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

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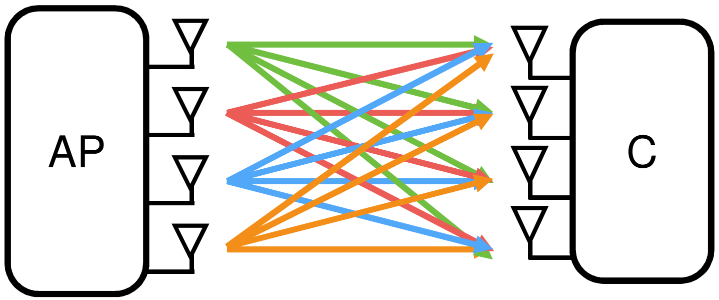
From SISO to MIMO

IEEE 802.11n: 2009

600 Mbps

4x4 MIMO – 40 MHz – 64QAM

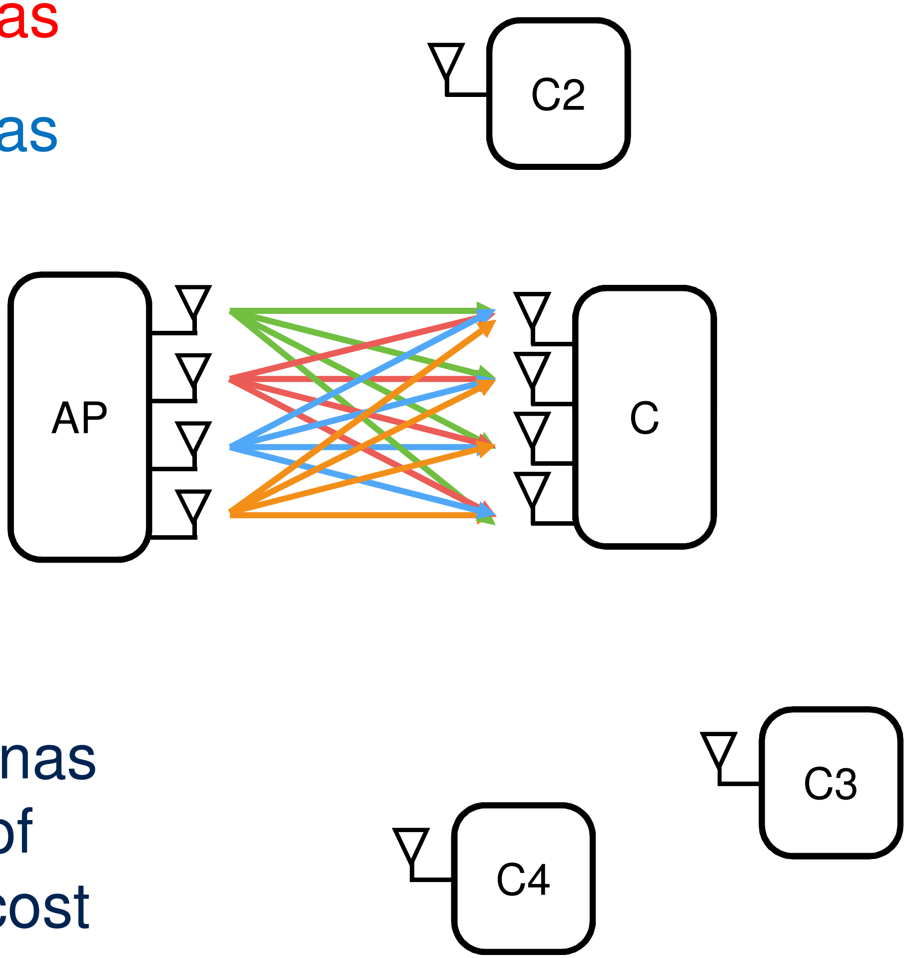


From SISO to MIMO

In **MxN** MIMO, **capacity increases** with *min(M, N)*

M: # of TX antennas

N: # of RX antennas



Real World:

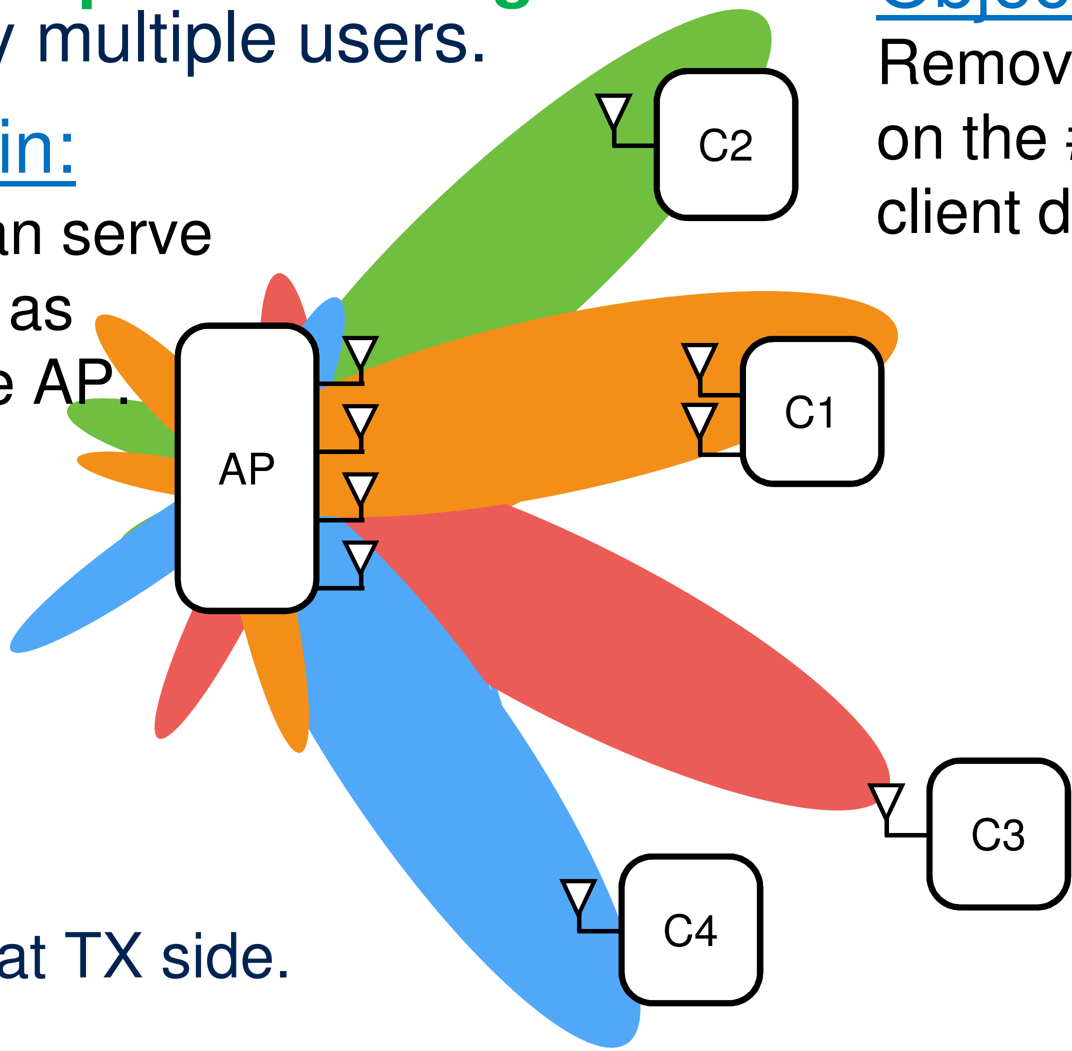
Low number of antennas due to form factor of mobile devices **and** cost

Multi-user MIMO

Simultaneous **spatial sharing** of medium by multiple users.

Capacity Gain:

The system can serve as many users as antennas at the AP.



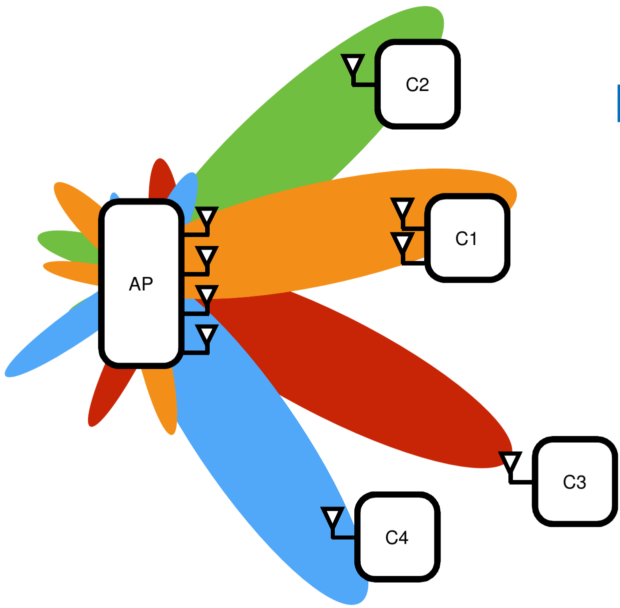
Objective:

Remove the constraint on the # of antennas at client devices.

MU-MIMO:

Beamforming at TX side.

Multi-user MIMO



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

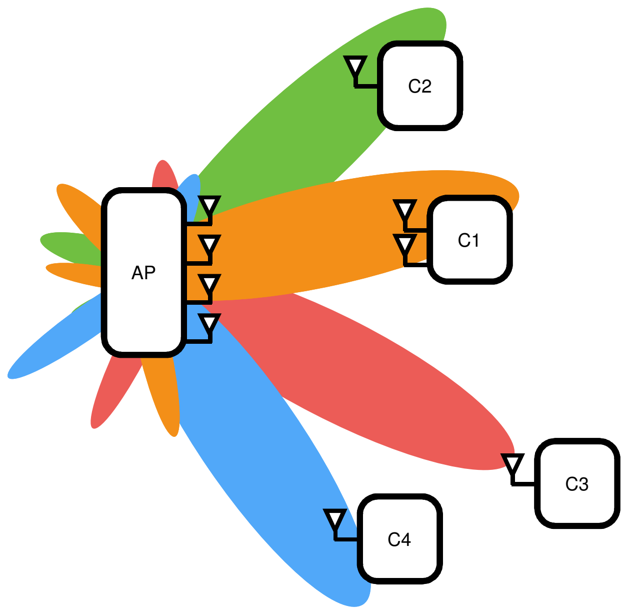
In practice, the accuracy of beam-steering weights used to **precode the TX signal** depends on

User mobility

Environmental mobility

Quantization

Out-of-cell interference



Challenge:

High susceptibility of the MU-MIMO performance with **inter-stream (multi-user) interference**.

Paper Contributions

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due to outdated and **inaccurate**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 b**E**amforming*

Roadmap

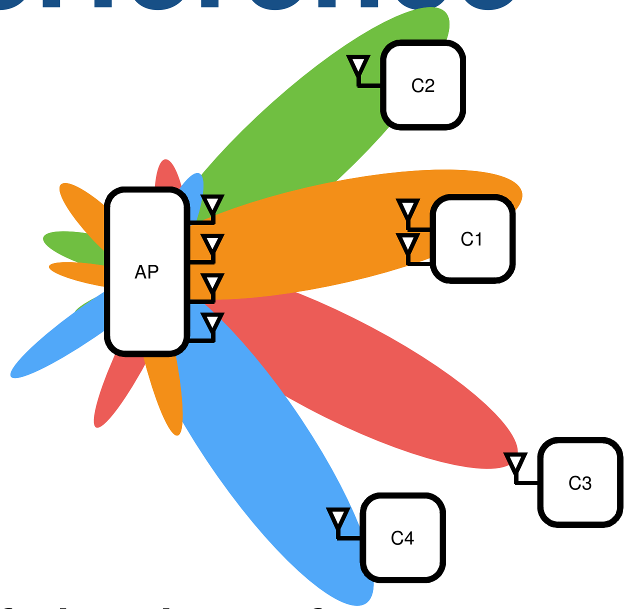
- Background and Motivation
- **Protocol Description – CHRoME**

  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**

Inter-Stream Interference



Ideal MU-MIMO scenario:

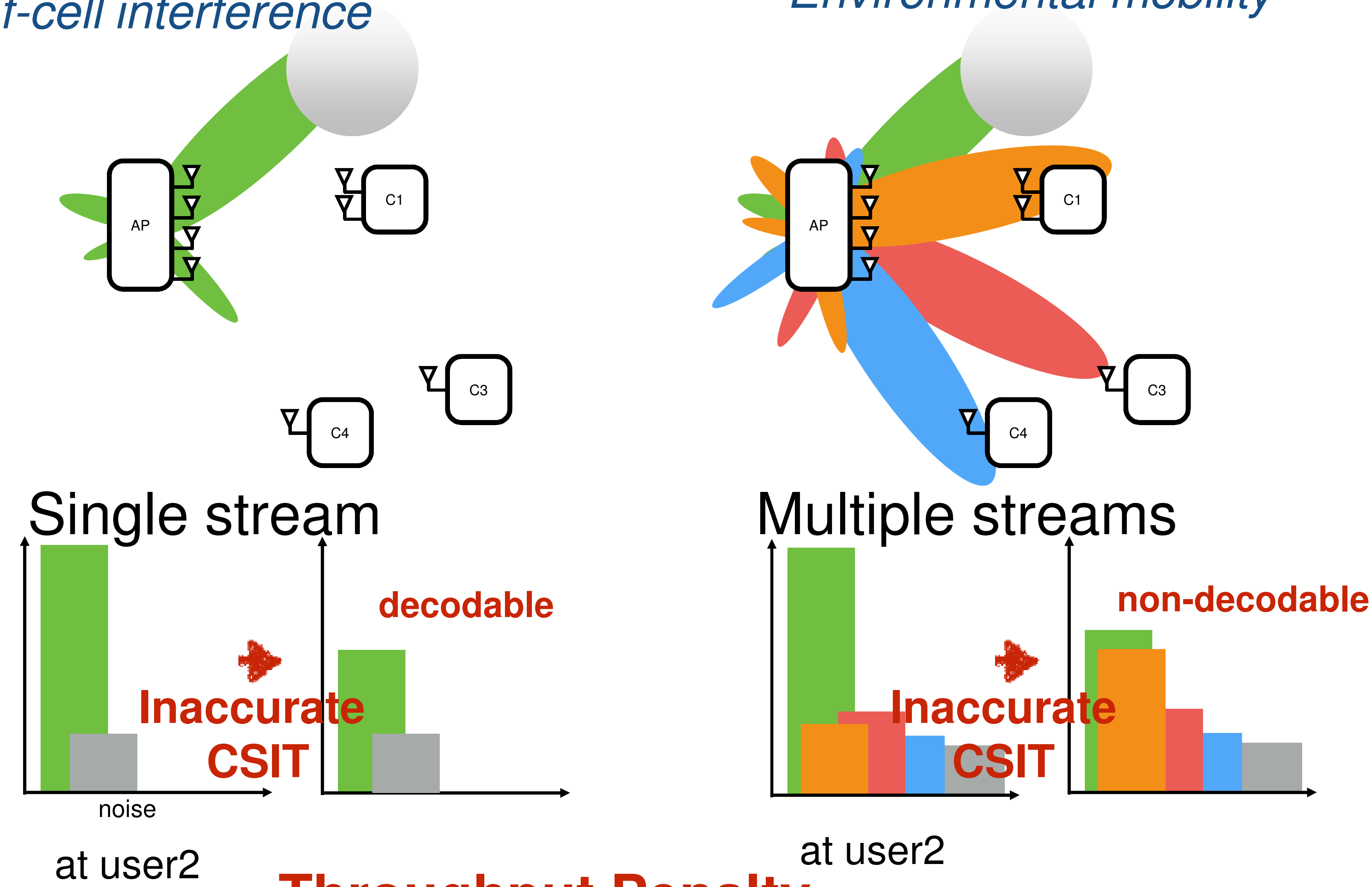
- Fully or partially suppressing of the interference to **maximize the SINR at the users**.
  - Accurate CSIT for beam-steering weight calculation;
  - **Beamformed transmission** within the channel coherence time.

Imperfect Bemforming:

Inter-Stream Interference

Quantization
Out-of-cell interference

User mobility
Environmental mobility



Throughput Penalty

CHRoME

CHannel **R**esilient **M**ulti-user b**E**amforming (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.**

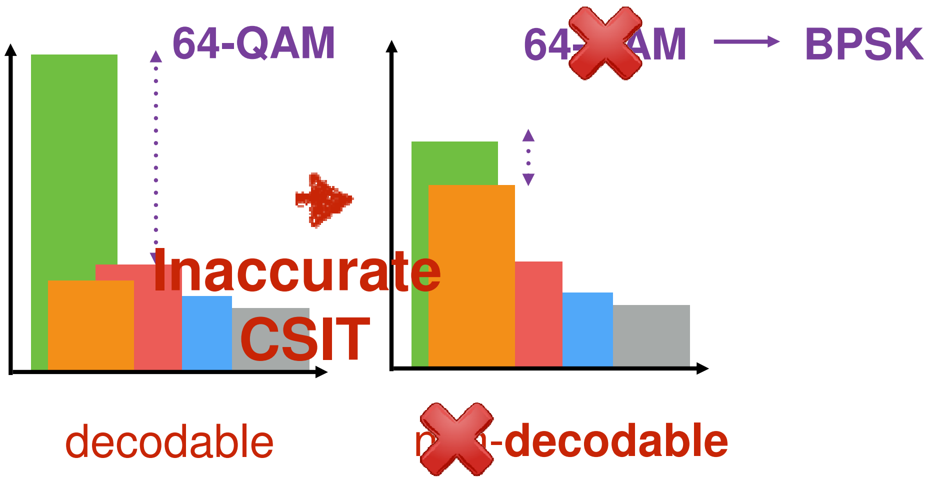
Fast soundless recovery:

- **One-time fast retransmission with "liberated" antenna resources**

MCS -> Modulation and Coding Scheme

MCS Selection in MU-MIMO

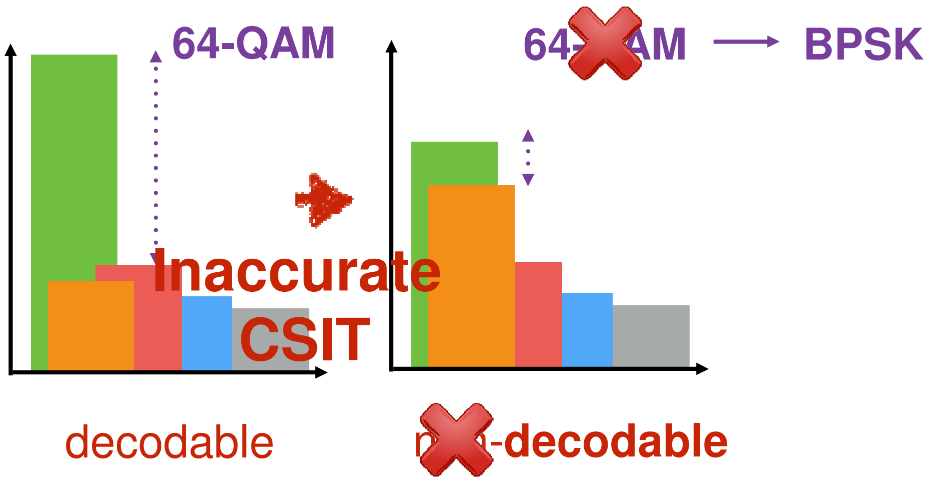
MCS
must be reduced
due to
imperfect beamforming!!
Throughput ↓



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



Basiline Protocol: ***MCS selection* based on *CSIT***

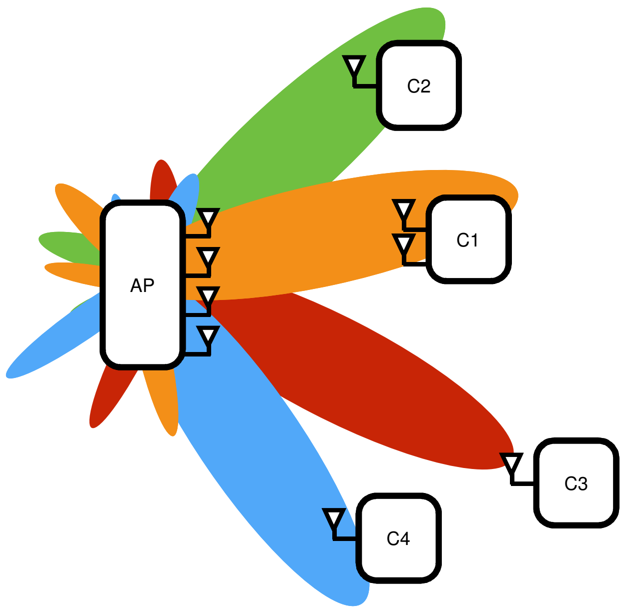
[Halperin11,Shen12]

Transmitter learns channel matrix (vectors to all receivers) and infers the post processing SÌNR (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.

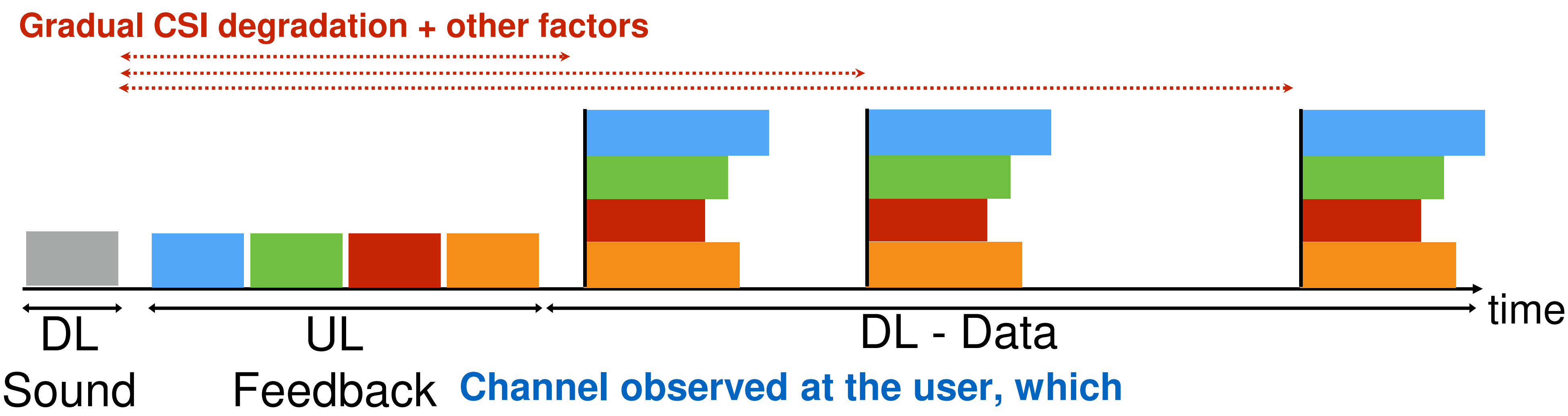


Limitations…

of CSIT-Based MCS Selection for data transmission

Illustrative example

explicit feedback

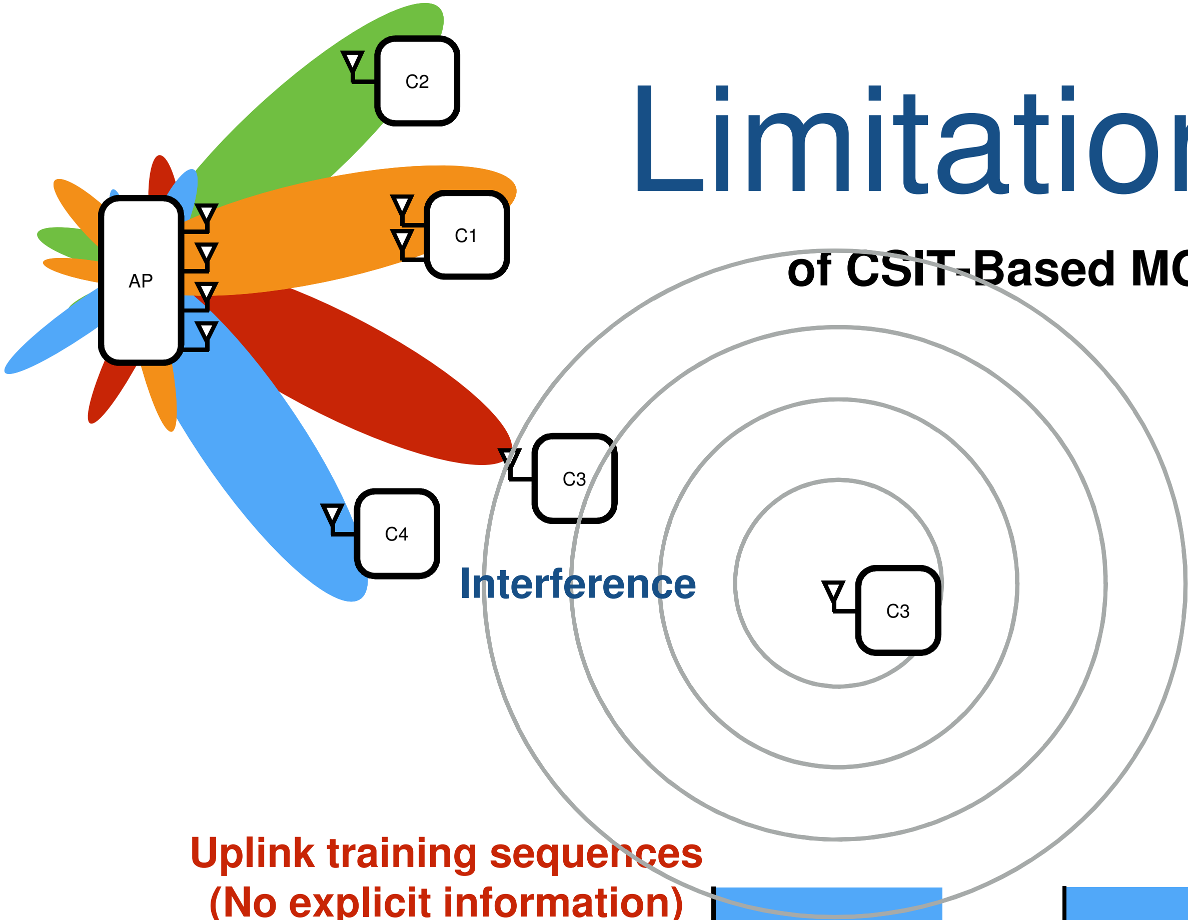


Channel observed at the user, which incorporates measured interference

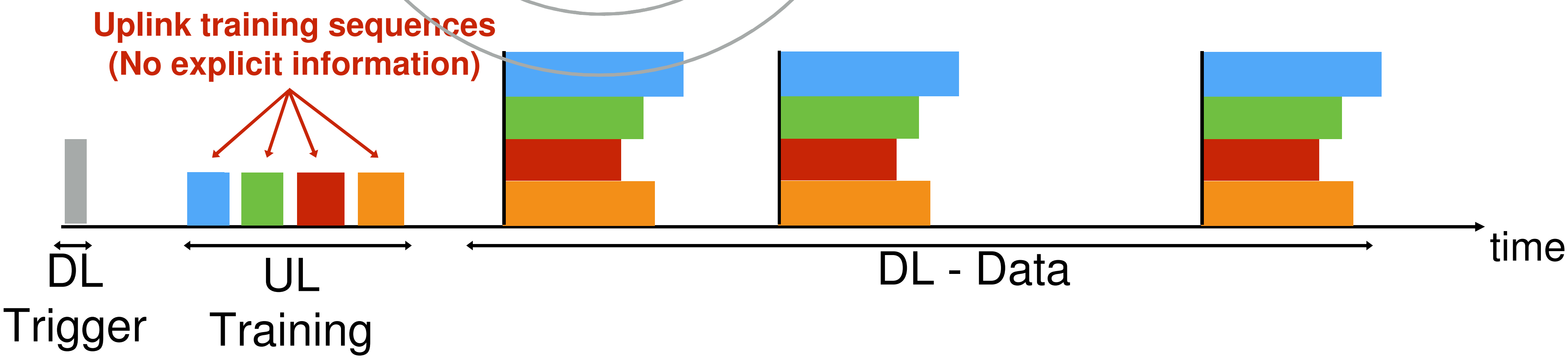
Best MCS, and *real* channel *unknown*

Limitations…

of CSIT-Based MCS Selection for data transmission



Illustrative example
implicit feedback



The AP is not aware of any source of interference at users ***since CSI is obtained from previous uplink transmissions***

Limitations…

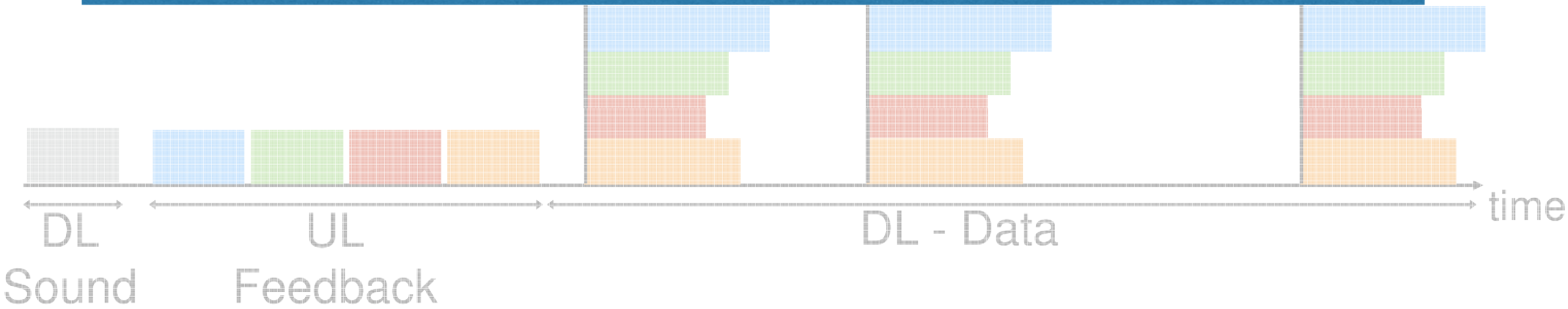
of CSIT-Based MCS Selection for data transmission

Illustrative example

explicit feedback

Gra

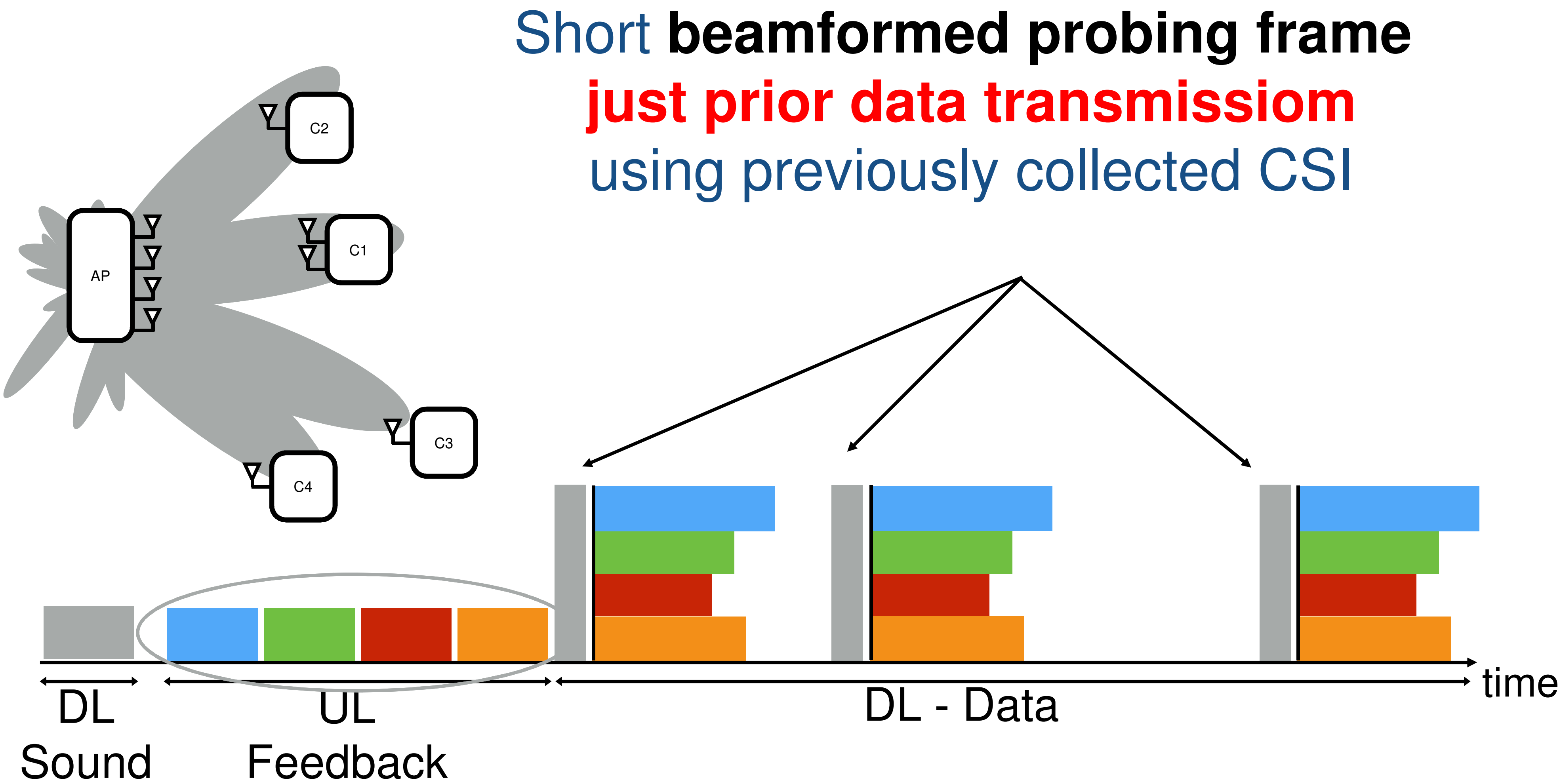
CHRoME - Introduces a mechanism for "just-in-time" multi-user MCS selection which implements a beamformed probe that captures the *real* channel observed at the users



Best (highest possible) MCS, and *real* channel *unknown*

(1)

Probing-Based MCS Selection

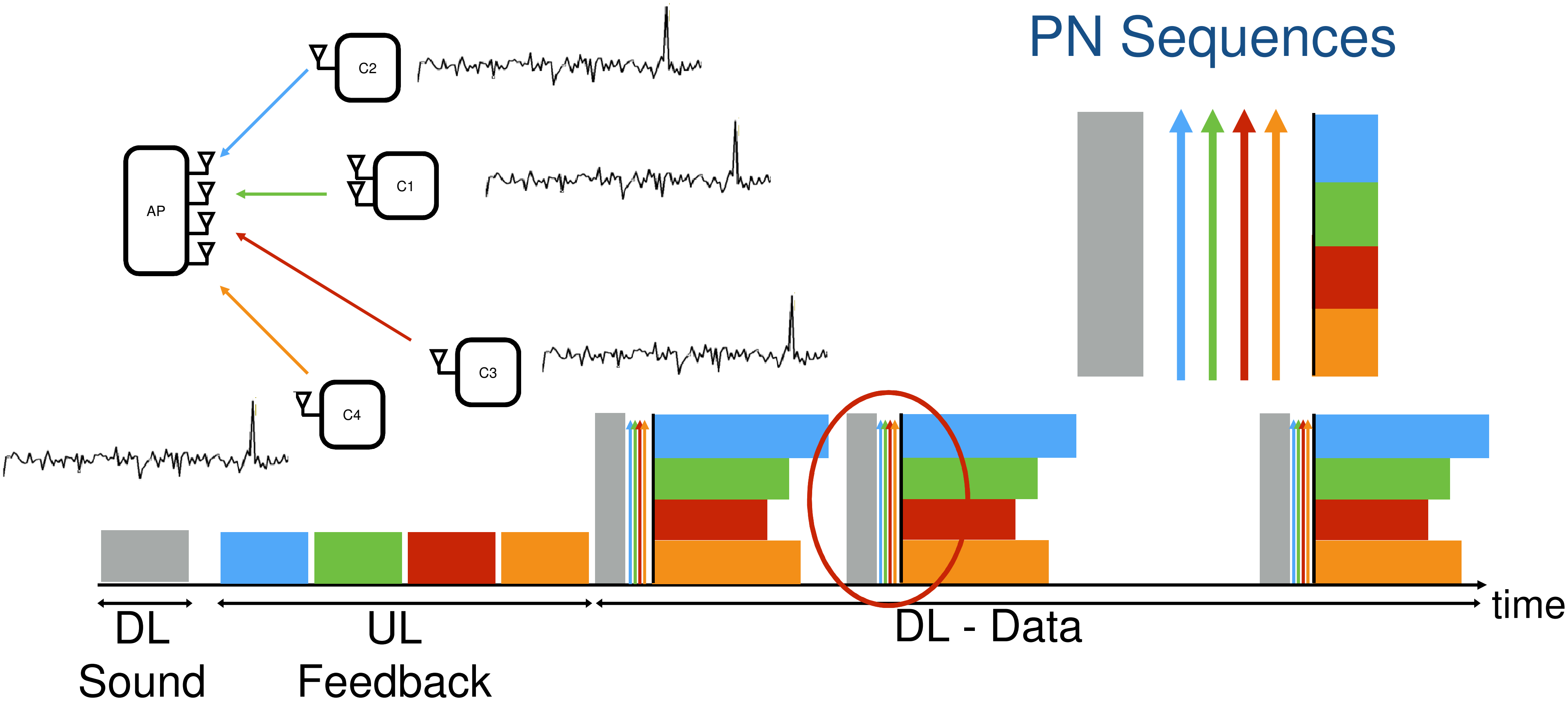


Users measure the precoded probe's SINR and select the highest possible MCS (considering all current sources of interference)

(3)

Probing-Based MCS Selection

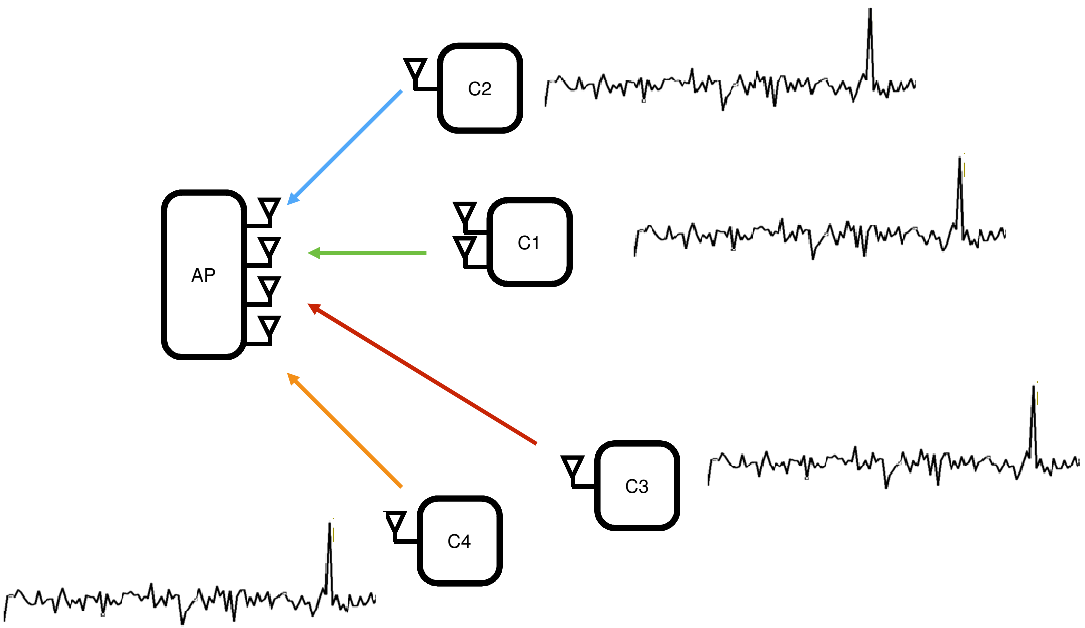
Feed back MCS selection:



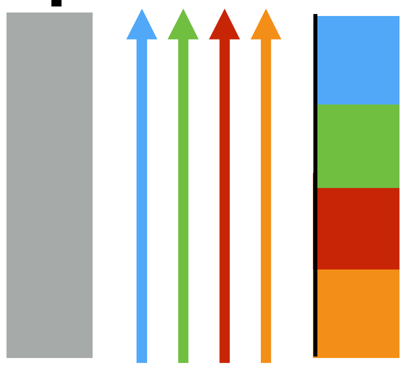
PN bit sequence: transport the MCS index

(4)

Probing-Based MCS Selection



Correlatable symbol sequences



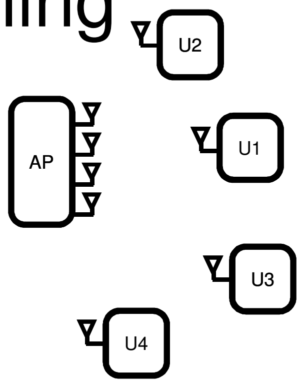
Advantages of PN Sequences:

- No decoding required (no preamble or data processing)
  6.35 μsec
- Highly reliable (detected at low SINR, i.e., -6 dB)

Low feedback overhead introduced

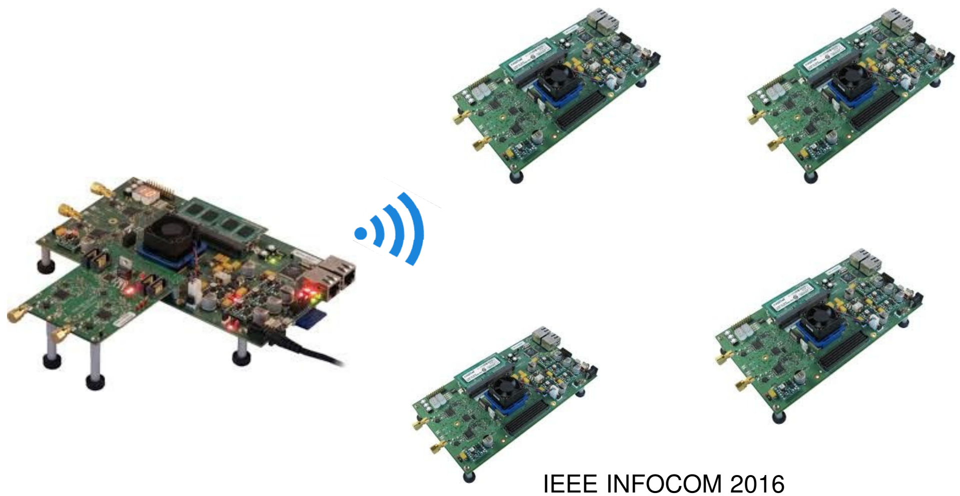
CHRoME: Evaluation

CHannel **R**esilient **M**ulti-user b**E**amforming



Methodology

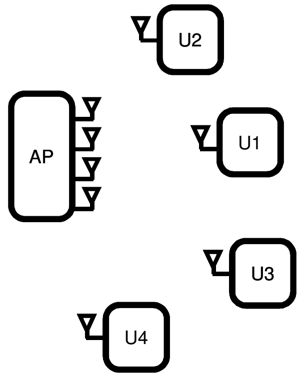
- **Trace-Driven Emulation**
- Emulation based on **over-the-air channel measurements** we collect
  - Enables repeatability for fair comparison



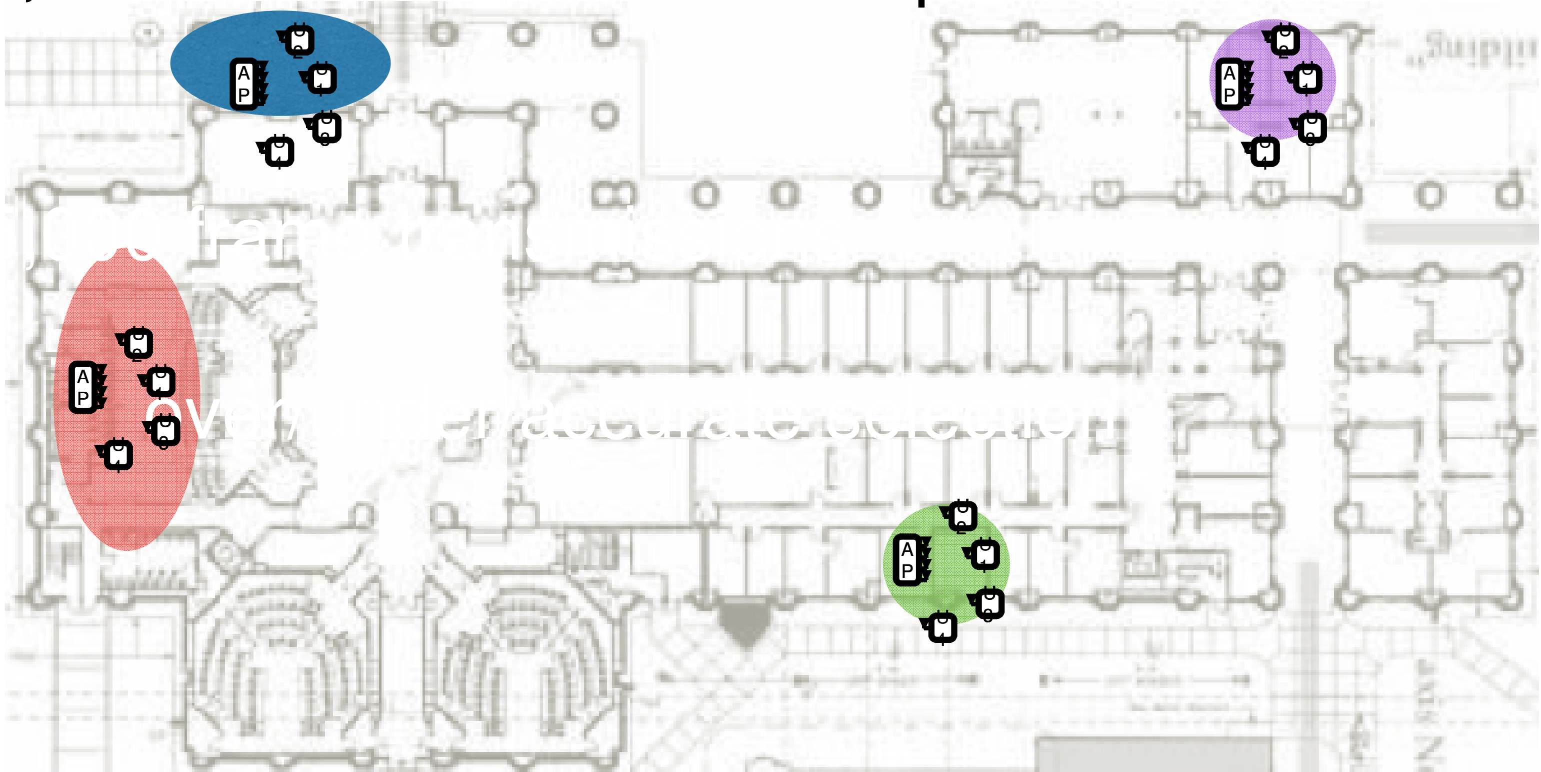
Evaluation

Methodology

Indoor channel traces - conference rooms/labs/offices environment

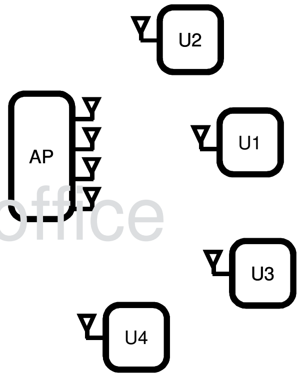


15,000+ frame transmissions per scheme



Evaluation

Methodology

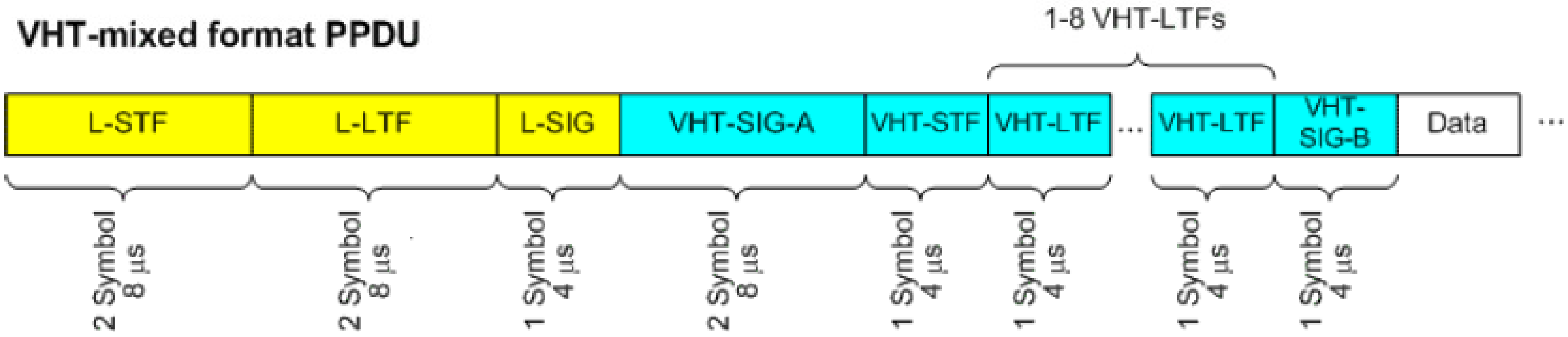


Indoor channel traces - conference rooms/lab/office environment.

15,000+ frame transmissions per scheme

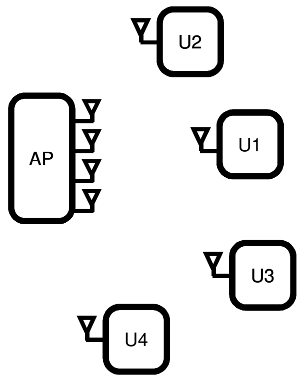
Very-High Throughput (VHT) **802.11ac frame**

- 802.11ac timings



Probing-Based MCS Selection

MCS selection accuracy in real indoor channels

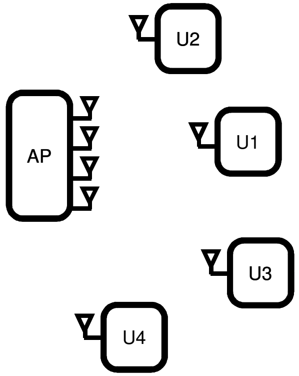


MCS selection solely based on CSIT	→	Over-selection
Conservatively decrease MCS	→	Under-selection
CHRoME	→	?

Ground truth found by measuring per subcarrier SINR during actual data transmission and mapping to MCS

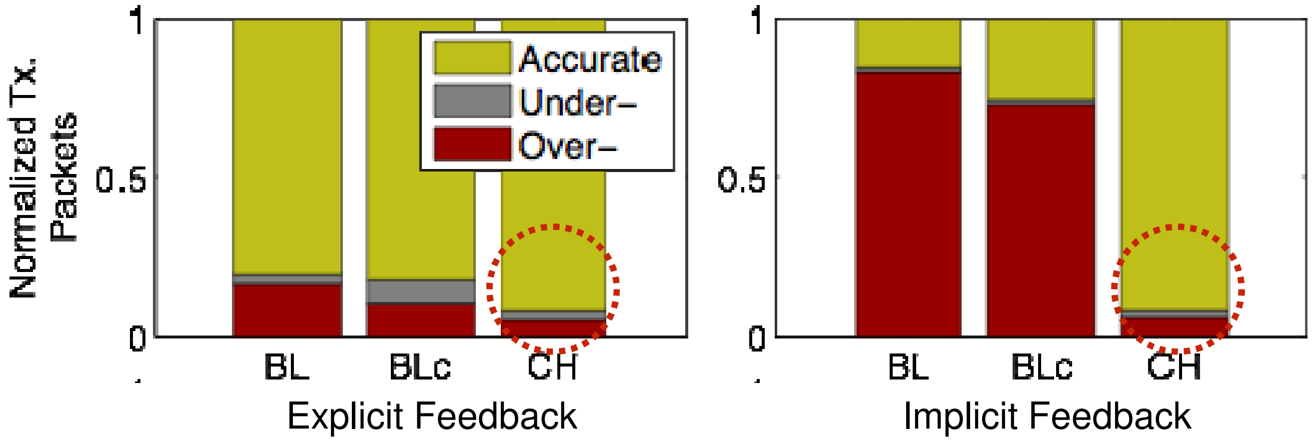
Probing-Based MCS Selection

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



MCS selection accuracy

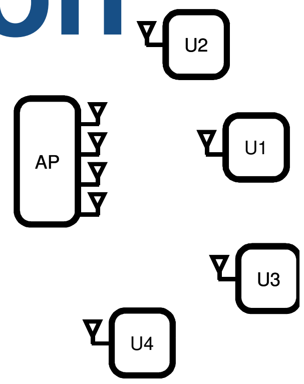
Out-of-cell interference
-70 to -90 dBm



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.**

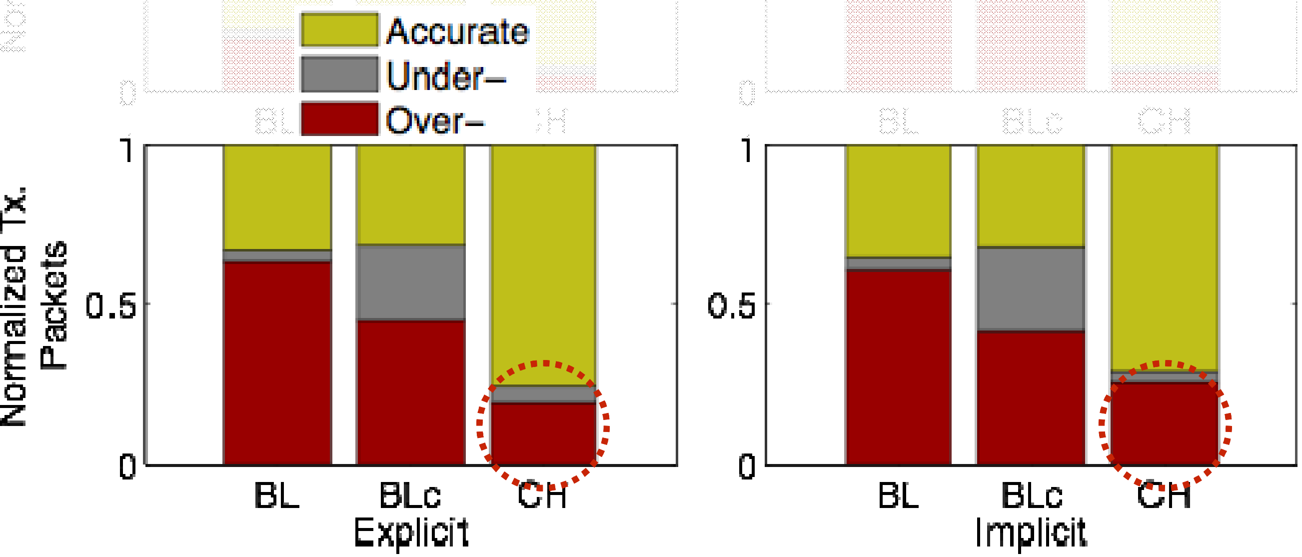
MCS selection accuracy

BL = Baseline CSIT-Based

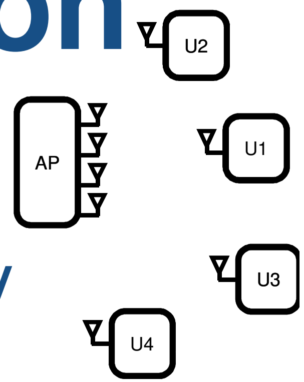
BLc = Baseline CSIT-Based Conservative (BL-1)

CH = CHRoME

No out-of-cell interference



Probing-Based MCS Selection



Percent gain of CHRoME

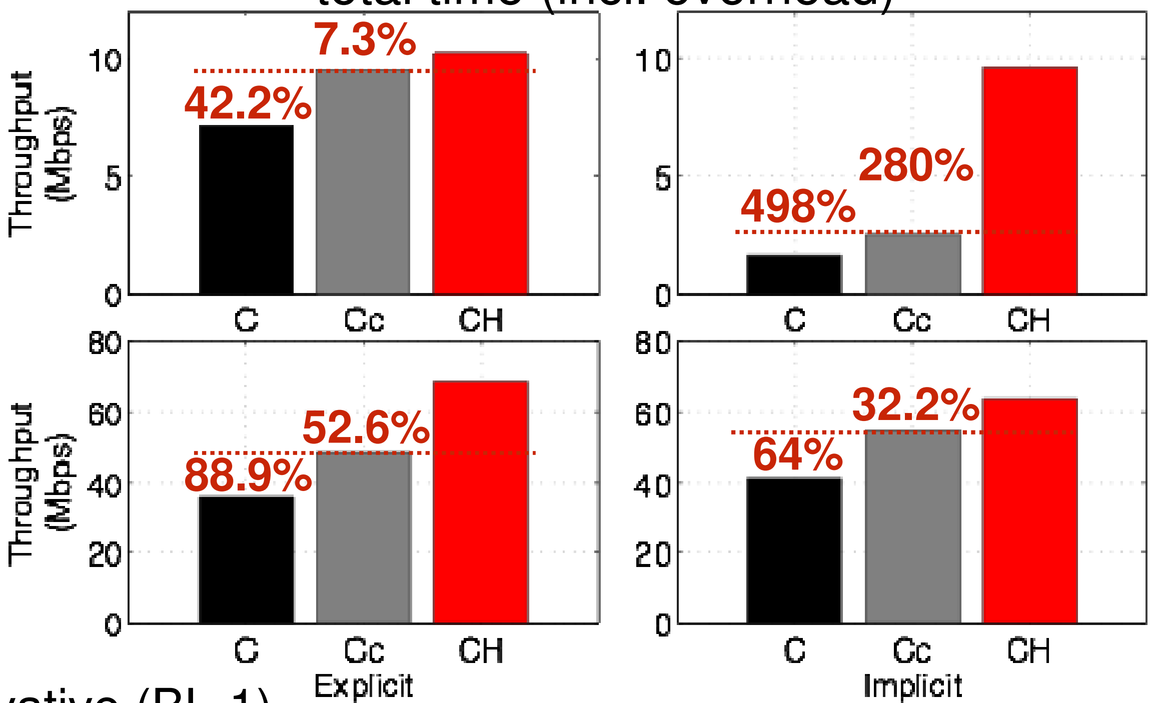
From 7% to 280% .

MCS selection accuracy (Throughput)

$$\frac{\text{\# succ. received data bits}}{\text{total time (incl. overhead)}}$$

(Top)
Out-of-cell interference

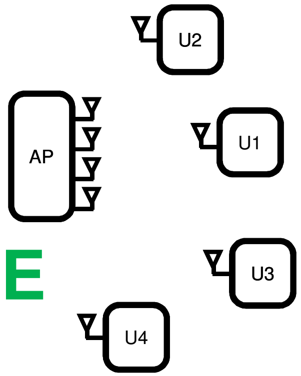
(Bottom)
No out-of-cell interference



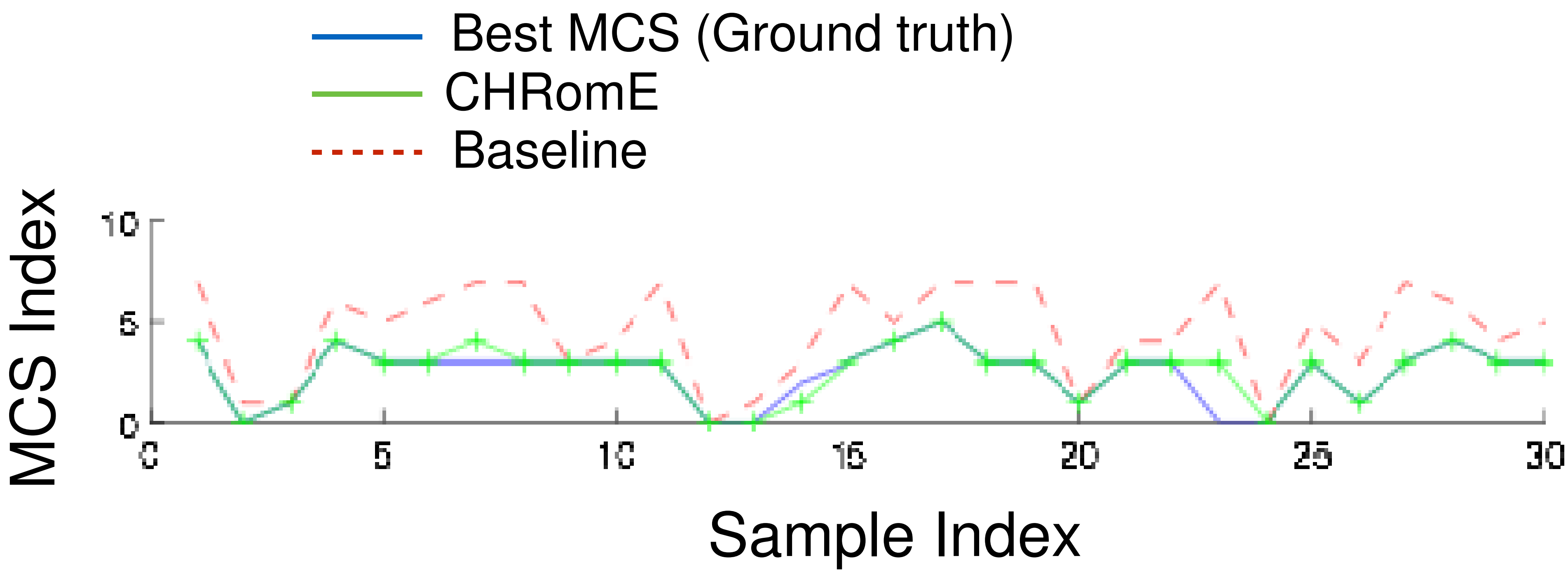
BL = Baseline CSIT-Based
BLc = Baseline CSIT-Based Conservative (BL-1)
CH = CHRoME

Probing-Based MCS Selection

MCS selection accuracy
(Adaptation response)

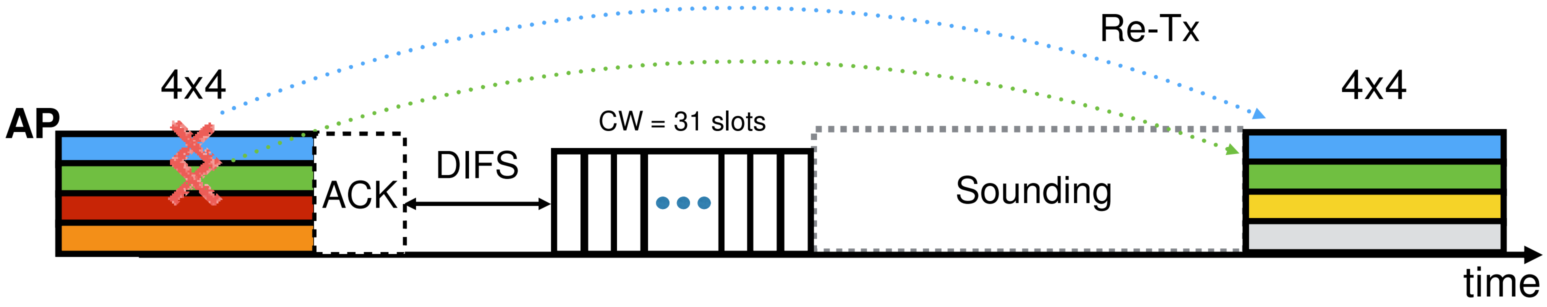


The baseline mostly overselects whereas CHRoME follows closely the ideal MCS selection



Retransmissions in 802.11-based networks

TX antennas: 4
4 users with 1 Rx antenna each

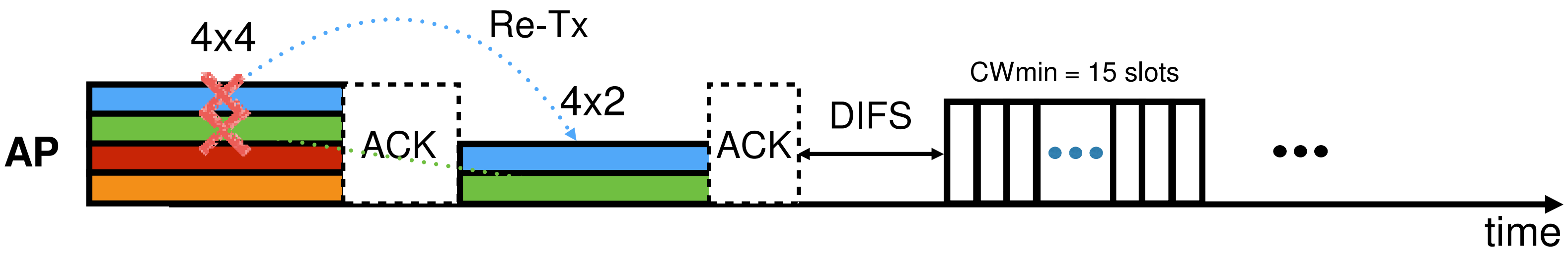


Corrupted packets require re-contention after doubled backoff window and sounding the channel again

Packet loss + **Additional time until retransmission** → **Stale CSI** *Resound!*

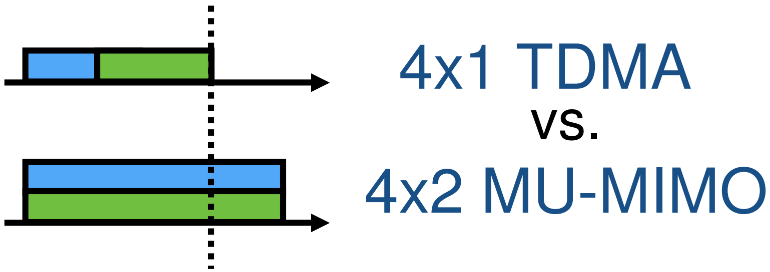
***High* overhead introduced**

MU-MIMO Fast Packet Recovery



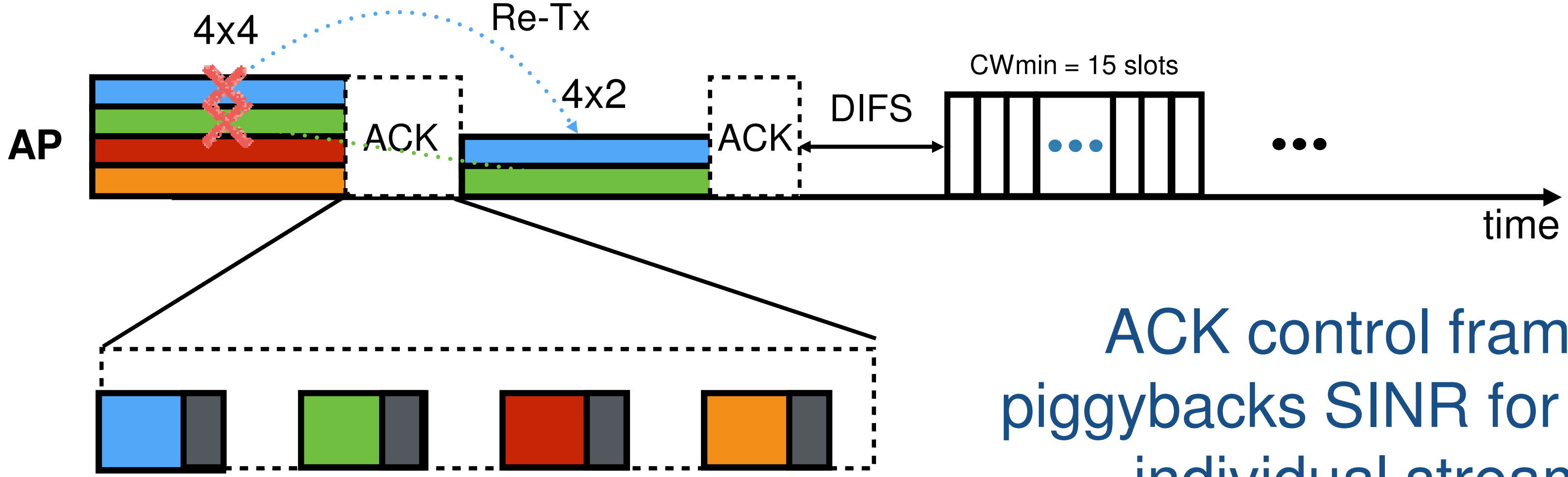
Exploit *liberated* antenna resources to obtain **diversity and power gain**, increasing robustness

Select configuration that minimizes the time to retransmit the corrupted packets



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)

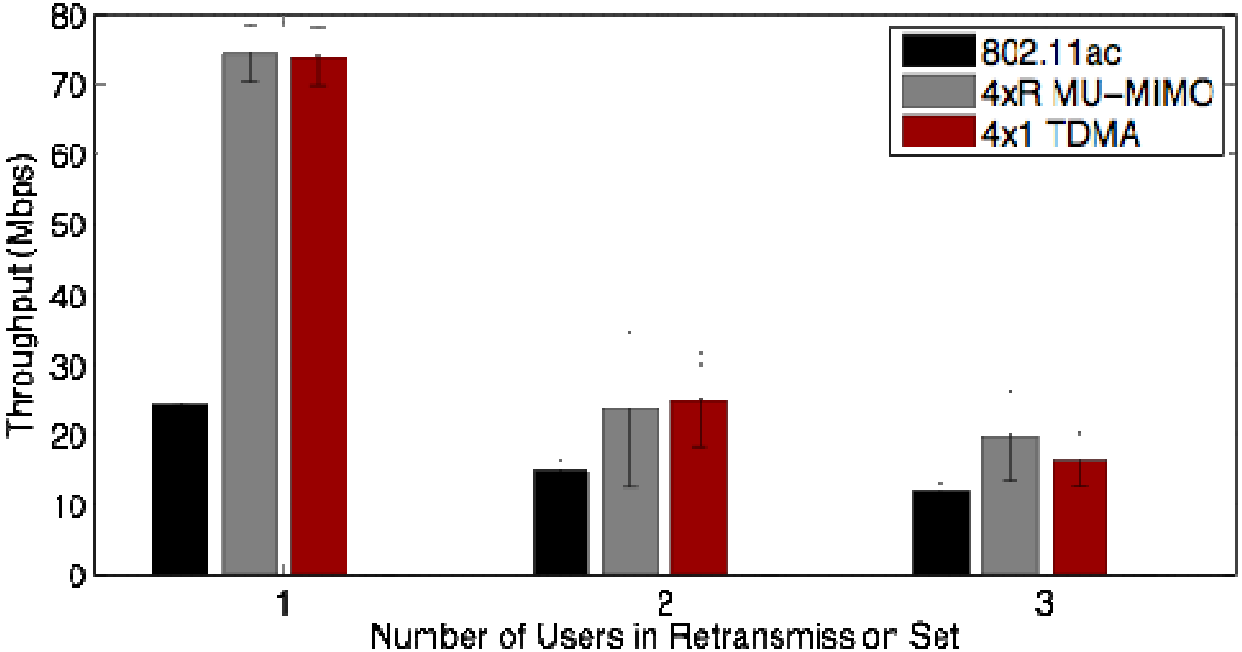
Beamforming with Increasingly outdated CSIT

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



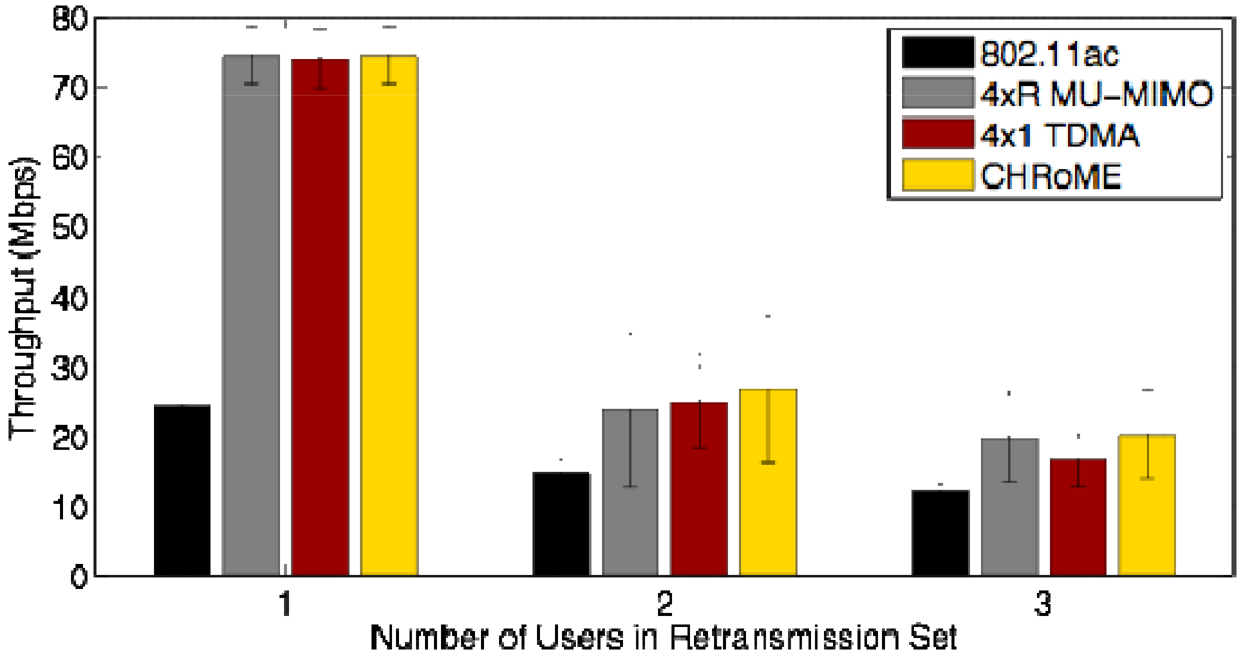
Similar performance of MU-MIMO and TDMA.

Performance depends on two major factors:

(i) Retransmission success rate;

(ii) Incurred overhead / overhead reduction.

Fast Recovery



CHRoME's lowest throughput is at least that of the best performing scheme

Conclusions: CHRoME

CHannel **R**esilient **M**ulti-user b**E**amforming

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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