The Case for UHF–Band MU–MIMO

Naren Anand
Ryan E. Guerra
Dr. Edward W. Knightly
MobiCom 2014
Introduction

The Case for UHF-Band MU-MIMO
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$2.4\text{GHz}$  
$5.8\text{GHz}$
Introduction

The Case for UHF - Band MU-MIMO

2.4GHz

5.8GHz
Introduction

TVWS are “beachfront property” of the RF Spectrum
– FCC 2010

Oneloa Bay, Maui
Introduction

The Case for UHF - Band MU-MIMO

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– FCC 2010

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TVWS are “beachfront property” of the RF Spectrum – FCC 2010

\[ \frac{P_r}{P_t} = G_b G_r \left( \frac{\lambda}{4\pi D} \right)^2 \]
Introduction

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\[ \frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4\pi D} \right)^2 \]
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The Case for UHF - Band MU-MIMO

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The Case for UHF - Band MU-MIMO

TVWS are “beachfront property” of the RF Spectrum – FCC 2010

Houston – 6 MHz

Oneloa Bay, Maui
Introduction

TVWS are “beachfront property” of the RF Spectrum – FCC 2010

UHF
- Better Propagation
- Limited Spectrum

Houston – 6 MHz

Oneloa Bay, Maui
**MU-MIMO**: Precoding technique that enables multi-antenna devices to transmit parallel streams.
MU-MIMO: Precoding technique that enables multi-antenna devices to transmit parallel streams

Properties of the UHF band uniquely benefit MU-MIMO transmissions while providing their own challenges

Channel Variability

Receiver Separability
**MU-MIMO**: Precoding technique that enables multi-antenna devices to transmit parallel streams

Properties of the UHF band uniquely benefit MU-MIMO transmissions while providing their own challenges.

We demonstrate that UHF combined with MU-MIMO can compensate for these challenges and overcome the spectral limitations of the UHF band.
MU-MIMO Background

Testbed Design and Integration

OTA Measurements and Analysis
Outline

MU-MIMO Background

Testbed Design and Integration

OTA Measurements and Analysis

The Case for UHF-Band MU-MIMO
MU-MIMO Background

- MU-MIMO: linear precoding method that allows a multi-antenna AP to transmit multiple parallel data streams to groups of clients.
MU-MIMO Background

- **MU-MIMO**: linear precoding method that allows a multi-antenna AP to transmit multiple parallel data streams to groups of clients.
  - Precoding: Applying complex magnitude and phase offsets (steering weights) to each data stream through the transmitting antenna array.

![Diagram of MU-MIMO transmission](image-url)
MU-MIMO Background

- **MU-MIMO**: linear precoding method that allows a multi-antenna AP to transmit multiple parallel data streams to groups of clients
  - Precoding: Applying complex magnitude and phase offsets (steering weights) to each data stream through the transmitting antenna array

\[
Tx_{1:4} = \sum_{x \in \{A, B, C\}} w_{x_{1:4}} \cdot D_x
\]
MU-MIMO Background

- **MU-MIMO**: linear precoding method that allows a multi-antenna AP to transmit multiple parallel data streams to groups of clients
  - Precoding: Applying complex magnitude and phase offsets (steering weights) to each data stream through the transmitting antenna array

- Steering Weights: $W$ matrix computation based on measured magnitude and phase offsets for each $Tx$-$Rx$ antenna path (CSI Matrix)
• MU-MIMO: linear precoding method that allows a multi-antenna AP to transmit multiple parallel data streams to groups of clients
  • Precoding: Applying complex magnitude and phase offsets (steering weights) to each data stream through the transmitting antenna array

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Tx_{1:4} = \sum_{x \in \{A, B, C\}} w_{x_{1:4}} \cdot D_x
\]

• Steering Weights: W matrix computation based on measured magnitude and phase offsets for each Tx->Rx antenna path (CSI Matrix)

\[
H = \begin{bmatrix}
h_{a1} & h_{a2} & h_{a3} & h_{a4} \\
h_{b1} & h_{b2} & h_{b3} & h_{b4} \\
h_{c1} & h_{c2} & h_{c3} & h_{c4}
\end{bmatrix}
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MU-MIMO Background

- **MU-MIMO**: linear precoding method that allows a multi-antenna AP to transmit multiple parallel data streams to groups of clients
  - Precoding: Applying complex magnitude and phase offsets (steering weights) to each data stream through the transmitting antenna array

- Steering Weights: $W$ matrix computation based on measured magnitude and phase offsets for each Tx-Rx antenna path (CSI Matrix)
  - e.g., Zero-forcing Beamforming

$$H = \begin{bmatrix} h_{a1} & h_{a2} & h_{a3} & h_{a4} \\ h_{b1} & h_{b2} & h_{b3} & h_{b4} \\ h_{c1} & h_{c2} & h_{c3} & h_{c4} \end{bmatrix}$$

$$W = H^*(HH^*)^{-1}$$

$$T_{x1:4} = \sum_{x\in\{A,B,C\}} w_{x1:4} \cdot D_x$$
MU-MIMO Background

• MU-MIMO: linear precoding method that allows a multi-antenna AP to transmit multiple parallel data streams to groups of clients
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\[ W = H^*(HH^*)^{-1} = \begin{bmatrix} w_{a1} & w_{b1} & w_{c1} \\ w_{a2} & w_{b2} & w_{c2} \\ w_{a3} & w_{b3} & w_{c3} \\ w_{a4} & w_{b4} & w_{c4} \end{bmatrix} \]
• Two step process:
• **Two step process:**
  
  • **SOUND**  
  – Measure channel between Tx and Rx antennas
MU-MIMO Tx Procedure

• **Two step process:**
  • **SOUND** – Measure channel between Tx and Rx antennas
  • **TRANSMIT** – Transmit parallel streams to multiple users

![Diagram showing TX and RX connections](image)
Two Key Performance-Determining Factors
Two Key Performance-Determining Factors

Receiver Separability
MU-MIMO Performance

Two Key Performance-Determining Factors

Receiver Separability

Channel Variability
Receiver Separability

Rx A

Rx B

Rx C

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The Case for UHF-Band MU-MIMO
Receiver Separability

• How close are the users’ channels?
Receiver Separability

• How close are the users’ channels?
  • Linear dependence of H matrix rows

\[ H = \begin{bmatrix}
  h_{a1} & h_{a2} & h_{a3} & h_{a4} \\
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- How close are the users’ channels?
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• **How close are the users’ channels?**
  • Linear dependence of H matrix rows
  • **NOT** necessarily dependent on physical location

\[ H = \begin{bmatrix} h_{a1} & h_{a2} & h_{a3} & h_{a4} \\ h_{b1} & h_{b2} & h_{b3} & h_{b4} \\ h_{c1} & h_{c2} & h_{c3} & h_{c4} \end{bmatrix} \]
Receiver Separability

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2.4 GHz
5.8 GHz
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2.4 GHz
5.8 GHz

UHF?

Tx

Rx A

Rx B

Rx C

The Case for UHF-Band MU-MIMO
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How to Quantify?
**Receiver Separability**

- How close are the users’ channels?
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**2.4 GHz**

**5.8 GHz**

**UHF?**

**How to Quantify?**
- Demmel Condition Number
**Receiver Separability**

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**How to Quantify?**

- Demmel Condition Number

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let \( \lambda_1, \lambda_2, \ldots, \lambda_n = \text{eig}(HH^*) \)

s.t. \( \lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_n \)

\[
d \triangleq \frac{\sum_{k=1}^{n} \lambda_k}{\lambda_n}
\]

- 2.4 GHz
- 5.8 GHz
- UHF?
Receiver Separability

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2.4 GHz
5.8 GHz
UHF?

How to Quantify?

- Demmel Condition Number
  - Based on Linear dependence

let $\lambda_1, \lambda_2, \ldots, \lambda_n = \text{eig}(HH^*)$

\[
d \triangleq \sum_{k=1}^{n} \frac{\lambda_k}{\lambda_n}
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UHF?

The Case for UHF-Band MU-MIMO

**How to Quantify?**

• Demmel Condition Number
  • \[ [35] \text{ C. Zhong, et. al. 2011} \]
  • Based on Linear dependence
  • Thus, invertibility

\[ \text{let } \lambda_1, \lambda_2, \ldots, \lambda_n = \text{eig}(HH^*) \]
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How to Quantify?

• Demmel Condition Number
  • Based on Linear dependence
  • Thus, invertibility
  • Reliably predicts performance
    • eg., use for MCS

How close are the users’ channels? How to Quantify?
**Receiver Separability**

- **How close are the users' channels?**
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\end{bmatrix} \]

**How to Quantify?**

- **Demmel Condition Number**
  - Based on Linear dependence
  - Thus, invertibility
  - Reliably predicts performance
    - e.g., use for MCS
  - \([1, \infty) : 1 \rightarrow \) perfectly separable (orthogonal) channels

\[ \text{let } \lambda_1, \lambda_2, \ldots, \lambda_n = \text{eig}(HH^*) \]
\[ \text{s.t. } \lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_n \]
\[ d \triangleq \frac{\sum_{k=1}^{n} \lambda_k}{\lambda_n} \]
Channel Variability

The Case for UHF-Band MU-MIMO
Channel Variability

• How much do the users (or their environments) move?
Channel Variability

- How much do the users (or their environments) move?
  - Between **SOUNDING**

Diagram:
- Tx to Rx A
- Tx to Rx B
- Tx to Rx C
Channel Variability

- How much do the users (or their environments) move?
  - Between **SOUNDING** and **TRANSMISSION**
Channel Variability

• How much do the users (or their environments) move?
  • Between **SOUNDING** and **TRANSMISSION**
  • How “fast” is the user/environment changing?

\[ \text{m/s} \]
Channel Variability

- How much do the users (or their environments) move?
  - Between **SOUNDING** and **TRANSMISSION**
  - How “fast” is the user/environment changing?

- **Rx A**: 13 m/s
- **Rx B**: 1.5 m/s
- **Rx C**: 4.5 m/s
Channel Variability

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  • Between **SOUNDING** and **TRANSMISSION**
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- Rx B: 1.5m/s
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Channel Variability

• How much do the users (or their environments) move?
  • Between SOUNDED and TRANSMISSION
  • How “fast” is the user/environment changing?

<table>
<thead>
<tr>
<th>Rx A</th>
<th>Rx B</th>
<th>Rx C</th>
</tr>
</thead>
<tbody>
<tr>
<td>13m/s</td>
<td>1.5m/s</td>
<td>4.5m/s</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>UHF</th>
<th>2.4 GHz</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
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</table>
Channel Variability

- How much do the users (or their environments) move?
  - Between **SOUNDING** and **TRANSMISSION**
  - How “fast” is the user/environment changing?

<table>
<thead>
<tr>
<th>λ</th>
<th>UHF</th>
<th>2.4 GHz</th>
<th>5.8 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ/s</td>
<td>60cm</td>
<td>12cm</td>
<td>5cm</td>
</tr>
</tbody>
</table>

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The Case for UHF-Band MU-MIMO
Channel Variability

- How much do the users (or their environments) move?
  - Between **SOUNDING** and **TRANSMISSION**
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<table>
<thead>
<tr>
<th></th>
<th>λ</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UHF</strong></td>
<td>60cm</td>
<td>x</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>12cm</td>
<td>5x</td>
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<td>5cm</td>
<td>12x</td>
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Channel Variability

• How much do the users (or their environments) move?
  • Between SOUN Dell g and TRANSMISSION
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<table>
<thead>
<tr>
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<th>X</th>
<th>m/s</th>
<th>λ/s</th>
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<tr>
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<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>12cm</td>
<td>5x</td>
<td></td>
<td>λ/s</td>
</tr>
<tr>
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<td>5cm</td>
<td>12x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tx

Rx A 13m/s
Rx B 1.5m/s
Rx C 4.5m/s

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The Case for UHF-Band MU-MIMO
Channel Variability

- How much do the users (or their environments) move?
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<table>
<thead>
<tr>
<th>λ</th>
<th>x</th>
<th>人</th>
<th>自行车</th>
<th>车</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF</td>
<td>60cm</td>
<td>x</td>
<td>2.5</td>
<td>7.5</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>12cm</td>
<td>5x</td>
<td>13</td>
<td>38</td>
</tr>
<tr>
<td>5.8 GHz</td>
<td>5cm</td>
<td>12x</td>
<td>30</td>
<td>90</td>
</tr>
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Channel Variability

• How much do the users (or their environments) move?
  • Between **SOUNDING** and **TRANSMISSION**
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<tr>
<td><strong>UHF</strong></td>
<td>60cm</td>
<td>x</td>
<td>2.5</td>
<td>7.5</td>
<td>21</td>
</tr>
<tr>
<td><strong>2.4 GHz</strong></td>
<td>12cm</td>
<td>5x</td>
<td>13</td>
<td>38</td>
<td>108</td>
</tr>
<tr>
<td><strong>5.8 GHz</strong></td>
<td>5cm</td>
<td>12x</td>
<td>30</td>
<td>90</td>
<td>260</td>
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### Channel Variability

- How much do the users (or their environments) move?
  - Between **SOUNDING** and **TRANSMISSION**
  - How “fast” is the user/environment changing?

#### How to Quantify?

<table>
<thead>
<tr>
<th>Frequency</th>
<th>( \lambda ) (cm)</th>
<th>( \chi )</th>
<th>User Speed</th>
<th>Device Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF</td>
<td>60</td>
<td>x</td>
<td>2.5</td>
<td>7.5</td>
</tr>
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<td>5</td>
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\( \lambda \) is the wavelength, \( \chi \) is a factor related to the environment, and the table shows the speed in m/s and \( \lambda/s \) for different scenarios.

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Channel Variability

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**How to Quantify**
- elem(H) autocorrelation

$$\rho_\ell = \frac{\mathbb{E}[H_{mn}[k]H^*_{mn}[k+\ell]]}{\mathbb{E}[H_{mn}[k]H^*_{mn}[k]]}$$

<table>
<thead>
<tr>
<th></th>
<th>$\lambda$</th>
<th>$\chi$</th>
<th>$\ell$</th>
<th>$\rho_\ell$</th>
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9/8/2014
Channel Variability

• How much do the users (or their environments) move?
  • Between **SOUNDING** and **TRANSMISSION**
  • How "fast" is the user/environment changing?

How to Quantify:
• elem(H) autocorrelation

\[\rho_\ell = \frac{\mathbb{E}[H_{mn}[k]H^*_{mn}[k + \ell]]}{\mathbb{E}[H_{mn}[k]H^*_{mn}[k]]}\]

• Measures change of each antenna path

<table>
<thead>
<tr>
<th></th>
<th>λ</th>
<th>x</th>
<th>2.5</th>
<th>7.5</th>
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<td>UHF</td>
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- elem($H$) autocorrelation
  - Measures change of each antenna path
  - $[0,1]: 1$-> identical for given lag

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Channel Variability

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• \( \text{elem(H)} \) autocorrelation

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\]

• Measures change of each antenna path
• \([0,1] : 1-> \text{identical for given lag}\)
• Rate of decay w.r.t. lag:
  • Slow decay, sound less
  • Fast Decay, sound more

<table>
<thead>
<tr>
<th></th>
<th>( \lambda )</th>
<th>( \chi )</th>
<th>( \text{m/s} )</th>
<th>( \lambda/s )</th>
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9/8/2014
MU-MIMO: UHF vs 2.4/5GHz

MU-MIMO

Channel Models

OTA Characterization
MU-MIMO: UHF vs 2.4/5GHz

Channel Models

- 5.8 GHz Indoor
  [27] Poutanen 2011

- 300 MHz Outdoor
  [36] Zhu 2013

OTA Characterization

Channel Variability

Receiver Separability
## MU-MIMO: UHF vs 2.4/5GHz

### Channel Models

<table>
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<tr>
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<th>Indoor</th>
<th>Outdoor</th>
</tr>
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<tbody>
<tr>
<td>5.8 GHz</td>
<td>?</td>
<td>?</td>
</tr>
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### OTA Characterization

- 300 MHz Outdoor: [36] Zhu 2013
- 5.8 GHz Indoor: [27] Poutanen 2011

### Receiver Separability

- ?
- ?
- ?
- ?

---

*The Case for UHF-Band MU-MIMO*
• COST 2100 -> MU-MIMO modelling framework
MU-MIMO Channel Models

- COST 2100 -> MU-MIMO modelling framework
- Parameterized for 300 MHz outdoor and 5 GHz indoor through exhaustive OTA measurements
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- Models tell us:
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Models tell us:
- UHF MU-MIMO users are harder to separate than 5GHz
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Order of magnitude
## MU-MIMO: UHF vs 2.4/5GHz

### Channel Models

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- **5.8 GHz Indoor**: [Poutanen 2011](#)
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MU-MIMO: UHF vs 2.4/5GHz

MU-MIMO Channel Models

- **5.8 GHz** Indoor
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OTA Characterization

The Case for UHF-Band MU-MIMO
### MU-MIMO: UHF vs 2.4/5GHz

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*References:*
- [27] Poutanen 2011
- [36] Zhu 2013
- [9] Aryafar 2010
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- More Variable: Easier to Separate
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## MU-MIMO: UHF vs 2.4/5GHz

### Channel Models
- **5.8 GHz Indoor**
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### OTA Characterization
- **2.4/5.8 GHz Indoor**
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- **UHF In/Outdoor**
  - [*] Anand 2014
  - ?
  - ?
Outline

- MU-MIMO Background
- Testbed Design and Integration
- OTA Measurements and Analysis
Outline

MU-MIMO Background

Testbed Design and Integration

OTA Measurements and Analysis
How do you build a UHF MU-MIMO array?
How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome -> especially for indoor deployments
How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome -> especially for indoor deployments

Log-periodic

35cm

40cm
How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome -> especially for indoor deployments

Log-periodic

Sector

100cm

50cm

35cm

40cm
How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome -> especially for indoor deployments.
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Enterprise AP and WARP SDR
How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome -> especially for indoor deployments.
How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome - especially for indoor deployments.

- **Sector**: 185cm x 100cm x 50cm
- **Enterprise AP and WARP SDR**: 40cm x 35cm x 12cm
- **Log-periodic**: λ/2 = 30cm
- **Enterprise AP and WARP SDR**: 25cm x 12cm x 100cm
How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome -> especially for indoor deployments.

- **Log-periodic**: 35 cm
- **Enterprise AP and WARP SDR**: 25 cm
- **Sector**: 100 cm
- **H**: 45 cm
- **λ/2**: 30 cm
- **40 cm**
- **12 cm**
How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome \( \rightarrow \) especially for indoor deployments.

Log-periodic

Sector
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How do you build a UHF MU-MIMO array?

Common UHF Antennas are cumbersome -> especially for indoor deployments

UHF array achieves MU-MIMO gains even with SFF antennas -> Indoor WLAN sized
WURC Array

- Open UHF MU-MIMO development platform
WURC Array

- Open UHF MU-MIMO development platform
- Side by side comparisons of 2.4/5Ghz and UHF band
WURC Array

- Open UHF MU-MIMO development platform
- Side by side comparisons of 2.4/5GHz and UHF band

$\lambda/2=30\text{cm}$

UHF Antenna
WURC Array

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WURC Array

- Open UHF MU-MIMO development platform
- Side by side comparisons of 2.4/5Ghz and UHF band
- 4 WARP + 4 WURC

λ/2 = 6 cm

λ/2 = 30 cm
WURC Array

- Open UHF MU-MIMO development platform
- Side by side comparisons of 2.4/5Ghz and UHF band
- 4 WARP + 4 WURC
- Clock and trigger sync. - > coherent transmitter
Open

High Power
Open

Frequency-Agile

High Power
The Case for UHF Band MU-MIMO
The Case for UHF Band MU-MIMO
High power, Multi-band radio front end

The Case for UHF-Band MU-MIMO
• High power, Multi-band radio front end
  • Custom design - built with LMS6002D
High power, Multi-band radio front end
- Custom design - built with LMS6002D
- Up to 1 Watt Tx power with custom PA chain
**High power, Multi-band radio front end**

- Custom design - built with LMS6002D
- Up to **1 Watt Tx power** with custom PA chain
- Demo: An Open-Source Development Platform for Long-Range UHF-Connected WiFi Hotspots
MU-MIMO
Background

Testbed Design and Integration

OTA Measurements and Analysis
• Exhaustively characterize the channel
• Exhaustively characterize the channel
• Zero-forcing Beamformer
• Exhaustively characterize the channel
• Zero-forcing Beamformer
  • Based on WARPLab design flow
OTA Measurement Methodology

- Exhaustively characterize the channel
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  - MATLAB Centric PHY layer prototyping platform
• Exhaustively characterize the channel
• **Zero-forcing Beamformer**
  • Based on WARPLab design flow
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  • Allows for less complex implementation of Zero-forcer
    • measure SINR -> Aggregate Shannon Capacity
OTA Measurement Methodology

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  - Allows for less complex implementation of Zero-forcer
    - measure SINR -> Aggregate Shannon Capacity
  - High communication latency.

\[
C = \sum_{x \in \text{Rx}} \log_2(1 + \text{SINR}_x)
\]
OTA Measurement Methodology

• Exhaustively characterize the channel

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  • Based on WARP-802.11 Reference Design

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High speed WARP-based channel sounder
- Based on WARP-802.11 Reference Design
  - Allows for MU-MIMO channel sounding
    with a relatively low cost set of SDRs

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OTA Measurement Methodology

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• **High speed WARP-based channel sounder**
  • Based on WARP-802.11 Reference Design
    • Allows for MU-MIMO channel sounding with a relatively low cost set of SDRs
  • LTS for OFDM channel estimation
  • Provides high speed channel snapshots
  • not actual beamforming

\[ C = \sum_{x \in Rx} \log_2(1 + \text{SINR}_x) \]
Indoor Scenario

• Typical, challenging Indoor Environment

3rd Floor (open area) 3m

3rd Floor

3m
• Typical, challenging Indoor Environment
  • Environmental mobility from office
Indoor Scenario

- **Typical, challenging Indoor Environment**
  - Environmental mobility from office
  - Industrial building: Concrete and steel propagation environment

![Diagram of indoor scenario with 3rd floor (open area) and concrete]
Indoor Scenario

• Typical, challenging Indoor Environment
  • Environmental mobility from office
  • Industrial building: Concrete and steel propagation environment
  • Non-Line of Sight

3rd Floor (open area)

Concrete

Walkway

3rd Floor

3m

9/8/2014
Indoor Scenario

• Typical, challenging Indoor Environment
  • Environmental mobility from office
  • Industrial building: Concrete and steel propagation environment
  • Non-Line of Sight
  • Close colocation of receivers
Indoor Scenario

• Typical, challenging Indoor Environment
  • Environmental mobility from office
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• **Will UHF propagation allow for user separation?**
Indoor Scenario

- Typical, challenging Indoor Environment
  - Environmental mobility from office
  - Industrial building: Concrete and steel propagation environment
  - Non-Line of Sight
  - Close colocation of receivers

- Will UHF propagation allow for user separation?
- Does the UHF MU-MIMO channel actually stay stable?
Indoor Scenario

- Sum capacity peaks at 4x3
  - [9] Aryafar 2010

2.4GHz

- Sum capacity peaks at 4x3
- Num Tx = 4
- Capacity (b/s/Hz)
- Num Rx

2.4GHz
Indoor Scenario

- Sum capacity peaks at 4x3
  - [9] Aryafar 2010
- Propagation of 5.8 GHz diminishes performance
Indoor Scenario

- Sum capacity peaks at 4x3
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- Propagation of 5.8 GHz diminishes performance
- Recall UHF user separability
Indoor Scenario

- Sum capacity peaks at 4x3
  - [9] Aryafar 2010
- Propagation of 5.8 GHz diminishes performance
- Recall UHF user separability
  - Propagation through obstacles should reduce multi-path

![Graph showing capacity vs. number of receive antennas for 2.4GHz and 5.8GHz bands.]

Num Tx = 4
Indoor Scenario

• Sum capacity peaks at 4x3
  • [9] Aryafar 2010
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• Recall UHF user separability
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<th>Num Rx</th>
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</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
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Num Tx = 4

- UHF
- 2.4GHz
- 5.8GHz
Indoor Scenario

- Sum capacity peaks at 4x3
  - [9] Aryafar 2010
- Propagation of 5.8 GHz diminishes performance
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- *Equivalent capacity to 2.4GHz*
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  - Propagation through obstacles should reduce multi-path
- Equivalent capacity to 2.4GHz
- Increasing Tx Distance would show larger performance gain over 2.4GHz
Indoor Scenario

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- Propagation of 5.8 GHz diminishes performance
- Recall UHF user separability
  - Propagation through obstacles should reduce multi-path
- Equivalent capacity to 2.4GHz
- Increasing Tx Distance would show larger performance gain over 2.4GHz

No spectral efficiency penalty for lower frequency
Will UHF propagation allow for user separation?
Indoor Scenario

- **Will UHF propagation allow for user separation?**
  - Previous capacity results confirm
  - Verify with Condition Number
Indoor Scenario

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Indoor Scenario

- **Will UHF propagation allow for user separation?**
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![CDF of Measured Indoor Demmel Condition Number](image)

**2.4GHz**  **5.8GHz**
Indoor Scenario

**Will UHF propagation allow for user separation?**

- Previous capacity results confirm
- Verify with Condition Number

![Graph showing CDF of Measured Indoor Demmel Condition Number for UHF, 2.4GHz, and 5.8GHz bands.](image)
Indoor Scenario

• **Will UHF propagation allow for user separation?**
  - Previous capacity results confirm
  - Verify with Condition Number
  - Similar H matrix conditioning yields similar capacity

![Graph showing measured indoor Demmel condition number for UHF, 2.4GHz, and 5.8GHz frequencies.](image)
Indoor Scenario

- **Will UHF propagation allow for user separation?**
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![Graph showing CDF of measured indoor Demmel Condition Number for UHF, 2.4GHz, and 5.8GHz bands.](image)
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- Models: **Indoor** 5.8 GHz and **Outdoor** UHF
Indoor Scenario

- **Will UHF propagation allow for user separation?**
  - Previous capacity results confirm
  - Verify with Condition Number
  - Similar H matrix conditioning yields similar capacity

- Models: **Indoor** 5.8 GHz and **Outdoor** UHF

*User separability is Environment Dependent, not band dependent*
Indoor Scenario

- Does the UHF MU-MIMO channel actually stay stable?
Indoor Scenario

• **Does the UHF MU-MIMO channel actually stay stable?**
  • Successful BF confirms
    • Atleast for WARPLab latency
Indoor Scenario

- **Does the UHF MU-MIMO channel actually stay stable?**
  - Successful BF confirms
    - Atleast for WARPLab latency
  - Verify with Temporal Correlation
Indoor Scenario

Does the UHF MU-MIMO channel actually stay stable?

- Successful BF confirms
  - Atleast for WARPLab latency
- Verify with Temporal Correlation

![Measured Indoor Temporal Correlation]

- 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
- 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

Correlation Coefficient

Time (s)
Indoor Scenario

• **Does the UHF MU-MIMO channel actually stay stable?**
  • Successful BF confirms
  • Atleast for WARPLab latency
  • Verify with Temporal Correlation

![Measured Indoor Temporal Correlation](image)
Indoor Scenario

Does the UHF MU-MIMO channel actually stay stable?

- Successful BF confirms
  - Atleast for WARPLab latency
- Verify with Temporal Correlation

Measured Indoor Temporal Correlation

Correlation Coefficient vs Time (s)

2.4GHz, 5.8GHz
Indoor Scenario

- **Does the UHF MU-MIMO channel actually stay stable?**
  - Successful BF confirms
    - Atleast for WARPLab latency
  - Verify with Temporal Correlation

![Measured Indoor Temporal Correlation](chart.png)

- **UHF**
- **2.4GHz**
- **5.8GHz**
Indoor Scenario

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  - UHF: low channel variability even at 802.11 Beacon Interval
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![Temporal Correlation Graph](image-url)

![UHF, 2.4GHz, 5.8GHz Correlation Coefficient vs Time](image-url)
Indoor Scenario

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- Models: **Indoor** 5.8 GHz and **Outdoor** UHF
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  ![Temporal Correlation](chart)

- Models: **Indoor** 5.8 GHz and **Outdoor** UHF

**Channel variability is band dependent**
Indoor Scenario

- **Relevance of MU-MIMO channel stability for protocol design**
Indoor Scenario

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  - MU-MIMO provides spectral efficiency
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![Diagram showing transmission and reception signals with time intervals]
Indoor Scenario

- **Relevance of MU-MIMO channel stability for protocol design**
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![Diagram](image_url)

**SOUND**
(500us)
• **Relevance of MU-MIMO channel stability for protocol design**
  - MU-MIMO provides spectral efficiency
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Indoor Scenario

**Relevance of MU-MIMO channel stability for protocol design**

- MU-MIMO provides spectral efficiency
- Setup/overhead for transmission?

- Less channel variability -> *less per packet sounding*
Indoor Scenario

- **Relevance of MU-MIMO channel stability for protocol design**
  - MU-MIMO provides spectral efficiency
  - Setup/overhead for transmission?

- **UHF allows for the gains of MU-MIMO with significantly less protocol overhead**

- Less channel variability -> *less per packet sounding*
Conclusion

• Design open UHF-MU-MIMO platform for side-by-side comparisons of UHF/2.4GHz/5GHz bands
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• WURC:
Conclusion

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• Our experiments confirm that UHF-band MU-MIMO exhibits decreased channel variability; however, they show that user separability is equivalent to 2.4/5GHz.
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  - **Channel Variability**\(\rightarrow\) Band dependent
Conclusion

• Design open UHF-MU-MIMO platform for side-by-side comparisons of UHF/2.4GHz/5GHz bands

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  • Channel Variability -> Band dependent
  • User Separability -> Environment dependent
Conclusion

• Design open UHF-MU-MIMO platform for side-by-side comparisons of UHF/2.4GHz/5GHz bands

• WURC:

• Our experiments confirm that UHF-band MU-MIMO exhibits decreased channel variability; however, they show that user separability is equivalent to 2.4/5GHz.
  • Channel Variability-\(\rightarrow\) Band dependent
  • User Separability-\(\rightarrow\) Environment dependent

• Thus, UHF-MU-MIMO leverages benefits of decreased channel variability (lower sounding rate) without suffering from decreased user separability