From Fixed WiMAX 802.16d to Mobile 802.16e: RF and Digital Baseband Testing

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presented by:

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A Capable and Complicated New Std.
This Presentation

Most Useful RF Measurements & Troubleshooting

• What we’ve learned as a Forum member and measurement partner

Extension of 802.16d eSeminar (Jan ’05)

• Previous principles, measurement techniques also apply to 802.16e OFDMA

Measurements for Success (however you define it)

• Find problems quickly and specifically
• Ensure compatibility, solve compatibility or interoperability issues
• Improve performance
• Reduce cost
• Improve manufacturability
Agenda

802.16d WiMAX & 802.16e OFDMA Overview
  • Brief review
  • Focus on OFDMA differences
    Resources suggested for OFDM & WiMAX review & tutorial

Digital Baseband & IF Tools

Measurement & Troubleshooting Sequence
  • Spectrum
  • Frequency & time domain
  • Basic digital demodulation
  • Advanced digital demodulation

Common Problems, How to Find Them

Resources
Incremental Approach

Troubleshooting 802.16-OFDMA vs. 802.16-OFDM

• Impairments causing problems in 802.16-OFDMA have the same effect and symptoms in 802.16-OFDM
• Major difference for testing is a more complicated test setup & greater opportunity for setup-related problems
• Typical impairments still include flatness, symbol timing, frequency error, RCE/EVM, IQ impairments, etc.
• All previous OFDM principles still apply
Resources, Tutorials, Demonstrations

New OFDMA Resources
• Upcoming OFDMA Ap-Note
• Technical overviews, step-by-step demonstration guides

WiMAX Resources
• New WiMAX Ap-Notes
• Trial VSA software--free demo/tutorial license
• Trial signal generation software
• Example captured signals (no hwr required for tutorial)

802.11a WLAN Materials for OFDM Background
• Magazine article on OFDM impairments
• OFDM analysis tutorial with case studies
• Meas. & setup demonstration videos (30 minutes) on CD
Contrast OFDMs--**802.11a vs. 802.16 WiMAX**

- **52 carriers, 312.5 kHz spacing**
  - 802.11a (18 MHz)
  - 4 BPSK Pilots
  - BPSK, QPSK, 16QAM, 64QAM

- **200 carriers, 90 kHz spacing**
  - 802.16 (20 MHz)
  - 8 BPSK Pilots
  - BPSK, QPSK, 16QAM, 64QAM

- **200 carriers, 6.7 kHz spacing**
  - 802.16 (1.5 MHz)
  - 10 MHz
  - 7.0 MHz
  - 3.5 MHz

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Contrasting OFDMs--\textit{802.16e OFDMA} “WiMAX mobile”

\textbf{802.16e}: Freq range: 2-6 GHz  Data rate: \leq 70Mbps  Mobile/Fixed: Mobile (60kph)

- **802.16e (20 MHz)**
  - FFT: 2048
  - Carriers: 1680
  - Spacing: 11kHz
  - 166-240 BPSK Pilots, variable location
  - QPSK, 16QAM, 64QAM

- **802.16e (10 MHz)**
  - FFT: 1024
  - Carriers: 840
  - Spacing: 11kHz
  - 83-120 Pilots

- **802.16e (5 MHz)**
  - FFT: 512
  - Carriers: 408
  - Spacing: 11kHz
  - 42-60 Pilots

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## Numeric Parameters: 1024 FFT Example

<table>
<thead>
<tr>
<th></th>
<th>802.16e</th>
<th>Korea (WiBro)</th>
<th>Total bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal BW</td>
<td>10MHz</td>
<td>8.75 MHz</td>
<td></td>
</tr>
<tr>
<td>Actual BW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UL/DL-PUSC</td>
<td>9.375 MHz</td>
<td>8.203 MHz</td>
<td>841</td>
</tr>
<tr>
<td>DL-FUSC</td>
<td>9.487 MHz</td>
<td>8.300 MHz</td>
<td>851</td>
</tr>
<tr>
<td>DL-OFUSC, UL-OPUSC</td>
<td>9.643 MHz</td>
<td>8.437 MHz</td>
<td>865</td>
</tr>
<tr>
<td>Carrier spacing</td>
<td>11.1607 kHz</td>
<td>9.7656 kHz</td>
<td></td>
</tr>
<tr>
<td>Symbol time</td>
<td>100.8 µs</td>
<td>115.2 µs</td>
<td></td>
</tr>
<tr>
<td>Guard Interval</td>
<td>1/8</td>
<td>1/8</td>
<td></td>
</tr>
<tr>
<td>Preamble</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulation format</td>
<td>QPSK</td>
<td>QPSK</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>1 sym (100.8µs)</td>
<td>1 sym (115.2 µs)</td>
<td></td>
</tr>
<tr>
<td>Actual bandwidth</td>
<td>9.498 MHz</td>
<td>8.310 MHz</td>
<td>852</td>
</tr>
<tr>
<td>Carrier spacing</td>
<td>33.48 kHz</td>
<td>29.297 kHz</td>
<td></td>
</tr>
<tr>
<td>Carrier sequence</td>
<td>1,4,7.../ 2,5,8.../ 3,6,9...</td>
<td>1,4,7.../ 2,5,8.../ 3,6,9...</td>
<td></td>
</tr>
</tbody>
</table>
802.16 Concepts: Sub-channelization

- The carriers are organized into “logical sub-channels”. The carriers are usually NOT adjacent carriers, they are randomly distributed across the entire bandwidth.

- 34 logical sub-channels,

- 24.7 carriers/sub-channel (10MHz)

- Carrier assignment changes for every symbol (p/o permutation formula)

Permutation formula = pseudo-random sequence determined by preamble index, cell ID and segment number. Provides more reliable link also signaling control.
802.16 OFDMA Concepts: Slots

• In OFDMA, the minimum possible data unit is a “Slot”
• A slot has 2 dimensions, one dimension is time, the other is subchannel number
• 3 most common slot sizes
  • 1 Subchannel and 1 OFDMA Symbol
  • 1 Subchannel and 2 OFDMA Symbols
  • 1 Subchannel and 3 OFDMA Symbols
• Different “Zones” will use different slot sizes
802.16 OFDMA Concepts

Example of a ‘data burst’ or ‘data region’ allocated to a user

- Slots are combined together to make a data burst (region)
- A data burst is a group of contiguous sub channels and symbols
- The base station assigns a data burst/region to a user to use to receive or transmit data.
802.16 OFDMA Concepts

Drawing of ‘data region’ or ‘data bursts’

- In OFDMA, data bursts overlap in time.

- Maximizes data flow in complex environment.

- In 802.16-2004 OFDM user data DO NOT overlap in time.
A Permutation Zone (or simply a Zone) is a number of contiguous OFDMA symbols in the DL or UL that use the same permutation formula. The permutation formula describes various configurations of pilot subcarriers, data subcarriers, subchannels, and slots.

- There are currently at least 7 zones that have been defined:
  - PUSC (partial usage of subchannels)
  - FUSC (full usage of subchannels)
  - PUSC with all subchannels
  - Optional FUSC
  - AAS (Adaptive Antenna System)
  - AMC (Adaptive Modulation and Coding)
  - Option FUSC with all subchannels

Zones are used to help implement basestation functionality such as beamforming, assigning subchannels to different sectors of a single cell, and to define subchannelization that reduces basestation to basestation interference.
Frame Structure: Some RF Implications

- A “permutation zone” is a contiguous set of symbols with a consistent subchannel-to-tones mapping. There are parameters for each zone which change the mapping on a zone-by-zone basis.
- Each permutation zone has independent pilot locations, pilot values, “data burst” definitions, and subchannel mapping algorithm.
- Pilot locations are not “fixed”, but have a pattern which recurs over multiple symbols.
- A “data burst” is a data message which is mapped to an abstract subchannel-vs-symbol grid.
- The abstract mapping means QPSK, 16QAM, and 64QAM are all present in the same OFDM symbol, separable only by using the correct “permutation equation”.
Well-Organized Measurement Approach

An Orderly Approach Will

• Reduce setup and measurement errors (correct center frequency, span, pulse/burst parameters)
• Find problems at the earliest stages of analysis
• Provide more understandable and useful measurement results
• Help avoid missing certain signal problems or impairments (some impairments are most clearly seen in vector measurements)
• Provide the fastest path to complete troubleshooting

It is often more useful to have a clear understanding of the signal and a reliable analysis approach than to know all the technical details of the standard
Digitized Analog

- N bits, parallel or serial
- Unsigned or 2’s complement formats
- I/Q, IF, polar format
- Clock
- Setup/Hold

1V = 0xff  
0V = 0x00
Digital I/Q or IF Signal Generation: FPGAs

Programmable development boards

or

Existing FPGAs

• Very Flexible
• High Level Knowledge in FPGA, DSP Programming Required
• Need Custom Software
Digital I/Q or IF Signal Generation: Signal Generators with Digital Outputs

- Pre-Configured and Proprietary Signals using Arbitrary Waveform Generator
- Solutions Optimized for Digital I/Q and IF
Digital I/Q or IF Signal Analysis: Logic Analyzers with VSA Software

- Time, Frequency, and Modulation Domain Analysis for Custom or Standard Formats
- Logic Analyzer Provides Digital Bus Analysis and Troubleshooting
A Meas. & Troubleshooting Sequence

One suggested sequence, especially for signals that are not fully understood

Frequency, Frequency & Time

Get basics right, find major problems

Basic Digital Demod

Signal quality numbers, constellation, basic error vector measurements

Advanced & Specific Demod

Find specific problems & causes

As signals become more complex, vector measurements are even MORE useful prior to digital demodulation
Two Major Types of Testing

Creating & Measuring Spectrally and Statistically Correct Signals

- Component & subsystem testing
- RCE/EVM interpretation of performance (compression, CFR, distortion, phase noise, etc.)

Creating & Measuring Fully Compliant Signals

- Configuring & verifying DSP
- Complete transmitter & receiver testing
- Compatibility/interoperability testing
- Margin testing
Meas. & Troubleshooting Sequence

Frequency, Frequency & Time
- Get basics right, find major problems

Basic Digital Demod
- Signal quality numbers, constellation, basic error vector measurements

Advanced & Specific Demod
- Find specific problems & causes

Wideband spectrum
Narrowband spectrum
Frequency & Time
Triggering, timing

Gated Spectrum
Gated power, CCDF
Time capture
Spectrogram

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Frequency Meas., then Freq. & Time

Frequency--Wideband Spectrum
- Approximate center frequency, occupied BW, power level/range
- Other signals present, spurs & interference

Frequency--Narrowband Spectrum
~1.1x(nominal BW)
- More accurate center frequency
- Transition to frequency & time
- Spectrum alone (even with averaging) is inadequate for pulsed signals with AM
- Accurate spectrum requires triggering
Simultaneous Freq. & Time Measurements

- Set time to log magnitude (burst envelope)
- Select IF triggering, pre-trigger delay, adjust trigger level, add holdoff (holdoff is often essential for pulsed signals with AM)
- Stabilize acquisition to make all other measurements reliable
- Adjust time record length to see entire burst(s)
  - Use very large number of frequency/time points
Measurement Triggering: RF Bursts

Similar Triggering for “Live” & Recorded Signals

Holdoff establishes unique trigger event

Playback IF level trigger with pre/post trigger delay sets trigger point or reveals timing of trigger event and associated events
Simultaneous Freq. & Time Meas.
Measure and Verify

Frequency & Time Measurements

• Center frequency, occupied bandwidth
• Amplitude--average, and variations during burst (transients, drift)
• Turn-on & turn-off behavior, on/off ratio
• Burst length, duty cycle, unanticipated frequency/time variations
• Band power measurements
• Occupied bandwidth marker (adjust for desired power %, but use carefully on signals with varying sideband energy)
On/Of Transitions & Timing
Time-Gated Spectrum Measurements

**Time-Gating Setup** (example: measuring preamble)
- Set main time length to approx. 5 symbol times
- Enable gating, set gate length for desired signal segment and RBW, then set gate length equal to the “OFDM symbol time” to see preamble sym.
- Set initial gate delay (beginning of time gate) to match pre-trigger delay

**Select Appropriate Gate Windows (RBW Shape)**
- Flat Top for amplitude accuracy, Uniform for frequency resolution

**Time-Gated CCDF**
- Preamble vs. data
Downlink Preamble

- 1 Symbol of QPSK
- Every third carrier, 1/3 of 852 active carriers
- No Pilots

284 active QPSK carriers

- Gate Length = 1 Symbol Time
- Uniform Window for Maximum Frequency Resolution

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Resolving All Carriers in Preamble
Measure and Verify

Time-Gated Spectrum Measurements

- Spectrum vs. time, any spectrum artifacts
- Power changes during burst, CCDF variations
- Carrier structure, missing or extra carriers, energy at exact CF
- Sidelobes (part of signal, not ACP), symmetry
- Frequency accuracy, carrier spacing
- Spurious, interference
- Flatness, tilt/ripple
- Preamble length, structure
- Confirm sampling factor, guard interval
Amplification Problems--Gain Compress.

Before Amplification

After Amplification

Use Time-Gated CCDF to Investigate Different Zones & Preamble
Amplification Effects

Measured Here and With Advanced Demodulation Operations

Gain Drift
• ADC reference changes with thermal effects
• Amplifier gain changes with temperature
• Power supply effects (sag/surge with loads)

Transients (usually occur at beginning of bursts)
• Fast thermal
• Short term power supply instability
• Oscillator instability (power supply/other couplings)
Other Meas. Before Digital Demodulation

Time Capture
- Reduce uncertainty by analyzing known signal (useful during transition to digital demodulation)
- Provides for “real-time” & overlapped analysis
- Identify patterns not otherwise seen
- Capture 2-10 bursts (generally avoid very large captures)

Spectrogram
- See entire burst in frequency and time on one display
- Find subtle patterns, errors

Find Problems Even if Demod. not yet Possible
- Example: Power problem could be seen in demodulation mode, but malformed pilots or preamble prevent demodulation--measure in vector mode
Spectrogram of Uniform Signal
Spectrogram of Non-Uniform Signal
Meas. & Troubleshooting Sequence

Frequency, Frequency & Time
Get basics right, find major problems

Basic
Digital Demod
Signal quality numbers, constellation, basic error vector measurements

Advanced & Specific Demod
Find specific problems & causes

Set up demod & displays
Constellation
Error Summary
Error vector spectrum
Error vector time

Cross-domain & cross-measurement links
Parameter adjustment
More time capture
Two Types of Demod Measurements

Two types of measurements

- “Uniform zone” similar to traditional OFDM, one modulation format and power level used over the entire permutation zone.
- “Data burst” uses definitions made by the user through the subchannel-by-symbol grid on the “Zone definition” tab.

Results are the same, except “Data Burst” mode also provides “Data Burst Summary” results

Uses

- Uniform zone analysis for component manufacturers (Amps, Repeaters, Antennas, etc.) and anyone not dealing with the baseband DSP
- Data Burst analysis for others
Digital Demodulation--Basic Setup

Uniform Zone Measurement

Data Burst Analysis Not Used
Basic Demodulation Results
Initial Demodulation Results

Constellation
• Successful demodulation?
• Expected modulation type(s)?
• Indications of error?

Symbols/Errors Table
• Relative constellation error (RCE) = EVM of data and pilot carriers
• Pilot & common pilot errors (CPE)
• I/Q errors including gain imbalance, quadrature error, delay mismatch
• Carrier frequency error, symbol clock error
Basic Demodulation

Manual Selection of Demod Type Incorrect, But Successfully Locked to Pilots
Data Burst Analysis

Manually Define and Select Zones or use Map File

Select any Zone or Combination, with or without FCH
Linking Vector and Demod Measurements
Multi-Format Constellation

Overlaid BPSK, QPSK, 16QAM, 64QAM
Color Coding Reveals Signal Structure
Initial Demodulation Results (cont.)

Error Vector Spectrum
- All symbols shown on Y-axis for each carrier on X-axis
- All-symbol average for each carrier is shown
- Examine for patterns/trends by carrier, differences between carriers & pilots
- Spurs will affect individual or few carriers, for all symbols

Error Vector Time
- All carriers shown on Y-axis for each symbol on X-axis
- All-carrier average for each symbol is shown
- Examine for patterns or changes according to symbol (time)
- Impulsive errors (DSP, interference, clocks, power) will affect all carriers for an individual symbol or group of symbols
Error Vector Spectrum

All Carriers, 2 Data Bursts

Zoomed
Initial Demodulation Results (cont.)

Coupled Markers

- Identify a symbol by time or frequency or error magnitude
- Link a symbol across time and frequency domains, and between different display types
- Link error peaks to constellation points, amplitude values, specific carriers, time points in a burst, as a way to pinpoint error mechanism
- Identify specific time instant or frequency to examine with advanced & specific demodulation techniques (next)

Change Measurement & Display Parameters Without Taking New Data

Use Time Capture to Provide Consistent Signal & Error Behavior
### Understanding IQ Errors in OFDM

**“Effects of physical layer impairments on OFDM systems”**
RF Design Magazine
http://rfdesign.com/mag/radio_effects_physical_layer/

<table>
<thead>
<tr>
<th>Impairment</th>
<th>OFDM</th>
<th>SCM OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>IQ gain balance</td>
<td>State spreading (uniform/carrier)</td>
<td>Distortion of constellation</td>
</tr>
<tr>
<td>IQ quadrature skew</td>
<td>State spreading (uniform/carrier)</td>
<td>Distortion of constellation</td>
</tr>
<tr>
<td>IQ channel mismatch</td>
<td>State spreading (nonuniform/carrier)</td>
<td>State spreading</td>
</tr>
<tr>
<td>Uncompensated frequency error</td>
<td>State spreading</td>
<td>Spinning constellation</td>
</tr>
<tr>
<td>Phase noise</td>
<td>State spreading (uniform/carrier)</td>
<td>Constellation phase arcing</td>
</tr>
<tr>
<td>Nonlinear distortion</td>
<td>State spreading</td>
<td>State Spreading (may be more pronounced on outer states)</td>
</tr>
<tr>
<td>Linear distortion</td>
<td>Usually no effect (equalized)</td>
<td>State spreading if not equalized</td>
</tr>
<tr>
<td>Carrier leakage</td>
<td>Offset constellation for center carrier only (if used)</td>
<td>Offset constellation</td>
</tr>
<tr>
<td>Frequency error</td>
<td>State spreading</td>
<td>Constellation phase arcing</td>
</tr>
<tr>
<td>Amplifier droop</td>
<td>Radial constellation distortion</td>
<td>Radial constellation distortion</td>
</tr>
<tr>
<td>Spurious</td>
<td>State spreading or shifting of affected subcarrier</td>
<td>State Spreading, generally circular</td>
</tr>
</tbody>
</table>

Table 1. A variety of common analog signal impairments and their effect on both OFDM signals and single-carrier modulations.
Meas. & Troubleshooting Sequence

Frequency, Frequency & Time
Get basics right, find major problems

Basic Digital Demod
Signal quality numbers, constellation, basic error vector measurements

Advanced & Specific Demod
Find specific problems & causes

Demod by carrier or symbol or both
Select pilot tracking types
Select carrier, timing
Preamble (equalization) analysis

Cross-domain & cross-measurement links
Demod parameter adjustments
More time capture

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Advanced & Specific Digital Demod.

Demod Specific Data Bursts
Demod By Specific Carriers
Demod by Specific Symbols
Enable/Disable Pilot Tracking of Amplitude, Phase, Timing
Data Sub-Carrier Manual Select
Symbol Timing Adjust
Equalizer Training Select (preamble only, preamble + data)
Preamble Error Measurements
X & Y-Axis Scaling (display zoom; actual demod results are not changed)
Data Burst Analysis

Specific to Time (Symbol index) and Frequency (Logical Subcarrier)
Uplink Analysis of Single Data Burst

Non-Uniform Signal, Single Data Burst

DL-PUSC bursts are rectangular
UL-PUSC bursts are wrapped
New Data Type “Data Burst Info”

![Graph showing data burst info]

<table>
<thead>
<tr>
<th>DataBurst</th>
<th>ModFmt</th>
<th>Size</th>
<th>Pwr(dB)</th>
<th>RCE(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;FCH&gt;</td>
<td>QPSK</td>
<td>4</td>
<td>-0.00112</td>
<td>-50.411</td>
</tr>
<tr>
<td>Burst01</td>
<td>QPSK</td>
<td>90</td>
<td>0.00443</td>
<td>-48.5</td>
</tr>
<tr>
<td>Burst02</td>
<td>16QAM</td>
<td>44</td>
<td>0.06639</td>
<td>-49.26</td>
</tr>
<tr>
<td>Burst03</td>
<td>64QAM</td>
<td>30</td>
<td>0.24939</td>
<td>-49.095</td>
</tr>
</tbody>
</table>

Mod Types and Parameters Listed
- Automatic measurement of individual data burst power and error
Pilot Tracking

In OFDMA, **Pilots Change Location and are Not Present for All Symbols**

In OFDMA, **Pilot Tracking can “Break” Demod**
  - Demod relative to incorrect (data) carriers

**Demodulation Is Adjusted During A Subframe**
Demod is Performed Relative to the BPSK Pilots
Some Errors are “Tracked Out” as Demod Follows Pilots

**Tracking Types can be Enabled/Disabled Independently**
  - Amplitude (default is off)
  - Phase (default is on)
  - Timing (default is off)

**Pilot Tracking Reduces Close-In Phase Noise**
Advanced Demodulation Results

Common Pilot Error

- Pilot carriers provide continuous amplitude & phase reference to receiver
- Difference between the measured and ideal pilot subcarrier symbols
- Reveals signal changes during burst
Channel Response from Equalizer

Channel Frequency & Impulse Response Derived From Preamble or Preamble + Data
Relative Subcarrier Power

New Data Type: Channel Frequency Response
Adjacent Difference

- Adjacent subcarrier power difference
- Measured from preamble, every 3rd physical subcarrier, or from selected data, with interpolation
Channel Freq. Resp. Adjacent Difference

A: D1 Ch1 OFDM Eq Ch Freq Resp Adj Diff
   Range: -15 dBm
   Center: 1.00000557813 GHz
   RBW: 11.1562 kHz
   Span: 9.37125 MHz

B: D2 Ch1 OFDM Eq Ch Freq Resp Adj Diff
   Range: -15 dBm
   Center: 1.00000557813 GHz
   RBW: 11.1562 kHz
   Span: 9.37125 MHz

C: Ch1 OFDM Eq Ch Freq Resp Adj Diff
   Range: -15 dBm
   Center: 1.00000557813 GHz
   RBW: 11.1562 kHz
   Span: 9.37125 MHz
Complete Physical Layer Analysis

89600 Series VSA Software (89601A opt. B7Y)

Broad RF Hardware Support

- 89600S VXI-based BW: 36 MHz
- PSA Series spectrum analyzers BW: 10 MHz
- 89650S bundle (PSA opt. 140/122) BW: 40/80 MHz
- Infiniium oscilloscopes BW: 0.5-13 GHz
- ESA Series spectrum analyzers BW: 10 MHz

Demo/Training Mode

- Available without contacting Agilent
- Does not expire
- Limited to supplied recordings
Physical Layer Signal Source Solution

ESG (E4438C) Series Vector Signal Generator With N7615A Signal Studio for 802.16 OFDMA

• Generates WiBro and 802.16e arbitrary waveform files for E4438C (ESG)
• Supports WirelessMAN-OFDMA PHY in IEEE 802.16-2004 and 802.16e standards

Trial Mode/Trial License Available for Software Available Interface for Digital Output
N7615A User Interface: Project Param.

Set OFDMA system parameters

Configure waveform parameters

Signal generator settings
Configuration AWGN settings (requires E4438C option 403)
N7615A User Interface: Downlink

Add multiple zones

Flexible burst configuration (auto or manual)
Resources

eSeminar Reference Page
• Provided at end of this presentation
• Includes link to previous WiMAX eSeminar

Agilent WiMAX Portal
http://www.agilent.com/find/wimax
• WiMAX Ap-Notes (3)
• New OFDMA Ap-Note (available soon)
• Analysis: 89600 opt. B7Y technical overview & demonstration guide
• Signal source: N7615A technical overview
• RF Design article “Effects of Physical Layer Impairments on OFDM Systems”

Trial Version Software (Mark eval. form at conclusion of eSeminar)
• 89600 VSA Software
• N7615A Signal Studio for 802.16 OFDMA