MUTE: Sounding Inhibition for MU-MIMO WLANs

Oscar Bejarano  
Rice University

Eugenio Magistretti  
Rice University

Omer Gurewitz  
Ben Gurion University

Edward W. Knightly  
Rice University

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Single-Antenna Systems (Downlink)

802.11-Based Networks
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802.11-Based Networks
Multi-Antenna Systems (Downlink)

802.11-Based Networks
Multi-Antenna Systems (Downlink)

802.11-Based Networks
Multi-Antenna Systems (Downlink)

**Motivation**

**Multi-User MIMO**
- Spatial multiplexing
- Simultaneous spatial sharing of medium by multiple users
- Sum capacity scales with $\min(M, \sum N_k)$

**Similarly to SU-MIMO**
- Increases spectral efficiency

**In contrast to SU-MIMO**
- As many users as antennas at AP
- Multiplexing gain at AP even with minimal number of antennas in users

Multi-User MIMO

Extensive body of literature (theoretical and recent experimental work) has demonstrated **vast capacity gains**

- Large PHY gains
- MAC not considered

<table>
<thead>
<tr>
<th>Experimental</th>
<th>Theoretical</th>
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<tbody>
<tr>
<td>Aryafar’10</td>
<td>Venkatesan’03</td>
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The Problem

Costly overhead
The Problem

Costly overhead

Signal precoding enables MU-MIMO transmissions

- Channel State Information at Transmitter (CSIT) necessary
- Beam-steering weight computation (for inter-stream interference cancellation)
- Obtained via *sounding*
The Problem

We demonstrate that the costs required to enable MU-MIMO can outweigh the benefits:

- Sounding process in current MU-MIMO systems is expensive and inefficient
- MAC enhancements necessary
- Large gap between innovative theoretical tools and protocol design

Our Objective

To provide a protocol-based framework that guarantees the benefits of MU-MIMO outweigh costs, with the goal of realizing PHY gains at the system level.
We propose **MUTE**

MUTE addresses the issue of overhead associated with channel sounding

- Temporarily inhibits sounding based on channel stability
- Leverages presence of static users and epochs characterized by slowly moving channels
- Best case: MU-MIMO transmissions without preceding channel sounding
- Worst case: Basic 802.11ac behavior
Roadmap

- Motivation
- Sounding process in MU-MIMO
- Sounding overhead reduction via sounding inhibition
  - Design of MUTE
  - Evaluation of MUTE
- Conclusion
IEEE 802.11ac Sounding Timeline

Null Data Packet Announcement: inform which users will be served next
IEEE 802.11ac Sounding Timeline

Null Data Packet: sound users (training sequences)
Compressed Beamforming Report: channel information for each user
Report poll: request beamforming report from each user
IEEE 802.11ac Sounding Timeline

Repeat for the remaining users
We demonstrate sounding overhead has a significant impact on the overall system performance.
IEEE 802.11ac Sounding Overhead Analysis

Metric

Fraction of airtime consumed by sounding overhead

Sounding

Data transmission

Parameters

Maximum subcarrier grouping
Minimum quantization bits
Packet Size 1500 bytes
IEEE 802.11ac Sounding Overhead Analysis

No frame aggregation

20 MHz Channel

80 MHz Channel

>70%
IEEE 802.11ac Sounding Overhead Analysis

18 kB aggregation

Frame Aggregation†

- Larger packets by aggregating frames to amortize overhead
- However, depends on traffic demands, contention, delay and channel stability

IEEE 802.11ac Sounding Overhead Analysis

96 kB aggregation

Frame Aggregation†
- Larger packets by aggregating frames to amortize overhead
- However, depends on traffic demands, contention, delay and channel stability

IEEE 802.11ac Sounding Overhead Analysis

Metric

Goodput

# of bits transmitted
Sounding time + Data transmission time

AP

Per-User Goodput (Mbps)

Frame Aggregation (Frames)

80 MHz

0 50 100 150 200 250 300 350 400

0 10 20 30 40 50 60

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IEEE 802.11ac Sounding Overhead Analysis

Metric
Goodput

# of bits transmitted
Sounding time + Data transmission time

AP

Per-User Goodput (Mbps)

Frame Aggregation (Frames)

80 MHz

2 Users MU−MIMO
2 Users SISO

SECON 2014

Bejarano
IEEE 802.11ac Sounding Overhead Analysis

**Metric**

Goodput

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**Per-User Goodput (Mbps)**

- **80 MHz**

  - 2 Users MU-MIMO
  - 2 Users SISO

**Costs** can outweigh the **benefits**
Roadmap

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Sounding Inhibition (MUTE)

Understanding MUTE

MUTE evaluates two key tradeoffs

Tradeoff 1:
Extensive channel knowledge at the AP VS increased sounding overhead

Tradeoff 2:
High channel estimate accuracy VS increased sounding overhead
**Sounding Inhibition (MUTE)**

**Tradeoff 1:**

- **Extensive channel knowledge at the AP** VS increased sounding overhead
  - Leverage User Diversity

  - Sound and serve 2 users (possibly correlated*), OR
  - sound all users and serve the rate maximizing group (orthogonal/semi-orthogonal)
  - **However**, prohibitive to sound more than 4 users

*NOTE: Notice, this correlation happens in signal space*
Sounding Inhibition (MUTE)

User Diversity - Find users with orthogonal/semi-orthogonal channels

Topology
One 4-antenna AP
30 single-antenna users

Experiment
1) Sound N random users (uniform distr.)
2) Choose the K users that maximize rate
Sounding Inhibition (MUTE)

User Diversity - Find users with orthogonal/semi-orthogonal channels

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One 4-antenna AP
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K = 4
N = 4 to 10
Sounding Inhibition (MUTE)

User Diversity - Find users with orthogonal/semi-orthogonal channels

Topology
One 4-antenna AP
30 single-antenna users

Experiment
1) Sound N random users (uniform distribution)
2) Choose the K users that maximize rate

Clear benefit from an increased number of monitored/sounded users

N = 4 to 10
Tradeoff 2:

High channel estimate accuracy VS increased sounding overhead

**Accuracy** - Channel estimates degrade with time, specially in highly mobile environments

VS

**Sounding Overhead** - Costly to sound every time before a transmission
Sounding Inhibition (MUTE)

MUTE strives to use the most accurate information available from as many users as possible while minimizing sounding overhead to guarantee a net throughput gain.

However, a fundamental change in traditional systems is needed.
Sounding Inhibition (*MUTE*)

Who to sound?

Traditional system - *sounding user set selection* coupled with *transmission user set selection*

Who to serve?
Sounding Inhibition (MUTE)

Traditional system - sounding user set selection coupled with transmission user set selection

Schedule transmissions for 4 users
Sounding Inhibition (MUTE)

Traditional system - sounding user set selection coupled with transmission user set selection

Sound all same 4 users

High overhead
Sounding Inhibition (MUTE)

Traditional system - sounding user set selection coupled with transmission user set selection

Serve all same 4 users

Poor user grouping
Sounding Inhibition (*MUTE*)

In contrast…
Sounding Inhibition (MUTE)

Traditional system - sounding user set selection coupled with transmission user set selection

Schedule transmissions for 4 users
Sounding Inhibition (MUTE)

Traditional system - sounding user set selection coupled with transmission user set selection

MUTE

decoupled from

Sound a subset of those 4 users, e.g., 2 in this case

Low overhead
Sounding Inhibition (*MUTE*)

**Traditional system** - sounding user set selection coupled with transmission user set selection

> Use previously collected channel statistics to select a better option

Serve a new set of users. Leverage user diversity based on historical information the AP already has

Rate Maximization
Sounding Inhibition (MUTE)

- Traditional system - sounding user set selection coupled with transmission user set selection
- Use previously collected channel statistics
- Serve a new set of users. Leverage user diversity based on historical information the AP already has
- Rate Maximization

MUTE

decoupled from
Therefore, a decoupled system:

- Allows the AP to sound only the users that need to be sounded
- Enables the AP to serve only the set of users that maximizes the aggregate rate
Sounding Inhibition (MUTE)

In MUTE, the AP relies on channel statistics to decide which users to sound.

Two Empirical Observations

- Variation in most recent samples provides insights into near-future samples (e.g., [1-5])
- Collected samples in static channels degrade similarly with time (e.g., coherence time)

We enable the AP to assess the tradeoff between predicted channel volatility and rate penalty due to inaccurate CSIT.

References:

Two Empirical Observations:

Variation in most recent samples provides insights into near-future samples

Collected samples in static channels degrade similarly with time

age: analogous to concept of coherence time
Sounding Inhibition (MUTE)

In principle, MUTE determines how much the last collected sample is expected to vary

- AP computes magnitude and phase change between each collected sample and selects relevant samples
  - Most recent samples
  - Samples within certain age

- Compute sample variance
- If variance above threshold, sound user (per-user threshold)
Roadmap

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Our evaluation answers the following question:

Can MUTE strike a balance between *overhead suppression* and *rate penalty* due to inaccurate channel estimates?
Experimental Evaluation of MUTE

- Comprehensive channel measurement collection (indoor static, dynamic, and mobile environments)

- Trace-driven emulation
  - Complete downlink zero-forcing beamforming system

- Flexible system, replay channels for different schemes

802.11ac timings
Experimental Evaluation of MUTE

Setup

- Benchmark
  - Always sound
  - Most updated information

- MUTE - Two tolerance levels
  - Set threshold to allow close to 2 bps/Hz loss
  - Set threshold to allow close to 1 bps/Hz loss
  - Tradeoff: overhead reduction vs rate loss

- Environments
  - Static - Static users and static environments
  - Dynamic - Static users and dynamic environments
Experimental Evaluation of MUTE

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Experimental Evaluation of MUTE

Evaluation of rate penalty due to infrequent sounding

- **Setup**
  - Overhead *not* considered
  - 4x4 system
  - 30-user topology
  - Compute rate loss
Experimental Evaluation of MUTE

Evaluation of rate penalty due to infrequent sounding

- **Setup**
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![Graph showing Per-User Rate (bps/Hz) for Static and Dynamic scenarios for MUTE 2bps/Hz tolerance, MUTE 1bps/Hz tolerance, and Benchmark.]
Experimental Evaluation of MUTE

Evaluation of rate penalty due to infrequent sounding

- Setup
  - Overhead not considered
  - 4x4 system
  - 30-user topology
  - Compute rate loss
- Penalty inversely proportional to overhead reduction
  - Smaller penalty in dynamic — more conservative
  - Higher penalty in static — less conservative
- Accurately tune how much we are willing to sacrifice in terms of rate performance
Experimental Evaluation of MUTE

Evaluation of overall throughput performance

- Setup
  - Overhead considered
  - 4x4 system
  - 30-user topology
  - 1.5 to 18 kBytes aggregation
  - Compute xput gain compared to benchmark

Significant gains in different environments
- Near 70% gains, and 30% even with large frame aggregation
- Close to 50% gains in dynamic

MUTE adapts to provide balance between overhead and estimate accuracy
Experimental Evaluation of MUTE

Evaluation of overall throughput performance

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![Throughput Gain Chart]

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- MUTE adapts to provide balance between overhead and estimate accuracy
Experimental Evaluation of MUTE

MUTE attains a net throughput gain

- Gains originated from sounding overhead reduction dominate the losses incurred due to inaccurate channel estimates
Conclusion

Costs to enable MU-MIMO can outweigh the benefits

Even without considering losses due to inter-stream interference

Sounding overhead in 802.11ac can be detrimental to MU-MIMO performance

We demonstrate the feasibility of sounding inhibition in MU-MIMO networks

MUTE strikes a balance between overhead reduction and rate penalty due to inaccurate channel estimates
Thank you!