mmWave MIMO Channel Sounding for 5G
— Technical Challenges and Prototype System

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5G Overview: Expectations

For the User:

- Amazingly fast
- Great service in a crowd
- Best experience follows you
- Super real-time & reliable communications
- Ubiquitous things communicating

All founded on a solid business model
By overlaying the contrasting demands of different types of service, an aggregate picture of 5G emerges.
5G Overview: Opportunities to Innovate

Enabling Technologies

1. New <6GHz PHY/MAC
2. mmWave (Carrier, BW, MU-MIMO)
3. Full Duplex
4. >>400GB/s Fiber
5. Hyper-Fast Data Buses
6. C-RAN & New NW Topologies

To-do list!
Design
Simulate
Emulate
Calibrate
Validate

100X Data Rates
1000X Capacity
100X Densification
1mS Latency
Reliability 99.999%
100X Energy Efficiency
5G Channel Measurement and Modeling Needs

– 5G spectrum choices and standardization

– 5G key technology choices
  • Massive MIMO
  • mmWave
  • Waveform design
  • Full duplex
  • etc

– 5G network planning

5G channel models not well studied. Channel sounding is needed to address the gap.
**Channel Sounding: Concept**

**RF channel** the heart of any wireless system

**Channel sounding** techniques to understand the characteristics of RF channel

\[
y(t) = h(t) \otimes x(t)
\]

\[
R_{xy}(\tau) = E[x^*(t)y(t - \tau)] \\
= h(t - \tau) \otimes R_x(\tau) \\
\approx h(t - \tau) \otimes \delta(\tau) = h(t)
\]

**RF**: Radio Frequency
Channel Sounding for 5G (I)

System Requirements

- mmWave Frequency Band
- Ultra-broad Bandwidth
- Massive MIMO
Channel Sounding for 5G (II)

Technical Challenges

- Sounding Approach & Architecture
- mmWave Frequency Band
- 5G Channel Sounding
- Ultra-broad Bandwidth Signal Generation & Acquisition
- Efficient Data Storage & Streaming
- Channel Parameter Estimation Processing
- Synchronization and Calibration
## Consideration on 5G Channel Sounding (1)

### Sounding Approach & Architecture

#### Sounding Technique

<table>
<thead>
<tr>
<th>Sliding Correlator</th>
<th>Wideband Correlation</th>
<th>Frequency Swept</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low measurement speed</td>
<td>• Fast measurement speed</td>
<td>• Slowest</td>
</tr>
<tr>
<td>• Amplitude information only</td>
<td>• Amp./phase information</td>
<td>• No cross-interference</td>
</tr>
</tbody>
</table>

#### MIMO Sounding Approach

- **Wideband Correlation**
  - Switching @ Tx & Rx
  - Slowest
  - No cross-interference
- **Switching @ Tx, parallel receiving**
  - Fast
  - No cross-interference
- **Parallel transmitting & receiving**
  - Fastest
  - Suffering cross-interference

### Advantages

- Fast measurement speed
- MIMO sounding capability
- High measurement performance
- Arbitrary sounding waveform support

### Keysight preferred sounding architecture

![Diagram showing the Keysight preferred sounding architecture](image)

- **Transmitter**
  - Wideband Signal Generator
  - RF switch
- **Receiver**
  - Wideband Multi-channel Receiver

*Image showing the Keysight preferred sounding architecture.*
Consideration on 5G Channel Sounding (2)

mmWave & Ultra-broadband

- mmWave Switch
- mmWave Antenna
- Channel
- mmWave VSG
  - Wideband I/Q Signal
- Wideband AWG
- mmWave Signal Generator
- mmWave Sounding Signal

- mmWave Multi-channel DC
- mmWave Multi-channel Digitizer
- IF Signal

1. AWG: Arbitrary Waveform Generator
2. VSG: Vector Signal Generator
3. DC: Down-Converter
Consideration on 5G Channel Sounding (3)

Data Streaming & Storage

Sounding signal

Raw Sounding Data

Transmitting period $T_p$

Effective Raw Data

Transmitting signal length $T_s$

Max. delay spread $T_d$

CIR

Effective CIR Data

1. CIR: Channel Impulse Response
2. 3.2GSa/s with 4 channels and 2Byte/sa, $T_p = 100\mu s$, $T_s = 20\mu s$, $T_d = 5\mu s$
## Consideration on 5G Channel Sounding (4)
### Parameter Estimating Algorithms

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Consistency</th>
<th>Coherent Signals</th>
<th>Estimation Performance</th>
<th>Computations</th>
<th>Max Num. of Path</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beamforming Based</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bartlett</td>
<td>L=1</td>
<td>No</td>
<td>Poor</td>
<td>1-D search</td>
<td></td>
</tr>
<tr>
<td>Capon</td>
<td>No</td>
<td>No</td>
<td>Poor</td>
<td>1-D search</td>
<td></td>
</tr>
<tr>
<td><strong>Subspace Based</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUSIC(^1)</td>
<td>Yes</td>
<td>No; Yes for ROOT-MUSIC</td>
<td>Good</td>
<td>EVD, 1-D search</td>
<td>&lt; Num. of Rx</td>
</tr>
<tr>
<td>ESPRIT(^2)</td>
<td>Yes</td>
<td>No; Yes for TLS-ESPRIT and Unitary-ESPRIT</td>
<td>Good</td>
<td>EVD</td>
<td>&lt; Num. of Rx</td>
</tr>
<tr>
<td><strong>ML Based</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAGE(^3)</td>
<td>Yes</td>
<td>Yes</td>
<td>Good</td>
<td>Iterative, 1-D search</td>
<td>No limitation</td>
</tr>
</tbody>
</table>

\(^1\)MUSIC: MUltiple SIgnal Classification  
\(^2\)ESPRIT: Estimating Signal Parameter via Rotation Invariance  
\(^3\)SAGE: Space-Alternating Generalized Expectation maximization  
\(^4\)EVD: Eigen-Value Decomposition
Consideration on 5G Channel Sounding (5)

Synchronization & Calibration

Wideband Signal Generator

mmWave VSG

Wideband AWG

I/Q Mismatch Calibration

Rubidium Clock

LO

Wideband Signal Generator

mmWave VSG

Wideband AWG

I/Q Mismatch Calibration

Rubidium Clock

LO

Wideband Multi-channel Receiver

mmWave Multi-channel Digitizer

Power Calibration

System Impulse Response Calibration

Antenna Calibration

Multi-channel Calibration

Acquisition Trigger

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Wideband Multi-channel Receiver

mmWave Multi-channel Digitizer

Power Calibration

System Impulse Response Calibration

Antenna Calibration

Multi-channel Calibration

Acquisition Trigger

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mmWave MIMO Channel Sounding System Architecture
Prototype for 5G Channel Sounding

Transmitter

- E8267D mmWave Signal Source
- M8190 12GHz BW AWG
- Rubidium Clock
- 85332B 50GHz SP4T Switch
- L4450A Digital I/O Switch Controller

PA

Receiver

- E8257D 67GHz LO
- M9703A 8CH Digitizer
- Rubidium Clock
- 33512 AWG
- BPF
- M9362 50 GHz 4CH Digital Convertor
- LNA
- ANT
- M9703A 8CH Digitizer
- Rubidium Clock
- SystemVue

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Prototype mmWave Sounding System: Phase I
SISO mmWave Channel Sounding

Channel Emulator (for validation)

Prototype mmWave Channel Sounding

mmWave Multi-path Fading Signal

mmWave Sounding Signal
Prototype mmWave Sounding System: Phase II

4x4 mmWave Channel Sounding

- 4x4
- CF: 28GHz
- BW: 1GHz
- Size: 2 mobile carts, 838mm(L)*585mm(W) *920mm(H) for each
- Power consumption: Tx ~1KW; Rx~800W
Phase II 4x4 Sounding System Validation
Preliminary Results

AoA, AoD, PDP validation results

<table>
<thead>
<tr>
<th>Path Index</th>
<th>Path Delay (ns)</th>
<th>Path Loss (dB)</th>
<th>AoA (deg)</th>
<th>AoD (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>-53.482</td>
<td>-6</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>5.75</td>
<td>-54.002</td>
<td>-5.75</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Scale to 60GHz mmWave System

**Tx**

- N5152A 57~65GHz Up-converter
- E8267D 10.625GHz 3rd LO
- M8190 wide BW AWG
- Rubidium Clock HJ5418B

**Rx**

- N1999A 57~65GHz Down-converter
- LNA BPF
- 5GHz IF Output

- Rubidium Clock
- N5173B 13.75 GHz LO
- AWG
- SystemVue

5GHz IF Input

Keysight Technologies
Scale to 94GHz mmWave System

**Tx**
- E257DV10: 75~110GHz, 6x Multiplier
- 15GHz Input
- E8267D
- M8190 wide BW AWG
- Rubidium Clock HJ5418B

**Rx**
- LNA BPF
- N9029AV10 SA frequency extension
- 1~5GHz IF Output
- AWG
- Rubidium Clock

**SystemVue**
Summary

– Channel sounding and modeling important for 5G
– 5G channel sounding challenges
– Keysight mmWave MIMO channel sounding research
– How to scale the prototype solution to address different needs