estimated by the lowest value of attenuation of 2.7dB, 20dB from the isolator, and 3dB for the power split in the combiner, adding up to at least 25.7dB in output-to-input isolation for the system. The input 1 to input 2 isolation should be no worse than the isolation specification of the combiner, which is 22dB.

Conclusions and Recommendations

Understanding power losses and how to determine their magnitude are essential for estimating actual circuit performance, factoring the information into the stimulus levels applied to the DUT, and interpreting the results read back by test instrumentation. Considerable power can be lost throughout a system as a result of impedance mismatches and resistive losses.

With the complexity of today's high frequency RF test systems, losses can be substantial. Even a simple signal path with only three components can attenuate a signal by 5.7dB. The mismatch error due to the path's VSWR of 1.389:1, compared to an ideal VSWR of 1.0:1, adds further uncertainty to the total power delivered through the path.

The more realistic test system shown in **Figure 1** can have as many as ten components, not including cabling, in a single path. Minimizing the number of components in a pathway is essential, and whenever possible, you should use components with the lowest available insertion loss and VSWR.

SECTION II

RF Glossary

μs (Microsecond). 10^{-6} seconds.

1dB Compression Point. The point on an RF amplifier's power output versus power input curve where the power output change is 1dB less than the power input change.

1xEV-DO (Single Carrier Evolution – Data Optimized). A 2.5 generation CDMA system that supports speeds of up to 2.4Mbps on the uplink and 307.2kbps on the downlink. It is also known as HDR. (1xEV-DO can also be called **One times Evolution Data Only** or **One times Enhanced Version – Data Only**.)

1xEV-DV (Single Carrier Evolution – Data and Voice). A 2.5 generation CDMA system that supports speeds of up to 5Mbps. It is able to transmit voice. (1xEV-DV can also be called **One times Evolution Data Voice** or **One times Enhanced Version – Data/Voice**.)

1xMC (1 times Multi-Carrier). A CDMA system that uses a narrow transmission bandwidth and 1.25GHz channels to support speeds of up to 384kbps. It is compatible with cdmaOne networks. It is also known as **1xRTT** and **IS-95c**.

1G (First Generation). First-generation mobile phone systems. These are analog systems that use circuit switched technology. In the United States, they use frequencies in the 900MHz band. They have poor security. It is fairly easy to listen to someone else's call.

1xRTT (1 times Radio Transmission Technology). *See* **1xMC**.

1Xtreme. A CDMA system that uses a narrow transmission bandwidth to support speeds of up to 5.2Mbps.

2G (Second Generation). Second-generation mobile phone systems, which are digital cellular networks that use circuit switched technology. These systems convert voice to a digital signal and usually encrypt the digital signal. They use frequencies in the 900MHz and 1900MHz bands and have a maximum throughput rate of 14Kbps.

2.5G. Updated 2G digital systems that include packet switching and support data throughput speeds similar to an analog modem (less than 40kbps).

3G (Third Generation). Third-generation mobile phone systems that provide performance similar to an ISDN line.

3G lite. Refers to both 3G networks that were upgraded from 2.5G networks and 3G networks with a throughput rate less than 144kbps.

3GPP (Third Generation Partnership Project). 3GPP is a cooperative project involving a number of telecommunications standards bodies from around the world. The original goal was to create a 3G mobile system standard that evolved into wideband CDMA. They have since incorporated GSM and EDGE into their portfolio of standards. Future standards will evolve from this group.

3xMC (3 times Multi-Carrier). A CDMA system that uses a wide transmission bandwidth to support speeds of up to 4Mbps. It is compatible with cdmaOne networks. It is also known as **3xRTT**.

3xRTT (3 times Radio Transmission Technology). *See* **3xMC**.

4G (Fourth Generation). Fourth-generation mobile phone system.

802.11. The name of the IEEE committee that sets wireless LAN standards. 802.11 also designates a family of standards that use a combination of CSMA/CA, FHSS, DSSS, infrared, and OFDM.

802.11a. This wireless LAN standard supports eleven 54Mbps channels in the 5GHz frequency band. It is also known as **Wi-Fi5**.

802.11b. This upgraded version of 802.11 is the most widely used wireless LAN standard. It supports three 1Mbps channels in the 2.4GHz frequency band. It is also known as **Wireless Ethernet** or **Wi-Fi**.

802.15. The name of the IEEE committee that created a standard similar to Bluetooth.

802.16. The name of the IEEE committee that sets wireless local loop standards.

802.16d. A version of WiMAX that supports fixed broadband wireless communications but does not support mobility. WiMAX uses OFDM modulation techniques.

802.16e. A version of WiMAX that supports mobile and fixed broadband wireless services such as voice, data, video, and gaming at high broadband speeds. It uses a wide range of frequencies and channel bandwidths and also uses multiple modulation and coding schemes.

802.16e Matrix A. Matrix A is a transmission technique defined in the IEEE 802.16e-2005 specifications. The technique implements space time coding by using two base station antennas to transmit two signals and then sequentially the complex conjugate of the two symbols. The mobile device receives the transmissions with a single antenna and uses an algorithm to recover the original symbols.

802.16e Matrix B. Matrix B is defined in the WiMAX system specifications and employs 2×2 spatial multiplexing. Matrix B uses pure spatial multiplexing. If the receiver uses a maximum-likelihood detection algorithm, the receiver gains a second-order diversity in addition to the spatial multiplexing.

802.16e Wave 1. Wave 1 networks are SISO systems that may support some mobility. Wave 1 and Wave 2 devices operate on both Wave 1 and Wave 2 networks; however, Wave 1 networks will not support the full feature set of Wave 2 devices.

802.16e Wave 2. Wave 2 networks support mobility, MIMO, beamforming, and SOFDMA. Wave 1 and Wave 2 devices operate on both Wave 1 and Wave 2 networks; however, Wave 1 networks will not support the full feature set of Wave 2 devices.

A/D (Analog to Digital). Converting an electrical signal from analog to digital.

AAA (Authentication, Authorization, and Accounting). How a system monitors users for security issues, billing, etc.

AAS (Advanced Antenna Systems or Adaptive Antenna Systems). *See* **Beam Forming**.

Absorption. The process RF energy (RF signals) undergoes as it converts to heat while penetrating an object.

Access Point. This hardware device allows wireless communication devices to connect to a wired LAN. The wireless devices will not remain connected if they move outside the area the access point supports (the Hot Spot).

Active Component. An electronic component that must use a power supply to operate correctly.

Adapter. A device that allows connectors from different families to be physically linked.

Adaptive Antenna Systems (AAS). *See* **Beam Forming**.

Adaptive Modulation and Coding. *See* **AMC**.

ADC (Analog to Digital Conversion). *See* **A/D**.

Additive White Gaussian Noise. *See* **AWGN**.

Advanced Antenna Systems (AAS). *See* **Beam Forming**.

Advanced Mobile Phone Service. *See* **AMPS**.

AGC (Automatic Gain Control). Adjusts the gain of a variable gain amplifier.

Air Interface. Techniques that allow a signal or bandwidth to carry more information. Examples include CDMA, FDMA, GSM, OFDM, and TDMA.

Air Link. *See* **WLL (Wireless Local Loop)**.

Altimeter. An instrument that calculates altitude by using pulsed radar technology to reflect RF signals from the ground.

AM (Amplifier Modulation). A transmission technique used in analog systems. It causes the amplitude of a carrier signal to change (be modulated) by superimposing the information signal onto the carrier signal. (AM can also be called **Amplitude Modulation**.)

AMC (Adaptive Modulation and Coding). A technique that analyzes the fluctuations in a channel and dynamically changes the Modulation and Coding scheme to transmit the maximum amount of data a receiver can support based on the attenuation of the channel.

American Mobile Phone Service. *See* **AMPS**.

American National Standards Institute. *See* **ANSI**.

Amplifier. A device that makes electrical signals stronger. There are a variety of amplifiers available, such as those that support variable gains, high power, low power, limits, etc.

Amplifier Modulation. *See* **AM**.

Amplitude. The height of a radio wave. It is usually measured from its axis to its peak.

Amplitude Modulation. *See* **AM**.

Amplitude Shift Keying. *See* **ASK**.

Amplitude Unbalance. A power divider specification that states the difference in insertion loss on any two paths of a power divider. Measured in dB.

AMPS (Advanced Mobile Phone Service). An analog cellular radio standard that represents the first generation of wireless networks. It is used in North and South America and in parts of Asia. It only supports voice, so it generally uses CDPD to transmit data. It uses frequencies in the 800MHz range, its channel size is 30kHz, and its maximum throughput rate is 9.6kbps. (AMPS can also be called **AMERICAN MOBILE PHONE SERVICE**.)

ANALOG. This technology uses a continuous wave (electrical signal) to carry information over radio channels. The value of an analog signal can range between its specified minimum and maximum values, and this value can change over time.

ANALOG TO DIGITAL. *See* **A/D**.

ANALOG TO DIGITAL CONVERSION. *See* **A/D**.

ANSI (AMERICAN NATIONAL STANDARDS INSTITUTE). An association in the United States that approves standards.

ANSI-136. A TDMA standard that uses a narrow transmission bandwidth and the same frequency as the AMPS system. It is also known as **D-AMPS**.

ANTENNA. A physical device that sends and/or receives radio (RF) signals by converting electrical signals from a conductor into airborne waves, and vice versa. Antennas come in a variety of shapes and sizes and can be active or passive devices. The size and shape of an antenna is carefully designed and tuned to the type of radio wave being transmitted and received.

ANTENNA DIVERSITY. A technique for avoiding multipath that uses multiple receiving antennas.

ANTENNA GAIN. The directional gain of an antenna compares how far a signal can be sent by a theoretical isotropic antenna and by the antenna being measured. It is usually expressed in dBi; a higher dBi indicates a stronger antenna. The power gain of an antenna describes the antenna's transmission power as a ratio of its output signal strength to its input signal strength.

ANTENNA PATTERN. A graphical representation of the RF signals being transmitted by an antenna.

APPLICATION SPECIFIC INTEGRATED CIRCUIT. *See* **ASIC**.

ARCHITECTURE. The hardware and software building blocks that form a network, including interfaces and protocols.

ASIC (APPLICATION SPECIFIC INTEGRATED CIRCUIT). An integrated circuit designed for a specific application.

ASK (AMPLITUDE SHIFT KEYING). Amplitude modulation of digital pulses (signals).

ASYNCHRONOUS TRANSFER MODE. *See* **ATM**.

ATM (ASYNCHRONOUS TRANSFER MODE). Data transfer technique that uses packet switching to combine data, voice, and other information. The packets are usually a fixed length of 48 bytes. ATM is also an acronym for automated teller machines.

Attenuation. The loss or weakening of a signal as it travels. Attenuation occurs whenever a signal moves through anything that is not a vacuum, including air. Signals with shorter wavelengths usually have more attenuation. Attenuation is typically measured in decibels.

Attenuator. This component reduces RF signal power by a predetermined amount. Attenuators are available in both fixed and variable/step configurations. Fixed attenuators reduce a signal by a specified (fixed) amount. They are also known as **Pads**. Variable attenuators reduce a signal as specified by an external control. The external control can cause the attenuation to change at any time. Variable attenuators come in two configurations: voltage variable attenuators and digital attenuators.

Automatic Gain Control. *See* **AGC**.

AWGN (Additive White Gaussian Noise). Noise whose frequency components have equal magnitude over a specified frequency band.

Balanced Amplifier. Two amplifiers placed in parallel. This configuration helps to reduce the amount of RF signal being reflected and also provides redundancy.

Band Pass Filter. *See* **BPF**.

Band Reject Filter. *See* **Notch Filter**.

Bandwidth. *See* **BW**.

Baseband. The original band of frequencies produced by a processor or a transducer, such as a microphone or other signal-initiating device, prior to modulation. In wireless voice, it is the sound frequencies of the voice before it is encoded and transmitted.

Base Station. *See* **BS**.

Base Station Controller. *See* **BSC**.

Base Station Subsystem. *See* **BSS**.

Base Transceiver Station. *See* **BTS**.

Basic Service Set. *See* **BSS**.

Basic Trading Area. *See* **BTA**.

Beam Forming. A technique used in MIMO systems that uses algorithms on an array of transmit antennas to focus signals towards the receiver. Also known as **Advanced Antenna Systems or Adaptive Antenna Systems (AAS)**.

Beamwidth. The width of the antenna pattern. Measured in degrees (of a circle).

BER (Bit Error Rate). The number of erroneous bits divided by the total number of bits transmitted, received, or processed over some time period. BER can also be the Bit Error Ratio, which is the number of digital bit errors per one million bits received. Measured in 10^{-6}.

Bias Tee. A component used to inject DC current or voltage into an RF transmission line without disturbing the RF signal.

Bidirectional. A two-way communications device that provides the same level of functionality in both directions.

Binary. A base-two number system that uses the numbers 0 and 1. In digital communications systems, it is important to realize that "0" and "1" are states and not necessarily 0 volts and another voltage.

Binary Digit. *See* **Bit**.

Binary Phase Shift Keying. *See* **BPSK**.

Bipolar Junction Transistor. *See* **BJT**.

Bit (Binary Digit). The smallest unit of information on electrical devices. A bit is a binary unit that is represented by either a "0" or a "1."

Bit Error Rate. *See* **BER**.

Bit Error Ratio. *See* **BER**.

Bits Per Second. *See* **bps**.

BJT (Bipolar Junction Transistor). A type of transistor that contains a base region, an emitter region, and a collector region.

BLAST (Bell Labs Layered Space Time). A signal transmission technique that increases throughput by using multipath to carry more information.

Bluetooth. A standard for wireless personal area networks (PANs) that connects phones, computers, etc. over short distances (less than 10m) by using low power radio frequencies (in the 2.4GHz band, ISM) and FHSS. Its maximum throughput rate is 720kbps. Devices with the Bluetooth logo on them have been tested for and meet all Bluetooth compatibility requirements.

BPF (Band Pass Filter). A signal filter that allows a specified range of frequencies to pass through it while attenuating frequencies outside that range.

bps (Bits Per Second). A measure of how fast binary digits can be sent through a channel. This is also known as a data rate.

BPSK (Binary Phase Shift Keying). This is a digital modulation technique. The phase of the RF carrier signal is switched between two values (usually 0° and 180°) based on whether the digital information signal is a 0 or a 1. With this technique, each sine wave of the carrier signal can carry one bit of information.

BRAN (Broadband Radio Access Network). The name of a committee in Europe that sets wireless LAN standards, such as HiperAccess, HiperLan, and LiperLink.

Bridge. A physical link between networks that allows data to pass from one network to the other.

Broadband. Signals with wide frequency spectrums. Broadband systems have bandwidths in excess of 1MHz. Examples are high speed Internet access and streaming video. An equivalent term is **Wideband**.

Broadband Radio Access Network. *See* **BRAN**.

Broadcast. When an RF signal is sent out from a single transmitter to many receivers.

BS (Base Station). A fixed station (wireless access point) used for communicating with mobile stations (such as cellular phones). It often consists of a cabinet, small building, and/or tower containing electronic equipment (such as RF transceivers and power supplies) and the associated antennas. It is generally located at or near the center of a cell. Also known as a **Base Transceiver Station**.

BSC (Base Station Controller). Converts signals sent and received by its base stations. It converts electrical signals to RF signals for transmission and RF signals to electrical signals when they are received.

BSS (Basic Service Set). The part of a cellular network that includes the BSC, BTS, and anything that connects them together. (BSS can also be called **Base Station Subsystem**.)

BTA (Basic Trading Area). A geographical area that a PCS is allowed to service.

BTS (Base Transceiver Station). *See* **BS (Base Station)**.

BW (Bandwidth). The range of frequencies that can be switched, conducted, or amplified within certain limits for a specific component or application. To calculate the bandwidth, subtract the lower frequency from the upper frequency. Bandwidth is typically measured in Hertz. Bandwidth is usually specified by the –3dB (half-power) points.

Byte. A byte is a sequence of eight consecutive bits that are usually treated as one unit. A byte can describe 256 unique states, ranging from 00000000 (0) to 11111111 (255).

Capacity. The throughput of (amount of data that can pass through) a communications link. Measured in bps. It can also be used to mean **Bandwidth**.

Carrier. Wireless carriers, also called service providers or operators, are the companies that operate the wireless networks and sell the use of those networks (the service). Another definition of carrier is the radio wave (RF signal) that carries voice or data. This is done by using modulation to superimpose an information signal onto the RF signal.

Carrier Frequency. Frequency of the RF signal used to carry voice or data.

Carrier Sense Multiple Access/Collision Avoidance. *See* **CSMA/CA**.

Carrier Sense Multiple Access/Collision Detection. *See* **CSMA/CD**.

Cavity. RF components that use hollow metal containers (cavities) instead of conductors to move RF signals. They are generally used in high power applications.

CB Radio (Citizens' Band Radio). Everyone throughout the world is permitted to use this frequency band (27MHz) for voice transmissions.

CBS (Cell Broadcast Service). A system that broadcasts text messages within a cell. When a message is broadcasted, all phones in that cell will receive the message. It supports text messages of up to 1,395 bytes (15 pages that are joined together (concatenated) with each page supporting 93 bytes). It is used in GSM networks.

CCK (Complementary Code Keying). A modulation technique that is an upgraded version of DSSS. It provides increased data throughput when the frequencies it is transmitting over are not affected by interference. It is one of the wireless LAN modulation schemes.

CDMA (CODE DIVISION MULTIPLE ACCESS). A digital spread-spectrum modulation technique for mobile phones that allows multiple phones to use the same frequency at the same time. It uses the 1.25MHz bandwidth. Signals are digitized and associated with a unique frequency code. The data is then scattered across the frequency band in a pseudo-random pattern. Spreading the data across the frequency spectrum greatly increases the bandwidth and also makes the signal resistant to noise, interference, and eavesdropping. The receiving device is instructed to decipher only the data corresponding to a particular code to reconstruct the signal. CDMA has no hard limit for the number of users that can share one base station. Instead, additional users can connect until the base station determines that call quality would suffer beyond a set limit.

CDMA2000. The 2.5 generation version of CDMA technology that is backwards compatible with IS-95a and IS-95b. It supports high speed data transmission, always-on data service, and greater voice network capacity than cdmaOne (1G). There are three variations: 1xRTT, 1xEV-DO, and 1xEV-DV.

- CDMA2000 **1xRTT** supports up to 144kbps packet data speeds. It also doubles voice capacity over previous CDMA networks (IS-95).
- CDMA2000 **1xEV-DO** stands for 1x Evolution Data Only and will support data rates up to 2.4Mbps.
- CDMA2000 **1xEV-DV** stands for 1x Evolution Data Voice and supports circuit and packet data rates that may reach up to 5Mbps. It fully integrates with 1xRTT voice networks and supports wireless Voice over IP (VoIP) services.

CDMAONE. The industry association, CDMA Development Group, uses this name to describe the IS-95a and IS-95b CDMA standards. These CDMA standards use a 1.28MHz spread spectrum signal for transmission. IS-95a supports data throughput of up to 14.4kbps, and IS-95b increased this to 115.2kbps. They both support voice transmissions. Uplinks and downlinks occur simultaneously. The modulation technique used for the downlink is QPSK and for the uplink is offset QPSK. cdmaOne uses the 800MHz and 1900MHz frequency bands.

CDPD (CELLULAR DIGITAL PACKET DATA). A narrowband PCS system used in Canada, China, the United States, and parts of South America. It is a method of wireless communication that uses packet switching, but does not support voice. Its maximum throughput rate is 19.2Kbps.

CELL. A cell is the basic geographic unit of a cellular system and contains a base station. A cell can be divided into many smaller cells, each of which contains a base station equipped with a low powered radio transmitter/receiver.

CELL BROADCAST SERVICE. *See* **CBS**.

CELL PHONE. A cell phone is a wireless telephone that sends and receives messages using radio frequency energy in the radio frequency (RF) spectrum.

CELL SITE. The location in which the base station (wireless antenna and network communications equipment) is placed. A cell site consists of a transmitter/receiver, antenna tower, transmission radios, and radio controllers.

Cellular. Wireless communications network architecture that uses cells or modular coverage areas (geographical areas). The area is normally serviced by a cell site and usually allows calls to be transferred (handed off) from one cell to another when a phone is being used while the user is moving.

Cellular Base Station. The transmission and reception equipment, including the base station antenna, that connects a cellular phone to the network. This is also known as a **Cell Site**.

Cellular Digital Packet Data. *See* **CDPD**.

Cellular Telecommunications & Internet Association. *See* **CTIA**.

Cellular Telecommunications Industry Association. *See* **CTIA**.

CEPT (Conference of European Post and Telecommunications Authorities). The intergovernmental committee responsible for the design of the GSM system.

CF (Crest Factor). A signal's crest factor is the peak amplitude of its waveform divided by its RMS value.

Channel. An electrical, electromagnetic, or optical path that supports communication between two points. In RF applications, a channel is a section of a bandwidth. A bandwidth can have many channels.

Channel Sounding. A technique used in wireless communication systems to measure the characteristics of a channel.

Chip. A single pulse or symbol of a pseudo random data stream that is used to create a spread spectrum signal.

Chipping Rate. The data rate of a pseudo random noise (PN) signal that is used to create a spread spectrum signal.

Circuit. Electrical components that are connected to perform specific tasks. A circuit can also mean a closed loop path that current flows through.

Circuit Switched. The technology used in landline telephone systems to link two phones together so communication can occur. It is also used in 1G and some 2G mobile phone systems.

Circulator. Component with three or more ports. It allows power to flow in only one direction. When a signal enters a port, it flows in the proper direction and exits at the first port it encounters.

Citizens' Band Radio. *See* **CB Radio**.

CL (Conversion Loss). In a passive mixer, this is the insertion loss that results when a signal moves from the RF port to the IF port and vice versa.

CLEC (Competitive Local Exchange Carrier). A company that offers telecommunications services and competes with the local phone company. It can operate its network over the local phone company's copper network.

Client. A user (actually a device, usually a computer) that accesses the Internet or other network.

Closed Loop MIMO. Also known as MIMO Beam Forming and Transmitter Adaptive Antenna (TX-AA). *See* **Beam Forming**.

Coaxial Cable. A concentric, two-conductor cable in which a central conductor (a wire) is surrounded and shielded by another. The two conductors are separated by dielectric material (an insulator). These cable are used to conduct RF signals. This cable is also known as **Coax**.

Codec (Coder/Decoder). An electronic device, circuit, or software that converts analog signals, such as video and voice, into digital form, and vice-versa. It usually includes digital compression technology for added efficiency.

Code Division Multiple Access. *See* **CDMA**.

Coder/Decoder. *See* **Codec**.

COFDM (Coded Orthogonal Frequency Division Multiplexing). This term is equivalent to OFDM. *See* **OFDM**.

Collision Avoidance. A radar system that is placed in cars and used to alert drivers when they become too close to the car in front of them. NODS is another radar system for cars. It is located on the rear bumper and turns on when the car is put into reverse.

Combiner. A component (usually passive) that creates an RF signal by combining RF signals from multiple (two or more) paths.

Competitive Local Exchange Carrier. *See* **CLEC**.

Complementary Code Keying. *See* **CCK**.

Component. A term used to reference any part (object) in a circuit, such as resistors, capacitors, etc. The word **device** is sometimes used in the same manner.

Compression. A technique that converts data into a different format that requires less space, which allows it to be transmitted faster. Compression can have a different meaning. In RF amplification, an amplifier is said to be "in compression" when the output is no longer increasing linearly with the input.

Conference of European Post and Telecommunications Authorities. *See* **CEPT**.

Connectionless. A technique that allows packets to be sent without first establishing a physical or logical connection between the sender and receiver. Each packet begins with a header that contains the address of the recipient.

Connection-Oriented. A system that requires that a connection be made before users can start communicating. The connection does not need to be physical. It can be logical.

Connector. A physical object that allows a cable to be connected to a device.

Constellation Diagram. Graphical display of the demodulated states of a transmission. The axes represent I (in-phase) and Q (quadrature). A demodulated state is expressed as an I,Q pair.

Continuous Wave. *See* **CW**.

Continuous Wave Radar. A radar system that is always transmitting a signal.

CONUS (Continental United States). The name the satellite industry has given to the continental United States.

Conversion Loss. *See* **CL**.

Conversion Gain. The increase in power a signal obtains in an active mixer. Measured in dB.

Cordless. A wireless system with a very short range (less than 100m). This system uses only one base station, which is connected to a landline phone network. It uses unlicensed spectrum.

Cordless Telephone System 2. *See* **CT-2**.

Coupler. A directional coupler has the capability to separate and sample signal components based on the direction of signal flow.

Coverage Area. The geographic area an RF system's signals reach.

Crest Factor. *See* **CF**.

Cross Channel Interference. Interference due to a receiver detecting signals from multiple channels. *Also see* **Crosstalk**.

Crosstalk. Electric or magnetic fields of one signal affecting a signal in another circuit or channel. On wireless networks, crosstalk can sometimes result in users hearing part of a voice conversation from another circuit or channel.

CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance). The protocol used in 802.11 (Wi-Fi) devices that determines if a device can access the airwaves.

CSMA/CD (Carrier Sense Multiple Access/Collision Detection). The protocol used in 802.3 Ethernet networks that determines if a device can access the Ethernet.

CT-2 (Cordless Telephone System 2). A system in the United Kingdom that allows cordless phones to make calls by sending signals to base stations located in public spaces such as shopping malls; however, they cannot receive calls. Its goal is to support communications in areas that cellular phones cannot. Also known as **Telepoint**.

CTIA (Cellular Telecommunications Industry Association). A non-profit organization that represents all members of the telecommunications industry, including manufacturers, service providers, etc. (CTIA can also be called **Cellular Telecommunications & Internet Association**.)

CW (Continuous Wave). An un-modulated carrier signal.

D/A (Digital to Analog). Converting an electrical signal from digital to analog. Also known as **DAC (digital to analog conversion)**.

DAB (Digital Audio Broadcasting). Technique used by FM radio stations to send data with their audio signals. It provides a maximum throughput rate of 2.4Mbps per channel.

DAC (Digital to Analog Conversion). *See* **D/A**.

Daisy Chaining. A technique used to connect devices serially.

D-AMPS (Digital AMPS). A mobile phone TDMA standard that was used in North and South America. It generally has been superceded by GSM systems. D-AMPS is known as **ANSI-136**.

Datagram. A block of data, typically a packet, that is transmitted with a connectionless technique.

dB (Decibels). A unit of measure used to express relative differences in power or intensity of sound (ratio in log scale).

dBc. Decibel relative to main carrier power.

dBi. The unit used to describe antenna gain relative to an isotropic antenna.

dBm. Decibel relative to one milliwatt.

DBS (Direct Broadcast Satellite). A satellite that is in geosynchronous orbit around the Earth. It is typically used to broadcast signals to dish antennas connected to homes. Also known as **DTH (Direct to Home**).

DBV-H (Digital Video Broadcast-Handheld). This communications standard is being developed by a group of public and private organizations in Europe. It is based on DVB-T, which was also developed by this standards body, and will transmit digital video signals to mobile handheld terminals. Two of the issues it focuses on include the short life span of batteries in handheld devices and the transmission issues involved with transmitting video to mobile receivers.

DC Block. A component that blocks transmissions from DC and low frequency components while allowing transmissions from high frequency components to pass.

DCS (Digital Communication Services). A second-generation system for cellular communications. It is used in Europe.

DDS (Direct Digital Synthesizer). Programmable solid state oscillator.

Decade. A bandwidth whose upper frequency is ten times the lower frequency.

Decibels. *See* **dB**.

DECT (Digital European Cordless Telephony). This is a European standard for cordless telephone systems that is compatible with GSM. It uses the TDD and TDMA transmission techniques and the GSMK frequency shift keying technique. Its channel bandwidth is 2MHz and its maximum throughput rate is 1,152kbps. (DECT can also be called **Digital Enhanced Cordless Telephone**.)

De Facto Standard. A standard that has become popular. This standard might not have been developed or formally approved by a standards organization.

Demodulate. To convert a modulated carrier signal back to the original RF carrier signal and information signal.

Demodulator. A device that takes a modulated signal and separates it into the original carrier signal and information signal.

De-spreading. The process used to recover narrowband information from a spread spectrum signal.

Detector. A device that converts RF power signals to voltage signals. The output is typically used in test equipment that does not support RF power signals.

Device. *See* **Component**.

DFT (Discrete Fourier Transform). A mathematical method for computing the spectral components of a sampled analog signal.

DGPS (Differential GPS). A GPS system that provides greater accuracy. It uses reference stations on Earth as well as satellites in MEO orbit.

Dielectric. An insulating medium. Insulating mediums do not conduct electricity.

Dielectrically Tuned Oscillator. *See* **DTO**.

Dielectric Resonator Oscillator. *See* **DRO**.

Differential GPS. *See* **DGPS**.

Differential Phase Shift Keying. *See* **DPSK**.

Differential Quadrature Phase Shift Keying. *See* **DQPSK**.

Digital AMPS. *See* D-AMPS.

Digital Audio Broadcasting. *See* **DAB**.

Digital Communication Services. *See* **DCS**.

Digital Enhanced Cordless Telephone. *See* **DECT**.

Digital European Cordless Telephony. *See* **DECT**.

Digital Modulation. A method of encoding information using a binary code of 0s and 1s from electrical pulses. The nature of this encoding allows greater data security and system capacity than analog modulation.

Digital Signal Processor. *See* **DSP**.

Digital Subscriber Line. *See* **DSL**.

Digital to Analog. *See* **D/A**.

Digital to Analog Conversion. *See* **D/A**.

Digital Video Broadcast-Handheld. *See* **DBV-H**.

Digital Video Broadcasting. *See* **DVB**.

Diode. An electronic device that allows current to move in only one direction.

Diplexer. *See* **Duplexer**.

Dipole Antenna. A type of antenna commonly used with wireless networking devices. It has a signal range of 360° horizontally (in two dimensions) and 75° vertically (in the third dimension).

Direct Broadcast Satellite. *See* **DBS**.

Direct Digital Synthesizer. *See* **DDS**.

Directional Antenna. There are many different types of directional antennas. They are generally used to redirect the signal received from a transmitter to enhance its strength in a certain direction.

Directivity. The ability of a directional coupler to send RF energy to the desired port based on the direction of power flow. Measured in dB. In electromagnetics, directivity is a property of the radiation pattern produced by an antenna. It is defined as the ratio of the power radiated in a given direction to the average of the power radiated in all directions.

DIRECTIONAL COUPLER. *See* **COUPLER**.

DIRECT SEQUENCE. *See* **DS**.

DIRECT SEQUENCE CODE DIVISION MULTIPLE ACCESS. *See* **DS-CDMA**.

DIRECT SEQUENCE SPREAD SPECTRUM. *See* **DSSS**.

DIRECT TO HOME. *See* **DTH**.

DISCRETE COMPONENT. A single electronic component (not an integrated circuit). It is usually housed in its own package and is usually designed to perform only one task.

DISCRETE FOURIER TRANSFORM. *See* **DFT**.

DISCRETE MULTI-TONE. *See* **DMT**.

DISTRIBUTED CIRCUIT. A type of RF circuit. It includes passive components that are created by manipulating traces into specific shapes.

DIVERSITY. Describes a receiver's ability to select between two receive antennas; often one is horizontal and the other is vertical. Diversity is useful when operating in areas susceptible to the effects of multi-path interference.

DIVIDER. A device that splits an incoming RF signal equally into two or more output signals.

DMT (DISCRETE MULTI-TONE). A method of separating a Digital Subscriber Line (DSL) signal so that the usable frequency range is separated into 256 frequency bands of 4.3125kHz each.

DOPPLER RADAR. A type of radar that measures an object's speed by analyzing the change in frequency of a return signal. One application is the radar guns used by police to monitor the speeds of motorists. Doppler radar is also used by meteorologists.

DOUBLE POLE – DOUBLE THROW. *See* **DPDT**.

DOUBLE SIDE BAND SUPPRESSED CARRIER. *See* **DSBSC**.

DOWNCONVERTER. Generally used in a receiver to lower the frequency of an RF signal. Also known as a **MIXER**.

DOWNLINK. The telecommunications path taken by an RF signal to travel from a satellite transmitter to a ground receiver or from a base station to a mobile phone.

DOWNSTREAM. The telecommunications path taken by an RF signal to travel from a base station to the end user.

DPDT (DOUBLE POLE – DOUBLE THROW). This is essentially two SPDT switches with each SPDT controlling a different input signal. The switches are controlled by one mechanism and operate synchronously. When one alters the signal path of its input signal, the other does the same.

DPSK (DIFFERENTIAL PHASE SHIFT KEYING). Phase-shift keying technique that uses the bits in the information signal to change the phase of the carrier wave. DPSK is a noncoherent form of phase-shift keying, which avoids the need for a coherent reference signal at the receiver. In DPSK systems, the input binary sequence is first differentially encoded and then modulated using a BPSK modulator.

DQPSK (Differential Quadrature Phase Shift Keying). This is a quadrature phase-shift keying technique that uses the differential encoding of the data bits to change the phase of the carrier wave.

DRO (Dielectric Resonator Oscillator). A type of oscillator that is typically used in applications that require high accuracy and high frequencies.

DS (Direct Sequence). A technique used in spread spectrum modulation where a pseudo-random code directly modulates the phase of a carrier. This increases the bandwidth of the transmission and results in a signal with a noise-like spectrum. The signal is de-spread by reversing the process using the same pseudo-random code.

DSBSC (Double Side Band Suppressed Carrier). A type of transmission in which frequencies produced by amplitude modulation are spaced symmetrically above and below the carrier frequency and the carrier level is suppressed to the lowest level that is practical.

DS-CDMA (Direct Sequence Code Division Multiple Access). A signal transmission technique based on DSSS that allows multiple users to share the same frequency band.

DSL (Digital Subscriber Line). A technology that sends high-speed data over the copper phone lines usually owned by landline telephone companies. DSL uses a different frequency than the landline telephone company.

DSP (Digital Signal Processor). A specialized microprocessor containing hardware features specifically for processing digital signals. DSP can also be Digital Signal Processing, which is a technique for analyzing digital signals.

DSSS (Direct Sequence Spread Spectrum). In this spread spectrum technique, multiple signals are transmitted simultaneously over a wide range of frequencies (usually MHz). Data is scattered across the frequency band in a pseudo-random pattern, which greatly increases the bandwidth and also makes the signal resistant to noise, interference, and eavesdropping. The receiving device is instructed to decipher only the data corresponding to a particular code to reconstruct the signal.

DTH (Direct To Home). *See* **DBS**.

DTO (Dielectrically Tuned Oscillator). This type of oscillator is a DRO with variable output frequencies.

Dual-Band. A dual-band digital phone will work in two frequency bands. For example, with North American TDMA and CDMA phones, dual-band indicates that the phone will work in both the 800/850MHz band and the 1900MHz band. Dual-band phones can also be dual-mode, working in both analog and digital modes.

Dual Directional Coupler. A type of coupler that processes signals in two directions. A signal from either direction can be coupled or sampled.

Dual-Mode. The phrase "dual-mode phone" can have different meanings around the globe. Common descriptions are:

- A phone that supports both analog (such as AMPS) and digital (such as CDMA or TDMA) technologies. In addition, the digital mode could be dual band, operating in either the 800/850MHz frequency band or the 1900MHz band.
- A phone that supports both 2G and 3G technologies, such as GSM/UMTS phones.

DUPLEX. The ability to provide separate, two-way transmission of data (usually transmit and receive) simultaneously.

DUPLEXER. An electronic component that contains two filters. It is also known as a **DIPLEXER**.

DUTY CYCLE. The percentage of "on time" (transmitting) vs. "off time" (not transmitting). Continuous transmitting is referred to as **100% DUTY CYCLE**.

DVB (DIGITAL VIDEO BROADCASTING). A suite of open standards for digital television that is internationally accepted.

DVB-C (DIGITAL VIDEO BROADCASTING – CABLE). A European standard for transmitting digital television over cable.

DVB-S (DIGITAL VIDEO BROADCASTING – SATELLITE). An international standard for broadcasting television signals over communications satellites. The standard includes modulation and forward error coding.

DVB-T (DIGITAL VIDEO BROADCASTING – TERRESTRIAL). A European standard for transmitting compressed digital signals (both audio and video) for digital terrestrial television. Digital terrestrial television is a technique for sending more data over the airwaves to antennas located on homes.

DYNAMIC RANGE. *See* **THIRD ORDER INTERCEPT POINT**.

EARTH STATION. A facility located on Earth that communicates with and usually controls a satellite.

EAS (ELECTRONIC ARTICLE SURVEILLANCE). An RFID system that detects merchandise with RFID tags attached to them. It is used to prevent shoplifting. When merchandise with an attached RFID tag passes through an antenna gate, an alarm will sound.

EBF (EIGEN BEAM FORMING). A closed-loop MIMO technique that is usually referred to as beam forming. *See* **BEAM FORMING**.

EBNR (ENERGY PER BIT TO NOISE RATIO). A measure of the signal to noise ratio. It is the energy per bit divided by the noise and interference level.

EDGE (ENHANCED DATA RATE FOR GLOBAL EVOLUTION). Standard based on GSM that uses TDMA multiplexing technology and the 600kHz frequency band. It has a channel size of 200kHz. Also known as **EGPRS**. (EDGE can also be called Enhanced Data GSM Environment.)

EFFECTIVE ISOTROPIC RADIATED POWER. *See* **EIRP** and **ERP**.

EFFECTIVE RADIATED POWER. *See* **ERP**.

EGPRS (ENHANCED GPRS). *See* **EDGE**.

EHF (EXTREMELY HIGH FREQUENCY). Frequencies between 30 and 300GHz with wavelengths from 1 to 10mm. It is typically used in radar and satellite applications.

eHSPA. *See* **HSPA+**.

EIRP (Effective Isotropic Radiated Power). Describes an antenna's transmission power as a ratio of its output signal strength to its input signal strength.

Electromagnetic Compatibility. *See* **EMC**.

Electromagnetic Interface. *See* **EMI**.

ElectroMotive Force (or voltage). *See* **EMF**.

Electronic Article Surveillance. *See* **EAS**.

Electronically Scanned Array. An antenna that sweeps an antenna pattern electronically. It does not move mechanically. It consists of many small transceivers.

EMC (Electromagnetic Compatibility). A study of electromagnetic energy and the effects (usually unintentional) this energy can cause.

EMF (ElectroMotive Force). A voltage difference caused by electromagnetic, electrochemical, or thermal effects.

EMI (Electromagnetic Interference). Unwanted signals that cause interference or noise, which can adversely affect the performance of signals or circuits. Also known as **RFI**.

EMS (Enhanced Messaging Service). Adds color and other features to SMS messages without adding more hardware anywhere on the cellular network. It is similar to **Smart Messaging**, although incompatible with it.

Encryption. The process of encoding a message, such as a digital phone signal, to prevent it from being read by parties other than the intended recipient.

Energy per Bit to Noise Ratio. *See* **EBNR**.

Enhanced Data GSM Environment. *See* **EDGE**.

Enhanced Data Rate for Global Evolution. *See* **EDGE**.

Enhanced GRPS. *See* **EGPRS**.

Enhanced Messaging Service. *See* **EMS**.

ERMES (European Radio Message System). A paging standard used in Europe and parts of Asia.

ERP (Effective Radiated Power). The effective isotropic radiated power is a calculated measurement of the effective power leaving an antenna. It is derived by comparing the actual power leaving the antenna to that of an isotropic antenna. ERP is also used to describe the amount of RF energy from a satellite that reaches the Earth within the satellite antenna's footprint.

Error Vector Magnitude. *See* **EVM**.

ESS (Extended Service Set). LANs and BSSs that are interconnected but appear to be one BSS to equipment that contact them.

Ethernet. An industry standard LAN (wired network) system that implements the IEEE's 802.3 protocols. It uses copper or fiber wires and can provide data rates of 10, 100, 1000, and 10,000Mbps. It uses CSMA/CD.

ETSI (European Telecommunications Standards Institute). A committee responsible for most of the telecommunications standards used in Europe, including DECT, GSM, and UMTS.

European Radio Message System. *See* **ERMES**.

European Telecommunications Standards Institute. *See* **ETSI**.

eV-DO. *See* **1xEV-DO**.

eV-DV. *See* **1xEV-DV**.

EVM (Error Vector Magnitude). EVM is a measurement of how well the modulated I-Q signal states can be demodulated into the original I-Q signal state, which helps to determine the quality of a signal generated by a transmitter and/or the quality of the demodulator. It compares the measured signal state vector against the ideal signal state vector, then calculates the root-mean-square (RMS) value of the error vector. EVM is measured in either % or dB.

Evolved HSPA. *See* **HSPA+**.

Extended Service Set. *See* **ESS**.

Extranet. The network an organization uses to contact employees who do not have access to the organization's local network. An Extranet can use existing networks, such as the Internet.

Extremely High Frequency. *See* **EHF**.

Fast Fourier Transform. *See* **FFT**.

Fast Infrared. *See* **FIR**.

FCC (Federal Communications Commission). The government agency responsible for regulating telecommunications in the United States. This includes licensing airwaves (spectrum).

FDD (Frequency Division Duplexing). Technique that uses two frequency bands in order to simultaneous transmit and receive signals. One frequency band will only transmit (uplink) signals and the other will only receive (downlink) signals. It is also known as **Paired Spectrum**.

FDM (Frequency Division Multiplexing). A technique that accommodates multiple simultaneous users in a radio band of frequency. This is done by dividing a frequency band into smaller bands.

FDMA (Frequency Division Multiple Access). *See* **FDM**.

FEC (Forward Error Correction). A system of error control for data transmission in which the receiving device can detect and correct any character or block of code that contains fewer than a predetermined number of erroneous symbols.

Federal Communications Commission. *See* **FCC**.

Feedback. When electrical signals at a specific point in a system are sampled (fed back) to verify they are within the desired specifications. If they are not, the system can usually make adjustments automatically.

Ferrite. The magnetic properties of this material make it ideal for use in transformers, isolators, and circulators.

FET (Field Effect Transistor). A type of transistor that uses an electric field to control the shape and conductivity of a semiconductor's channel.

FFT (Fast Fourier Transform). FFTs are computer algorithms optimized to calculate the spectral components of a sampled analog signal. It calculates a DFT with a minimum of mathematical operations and does it much faster than using conventional math techniques. FFTs can be used to demodulate OFDM signals.

FH (Frequency Hopping). A technique where the transmitter frequency hops from channel to channel in a predetermined but pseudo-random manner. At the receiver, the same is done in reverse to recover the original signal. This technique is used to minimize the effect of interference between a transmitter and receiver.

FHSS (Frequency Hopping Spread Spectrum). A spread spectrum encoding technique that is used in conjunction with frequency hopping. In this technique, the sender and receiver hop (move) together from one frequency to another in a seemingly random fashion to avoid detection or interference.

Fiber. Glass cable (strands of glass) that carry optical signals. Lasers or LEDs on each end of a cable transmit and receive the signals in the infrared range (1,000GHz), not in the visible light range. Signals move slower through fiber than they do through air or copper wire. Its maximum throughput rate is 10Gbps.

Fiber Optic Cable. *See* **Fiber**.

Field Effect Transistor. *See* **FET**.

Filter. This device allows only signals with specific frequencies to pass through it. Common filter types are bandpass, band reject, high pass, and low pass.

Finite Impulse Response. *See* **FIR**.

FIR (Finite Impulse Response). A digital filter that eventually settles to zero after it receives an impulse. FIR is also an acronym for **Fast Infrared**, a standard developed by IrDA. Its maximum throughput rate is 4Mbps.

Fire Control Radar. A radar system that controls the flight of a missile. Typically used in fighter aircraft.

Firewall. Protects a computer (or network) from unauthorized access. It is usually a program, but can be hardware, that typically blocks specific types of TCP or UDP traffic.

First Generation. *See* **1G**.

Fixed Satellite Service. *See* **FSS**.

Fixed Satellite Systems. *See* **FSS**.

Fixed Wireless. A wireless system whose phones (transmitters and receivers) are stationary.

Flex. A paging system used in the United States. **ReFlex** is an upgrade of Flex that supports two-way transmissions.

FM (Frequency Modulation). In analog applications, frequency modulation techniques vary the frequency of the carrier signal in proportion to the amplitude of the information signal. It does not change the amplitude of the carrier signal. In digital applications, frequency shift keying is used.

FOMA (Freedom of Mobile Multimedia Access). A W-CDMA based system developed by NTT DoCoMo for Japan.

Footprint. A geographic area on Earth (antenna pattern) supported by an antenna located on a satellite.

Forward Error Correction. *See* **FEC**.

Forward Link. The wireless connection over which information is sent from a cellular base station to a mobile phone. The reverse link is the send connection from a mobile phone to the base station.

Fourth Generation. *See* **4G**.

Freedom of Mobile Multimedia Access. *See* **FOMA**.

Free Space Loss. The loss of signal strength as it moves through the air. It does not take into consideration any effects an object can cause to a signal. For example, objects can absorb, block, reflect, and/or refract signals.

Frequency. The number of oscillations (complete wave cycles) of radio waves per unit of time, usually expressed in either cycles-per-second or Hertz (Hz).

Frequency Division Duplexing. *See* **FDD**.

Frequency Division Multiple Access. *See* **FDMA**.

Frequency Division Multiplexing. *See* **FDM**.

Frequency Hopping. *See* **FH**.

Frequency Hopping Spread Spectrum. *See* **FHSS**.

Frequency Modulation. *See* **FM**.

Frequency Response. The amount of amplitude gained or lost when a signal's frequency changes.

Frequency Reuse. The ability to use the same frequencies repeatedly across a cellular system at the same time. Each cell is designed to use radio frequencies only within its boundaries. By design, the same frequencies can be reused in other cells not far away with little potential for interference.

Frequency Shift Keying. *See* **FSK**.

FSK (Frequency Shift Keying). A type of frequency modulation used for digital signals.

FSS (Fixed Satellite Systems). A system onboard a satellite that provides service to stationary receivers on Earth. (FSS can also be called **Fixed Satellite Service**.)

Full-Duplex Transmission. A channel that allows transmission in two directions at the same time, for example, talking and listening.

Full Usage of Subcarriers. *See* **FUSC**.

FUSC (Full Usage of Subcarriers). In WiMAX (802.16e-2005), the FUSC technique for downlink uses all the data subcarriers to create the subchannels. The subcarriers are mapped into the subchannels using standard defined permutation schemes, and are evenly distributed over the frequency band. Up to 48 subcarriers make up a subchannel.

GaAs (Gallium Arsenide). A material used to create semiconductors. These include high frequency RF devices such as RF diodes and transistors.

Gain. The ratio of the input signal to the output signal as it enters and leaves a component. It is usually measured in dB.

Gain Flatness (ΔG). In an amplifier, this measures how the gain varies. It is usually measured in dB.

Gallium Arsenide. *See* **GaAs**.

Gateway. A device that links networks using incompatible protocols. It converts the information flowing from one network to a format that is acceptable to the network being sent the information.

Gateway GPRS Support Node. *See* **GGSN**.

Gateway Mobile Switching Center. *See* **GMSC**.

Gaussian Filter. A Gaussian filter modifies the input signal by convolution with a Gaussian function. A Gaussian filter has a smooth transfer function with no zero crossing and also has narrow bandwidth, sharp cutoff, low overshoot, and pulse preservation properties, which make it useful in modulation techniques with non-linear RF amplifiers.

Gaussian Minimum Shift Keying. *See* **GMSK**.

General Packet Radio Services. *See* **GPRS**.

Generalized Packet Radio System. *See* **GPRS**.

GEO (Geosynchronous Orbit). A typically circular orbit located 22,000 miles (35,785km) above the Earth's equator. A satellite at this orbit appears to be stationary although it is moving in correspondence with the Earth's rotation.

Geostationary Orbit. *See* **Geosynchronous Orbit**.

Geosynchronous Orbit. *See* **GEO**.

GGSN (Gateway GPRS Support Node). A device that links a GPRS network with another network, for example, the Internet.

GHz (Gigahertz). 10^9 Hz.

Gigahertz. *See* **GHz**.

Global Positioning System. *See* **GPS**.

Global System for Mobile Communications. *See* **GSM**.

GMSC (Gateway Mobile Switching Center). A device that links a mobile network with a PSTN (a landline telephone network) and to other mobile networks with which it has interconnect agreements.

GMSK (Gaussian Minimum Shift Keying). A form of frequency shift keying used in GSM systems. This technique uses Gaussian filtering and allows frequency spacing that is one-half as wide as FSK modulation. This technique has good spectral efficiency.

GPS (Global Positioning System). A system of 24 satellites used to identify locations on Earth. By using signals from four satellites, a receiving unit can pinpoint its current location anywhere on Earth to within a few meters. The signals from three of the satellites are used for triangulation, and the signal from the fourth is for time synchronization. Time synchronization is necessary because these satellites are not in geosynchronous orbit; they are in medium earth orbit, so they are moving.

GPRS (Generalized Packet Radio System). An upgraded version of GSM systems. Enhancements include the use of packet switching and a maximum throughput rate of 115.2kbps. (GPRS can also be called **General Packet Radio Services**.)

Ground Station. A facility located on Earth that tracks and controls satellites and spacecraft.

Group Special Mobile. *See* **GSM**.

GSM (Global System for Mobile Communications). This wideband TDMA standard was originally developed as a pan-European standard for digital mobile telephones. GSM is now the world's most widely used mobile system. It uses eight time slots and the GMSK phase modulation technique. Its maximum throughput rate is 14.4kbps (15.2Kbps per channel). It is used on the 800 to 900MHz and 1800MHz frequencies in Europe, Asia, and Australia, and the 900MHz and 1800 to 1900MHz frequencies in North America and Latin America. (GSM can also be called **Group Special Mobile**.)

Half-Duplex Transmission. *See* **HDX**.

Handheld PC. Small devices developed by Microsoft® that include a keyboard and a Windows® operating system.

Handoff. In wireless mobile phone systems, a handoff is the process of transferring a phone call in progress from one base station to another base station without interrupting (dropping) the call. This is usually done when a mobile phone moves between cells.

Harmonic Distortion. Distortion in a device's output signal due to the presence of frequencies that are not present in the input signal. Harmonic distortion is caused by nonlinearities within the device.

Harmonics (suppression). The amount of unwanted signals generated due to a device's nonlinearity. Harmonic components are at multiples of the original signal frequency. Measured in dBc.

HBT (Heterojunction Bipolar Transistor). A transistor made from both silicon and GaAs.

HDR (High Data Rate). *See* **1xEV-DO**.

HDTV (High Definition Television). A system for broadcasting television signals that provides high resolution images on televisions. It uses 720 picture lines.

HDX (Half-Duplex Transmission). A channel that allows transmission in only one direction at a time. Transmitting and receiving of signals cannot occur simultaneously.

HEMT (HIGH ELECTRON MOBILITY TRANSISTOR). A transistor that supports very high frequencies and low noise.

HERTZ. *See* **HZ**.

HETEROJUNCTION BIPOLAR TRANSISTOR. *See* **HBT**.

HF (HIGH FREQUENCY). Frequencies between 3 and 30MHz with wavelengths from 10 to 100m. It is typically used for amateur radio and AM radio signals.

HIGH DATA RATE. *See* **HDR**.

HIGH DEFINITION TELEVISION. *See* **HDTV**.

HIGH ELECTRON MOBILITY TRANSISTOR. *See* **HEMT**.

HIGH FREQUENCY. *See* **HF**.

HIGH PASS FILTER. *See* **HPF**.

HIGH POWER AMPLIFIER. *See* **HPA**.

HIGH SPEED CIRCUIT SWITCHED DATA. *See* **HSCSD**.

HIGH SPEED DOWNLINK PACKET ACCESS. *See* **HSPA**.

HIGH SPEED PACKET ACCESS. *See* **HSPA**.

HIGH SPEED UPLINK PACKET ACCESS. *See* **HSPA**.

HIPERACCESS. *See* **HIPERLAN3**.

HIPERLAN. *See* **HIPERLAN1**.

HIPERLAN1. A proposed high-speed wireless LAN system for Europe that would support up to 23.5Mbps data throughput. The frequencies it uses are 5.15 to 5.35GHz and 5.47 to 5.875GHz. The bandwidths it would use are 455MHz, dedicated, and 150MHz, ISM. Also known as **HIPERLAN**.

HIPERLAN2. This is a wireless LAN specification developed by ETSI. This high-speed wireless LAN system supports up to 52Mbps data throughput.

HIPERLAN3. This is a proposed LAN standard for wireless loop technology in Europe. The frequencies it would use are in the 5GHz band and it would have a range of 5km. It is also known as **HIPERACCESS**.

HIPERLAN4. *See* **HIPERLINK**.

HIPERLINK. This proposed high-speed wireless LAN system for Europe would use frequencies from 17.1 to 17.3GHz and a bandwidth of 200MHz (dedicated). It is intended to be used in large buildings. HiperLink is also known as **HIPERLAN4**.

HLR (HOME LOCATION REGISTER). A database for a group of cells. It contains information about the mobile terminals that generally use these cells.

HOME LOCATION REGISTER. *See* **HLR**.

HOME RADIO FREQUENCY. *See* **HOMERF**.

HOMERF (HOME RADIO FREQUENCY). This is a wireless LAN standard that uses frequencies in the 2.4GHz ISM band and FHSS.

Hot Spot. In wireless networking, a hot spot is the specific part of an access point's range in which members of the general public can walk up and use the network. The service may be available for a fee, and has a short range to control the physical proximity of users.

HPA (High Power Amplifier). This is the last amplifier a signal passes through before it is sent out of an antenna.

HPF (High Pass Filter). A signal filter that passes frequencies above a certain frequency and attenuates frequencies below that frequency.

HSCSD (High Speed Circuit Switched Data). This is an upgrade for GSM networks. It supports more calls by allowing a call to use more than one time slot. Its maximum throughput rate is 57.6kbps (four channels that support up to 14.4kbps each). It is based on TDMA technology.

HSDPA (High Speed Downlink Packet Access). *See* **HSPA.**

HSPA (High Speed Packet Access). HSPA is an upgrade of W-CDMA and uses the same spectrum and carriers. HSPA is divided into two wireless broadband protocols: HSDPA (High Speed Downlink Packet Access) and HSPUA (High Speed Uplink Packet Access). HSDPA is expected to increase downlink throughput to 14Mbit/s and increase downlink system capacity 500%. HPUSA is expected to increase uplink throughput to 5.8Mbit/s and increase uplink system capacity 200%. HSDPA uses 16QAM and HSPUA uses 64QAM, so as HSPA evolves, it can possibly support up to 12Mbit/s in the uplink and up to 21Mbits/s in the downlink. HSPA also reduces latency.

HSPA+. HSPA+ is an upgrade of HSPA. It is expected to provide significant improvements over HSPA, such as increased data rates, increased VoIP capacity, and better spectral efficiency. It is expected to be comparable to LTE in 5MHz. HSPA+ is also known as **eHSPA**, **Evolved HSPA**, **HSPA Evolution**, **I-HSPA**, and **Internet HSPA**.

HSPA Evolution. *See* **HSPA+**.

HSPUA (High Speed Uplink Packet Access). *See* **HSPA.**

HTTP (Hypertext Transfer Protocol). A protocol for the Internet that specifies how to transfer information. It was originally designed for HTML pages.

Hybrid. *See* **MIC**.

Hypertext Transfer Protocol. *See* **HTTP**.

Hz (Hertz). The unit of frequency measurement, expressed in wave cycles per second. Named after Heinrich R. Hertz.

I/Q (In-phase/Quadrature) Signals. The orthogonal components of a signal. In-phase and quadrature phase are two components of a signal that are 90° out of phase with each other.

IC (Integrated Circuit). Electrical components that are connected on or in a continuous material, such as silicon or GaAs.

ICI (Inter-Carrier Interference). An effect where the data from one subcarrier cannot be distinguished from its adjacent subcarriers.

iDEN (Integrated Digital Enhanced Network). A digital PMR system used in the United States. Its base stations allow users to communicate with each other. It is a 2G system with packet-switching capability.

IDFT (Inverse Discrete Fourier Transform). Recreates the analog signal from the DFT frequency spectrum coefficients.

IEEE (Institute of Electrical and Electronics Engineers). A professional society that creates standards, such as Ethernet.

IEEE 802.11. *See* **802.11**.

IEEE 802.11a. *See* **802.11a**.

IEEE 802.11b. *See* **802.11b**.

IEEE 802.15. *See* **802.15**.

IEEE 802.16. *See* **802.16**.

IEGMP (Independent Experts Group on Mobile Phones). A government committee that develops safety guidelines for mobile phones in the United Kingdom.

IF (Intermediate Frequency). A carrier signal's frequency is shifted to this frequency (the IF frequency) as an intermediate step in transmission or reception.

IFFT (Inverse Fast Fourier Transform). Recreates the analog signal from the Fourier frequency spectrum coefficients. It is optimized for computer processing. IFFTs can be used to modulate OFDM signals.

I-HSPA. *See* **HSPA+**.

IL (Insertion Loss). *See* **Insertion Loss**.

Image Rejection. A mixer provides two output signals. Image rejection is the attenuation of the signal that will not be used. Measured in dB.

IMD (Intermodulation Distortion). Nonlinear distortion that's characterized by the appearance (in a device's output) of frequencies that are linear combinations of the fundamental frequencies and all harmonics present in the input signals.

i-mode. A service on a PDC network of the NTT DoCoMo Company. The original version supports SMS messaging and C-HTML browsing. The upgraded version supports multimedia messaging and XHTML. It is the first cellular system to offer Internet access from a mobile phone. Websites need to be specially coded to fit a phone's display screen.

Impedance. The total passive opposition offered to the flow of electric current. Impedance is determined by the combination of resistance, inductive reactance, and capacitive reactance in a given circuit. Impedance is a function of frequency, except in the case of purely resistive networks. Measured in ohms. 50Ω is the standard impedance of RF components.

Impedance Matching. When a device changes the impedance of its incoming RF signal to an impedance acceptable to the device that will receive its output signal. The standard impedance of RF components is 50Ω.

IMPEDANCE RATIO (N:1). Indicates the amount of change a transformer will perform on an RF signal's impedance. For example, if a transformer had a 3:1 impedance ratio, it would be able to change a 300Ω impedance to 100Ω.

IMT (INTERNATIONAL MOBILE TELEPHONE). A third generation cellular phone system.

IMT-2000 (INTERNATIONAL MOBILE TELECOMMUNICATIONS 2000). This is the "umbrella specification" for all 3G systems. It supports a maximum throughput of 2Mbps when stationary and 384kbps when mobile. It can use CDMA2000, EDGE/UWC-136, and UMTS/WCDMA. This standard was developed by ITU for the global market. It uses frequencies from 1885 to 2200MHz.

INDEPENDENT EXPERTS GROUP ON MOBILE PHONES. *See* **IEGMP**.

INDIUM PHOSPHIDE. *See* **INP**.

INDUSTRIAL, SCIENTIFIC, MEDICAL. *See* **ISM**.

INFRARED. Frequencies just below the visible spectrum. Its wavelengths (750nm to 1mm) are longer than visible light and shorter than microwave.

INFRARED DATA ASSOCIATION. *See* **IRDA**.

INP (INDIUM PHOSPHIDE). A material used to create semiconductors for RF applications.

IN-PHASE/QUADRATURE SIGNALS. *See* **I/Q SIGNALS**.

INSERTION LOSS. The power loss resulting from a signal passing through a device, a component, or a transmission medium. Measured in dB.
Insertion Loss = $-10 \cdot \text{Log}(P_{out}/P_{in})$.

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS. *See* **IEEE**.

INSULATOR. A material that does not conduct electricity. There are also insulators that do not conduct heat or sound.

INTEGRATED CIRCUIT. *See* **IC**.

INTEGRATED DIGITAL ENHANCED NETWORK. *See* **IDEN**.

INTEGRATED SERVICES DIGITAL NETWORK. *See* **ISDN**.

INTER-CARRIER INTERFERENCE. *See* **ICI**.

INTERCEPT POINT. *See* **THIRD ORDER INTERCEPT POINT**.

INTERCONNECT AGREEMENT. Regulations that telecommunications companies follow when they agree to support one another's networks by accepting handoffs from each other.

INTERFERENCE. RF energy that prevents the clear reception of incoming signals.
CONSTRUCTIVE INTERFERENCE occurs when the incoming signal and the interfering signal are in phase (have peaks and troughs at the same time), which causes them to be added together.
DESTRUCTIVE INTERFERENCE occurs when the signals are out of phase, which causes them to combine and subtract from each other.

INTERLEAVING. A technique for sending voice and data during the same cellular call by alternating the voice signal and the data signal.

INTERMEDIATE FREQUENCY. *See* **IF**.

INTERMODULATION. Phenomenon associated with the mixing of multiple fundamental frequencies, resulting in the generation of predictable high order harmonics, causing the degradation of usable frequency spectrum.

INTERMODULATION DISTORTION. *See* **IMD**.

INTERNATIONAL MOBILE TELEPHONE. *See* **IMT**.

INTERNATIONAL MOBILE TELECOMMUNICATIONS 2000. *See* **IMT-2000**.

INTERNATIONAL TELECOMMUNICATIONS UNION. *See* **ITU**.

INTERNET HSPA. *See* **HSPA+**.

INTERNET PROTOCOL. *See* **IP**.

INTERNET SATELLITE PROVIDER. *See* **ISP**.

INTERNET SERVICE PROVIDER. *See* **ISP**.

INTERROGATOR. In an RFID system, it is the device that senses transponders that have been placed on objects. To sense a transponder, the interrogator continuously sends out signals. When a transponder receives a signal, it immediately sends the signal back to the interrogator. The interrogator then causes an action to occur.

INTER-SYMBOL INTERFERENCE. *See* **ISI**.

INVERSE DISCRETE FOURIER TRANSFORM. *See* **IDFT**.

INVERSE FAST FOURIER TRANSFORM. *See* **IFFT**.

IP (INTERNET PROTOCOL). A standard used world-wide that dictates how data packets are managed (sent, routed, received, etc.) on the Internet.

IP ADDRESS. How a device is identified on the Internet or other IP network. Each IP address on a network must be unique.

IQ BALANCE. The measure of the difference in the gain between the I transmission path and the Q transmission in a transmitter. *Also see* **PHASE UNBALANCE**.

IQ DETECTOR. The circuit block in a receiver that decomposes the received signal into its I and Q components.

IQ SIGNALS. *See* **I/Q SIGNALS**.

IRDA (INFRARED DATA ASSOCIATION). An association that creates standards for infrared communications. Most of their standards apply to laptop computers and PDAs.

IS-54. The standard on which ANSI-136 (also known as D-AMPS) was based.

IS-95. A mobile phone standard using the CDMA transmission method.

IS-95A. *See* **CDMAONE**.

IS-95B. This standard increases the throughput rate of IS-95a to 115.2kbps.

IS-95C. This standard increases the throughput rate of IS-95b to 384kbps. Also known as **1XMC**.

ISDN (Integrated Services Digital Network). A communications network with 64kbps channels.

ISI (Inter-Symbol Interference). The interference between adjacent pulses of a transmitted code.

ISM (Industrial, Scientific, Medical). Frequency allocations used in wireless applications for industrial, scientific, and medical purposes. These unlicensed frequencies are also used by some cordless phones and some wireless LAN systems.

ISM-2.4. The FCC frequency of this ISM band is 2.4 to 2.4835GHz. The ETSI frequency is 2.4 to 2.5GHz. It is primarily used in microwave ovens.

ISM-5.8. The FCC frequency of this ISM band is 5.725 to 5.850GHz. The ETSI frequency is 5.725 to 5.875GHz. It is primarily used in medical scanners.

ISM-9000. The FCC frequency of this ISM band is 902 to 928MHz. The ETSI frequency is 890 to 906MHz. It is primarily used in food processing.

Isolation. A measure of the RF power generated at a non-electrically connected terminal. This RF power is caused by the RF power at the primary terminal. Lower dB levels indicate higher isolation. Isolation is measured relative to the initial or carrier power.

Isolator. A type of circulator. It has three ports. One port has only one function, which is to send the signal to a load.

Isotropic Antenna. A theoretical, ideal antenna whose signal range is 360° in all directions (in all three dimensions – creating an antenna pattern that looks like a sphere). It is used as a baseline for measuring a real antenna's signal strength in dBi, where the "i" stands for isotropic antenna.

ISP (Internet Service Provider). A company that provides Internet service, such as access to the Internet. (ISP can also be called **Internet Satellite Provider**.)

ITU (International Telecommunications Union). An agency of the United Nations responsible for regulating telecommunications around the world. This includes licensing airwaves (spectrum), allocating satellite frequencies, and specifying the orbits of satellites.

Jamming. Typically, the intentional interference with another radio signal.

Japanese Digital Cellular. *See* **JDC**.

Japan TACS. *See* **JTACS**.

JDC (Japanese Digital Cellular). *See* **PDC**.

Jitter. An abrupt and unwanted variation of one or more signal characteristics, such as the interval between successive pulses, the amplitude of successive cycles, or the frequency or phase of successive cycles.

JTACS (Japan TACS). An analog cellular system formerly used in Japan. It is similar to TACS. It uses frequencies in the 900MHz range, its channel size is 25kHz, and its maximum throughput rate is 0.3kbps.

Kbyte (Kilobyte). 1,024 bytes. It is not based on a decimal system (power of 10). It is based on computers' binary system (power of 2).

KBPS (KILOBITS PER SECOND). Thousands of bits per second.

KILOBITS PER SECOND. *See* **KBPS**.

KILOBYTE. *See* **KBYTE**.

LAN (LOCAL AREA NETWORK). A short-distance network (less than 100m) used to link a group of computers together, generally within a building. Ethernet is the most commonly used type of LAN. A hub serves as the common wiring point, enabling data to be sent from one machine to another over the network.

LAND LINE. Traditional wired phone service providing voice, video, and data transmission over wires.

LAND MOBILE RADIO. *See* **LMR**.

LANGE COUPLER. A type of coupler that takes an RF signal and divides it evenly, but phase-shifts one of the divided signals before sending each through a different port. Also known as a **QUADRATURE COUPLER**, **QUAD COUPLER**, or **QUAD HYBRID**.

LATENCY. The amount of time it takes for a packet of data to reach its specified destination (after its source releases it).

LATERALLY DIFFUSED METAL OXIDE SEMICONDUCTOR. *See* **LDMOS**.

LCC (LEADLESS CHIP CARRIER). A type of packaging for ICs that uses rounded pins instead of leads.

LDMOS (LATERALLY DIFFUSED METAL OXIDE SEMICONDUCTOR). A transistor that is generally used in applications that require frequencies greater than 1GHz. This transistor is made from silicon.

LEADLESS CHIP CARRIER. *See* **LCC**.

LED (LIGHT EMITTING DIODE). A semiconductor device that can generate light that is infrared, visible, or near ultraviolet.

LEO (LOW EARTH ORBIT). Orbit located a few hundred miles above the Earth.

LIGHT EMITTING DIODE. *See* **LED**.

LIMITING AMPLIFIER. The output of this amplifier never exceeds a predetermined level.

LINEAR AMPLIFIER. A device that accurately reproduces a radio wave in magnified form. The output signal has a linear relationship to the input signal.

LINEARITY. Describes how closely the relationship between the output and the input approaches a constant slope.

LINE OF SIGHT. *See* **LOS**.

LMCS (LOCAL MULTIPOINT COMMUNICATIONS SYSTEM). Applications that use high frequency signals.

LMDS (LOCAL MULTIPOINT DISTRIBUTION SERVICE). A fixed wireless service often used in local loop applications. To transmit signals successfully, it must have line-of-sight between the transmitter and receiver. It uses frequencies around 28GHz, so precipitation (rain, snow, etc.) can cause interference. It has a maximum throughput rate of 155Mbps and supports distances of up to 8km.

LMR (Land Mobile Radio). Wireless systems typically used by emergency response organizations and companies with large fleets of trucks. These systems can be independent or connected to other wireless systems.

LNA (Low Noise Amplifier). This is typically a precision, small-signal amplifier with low output noise. LNAs are used as the input amplifiers for receivers.

LNB (Low Noise Block Converter). In satellite communications, an LNB is placed on a satellite dish. It converts the incoming signals to a lower frequency and also amplifies the signal. Another component on the dish then sends the converted signal along coaxial cables into the home or facility.

LO (Local Oscillator). An oscillator that provides one of the input signals used in a mixer.

Local Area Network. *See* **LAN**.

Local Loop. The section of a telephone network that connects the local telephone company to the user's facility (home, office, manufacturing site, etc.). *Also see* **Wireless Local Loop**.

Local Multipoint Communications System. *See* **LMCS**.

Local Multipoint Distribution Service. *See* **LMDS**.

Local Oscillator. *See* **LO**.

Long Term Evolution. *See* **LTE**.

LOS (Line of Sight). When there are no visual obstructions between the transmitting and receiving antennas.

Loss. How much a signal decreases as it passes through a component. Measured in dB. *Also see* **Attenuation**.

Low Earth Orbit. *See* **LEO**.

Low Noise Amplifier. *See* **LNA**.

Low Noise Block Converter. *See* **LNB**.

Low Pass Filter. This type of signal filter passes all frequencies less than a certain frequency and attenuates all other frequencies.

Low Temperature Co-Fired Ceramic. *See* **LTCC**.

LTCC (Low Temperature Co-Fired Ceramic). A type of MIC technology that uses multiple layers of ceramic to support multiple layers of traces.

LTE (Long Term Evolution). LTE is a migration path from 3G technology to 4G technology that uses OFDM technology and MIMO. 3GPP is developing the specifications.

Lumped Element Circuit. An RF technique that groups discrete components together to perform a specific function.

MAC Address (Media Access Control Address). Each device connected to an Ethernet network has a unique numeric identifier called a MAC address, which is used for data transmission and security functions. For example, the MAC address lets devices on the network find each other and it accompanies each data packet to identify its sender.

MAC Filtering (Media Access Control Filtering). The process a network uses to check a device's Media Access Control address against a database to see if it is authorized to access the network.

Macrocell. A large geographic coverage area supported by a single base station in a cellular system.

MAN (Metropolitan Area Network). A fiber or wireless network located in a city. It is usually a WAN and usually services a geographic area of a few miles.

Match. A measure of how close an instrument's, device's, or component's input terminals and output terminals are equivalent to 50Ω. It is also a measure of the amount of power reflected from input or output terminals. Usually specified in terms of **VSWR** and **Return Loss**.

Matrix Condition Number. This number is a measure of the MIMO channel performance. It represents the ratio of the singular values from a transposed channel matrix.

Mbps (Megabits per Second). A megabit is approximately one million (10^6) bits of data, which is the amount of data per second being specified.

MCDN (Micro Cellular Digital Network). A network that uses both licensed and unlicensed frequencies. It does not support voice. Its maximum throughput rate is 128kbps.

M-commerce (Mobile E-Commerce). When a mobile network is used to link buyers and sellers.

MCPA (Multi-Carrier Power Amplifier). A type of very linear power amplifier used to transmit signals composed of multiple carriers such as OFDM signals.

MCS (Modulation and Coding Scheme). Combinations of modulation and coding techniques permitted in some wireless standards. Three example standards that use MCS indices are EDGE, WiMAX, and WLAN.

Media Access Control Address. *See* **MAC Address**.

Media Access Control Filtering. *See* **MAC Filtering**.

Medium Earth Orbit. *See* **MEO**.

Medium Infrared. *See* **MIR**.

Megabits per Second. *See* **Mbps**.

Megahertz. *See* **MHz**.

MEMS (Microelectromechanical Systems). Integrated circuits (ICs) with parts that can move.

MEO (Medium Earth Orbit). The orbit of MEO satellites is approximately 10,000km above the Earth.

MESFET (METAL SEMICONDUCTOR FIELD EFFECT TRANSISTOR). This transistor is generally used in applications that require frequencies of more than 1GHz. This transistor is made from GaAs.

METAL OXIDE SEMICONDUCTOR FIELD EFFECT TRANSISTOR. *See* **MOSFET**.

METAL SEMICONDUCTOR FIELD EFFECT TRANSISTOR. *See* **MESFET**.

METROPOLITAN AREA NETWORK. *See* **MAN**.

METROPOLITAN STATISTICAL AREA. *See* **MSA**.

METROPOLITAN TRADING AREA. *See* **MTA**.

MExE (MOBILE EXECUTION ENVIRONMENT). A standard for wireless devices that is used in Europe. This standard supports WAP and Java.

MHz (MEGAHERTZ). 10^6 Hertz.

MIC (MICROWAVE INTEGRATED CIRCUIT). An RF circuit technology that uses semiconductor devices, other discrete components, and traces that are lumped circuits and/or distributed circuits and places them on a ceramic substrate. Also known as hybrid circuit technology.

MICROCELL. When an existing cell cannot support the demand for its service, one or more microcells can be added within it to support the greater density of communications traffic in a small area.

MICRO CELLULAR DIGITAL NETWORK. *See* **MCDN**.

MICROELECTROMECHANICAL SYSTEMS. *See* **MEMS**.

MICROWAVE. Usually refers to electromagnetic waves with wavelengths longer than those of infrared light, but shorter than those of radio waves. The microwave range includes ultra-high frequency (0.3–3GHz), super-high frequency (3–30GHz), and extremely high frequency (30–300GHz) signals. It has a maximum throughput rate of 155Mbps.

MICROWAVE INTEGRATED CIRCUIT. *See* **MIC**.

MILLIMETER WAVE. Frequencies above the 40GHz bandwidth.

MIMO (MULTIPLE INPUT, MULTIPLE OUTPUT). This is a spatial multiplexing technique that uses up to four transmitters and four receivers with individual antennas to send and receive signals over the same frequency. This can increase throughput up to 3.5 times in the same bandwidth when compared to a single OFDM carrier. Signals can be spatially multiplexed because they are three dimensional and can be defined by frequency, time, and space parameters. A receiver can re-assemble a specific signal through a code at the beginning of a packet.

MIMO BEAM FORMING. These techniques are generally referred to as beam forming. They are considered closed-loop systems because information from the transmitter is used to optimize communications to the receiver. Also known as Closed Loop MIMO and Transmitter Adaptive Antenna (TX-AA). *See* **BEAM FORMING**.

MINIMUM SHIFT KEYING. *See* **MSK**.

MIR (MEDIUM INFRARED). A standard developed by IrDA that has a maximum throughput rate of 1.152Mbps.

Mixer. An RF component with two input ports and one output port. Two signals exit the output port. One has a frequency that is the sum of the two input frequencies. The other has a frequency that is the difference of the two input frequencies.

MMDS (Multipoint Multichannel Distribution System). This analog system was originally designed as a television broadcast system. It is now used as a fixed wireless service that is often used in local loop applications. It requires line of sight, uses frequencies around 2GHz, and has a maximum throughput rate of 36Mbps. It supports distances of up to 45km. (MMDS can also be called **Multipoint Multichannel Distribution Service**.)

MMIC (Monolothic Microwave Integrated Circuit). An integrated circuit created by connecting electrical components on or in a semiconductor material such as silicon or GaAs. MMICs are typically used in RF applications.

MMS (Multimedia Messaging Service). A system that provides both messaging and e-mail on mobile networks. There is no limit to the length of its text messages. It is a packet switching technology that can be used in GPRS, UMTS, and a number of other networks.

Mobile Commerce. *See* **M-commerce**.

Mobile E-Commerce. *See* **M-commerce**.

Mobile Execution Environment. *See* **MexE**.

Mobile Network. A telecommunications network that allows calls in progress to remain connected, even while users are changing their geographic locations.

Mobile Phone. Telephones used in mobile, cellular, or wireless networks.

Mobile Satellite Service. *See* **MSS**.

Mobile Satellite Systems. *See* **MSS**.

Mobile Station. *See* **MS**.

Mobile Switching Center. *See* **MSC**.

Mobile Telephone Switching Office. *See* **MTSO**.

Mobile Virtual Network Operator. *See* **MVNO**.

Mobitex. A mobile data network used in the United States. It is a narrowband PCS system based on packet-switching technology that does not support voice. Its maximum throughput rate is 8kbps.

Modem (Modulator-Demodulator). Device that demodulates an input signal and modulates an output signal.

Modulation. A technique that uses the characteristics of the information signal to modify the amplitude, frequency, or phase of the RF carrier signal.

Modulator. A device that receives a carrier signal and an information signal and outputs a modulated signal.

Modulator-Demodulator. *See* **Modem**.

Monocycle. One complete sine wave.

MONOLITHIC MICROWAVE INTEGRATED CIRCUIT. *See* **MMIC**.

MONOPOLE ANTENNA. A straight wire antenna. Its length is determined by the wavelength of the RF signal it transmits.

MOSFET (METAL OXIDE SEMICONDUCTOR FIELD EFFECT TRANSISTOR). A transistor that is generally used in low frequency (less than 1GHz) applications. It is made of silicon.

MRT (MAXIMUM RATIO TRANSMISSION). A transmission methodology that uses beam forming vectors.

MS (MOBILE STATION). The device people use to communicate over a wireless network. These devices include cellular phones and PDAs.

MSA (METROPOLITAN STATISTICAL AREA). An urban area that is supported by cellular network(s).

MSC (MOBILE SWITCHING CENTER). The control system of a wireless network. A network can have multiple MSCs. An MSC is responsible for managing calls, including tasks such as handing off calls to its basestations, to other mobile networks, and to landline networks. It is also known as the mobile telephone switching office.

MSK (MINIMUM SHIFT KEYING). A type of frequency shift keying in which the peak frequency deviation is equal to half the data bit rate. The modulation index is 0.5 and represents the minimum frequency spacing that allows two signals to be orthogonal.

MSS (MOBILE SATELLITE SYSTEMS). A system onboard a satellite that provides services to receivers that move on Earth. MSS can also be an IMT-2000 system that provides access to the system even when the user is not in a cell supported by that system. (MSS can also be called **MOBILE SATELLITE SERVICE**.)

MTA (METROPOLITAN TRADING AREA). An urban area that is supported by PCS.

MTSO (MOBILE TELEPHONE SWITCHING OFFICE). The central processing center for a cellular base station.

MULTI-CARRIER POWER AMPLIFIER. *See* **MCPA**.

MULTICAST. When a message is sent to more than one user or device. The recipients of the message are specified by the sender.

MULTIMEDIA. When more than one form of media is used, such as data, video, and sound.

MULTIMEDIA MESSAGING SERVICE. *See* **MMS**.

MULTIPATH. The phenomenon of a radio device receiving the same signal multiple times, usually from multiple paths, slightly offset in time. This often happens when a radio signal is received directly from the transmitter and the signal is also reflected off of one or more nearby objects. A reflected signal takes a longer path, so it arrives slightly later than the direct signal. Although many standard formats are degraded by multi-path, CDMA signals can actually benefit from multi-path.

MULTIPATH INTERFERENCE. When signal reflections and delayed signal images interfere with the desired signal. These situations are typically associated with high rise city buildings and indoor wireless LAN applications.

Multiple Access. A technique for accommodating many users in the same frequency band.

Multiple Input, Multiple Output. *See* **MIMO**.

Multiplexing. When multiple signals are carried in the same frequency band at the same time. In wireless communications, common multiplexing methods include TDMA, FDMA, and CDMA.

Multipoint Multichannel Distribution Service. *See* **MMDS**.

Multipoint Multichannel Distribution System. *See* **MMDS**.

MVNO (Mobile Virtual Network Operator). A telecommunications company that does not own a telecommunications network. It buys or rents the services it sells from another company.

NADC (North American Digital Cellular). A standard for digital cellular communications that was formerly used in the Americas.

Narrowband. A frequency band that uses a small amount of spectrum. This is a relative term. For example, audio signals for television are considered narrowband and have a 25kHz bandwidth. In telephony applications, narrowband is the 300–3400Hz frequency band.

National Television Systems Committee. *See* **NTSC**.

Near Object Detection System. *See* **NODS**.

Network. A system designed to provide communication paths between users at different geographic locations. Networks may be designed for voice, text, data, facsimile, and video. They may feature limited access (private networks) or open access (public networks). The analog or digital switching and transmission technologies used can vary greatly between networks.

Network Address. A unique number associated with a host that identifies it to other hosts during network transactions.

Network Interface Card. *See* **NIC**.

NF (Noise Figure). The degradation of the signal-to-noise ratio between the input and output of a component. Measured in dB.

NIC (Network Interface Card). A card (circuit board) that connects a computer to a network, such as Bluetooth, Ethernet, and/or IEEE 802.11b. The card is usually placed in a slot inside the computer.

NLOS (Non-Line of Sight). When there is one or more visual obstructions between the transmitting and receiving antennas.

NMT (Nordic Mobile Telephone). A standard for analog cellular communications that is used in Scandinavian countries. It uses frequencies in the 400MHz and 900MHz ranges, its channel size is 25kHz, and its maximum throughput rate is 1.2kbps.

Node. Nodes are computers, servers, and the other devices connected on a network. Nodes in a wireless fiber network are the optical transceiver terminals that require line of sight to successfully send and receive signals.

NODS (NEAR OBJECT DETECTION SYSTEM). A radar system for automobiles. It is located on the rear bumper and turns on when the car is placed in reverse. Collision avoidance is another radar system for cars. It is located on the front of the car.

NOISE. The undesired part of signal that is usually caused by phenomena such as temperature and atomic activity.

NOISE FIGURE. *See* **NF**.

NOISE TEMPERATURE. A measure of the available noise power from a source. Measure in degrees Kelvin. $T = P_a/kB$.

NON-LINE OF SIGHT. *See* **NLOS**.

NORDIC MOBILE TELEPHONE. *See* **NMT**.

NORTH AMERICAN DIGITAL CELLULAR. *See* **NADC**.

NOTCH FILTER. This filter prevents frequencies within a narrowly specified range from passing through it. All other frequencies are allowed to pass. Also known as a **BAND REJECT FILTER**.

NTSC (NATIONAL TELEVISION SYSTEMS COMMITTEE). A television system that is used in North America and Japan. This analog system broadcasts its signals, uses 525 picture lines, and is based on 60Hz.

NYQUIST BANDWIDTH. The minimum signal capture bandwidth that enables the reconstruction of a band-limited waveform with minimal error.

OCTAVE. Describes a bandwidth in which the upper frequency is twice the lower frequency.

OCXO (OVEN CONTROLLED CRYSTAL OSCILLATOR). A technique used with piezoelectrical crystals to prevent changes in temperature from effecting the frequency of the crystal. This is done by placing a crystal, a heating element, and a temperature sensor in an insulated container and keeping the temperature in the container constant and above the temperature of the surrounding environment.

OFDM (ORTHOGONAL FREQUENCY DIVISION MULTIPLEX). A wireless transmission system that splits up a signal and sends it over many narrowband frequencies. It uses orthogonal carrier waves to reduce the interference caused by using a multipath technique. (OFDM can also be called **ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING**.)

OFDMA (ORTHOGONAL FREQUENCY DIVISION MULTIPLE ACCESS). OFDMA is a multiple-access transmission technique that uses OFDM modulation techniques. However, individual sets of subcarriers can be assigned to different users so that many users can simultaneously use the channel at the same time. WiMAX dynamically adjusts the allocation of subcarriers, time slots, and bandwidth for optimal throughput for multiple uses. OFDM is the modulation technique used in WiMAX.

OMNIDIRECTIONAL ANTENNA. Like a dipole antenna, an omnidirectional antenna radiates its signals 360° horizontally (in two dimensions); however, because its signal is flatter than a dipole's, it has a higher gain.

Open Loop MIMO. These techniques do not use information on the channel to optimize communications with the receiver. Instead, the multi-antenna systems at the base station and destination device are optimized using either a Matrix A algorithm for space time block coding or a Matrix B spatial multiplexing technique.

Optical Fiber. *See* **Fiber**.

Orthogonal Frequency Division Multiple Access. *See* **OFDMA**.

Orthogonal Frequency Division Multiplex. *See* **OFDM**.

Orthogonal Frequency Division Multiplexing. *See* **OFDM**.

Orthogonal Functions. Different functions are orthogonal if the integral of their product is zero. Orthogonal functions are independent functions.

Oscillator. A circuit that generates a sine wave at a predetermined frequency or at predetermined variable frequencies.

Oven Controlled Crystal Oscillator. *See* **OCXO**.

PA (Power Amplifier). The amplifier that increases the power of a signal to a sufficient level to drive an antenna.

Packet. In data communications, a packet is a sequence of binary digits, including control signals and a small amount of data, which is transmitted and switched as a unit. In network applications, a large file can be broken into many packets that can be sent to the same destination over different network paths and reassembled at the destination.

Packet Control Unit. *See* **PCU**.

Packet Switching. The process of routing and transferring data by means of addressed packets. A channel is only occupied during the transmission of a packet. Upon completion of the transmission, the channel is made available for the transfer of other packets or traffic. The transmission of packet-switched data is generally faster than circuit-switched data.

Pad. *See* **Attenuator**.

PAE (Power Added Efficiency). A measure of how well a power amplifier converts DC power into RF power. Measured in %.

Paging. A radio system that allows short text messages to be transmitted in only one direction. Some newer systems support two-way communication, but these systems require the use of paired spectrum.

PAL (Phase Alternating Line). A television system that is used in Germany and the United Kingdom. This system broadcasts analog signals, uses 650 picture lines, and is based on 50Hz.

PAN (Personal Area Network). A computer network used for communication between devices (such as telephones, printers, and PDAs) in close proximity to one person (less than 10m).

PAPR (Peak to Average Power Ratio). The ratio of the peak power to the average power of a signal. This is similar to **crest factor** (**CF**).

Partial Usage of Subcarriers. *See* **PUSC**.

PASSBAND. The specified frequency band that a bandpass filter allows to pass through it.

PASSIVE COMPONENT. An electrical component that does not require a power supply.

PATH LOSS. The weakening of a signal over its path of travel due to factors such as terrain and environmental conditions.

PCB (PRINTED CIRCUIT BOARD). A circuit that is wired or etched on a nonconducting material (such as a phenolic or fiberglass material) and connects electrical components (resistor, conductors, etc.).

PCN (PERSONAL COMMUNICATIONS NETWORK). *See* **GSM**.

PCS (PERSONAL COMMUNICATION SERVICES). A second generation cellular phone system with frequencies in the 1900MHz range. It is used in the United States.

PCU (PACKET CONTROL UNIT). A device that is needed in some GSM systems if they are to support GPRS traffic that uses packet data.

PDA (PERSONAL DIGITAL ASSISTANT). An electronic device that was originally designed to store names, addresses, and telephone numbers. It has been upgraded to include support for a number of wireless communications functions.

PDC (PERSONAL DIGITAL CELLULAR). A cellular standard based on TDMA and D-AMPs that supports packet switching technology. It is used in Japan. It uses the same phase modulation technique as D-AMPS (DQPSK), but uses 25MHz channels. Its maximum throughput is 14.4kbps. It is also known as **JDC**.

PEAK TO AVERAGE POWER RATIO. *See* **PAPR**.

PERSONAL AREA NETWORK. *See* **PAN**.

PERSONAL COMMUNICATIONS NETWORK. *See* **PCN**.

PERSONAL COMMUNICATION SERVICES. *See* **PCS**.

PERSONAL DIGITAL ASSISTANT. *See* **PDA**.

PERSONAL DIGITAL CELLULAR. *See* **PDC**.

PERSONAL HANDYPHONE SYSTEM. *See* **PHS**.

PHASE. The instantaneous angle of a signal relative to 0° (the horizontal line on a polar plot).

PHASE ALTERNATING LINE. *See* **PAL**.

PHASE LOCKED LOOP. *See* **PLL**.

PHASE LOCKED OSCILLATOR. *See* **PLO**.

PHASE MODULATION. *See* **PM**.

PHASE NOISE. A noise component associated with an oscillator circuit that produces frequency or phase modulation. This is seen on a spectrum analyzer as a skirt on a single tone signal. In instruments, their phase noise is measured in dBc/Hz at an offset from a carrier signal.

PHASE SHIFT ($\Delta\varphi$). A change in phase of a signal due to transmission through a medium or a device. Phase shift is a phase value that is relative to the phase of the original signal or the signal before it has entered the device or medium.

PHASE SHIFT KEYING. *See* **PSK**.

PHASE UNBALANCE. The difference in the amount of phase shift through two paths of a power divider. Measured in degrees.

PHEMT (PSEUDOMORPHIC HIGH ELECTRON MOBILITY TRANSISTOR). A transistor that is generally used in applications that require very high frequencies.

PHS (PERSONAL HANDYPHONE SYSTEM). A telephone standard used in Japan. When users are roaming, they are able to make calls but not receive them. It uses the TDD and TDMA transmission techniques and the QPSK phase modulation technique. Its channel bandwidth is 300kHz, and it supports a maximum throughput rate of 384kbps.

PICOCELL. These are small cell sites located in buildings. A picocell's base station is able to send and receive calls over both a cellular and landline network.

PICONET. A wireless personal network with up to eight devices (phones, computers, etc.) connected to it. One device is the master and the others are slaves. Any device can be either a master or a slave. Piconet is based on the Bluetooth standard.

PLL (PHASE LOCKED LOOP). In this feedback technique, an electronic circuit controls an oscillator so that it maintains a constant phase angle relative to a reference signal.

PLO (PHASE LOCKED OSCILLATOR). A type of oscillator that uses the PLL feedback technique.

PM (PHASE MODULATION). A type of FM (frequency modulation) in which the phase angle of the RF carrier signal departs from its reference value by an amount that is proportional to the instantaneous value of the modulating signal (the information signal).

PMR (PRIVATE MOBILE RADIO). A type of communications system that does not always require the use of a base station for users to communicate with each other. The users can interact directly when a base station is out of range. This type of system usually has only one base station.

PN (PSEUDO RANDOM NOISE). A signal that appears to be random, but it repeats itself.

POINT-TO-MULTIPOINT. A communications channel that transmits between one point and several other points.

POINT-TO-POINT. A communications channel that transmits between one point and one other point.

POLARIZATION. The angle at which a wave oscillates. It is measured against the direction the wave is traveling. There are three types of polarization: circular, horizontal, and vertical. Circular polarization indicates that the sine wave continuously alternates between horizontal polarization and vertical polarization.

POWER AMPLIFIER. *See* **PA**.

POWER ADDED EFFICIENCY. *See* **PAE**.

POWER DENSITY. The amount of RF energy (radiation) moving through an area. Measured in W/m^2.

POWER DIVIDER. A component that splits an RF signal and directs the resulting signals to multiple (two or more) paths. It is also known as a **DIVIDER**.

Power Meter. A device used to measure transmitted RF power. This is often a broadband instrument.

Printed Circuit Board. *See* **PCB**.

Private Mobile Radio. *See* **PMR**.

Propagation. How a signal travels through a medium such as air or a conductor.

Propagation Delay. The amount of time a signal uses to travel from its transmitter to its receiver. For example, this could be from a base station to a cellular phone or from a satellite to a receiver on Earth. It could also be the time it takes for a signal to be routed through an electrical circuit path.

Protocol. A standard (set of rules) created by a company or a professional association that specifies. how data must be formatted and transmitted through a medium.

Pseudomorphic High Electron Mobility Transistor. *See* **PHEMT**.

Pseudo Random Noise. *See* **PN**.

PSK (Phase Shift Keying). A digital modulation technique in which the phase of the carrier signal is changed with reference to the information signal.

PSTN (Public Switched Telephone Network). A landline telephone system.

Public Switched Telephone Network. *See* **PSTN**.

Pulling Factor. The amount an oscillator's output frequency changes when the input impedance of the device it is driving changes. Measured in MHz.

PUSC (Partial Usage of Subcarriers). A WiMAX (802.16e-2005) scheme in which not all the subcarriers are used for transmission. The subcarriers are first divided into six groups and then within each group a unique permutation scheme is used to assign subcarriers to subchannels.

Pushing Factor. The amount an oscillator's output frequency changes when the voltage of its power supply changes. Measured in MHz/V.

QAM (Quadrature Amplitude Modulation). A modulation technique that can change both the amplitude and phase of an RF carrier wave. This allows the carrier signal to simultaneously transfer a large number of information bits. The following lists a few example modulations and the number of bits each can transfer simultaneously.

Example Modulation	Number of Bits Transferred Simultaneously
16 QAM	4 bits
64 QAM	6 bits
256 QAM	8 bits

QoS (Quality of Service). Used to describe the ways in which a network provider guarantees a service's performance.

QPSK (Quadrature Phase Shift Keying). This method of digital modulation uses four different phase angles to modulate an RF carrier signal with a digital information signal.

The four angles are usually out of phase by 90° (0°, 90°, 180°, and 270°). This allows a sine wave of the carrier signal to carry two information bits from the digital information signal.

QUADRATURE AMPLITUDE MODULATION. *See* **QAM**.

QUADRATURE PHASE SHIFT KEYING. *See* **QPSK**.

QUADRATURE (QUAD) COUPLER. *See* **LANGE COUPLER**.

QUADRATURE (QUAD) HYBRID. *See* **LANGE COUPLER**.

QUALITY OF SERVICE. *See* **QOS**.

RADAR (RADIO DETECTING AND RANGING). Systems that reflect RF signals off objects to determine their location and speed.

RADAR CROSS SECTION. The area reflecting the RF energy being used by radar.

RADIATION. Electromagnetic energy, such as radio waves projected from a transmitter.

RADIO DETECTING AND RANGING. *See* **RADAR**.

RADIO FREQUENCY. *See* **RF**.

RADIO FREQUENCY IDENTIFICATION. *See* **RFID**.

RADIO FREQUENCY INTEGRATED CIRCUIT. *See* **RFIC**.

RADIO FREQUENCY INTERFERENCE. *See* **RFI**.

RADIO WAVE. A combination of electric and magnetic fields varying at a radio frequency and traveling through space. Radio waves are often described as electromagnetic energy with frequencies in the kilohertz to 300GHz portion of the electromagnetic spectrum. Radio waves travel at the speed of light.

RADOME. This covers an antenna to protect it from the weather, but does not interfere with the RF signals going to/from the antenna.

RAISED COSINE. *See* **RC**.

RC (RAISED COSINE). This is typically used as a filtering method to reduce inter-symbol interference (ISI).

RCE (RELATIVE CONSTELLATION ERROR). RCE is a measurement of the transmitter's modulation accuracy. It is similar to an EVM (error vector magnitude) measurement. RCE determines the magnitude of error of each constellation point and RMS averages them together across multiple frames, packets, and symbols. RCE is specific to the 802.16 WiMAX standard.

RECEIVE GAIN. A measure of the amplification contributed by an amplifier or antenna system.

RECEIVER. A device located between the antenna and demodulator. It converts the RF signals received by the antenna to a frequency the demodulator can use.

RECEIVER SENSITIVITY. The ability of a receiver to differentiate a signal from the background noise.

REFLECTION. When an RF signal bounces off a solid object or meets an impedance mismatch. If the signal hits a solid object, it is reflected at the same angle it hit the object. If the signal meets an impedance mismatch, some, possibly all, of the signal is reflected back (at a 180° angle).

Reflection Coefficient $$\rho = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z - Z_0}{Z + Z_0}\ ; Z_0 = Z_{\text{transmission line}}$$ Characteristic impedance

Repeater. A digital device that amplifies, reshapes, retimes, or performs any combination of these functions on a digital input signal it is transmitting.

Resistor. A passive component that reduces the electric current flowing through the circuit.

Response Time. *See* **Settling Time**.

Return Loss. The difference between the reflected power and the incident power. It is measured in dB. The return loss can vary between ∞ (no power reflected, ∞ return loss) for perfectly matched impedance loads to 0 (all power reflected, no return loss) for an open or short load.

$$\text{Return Loss} = 10\ \text{Log}_{10} \frac{P_{\text{incident}}}{P_{\text{reflected}}} = 20\ \text{Log}_{10} \frac{1}{\rho}$$

$$= 20\ \text{Log}_{10} \left(\frac{\text{VSWR} + 1}{\text{VSWR} - 1} \right)$$

Reverse Link. The wireless connection over which information is sent from a mobile phone to a cellular base station.

RF (Radio Frequency). The range of frequencies (from about 3kHz to 300GHz) over which the electromagnetic spectrum is used in radio transmission. RF can refer to the radio waves themselves or to the systems that handle radio signals directly, such as the circuits connected directly to the antenna.

RFI (Radio Frequency Interference). *See* **EMI (Electromagnetic Interference)**.

RFIC (Radio Frequency Integrated Circuit). A high frequency solid state device.

RFID (Radio Frequency Identification). A wireless system that uses one of three frequency ranges (less than 500kHz, 10–15MHz, or 900MHz) to detect electronic tags and cause actions to occur when a tag is sensed in a specific location. An RFID system consists of interrogators and transponders (electronic tags).

Roaming. The ability to use a cellular phone when traveling outside of the home service area, as defined by a service provider.

RSSI (Received Signal Strength Indicator). A circuit that measures the power (strength) of a signal detected by a receiver.

S-Parameters (Scattering Parameters). There are four parameters that define a high frequency, two-port network model:

S_{11} = Input reflection coefficient.
S_{21} = Forward transmission coefficient.
S_{22} = Output reflection coefficient.
S_{12} = Reverse transmission coefficient.

SAR (Specific Absorption Rate). Amount of thermal heating caused by the radiation (RF energy) absorbed in an object.

Saturated Power (P_{SAT}). The maximum power that an amplifier can produce. Measured in dBm.

Saturation. Describes the point at which the output can no longer increase even if the input increases.

SAW (Surface Acoustic Wave). A sound wave that travels along the surface of a material.

SAW Filter (Surface Acoustic Wave Filter). An RF filter made with piezoelectric material. It permits long signal delays to be generated with short path lengths. It also has sharp filter cutoff characteristics.

Scalable OFDMA. *See* **SOFDMA**.

Scattering Parameters. *See* **S-Parameters**.

SDMA (Spatial Division Multiple Access). This technique divides the geographic area of a cell and uses directional antennas. A directional antenna only services a specific part of a cell. (SDMA can also be called **Space Division Multiple Access**.)

SDR (Software Defined Radio). SDR is a radio communication architecture technology that uses software to modulate and demodulate radio signals instead of hardware. With the rapid development of new communication standards, which often require new modulation technologies, SDR offers an approach that allows instruments to adapt to new requirements with software or firmware rather than with specialized hardware to meet the new challenges.

Second Order Intercept (IP2). The theoretical point on an amplifier's output power versus input power plot where the theoretical linear gain line intersects the gain line of the second order distortion products.

Selectivity (Q). How well a filter can remove unwanted frequencies.

Self-Resonant Frequency. The frequency (if delivered with enough energy) that can cause a solid object to vibrate and create a sine wave.

Settling Time. For a measuring instrument, the time between application of a step input signal and the indication of its magnitude within a rated accuracy. For a sourcing instrument, circuit, or electronic device, this is the time between a programmed change and the availability of the value at its output terminals. Also known as **Response Time**.

Short Message Service. *See* **SMS**.

Short Wave. *See* **SW**.

Si (Silicon). A low-cost material often used to create semiconductor devices such as RF diodes and transistors.

Sidebands. In analog modulation techniques, these are the frequencies above and below the carrier signal frequency.

SiGe (Silicon Germanium). A material used to create RF semiconductor devices.

Signal. An electronic waveform that carries information.

Signal to Interference Ratio. *See* **SIR**.

Signal-to-Noise Ratio. *See* **SNR**.

Silicon. *See* **Si**.

Silicon Germanium. *See* **SiGe**.

SIM (Subscriber Identity Module). An identification card in a wireless device that contains information about the subscriber.

Simplex. A system that can transmit RF signals in only one direction at a time.

Single Input, Single Output. *See* **SISO**.

Single Pole-Double Throw. *See* **SPDT**.

Single Pole-Single Throw. *See* **SPST**.

Single Side Band. *See* **SSB**.

SIR (Signal to Interference Ratio). The ratio of the wanted signal power in the channel to the interference in the channel. SIR is also an acronym for **Serial Infrared**, a standard developed by IrDA, which has a maximum throughput rate of 115kbps.

SISO (Single Input, Single Output). A typical SISO system uses one transmitter and one receiver and information is sent over a single data channel. In some applications, another antenna can be used for spatial diversity. (Only one antenna is used at a time. The antennas are constantly switched to find the best signal path.) The system usually contains one up converter, one down converter, one demodulator/modulator, and one data stream.

Skin Effect. How an RF signal moves along the outer surface of a conductor. (RF signals do not pass through the surface of a conductor.)

Smart Antenna. An antenna system that continuously tracks the location of a mobile user so signals can be sent (aimed) directly to the user's location and change direction as the user moves. This type of SDMA technology helps to improve call quality, improve channel capacity, and reduce power consumption.

Smartphone. A cellular phone that provides features that before were only found on computers. An Internet browser is one example of a feature it might offer.

SMR (Specialized Mobile Radio). A type of PMR (Private Mobile Radio) system. In the United States, it uses frequencies in the 800MHz range.

SMS (Short Message Service). This feature allows users to send and receive text messages over their mobile phones. It does not matter if the users are speaking on the phone at the same time. It supports text messages up to 260 bytes long, depending on the type of network that is using it. For example, GSM networks only support messages up to 160 bytes long.

SNR (Signal-to-Noise Ratio). The measure of the magnitude of a desired signal relative to the magnitude of an undesired signal or noise.

SOFDM (Scalable OFDM). An OFDM technique that allows a variable amount of bandwidth and therefore a variable number of subchannel carriers for a transmission. WiMAX uses this technology.

SOFDMA (Scalable OFDMA). Used in both fixed and mobile WiMAX to achieve maximum performance in the 1.25MHz to 20MHz channel bandwidths. It supports AMC and can shift between the 128, 512, 1K, and 2K FFT sizes to maximize throughput. The FFT size determines the amount of channel bandwidth used.

Soft Handoff. In wireless mobile phone systems, a soft handoff is the process of transferring a phone call in progress from one base station to another base station. Both base stations hold onto the call until the handoff is completed. The first base station does not cut off the conversation until it receives information that the second is maintaining the call.

Software Defined Radio. *See* **SDR**.

Source. *See* **Oscillator**.

Space Division Multiple Access. *See* **SDMA**.

Spatial Diversity. Obtains more reliable detection of the original signal at the receiver by transmitting and receiving identical signals on different paths over spatially separated antennas.

Spatial Division Multiple Access. *See* **SDMA**.

Spatial Multiplexing. A MIMO technique that allows multiple data streams to transmit at the same frequency but over different spatial channels. This technique divides (multiplexes) a stream of data between multiple transmitting antennas. The antennas can send the data on the same or different channels.

SPDT (Single Pole-Double Throw). A switch that directs an input signal to one of two output paths.

Specialized Mobile Radio. *See* **SMR**.

Specific Absorption Rate. *See* **SAR**.

Spectral Efficiency. The amount of data a wireless system can support. Measured in bps/Hz.

Spectral Mask. The maximum allowable magnitude of a signal component at specified frequency offsets from the center frequency. Each standard has a unique transmitter spectral mask to minimize interference with other channels.

Spectrum. A range of electromagnetic radio frequencies.

Spectrum Analyzer. An instrument used to view the frequency spectrum of a signal. Some spectrum analyzers can measure both amplitude and phase and can demodulate complex digital modulation formats.

Spectrum Assignment. In the United States, spectrum is assigned or authorized by the Federal government (FCC). It specifies the frequencies that can be used at specific geographic locations.

Splitter/Combiner. A transmission component that divides or sums power between two or more ports.

Spread Spectrum. *See* **SS**.

SPST (Single-Pole Single-Throw). This is essentially an on/off switch.

SPURIOUS EMISSIONS (SPURS). Unwanted frequency signals that can cause interference in receiver systems. It is measured in dBc or dBm.

SPURIOUS NOISE (SPURS). *See* **SPURIOUS EMISSIONS**.

SPURS. *See* **SPURIOUS EMISSIONS**.

SS (SPREAD SPECTRUM). A modulation technique that uses transmission bandwidth that is orders of magnitude larger than the signal bandwidth. The advantage of spread spectrum is that many users can transmit and receive in the same bandwidth without interfering with each other. CDMA technology uses spread spectrum modulation techniques.

SSB MODULATION (SINGLE SIDE BAND MODULATION). Single side band modulation is a refinement of amplitude modulation. It is designed to be more efficient in its use of electrical power and bandwidth by eliminating one of the sidebands.

STABILITY. A measure of how much a parameter changes with time or temperature. For example, a crystal oscillator is specified for an aging rate in ppm/year and a temperature stability in terms of ppm/°C.

STOPBAND. The frequencies that a bandpass filter will not allow to pass.

SUBSCRIBER IDENTITY MODULE. *See* **SIM**.

SURFACE ACOUSTIC WAVE. *See* **SAW**.

SURFACE ACOUSTIC WAVE FILTER. *See* **SAW FILTER**.

SW (SHORT WAVE). *See* **HF (HIGH FREQUENCY)**.

SYMMETRIC. A communications link that supports two-way data transmission with equivalent data traffic in each direction. This is used for most landline and cellular communications.

SYNTHESIZER. An oscillator and other electronic circuitry that are combined together to produce sine waves.

T/R SWITCH (TRANSMIT-RECEIVE SWITCH). This switch allows an antenna to be used for both transmitting and receiving signals. It is a single-pole, double-throw switch.

TACS (TOTAL ACCESS COMMUNICATION SYSTEM). An analog cellular system formerly used in Europe and Africa that is similar to AMPS. It used frequencies in the 900MHz range, its channel size was 25kHz, and its maximum throughput rate was 8kbps.

TCXO (TEMPERATURE CONTROLLED CRYSTAL OSCILLATOR). A type of oscillator whose frequency output is stabilized by keeping the device at a constant temperature. (TCXO can also be called **TEMPERATURE COMPENSATED OSCILLATOR**.)

TDD (TIME DIVISION DUPLEXING). A technique that uses one frequency to send and receive. Because only one frequency is used, sending and receiving cannot occur simultaneously, they are performed alternately.

TDM (TIME DIVISION MULTIPLEXING). A multiplexing technique in which two or more channels are derived from a transmission medium by dividing access to the medium into sequential intervals. Each channel has access to the entire bandwidth of the medium during its interval.

TDMA (Time Division Multiple Access). A digital multiplexing technique that allows one frequency to be shared by several users. A frequency is divided into time slots (usually eight). A cell phone sends and receives signals only during its allocated time slot, and the transmitter and receiver must be time-synchronized so as to demodulate the signal at the receive end. These time slots are short (usually about 577μs) so the people talking and listening during the call will not be aware that they do not have 100% use of the frequency.

TD-SCDMA (Time Division Synchronous Code Division Multiple Access). This 3G standard for mobile telephones was developed in China and has been accepted as a worldwide standard. It combines TDD, TDMA, and synchronous CDMA technologies. TD-SCDMA transmits and receives on the same frequency, uses multiple timeslots, is 1.6MHz wide, and provides a throughput of up to 2Mbps. It supports both circuit-switched and packet-switched data. Circuit-switched data is typically voice and video transmissions and packet-switched data is usually multimedia services and mobile Internet.

Telecommunications. The transmission of words, sounds, or images, usually over great distances, in the form of electromagnetic energy, for example, by telephone, radio, or television.

Telepoint. *See* **CT-2**.

Temperature Controlled Crystal Oscillator. *See* **TCXO**.

Terrestrial Trunked Radio. *See* **TETRA**.

TETRA (Terrestrial Trunked Radio). A European standard for digital PMR that supports data rates of up to 28.8kbps. It provides excellent security.

Thermal Impedance (θjc). This is a measure of how much a component's temperature increases when it is dissipating power. It is measured in °C/Watt.

Third Generation. *See* **3G**.

Third Generation Partnership Project. *See* **3GPP**.

Third Order Intercept Point. A measure of an amplifier's linearity. It is the theoretical point on an amplifier's Output Power Versus Input Power plot where the theoretical linear gain line intersects the gain line of the third order distortion products. Larger numbers indicate greater linearity. The more linearity an amplifier has, the less distortion it causes to the RF signal.

Throughput. The volume of data that can be transmitted through a communications system.

THSS (Time Hopping Spread Spectrum). *See* **UWB (Ultra Wideband)**.

Time Division Duplexing. *See* **TDD**.

Time Division Multiple Access. *See* **TDMA**.

Time Division Multiplexing. *See* **TDM**.

Time Division Synchronous Code Division Multiple Access. *See* **TD-SCDMA**.

Time Hopping Spread Spectrum. *See* **THSS**.

Total Access Communication System. *See* **TACS**.

TRANSCEIVER. A combination of a transmitter and a receiver in a single device.

TRANSFORMER. A device that is typically used to convert the impedance of the incoming signal to an impedance acceptable to the device it is sending the signal to. Most RF devices require a 50Ω impedance.

TRANSISTOR. A semiconductor device made from a variety of materials. It is often used to perform amplification, switching, and rectification.

TRANSMIT-RECEIVE SWITCH. *See* **T/R SWITCH**.

TRANSMITTER. A device located between the antenna and modulator. It increases the RF signal (power) from the modulator and sends it to the antenna.

TRANSMITTER ADAPTIVE ANTENNA. *See* **TX-AA**.

TRANSPONDER. The word transponder has a number of different meanings in the RF industry. In an RFID system, transponders are placed on objects. When a transponder receives a signal from an interrogator, it immediately sends the signal back to the interrogator. The interrogator then causes an action to occur. In a satellite system, a transponder receives and retransmits signals. It will also convert the frequency of a signal if the uplink and downlink frequencies are different. A transponder can have another definition in the satellite industry. It can mean blocks of bandwidth leased to satellite service providers.

TRAVELING WAVE TUBE. *See* **TWT**.

TRAVELING WAVE TUBE AMPLIFIER. *See* **TWTA**.

TRIANGULATION. When signals from three locations are used to calculate a location. Some techniques used to locate the position of a mobile phone require fewer signals. The TOA (Time of Arrival) technique uses two signals, and the AOA (Angle of Arrival) technique uses only one.

TRIPLEXER. A device with three bandpass filters. Each filter can use a different frequency range.

TUNER. A device in a receiver that selects signals by their frequency and then converts the signals to another frequency.

TUNING SENSITIVITY. The change caused to the output frequency of a VCO due to a change in the control voltage. Measured in MHz/V.

TWT (TRAVELING WAVE TUBE). An older technology that amplifies RF signals in a vacuum.

TWTA (TRAVELING WAVE TUBE AMPLIFIER). An electronic device used to produce high power radio frequency signals.

TX-AA (TRANSMITTER ADAPTIVE ANTENNA). Also known as Closed Loop MIMO and MIMO Beam Forming. *See* **BEAM FORMING**.

UHF (ULTRA HIGH FREQUENCY). Ultra-high frequency radio waves are in the 300 to 3GHz frequency range with wavelengths from 0.1 to 1m. It is typically used by cellular and television systems.

ULTRA HIGH FREQUENCY. *See* **UHF**.

ULTRA MOBILE BROADBAND. *See* **UMB**.

ULTRA WIDEBAND. *See* **UWB**.

UMB (ULTRA MOBILE BROADBAND). UMB combines the CDMA, TDM, and OFDM standards and uses MIMO, SDMA, and beamforming antenna technologies. Its bandwidth is from 1.25MHz to 20MHz, and is expected to have low latency and high spectral efficiency.

UMTS (UNIVERSAL MOBILE TELECOMMUNICATIONS SYSTEM). This is a third-generation cellular system that is used in Europe. It is based on wideband CDMA technology. This wireless network moves data and multimedia rapidly over wireless devices. The goal of UMTS is to allow networks to provide true global roaming. It supports a wide range of voice, data, and multimedia services in the 2GHz band. Its maximum throughput rate is 4Mbps.

U-NII (UNLICENSED NATIONAL INFORMATION INFRASTRUCTURE). A spectrum for high-speed wireless LAN and local loop systems in the United States. The FCC allocated this spectrum for unlicensed frequencies. The frequencies U-NII uses are 5.15 to 5.35GHz and 5.725 to 5.825GHz. Its bandwidths are 200MHz, dedicated, and 100MHz, ISM.

UNIVERSAL MOBILE TELECOMMUNICATIONS SYSTEM. *See* **UMTS**.

UNLICENSED NATIONAL INFORMATION INFRASTRUCTURE. *See* **U-NII**.

UPCONVERTER. Typically used in a transmitter to increase the frequency of an RF signal. Also known as a **MIXER**.

UPLINK. The uplink portion of a telecommunications path is from a ground transmitter to a satellite receiver or from a mobile phone to a base station. It is also known as **FORWARD LINK**.

UWB (ULTRA WIDEBAND). A mobile communication standard whose channel width may exceed 500MHz.

VARACTOR. A diode located in a VCO that is used to vary the frequency of the VCO.

VARIABLE GAIN AMPLIFIER. *See* **VGA**.

VCO (VOLTAGE CONTROLLED OSCILLATOR). An oscillator whose output frequency can be changed by an external control. The external control is often the input voltage.

VCXO (VOLTAGE CONTROLLED CRYSTAL OSCILLATOR). This is an oscillator with a variable frequency, like the VCO, but provides higher accuracy than the VCO.

VECTOR SIGNAL ANALYZER. A spectrum analyzer that can decompose a signal into its I and Q components and can demodulate some types of signals.

VERY FAST INFRARED. *See* **VFIR**.

VERY HIGH FREQUENCY. *See* **VHF**.

VERY LOW FREQUENCY. *See* **VLF**.

VERY SMALL APERTURE TERMINAL. *See* **VSAT**.

VESTIGIAL SIDE BAND. *See* **VSB**.

VFIR (VERY FAST INFRARED). A standard developed by IrDA that has a maximum throughput rate of 16Mbps.

VGA (Variable Gain Amplifier). An amplifier whose gain can be changed by an external control. VGA is also an acronym for **Video Graphics Array**, a standard for computer monitors.

VHF (Very High Frequency). Any frequency in the 30 to 300MHz frequency range with wavelengths from 1 to 10m. It is typically used to broadcast FM and television signals.

VLF (Very Low Frequency). Any frequency in the 3 to 30kHz frequency range with wavelengths from 10 to 100km. It is typically used for maritime communications.

Voltage Controlled Crystal Oscillator. *See* **VCXO**.

Voltage Controlled Oscillator. *See* **VCO**.

Voltage Standing Wave Ratio. *See* **VSWR**.

Voltage Tuned Oscillator. *See* **VTO**.

Voltage Variable Attenuator. *See* **VVA**.

VSAT (Very Small Aperture Terminal). Devices that can be used on satellites in geosynchronous orbit around the Earth. They include directional antennas with a dish diameter of less than 1m. They can also be used on Earth for multipoint-to-point communications.

VSB (Vestigial Side Band). A side band that has been partially cut off or suppressed.

VSWR (Voltage Standing Wave Ratio). The measure of how closely the impedance of a device (device 1) or its interconnection matches the impedance of the device (device 2) it is connected to. An ideal VSWR is when no energy is being reflected at the intersection between two connections. This is represented as 1.0:1. As the VSWR exceeds 1.0:1, the reflected power increases.

$$\mathrm{VSWR} = \frac{V_{\mathrm{max}}}{V_{\mathrm{min}}} = \frac{V_{\mathrm{incident}} + V_{\mathrm{reflected}}}{V_{\mathrm{incident}} - V_{\mathrm{reflected}}} = \frac{1+\rho}{1-\rho}$$

$$\rho = \frac{\mathrm{VSWR} - 1}{\mathrm{VSWR} + 1}$$

VTO (Voltage Tuned Oscillator). *See* **VCO**.

VVA (Voltage Variable Attenuator). A component that reduces RF power by the amount specified by an external control voltage. The external control can cause the attenuation to change at any time.

W (Watt). A measure of energy per unit time. One watt is one joule per second.

WAP (Wireless Application Protocol). An open standard for communication between wireless handsets and the Internet. (WAP can also be called **Wireless Access Protocol**.)

WAP Gateway. Converts data from its original Internet protocol to/from WAP protocols. It does not support conversion to/from all Internet protocols. For example, because WAP's WML protocol does not provide as wide a range of features as HTML, it cannot convert HTML web pages to WAP.

WASP (Wireless ASP). A type of company that uses mobile data links to connect buyers and sellers, to provide remote access to e-mail, and/or to support WAP web sites.

Watt. *See* **W**.

Waveguide. Pipes that carry and control high frequency microwave signals from one point to another with very low insertion loss. These pipes have rectangular cross sections (if a pipe is cut through its width, not its length, the cut part of the pipe would be rectangular).

Wavelength. The distance covered by one cycle of a wave. The length of a wave cycle determines the frequency of an RF signal. The shorter the wavelength, the higher the frequency; and the longer the wavelength, the lower the frequency.

W-CDMA (Wideband Code Division Multiple Access). W-CDMA is a wideband (5MHz) CDMA for PCS telephony. It was designed for high speed data services and, more particularly, Internet-based packet data. It uses 5GHz frequency channels and supports a maximum throughput rate of up to 2Mbps in stationary or office environments and up to 384kbps in wide area or mobile environments. It also increases data transmission rates in GSM systems by using CDMA instead of TDMA.

WEP (Wired Equivalent Privacy). This security system is included in WLAN version 802.11. It is an encryption protocol that uses 40-bit RC4 keys.

WEP2. This is an upgraded version of WEP that uses 128-bit RC4 keys. It is also known as **TKIP**.

Wideband. A wide range of frequencies in a spectrum. This is a relative term. For example, in TDMA technology, GSM has a minimum bandwidth of 200kHz and is considered wideband because it uses more bandwidth than the other TDMA technologies. In CDMA systems, cdmaOne has a minimum bandwidth of 1,250kHz, but it is not considered wideband because it uses less bandwidth than the other CDMA systems.

Wideband Code Division Multiple Access. *See* **W-CDMA**.

Wi-Fi (Wireless Fidelity). This term originally referred to the 802.11b specification for wireless LANs, but it is now used to describe any of the 802.11 wireless networking specifications. A manufacturer can place a Wi-Fi logo on its product only if that product has been tested for and meets all Ethernet compatibility requirements specified by WECA (Wireless Ethernet Compatibility Alliance).

Wi-Fi Protected Access. *See* **WPA**.

WiMAX (Worldwide Interoperability for Microwave Access). A wireless broadband standard based on IEEE 802.16.

WiMAX Wave 2. *See* **802.16e Wave 2**.

Wired Equivalent Privacy. *See* **WEP**.

Wireless. A system that uses an RF communication link instead of physical wires.

Wireless Access Protocol. *See* **WAP**.

Wireless Application Protocol. *See* **WAP**.

Wireless ASP. *See* **WASP**.

Wireless Fidelity. *See* **Wi-Fi**.

WIRELESS LOCAL AREA NETWORK. *See* **WLAN**.

WIRELESS LOCAL LOOP. *See* **WLL**.

WIRELESS MARKUP LANGUAGE. *See* **WML**.

WIRELESS PERSONAL AREA NETWORK. *See* **WPAN**.

WIRELESS TRANSPORT LAYER SECURITY. *See* **WTLS**.

WIRELINE. A term associated with a network or terminal that uses metallic wire conductors and/or optical fibers for telecommunications.

WLAN (WIRELESS LOCAL AREA NETWORK). WLAN is a wirelessly connected LAN, such as an IEEE 802.11 network.

WLL (WIRELESS LOCAL LOOP). The section of a telephone network that connects an ISP to the user's facility (home, office, manufacturing site, etc.). Also known as **AIR LINK**.

WML (WIRELESS MARKUP LANGUAGE). Code used to create Web pages that can be downloaded to wireless mobile handsets.

WPA (WI-FI PROTECTED ACCESS). A specification for improving the security of Wi-Fi networks. It replaces WEP in 802.11 standards.

WPAN (WIRELESS PERSONAL AREA NETWORK). A WPAN is a PAN that uses wireless connections. However, all current PAN technologies are wireless, so the terms WPAN and PAN are synonymous.

WTLS (WIRELESS TRANSPORT LAYER SECURITY). A security protocol for WAP version 1.2 that uses encryption.

YIG (YTTRIUM-IRON-GARNET). A material used to create oscillators. These oscillators tend to be highly accurate and provide very high frequencies.

YIG TUNED OSCILLATOR. *See* **YTO**.

YTO (YIG TUNED OSCILLATOR). A type of oscillator whose output frequency can be changed. It is made from YIG.

YTTRIUM-IRON-GARNET. *See* **YIG**.

SECTION III

Useful Tables

Wireless Communications Standards

Digital Cellular Phones/Data

Standard	Frequency Range	Modulation	Multiple Access
GSM[1]/GPRS[2]	824–1990 MHz	GMSK	TDMA/FDMA
EDGE	824–1990 MHz	8PSK	TDMA/FDMA
HSDPA/HSUPA[3] (FDD)	880 to 960 MHz, 1749.9 to 1879.9 MHz, 2500 to 2690 MHz	HPSK, QPSK, 16QAM	TDMA/CDMA
PDC[4]	810–1501 MHz	$\pi/4$ DQPSK	TDMA/FDMA
cdmaOne	824–1990 MHz	QPSK/OQPSK	CDMA/FDMA
CDMA2000 (1x RTT) CDMA2000 (1xEV-DO) CDMA2000 (1xEV-DV)	824–2170 MHz 824–2170 MHz 824–2170 MHz	HPSK HPSK HPSK	CDMA TDMA/CDMA CDMA
W-CDMA[5] 3GPP/FDD W-CDMA 3GPP/TDD	869–2690 MHz 1850–2025 MHz	Dual BPSK/QPSK/16QAM QPSK/16QAM	CDMA CDMA/TDMA
TD-SCDMA	1850–2025 MHz	QPSK/8PSK/16QAM	CDMA/TDMA

Wireless LAN & Broadband Wireless Access

Standard	Frequency Range	Modulation	Multiple Access
IEEE 802.11a	5.15–5.825 GHz	BPSK/QPSK/16QAM/64QAM/OFDM	CSMA/CA
IEEE 802.11b	2.4–2.97 GHz	BPSK/QPSK/DQPSK CCK/PBCC	CSMA/CA
IEEE 802.11g	2.4–2.97 GHz	BPSK/QPSK/DQPSK CCK/PBCC 16QAM/64QAM/OFDM	CSMA/CA
IEEE 802.11j	4.9-5 GHz, 5.03-5.091 GHz	BPSK/QPSK/16QAM/64QAM	OFDM
IEEE 802.11n	2.4–5.8 GHz	BPSK/QPSK, 16QAM, 64QAM	CSMA/CA, OFDM
Ultra Wideband (IEEE 802.15.3a)	3.17 to 10.56 GHz (North America); 3.17 to 4.22 GHz (Europe); 7.39 to 10.03 GHz, 4.22 to 4.75 GHz, 3.70 to 4.22 GHz (Japan)	OFDM	CSMA-CA/TDMA
WiMAX[6] (IEEE 802.16-rel. 20	2–66 GHz	BPSK/QPSK/16QAM/64QAM/OFDM/SC	TDMA/OFDMA
WiMAX (IEEE 802.16e)	2–11 GHz	BPSK/QPSK/16QAM/64QAM/OFDM/SC	TDMA/OFDMA

1. Global System for Mobile Communications
2. Generalized Packet Radio System
3. High Speed Downlink Packet Access/High Speed Uplink Packet Access
4. Personal Digital Cellular
5. Wideband Code Division Multiple Access
6. Worldwide Interoperability for Microwave Access

Wireless Communications Standards (continued)

Personal Area Networks			
Standard	**Frequency Range**	**Modulation**	**Multiple Access**
Bluetooth (IEEE 802.15.1)	2402–2480 MHz	GFSK	TDMA
RFID[7]	860 to 960 MHz, 2.4 to 2.4835 GHz	DSB-ASK, SSB-ASK, PR-ASK, ASK/PSK	TDMA/FDMA
ZigBee[8] (IEEE 802.15.4)	868.3–2483.5 MHz	BPSK/QPSK	CSMA/CA
Two-Way Trunked Radio			
Standard	**Frequency Range**	**Modulation**	**Multiple Access**
iDEN/WiDEN[9]	800 MHz band, 900 MHz band, 1.5 GHz band	iDEN: QPSK, M16QAM WiDEN: QPSK, M16QAM, M64QAM	TDMA
HPD/SAM[10]	700 MHz band	QPSK, 16QAM, 64QAM	TDMA
TETRA/TEDS[11]	380 MHz to 950 MHz	TETRA: D-QPSK TEDS: 8DQPSK, 16QAM, 64QAM, DPSK	TDMA
APCO 25[12]	764 to 869 MHz	CQPSK, C4FM	FDMA
Mobile Video Broadcasting			
Standard	**Frequency Range**	**Modulation**	**Multiple Access**
DVB-H[13]	174 to 245 MHz (VHF), 470 to 850 MHz (UHF), 1452 to 1492 MHz (L, Europe), 1670 to 1675 MHz (L, U.S.)	COFDM, QPSK, 16QAM, 64QAM	N/A
T-DMB[14]	174 to 245 MHz (VHF), 1452 to 1492 MHz (L, Europe)	COFDM, D-QPSK	N/A
ISDB-T[15]	470 to 770 MHz	COFDM, D-QPSK, QPSK, 16QAM, 64QAM	N/A
MediaFlo	716 to 722 MHz	COFDM, QPSK, 16QAM	N/A
Digital Cordless Phones			
Standard	**Frequency Range**	**Modulation**	**Multiple Access**
DECT[16]	1880–1990 MHz	GFSK	FDMA/TDMA
PHS[17]	1895–1918 MHz	$\pi/4$ DQPSK	FDMA/TDMA

7. Radio Frequency Identification
8. Low Data Rate Wireless
9. Integrated Dispatch Enhanced Network/Wideband Integrated Dispatch Network
10. High Performance Data/Scalable Adaptive Modulation
11. Terrestrial Trunked Radio/TETRA Enhanced Data
12. Association of Public Safety Communications Project 25
13. Digital Video Broadcasting – Handheld
14. Terrestrial Digital Media Broadcast
15. Integrated Services Digital Broadcasting
16. Digital European Cordless Telephone
17. Personal Handyphone System

802.16 and 802.20 Standards

	WiMAX IEEE 802.16-2004	WiMAX IEEE 802.16e	WiBro IEEE 802.16e	WWAN IEEE 802.20 (Wireless Wide Area Network)	WRAN IEEE 802.22 (Wireless Regional Area Network)
Frequency range	10–66 GHz (single carrier) and 2–11 GHz (OFDM) Frequencies currently used: 2.495–2.686 GHz, 3.3–3.8 GHz, 5.15–5.35 GHz, 5.75–5.825 GHz.	2–<6 GHz Frequencies currently used: 2.305–2.32 GHz, 2.345–2.36 GHz, 2.496–2.69 GHz, 3.3–3.8 GHz.	2.305–2.32 GHz, 2.345–2.36 GHz	< 3.5 GHz	48–798 MHz
Channel bandwidth	1.25 to 28 MHz	1.25 to 28 MHz	10 MHz	1.25 MHz in FDD, 5 MHz in TDD, 635 kHz/Carrier in MC mode	6 MHz
Number of channels	3 to 20	3 to 20	3×3 channel @ 9 MHz (3 providers)	TBD	TBD
Peak data rate	134 Mbits/s (28 MHz channel bandwidth), 75 Mbit/s OFDM	15 Mbit/s (in 5 MHz channel)	Sector: Downlink: 18 Mbit/s Uplink: 6 Mbit/s Cell edge @ 60 km/h: Downlink: 512 kbit/s Uplink: 128 kBit/s	<4 Mbit/s	18 Mbit/s (1.5Mbit/s Subs forward, 384 kbit/s Subs return)
Modulation	BPSK, QPSK, 16QAM, 64QAM, 256QAM	BPSK, QPSK, 16QAM, 64QAM	Uplink: QPSK, 16QAM. Downlink: QPSK, 16QAM, 64QAM.	BPSK, QPSK, 8PSK, 12QAM, 16QAM, 24QAM, 32QAM, 64QAM	64QAM
Multiple access	TDMA, OFDM 256, OFDMA 2048	TDMA, OFDM 256, OFDMA (128, 512, 1024, 2048)	OFDMA 1024	OFDMA (512, 1024, 2048)	OFDM, OFDMA (1000 carriers) (8000 carriers with on-channel repeaters)
Duplex (uplink/ downlink)	TDD/FDD	TDD/FDD	TDD	TDD/FDD	FDD

Long Term Evolution (4G) Preliminary Definitions

Feature	Definition
Channel bandwidths	1.4, 3, 5, 10, 15, and 20 MHz.
Transmission modulation schemes:	
Downlink	OFDMA using QPSK, 16QAM, 64QAM.
Uplink	Single carrier FDMA using QPSK, 16QAM, 64QAM.
Access modes	FDD and TDD.
Data rates	Downlink: 172.8 Mbps (2×2 single user MIMO, 64QAM). Uplink: 86.4 Mbps (single link 64QAM).
Spatial diversity:	
Downlink	Open loop transmit diversity. Single user MIMO, up to 4×4 supportable.
Uplink	Optional open loop transmit diversity. 2×2 multi-user MIMO, optional 2×2 single user MIMO.
Transmission time interval	1 ms.
Frequency hopping	Uplink once per 0.5 ms slot. Downlink once per 66 µs symbol.
Scheduling schemes:	
Unicast	Frequency selective (partial band). Frequency diversity by frequency hopping.
Multicast	Enhanced multimedia broadcast/multicast service supporting a single frequency network and cell specific content.
User equipment	20 MHz uplink and downlink. Antennas: two receive and one transmit.

Frequency Ranges, Propagation Characteristics, and Applications

Frequency Range	Sub Bands		Propagation Characteristics	Applications
	Frequency	Identifier		
3–30 kHz (very low frequency, VLF)			Ground wave with low attenuation. Has a high atmospheric noise level.	Submarine communications, long range navigation
30–300 kHz (low frequency, LF)			Similar to VLF. Its attenuation is higher during the day.	Maritime communications, long range navigation
300–3000 kHz (medium frequency, MF)			Low attenuation at night and high attenuation during the day. Susceptible to atmospheric noise.	AM broadcasting, Maritime radio, Emergency frequencies
3–30 MHz (high frequency, HF)			Ionospheric reflection changes throughout the day and as the seasons change.	Telegraph, facsimile, international broadcasting, amateur radio, military communications, long distance ship and aircraft communications
30–300 MHz (very high frequency, VHF)			Susceptible to atmospheric noise. Scattering can occur during temperature inversions.	Mobile radio, mobile video, VHF television, AM aircraft communications, aircraft navigation
0.3–3 GHz (ultra high frequency, UHF)	1–2 GHz 2–4 GHz	L band S band	Propagation is line-of-sight. Susceptible to atmospheric noise.	Cellular phones (WLAN, WiMAX systems), cordless phones, mobile radio, mobile video, RFID devices, personal area networks (Bluetooth, Zigbee), wireless medical devices, UHF television, navigation, radar, microwave links
3–30 GHz (super high frequency, SHF)	2–4 GHz 4–8 GHz 8–12 GHz 12–18 GHz 18–27 GHz 27–40 GHz	S band C band X band Ku band K band Ka band	Propagation is line-of-sight. Susceptible to attenuation when there is rain.	Cordless phones (WLAN, WiMAX systems), satellite communications, radar and microwave links
30–300 GHz (extremely high frequency, EHF)	27–40 GHz 33–50 GHz 40–75 GHz 75–110 GHz	Ka band Q band V band W band	Propagation is line-of-sight. Susceptible to attenuation when there is rain.	Satellites, radar
10^3–10^7 GHz (infrared, visible, and ultraviolet light)			Propagation is line-of-sight.	Optical communications

dBm–Watts–Volts Conversion Table

Power (dBm)	Power (Watts)	V_{RMS} (volts referenced to 50Ω)
50	100	70.71
40	10	22.36
30	1	7.07
27	5.01E–1	5.01
24	2.51E–1	3.54
20	1.00E–1	2.24
18	6.31E–2	1.78
16	3.98E–2	1.41
14	2.51E–2	1.12
12	1.58E–2	0.89
10	1.00E–2	0.71
8	6.31E–3	0.56
6	3.98E–3	0.45
4	2.51E–3	0.35
2	1.58E–3	0.28
0	1.00E–3	0.22
–2	6.31E–4	0.18
–4	3.98E–4	0.14
–6	2.51E–4	0.11
–8	1.58E–4	8.90E–2
–10	1.00E–4	7.07E–2
–12	6.31E–5	5.62E–2
–14	3.98E–5	4.46E–2
–16	2.51E–5	3.54E–2
–18	1.58E–5	2.82E–2
–20	1.00E–5	2.24E–2
–22	6.31E–6	1.78E–2
–24	3.98E–6	1.41E–2
–26	2.51E–6	1.12E–2
–28	1.58E–6	8.90E–3
–30	1.00E–6	7.07E–3
–32	6.31E–7	5.62E–3
–34	3.98E–7	4.46E–3
–36	2.51E–7	3.54E–3
–38	1.58E–7	2.82E–3
–40	1.00E–7	2.24E–3
–42	6.31E–8	1.78E–3
–44	3.98E–8	1.41E–3
–46	2.51E–8	1.12E–3
–48	1.58E–8	8.90E–4
–50	1.00E–8	7.07E–4
–52	6.31E–9	5.62E–4
–54	3.98E–9	4.46E–4
–56	2.51E–9	3.54E–4
–58	1.58E–9	2.82E–4
–60	1.00E–9	2.24E–4

dBm = $10*\log(P/1\text{mW})$

Power = $V^2_{RMS}/50$

VSWR–Reflection Coefficient–Return Loss Conversion Table

VSWR	Reflection Coefficient	Return Loss (dB)
1.006	0.003	50
1.007	0.004	49
1.008	0.004	48
1.009	0.004	47
1.010	0.005	46
1.011	0.006	45
1.013	0.006	44
1.014	0.007	43
1.016	0.008	42
1.018	0.009	41
1.020	0.010	40
1.023	0.011	39
1.026	0.013	38
1.029	0.014	37
1.032	0.016	36
1.036	0.018	35
1.041	0.020	34
1.046	0.022	33
1.052	0.025	32
1.058	0.028	31
1.065	0.032	30
1.074	0.035	29
1.083	0.040	28
1.094	0.045	27
1.106	0.050	26
1.119	0.056	25
1.135	0.063	24
1.152	0.071	23
1.173	0.079	22
1.196	0.089	21
1.222	0.100	20
1.253	0.112	19
1.288	0.126	18
1.329	0.141	17
1.377	0.158	16
1.433	0.178	15
1.499	0.200	14
1.577	0.224	13
1.671	0.251	12
1.785	0.282	11
1.925	0.316	10
2.100	0.355	9
2.323	0.398	8
2.615	0.447	7
3.010	0.501	6
3.570	0.562	5
4.419	0.631	4
5.848	0.708	3
8.724	0.794	2
17.391	0.891	1

$\text{VSWR} = \frac{1+\Gamma}{1-\Gamma}$,where Γ is the reflection coefficient

Return Loss = 20 log $(1/\Gamma)$

Reflection Coefficient – VSWR – Return Loss Compared with Reflected Power

ρ	VSWR	Return Loss	Reflected Power
0	1.0:1	∞ dB	0.0%
0.047	1.10:1	26.4 dB	0.2%
0.099	1.22:1	20.1 dB	1.0%
0.224	1.58:1	13.0 dB	5.0%
0	∞	0 dB	100.0%

No reflection
$Z_L = Z_O$

Full reflection
Z_L = open, short

SECTION IV

Selected RF Products

Measure wideband modulated signals

Model 2810 RF vector signal analyzer

- Continuous frequency range of 400MHz–2.5GHz spans key mobile wireless frequency bands
- >30MHz modulation measurement bandwidth for capturing signals based on the latest high bandwidth wireless standards
- Signal analysis options include: GSM/EDGE, CDMA2000 Reverse Link, W-CDMA Uplink
- Highly intuitive graphical user interface and simple operation allow even occasional users to make measurements with confidence
- Single port interface version for connecting the Model 2910 RF vector signal generator and the Model 2810 to a transceiver's antenna port

MODEL 2810 RF VECTOR SIGNAL ANALYZER

FREQUENCY RANGE: 400MHz to 2.5GHz (unspecified extended range performance from 325MHz to 2.975GHz).

IF 3dB BANDWIDTH: >30MHz.

MAXIMUM SAFE INPUT POWER: +35dBm.

DISPLAYED AVERAGE NOISE LEVEL: –141dBm/Hz, pre-amp off, –148dBm/Hz, pre-amp on.

CHANNEL POWER ACCURACY: ±0.6dB.

EDGE EVM RMS ACCURACY: ±0.5%.

cdma2000 ADJACENT CHANNEL POWER, DYNAMIC RANGE: 65dBc @ 885kHz offset.

WCDMA RMS EVM ACCURACY: ±2%.

Keithley's Model 2810 combines complex signal analysis and spectrum analysis capabilities with high performance and unprecedented ease of use. It is designed to address a wide range of measurement needs for wireless devices, wireless transceiver modules, and RF components.

For production testing applications, the Model 2810 offers fast frequency tuning of <3ms, rapid switching with solid-state variable attenuators, and high speed digital signal processing. These reduce test time significantly, which helps to minimize overall testing costs.

Research and development engineers will appreciate how the Model 2810's fast sweep times with narrow resolution bandwidths over wide frequency spans allow them to obtain the maximum information from a spectrum for characterization and analysis. A 15-second sweep can display 200MHz of a signal's spectrum with a 100Hz resolution bandwidth.

Measure wideband modulated signals out to 6GHz

Model 2820 RF vector signal analyzer

- Frequency range of 400MHz to 4 or 6GHz spans all WLAN and WiMAX frequency bands
- 40MHz signal bandwidth
- MIMO-ready capability for WLAN and WiMAX
- Extensive range of signal analysis options including: GSM, EDGE, W-CDMA, CDMA2000 Reverse Link, and WLAN

MODEL 2820 RF VECTOR SIGNAL ANALYZER

FREQUENCY RANGE: 2820-004: 200Hz to 3.6GHz. **2820-006:** 200Hz to 5.6GHz. Zero Span mode available.

IF 3DB BANDWIDTH: >30MHz (typical).

MAXIMUM SAFE INPUT POWER: +35dBm.

CHANNEL POWER ACCURACY: ±0.6dBm (typical).

EDGE EVM RMS ACCURACY: ±0.5%.

CDMA2000 ADJACENT CHANNEL POWER: **Dynamic Range:** 70dBc @ 885kHz offset (typical), 82dBc @ 1980kHz offset (typical).

W-CDMA RMS EVM ACCURACY: ±2%.

WLAN 802.11n 40MHz BANDWIDTH: **EVM Floor:** –35dB @ 5.8GHz.

This next-generation instrument combines state-of-the-art RF and digital signal processing technology to measure RF test signals rapidly with high accuracy and excellent repeatability. The Model 2820's software-defined radio architecture and 40MHz bandwidth ensures it has the capability to measure today's signals and the flexibility to handle tomorrow's. As new wireless standards emerge, the Model 2820 is engineered for easy upgrades, which extends its useful life and provides an ongoing return on investment far longer than traditional instruments.

The Model 2820 is designed to make fast measurements without compromising accuracy. For example, when using the traditional spectrum analysis function, it can sweep 650MHz/s in a 1kHz bandwidth, which is more than 800 times faster than traditional spectrum analyzers. It can also switch frequencies in 1.3ms using List or Sweep modes and in 3ms using a remote SCPI command.

The Model 2820's Windows CE® operating system and intuitive graphical user interface allow users their choice of controlling the instrument via the touch screen user interface, the front panel controls, or with a mouse. GPIB, USB, and 100Base-T Ethernet LAN ports offer a variety of options for connecting to a PC. It is LXI Class C compliant, so it is equally easy to connect to an internal network or the Internet.

Fast, modulated RF signal generation at your fingertip

Model 2910 RF vector signal generator

- Continuous frequency range of 400MHz–2.5GHz spans key mobile wireless frequency bands
- 40MHz modulation bandwidth, 200MB arbitrary waveform generator
- Signal analysis options include: GSM/EDGE, CDMA2000 Forward Link, W-CDMA Downlink, GPS, analog and digital modulations
- Fast signal tuning for faster test execution: 1.3ms for most signals
- Intuitive, easy-to-use GUI

The capabilities and ranges of the Model 2910 RF Vector Signal Generator are ideal for testing sophisticated mobile handsets, mobile communications infrastructure, RFICs, and wireless connectivity devices. It executes key tasks like the following significantly faster than any other products currently available: frequency tuning in approximately 1ms, amplitude switching in <3ms, and waveform changes in <1.6ms.

The 64 mega-sample Arbitrary Waveform Generator (ARB) and 40MHz modulation bandwidth support downloading externally generated waveforms. The ARB provides built-in waveforms for digital (GSM/GPRS/EDGE, cdmaOne/CDMA2000 1xRTT, WCDMA, ASK, FSK, PSK, and QAM) and analog (CW, AM, FM, noise, two-tone CW, and pulsed) signal formats.

MODEL 2910 RF VECTOR SIGNAL GENERATOR

FREQUENCY RANGE: 400MHz to 2.5GHz (unspecified extended range performance from 325MHz to 2.7GHz).

FREQUENCY SWITCHING TIME: ≤1.8ms (Modulation on, List or Sweep Mode).

SSB PHASE NOISE: PHASE NOISE (1GHz carrier, 20kHz offset): ≤–120dBc/Hz.

AMPLITUDE LEVEL RANGE (CW Signals): –125dBm to +13dBm.

AMPLITUDE LEVEL ACCURACY: CW Signals, –75dBm to +13dBm: ±0.5dB, **–110dBm to –75dBm:** ±0.6dB.

RELATIVE AMPLITUDE ACCURACY: ≤±0.05dB.

EXTERNAL MODULATION BANDWIDTH: ≥200MHz.

ARBITRARY WAVEFORM GENERATOR:
Memory: 64Msamples (16-bit I, Q pairs) in 256MB of memory.
Maximum Modulation Bandwidth: 40MHz.

EDGE RMS EVM: <0.5%.

cdma2000 RHO: >0.9995.

WCDMA RMS EVM: <1.2%.

Wideband, modulated RF signal generation

Model 2920 RF vector signal generator

- Frequency range of 10MHz to 4 or 6GHz spans WLAN and WiMAX frequency bands
- 80MHz modulation bandwidth, 100 megasample arbitrary waveform generator option
- Extensive range of signal generation options: mobile phone standards (GPS, ALG, W-CDMA downlink, cdmaONE, CDMA2000, GSM/EDGE, TD-SCDMA) and digital and analog modulations
- MIMO-ready capability for WLAN and WiMAX

The Model 2920 simplifies testing wireless devices by generating signals compatible with an array of RF communication standards. It can create virtually any signal with up to 80MHz bandwidth:

- Analog modulation signals such as AM, FM, PM, pulse RF, AWG noise, and two-tone signals
- Digital modulation signals with ASK, FSK, PSK, and QAM signal types
- Coded L1 signals of a Global Positioning System satellite with a variety of data types
- Signals defined by custom or user-defined I-Q data files loaded into the Arbitrary Waveform Generator (ARB). Multiple signals can be stored in the ARB and output in programmable sequences.

MODEL 2920 RF VECTOR SIGNAL GENERATOR

FREQUENCY RANGE: 2920-004: 10MHz to 4GHz. **2920-006:** 10MHz to 6GHz.

FREQUENCY SWITCHING TIME: ≤1.6ms (modulation off), ≤1.8ms (modulation on), ≤3ms (characteristic).

SSB PHASE NOISE: Phase Noise (1GHz carrier, 20kHz offset): ≤–121dBc/Hz (low phase noise option).

AMPLITUDE LEVEL RANGE (CW Signals): –120 to +13dBm (300MHz to <3GHz).

AMPLITUDE LEVEL ACCURACY: CW Signals, +13dBm to –75dBm: ±0.6dB (300MHz to <3GHz).

RELATIVE AMPLITUDE ACCURACY: <±0.05dB.

EXTERNAL MODULATION BANDWIDTH: 200MHz.

ARBITRARY WAVEFORM GENERATOR:

Memory: 100MS in 400MB of memory.

Maximum Modulation Bandwidth: 20MHz, 40MHz, or 80MHz.

Maximum Number of Waveform Segments: 1000.

EDGE RMS EVM: <0.35% (typical).

CDMA2000 RHO: >0.995 (typical).

W-CDMA RMS EVM: <0.85% (typical).

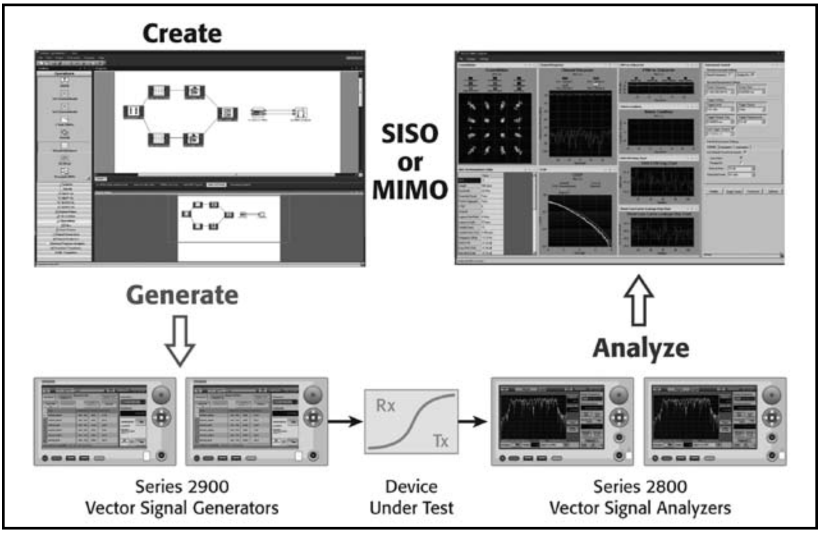
TD-SCDMA EVM: <0.3%.

Create and analyze waveforms with this software designed for Series 2900 Vector Signal Generators, Series 2800 Vector Signal analyzers, and MIMO systems

SignalMeister™ RF Communications Test Toolkit 290101 v. 3.0

- Industry's only fully integrated signal generation and analysis software package
- Unique, seamless SISO-to-8×8 MIMO signal creation and measurements
- WiMAX 802.16e Wave 2 and WLAN 802.11n signal generation and analysis
- WLAN 802.11n channel modeling
- Simulation mode for studies without RF instruments
- Intuitive, object-oriented graphical user interface

The SignalMeister RF Communications Test Toolkit is a next-generation software tool that allows engineers to create and analyze the complex signals used in the most advanced wireless transmission protocols. SignalMeister software generates and analyzes both single-input, single output (SISO) signals and multiple-input, multiple-

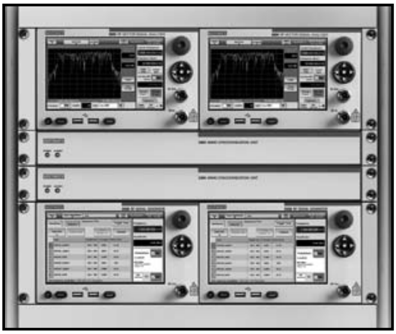


Maximizing engineering productivity: create waveforms, generate RF signals with the Series 2900 Vector Signal Generators, control the instruments, and analyze the measurements with a Series 2800 Vector Signal Analyzer—all with SignalMeister.

output (MIMO) signals used in the latest versions of the WLAN and WiMAX protocol standards. In addition to creating high quality signals, it can create impairments to model non-ideal transmitter conditions and real channel conditions such as fading and noise. The SignalMeister software has the unique ability to analyze the transmitted signals, acquiring and demodulating the signals, then computing and displaying a wide range of parametric data. In addition, it can perform simulation studies without the need to use the actual hardware, which allows researchers and designers to study the impacts of transmitter impairments and channel effects on signal transmissions easily.

Test MIMO systems with up to 8 transmitters and 8 receivers (8×8)

MIMO RF signal analysis and generation test systems and software



- 40MHz signal generation and signal analysis bandwidths
- +1ns signal sampler synchronization
- <1ns peak-to-peak signal sampler jitter
- <1° peak-to-peak RF-carrier phase jitter
- Two-, three-, or four-channel configurations
- Ideal for 802.11n WLAN and 802.16e WiMAX wave 2
- Powerful MIMO signal analysis software package option evaluates up to four OFDM channels with up to 16 signals

The System 2800-MIMO RF signal analyzer and System 2900-MIMO RF signal generator are high performance MIMO tests systems designed to meet the requirements of the 802.11n WiFi and 802.16e WiMAX multi-input, multi-output communications standards. Each system can be configured with up to eight channels with 40MHz signal bandwidth using the Model 2820 RF vector signal analyzer or Model 2920 RF vector signal generator instruments. These instruments are MIMO-ready with the hardware connections and firmware built into every instrument. The MIMO systems can be initially configured as a 2×2 system then upgraded later to up to 8×8.

The MIMO systems are designed to have a stable RF carrier and a precise signal sampler alignment between all instruments in the system. The Model 2895 MIMO Synchronization Unit distributes a common local oscillator, common clock, and precise trigger to all the signal analyzers or generators connected in the systems. This alignment enables the system to make accurate and repeatable measurements of OFDM MIMO signals.

Lab grade measurements and USB interface in the palm of your hand.

Model 3500 portable RF power meter

- Broad 10MHz to 6GHz frequency range enables use in a wide variety of applications
- Large dynamic range of +20dBm to –63dBm measures a wide variety of signals
- Integrated power sensor eliminates the need to carry a separate sensor
- Internal power reference enables self-calibration
- Built-in USB interface for transferring data to a computer

The Model 3500 Portable RF Power Meter is a compact, handheld instrument that makes lab quality RF power measurements in both field and R&D laboratory environments. With an absolute accuracy as good as ±0.21dB, a wide frequency range of 10MHz to 6GHz, and a measurement range of –63dBM to +20dBM, the Model 3500 is suitable for a wide variety of RF measurement applications, including testing mobile phones and infrastructures, WLAN devices, RFID readers, and WiMAX devices.

Its built-in power sensor eliminates the need for users to carry both an instrument and a separate sensor module, and the same sensor is used when duplicating tests or measurements for better repeatability. Truly portable, the Model 3500 fits easily into your hand or a toolkit. To optimize flexibility, it is capable of drawing operating power from batteries, an AC-DC converter module, or a computer via the USB interface.

MODEL 3500 PORTABLE RF POWER METER

FREQUENCY RANGE: 10MHz to 6GHz.

POWER RANGE: +20dBm to –63dBm.
Max. Power: +23dBm, 5VDC.

POWER ACCURACY (at 23°C ±5°C):
+20dBm to +6dBm:
±0.24dB, 10MHz to 3GHz (characteristic).
±0.16dB, 3GHz to 5GHz (characteristic).
±0.22dB, 5GHz to 6GHz (characteristic).
+6dBm to –9dBm:
±0.26dB, 10MHz to 3.75GHz; ±0.07dB typical.
±0.40dB, 3.75GHz to 6GHz; ±0.07dB typical.
–10dBm to –29dBm:
±0.26dB, 10MHz to 3.75GHz; ±0.05dB typical.
±0.37dB, 3.75GHz to 6GHz; ±0.05dB typical.
–30dBm to –40dBm:
±0.21dB, 10MHz to 3.75GHz; ±0.12dB typical.
±0.27dB, 3.75GHz to 6GHz; ±0.13dB typical.

LINEARITY (at 23°C ±5°C): ±0.10dB, +6dBm to –40dBm.

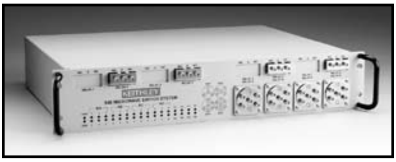
NOISE FLOOR: –63dBm.

SWR: 1.12:1, 10MHz to 3.75GHz. 1.20:1, 3.75GHz to 6GHz.

Flexible, small, and simplified RF and microwave switching

System 46 unterminated and System 46T terminated RF/microwave switch systems

- Compact RF/microwave IEEE-488 switching systems, only 2U high
- Built-in contact closure counter monitors switch cycles
- Standard configuration allows up to 32 channels of switching
- Simple control with built-in GPIB/ IEEE-488 interface bus
- Frequency ranges up to 40GHz



SYSTEM 46 AND 46T RF/MICROWAVE SWITCH SYSTEMS

Configurable up to 32 channels of RF switching with a maximum of 8 SPDT switches and 4 SP6T switches.

FREQUENCY RANGES (Unterminated Relays): DC–18GHz, DC–26.5GHz, DC–40GHz. **(Terminated Relays, Model S46T):** DC–26.5GHz.

CONTACT CLOSURE COUNTER: 1 counter/channel, up to 10 million counts, stored in non-volatile memory.

CHANNEL CHARACTERIZATION DATA STORAGE: 1 location/channel, 68 bytes, stored in non-volatile memory.

INSERTION LOSS: ≤0.4dB for frequencies up to 12.4GHz.

VSWR: ≤1.40:1 for frequencies up to 12.4GHz.

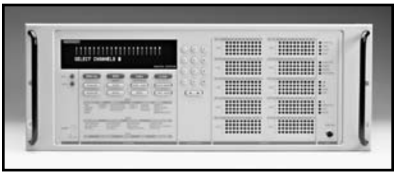
These Microwave Switch Systems are designed to simplify the automated switching needed to test a wide range of telecommunications products and devices. They can control 32 relay contacts in a package as small as a 2U high (3.5 in) full-rack enclosure.

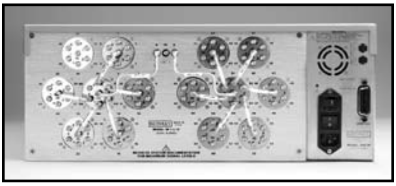
A variety of standard configurations are available as well as fully custom systems with up to 32 channels for controlling microwave relays, programmable attenuators, and other components. The choice of standard and custom configurations makes it simple to select a system that meets the specifications of the test application without the expense of unnecessary switches or other features. This “just what you need and no more” design philosophy allows these systems to provide an outstanding price/performance value.

In addition to counting contact closures, these systems have a portion of their memory available to store S-parameters or calibration constants for each relay contact or pathway. If a specific performance parameter is critical, such as VSWR or insertion loss, the parameter can be stored in memory for use in trend analysis between scheduled maintenance shutdowns. Stored parameters can also be used for compensation to enhance accuracy during RF measurements.

Test more devices simultaneously with high density microwave switching

System 41 RF/microwave signal routing mainframe





- Integrated solution, including both controller and microwave components in a 4U (7 inch) package
- Add one of three standard microwave switch modules
- Unique front panel provides interactive control and real-time status display
- DC–18GHz solutions
- Pre-programmed, turnkey solutions
- Light pen for point-and-click programming from the front panel

The System 41 is optimized for RF and microwave signal routing applications. It integrates the ability to control up to 240 RF/microwave channels within the same chassis that houses the switches. This provides an optimum combination of space and performance.

Three standard microwave switching modules are available: an 18GHz 10×10 non-blocking matrix, an 18GHz 6×6 non-blocking matrix, and an 18GHz 1×72 multiplexer that can be configured as two independent 1×36 multiplexers.

The control unit's front panel display provides continuous, real-time information on the status of all controlled components. This makes it possible to operate the system manually, not just automatically, speeding and simplifying test verification and troubleshooting. Both start-up time and downtime are minimized, which helps maximize production time.

To begin using the System 41, simply install it in a rack and connect the input and output lines.

Combine DC and RF switching up to 2GHz in one compact package

Model 7001 80-channel switch/control mainframe

- DC, RF, and optical switch capability
- Supports industry's broadest range of signals
- Family of more than 30 switch/control cards

The Model 7001 is a half-rack, high density, two-slot mainframe that supports the widest range of signals in the test and measurement industry. DC switching capabilities from nanovolts to 1100V and femtoamps to 5A, as well as RF and optical switch support, make the Model 7001 a versatile production test tool for a wide array of applications.

Built-in scan control eliminates the need for a computer to control every step of the test procedure. Simply program the Model 7001 to control channel spacing, scan spacing, and the number of scans. A built-in non-volatile memory stores up to 100 complete switch patterns.

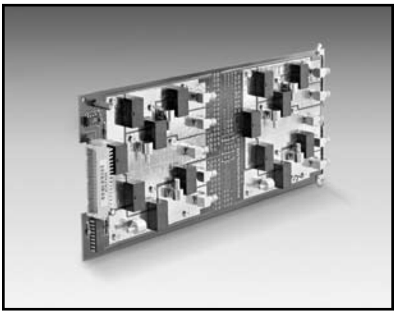
Each slot of the Model 7001 can accommodate up to 40 channels. This means that fewer switch cards are required, reducing the amount of switching hardware needed. In addition, the Model 7001's analog backplane eliminates intercard wiring and increases configuration flexibility. Two cards can be connected through the backplane to create a 1×80 multiplexer, a 4×20 matrix, or a multiplexer/matrix combination that provides matrix row expansion.

The vacuum fluorescent display of the Model 7001 shows the open/closed status of each channel in the mainframe simultaneously. The graphical display pattern makes it much easier to configure a test system, make modifications, or debug an existing program. The status of the cards in both slots is displayed side by side on the same screen.

RF switch cards for the Model 7001

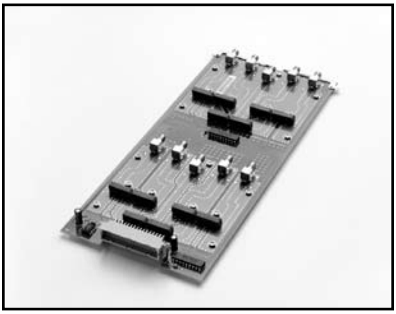
Model 7016A 2GHz RF switch card

- Dual 1×4 configuration
- DC to 2GHz, 50Ω, signal switching
- Off channels can be resistively terminated



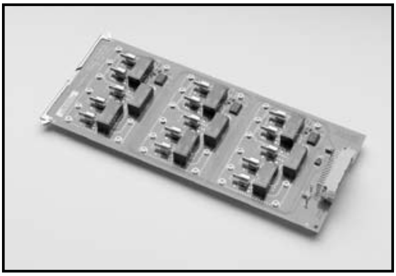
Model 7017 800MHz RF switch card

- Dual 1×4 configuration
- DC to 800MHz, 50Ω, signal switching
- <10mΩ contact resistance variation



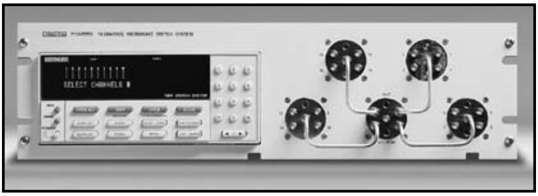
Model 7038 2GHz RF switch card

- 3 isolated 1×4 multiplexers
- DC to 2GHz, 75Ω, signal switching
- High channel to channel isolation



Combine 18GHz microwave switching, low frequency switching and control in a standard assembly

Model 7116-MWS microwave switch system



- Integrated solution, including controller and RF/microwave switches
- Compact RF/microwave switching system only 3U high
- Configurable as one 1×16 or five independent 1×4 multiplexers
- 18GHz bandwidth relays
- Real time status display of all switches
- Local and remote control

The Model 7116-MWS is a fully assembled 16-channel RF/microwave switch system that is designed to simplify controlling high frequency switching. It contains the IEEE-488 compatible Model 7001 Switch Mainframe as a switch controller and electromechanical coaxial relays with a bandwidth from DC to 18GHz. It is ideal for production and laboratory testing of a variety of communications devices and systems.

The non-volatile memory in the Model 7001 is preprogrammed in a 1×16 multiplexer switching pattern, allowing users to begin operating it immediately. All RF/microwave relay interconnections are implemented using low-loss, semi-rigid RF cabling to ensure high signal integrity. Signal paths are of equal length to ensure similar transmission line characteristics and performance in every channel. The relays used provide high isolation to minimize channel crosstalk. The Model 7116-MWS's combination of low insertion loss and high isolation ensures high quality measurement pathways for signal routing and measurement. Also, a spare card slot is available that allows control of up to 40 additional switch channels.

Operating Frequency	DC–3 GHz	3–6 GHz	6–12 GHz	12–18 GHz
Insertion Loss dB, maximum	0.5 (0.2)	0.75 (0.3)	1 (0.4)	1.3 (0.5)
Isolation dB, minimum	80	70	60	60
RF Power W, maximum	30 (34)	20 (34)	15 (34)	10 (34)
VSWR	1.35 (1.2)	1.5 (1.3)	1.7 (1.4)	1.9 (1.5)

Values in parentheses are for individual SP4T switches.

Low frequency measurement and control with RF switching to 3.5GHz

Integra Series multimeter/switch systems

- Combines the functions of a digital multimeter, switch system, and datalogger
- True 6½-digit (22-bit) resolution
- Choice of 12 switch/control plug-in modules, including two RF switch cards
- Up to 200 differential input channels (with 300V isolation) for measurement and control
- Convenient front panel inputs

Each instrument in the Integra Series combines precision measurement, switching, and control in a single, tightly integrated enclosure for either rack-mounted or benchtop applications. These cost-effective, high performance test platforms offer affordable alternatives to separate digital multimeters, switch systems, dataloggers/recorders, data acquisition equipment, and VXI/PXI systems.

Their family of plug-in switching and control modules offers unmatched flexibility and testing efficiency for a wide range of industries and applications. System builders can create test solutions with a combination of channel count, cost per channel, and system performance unmatched by any other single-box measurement system. The input modules provide the flexibility to vary the channel count from 20 to 200 (2-pole), apply a stimulus to the device under test, route signals, control system components, and make precision measurements with up to 14 functions.

The robust digital I/O capabilities can be used for triggering, handshaking with other automation equipment, and alarm limit outputs. In addition, it offers scan rates of more than 200 channels/second (up to 2500 readings/second) to increase test productivity.

RF cards for Integra Series systems

Model 7711 2GHz, 50Ω, RF module

- Signal routing performance to 2GHz
- Switches up to 60VDC
- Onboard switch closure counter and S parameter storage

Model 7712 3.5GHz, 50Ω, RF module

- 3.5GHz bandwidth
- Dual 1×4 configuration
- Onboard switch closure counter and S parameter storage

SECTION V

Selected DC Products

Access all DC levels and low frequency baseband signals with high accuracy and high speed switching

Series 3700 system switch/multimeter and plug-in cards

- Six slot system switch mainframe with optional high performance multimeter
- Multi-processor architecture optimized for high throughput scanning and pattern switching applications
- Remote PC control via Ethernet, USB, and GPIB interfaces
- Up to 576 two-wire multiplexer channels in one mainframe
- LXI Class B compliance
- Embedded Test Script Processor (TSP) offers unparalleled system automation, throughput, and flexibility
- TSP-Link master/slave connection provides easy system expansion and seamless connection to Series 2600A SourceMeter instruments

The Series 3700 offers scalable, instrument grade switching and multi-channel measurement solutions that are optimized for automated testing of electronic products and components. When ordered with the high performance multimeter, you receive a tightly integrated switch and measurement system that can meet the demanding application requirements in a functional test system or provide the flexibility needed in stand-alone data acquisition and measurement applications.

The switching capability includes multiplexer cards with a capacity of up to 1×96 crosspoints and matrix switching with matrices as large as 6×16.

The high performance multimeter option provides low noise, high stability 3½- to 7½-digit readings for leading-edge measurement performance. This flexible resolution supplies a DC reading rate of >14,000 readings/second at 3½ digits to 60 readings/second at 7½ digits, offering customers maximum reading throughput and accuracy. The multimeter also provides an expanded low ohms (1Ω) range, low current (10μA) range, and dry circuit (1Ω to 1kΩ) range, extending utility beyond typical DMM applications.

Characterize DC I-V, C-V, and pulse performance of RF semiconductors

Model 4200-SCS semiconductor characterization system

- Intuitive, point-and-click Windows®-based environment
- Remote PreAmps extend the resolution of SMUs to 0.1fA
- New C-V instrument makes C-V measurements as easy to perform as DC I-V measurements
- New pulse and pulse I-V capabilities for advanced semiconductor testing
- New scope card provides integrated scope and pulse measure functionality
- Self-contained PC provides fast test setup, powerful data analysis, graphing and printing, and on-board mass storage of test results

The easy-to-use Model 4200-SCS Semiconductor Characterization System performs lab grade DC I-V, C-V, and pulse device characterization, real-time plotting, and analysis with high precision and sub-femtoamp resolution. It offers the most advanced capabilities available in a fully integrated characterization system, including a complete, embedded PC with Windows operating system and mass storage.

Its self-documenting, point-and-click interface speeds and simplifies the process of taking data, so users can begin analyzing their results sooner. The powerful test library management tools allow standardization of test methods and extractions to ensure consistent test results.

The Model 4200-SCS offers tremendous flexibility, with hardware options that include four different switch matrix configurations, a variety of LCR meters, and pulse generators. The 4200-SCS is modular and configurable. The system supports up to eight Source-Measure Units (SMUs), including up to eight high power SMUs with 1A/20W capability. An optional Remote PreAmp, the 4200-PA, extends the system's measurement resolution from 100fA to 0.1fA.

Bias RF components and measure a wide range of currents from leakage levels to V_{cc} load levels

Series 2600A System SourceMeter® multi-channel I-V test solutions

- Combines a power supply, true current source, DMM, arbitrary waveform generator, V or I pulse generator with measurement, electronic load, and trigger controller – all in one instrument
- TSP® Express software tool for quick and easy I-V test
- Precision timing and channel synchronization (<500ns)
- Parallel test execution for unmatched throughput
- 20,000 rdg/s provides faster test times and ability to capture transient device behavior
- Family of products offers wide dynamic range: 1fA to 10A and 1μV to 200V
- TSP-Link® bus allows up to 32 units/64 channels of channel expansion per GPIB or IP address
- LXI Class C compliance provides high speed data transfer and enables quick, easy remote testing, monitoring, and troubleshooting

Series 2600A System SourceMeter instruments are Keithley's latest I-V source-measure instruments for use as either a bench-top I-V characterization tool or as a building block component of multi-channel I-V test systems. For bench-top use, Series 2600A instruments feature an embedded TSP Express Software Tool that allows users to quickly and easily perform common I-V tests without programming or installing software. For system level applications, Series 2600A's Test Script Processor (TSP) architecture along with new capabilities such as parallel test execution and precision timing provides the highest throughput in the industry to lower the cost of test.

The user can easily connect the Series 2600A SourceMeter instrument to the PC by using the Ethernet cable (provided with the instrument) and by entering the IP address in the web browser to automatically load the built-in LXI web page. TSP Express can then be launched from the built-in LXI web page, so neither software installation nor GPIB connection are needed. The TSP Express Software Tool provides an intuitive user interface to set up and run basic and advanced tests quickly, including nested step/sweeps, pulse sweeps, and custom sweeps for device characterization applications. For applications where single-point I-V source-delay-measure is all that is needed, the tool also provides an interface to configure and measure discrete points quickly. The data can then be viewed in graphical or tabular formats and can be readily exported to a .csv file for use with spreadsheet applications. For more advanced test requirements, the automatic script generation feature simplifies the process of writing custom programs.

Test devices and avoid self-heating with precision pulse generators

Series 3400 pulse/pattern generators

- Broad-purpose voltage pulse and pattern generation
- Pulse and burst modes for material and device characterization
- Serial data pattern simulation for functional characterization tasks
- 1mHz–165MHz frequency output range
- Independently adjustable rise and fall times
- 3ns–1000s pulse width range

Series 3400 Pulse/Pattern Generators offer users extensive control over a wide variety of pulse parameters, including pulse amplitude, rise time, fall time, width, and duty cycle via the instrument's flexible user interface or over the GPIB and USB interfaces. The built-in pattern generation capabilities simplify the simulation of serial data patterns when testing devices to characterize their performance while operating under sub-optimal conditions.

BASIC MODES OF OPERATION

The 340x generator may be set in one of four available modes: Pulse, Pattern, Burst, and External Width.

Pulse Mode delivers a single pulse per trigger event to the outputs. The pulse is programmable in delay and duration.

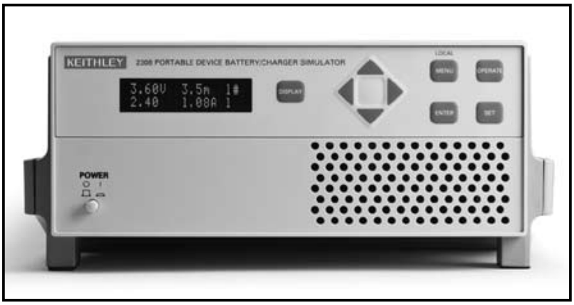
Burst Mode results in a "burst" of *n* pulses per trigger event, with pulses configured similarly to single pulses in Pulse mode.

Pattern Mode delivers a programmable pattern per trigger event to the outputs. The pattern is programmable or may be selected from a library of pre-configured patterns. The pattern may be presented in either NRZ or RZ formats. In NRZ mode, the pattern crossing point is programmable. In RZ mode, the duration (duty cycle) of the pattern pulse is programmable.

External Width Mode makes the pulse level follow the edges of the Ext In input. A rising edge causes the output to go high, while a falling edge causes the output to go low.

Simulate a battery source on V_{CC}

Model 2308 portable device battery/charger simulator



- Specialized dual channel power supply for design and testing of portable, battery-operated devices
- Ultra-fast response to pulsed load operation
- Variable output resistance for simulating an actual battery's output response
- Pulse peak, average, and baseline current measurements
- Built in digital voltmeter

The Model 2308 Portable Device Battery/Charger Simulator is optimized for use in testing mobile phones and other portable, battery-operated devices. When a device-under-test (DUT) transitions nearly instantaneously from a sleep or standby mode to the full power transmit state, the Model 2308's rapid response to load changes means there's little transient voltage drop from the programmed output voltage and the output recovers quickly. This fast response is particularly critical when testing portable devices with a pulsed mode of operation because it allows the device to perform properly while it's being tested. In contrast, the slow-responding source voltage typical

MODEL 2308 FEATURES

NUMBER OF CHANNELS: 2.

TOTAL AVAILABLE POWER: 45W.

MAXIMUM VOLTAGE, EACH CHANNEL: 15V.

MAXIMUM CURRENT, EACH CHANNEL: 3A @15V. 5A @ ≤4V.

CHANNEL OPERATING MODES: Source and sink.

CURRENT RANGES AND RESOLUTION:

Range	Resolution
5 A	100 µA
500 mA	10 µA
50 mA	1 µA
5 mA	0.1 µA

PULSE CURRENT MEASUREMENT INTERVALS: 33.3µs to 833µs in 33.3µs intervals.

BASIC CURRENT MEASUREMENT ACCURACY: 0.2%.

ANALOG OUTPUT (Battery Channel):
5A/500mA Ranges: 1V/A;
50mA/5mA Ranges: 100mV/mA.

DVM MEASUREMENT (Charger Channel): 0–15V DC.

of conventional power supplies causes the DUT to perform improperly, leading to production yield problems and costly retesting.

The Model 2308 offers a complete solution for portable device sourcing and load current measurement. It has two independent power supply channels: one is optimized to simulate a battery; the second channel is optimized to perform like a charger for a rechargeable battery. The battery channel's variable output resistance can be used to simulate the internal resistance of a battery so design and test engineers can simulate a battery's output for testing devices under realistic operating conditions. This channel also sinks current to simulate a discharged battery. The charger channel can supply a voltage to test a portable device's battery charge control circuitry, with the battery channel acting as the discharged battery load. In addition to maintaining output voltage levels under difficult load conditions, the Model 2308 can measure a wide dynamic range of load current levels and can measure narrow current pulses (or pulses as narrow as $50\mu s$). That makes it ideal for characterizing device power consumption by making low-level sleep mode measurements as well as pulsed operating load currents.

Get superior waveform generation functionality and flexibility at an unparalleled price

Model 3390 50MHz arbitrary waveform/function generator

- 50MHz sine wave frequency
- 25MHz pulse frequency
- 256k-point, 14-bit resolution
- Built-in function generator capability includes sine, square, triangle, noise, DC, etc.
- LXI Class C compliant

The Model 3390 generates highly stable and accurate waveforms for creating almost any desired shape, using direct digital synthesis (DDS) techniques to ensure superior performance and functionality.

The exceptional signal quality of the Model 3390 is a result of its high resolution, fast rise and fall times, and deep memory. The combination of high signal quality and low price makes it the ideal solution for applications that use the 50MHz bandwidth and below. Lower speed instruments cannot provide the signal accuracy of the Model 3390, even at bandwidths for which they were specifically designed.

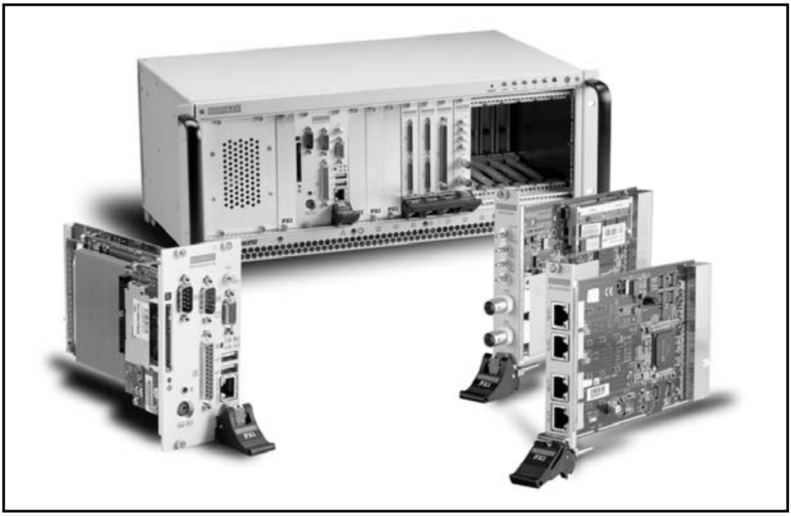
The Model 3390 is engineered to replicate real world signals precisely. A14-bit arbitrary waveform generator (ARB) allows defining waveforms with up to 256,000 data points and generating them at a sampling rate of 125MSamples/second. Up to four user-defined waveforms can be stored in the onboard non-volatile memory.

Ten standard waveforms or functions are provided, including the basic sine, square, ramp, and triangle shapes. All of these standard shapes can be created simply by pressing one button on the front panel. The Model 3390 offers the highest repetition rates of any instrument in its class, making it easier to emulate real-world signals.

Pulse capabilities have become critically important as devices being tested have become smaller, more sensitive, and more complex. Accurately duplicating the signals these tiny devices receive demands very clean pulses with crisp edges, which is why the Model 3390 offers the fastest rise time (5ns) and cleanest pulse shapes for this class of instrument.

The Model 3390's ability to modulate at high internal frequencies allows simulating real-world conditions accurately. Signals can be modulated with the built-in AM, FM, PM, PWM, or FSK source, or with an external modulation source.

Control RF test systems and verify baseband performance with reliable, high speed data acquisition and control



Series KPXI System Products

- Allows you to combine instruments that use different platforms, such as GPIB, LXI, PXI, and TSP
- Supports distributed programming and concurrent execution for dramatically improved test times
- Includes start-up software and drivers for C, Visual Basic, .NET, and LabView™ with most KPXI products

SERIES KPXI SYSTEM PRODUCTS

CHASSES: 6-slot, 8-slot, 14-slot, and 18-slot options.

SYSTEM CONTROLLERS: Three modules with up to 1.8GHz CPU speed, 2GB RAM, and 80GB hard drive.

DIGITIZER: 130MS/s, 512MB memory, dual channel @ 60MS/s, 14-bit resolution, >30MHz 3dB bandwidth.

MULTIFUNCTION MODULES: Six modules with up to 96 analog inputs, 2 analog outputs, 24 digital I/O lines, and 2 counter/timers.

WAVEFORM GENERATION ANALOG OUTPUT MODULES: Two modules with up to 8 channels, 1MS/s analog outputs, 8 analog input channels, 24 digital I/O lines, and 2 counter/timer channels.

DIGITAL I/O MODULES: Eight modules with up to 64 I/O ports.

Series KPXI System Solutions make it easy to create hybrid systems that use a mixture of LXI, PXI, TSP, and GPIB based products. Keithley's hybrid test offering is an industry leading mix of PXI and instrumentation capabilities that enable dramatically improved test times through distributed programming and concurrent execution.

Keithley's KPXI products include:

- PXI system controllers that provide extraordinary reliability, high computing performance, and low power consumption
- PXI digitizer (with deep memory) that is ideal for capturing high-speed waveforms, pulse response measurements, wireless testing, and much more
- PXI data acquisition modules that offer high channel density, high-speed analog outputs, simultaneous sampling of analog and digital inputs while generating waveforms through analog output channels, etc.
- PXI chassis that are a great system core for robust hybrid applications
- PXI extension modules that make it easy to create multi-chassis configurations and to separate a control system from a harsh environment with an auxiliary chassis

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Keithley Instruments, Inc.
Corporate Headquarters • 28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168
1-888-KEITHLEY (534-8453) www.keithley.com

No. 2965
12.15.08