Vector Signal Analysis Workshop

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See through the complexity.
89601B Vector Signal Analysis Workshop

Agenda

➢ Introduction to technologies adopted in modern wireless systems
  – Digital modulation fundamentals
  – IQ Modulator
  – Channelization (FDMA, TDMA, CDMA)
  – Concepts of CDMA
  – Concepts of OFDM
  – Wireless communications standards

➢ Modulation quality measurements and troubleshooting
  – Vector Signal Analyzers
  – Time domain analysis
  – Frequency domain Analysis
  – Analog demodulation
  – Digital demodulation
  – Digital radio troubleshooting
Wireless Evolution 1990 - 2011

Increasing efficiency, bandwidth and data rates

802.11b
802.11a
802.11g
802.11h
802.11n
802.16d Fixed WiMAX™
802.16e Mobile WiMAX™
WiBRO
802.11ac
802.11ad

GSM
IS-136 TDMA
PDC
IS-95A cdma

HSCSD
GPRS
iMode
IS-95B cdma

W-CDMA FDD
W-CDMA TDD
TD-SCDMA LCR-TDD
E-GPRS EDGE
IS-95C cdma2000

HSDPA/HSUPA FDD & TDD
EDGE Evolution
1xEV-DO Release 0 ▶ A ▶ B

HSPA+
LTE FDD & TDD Rel-8/9
802.16e Mobile WiMAX™

LTE-Advanced Rel 10 and Beyond
WiMAX 802.16m
802.16d Fixed WiMAX™
Drivers for the wireless evolution

**Demand for:**
- Higher System Capacity and Quality of Service
- Increase availability of data services (higher bit rates)
- Greater Information Security
- Increased System Availability

**Limited by:**
- Available Bandwidth
- Permissible Power
- Inherent Noise Level

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- **Market Demands**
- **Physics & Regulatory Restrictions**
- **Engineers!**
The Fundamental Trade-Off

Simple Hardware

More Spectrum

Simple Hardware

Complex Hardware

Complex Hardware
The trend in the industry

Analog Modulations
AM/FM

Vector Modulations
PSK/QAM/FSK

Time-variant Vector Modulations
TDMA
GSM
Bluetooth

"Coded" Vector Modulations
CDMA/OFDM
WCDMA
802.11a Wlan
WiMAX
DVB-T
LTE

MW Radio Links
Introduction to Digital Modulation
Transmitting Information . . . (Analog or Digital)

Modify a Signal
"Modulate"

Detect the Modifications
"Demodulate"

Any *reliably detectable* change in signal characteristics can carry information
Part A --- Fundamental Modulation Types:

- Amplitude
- Frequency or Phase
- Both Amplitude and Phase
Vector Modulation:

Quadrature modulator
- Two mixers in phase quadrature
- I (in-phase) & Q (quadrature) signals
- Use I and Q signals to map to any point in signal space (amplitude and phase)
- The IQ position (Symbol State) represents a bit or bit pattern (multiple bits)

- Use to create higher order modulation schemes
  - e.g. 64-QAM (64 amplitude and phase states)

\[
\begin{align*}
\text{Mag} & \quad M = \sqrt{I^2 + Q^2} \\
\text{Phase} & \quad \phi = \arctan\left(\frac{Q}{I}\right)
\end{align*}
\]
Two General Shapes of Vector Modulation:

Rectangular Shapes

- 16-QAM

Many other formats

Circular Shapes

- 8-PSK
  Symbol spacing: $\pi/4=45^\circ$

- 16-PSK
  Symbol spacing: $\pi/8=22.5^\circ$

QPSK #1
(even symbol times)

QPSK #2
(odd symbol times)

$\pi/4$QPSK
(no zero crossings)

Many other formats
Identify Parameters of Modulation:

<table>
<thead>
<tr>
<th>Modulation Scheme</th>
<th>Amplitude Variation</th>
<th>Phase Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>Yes</td>
<td>None or very little</td>
</tr>
<tr>
<td>FM or PM</td>
<td>None or very little</td>
<td>Yes</td>
</tr>
<tr>
<td>Vector Modulation</td>
<td>Almost Always *</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* MSK is one vector modulation format where there is little or no Amplitude variation
SCM Technology
SCM=Single Carrier Modulation

- Direct evolution from analog modulation
- Bits are first mapped onto symbols taken from a predefined alphabet

ANALOG: Faithful reproduction of signal at RX?
DIGITAL: Decide which symbol was sent from a pre-defined alphabet
A SCM Transmitter Block Diagram

Note:

Occupied Spectrum is related to I/Q bandwidth (i.e. to information rate), and baseband filter shaping
The rectangular coder

Mapping bits onto analog waveforms

...0 1 0 0 1 1 0 0...
Channelization
Multiplexing or "Channelization"

Definition:
Any characteristic of a signal or system which can be varied to separate different users of the frequency spectrum

Purpose:
Allow different users to communicate over the same frequency spectrum
Signal Properties

Here’s a list of physical properties of a signal that can be used to separate users sharing the same RF spectrum:

- Frequency
- Time
- Space
- Code
Frequency

User #1
User #2
User #3
FDMA Frequency Division Multiple-Access
Traditional simple solution to let two users talking on the same frequency:

TIME DIVISION DUPLEX (TDD)
Multiple transmitters are divided in time for multiple access to the same frequency.

**TDMA** Time Division Multiple-Access

1. Time axis is divided into timeslots. N timeslots are grouped in a repeating structure called **frame**.
2. Typically, one user can use only one timeslot per frame.
3. The transmitter has to switch on and off periodically.
Typical digital radios have only one tranceiver section, i.e. they cannot transmit and received *at the same time*.

Usually, a radio uses two different frequencies to transmit and to receive.

The timeslot/frame structure idea is used both on the transmitting and receiving channels, but the two time axes are not aligned.

The tranceiver has time to switch from the transmission mode to the reception mode.
Switch on and off of the power amp may cause distortion problems and spectral regrowth.
Space Division Multiple Access
the cellular approach

Small coverage areas
Low power transmitters
Frequency re-use
Central control
Over-the-air mobile control
Cell to cell handoffs
Frequency reuse

BS₁

D

BS₂

Wanted signal in cell 1
Signal from BS₂ is interference in cell 1

Wanted signal in cell 2
Signal from BS₁ is interference in cell 2
Frequency Reuse

GSM uses cell concept

One cell covers a small part of the network

The network has many cells

A frequency used in one cell can be used in other cells

This is known as

Frequency Re-use

Co-Channel (Re-use) Cells
Code Division Multiple Access (CDMA)

- a code is associated to every channel

- several channels can overlap on the same bandwidth
CDMA Paradigm Shift

Traditional FDMA/TDMA are capacity-limited

- Given N timeslots per frame and K frequency channels, maximum number of users is KN;
- To increase the number of users in the system, frequency reuse is used

CDMA systems are interference-limited.

- There is not a hard limit on capacity;
- Each new user in the system just adds some interference to all others already present;
Cellular Frequency Reuse Patterns

FDMA Reuse

CDMA Reuse
## Most used digital formats

<table>
<thead>
<tr>
<th>Modulation format</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSK, GMSK</td>
<td>GSM, CDPD</td>
</tr>
<tr>
<td>BPSK</td>
<td>Deep space telemetry, cable modems</td>
</tr>
<tr>
<td>QPSK, $\frac{\pi}{4}$ DQPSK</td>
<td>Satellite, CDMA, NADC, TETRA, PHS, PDC, LMDS, DVB-S, cable (return path), cable modems, TFTS</td>
</tr>
<tr>
<td>OQPSK</td>
<td>CDMA, satellite</td>
</tr>
<tr>
<td>FSK, GFSK</td>
<td>DECT, paging, RAM mobile data, AMPS, CT2, ERMES, land mobile, public safety</td>
</tr>
<tr>
<td>8, 16 VSB</td>
<td>North American digital TV (ATV), broadcast, cable</td>
</tr>
<tr>
<td>8PSK</td>
<td>Satellite, aircraft, telemetry pilots for monitoring broadband video systems</td>
</tr>
<tr>
<td>16 QAM</td>
<td>Microwave digital radio, modems, DVB-C, DVB-T</td>
</tr>
<tr>
<td>32 QAM</td>
<td>Terrestrial microwave, DVB-T</td>
</tr>
<tr>
<td>64 QAM</td>
<td>DVB-C, modems, broadband set top boxes, MMDS</td>
</tr>
<tr>
<td>256 QAM</td>
<td>Modems, DVB-C (Europe), Digital Video (US)</td>
</tr>
</tbody>
</table>
Wireless Propagation Channel: interference is given by multiple reflections

In a wireless environment, main limitation is interference caused by multipath
Channel delay spread and bit rate

- $\tau$ is the delay spread for the propagation channel
- $T_s$ is the symbol period for the transmission

**A)**

$\tau < T_s$

Reception Ok, with equalization

**B)**

$\tau > T_s$

Reception is Distorted, NOT recoverable

High bit-rate streams are sensitive to irreducible distortion due to multipath
Data Rates used by most common radio technologies

- GSM: 270Kbps (33.8Kbps per user)
- Private Mobile Networks: ex. TETRA: 36Kbps
- UMTS: up to 2Mbps → but uses CDMA technology
- Bluetooth: roughly 700 Kbps → but uses frequency hopping
- Digital Radio Links: hundreds of Mbps → but point-to-point
- Wireless LAN: 1Mbps/11Mbps/54Mbps/…
- Digital TV: MPEG stream at >20 Mbps → OFDM
- LTE: up to 173 Mbps
How Do Current Technologies deal with Multipath?

Two main technologies:

• Wide-band Code Division Multiple Access (W-CDMA/HSDPA)
  – 3G cellular networks (UMTS)

• Orthogonal Frequency Division Multiplexing (OFDM)
  – Wireless Connectivity: 802.11a (W-LAN)
  – Digital TV and audio broadcast: DVB-T and DAB
  – Broadband Wireless Access: 802.16 (WiMAX)
  – 4G cellular networks (LTE)
Spread Spectrum systems: advantages

Protection against multipath interference
Protection against narrowband interfering sources
Multiple users on the same frequency band
Privacy
Low probability of interception (military use)
Traditional approach vs spread spectrum systems

Data stream

R, bit/s
1-111

Data stream

R, bit/s
1-111

Spreading code

1-1-11 (chips)

X

+1 -1 -1+1 | -1+1+1 -1 | +1 -1 -1+1 | +1 -1 -1+1

4*R, chip/s

4*R, chip/s

I

Q

~R

~4R

frequency
Spreading codes are orthogonal codes

\[ C_1 = 1 \quad 1 \quad 1 \quad 1 \]
\[ C_2 = 1 \quad -1 \quad 1 \quad -1 \]
\[ C_3 = 1 \quad 1 \quad -1 \quad -1 \]
\[ C_4 = 1 \quad -1 \quad -1 \quad 1 \]

\[ C_5 = 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \]
\[ C_6 = 1 \quad -1 \quad 1 \quad -1 \quad 1 \quad -1 \quad 1 \quad -1 \]
\[ C_7 = 1 \quad 1 \quad -1 \quad -1 \quad 1 \quad 1 \quad -1 \quad -1 \]
\[ C_8 = 1 \quad -1 \quad -1 \quad 1 \quad -1 \quad 1 \quad 1 \quad -1 \]

\[ C_k \cdot C_k \neq 0 \]
\[ C_k \cdot C_j = 0, \; k \neq j \]

Examples:

\[
\begin{pmatrix}
1 \\
1 \\
1 \\
1
\end{pmatrix} \cdot \begin{pmatrix}
1 \\
1 \\
1 \\
1
\end{pmatrix} = +4 \\
\begin{pmatrix}
1 \\
-1 \\
-1 \\
1
\end{pmatrix} \cdot \begin{pmatrix}
1 \\
-1 \\
-1 \\
1
\end{pmatrix} = 0
\]
The Code Domain

Interference Sources

- CDMA Transmitter
  - Baseband Data
  - Encoding & Interleaving
  - Walsh/OVSF Spreading

- CDMA Receiver
  - Walsh/OVSF Correlator
  - Decode & De-Interleaving
  - Baseband Data

- KTBF function
- Spurious Signals
- Spread BW
- Spread BW

- Background Noise
- External Interference
- Other Cell Interference
- Other User Noise
Code Orthogonality allows overlapping multiple channels/services on same band

Data stream 1

Data stream 2

Spreading code, $c_1$

Spreading code, $c_2$

$\begin{align*}
    & b_1 \\
    & \times
    & b_1 \cdot c_1
    & \sum
    & b_1 \cdot c_1 + b_2 \cdot c_2
    & \text{IQ mod}
\end{align*}$

$\begin{align*}
    & b_2 \\
    & \times
    & b_2 \cdot c_2
\end{align*}$
Receiver side:
Orthogonality allows code separation

\[ b_1 \cdot c_1 \cdot c_1 + b_2 \cdot c_2 \cdot c_1 = 0 \]

\[ b_1 \cdot c_1 \cdot c_2 + b_2 \cdot c_2 \cdot c_2 = 0 \]
How CDMA systems counteract multipath?

- CDMA signals are protected against multipath interference by code orthogonality.
- CDMA correlator receiver synchronizes with the strongest signal received.
- Other replicas of the transmitted signals that arrive with delays result to be un-correlated, and so are discarded.
Other approach: Frequency Division Multiplexing

• Given a propagation channel affected by multipath, irreversible interference happens when multipath delay is larger than bit period

• IDEA: Divide the total information rate, $R$, into $N$ subchannels with rates $R/N$ where the bit period $1/(R/N)$ is much larger than the multipath delay (NO ISI).
From Single Carrier Modulation (SCM) to Frequency Division Multiplexing (FDM)

- A single high-rate information stream modulated on a single carrier is too sensitive to multipath,
- IDEA: divide it in multiple lower-rate information streams!
FDM Bandwidth Efficiency Example: N=3

\[ BW_{TOT} > 2B \]

Not very efficient!
Advance: from FDM to Orthogonal FDM (OFDM)

- If the sub-carrier frequencies are chosen from an orthogonal set, individual sub-bands can be partially super-imposed.

What does it mean that frequencies are orthogonal??
But also sinewaves at different frequencies can be orthogonal...

Period = \( NT, F = \frac{1}{NT} \)

\( F_1(t) = \sin(2\pi F t) \)

\( F_2(t) = \sin(2\pi \times 2F t) \)

\( F_3(t) = \sin(2\pi \times 3F t) \)

\( F_1, F_2, F_3 \) are orthogonal!
Spectrum has a Sin(x)/x Shape
OFDM: Orthogonal Carriers

- Closely spaced carriers overlap
- Nulls in each carrier’s spectrum land at the center of all other carriers for Zero Inter-Carrier Interference
OFDM – Basic Concepts

- **bits** → map onto constellation
- load complex values into frequency bins
- carrier number: \([-26-25-24 \ldots -3 -2 -1 0 +1 +2 +3 \ldots +2 +2 +2\]
- do inverse FFT to create time waveform
- transmit as 1 symbol
- repeat

1011

\[0.29 + j0.85\]
The constellation shows the magnitude and phase of the carrier.

Each FFT bin corresponds to a single carrier.
IFFT Used to Create TX Signal
Multiple Carrier example

there are two modulations: BPSK for the Pilots and BPSK, QPSK, 16 or 64 QAM for the data carriers
Receiving an OFDM Signal

FFT

Tu
Nulls are *On Bin* if the Tone is *On Bin*

FFT Bin Spacing is $1/T$
Loss of Carrier Orthogonality

Frequency Errors Cause “Leakage” or Inter-Carrier Interference

FFT Bin Spacing is $1/T$
Receiver FFT

Phase Noise Also Causes “Leakage” Inter-Carrier Interference

FFT Bin Spacing is 1/T
OFDM Technology Review
Conclusion

• Advantages:
  – Robust to multipath interference
  – Convenient implementation using FFT algorithms

• Disadvantages:
  • Sensitive to phase noise problems
  • Sensitive to frequency accuracy problems
  • Sensitive to timing issues
OFDM vs. Single Carrier Modulation

Frequency Domain View

1 carrier

\[ BW = \text{SymRate}(1 + \alpha) \]

Adj Chan = Distortion

N carriers

\[ BW = \text{#carriers} \times \text{spacing} \]

Adj Chan = Normal Rolloff
## Comparing OFDM Systems

<table>
<thead>
<tr>
<th></th>
<th><strong>DVB-T</strong></th>
<th><strong>DAB</strong></th>
<th><strong>802.11A</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BW</strong></td>
<td>8 MHz</td>
<td>1.5 MHz</td>
<td>18 MHz</td>
</tr>
<tr>
<td><strong>Carriers</strong></td>
<td>1705</td>
<td>1536</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>6817</td>
<td>384</td>
<td>4 (sync)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>192</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>768</td>
<td></td>
</tr>
<tr>
<td><strong>Carrier Spacing</strong></td>
<td>4.464 kHz</td>
<td>1 kHz</td>
<td>312.5 kHz</td>
</tr>
<tr>
<td></td>
<td>1.116 kHz</td>
<td>4 kHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 kHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 kHz</td>
<td></td>
</tr>
<tr>
<td><strong>Pilot/Sync Mod.</strong></td>
<td>BPSK</td>
<td>QPSK</td>
<td>BPSK</td>
</tr>
<tr>
<td><strong>Data Modulation</strong></td>
<td>QPSK</td>
<td>DQPSK</td>
<td>BPSK, QPSK</td>
</tr>
<tr>
<td></td>
<td>16 QAM</td>
<td></td>
<td>16 QAM</td>
</tr>
<tr>
<td></td>
<td>64 QAM</td>
<td></td>
<td>64 QAM</td>
</tr>
</tbody>
</table>
DVB-T2 Technical Summary

• Two modes: Single PLP and Multiple PLP (Physical Layer Pipe)
  – Each PLP has an input stream and can be independently coded and modulated
    • Modulation scheme: QPSK, 16QAM, 64QAM, 256QAM with constellation rotation
    – Up to 255 PLPs
• OFDM in 1.7/5/6/7/8/10MHz bandwidth
  – Modes: 1k, 2K, 4k, 8k, 16k, 32k
  – Guard Interval: 1/128, 1/32, 1/16, 19/256, 1/8, 19/128, 1/4
• PAPR reduction used
• Support both terrestrial and mobile services
IEEE 802.xx – A family of Wireless Standards

**Metro Area Network (WMAN)**
- IEEE 802.16-2004 (Fixed)
- IEEE 802.16e (Mobile)

**Local Area Network (WLAN)**
- **WLAN** IEEE 802.11a/b/g/h/i/j/n
- **Wi-Fi** IEEE 802.11a/b/g

**Personal Area Network (WPAN)**
- **UWB** IEEE 802.15.3a
- **Bluetooth** IEEE 802.15.1.1a
- **ZigBee** IEEE 802.15.4
<table>
<thead>
<tr>
<th></th>
<th>802.15.3a UWB</th>
<th>802.15.1 Bluetooth</th>
<th>802.11b WLAN</th>
<th>802.11a WLAN</th>
<th>802.11g WLAN</th>
<th>802.16-2004 WiMAX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Freq</strong></td>
<td>6GHz</td>
<td>2.4GHz</td>
<td>2.4GHz</td>
<td>5GHz</td>
<td>2.4GHz</td>
<td>2-11GHz</td>
</tr>
<tr>
<td><strong>Transmission Speed (Mbps)</strong></td>
<td>100+</td>
<td>1</td>
<td>11</td>
<td>54</td>
<td>54</td>
<td>70</td>
</tr>
<tr>
<td><strong>Effective Range (meters)</strong></td>
<td>10</td>
<td>10</td>
<td>100</td>
<td>60</td>
<td>100</td>
<td>4-6 miles (up to 20)</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>1.5GHz</td>
<td>1.5MHz</td>
<td>18MHz</td>
<td>18MHz</td>
<td>18MHz</td>
<td>1.7–20MHz</td>
</tr>
<tr>
<td><strong>Modulation Type</strong></td>
<td>OFDM or Pulsed</td>
<td>FM, hopping</td>
<td>CCK</td>
<td>OFDM + BPSK thru 64QAM</td>
<td>OFDM + BPSK thru 64QAM</td>
<td>OFDM</td>
</tr>
<tr>
<td><strong>Power Efficiency</strong></td>
<td>High+</td>
<td>High</td>
<td>Med</td>
<td>Low</td>
<td>Low/Med</td>
<td>Not battery powered</td>
</tr>
</tbody>
</table>
Contrasting OFDMs -- 802.11a vs. 802.16 WiMAX

802.11a
52 carriers, 312.5 kHz spacing

802.16
200 carriers, 90 kHz spacing

200 carriers, 6.7 kHz spacing

A smaller sub-carrier spacing gives greater immunity to multipath fading

BPSK, QPSK, 16QAM, 64QAM

4 BPSK Pilots

8 BPSK Pilots

802.11a (18 MHz)

802.16 (20 MHz)

802.16 (1.5 MHz)

10 MHz
7.0 MHz
3.5 MHz
### 802.16e OFDMA* “WiMAX mobile”

*OFDMA = Orthogonal Frequency Division MULTIPLE ACCESS

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Data Rate</th>
<th>Mobile/Fixed</th>
<th>FFT</th>
<th>Carriers</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 - 6 GHz</td>
<td>≤ 70 Mbps</td>
<td>Mobile (60-100 kmph)</td>
<td>2048</td>
<td>1680</td>
<td>~11 kHz</td>
</tr>
<tr>
<td>2 - 6 GHz</td>
<td>≤ 70 Mbps</td>
<td>Mobile (60-100 kmph)</td>
<td>1024</td>
<td>840</td>
<td>~11 kHz</td>
</tr>
<tr>
<td>2 - 6 GHz</td>
<td>≤ 70 Mbps</td>
<td>Mobile (60-100 kmph)</td>
<td>512</td>
<td>408</td>
<td>~11 kHz</td>
</tr>
</tbody>
</table>

**802.16e (20 MHz)**

- 166-240 BPSK Pilots, variable location
- QPSK, 16QAM, 64QAM

**802.16e (10 MHz)**

- 83-120 Pilots

**802.16e (5 MHz)**

- 42-60 Pilots

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**Agilent Technologies**

Digital Radio Technologies and Measurements - 2011
LTE PHY Layer Characteristics

**Service Goals**
- Data transfer rate (max)
  - DL: 300Mbps, UL: 75Mbps
- Users/cell (max)
  - 200 active
- Mobility
  - 0-15 km/h best performance
  - 15-120 km/h high performance

**Physical Layer Details**
- Duplex Modes
  - FDD, TDD
- Frequency assignments
  - 840, 940, 1750, 1930, 2150, 2570 MHz
- Channel bandwidths
  - FDD: 1.4, 3, 5, 10, 15, 20 MHz
- DL transmission
  - OFDM using QPSK, 16QAM, 64QAM
- UL transmission
  - SC-FDMA using QPSK, 16QAM
- Number of carriers
  - 72 to 1200
- Carrier spacing
  - Fixed 15 kHz (7.5 kHz extended CP)
- Additional mod types
  - Zadaoff-Chu, BPSK (CMD)
## Comparing LTE and LTE-Advanced to IMT-Advanced

<table>
<thead>
<tr>
<th></th>
<th>LTE</th>
<th>LTE-Advanced</th>
<th>IMT-Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak Data Rate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>300 Mbps</td>
<td>1 Gbps</td>
<td>100 Mbps (high mobility)</td>
</tr>
<tr>
<td>UL</td>
<td>75 Mbps</td>
<td>500 Mbps</td>
<td>1 Gbps (low mobility)</td>
</tr>
<tr>
<td><strong>Peak Spectrum Efficiency [bps/Hz]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>15</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>UL</td>
<td>3.75</td>
<td>15</td>
<td>6.75</td>
</tr>
<tr>
<td><strong>Tx Bandwidth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UL &amp; DL</td>
<td>Up to 20 MHz</td>
<td>Up to 100 MHz</td>
<td>Up to 40 MHz</td>
</tr>
<tr>
<td><strong>MIMO (spatial multiplexing)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>Up to 4x4</td>
<td>Up to 8x8</td>
<td>Up to 4x4</td>
</tr>
<tr>
<td>UL</td>
<td>N/A</td>
<td>Up to 4x4</td>
<td>Up to 2x4</td>
</tr>
</tbody>
</table>
What’s New: LTE-Advanced at a Glance

1. **Carrier aggregation**
   - Support for up to 5 Aggregated Carriers
   - Up to 100 MHz Bandwidth

2. **Enhanced uplink multiple access**
   - Clustered SC-FDMA
   - Simultaneous Control and Data

3. **Higher order MIMO**
   - Downlink 8x8
   - Uplink 4x4
You take new technologies forward.

Agilent clears the way.