Advanced Measurement Techniques for OFDM- and MIMO-based Radio Systems
Demystifying WLAN and WiMAX Testing

1st Revised Edition
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SECTION 1

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.](image)

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...
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 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.

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, $T_{\text{sym}}$.

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 $T_{\text{sym}}$. 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

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![Diagram](image) - Figure 4. This block diagram shows the digital circuit in the Model 2810 Vector Signal Analyzer and the Model 2910 Vector Signal Generator.
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 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.

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.

![Constitution Diagram of a WLAN Signal](image)

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**

<table>
<thead>
<tr>
<th>Wireless</th>
<th>Wireline</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.11a, g, n (WiFi) Wireless LANs</td>
<td>ADSL and VDSL broadband access via POTS copper wiring</td>
</tr>
<tr>
<td>IEEE 802.15.3a Ultra Wideband (UWB) Wireless PAN</td>
<td>MoCA (Multi-media over Coax Alliance) home networking</td>
</tr>
<tr>
<td>IEEE 802.16d, e (WiMAX), WiBro, and HiperMAN Wireless MANs</td>
<td>PLC (Power Line Communication)</td>
</tr>
<tr>
<td>IEEE 802.20 Mobile Broadband Wireless Access (MBWA)</td>
<td></td>
</tr>
<tr>
<td>DVB (Digital Video Broadcast) terrestrial TV systems: DVB-T, DVB-H, T-DMB, and ISDB-T</td>
<td></td>
</tr>
<tr>
<td>DAB (Digital Audio Broadcast) systems: EUREKA 147, Digital Radio Mondiale, HD Radio, T-DMB, and ISDB-TSB</td>
<td></td>
</tr>
<tr>
<td>Flash-OFDM cellular systems</td>
<td></td>
</tr>
<tr>
<td>3GPP UMTS &amp; 3GPP@ LTE (Long-Term Evolution) and 4G</td>
<td></td>
</tr>
</tbody>
</table>

**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,
+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.

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

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
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
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.

**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.