Software-based MIMO Channel Emulator

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Outline

• What is channel emulation and why is it critical for MIMO systems?
• Channel modeling standards and technologies
• Channel model statistics
• Channel emulator implementation
Wireless Channel

- Frequency and time variable wireless channel

- Multipath creates a sum of multiple versions of the TX signal at the RX

- Mobility of reflectors and wireless devices causes Doppler-based fading

- Multiple antenna techniques are used to optimize transmission in the presence of multipath and Doppler fading

MIMO=Multiple Input Multiple Output
Multipath and Flat Fading

• In a wireless channel the signal propagating from TX to RX experiences
  - Flat fading
  - Multipath/Doppler fading

Multipath reflections occur in clusters.

-10 dB flat fading component
-15 dB flat fading component

Time
Multiple Antenna Techniques

- **SISO (Single Input Single Output)**
  - Traditional radio

- **MISO (Multiple Input Single Output)**
  - Transmit diversity (STBC, SFBC, CDD)

- **SIMO (Single Input Multiple Output)**
  - Receive diversity, MRC

- **MIMO (Multiple Input Multiple Output)**
  - SM to transmit multiple streams simultaneously; can be used in conjunction with CDD; works best in high SNR environments and channels de-correlated by multipath
  - TX and RX diversity, used independently or together; used to enhance throughput in the presence of adverse channel conditions

- **Beamforming**

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SM = spatial multiplexing
SFBC = space frequency block coding
STBC = space time block coding
CDD = cyclic delay diversity
MRC = maximal ratio combining
SM = Spatial Multiplexing
SNR = signal to noise ratio
MIMO Based RX and TX Diversity

- When 2 receivers are available in a MIMO radio MRC can be used to combine signals from two or more antennas, improving SNR.
- MIMO also enables transmit diversity techniques, including CDD, STBC, SFBC.
- TX diversity spreads the signal creating artificial multipath to decorrelate signals from different transmitters so as to optimize signal reception.

MIMO = multiple input multiple output
SIMO = single input multiple outputs
SM = spatial multiplexing
SFBC = space frequency block coding
STBC = space time block coding
CDD = cyclic delay diversity
MRC = maximal ratio combining
SM = Spatial Multiplexing
SNR = signal to noise ratio
802.11 Modulation

- **11b (DSSS-CCK)** – 1, 2, 5.5, 11 Mbps in 2.4 GHz band
- **11a (OFDM)** – 6, 9, 12, 18, 24, 36, 48, 54 Mbps in 5 GHz band
- **11g** – both 11b and 11a rates in 2.4 GHz band
- **802.11n** – 6 to 600 Mbps in 2.4 and 5 GHz bands
  - MIMO introduces concept of Modulation and Coding Scheme (MCS)
  - Each MCS is determined by modulation, coding rate, # spatial streams, # FEC encoders

Data rate and MCS are automatically selected by the radio based on channel conditions. Above plot shows automatic adaptation of data rate as path loss increases.

MIMO = multiple input multiple output
MCS = modulation coding scheme
## IEEE 802.11a, b, g, n Data Rates

<table>
<thead>
<tr>
<th></th>
<th>20 MHz Channel</th>
<th>40 MHz Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 stream</td>
<td>2 streams</td>
</tr>
<tr>
<td><strong>20 MHz Channel</strong></td>
<td>1, 2, 5.5, 11</td>
<td></td>
</tr>
<tr>
<td><strong>40 MHz Channel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>802.11b</strong></td>
<td>1, 2, 5.5, 11, 11</td>
<td></td>
</tr>
<tr>
<td><strong>802.11a</strong></td>
<td>6, 9, 12, 18, 24, 36, 48, 54</td>
<td></td>
</tr>
<tr>
<td><strong>802.11g</strong></td>
<td>1, 2, 6, 9, 12, 18, 24, 36, 48, 54</td>
<td></td>
</tr>
<tr>
<td><strong>802.11n</strong></td>
<td>6.5, 13, 19.5, 26, 39, 52, 58.5, 65</td>
<td></td>
</tr>
<tr>
<td><strong>802.11n, SGI enabled</strong></td>
<td>7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2</td>
<td></td>
</tr>
<tr>
<td><strong>IEEE 802.11a,b,g,n Data Rates</strong></td>
<td>Data Rate, in Mbps</td>
<td></td>
</tr>
</tbody>
</table>
Validating Radio DSP

- A variety of channel conditions and complex multiple-antenna algorithms for adapting to these conditions make a channel emulator necessary for developing and testing radio DSP.
Channel Modeling

A SISO channel is modeled by a TDL

A MIMO channel is modeled by multiple TDLs with spatially correlated coefficients, each representing a MIMO path

Channel Emulator

Transmitter (Input file)

Fading generators and correlators

Receiver (Output file)

2 x 2 MIMO channel

TDL = tapped delay line
Data Flow Through Emulator

Coefficients (N x M per clock cycle, 1 for each Hij)

Input MIMO streams of I/Q samples

\[ \text{Hij} = \text{tapped delay line with up to 18 taps, depending on the model (A-F)} \]

Number of Hij’s = N x M

= 16 for a 4x4 MIMO channel

4 x 4 MIMO channel

Output MIMO streams of I/Q samples
2 x 2 Channel Emulator Example

Complex Tap Coefficient Generator, k

Tapped Delay Line H_{m,n}

Interpolation to 100 Msps

Rician K-factor

NLOS component

LOS component

802.11n

Complex Coefficients, Tap 1

Complex Coefficients, Tap 2

Complex Coefficients, Tap 18

I, Q @ 100 Msps

100 Msps

Complex Coefficients, Tap k

H_{m,n}

I, Q @ 100 Msps

LOS = line of sight
NLOS = non-line of sight
PDP = power delay profile
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## 802.11n Channel Models A through F

<table>
<thead>
<tr>
<th>Model</th>
<th>Distance to 1&lt;sup&gt;st&lt;/sup&gt; wall (avg)</th>
<th># taps</th>
<th>Delay spread (rms)</th>
<th>Max delay</th>
<th># clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A* test model</td>
<td>1</td>
<td>0</td>
<td>0 ns</td>
<td>0 ns</td>
<td>0</td>
</tr>
<tr>
<td>B Residential</td>
<td>5 m</td>
<td>9</td>
<td>15 ns</td>
<td>80 ns</td>
<td>2</td>
</tr>
<tr>
<td>C small office</td>
<td>5 m</td>
<td>14</td>
<td>30 ns</td>
<td>200 ns</td>
<td>2</td>
</tr>
<tr>
<td>D typical office</td>
<td>10 m</td>
<td>18</td>
<td>50 ns</td>
<td>390 ns</td>
<td>3</td>
</tr>
<tr>
<td>E large office</td>
<td>20 m</td>
<td>18</td>
<td>100 ns</td>
<td>730 ns</td>
<td>4</td>
</tr>
<tr>
<td>F large space</td>
<td>30 m</td>
<td>18</td>
<td>150 ns</td>
<td>1050 ns</td>
<td>6</td>
</tr>
</tbody>
</table>

* Model A is a flat fading model; no delay spread and no multipath
Test Scenarios

Certification

Downlink channel impairments

Base Station Emulator

2-way test with 2 or more DUTs

Bi-directional channel modeling

MIMO OTA (over the air) test

Base Station Emulator

Downlink OTA channel emulator

OTA = over the air
DUT = device under test
LTE Test Configuration Example

- Primary antenna for transmit and receive functions
- Secondary antenna for MIMO and receive diversity functions
- Downlink 2x2 and 4x2 transmit diversity
- Downlink 2x2 and 4x2 spatial multiplexing
Geometry Based Stochastic Models

Work being done by
- 3GPP – RAN 4
- COST 2100 - Sub Working Group 2.2
- CTIA

Source: 3GPP R4-103856
### Outdoor Channel Models from 3GPP/3GPP2

Source: 3GPP TR 25.996 V9.0.0 (2009-12)

<table>
<thead>
<tr>
<th>Model</th>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
<th>Case IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corresponding 3GPP Designator*</td>
<td>Case B</td>
<td>Case C</td>
<td>Case D</td>
<td>Case A</td>
</tr>
<tr>
<td>Corresponding 3GPP2 Designator*</td>
<td>Model A, D, E</td>
<td>Model C</td>
<td>Model B</td>
<td>Model F</td>
</tr>
<tr>
<td>PDP</td>
<td>Modified Pedestrian A</td>
<td>Vehicular A</td>
<td>Pedestrian B</td>
<td>Single Path</td>
</tr>
<tr>
<td># of Paths</td>
<td>1) 4+1 (LOS on, K = 6dB) 2) 4 (LOS off)</td>
<td>6</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

- **Spatial Channel Models (SCM)**
- Fewer taps (paths), but faster Doppler speeds to model high speed trains and other transport
60 GHz IEEE 802.11ad Channel Models

- Living room, conference room, office cubicles
- 60 GHz channel models incorporate
  - Path loss
  - Human-induced shadowing
  - LOS and NLOS environments
  - Clustering, Beamforming, Polarization

Source: IEEE 11-09-0334-08-00ad-channel-models-for-60-ghz-wlan-systems
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Doppler Spectrum – Model F

- Example of Doppler spectrum plots for IEEE 802.11n model F

- Environment velocity is 1.2 km/hr and is modeled on all taps for all models

- Tap 3 for model F includes automotive velocity spike at 40 km/hr

The Doppler spread is 3 Hz at 2.4 and 6 Hz at 5.25 GHz for environment speed of 1.2 km/h
Doppler Spectrum – Model F, Tap 3

FFT-based power estimation using entire long realization

$F_{\text{spike}} = \frac{(40 \text{ km/h}) f_c}{c} = 194.4 \text{ Hz} @ f_c = 5.25 \text{ GHz}$

speed of light
Doppler Spectrum – Model E, Tap 3

Fluorescent light effects at 120, 360, and 600 Hz – harmonics of the power line frequency of 60 Hz
Cumulative Distribution Function (CDF)

- IEEE 802.11n, Model F, CDF for 18 taps

Tap 1 with LOS component
Power Delay Profile (PDP) – Model F

- Power decreases with increasing tap delay.
- Red points are for the normalized PDP under NLOS conditions. Blue points are simulated normalized PDP under LOS conditions.
Channel Impulse Response

- Impulse response, IEEE 802.11n model F
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Software-based Channel Emulator

802.11n 4x4 channel emulator

Sample rate conversion

Channel model statistics viewer

Distortion (AWGN, spurious, phase noise, frequency shift)

Sample rate conversion

File viewer

TDMS file

File viewer

TDMS file

Sample rate conversion

100 Msp

1-4 streams

IQ samples

TDMS file or Linux file set

IQ samples

1-4 streams

100 Msp
Channel Emulator Console

Configure Input
- File: test.tdms
- Streams: 4
- Sample Rate: 80,000 Msp
- Bandwidth: 20.0 MHz

Configure Output
- File: output.tdms
- Streams: 1
- Sample Rate: 100,000 Msp

Play time: 0:45

Configure Channel Model
- Model: E - Large Office
- Carrier frequency: 2450.000 MHz
- TX antenna spacing: 0.5 wavelengths
- RX antenna spacing: 1.0 wavelengths
- Environmental velocity: 1.2 km/hr
- Vehicle velocity: 40.0 km/hr
- Fluorescent light frequency: 60.0 Hz
- LOS present: Yes
- Correlation: Complex

Configure Distortion
- SNR: 15.6 dB
- Frequency shift: 15 ppm
- Phase noise: 1.2 deg. RMS, 3dB @ 10.0 kHz
- Spurious: N/A

National Instruments LabVIEW application
Graphical programming environment

www.octoscope.com
Viewing Input and Output Streams

National Instruments TDMS file view

TDMS = TDM streaming
TDM = technical data management
Waveform Analysis

National Instruments WLAN Toolkit
Channel and Distortion Settings

Channel Model Configuration
- Protocol: 802.11n
- Channel Model: E - Large Office
- LOS present: checked
- Carrier frequency, MHz (2000 - 6000): 2450
- Antenna Spacing (wavelengths):
  - TX: 0.5 (2.9 cm)
  - RX: 1.0 (5.8 cm)
- Correlation: Complex
- Fluorescent Light Frequency, Hz: 60
- Keep seed fixed: unchecked

Distortion Configuration
- Es/No (SNR), dB (-30.0 to +80): 15.6
- Frequency Shift, ppm (-50 to +50): 15
- Phase Noise: checked
- Phase noise 3dB BW, kHz (? to ?): 10
- RMS phase noise, deg (? to ?): 1.2
- IQ imbalance: checked
- Amplitude, dB (? to ?): 2
- Phase, deg (? to ?): 3.5
- # of Spurs (0 to 40): 10
- Spur Levels, dBc (-90.0 to +20.0):
  - Spur Frequencies, MHz (-20.0 to +20.0):
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
  - Spur Levels, dBc (-90.0 to +20.0):
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0
    - 0

Return
Software Operation

- **LabVIEW/Wrapper**
  - Read block to waveform array/file

- **Library** (Windows .dll or Linux .so)
  - Sample rate conversion
  - Apply channel modeling to a block of input samples
  - Add impairments

- **Waveforms can be used for software simulation or hardware playback**

- **Play time reached**
  - or user interrupt

- Append block to waveform array/file

- Close files; done

- LabVIEW/Wrapper

Create a library of waveforms in the graphical LabVIEW environment
- Controlled channel modeling
- Impairments
References

- IEEE, 802.11-03/940r4: TGn Channel Models; May 10, 2004

- Schumacher et al, "Description of a MATLAB® implementation of the Indoor MIMO WLAN channel model proposed by the IEEE 802.11 TGn Channel Model Special Committee", May 2004

- Schumacher et al, "From antenna spacings to theoretical capacities - guidelines for simulating MIMO systems"


- 3GPP 36-521, UE Conformance Specification, Annex B

- 3GPP TR 25.996, "3rd Generation Partnership Project; technical specification group radio access networks; Spatial channel model for MIMO simulations"


- 3GPP TR37.976, MIMO OTA channel models

- IEEE, 11-09-0334-08-00ad-channel-models-for-60-ghz-wlan-systems