A Scalable Multi-User Uplink for Wi-Fi

Adriana B. Flores
Sadia Quadri, and Edward W. Knightly

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Start of Wi-Fi

- Standardized in 1997
- SISO
- Single user at a time
- Omni-directional transmission
MIMO in 802.11

- Multiple concurrent transmissions
- MxN MIMO increases throughput by $\min(Tx\ antennas, \ Rx\ antennas)$
MIMO in 802.11

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Antenna Asymmetry

• MxN MIMO increases throughput by \( \min(Tx \text{ antennas}, Rx \text{ antennas}) \)
• Client devices often have \( N=1 \) antenna due to cost and space
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Downlink Multi-User MIMO

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- Downlink Multi-User MIMO allows for APs to leverage antennas
- Transmitter sends multiple streams concurrently to different users
- Remove Interference by “Zero-Forcing Beamforming” (ZFBF)
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Uplink Multi-User MIMO?

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• Back to 1997 – SISO transmission
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Why Not Mimic Downlink MU-MIMO?

• Paradigm Shift
• Many $\rightarrow$ One
• No connection between devices
• How do we remove interference?
MUSE: **Multi-User Scalable** Uplink

- Match the number of transmitters to the number of antennas at AP
- No control signaling

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MUSE: Multi-User Scalable E Uplink

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MUSE: Multi-User Scalable Uplink

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- Multiple transmitters act as a single device with multiple antennas
  - No control channel
  - Remove interference

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Transmit Simultaneously

- **Association ID** for user selection and grouping
- **Arbitrary index** for each user
- AP informs the network the Max ID

![Diagram of AP Receiver and Users]

**Rx AP**

**User 1**

**User 2**

**User 3**

**User 4**

**User 5**

**User 6**

**User 7**

**Time**
Transmit Simultaneously

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![Diagram showing AP Receiver and users with associated IDs and data transmission]

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![Diagram](image-url)

- AP Receiver
- Circular ID Vicinity
- Association ID for user selection and grouping
- Arbitrary index for each user
- AP informs the network the Max ID

![Timeline Diagram](image-url)

- Rx AP
- User 1
- User 2
- User 3
- User 4
- User 5
- User 6
- User 7

**Data**

Time
Transmit Simultaneously

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![Diagram showing simultaneous transmission with AP receiver and user connections]
Remove Interference

- Environmental Multipath
- Independent paths (channels)
- Receiver (AP) estimate channels
Remove Interference

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- Independent paths (channels)
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Receiver Channel Estimation

• Known set of training signals
• Enable distributed usage
• Fixed size (# Streams = # Rx antennas)
• User has assigned set of training signals
• Assignment through Association ID
• No control signaling (coordination) required
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Group Adaptation

- **Association ID** Reassignment
- AP learning process: which users are most likely to transmit

![Diagram showing AP Receiver and associated devices with association IDs over time](image)
Group Adaptation

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Group Adaptation

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MUSE Implementation

• OTA experiments WARPLab
• 1 to 4 concurrent spatial streams

Evaluation Setup:
  • Clients: single WARP board with independent RF clocks
  • Time synchronized through triggering cables
  • Conference room 645 sq ft or 60 sq m
  • Evaluate over 20 locations
MUSE Scalability

- Scalability can be limited by inter-stream interference and channel correlation between users
- MUSE PHY ability to achieve full-rank capacity and permit scaling

Setup:
- 1x1, 2x2, 3x3, 4x4
- 2000 packets
- 24 Mbps
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Tx Beamforming is **NOT** needed for distributed uplink multi-user transmission
MUSE Scalability

- Empirical capacity with estimated channels

\[ C(\text{bps/Hz}) = \log_2[\det(I_N + (\text{SNR}/M)(HH^*))] \] [1]

Graph showing capacity vs. SNR for different MUSE configurations:
- MUSE 1x1
- MUSE 2x2
- MUSE 3x3
- MUSE 4x4

SNR (dB) vs. Capacity (bits/s/Hz)

193 Mbps to 669 Mbps

Conclusion MUSE

- **Scalable** Multi-User MIMO uplink WLAN
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**Emulate Single Multi-Antenna device**
- Transmit Simultaneously
- ID-Based Grouping and Synchronization
- Enable distributed and dynamic Rx channel estimation
- Leverage environmental multipath
- Standard compatible
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