Resilient Multi-User Beamforming WLANs: Mobility, Interference, and Imperfect CSI

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From SISO to MIMO

IEEE 802.11n: 2009
600 Mbps
4x4 MIMO – 40 MHz – 64QAM
From SISO to MIMO

In $M \times N$ MIMO, capacity increases with $\min(M, N)$

$M$: # of TX antennas
$N$: # of RX antennas

Real World:
Low number of antennas due to form factor of mobile devices and cost
Multi-user MIMO

Simultaneous spatial sharing of medium by multiple users.

**Objective:** Remove the constraint on the # of antennas at client devices.

**Capacity Gain:** The system can serve as many users as antennas at the AP.

**MU-MIMO:** Beamforming at TX side.
The IEEE 802.11ac amendment (2013) specifies optional MU-MIMO operation: Maximum of four users and two spatial streams (SS) per user.

Throughput Gains
Shown in prior works: [Tse05, Yoo06, Aryafar10, Balan12, Shepard12]

However, in this work we identify one key challenge…
Inter-Stream Interference

In practice, the accuracy of beam-steering weights used to **precode the TX signal** depends on

- **User mobility**
- **Environmental mobility**
- **Quantization**
- **Out-of-cell interference**

**Challenge:**

High susceptibility of the MU-MIMO performance with **inter-stream (multi-user) interference.**
Design and evaluate one protocol to enable resilient MU-MIMO by removing the adverse effects of inter-stream interference due to outdated and inaccurate Channel State Information at Transmit Side (CSIT) using MU-MIMO bit rate selection and loss recovery.

CHRoME: Channel Resilient Multi-user beamforming
Roadmap

‣ Background and Motivation

‣ Protocol Description – CHRoME

Channel Resilient Multi-user bEamforming

Objective: reduce the effects of Inter-Stream Interference in the throughput.

‣ Protocol Evaluation:

Trace Driven Emulation using Over the Air Channel Measurements

‣ Conclusions
Ideal MU-MIMO scenario:

- Fully or partially suppressing of the interference to maximize the SINR at the users.

- **Accurate CSIT** for beam-steering weight calculation;

- **Beamformed transmission** within the channel coherence time.
Imperfect Bemforming: Inter-Stream Interference

Quantization
Out-of-cell interference

User mobility
Environmental mobility

Single stream

Multiple streams

Inaccurate CSIT

Throughput Penalty

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CHRoME

**CHannel Resilient Multi-user bEamforming** (CHRoME)

Avoids or resolves the problem of co-channel interference using:

**Inter-stream/Out-of-cell interference estimation and MCS adaptation:**

- Beamformed probing for “just-in-time” MCS selection prior to data transmission.

**Fast soundless recovery:**

- One-time fast retransmission with “liberated” antenna resources

MCS -> Modulation and Coding Scheme
MCS Selection in MU-MIMO

MCS must be reduced due to imperfect beamforming!!

Throughput ↓

MCS selection is increasingly more difficult for MU-MIMO compared to SU-MIMO:

- **SINR** depends on channels to other concurrent users;
- Inter-stream/out-of-cell interference need to be taken into consideration.`
MCS Selection in MU-MIMO

Baseline Protocol: *MCS selection based on CSIT*

[Halperin11, Shen12]

Transmitter learns channel matrix (vectors to all receivers) and infers the post processing SINR (e.g., projection onto null space of the vectors to the other users) to select the MCS.

**Drawbacks:**
- SINR depends on channels to other concurrent users
- Inter-stream/out-of-cell interference need to be taken into account.
Limitations... of CSIT-Based MCS Selection for data transmission

Illustrative example explicit feedback

Gradual CSI degradation + other factors

Channel observed at the user, which incorporates measured interference

Best MCS, and real channel unknown
The AP is not aware of any source of interference at users since CSI is obtained from previous uplink transmissions.
Limitations...

of CSIT-Based MCS Selection for data transmission

Illustrative example

explicit feedback

CHRoME - Introduces a mechanism for “just-in-time” multi-user MCS selection which implements a beamformed probe that captures the real channel observed at the users

Best (highest possible) MCS, and real channel unknown
**Probing-Based MCS Selection**

Short beamformed probing frame just prior to data transmission using previously collected CSI.

Users measure the precoded probe’s SINR and select the highest possible MCS (considering all current sources of interference).
Probing-Based MCS Selection

Feed back MCS selection:

PN Sequences

PN bit sequence: transport the MCS index
Advantages of PN Sequences:
• No decoding required (no preamble or data processing) 6.35 \( \mu \text{sec} \)
• Highly reliable (detected at low SINR, i.e., -6 dB)

Low feedback overhead introduced
CHRoME: Evaluation

Methodology

- Trace-Driven Emulation
- Emulation based on over-the-air channel measurements we collect
  - Enables repeatability for fair comparison
Evaluation

Methodology

Indoor channel traces - conference rooms/labs/offices environment

15,000+ frame transmissions per scheme
Evaluation

Methodology

Indoor channel traces - conference rooms/lab/office environment.
15,000+ frame transmissions per scheme

Very-High Throughput (VHT) 802.11ac frame
• 802.11ac timings
Probing-Based MCS Selection

MCS selection accuracy in real indoor channels

<table>
<thead>
<tr>
<th>MCS selection solely based on CSIT</th>
<th>Over-selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservatively decrease MCS</td>
<td>Under-selection</td>
</tr>
<tr>
<td>CHRoME</td>
<td>?</td>
</tr>
</tbody>
</table>

*Ground truth* found by measuring per subcarrier SINR during actual data transmission and mapping to MCS
Probing-Based MCS Selection

**BL** = Baseline CSIT-Based

**BLc** = Baseline CSIT-Based Conservative (BL-1)

**CH** = CHRoME

MCS selection accuracy

Out-of-cell interference
-70 to -90 dBm

Conclusions:
1. Higher accuracy of CHRoME compared to the baselines.
2. Much higher gain in implicit since the AP does not consider the interference at the STAs in CSI estimation.
Probing-Based MCS Selection

Basic Conclusion:

1. Much higher accuracy of CHRoME compared to the baselines since there is no interference and there is more room to make mistakes due to outdated CSI.

MCS selection accuracy

\[ \text{BL} = \text{Baseline CSIT-Based} \]
\[ \text{BLc} = \text{Baseline CSIT-Based Conservative (BL-1)} \]
\[ \text{CH} = \text{CHRoME} \]

No out-of-cell interference
Probing-Based MCS Selection

Percent gain of CHRoME
From 7% to 280%.

MCS selection accuracy (Throughput)

(Top)
Out-of-cell interference

(Bottom)
No out-of-cell interference

BL = Baseline CSIT-Based
BLc = Baseline CSIT-Based Conservative (BL-1)
CH = CHRoME

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Probing-Based MCS Selection

MCS selection accuracy (Adaptation response)

The baseline mostly overselects whereas CHRoME follows closely the ideal MCS selection
Retransmissions in 802.11-based networks

# TX antennas: 4
4 users with 1 Rx antenna each

Corrupted packets require re-contention after doubled backoff window and sounding the channel again

Packet loss + Additional time until retransmission → Stale CSI

High overhead introduced
MU-MIMO Fast Packet Recovery

Exploit \textit{liberated} antenna resources to obtain diversity and power gain, increasing robustness

Select configuration that minimizes the time to retransmit the corrupted packets

4x1 TDMA vs.

4x2 MU-MIMO
Fast Recovery: MCS Selection

The AP performs **MCS selection** based on the report of individual inter-stream interference components piggybacked in the ACK control frame.

ACK control frame piggybacks SINR for each individual stream.
Fast Recovery

**Advantages:** reduce the overhead

Obviate the need to re-sound the channel

Avoid doubling backoff window of CSMA mechanism.

**Disadvantages**

Neglect higher multiplexing gain during retransmission (e.g. 4x4 vs 4x2)

**Beamforming with Increasingly outdated CSIT**
Fast Recovery

802.11ac: always uses all DoF in re-tx and re-tx.is always *successful*

TDMA 4X1: diversity gain with overhead penalty.

MU-MIMO 4XR: retransmission to $R$ users with outdated CSI

![Graph showing throughput comparison between 802.11ac, 4xR MU-MIMO, and 4x1 TDMA across different numbers of users in retransmission set.

Similar performance of MU-MIMO and TDMA.

Performance depends on two major factors:

(i) Retransmission success rate;
(ii) Incurred overhead / overhead reduction.
CHRoME’s lowest throughput is at least that of the best performing scheme
Conclusions: CHRoME

Channel Resilient Multi-user beamforming

Probing-based MCS selection

MCS selection mechanism that assesses the channel and inter-stream interference affecting each user, and adapts rate accordingly

Fast, soundless MU-MIMO recovery

Immediate retransmission mechanism that precludes the need to re-sound the channel by leveraging liberated DoF at the transmitter

Take away message:
Incorporating knowledge with respect to co-channel interference into protocol decisions leads to substantial mitigation of its effects
Thank you for your kind attention!

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