Decoupling Beam Steering and User Selection for Scaling Multi-User 60 GHz WLANs

Yasaman Ghasempour and Edward Knightly
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60 GHz WLANs

• **Capabilities and propagation characteristics**
  - 7-14 GHz available unlicensed bandwidth
  - 20-40 dB increased signal attenuation
60 GHz WLANs

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  o 7-14 GHz available unlicensed bandwidth
  o 20-40 dB increased signal attenuation

• **Directional transmission**
  o Small form factor with mm-scale antennas
  o Standardized via IEEE 802.11ad
  o Up to 7 Gbps data rate
Goal

• **Enabling multi-user directional transmission**
  o Opportunity for spatial reuse
  o Simultaneous downlink transmission
  o Scaling total throughput
  o Which users and which beams (directions)?
Multi-user 60 GHz system model

- Multi-RF chain AP
Multi-user 60 GHz system model

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- Each RF chain is connected to multiple antennas (vs. one in 2.4/5 GHz)
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- Capable of analog beam steering
- Capable of digital precoding

![Diagram showing AP, RF chains, and phase shifters connected to an antenna array.](image-url)
Multi-user 60 GHz system model

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- Each RF chain is connected to multiple antennas (vs. one in 2.4/5 GHz)
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Key steps before a MU transmission

- Selecting users to be served (G)
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• Selecting users to be served (G)
• Transmit and receive analog beamforming vectors
• Digital beamforming weights ($F_{BB}$)

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\begin{align*}
    w_{u,tx} &\in \mathbb{C}^{N_{AP} \times 1} \\
    w_{u,rx} &\in \mathbb{C}^{N_u \times 1}
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Achievable data rate

\[ R_{\text{sum}} (G) = \sum_{u=1}^{U} R_{u} (G, w_{u,tx}, w_{u,rx}, F_{BB}) \]
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- Maximizing sum-rate

\[ \{G^{\text{opt}}, w_{u,tx}^{\text{opt}}, w_{u,rx}^{\text{opt}}, F_{BB}^{\text{opt}}\} = \arg\max \sum_{u=1}^{U} R_u(G, w_{u,tx}, w_{u,rx}, F_{BB}) \]

- Constraints:
  - Analog beams limited to a codebook
  - No. of users limited to no. RF chains

\[ w_{u,tx} \in F, u = 1, 2, \ldots, U, \]
\[ w_{u,rx} \in W, u = 1, 2, \ldots, U, \]
\[ |G| \leq N_{RF}. \]
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• Requires jointly selection of users, RF beams and digital weights
• Requires channel state info of every client (channel size : \(N_{\text{AP}} \times N_u\))
• Prohibitively large training and feedback overhead
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Prior Work

Hybrid beamforming for 60 GHz MU transmissions\cite{1,2}
- For a given group of users $\rightarrow$ no user grouping
- Developing low-complexity algorithms for hybrid analog and digital beamforming
  Maximizing sum-rate considering the hardware limitation and channel specification with limited feedback
- No protocol for user selection

MU-MIMO in sub 6 GHz
- One antenna per RF chain $\rightarrow$ no analog beam steering, smaller channel size
- User grouping based on channel state info \cite{3}
- User grouping without channel info exploiting the rich scattering propagation environment below 6 GHz \cite{4}
- In contrast, we consider a different frequency band and node architecture

\cite{2} R.A. Stirling-Gallacher, et. al. Multi-user MIMO strategies for a millimeter wave communication system using hybrid beam-forming. ICC’15.
\cite{3} S. Sur, et. al. Practical MU-MIMO user selection on 802.11ac commodity networks. MobiCom 2016
\cite{4} N. Anand, et. al., Mode and user selection for multi-user MIMO WLANs without CSI. INFOCOM 2015.
Decoupling User and Beam Selection

- Choosing analog beams independent from potential user selection
Decoupling User and Beam Selection

- Choosing analog beams independent from potential user selection
- Sub-optimal approach
Decoupling User and Beam Selection

- **Single-User beam Training (SUT):**
  - Training every user individually
  - Repeat only when the old transmit/receive beams are not reliable

- **User selection**
  - Selecting a set of users
  - Right before a multi-user transmission

\[\text{SUT} \quad \text{U. S.} \quad \text{Data} \quad \text{U. S.} \quad \text{Data} \quad \cdots \quad \text{SUT} \quad \text{U. S.} \quad \text{Data}\]
Single-User beam Training (SUT)

- The AP and each user discover the best analog beam to communicate
- Beams are selected from a pre-determined codebook
- E.g. 802.11ad beam training
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Beam 16

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<td>3</td>
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</tr>
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<td>4</td>
<td>Beam 2</td>
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User Selection Framework

- Available info after SUT:
  - Beam ID selected for all users
  - Received SNR of SU transmission

- Two general classes for user selection:

  **Class I**: Only based on information acquired in SUT → Single-Shot ($S^2$)

  **Class II**: Collecting further info before choosing users
Single-Shot ($S^2$) user selection example

- Maximum beAm Separation ($S^2$-MAS)
  - Choosing users with maximum beam separation
  - Which user should be grouped with user 1?

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Single-Shot ($S^2$) user selection example

- Maximum beam Separation ($S^2$-MAS)
  - Choosing users with maximum beam separation
  - Which user should be grouped with user 1? **User 2**
Single-Shot ($S^2$) timeline

- **Phase 1**: SUT
- **Phase 2**: Single-shot user selection
- **Phase 3**: digital precoding, e.g. zero-forcing, to cancel any residual inter-user interference between selected users
Class II user selection

- Measuring interference before selecting a user
- Incremental user addition in multiple rounds
Class II user selection

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- Incremental user addition in multiple rounds
- In each round: Measuring interference of a set of candidate users
Class II user selection

• Measuring interference before selecting a user
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• At the end of each round:
  - Add user that provides the highest sum-rate boost when grouped with already selected users
  - If no such user is found → stop user selection
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- We call this class, Interference-aware Incremental (I²) user selection
I^2 user selection example

- Example: I^2-Partitioned multi-test (I^2-PM)
  - Assume U=9, N_{RF}=3
\(I^2\) user selection example

- Example: \(I^2\)-Partitioned multi-test (\(I^2\)-PM)
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  - Assume the prime user index=1 \(\rightarrow G=\{1\}\)
I^2 user selection example

- Example: I^2-Partitioned multi-test (I^2-PM)
  - Assume U=9, N_{RF}=3
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- Steps:
  1. Sort users based on achievable SNR via selected beams in SUT
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Sorted users:

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- **Steps:**
  1. Sort users based on achievable SNR via selected beams in SUT
  2. Partitions into $N_{RF}$ batches

Sorted users

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<td>4</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
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I² user selection example

• Example: I²-Partitioned multi-test (I²-PM)
  - Assume U=9, N_{RF}=3
  - Assume the prime user index=1 \Rightarrow G=\{1\}

• Steps:
  1. Sort users based on achievable SNR via selected beams in SUT
  2. Partitions into N_{RF} batches
  3. Find the prime user

Sorted users

Batch 1 Batch 2 Batch 3

Sorted users:

6 2 1 8 4 7 3 9 5
\(I^2\) user selection example

- **Example:** \(I^2\)-Partitioned multi-test (\(I^2\)-PM)
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**Candidate users**

- **Candidate users for round 1**
  - Batch 1: 6, 2, 1
  - Batch 2: 8, 4, 7

- **Candidate users for round 2**
  - Batch 3: 3, 9, 5
I² user selection timeline

Phase 1 (SUT)  

Sorted users

Batch 1
Candidate users for round 1

Batch 2
Candidate users for round 2

Batch 3

User addition

Data Tr.

Phase 1 (SUT)
# User Selection Framework - Summary

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<th>Interference-aware Incremental ($I^2$)</th>
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<tr>
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<td>Interference measurements</td>
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<td>One-shot</td>
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  - Lower complexity |
  - Zero grouping overhead |
  - Higher complexity |
  - Higher overhead |
| Example: $S^2$-MAS | Example: $I^2$-PM |
Benchmarking algorithms

- **Exhaustive Joint**: Exhaustively test all user-beam combinations
- **Exhaustive Decoupled**: - SUT for beam selection
  - Exhaustively test all user combinations

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<td>$U \times (F \times W)$</td>
<td>$\left(\frac{U}{N_{RF}}\right) \times (N_{RF} - 1)$</td>
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Testbed

- Commercial 60 GHz VubIQ transceivers
- WARP v1 boards with only one RF chain
- Horn antennas instead of phased array
- Using NYU channel model to validate RSS with over the air measurements
- Extensive measurements: over 10000 measurements varying receiver location, antenna orientation, antenna beamwidth
Performance loss due to decoupling

• Comparing “exhaustive joint” and “exhaustive decoupled” algorithms
• Scenario: $U=20$, $|F|=24$, $N_{RF}=2,3,4$, $|W|=1$
• Two different extremes: all users having LOS or NLOS connectivity
• $R_j$: Achievable sum-rate via Exhaustive joint algorithm
• $R_d$: Achievable sum-rate via Exhaustive decoupled algorithm
• Metric 1: $R_d/R_j\%$
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Joint User-Beam Selection vs. Decoupled

• $R_d/R_j \% > 95$
• $R_d/R_j \%$ slightly decreases with increasing number of RF chains
• Increasing no. RF chains → group size increases → higher inter-user interference

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Decoupling beam steering and user selection results in 5% capacity loss with 4 streams. The capacity loss increases in NLOS case and as the group size increases.

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$S^2$ and $l^2$ user selection comparison

- Scenario: $U=40$, $N_{RF}=2,3,4,5$, $|F|=32$, $|w|=4$
- LOS connectivity
\(S^2\) and \(l^2\) user selection comparison

- Scenario: \(U=40, N_{RF}=2,3,4,5, |F|=32, |w|=4\)
- LOS connectivity
- SUT for beam selection
- \(S^2\)-MAS, \(l^2\)-PM for user selection
- Random and Exhaustive decoupled user selection strategies for comparison
- Zero-forcing as digital precoding scheme
S² and I² user selection comparison

- Random selection can yield to choosing users with significant overlapping beam
$S^2$ and $l^2$ user selection comparison

- Random selection can yield to choosing users with significant overlapping beam
- MAS makes sure that users with separated beams are chosen
S² and I² user selection comparison

- Random selection can yield to choosing users with significant overlapping beam
- MAS makes sure that users with separated beams are chosen
- With $N_{RF}=2$, MAS >70 % of Exhaustive approach
- With $N_{RF}=5$, MAS <50 % of Exhaustive approach
S^2 and I^2 user selection comparison

- Random selection can yield to choosing users with significant overlapping beam
- MAS makes sure that users with separated beams are chosen
- With N_{RF}=2, MAS >70 % of Exhaustive approach
- With N_{RF}=5, MAS <50 % of Exhaustive approach
- I^2-PM never loses capacity due to an additional RF chain at the AP
For smaller group size, the single-shot user selection policies can provide around 70% of the maximum possible PHY capacity with zero grouping overhead.
Conclusion

• Joint selection of users and beams requires prohibitively large training and feedback overhead.

• We introduced decoupling user and beam selection for multi-user 60 GHz WLANs.

• Decoupling beam steering and user selection results in 5% capacity loss with 4 streams. The capacity loss increases in NLOS case and as the group size increases.

• We introduced and evaluated two structures, $S^2$ and $I^2$ for user selection in the decoupled framework.

• For smaller groups, the single-shot user selection policies can provide around 70% of the maximum possible capacity with zero grouping overhead.
If you have any questions, email me at ghasempour@rice.edu