Wireless InSite® Simulation of MIMO Antennas for 5G Telecommunications
Overview

- To keep up with rising demand and new technologies, the wireless industry is researching a wide array of solutions for 5G, the next generation of wireless networking.

- Technologies based on **Multiple Input, Multiple Output (MIMO)**, including Massive MIMO, are among key concepts.

- As a leading provider of wireless simulation tools, Remcom is developing an innovative and efficient MIMO simulation capability.

- In this talk, we give an overview of 5G and MIMO concepts, and a preview of our upcoming Wireless InSite MIMO simulation capability.
5G OBJECTIVES AND CHALLENGES
Challenges For 5G

Massive Growth In Mobile Data Demand

- 1000x Increase

Massive Growth of Connected Devices

- 5 Billion (2010)
- 50 Billion+ (2020)

Increasingly Diverse Use Cases and Requirements

- Traditional
  - Cell Phones
  - Tablets
  - Laptops

- Emerging Technologies
  - Connected Cars
  - Machine-to-Machine
  - Internet of Things
Challenges and Objectives of 5G

**Challenges**
- Massive Growth in Mobile Data Demand
- Massive Growth in Connected Devices
- Increasingly Diverse Use Cases and Requirements

**Objectives**
- 1000x Capacity
- 10-100x Devices (50-500B)
- 10-100x Data Rates (~10 Gbps)
- 5x Lower Latency
- 100x Energy Efficiency
- 10x Longer Battery Life for low-power devices
Challenges and Scenarios for 5G

**Challenges**
- Very High Data Rate
- Very Dense Crowds of Users
- Very Low Latency
- Mobility
- Many Devices w/Low Energy Cost

**Scenarios**
- Amazingly Fast
- Great Service in a Crowd
- Real-Time, Reliable Connections
- Best Experience Follows You
- Ubiquitous Things Communicating

Some of the Key Solutions

Some of the key solutions

- Increased spectrum, much of it at higher frequencies (e.g., mm waves)
- Massive MIMO
- Ultra-Dense Networks
- Moving Networks
- Machine-to-machine/Device-to-device Communications

Focus of this talk is on MIMO, including Massive MIMO, with some reference to its use with millimeter waves
How MIMO Helps to Address 5G Challenges

**MIMO AND 5G**
Multiple Input, Multiple Output

Use techniques such as spatial multiplexing and precoding

- Create multiple streams to increase data rate
- May use beamforming to increase SNR
- Techniques require varying levels of channel state info (CSI)

<table>
<thead>
<tr>
<th>MIMO Techniques</th>
<th>Requires CSI?</th>
<th>Description of Technique</th>
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<tbody>
<tr>
<td>Precoding</td>
<td>Both ends</td>
<td>Split signal into multiple streams and use coding for beamforming</td>
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</table>
| Spatial Multiplexing  | At transmitter| - Split signal; transmit different streams from each antenna  
                            - Works if channel characteristics (spatial signature) uncorrelated  
                            - Can be combined with precoding if have channel state info (CSI) |
| Diversity Coding      | Not required  | Takes advantage of variation in fading for each antenna pair to provide diversity; can use if no channel state information |
Multipath and Fading

Wireless InSite example showing multipath between base station and user equipment.

Small-scale fading from multipath causes rapid fluctuations along route.
Multi-User MIMO (MU-MIMO)

- MIMO transmission to multiple terminals at same time

<table>
<thead>
<tr>
<th>Key Advantages [2]:</th>
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<tbody>
<tr>
<td><strong>Increased Data Rate</strong></td>
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<tr>
<td>More independent, simultaneous data streams</td>
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<td><strong>Improved Reliability</strong></td>
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<tr>
<td>More antennas means more distinct propagation paths</td>
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<tr>
<td><strong>More Energy Efficient</strong></td>
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<tr>
<td>Can focus energy toward terminals</td>
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<tr>
<td><strong>Reduced Interference</strong></td>
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<td>Can avoid directions where interference harmful</td>
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- Exists in 4G LTE and LTE-A, but with small # antennas
  - LTE-Advanced allows for up to just 8 antennas, and most systems have far fewer
Massive MIMO

- Scales up current state-of-the-art by orders of magnitude
  - Arrays with 100s of antennas serving 10s of users in same time-frequency
  - Enabler for future broadband, connecting people and things with network infrastructure
  - If used with mm wave, large arrays could be very compact

- MIMO antenna layouts
  - Linear, rectangular, or cylindrical arrays
  - Distributed antennas

- Core method: spatial multiplexing
  - Relies on knowledge of propagation channel on uplink and downlink
Beamforming Using Spatial Multiplexing

- Massive MIMO uses beamforming to send multiple data streams
  - Offers way to share frequency in close proximity, increasing capacity / data rate
  - Uses pilot signals to characterize channel

Typical Conceptualized

Each case demonstrates idea of optimizing for one user (■) while minimizing interference to others (■)

Wireless InSite showing how multipath could influence beamforming to > one device
Potential Benefits of Massive MIMO\cite{2,3}

- Increase Capacity 10x+
  - Aggressive spatial multiplexing with large numbers of antennas

- Improve radiated energy-efficiency 100x
  - With large arrays, energy can also be focused with extreme sharpness
  - Reduces both power consumption and potential interference

- Can use inexpensive, low-power components
  - Conventional 50 Watt amplifiers replaced by hundreds of low-cost, milliWatt amplifiers

- Significantly reduces latency (eliminates impact of fading)

- Increases robustness to interference and jamming
  - With large arrays, algorithms can reduce these effects
Key Challenges for Massive MIMO

- Reciprocity and uplink/downlink calibration
  - Pilot signals used to get channel state information; larger arrays means much more channel data for mobile devices to process and send
  - Solution is generally to use pilots received at base station and assume reciprocity
    - Propagation follows reciprocity, but hardware differences must be calibrated

- Pilot “contamination”
  - Pilot signals typically used to characterize channel between MIMO elements
  - With massive MIMO, easy to use up all available pilot sequences
  - May get duplicate pilot sequences, contaminating processing for beam-forming

- Need for “favorable” propagation
  - Channel responses from base station to terminals must be sufficiently different
  - Evidence in research seems to suggest that conditions typically are valid for favorable propagation, so not likely to be a significant issue
Use of Simulations in MIMO R&D

- MIMO R&D: simulations can support active research areas
  - Better channel characterization for R&D
    - Good channel state information (CSI) is key to success of method; deterministic simulations can provide more realistic prediction of multipath channels than statistical methods
  - Predict potential for pilot contamination for typical scenarios
  - Examples: study impact of antenna alignments, polarization, correlation between channels – evaluate algorithms using predicted channel characteristics

- Virtual prototyping
  - Industry and researchers are prototyping solutions and testing concepts
  - While testbeds now exist with 32 or 64 element arrays [4, 5], some value to being able to test in any arbitrary environment with any antenna array technology using simulation
  - Virtual testbeds could evaluate alternatives before even reaching prototype stages
MIMO in Wireless Insite with a demonstration

WIRELESS INSITE’S MIMO CAPABILITY
Overview of Wireless InSite MIMO Capability

- New capability will target these key shortfalls in tools used in industry:
  - Most channel models in industry are statistical and cannot predict potential correlation between channels
    - Research suggests that correlation coefficient between channels is much larger than would be expected using independent, identically distributed random variables [3] – typical assumption used in many channel models
  - With Massive MIMO, computational complexity for a deterministic ray-tracing model will rise by orders of magnitude
    - One base station becomes hundreds of transmitting elements!
  - Details of antenna pattern, polarization, and phase will be critical to properly modeling effects
    - Most models simply don’t have this level of detail
# Key Benefits of Wireless InSite MIMO Capability

<table>
<thead>
<tr>
<th>Key Benefits of Wireless InSite MIMO</th>
<th>Complex Impulse Response</th>
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<tbody>
<tr>
<td>1. Positions and moves MIMO Arrays</td>
<td>Time of Arrival (s)</td>
</tr>
<tr>
<td>2. Predicts channel characteristics between each MIMO element</td>
<td>Received Power (dBm)</td>
</tr>
<tr>
<td>‧ Magnitude, phase, time of arrival per path within channel</td>
<td>0</td>
</tr>
<tr>
<td>‧ Includes antenna and polarization effects</td>
<td>0</td>
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<tr>
<td>‧ Heterogeneous arrays (independent patterns and rotations)</td>
<td>0</td>
</tr>
<tr>
<td>3. Rapid frequency sweeps</td>
<td>0</td>
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<tr>
<td>‧ Gather information across one or more bands</td>
<td>0</td>
</tr>
<tr>
<td>4. Optimizes to minimize increase in Run-time from significant increase in antennas</td>
<td>0</td>
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<tr>
<td>5. Preliminary Tests: 4x4 MIMO: just 1.3x increase</td>
<td>0</td>
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<tr>
<td>64x4 MIMO: just 4x increase</td>
<td>0</td>
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Adjacent Path Generation (APG) further reduces Run-time and memory footprint for mobile devices

- Limits full ray-tracing to coarse spacing along route of travel
- Uses Remcom proprietary techniques to find exact paths to each mobile location
- Then finds exact paths to each MIMO array element on each end of link (uplink/downlink)

Run-time reduction may be order of magnitude or more, depending on the spacing of points along route.
Value of Wireless InSite Capability

- Provides efficient simulation of MIMO antennas with ability to model details of antennas and channel characteristics
  - Ability to deterministically predict variation of paths across MIMO array elements overcomes significant shortfall in statistical models commonly used today
  - Efficient calculation of paths for large arrays overcomes shortfall of current brute-force ray models

- Used to perform virtual assessment of systems, scenarios, and performance in complex environments

- Offers tool for R&D, virtual testing and evaluation of concepts, enabling 5G research of potential MIMO solutions
MIMO for Small Cell in Rosslyn, VA
Small Cell Scenario

- Small cell base station
  - At intersection of Wilson and Lynn
  - Mounted on lamp post in median on Lynn Street

- Predict signal received by mobile device (red route)
  - Travels along Wilson, turns onto Lynn, then turns onto side street
  - Moving at ~10m/s (22 mph)

- Start with single antennas
  - Use dipoles, 3.55 GHz
Baseline SISO Scenario

- 1 Dipole at Base Station and Handset

- Field Map shows significant urban multipath in area
  - Much of route within LOS
  - Still may have spatial diversity due to multipath
  - End of route is beyond LOS and has significant shadowing
Baseline SISO Scenario

- Plot showing received power along route

- Wireless InSite results show:
  - Shadowing at beginning of route (hill and structures)
  - Shadowing at end (turns corner)
  - Small-scale fading along route due to multipath

(Note: 10 points/second)
4x4 MIMO Scenario

- Define 4-element MIMO antenna
  - 4-element arrays (2x2)
  - Frequency: 3.55 GHz
  - \( \frac{1}{2} \lambda \) Spacing (4.225 cm)

- Assign to both base station and mobile device

- Channel matrix: 4 x 4 (16 total pairs)
4x4 Channel Matrix Output

- Large-scale fading consistent across channels, but deep fades from multipath vary significantly
  - Simple diversity techniques (e.g., using max received power) can eliminate deep fades
  - MIMO techniques can use this to transmit multiple streams over same frequency with “orthogonal” coding
Channel Impulse Responses

- Wireless InSite multipath results can be used to generate MIMO channel impulse responses for each element of channel matrix
  - Could apply various MIMO techniques to evaluate how best to maximize capacity, data rate, etc. for small cell
  - Deterministic simulation results can be used to predict correlation between channels (key requirement for MIMO spatial multiplexing gain)

Some key differences in impulse response
Sample Signal Traces

- Signal Traces for two MIMO channels (same mobile device location)
- Shows just how much signal impacted by multipath with changes in position of just a few cm on each end
30 GHz Massive MIMO Scenario

- Define 128-element Massive MIMO Base Station antenna
  - 64-element array (8x8)
  - Dual Polarization (2x elements)
  - Frequency: 30 GHz
  - $\frac{1}{2} \lambda$ Spacing (0.5 cm)

- Mobile devices still uses 4-element array

- Channel matrix: $128 \times 4$ (512 total pairs)
Baseline SISO Scenario

- SISO scenario simulated at 30 GHz
- Results similar to 3.55 GHz
  - Similar shadowing and fading
- Received power is about 20dB lower
  - Caused by higher path loss at mmWave frequencies
128x4 Channel Matrix Output

- Wireless InSite results are similar to 4x4 case, but even more variation between channels and even deeper fading
  - Simple diversity technique (e.g., max power) does even better at eliminating small-scale fading
  - Likely much more spatial diversity allowing for multiple streams and beamforming
Massive MIMO Scenario

- Plots show complex impulse response for 2 sample areas where fading was significant
  - At superficial level, appears to be even more variation for this case
References


Wireless InSite’s MIMO Capability

SUMMARY
MIMO in Wireless InSite

- MIMO and Massive MIMO are key concepts for 5G

- Remcom’s Wireless InSite MIMO capability provides an efficient method to predict channel characteristics for large-array MIMO antennas in complex multipath environments

- Key benefits to the wireless industry
  - Provides capability to perform R&D and assessment of MIMO solutions and algorithms
  - Enables virtual testing of prototypes and design concepts in simulated environment that captures complex aspects of realistic deployment scenarios

- Status of Development
  - Beta versions of computational engine are in development and testing, and the graphical interface and planned outputs are still being finalized
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