MIMO wireless channel emulation

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Overview:
- Wireless systems
- Mobile channel
- OFDM
- MIMO
- IEEE 802.11n
- Channel models
- Simulation/Emulation
- Wireless channel emulation
- Future work
Wireless systems

Why wireless systems?
Mobile channel

- The mobile channel is a complex channel:
  - Multipath, scattering
  - Doppler spectrum
  - Shadowing
Mobile channel

- Multipath \( \rightarrow \) Frequency selective channel
  - Time domain response of the channel consists of various rays having a complex Gaussian distribution
  - Channel frequency response is not flat
  - Coherence bandwidth
Mobile channel

- Doppler spectrum/fading ➔ Time varying channel
  - Change in the carrier frequency due to relative movement between the mobile and the BS
  - \( f_{D\text{max}} = \frac{v}{\lambda} \) ➔ Coherence time \( \approx \frac{1}{f_{D\text{max}}} \)
  - Fading channel ➔ severe changes in the received signal power every coherence time

How can we overcome or mitigate the negative effects of the mobile channel?
Mobile channel

- New techniques to handle frequency selectivity and fading channels, such as...
  - OFDM
  - MIMO
Orthogonal Frequency-Division Multiplexing (OFDM)

- OFDM converts a wideband signal into multiple narrowband signals placed side by side in the frequency domain.
  - Part of the signal is modulated in each subchannel and transmitted through an almost flat fading channel.
  - If one of the subchannels is affected by a severe fading, simply nothing is transmitted in that subchannel.
- This results in a strong resiliency against frequency selective channels.
Multiple Input-Multiple Output (MIMO)

- Traditionally multiple antennas placed at the receiver to apply diversity
  - Spatial diversity (each antenna will see a different and independent channel)
  - Significant immunity to fading
  - Results improve as the number of antennas increase

- Even better results are achieved when multiple antennas placed also at the transmitter
  - Total available transmit power is split uniformly across transmit antennas
  - Finite optimum number of tx antennas
IEEE 802.11n

- OFDM $\rightarrow$ Resilency against frequency selective channels
- MIMO $\rightarrow$ Resilency against fading channels
- Mobile channel is a fading and frequency selective channel

MIMO+OFDM is a good solution for mobile communications

- IEEE 802.11n standard
IEEE 802.11n

- IEEE 802.11n standard
  - WLAN standard improving the Physical Layer and MAC Layer of the traditional WLAN's
  - Indoor MIMO/OFDM system
  - Range ~ 100 meters
  - Maximum bit rate: 600Mbps (3x3 antennas) (typical bit rate 74 Mbps)
  - Carrier frequency: 2.4 or 5 GHz
  - Full compatibility with current WLANs

- Project to develop IEEE 802.11n began in 2003
- Just starting to be in a commercial stage
- Intel has started to add 802.11n in some of its products
- For future commercialization, many tests have to be done

Wireless channel on OFDM-MIMO systems simulation
Channel models

- MxN MIMO channel is equivalent to MN impulse responses, each representing a subchannel.
- Model a SISO channel, then extend to MIMO (repeat MN times plus adding other artifacts, such as spatial correlation between antenna elements...).
Channel models

- Statistical Model for Indoor Multipath Propagation (A. Saleh, R. Valenzuela)
  - Channel measurement

- Results (Power Delay Profile)
Channel models

- Wireless indoor channel modeling
  - Channel modeled as an FIR
    \[ h(t) = \sum_{\ell=0}^{\infty} \sum_{k=0}^{\infty} \beta_{\ell k} e^{j\theta_{\ell k}} \delta(t - T_{\ell} - \tau_{\ell k}). \]
  - Multipath: clustering of arriving rays (angular clusters)

- Double exponential decay of the impulses (clusters and rays within a cluster)
Channel models

- Clustering of rays
- Doppler spectrum/Fading
- Shadow fading
- Path loss model
  - Free space loss ($L_{FS}$) up to a breakpoint distance ($d_{BP}$)
  - Slope of 3.5 after $d_{BP}$

\[
L(d) = L_{FS}(d) \quad \text{for } d \leq d_{BP}
\]
\[
L(d) = L_{FS}(d_{BP}) + 35 \log_{10}(d / d_{BP}) \quad \text{for } d > d_{BP}
\]

- Adding these elements together → SISO channel model
Channel models

- Set of channel models applicable to indoor WLAN systems

<table>
<thead>
<tr>
<th>Model</th>
<th>Environment</th>
<th>LOS/NLOS</th>
<th>RMS delay spread (ns)</th>
<th># of clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Flat fading</td>
<td>NLOS</td>
<td>0</td>
<td>1 tap</td>
</tr>
<tr>
<td>B</td>
<td>Residential</td>
<td>LOS</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>Residential/Small Office</td>
<td>LOS/NLOS</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>Typical Office</td>
<td>NLOS</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>E</td>
<td>Large Office</td>
<td>NLOS</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>Large Space/Indoors and Outdoors</td>
<td>NLOS</td>
<td>150</td>
<td>6</td>
</tr>
</tbody>
</table>

- Channel model is a FIR $\rightarrow$ Extend to MIMO (matrix of MxN FIRs)
- Other MIMO channel artifacts should be added
Channel models (MIMO)

- MIMO matrix formulation (for each tap)

\[ H = \sqrt{P} \left( \frac{K}{K+1} H_F + \sqrt{\frac{1}{K+1}} H_v \right) \]

- Power of each tap
- Ricean K-factor (0 for NLOS taps)

**LOS**
- \([S]\) (constant Rice Steering matrix)

**NLOS**
- \([X]\) (time varying Rayleigh and Correlation matrix)
Channel models (MIMO)

- LOS $\rightarrow$ Rice Steering matrix
  - Difference in phase between the rays arriving/leaving the tx and rx antenna elements
  - Constant matrix
  - Only first tap (LOS)

\[
\begin{bmatrix}
1 \\
\exp\left(2 j \pi \frac{d_{tx}}{\lambda} \sin(\text{AoA}_{tx})\right) \\
\vdots \\
\exp\left(2 j \pi \frac{d_{tx}}{\lambda} \sin[(n_{tx} - 1) \text{AoA}_{tx}]\right)
\end{bmatrix}
\begin{bmatrix}
1 \\
\exp\left(2 j \pi \frac{d_{rx}}{\lambda} \sin(\text{AoD}_{tx})\right) \\
\vdots \\
\exp\left(2 j \pi \frac{d_{rx}}{\lambda} \sin[(n_{rx} - 1) \text{AoD}_{tx}]\right)
\end{bmatrix}^T
\]

MxN matrix

Rx antenna elements

Tx antenna elements
Channel models (MIMO)

- NLOS $\rightarrow$ Rayleigh and Correlation matrix (I)
  - Correlation between tx antennas and rx antennas ([Rtx] and [Rrx] matrixes)
    - From antenna spacings to theoretical capacities (L. Schumacher, K. Pedersen, P. Morgensen)
    - Power Angular Spectrum (PAS): Uniform, Gaussian or Laplacian

- Uniform linear antenna array $\rightarrow$ correlation of rx/tx signals between antenna elements

$$
\rho_{ij} = \int_{-\pi}^{\pi} e^{\frac{2\pi}{\lambda}kd\sin(\theta)} \cdot PAS(\theta) \cdot A_i(\theta) \cdot A_j(\theta) d\theta
$$

Spacing between antennas  
Element electromagnetic pattern
Channel models (MIMO)

- NLOS $\rightarrow$ Rayleigh and Correlation matrix (II)
  - Correlation between tx antennas and rx antennas ([Rtx] and [Rrx] matrixes)
    - Generation of the correlation matrixes

\[
\begin{align*}
\mathbf{R}_{tx} &= \begin{bmatrix}
1 & \rho_{tx12}^* & \rho_{tx13}^* & \rho_{tx14}^* \\
\rho_{tx21} & 1 & \rho_{tx23}^* & \rho_{tx24}^* \\
\rho_{tx31} & \rho_{tx32} & 1 & \rho_{tx34}^* \\
\rho_{tx41} & \rho_{tx42} & \rho_{tx43} & 1
\end{bmatrix} \\
\mathbf{R}_{rx} &= \begin{bmatrix}
1 & \rho_{rx12}^* & \rho_{rx13}^* & \rho_{rx14}^* \\
\rho_{rx21} & 1 & \rho_{rx23}^* & \rho_{rx24}^* \\
\rho_{rx31} & \rho_{rx32} & 1 & \rho_{rx34}^* \\
\rho_{rx41} & \rho_{rx42} & \rho_{rx43} & 1
\end{bmatrix}
\end{align*}
\]

Example: 4x4 MIMO channel
Channel models (MIMO)

- NLOS $\rightarrow$ Rayleigh and Correlation matrix (III)
  - Rayleigh fading
    - Generation of a Rayleigh vector
    - Shaping of the vector with a FIR (order=7) to generate the adequate Doppler spectrum
  - Combination of the Correlation and the Rayleigh fading
    \[
    [X] = ([R_{tx} \otimes [R_{rx}])^{1/2} [H_{iid}]
    \]
    Kronecker product $\rightarrow$ Rayleigh vector
  - Adding other artifacts
    - Shadow fading
    - Doppler component due to a moving vehicle (optional)
    - Doppler components due to fluorescent lights (optional)

Bell shape doppler spectrum with a 200Hz Doppler component
Simulation/Emulation

- IEEE 802.11n still in testing stage (already being implemented by Intel)
- Performance of advanced wireless techniques such as MIMO is highly dependent on the channel
  - Necessity of realising credible tests and validations under realistic conditions
  - Inefficiency of real measurements (moving the rx along a specific indoor location)

D.P. McNamara, M.A. Beach, P.N. Fletcher, P. Karlsson, Initial Investigation of MIMO Channels in Indoor Environments

Necessity of replicating the wireless channel in the laboratory
Simulation/Emulation

- Wireless channel replication in the laboratory
  - Traditional option → Simulation
  - “Easy” solution, but...

$$ H = \sqrt{P} \left( \sqrt{\frac{K}{K+1}} H_F + \sqrt{\frac{1}{K+1}} H_v \right) $$

- MIMO systems → The channel matrix \([H]\) has to be generated at least every coherence time!
- A more realistic simulation will require many samples per coherence time
- **Huge computational complexity** (that even grows quadratically with the number of tx and rx antennas)

Simulation is not enough → Real time emulation
Wireless channel emulation

- Channel emulator
  - A platform that replicates an actual wireless channel and all its artifacts in the lab environment
  - Due to the large amount of real-time operations demanded, usually implemented as high speed dedicated hardware platforms

- Traditional approach
  - Represent the channel as a FIR filter compliant to the PDP
  - Emulation core performs convolution in time over the incoming data and the channel response
  - Replicate for the number of subchannels (MxN)
  - Computations are a function of the channel response length and increase quadratically with M and N
Wireless channel emulation

- New scalable solutions → Frequency domain channel emulation
- A real-time wireless channel emulator for MIMO systems (H. Eslami, A. Eltawil)
  - Generate the frequency response for each subchannel ($H_{ij}(f)$)
    - One sample of the channel state every coherence time
    - For accurate emulations, multiple samples can be generated every coherence time
  - 1 FFT/IFFT per each tx/rx element (M FFT, N IFFT) as oppose to one FIR per each subchannel
- Emulator core is a single multiplier for each subchannel

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Wireless channel emulation

- Improvements
  - Each extra sub-channel is only an additional multiplier
  - Less computational complexity
  - Scalable (no changes needed if the length of the channel FIR varies)
- For example, for a 4x4 MIMO system
  - 4 FFT engines at the input of the emulator
  - 16 multipliers (1 per each subchannel)
  - 4 IFFT engines at the output of the emulator
Wireless channel emulation

- Some results...
  - FPGA implementation of the time domain emulator vs the frequency domain emulator
Future work

- Optimize and reduce computational complexity
  - Hybrid time/frequency channel emulator
- ...