802.11n Channel Model Validation

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Outline

• Overview of 802.11n channel models
• Intel’s validation
  – Office environment
  – Delay spread
  – Channel capacity
  – Ricean K factor
• Zyray’s validation
  – Hot spot, large office, and open space
  – Ricean K factor
  – Channel capacity
• Metalink’s validation
  – Office environment
  – Time variation
  – Channel capacity
• Conclusion
802.11n Channel Models

- Extended from Medbo’s SISO models for HIPERLAN/2

**Medbo’s SISO model**

- Cluster decomposition and angle assignment
- Angular power delay profile for all taps
- Integration over all angles for each tap
- Correlation matrixes seen from Rx and Tx for each tap
- Kronecker product of Rx and Tx correlation matrixes
- Correlation matrix for channel matrix entries and for each tap
- Cholesky decomposition
- Generate channel matrix from i.i.d. Gaussian random variables for each tap
Multipath profile seen from receiver

November 2003
Multipath profile seen from transmitter

November 2003
Correlation Matrix on Transmit (Receive) Side

- For 2x2 MIMO channel, transmit (receive) correlation matrix

\[
R_{tx} = \begin{bmatrix}
1 & \rho_{tx12}^* \\
\rho_{tx21} & 1
\end{bmatrix} \quad \quad R_{rx} = \begin{bmatrix}
1 & \rho_{rx12}^* \\
\rho_{rx21} & 1
\end{bmatrix}
\]

- Channel matrix \( H \) for the \( i \)th tap

\[
H(i) = \left[ R_{rx}(i) \right]^{1/2} \left[ H_{iid} \right] \left[ R_{tx}(i) \right]^{1/2}
\]
User Interface

- Simple user interface: No. of antennas, spacing, 2.4/5.2 GHz, channel type
- The model delivers time domain channel impulse response for each Tx/Rx antenna pair.
Intel’s Measurements

- One (typical) office environment
- Distance 5-25 m and RMS delay 23-79 ns
- 2.4 GHz and 5.2 GHz
- 2 inch and 4 inch antenna spacing
- 20,000 measured 4x4 channels and 9 locations.
Measurement Locations
RMS Delay Spread

• Mean and standard deviation of RMS delay spreads in measurements

<table>
<thead>
<tr>
<th></th>
<th>S16—seq. 30</th>
<th>S15—seq. 29</th>
<th>S17—seq. 31</th>
<th>S18—seq. 32</th>
<th>S6—seq. 15</th>
<th>S8—seq. 20</th>
<th>S10—seq. 22</th>
<th>S7—seq. 19</th>
<th>S9—seq. 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_{\text{rms}}) Mean (ns)</td>
<td>23.6</td>
<td>27.4</td>
<td>34.1</td>
<td>38.5</td>
<td>56.5</td>
<td>63.4</td>
<td>67.3</td>
<td>68.2</td>
<td>79.2</td>
</tr>
<tr>
<td>(\tau_{\text{rms}}) STD (ns)</td>
<td>5.5</td>
<td>4.9</td>
<td>6.1</td>
<td>6.2</td>
<td>5.6</td>
<td>6.4</td>
<td>8.0</td>
<td>6.2</td>
<td>9.1</td>
</tr>
</tbody>
</table>

• RMS delay spreads in the models
  - Model C: 30 ns small office
  - Model D: 50 ns typical office
  - Model E: 100 ns large office
1x1 and 4x4 Channel Capacity

- SNR 15 dB; 5.2 GHz band; 20 MHz bandwidth; 4” spacing
- CDF of 1x1 and 4x4 capacity

![Graph showing the CDF of 1x1 and 4x4 channel capacity with various markers and lines representing i.i.d., measured with rms 30.8ns, and model C with rms 30ns.]
Capacity of 4x4 Channels in 5.2 GHz Band

- 4x4 channel with 20 MHz bandwidth and 4” spacing
- SNR 15dB
- Model error is less than 5%

<table>
<thead>
<tr>
<th></th>
<th>Model Capacity (Mbps)</th>
<th>Measured Capacity (Mbps)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model C</td>
<td>315</td>
<td>305</td>
<td>3.4</td>
</tr>
<tr>
<td>Model D</td>
<td>324</td>
<td>312</td>
<td>3.9</td>
</tr>
<tr>
<td>Model E</td>
<td>311</td>
<td>299</td>
<td>4.1</td>
</tr>
<tr>
<td>IID Channel</td>
<td>325</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Capacity of 4x4 Channels in 2.4 GHz Band

- 4x4 channel with 20 MHz bandwidth and 2” spacing
- SNR 15dB
- Model error is less than 15%

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Capacity (Mbps)</th>
<th>Measured Capacity (Mbps)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model C</td>
<td>245</td>
<td>288</td>
<td>14.9</td>
</tr>
<tr>
<td>Model D</td>
<td>285</td>
<td>290</td>
<td>1.6</td>
</tr>
<tr>
<td>IID Channel</td>
<td>325</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MIMO Multiplier in 5.2 GHz Band

- 1x1 and 4x4 channels with 20 MHz bandwidth
- SNR 15dB
- MIMO multiplier is about 3.6
- Models match measurements for both 1x1 and 4x4 channels

<table>
<thead>
<tr>
<th>Model</th>
<th>1x1 Capacity (mbps)</th>
<th>4x4 Capacity (mbps)</th>
<th>4x4 Cap. / 1x1 Cap.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model, Measured</td>
<td>Model, Measured</td>
<td>Model, Measured</td>
</tr>
<tr>
<td>Model C</td>
<td>88, 87</td>
<td>315, 305</td>
<td>3.5, 3.6</td>
</tr>
<tr>
<td>Model D</td>
<td>86, 87</td>
<td>324, 312</td>
<td>3.6, 3.7</td>
</tr>
<tr>
<td>Model E</td>
<td>87, 86</td>
<td>311, 299</td>
<td>3.5, 3.6</td>
</tr>
<tr>
<td>IID Channel Model</td>
<td>87</td>
<td>325</td>
<td>3.7</td>
</tr>
</tbody>
</table>
MIMO Multiplier in 2.4 GHz Band

- 1x1 and 4x4 channels with 20 MHz bandwidth
- SNR 15dB
- MIMO multiplier is about 3.3
- Models match measurements for 1x1 and 4x4 channels
- Model C slightly underestimates 4x4 capacity

<table>
<thead>
<tr>
<th>Model</th>
<th>1x1 Capacity (mbps)</th>
<th>4x4 Capacity (mbps)</th>
<th>4x4 Cap. / 1x1 Cap.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model, Measured</td>
<td>Model, Measured</td>
<td>Model, Measured</td>
</tr>
<tr>
<td>Model C</td>
<td>88, 88</td>
<td>245, 288</td>
<td>2.8, 3.3</td>
</tr>
<tr>
<td>Model D</td>
<td>87, 87</td>
<td>285, 290</td>
<td>3.3, 3.3</td>
</tr>
<tr>
<td>IID Channel Model</td>
<td>87</td>
<td>325</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Measured K Factors

- K factor is less than 0 dB in measured channels
- LOS component is not dominant

<table>
<thead>
<tr>
<th>Set #</th>
<th>Perspective</th>
<th>STA Location</th>
<th>Distance (m)</th>
<th>LOS/NLOS</th>
<th>K factor (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AP</td>
<td>S1</td>
<td>3</td>
<td>LOS</td>
<td>-3.56</td>
</tr>
<tr>
<td>1</td>
<td>STA</td>
<td>S1</td>
<td>3</td>
<td>LOS</td>
<td>-6.24</td>
</tr>
<tr>
<td>2</td>
<td>STA</td>
<td>S2</td>
<td>19</td>
<td>NLOS</td>
<td>-∞</td>
</tr>
<tr>
<td>3</td>
<td>AP</td>
<td>S4</td>
<td>11</td>
<td>NLOS</td>
<td>-3.86</td>
</tr>
<tr>
<td>4</td>
<td>AP</td>
<td>S5</td>
<td>13</td>
<td>NLOS</td>
<td>-∞</td>
</tr>
<tr>
<td>5</td>
<td>AP</td>
<td>S12</td>
<td>13</td>
<td>NLOS</td>
<td>-∞</td>
</tr>
<tr>
<td>5</td>
<td>STA</td>
<td>S12</td>
<td>13</td>
<td>NLOS</td>
<td>-4.18</td>
</tr>
<tr>
<td>6</td>
<td>AP</td>
<td>S13</td>
<td>12</td>
<td>NLOS</td>
<td>-1.11</td>
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<tr>
<td>6</td>
<td>STA, conf.</td>
<td>S13</td>
<td>12</td>
<td>NLOS</td>
<td>-∞</td>
</tr>
<tr>
<td>7</td>
<td>AP</td>
<td>S20</td>
<td>8.5</td>
<td>NLOS</td>
<td>-2.23</td>
</tr>
<tr>
<td>7</td>
<td>STA</td>
<td>S20</td>
<td>8.5</td>
<td>NLOS</td>
<td>-5.71</td>
</tr>
</tbody>
</table>

Summary of Intel’s Validation

- Channel capacities of three office models (C,D,E) match measurements for 2.4 GHz band, 5.2 GHz band, and 2 antenna spacings.

- Measured delay spreads match measurements.

- 4x4 capacity is 3.6 and 3.3 times of 1x1 capacity for $2\lambda$ and $\lambda/2$ spacing respectively.

- $K$ factor is small in the office environment.
Zyray’s Measurements

- Large indoor environments (office, cafeteria) - Mainly Models D and E equivalent, partially F (only LOS).
- 5.25 GHz frequency
- 4x4 MIMO measurements
- Dipole antennas
- Antenna spacing: $\lambda/2$
- LOS and NLOS conditions, 1 – 50 m
- 500 MIMO channel snapshots at each location over 2.5 m distance (10 sec. measurement), 40 locations
K-factor Experimental Data Results
LOS, d=23.5m

High K-factor on the first tap
K-factor Experimental Data Results
LOS, d=43.5m

High K-factor on the first tap
K-factor Experimental Data Results
NLOS, d=16.8m

Generally no high K-factors
4 x 4 MIMO Capacity Results

LOS

Capacity is approx. 70% of iid capacity

Parameters:
SNR = 10 dB
Antennas: Dipole
Antenna spacing: \( \lambda/2 \)
4 x 4 MIMO Capacity Results

NLOS

Capacity is approx. 80% of iid capacity

Parameters:
SNR = 10 dB
Antennas: Dipole
Antenna spacing: $\lambda/2$
Summary of Zyray’s Validation

For the Models D and E and partially F (only LOS) equivalent environments following was found from the experimental data:

- LOS K-factor is in the range 2-10 dB
- NLOS K-factor is < - 2 dB in most cases
- LOS 4x4 MIMO capacity is approx. 70% of iid
- NLOS 4x4 MIMO capacity is approx. 80% of iid

The results match proposed models well.
Metalink’s Measurements

- About 500,000 measurements taken at various locations and scenarios within the company.
- Measurements were taken at the lower UNII band (~5.2 GHz)
- Receive antennas fixed at a height of ~2m (e.g. AP position)
- TX setup moves between measurement positions
Measurement Set Up

• Philosophy:
  – Full simultaneous MIMO measurements
  – Relatively slow sampling rate (46MHz)– long sampling period (100msec)
  – Store all samples and post-process offline
  – Use wideband transmission signals (>20MHz)
  – Omni reception and transmission antennas with ~λ/2 spacing
Real-Environment Calculated Capacity
(M11-14)

Capacity vs. Time

(MIMO Capacity)/2
MIMO Capacity Enhancement - NLOS, Dist= 25.6m (M11-XX)

Median MIMO Capacity vs. Median SISO Capacity, slope=1.88
MIMO Capacity Enhancement-LOS, Dist=25m (M11-XX)
Periodic Modulation

- In nearly all tests, a strong AM-like periodicity is clearly seen.
- The period of this modulation was tested to be exactly 100Hz
The Fluorescent Effect

- Fluorescent lights become conductive twice every AC power cycle.
- During that period, the electromagnetic environment (reflections) are changed.
- The channels in such environment exhibit strong AM modulation in all parameters (frequency response, RMS delay spread, capacity, etc.)
- The Fluorescent effect has been incorporated into the channel model
Summary of Metalink’s Validation [6]

- In typical enterprise scenario 2 antenna MIMO enhances the median capacity by 1.5-2x (NLOS and LOS)
- Channels exhibits “slow” variability changes over 100ms (f<10Hz)
- In the vicinity of fluorescence lights the channel is modulated by a 100/120Hz AM modulation
- These results are already integrated into the channel models
Conclusion

• Validation covers model C, D, E, and F
• 1x1, 2x2, and 4x4 channel capacity match measurements on both 2.4 and 5.2 GHz
• Model K factors match measurements
• Time variation due to fluorescent lights are included in the models
• MIMO multipliers are about 1.8 and 3.5 for 2x2 and 4x4 channels respectively
References