MUTE: Sounding Inhibition for MU-MIMO WLANs

Oscar Bejarano
Rice University

Eugenio Magistretti
Rice University

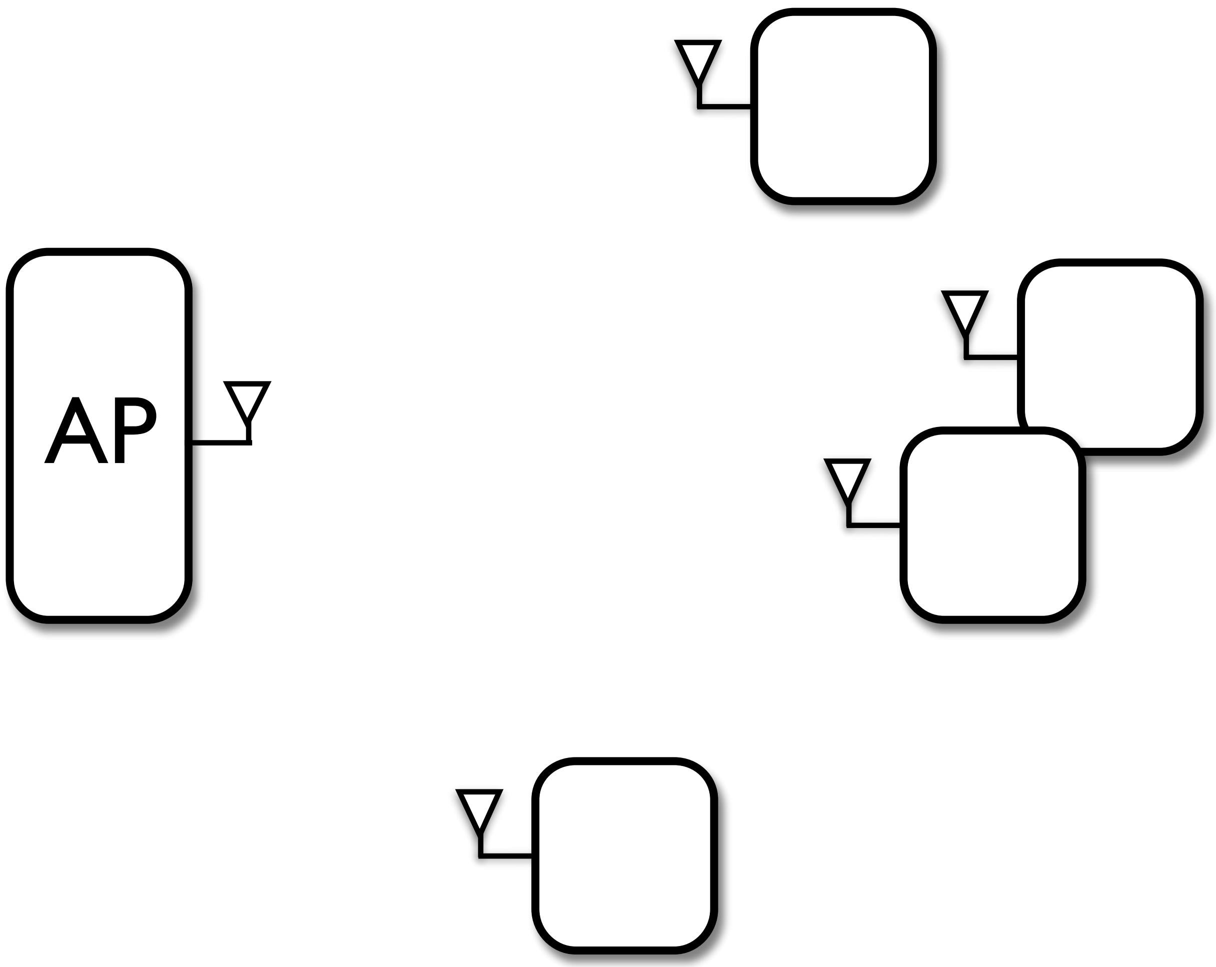
Omer Gurewitz
Ben Gurion University

Edward W. Knightly
Rice University

July 1st, 2014

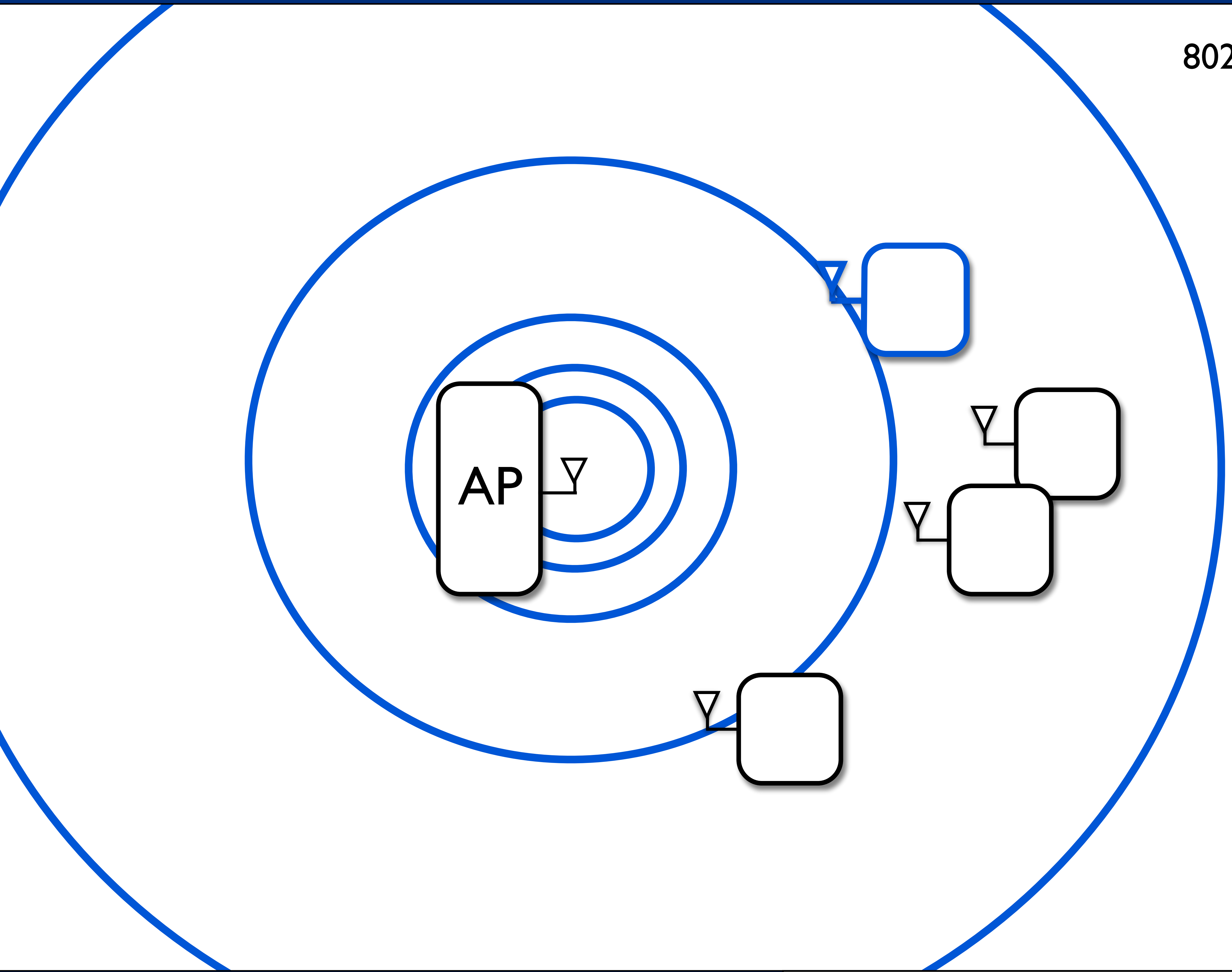
Single-Antenna Systems (Downlink)

802.11-Based Networks



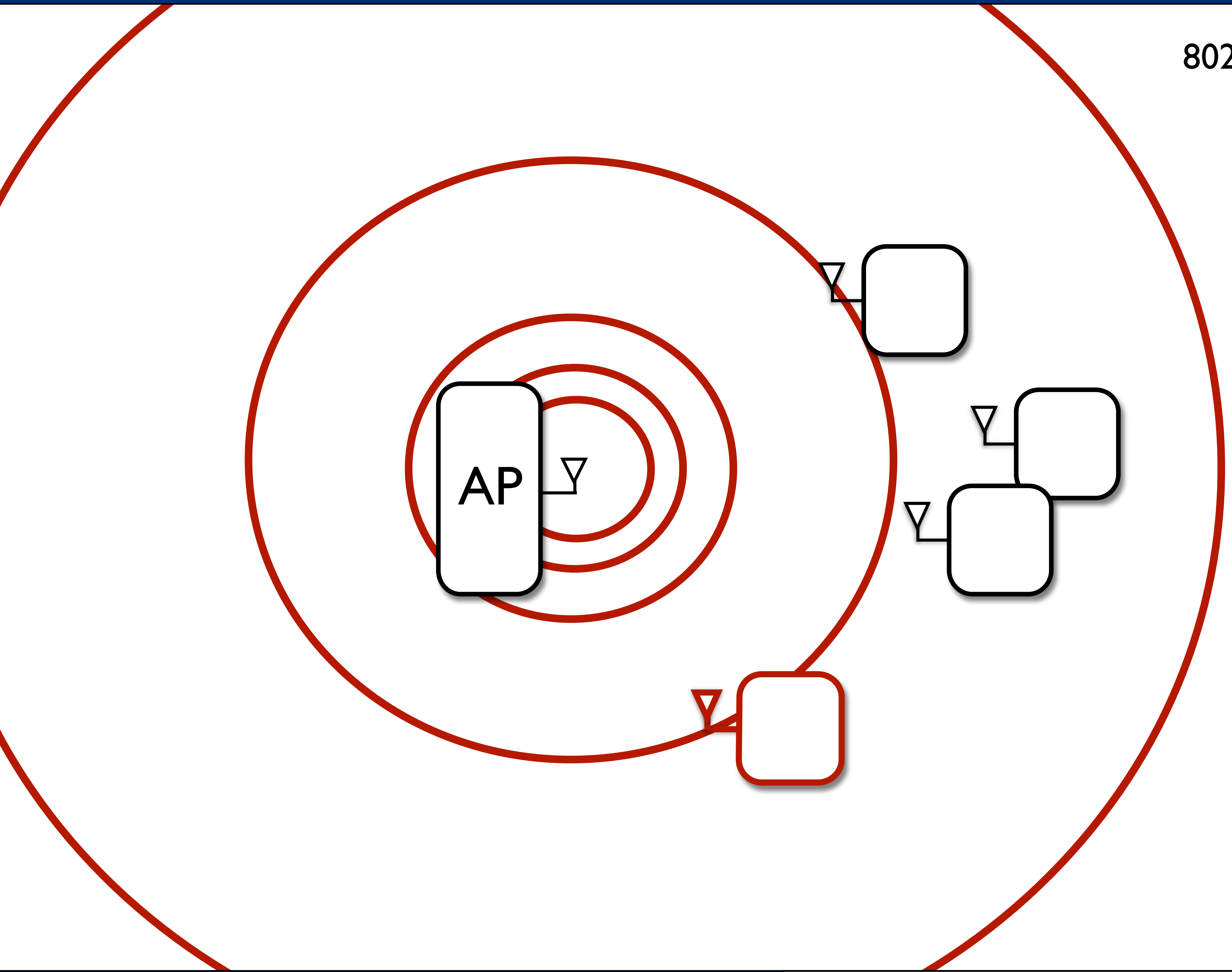
Single-Antenna Systems (Downlink)

802.11-Based Networks



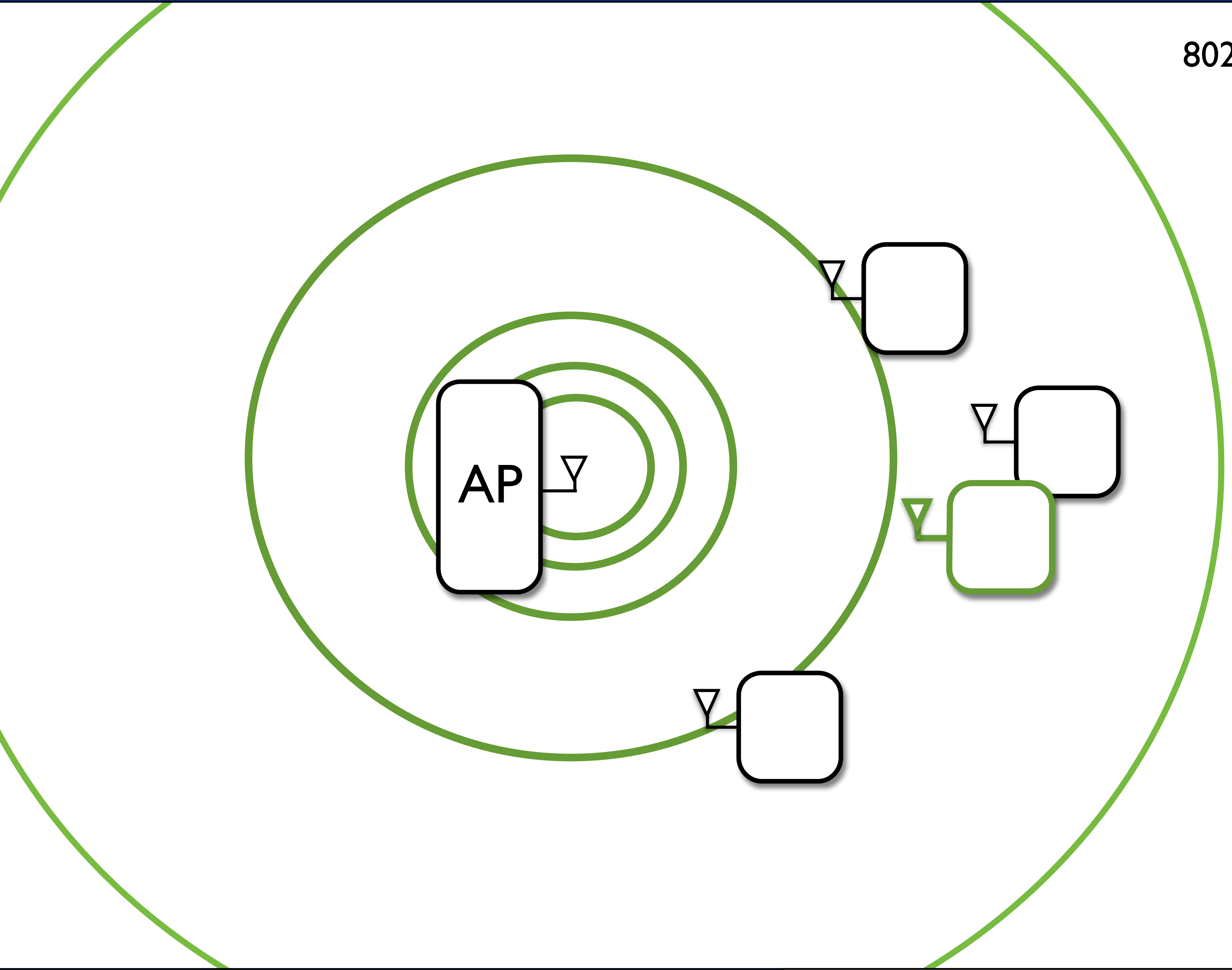
Single-Antenna Systems (Downlink)

802.11-Based Networks



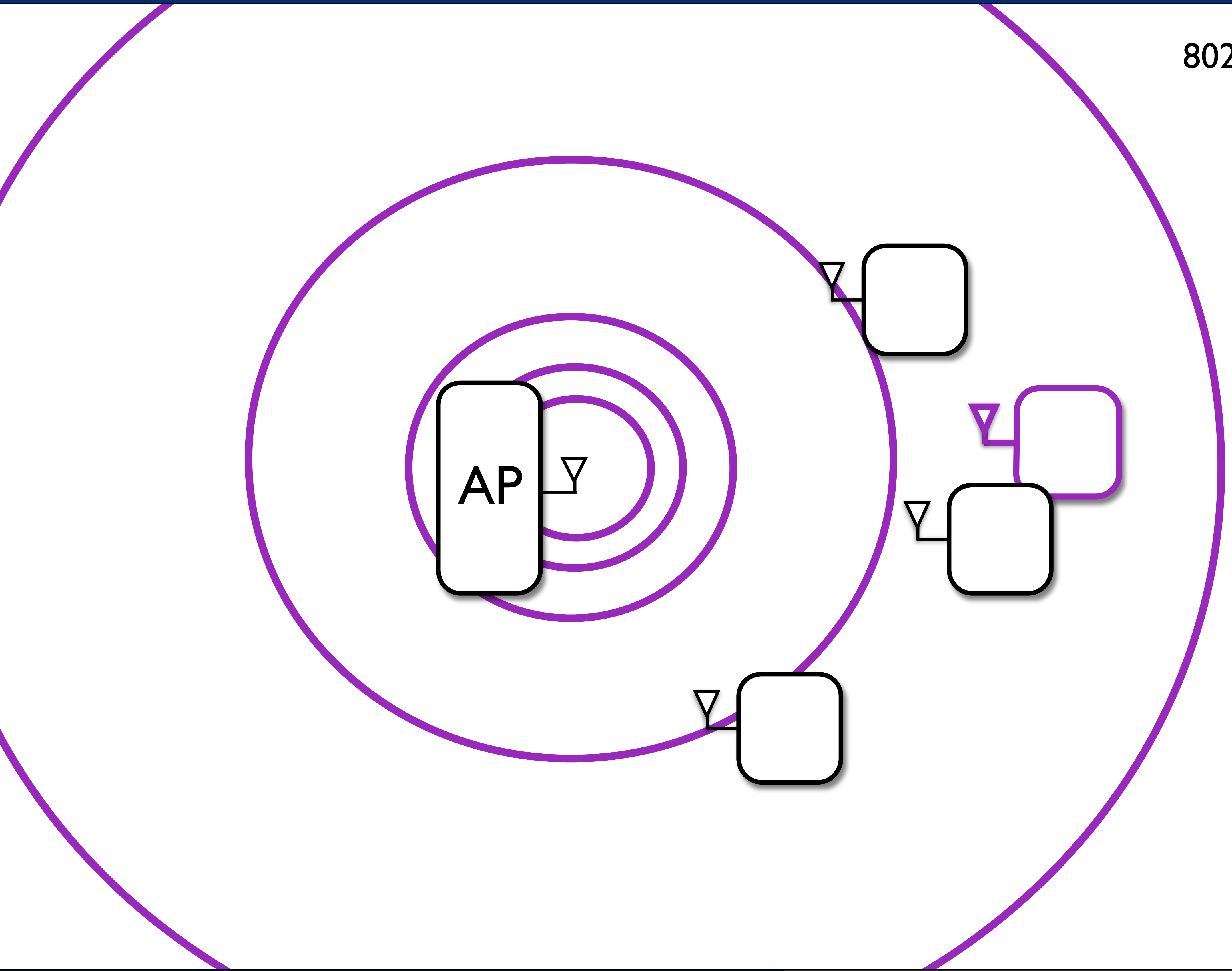
Single-Antenna Systems (Downlink)

802.11-Based Networks



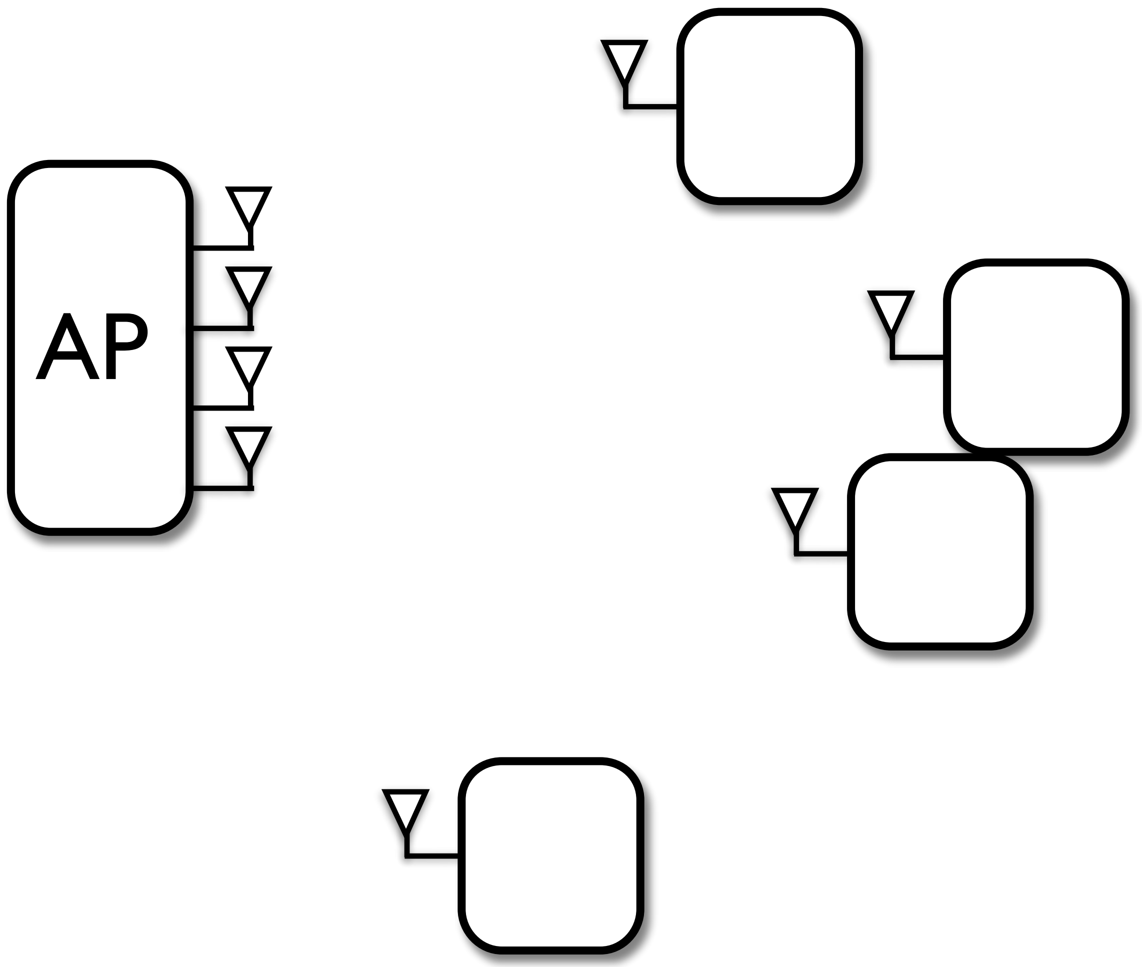
Single-Antenna Systems (Downlink)

802.11-Based Networks



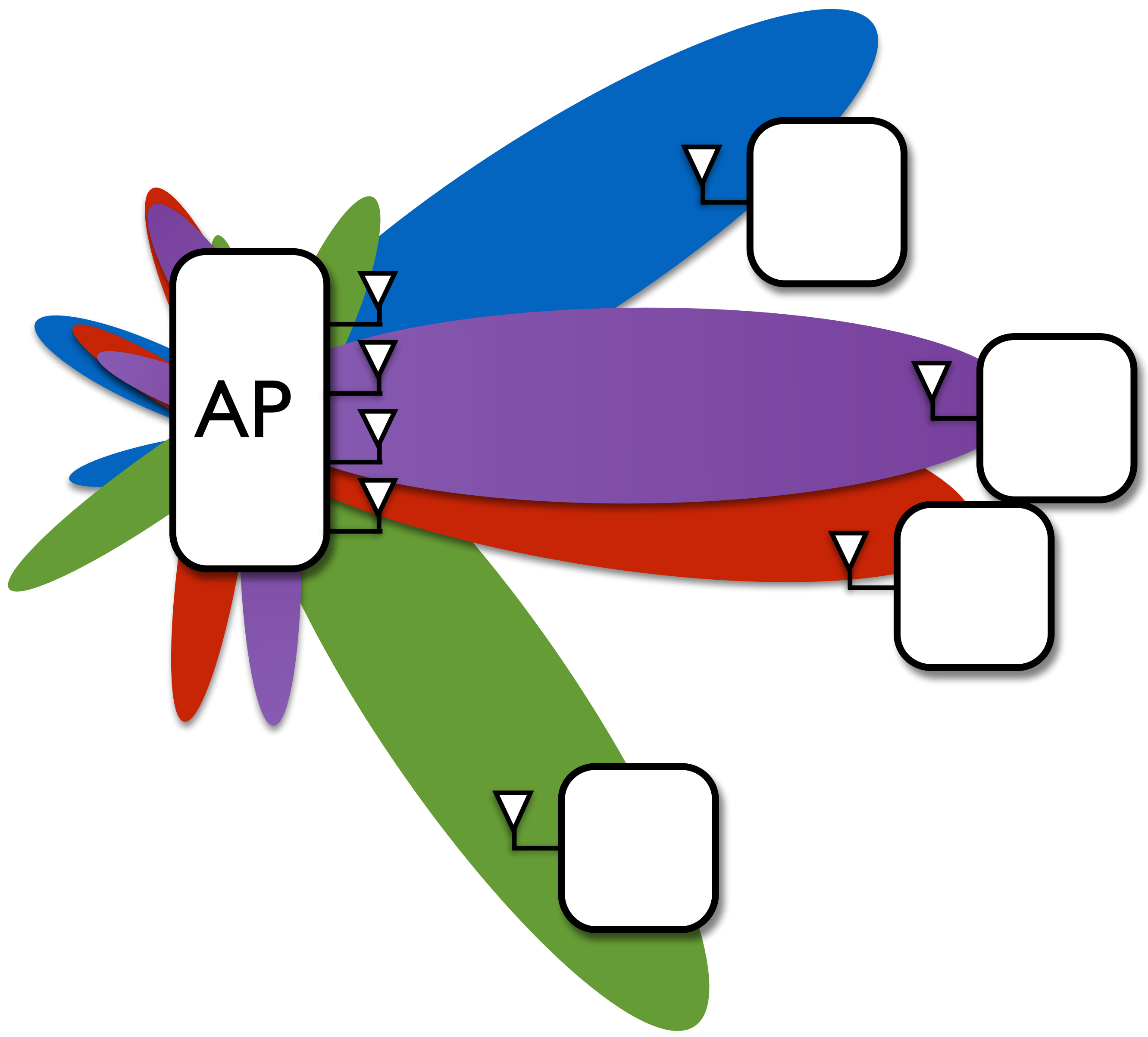
Multi-Antenna Systems (Downlink)

802.11-Based Networks

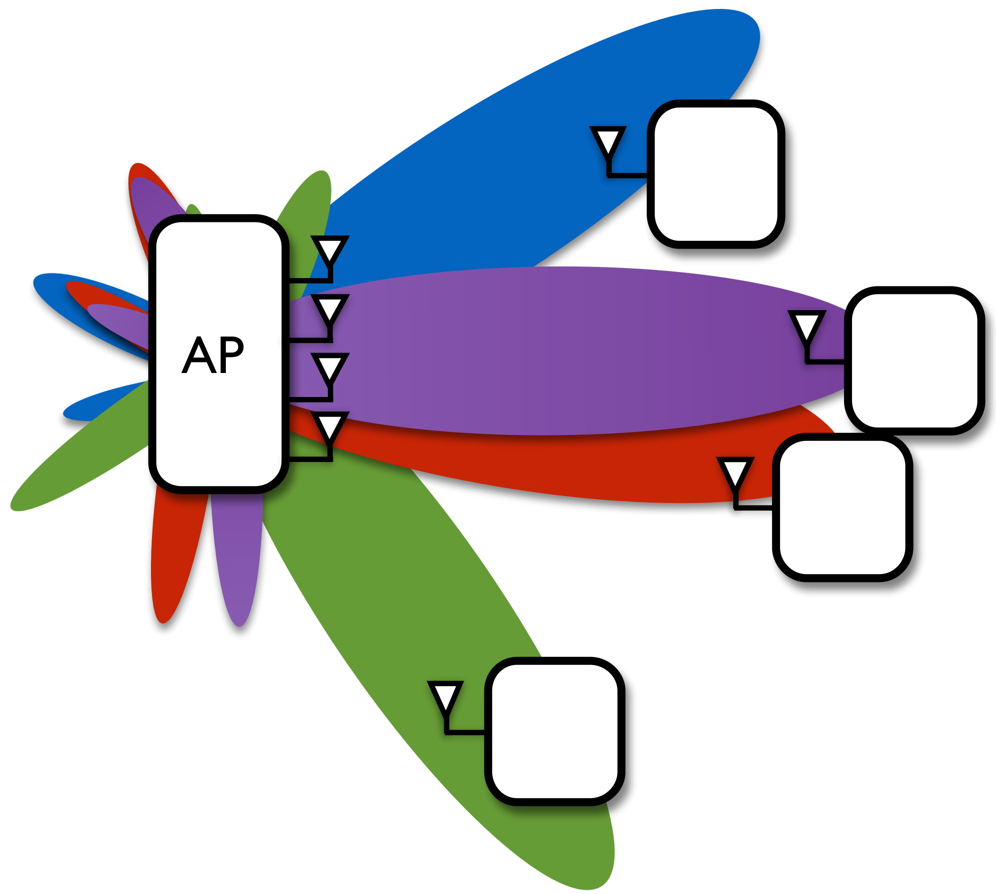


Multi-Antenna Systems (Downlink)

802.11-Based Networks



Multi-Antenna Systems (Downlink)



M antennas at AP
N_k antennas at user k

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

Spencer, Q. H., Peel, C. B., Swindlehurst, A. L., & Haardt, M. (2004). An introduction to the multi-user MIMO downlink. *Communications Magazine, IEEE*, *42*(10), 60-67.

Multi-User MIMO

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

- Large PHY gains
- MAC not considered

Experimental	Theoretical
Aryafar'10	Venkatesan'03
Rahul'12	Viswanathan'03
Balan'12	Caire'03
Shepard'12	Jindal'04
Shen'12	Spencer'04
Yang'13	Sharif'05
Zhang'13	Yoo'06
Chen'13	Gesbert'07
	Caire'10

The Problem

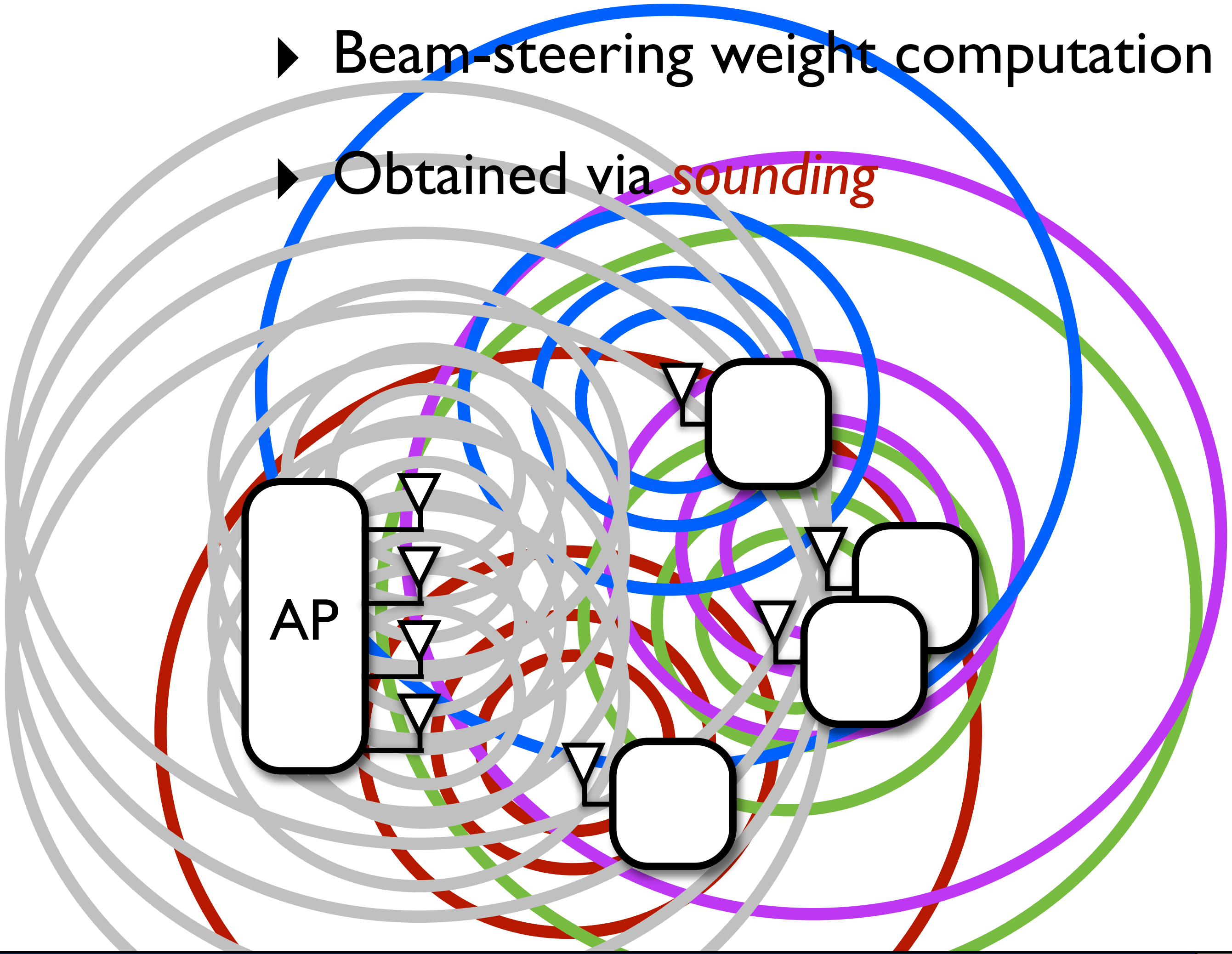
Costly overhead

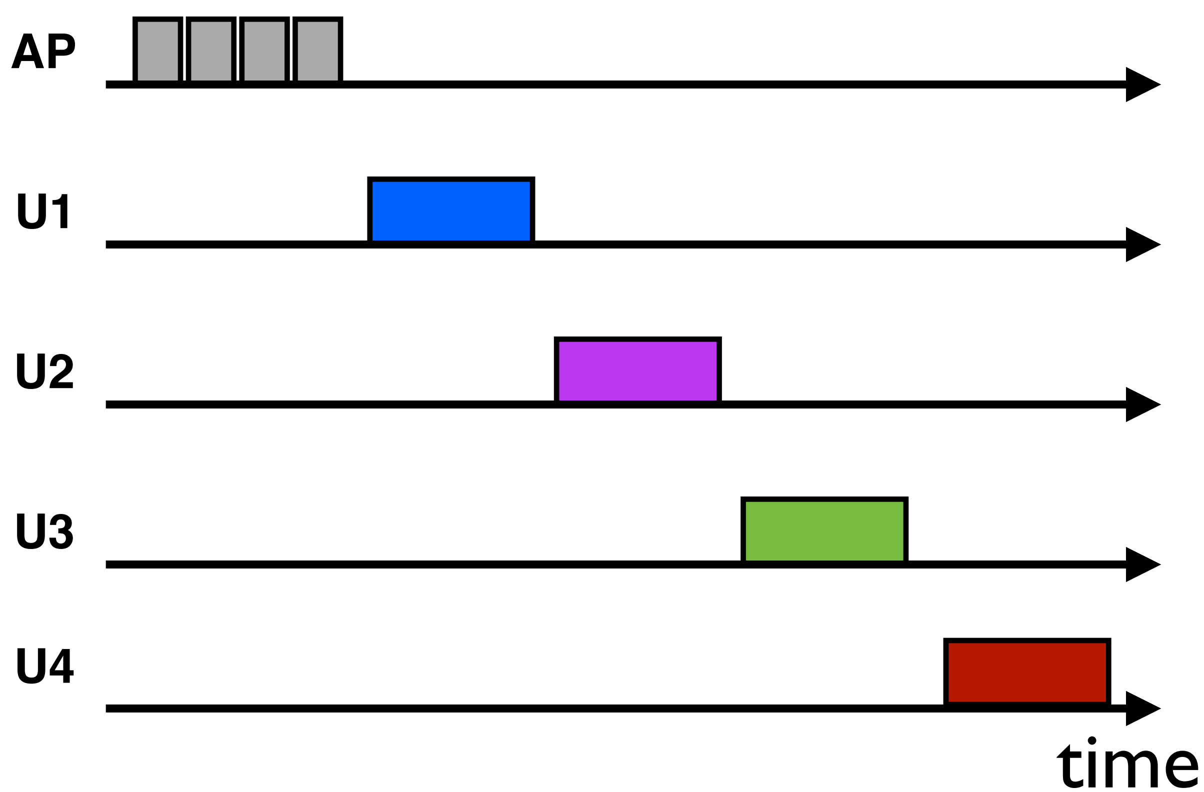
The Problem

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

Proposed Solution

We propose MUTE

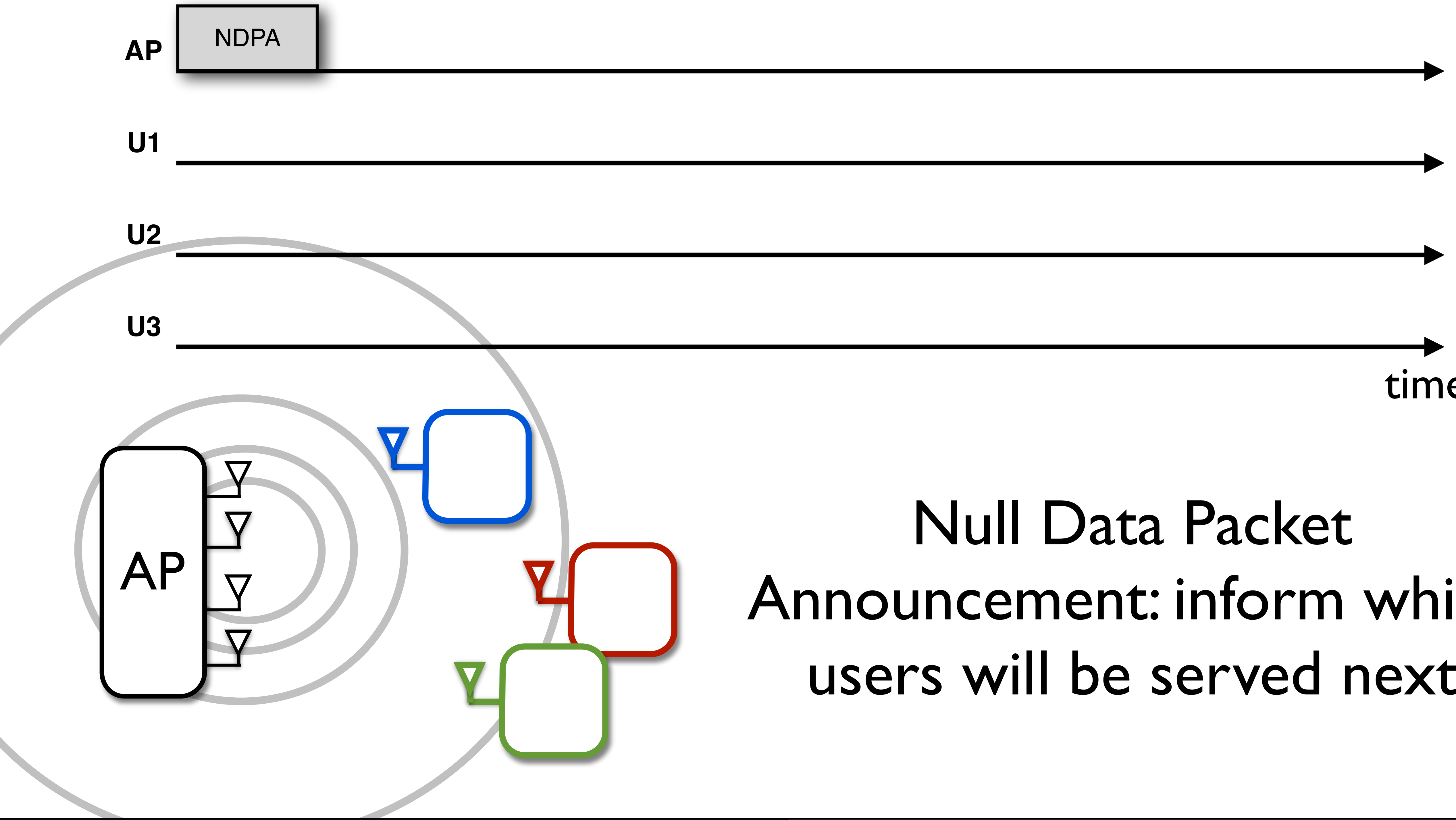
MUTE addresses the issue of overhead associated with channel sounding

- 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

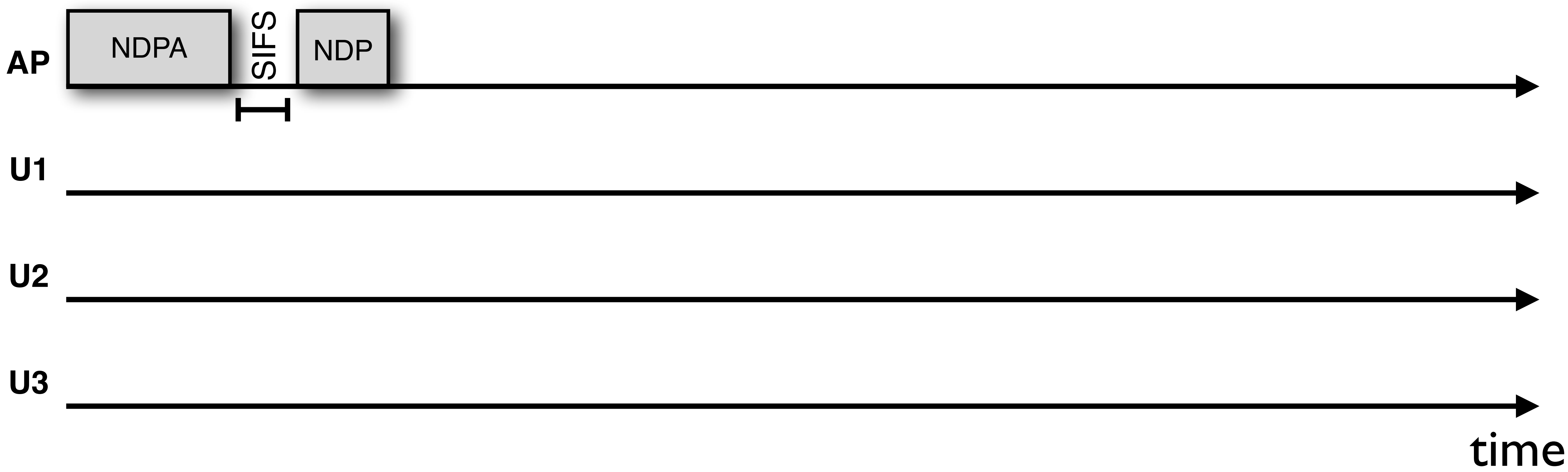
- Motivation
- Sounding process in MU-MIMO
- Sounding overhead reduction via sounding inhibition
  - Design of MUTE
  - Evaluation of MUTE
- Conclusion

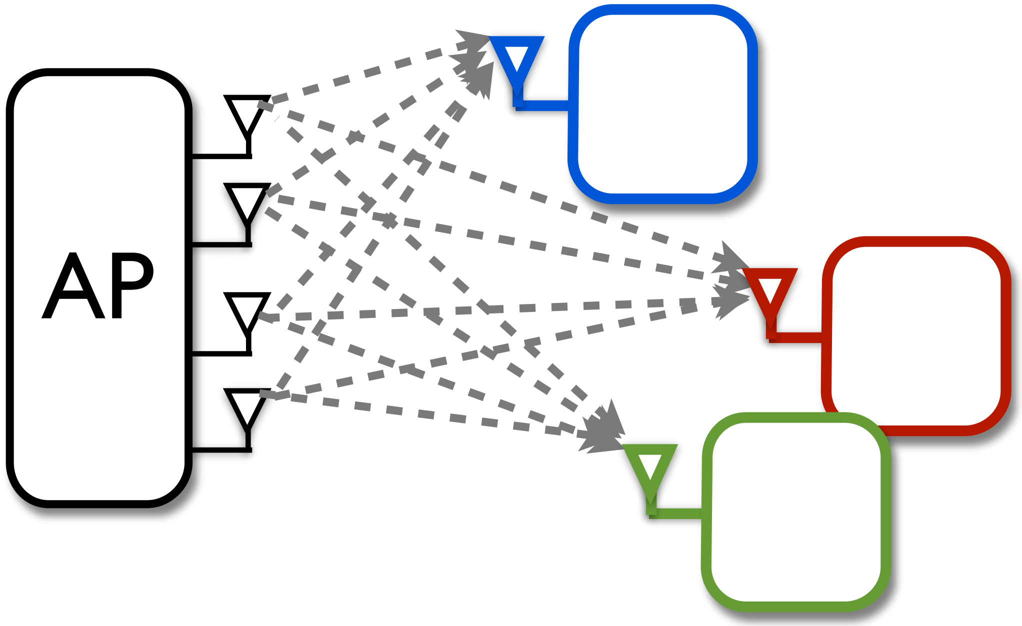
IEEE 802.11ac Sounding Timeline



Null Data Packet Announcement: inform which users will be served next

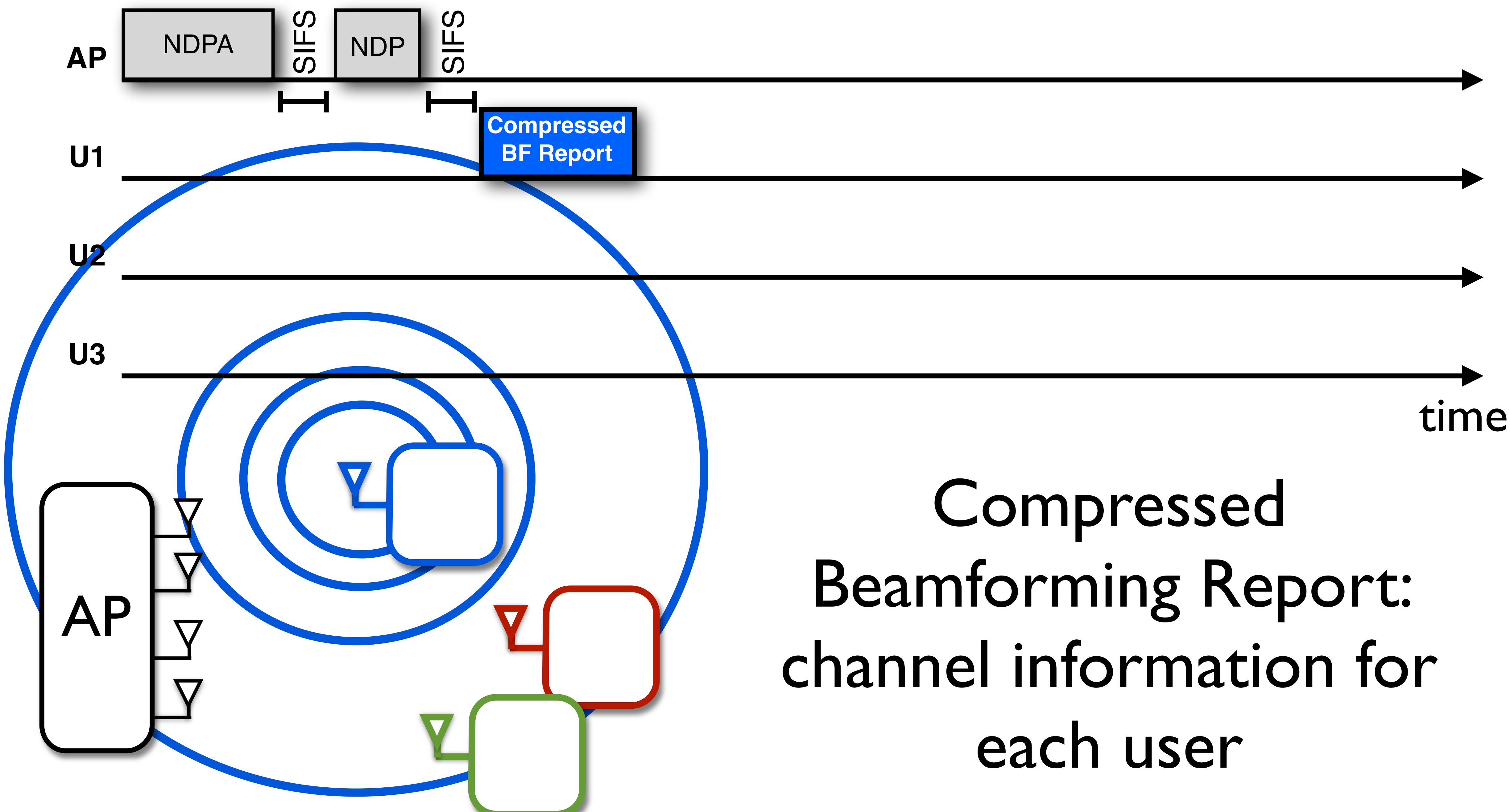
IEEE 802.11ac Sounding Timeline





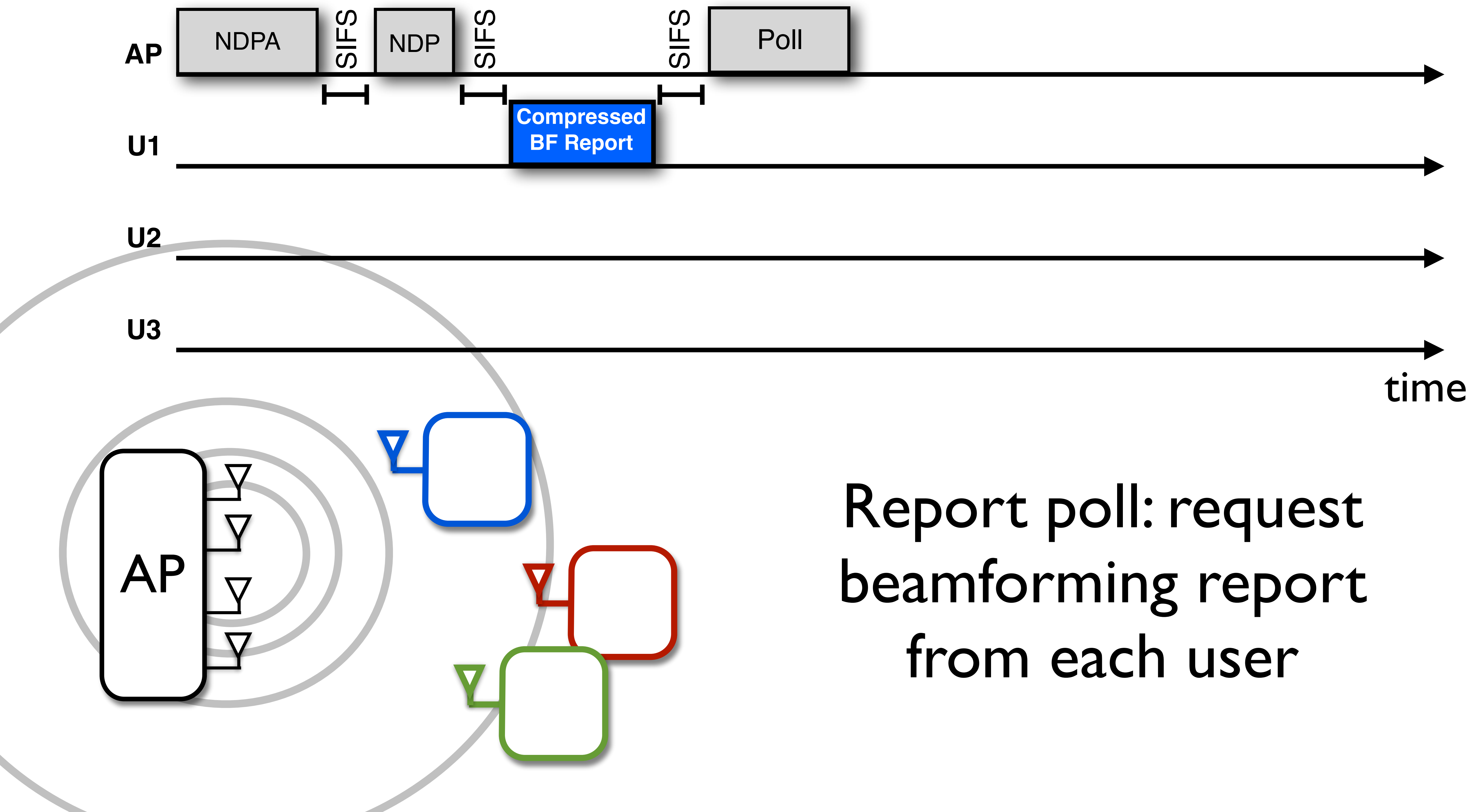
Null Data Packet: sound users (training sequences)

IEEE 802.11ac Sounding Timeline



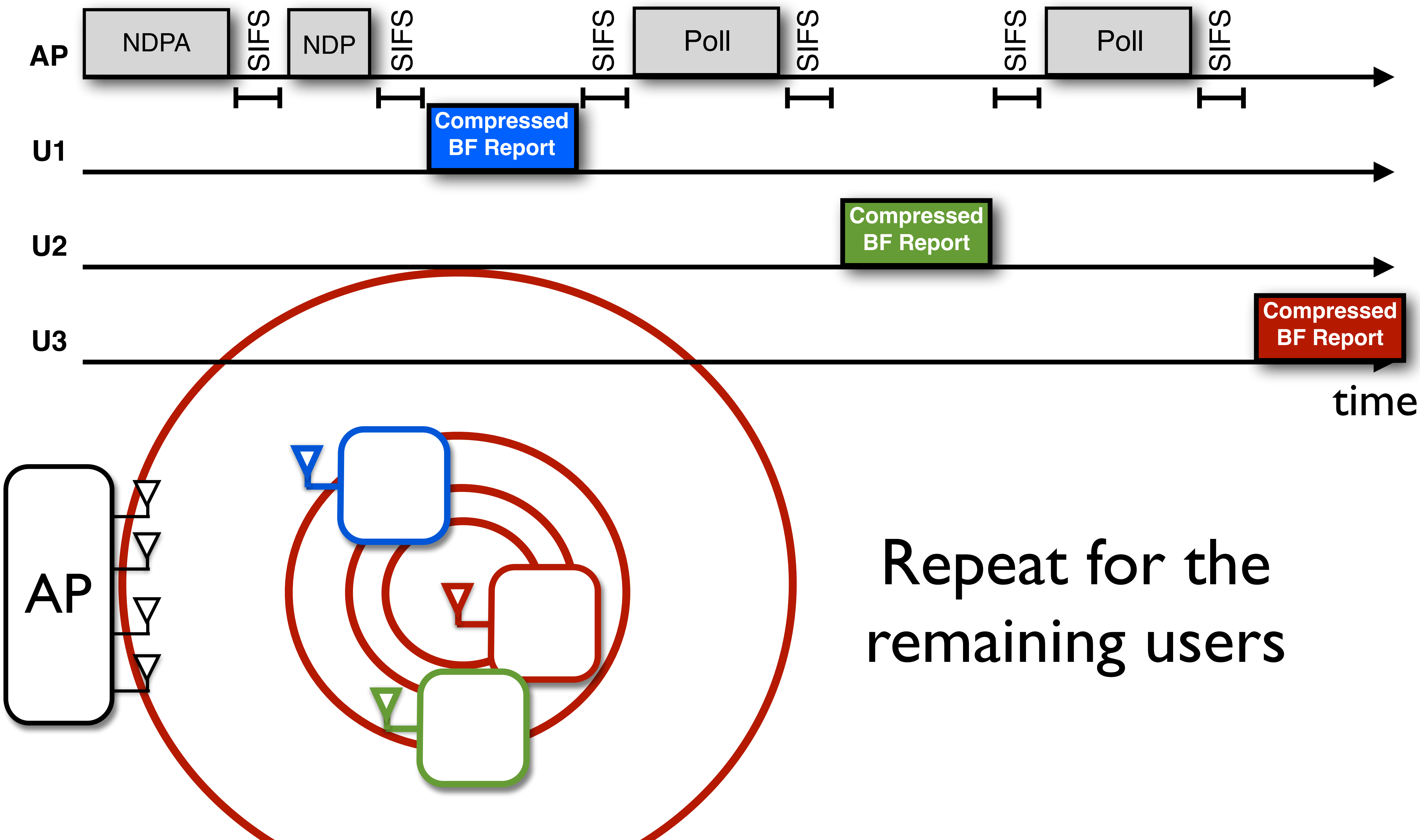
Compressed Beamforming Report: channel information for each user

IEEE 802.11ac Sounding Timeline



Report poll: request beamforming report from each user

IEEE 802.11ac Sounding Timeline



Repeat for the remaining users

IEEE 802.11ac Sounding Overhead Analysis

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

$$\frac{\text{Sounding time}}{\text{Sounding time + Data transmission time}}$$

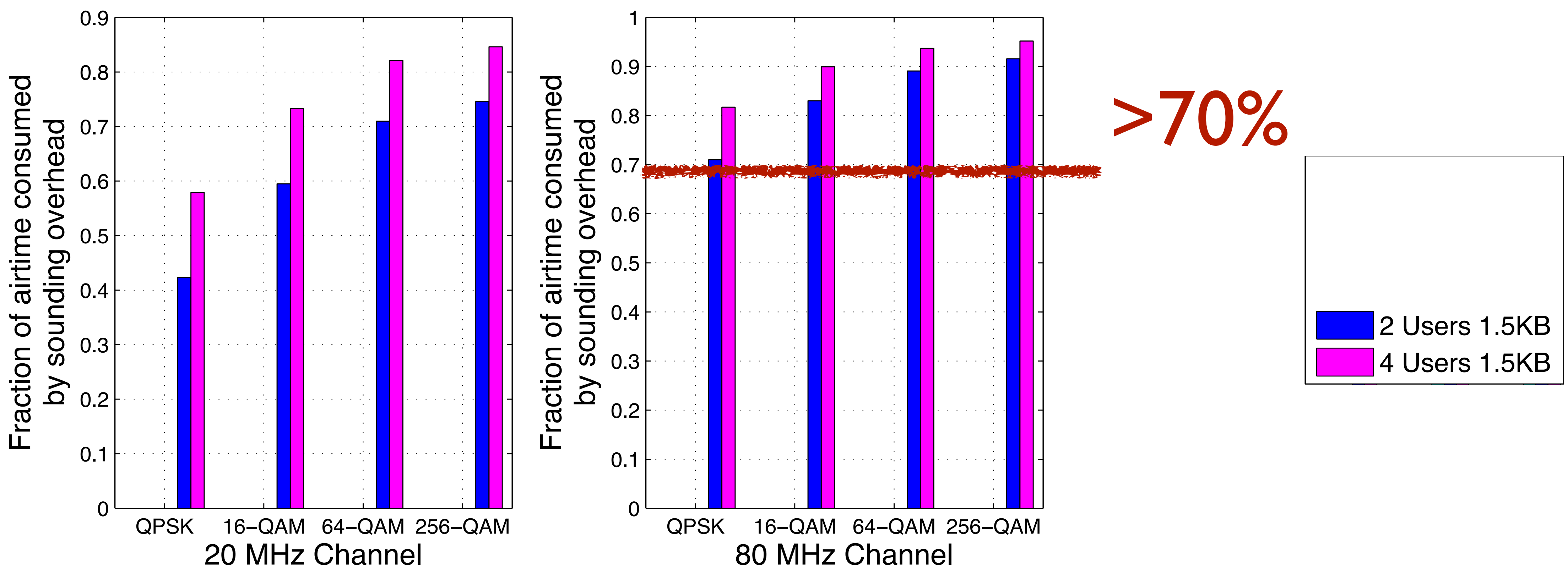
Parameters

Maximum subcarrier grouping
Minimum quantization bits
Packet Size 1500 bytes

Lower-Bound

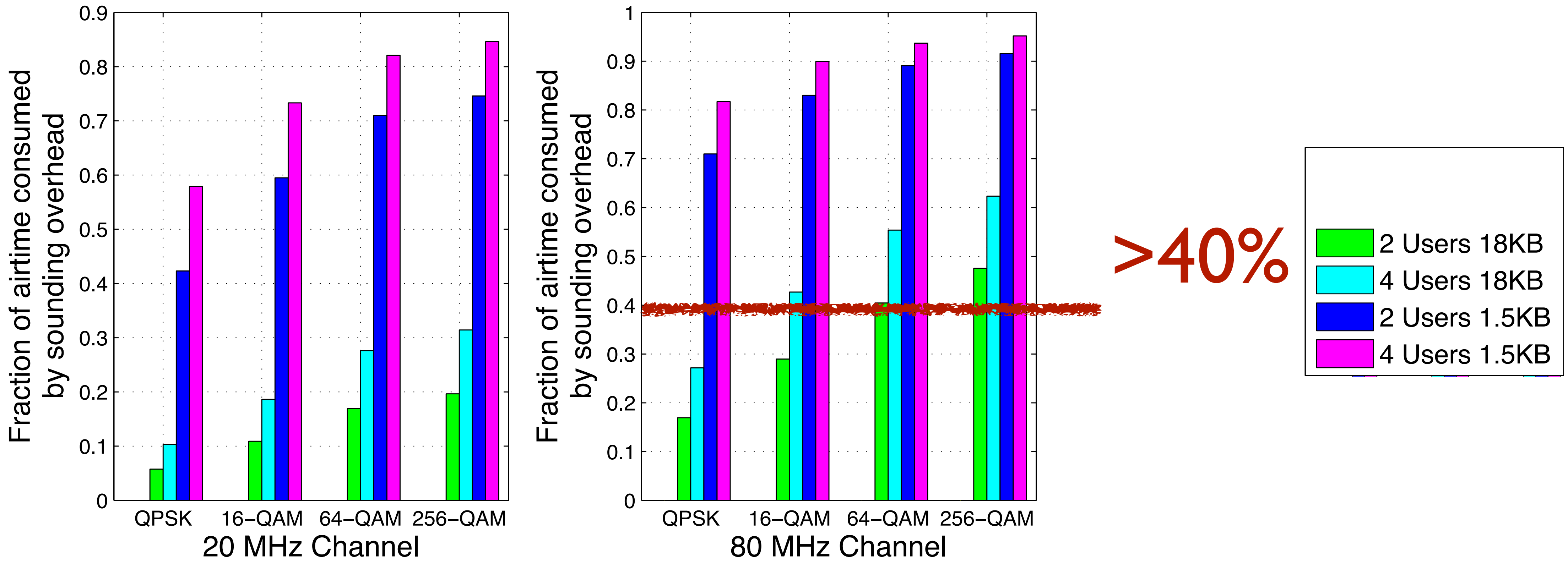
IEEE 802.11ac Sounding Overhead Analysis

No frame aggregation



IEEE 802.11ac Sounding Overhead Analysis

18 kB aggregation



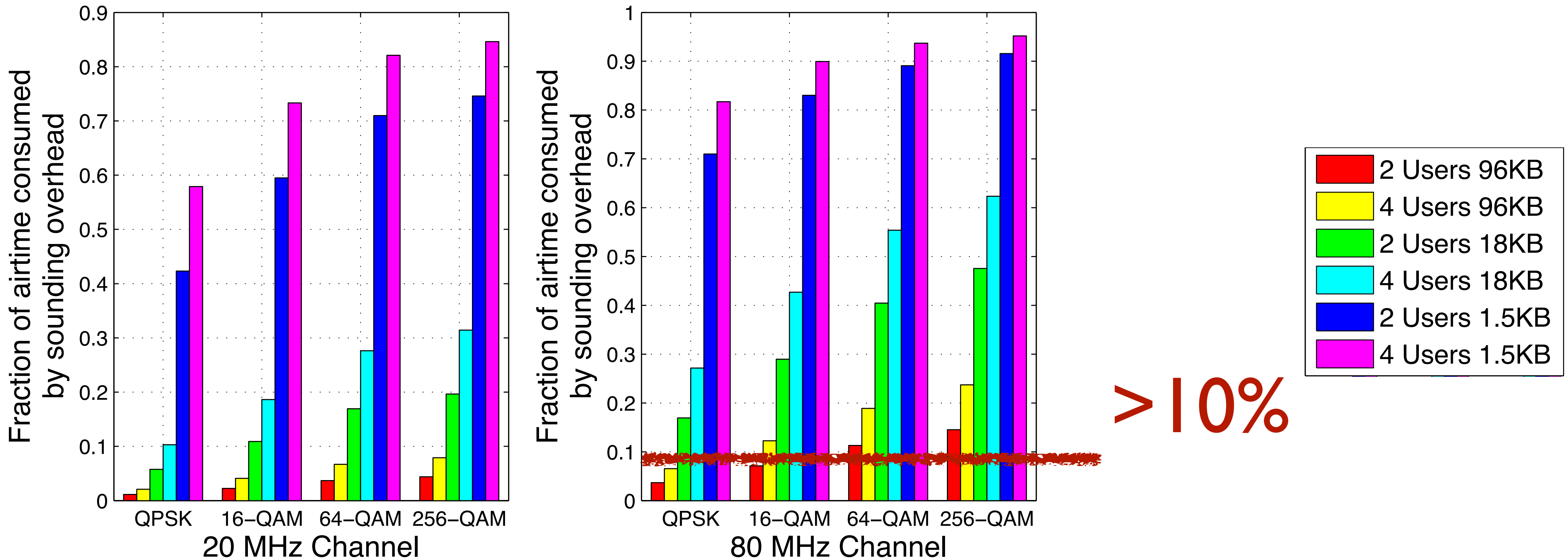
Frame Aggregation†

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

K.Tan, et al., "Fine-Grained Channel Access in Wireless LANs." In Proc. of ACM SIGCOMM, 2010.

IEEE 802.11ac Sounding Overhead Analysis

96 kB aggregation

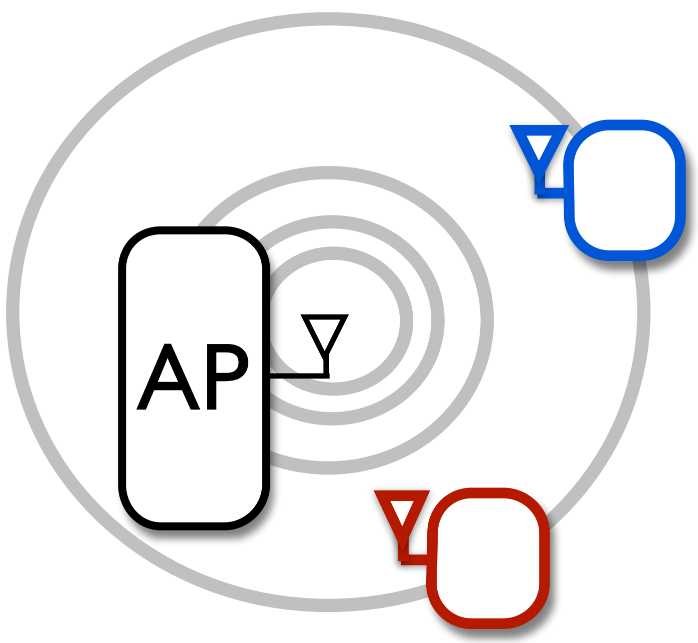


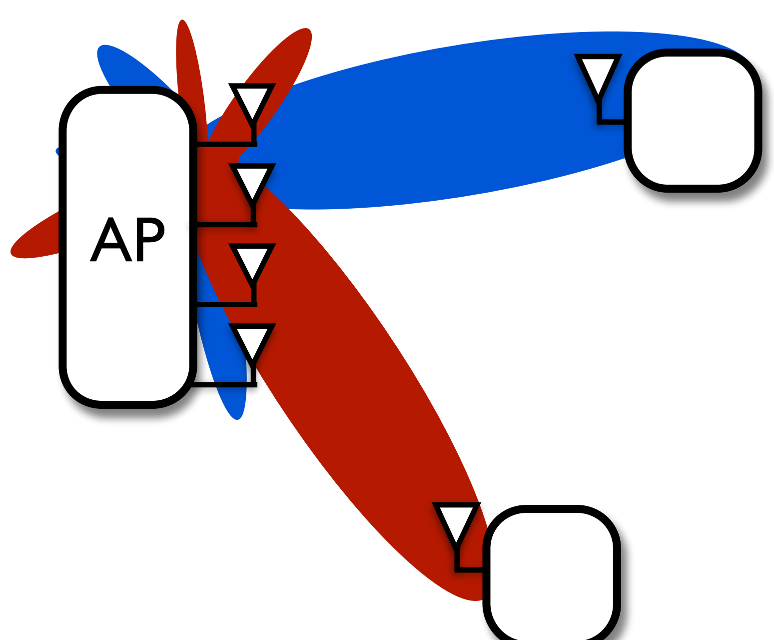
Frame Aggregation†

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

K. Tan, et al., "Fine-Grained Channel Access in Wireless LANs." In Proc. of ACM SIGCOMM, 2010.

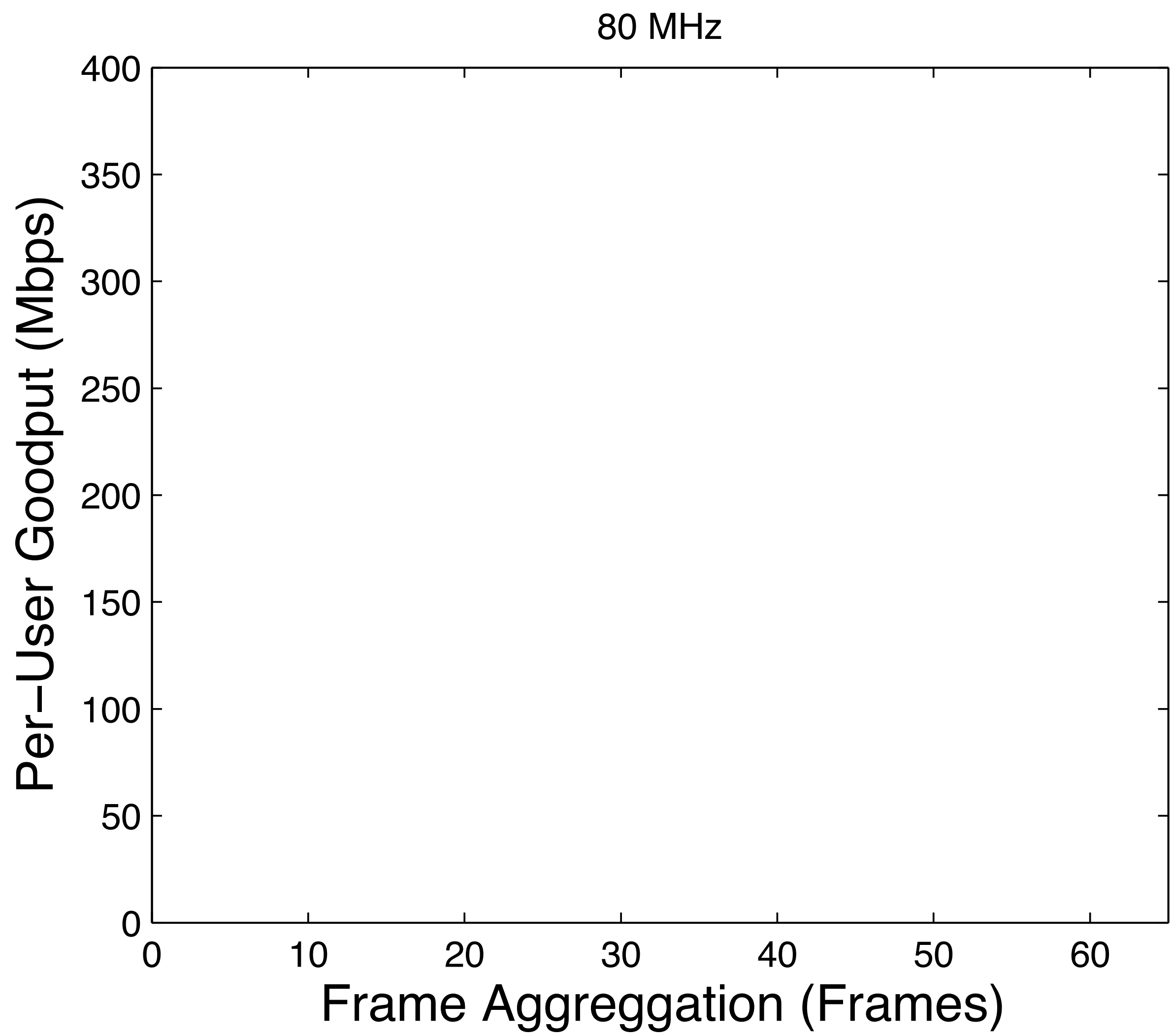
IEEE 802.11ac Sounding Overhead Analysis



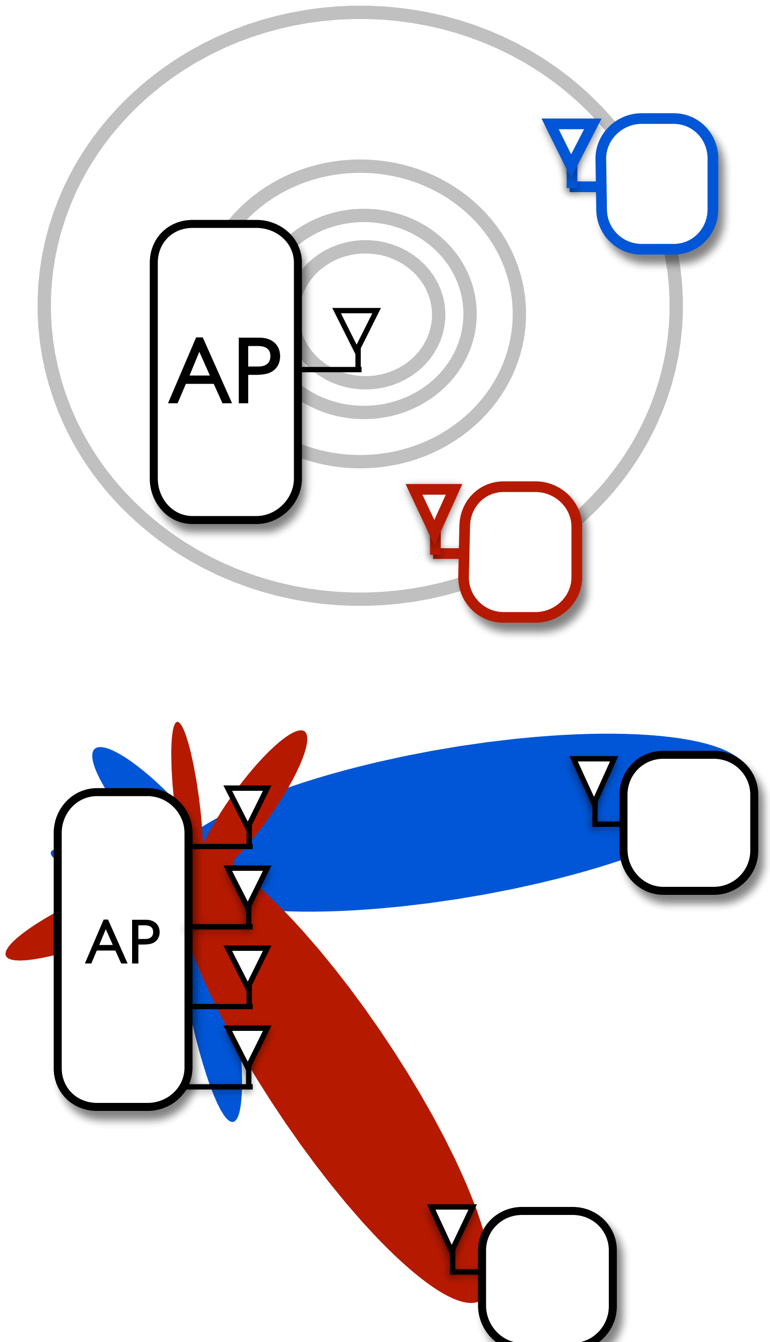


Metric

Goodput $= \dfrac{\text{\# of bits transmitted}}{\text{Sounding time + Data transmission time}}$

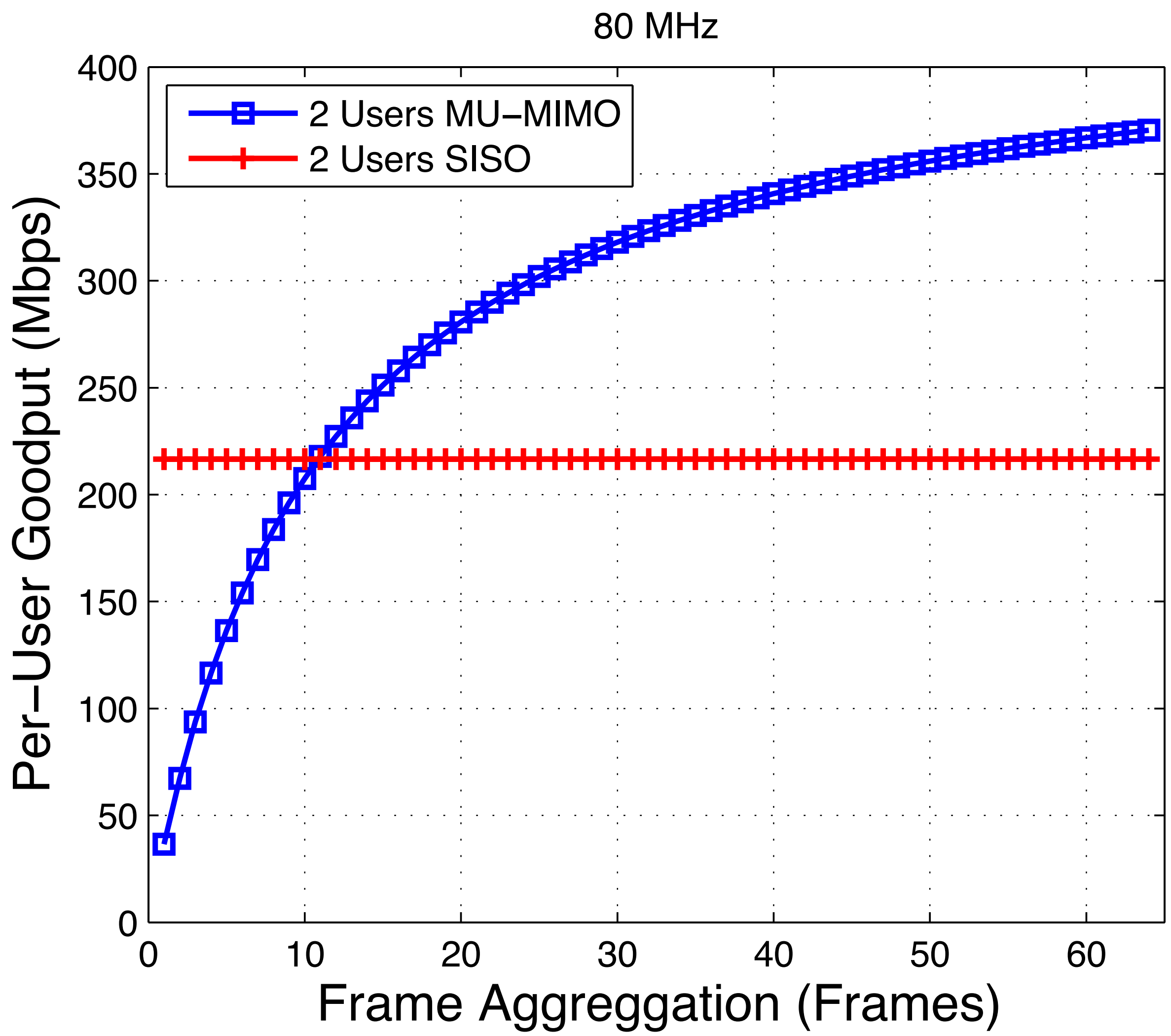


IEEE 802.11ac Sounding Overhead Analysis

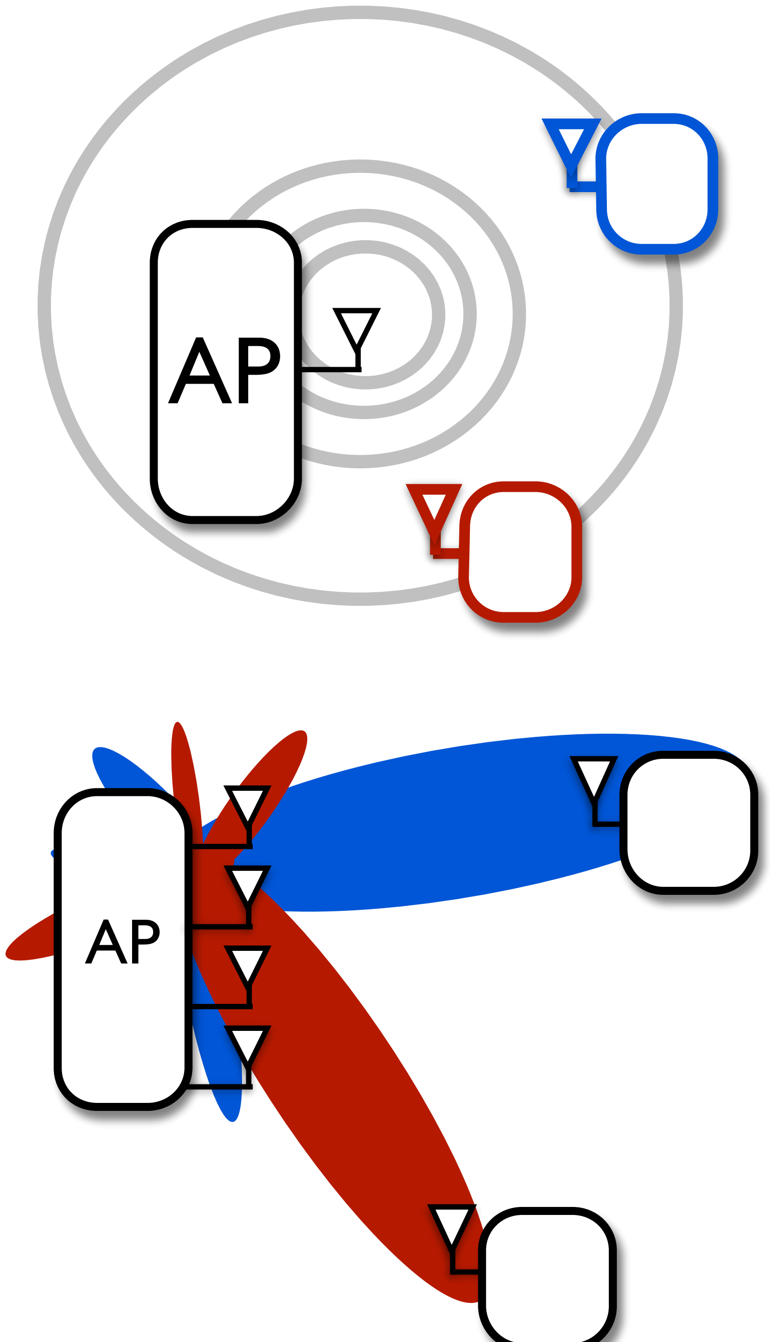


Metric

Goodput $= \dfrac{\text{\# of bits transmitted}}{\text{Sounding time + Data transmission time}}$

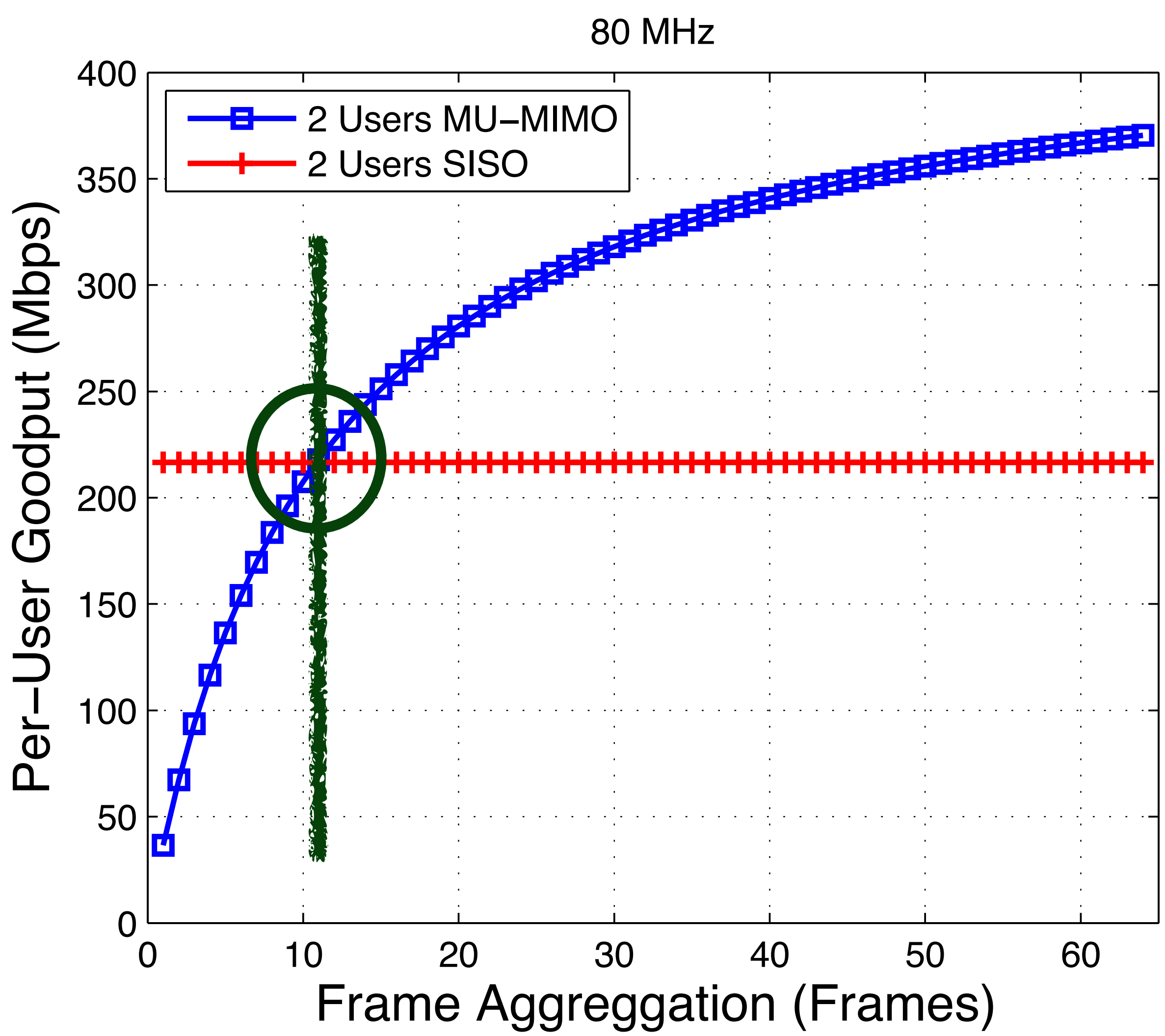


IEEE 802.11ac Sounding Overhead Analysis



Metric
Goodput

$$\frac{\text{\# of bits transmitted}}{\text{Sounding time + Data transmission time}}$$



Costs can outweigh the *benefits*

Roadmap

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

Sounding Inhibition (*MUTE*)

Understanding MUTE

MUTE evaluates two *key* tradeoffs

Tradeoff 1:

Extensive channel knowledge at the AP VS increased sounding overhead

Tradeoff 2:

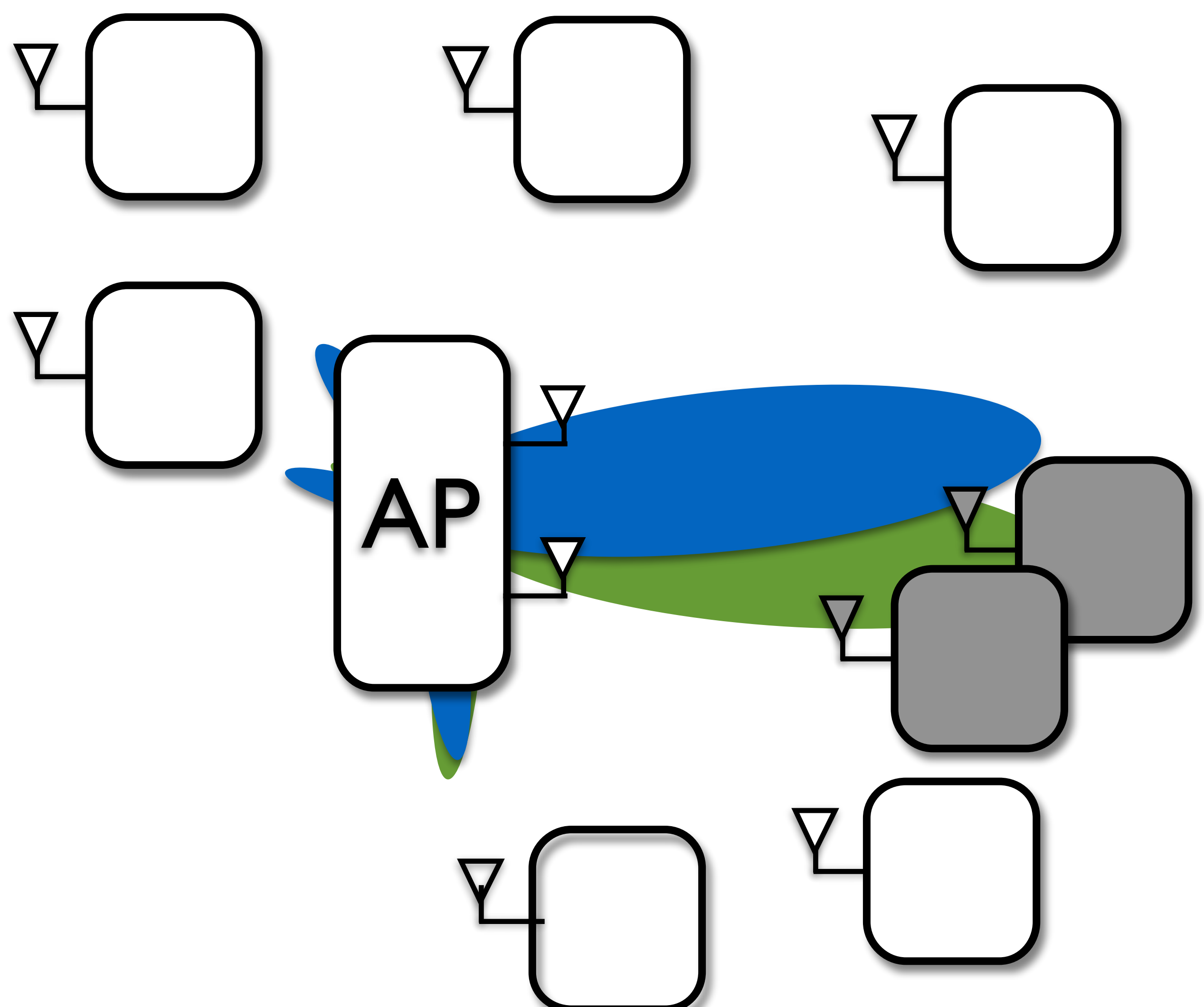
High channel estimate accuracy VS increased sounding overhead

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)
- **<u>However</u>**, prohibitive to sound more than 4 users

*NOTE:
Notice, this correlation happens in signal space

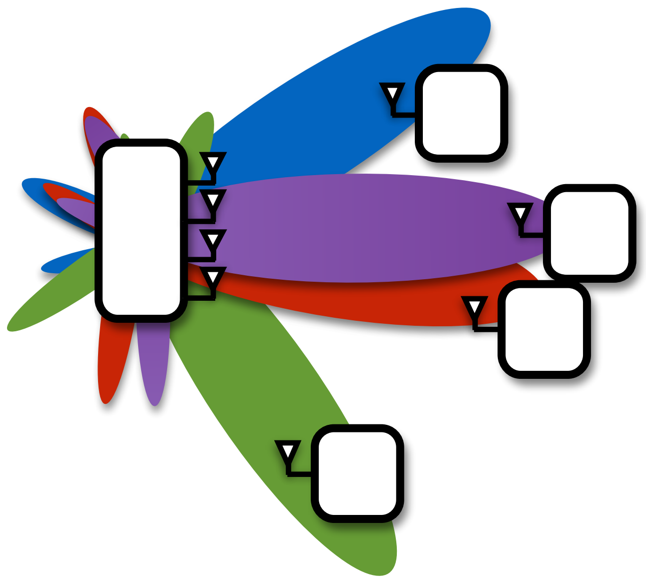
Sounding Inhibition (*MUTE*)

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

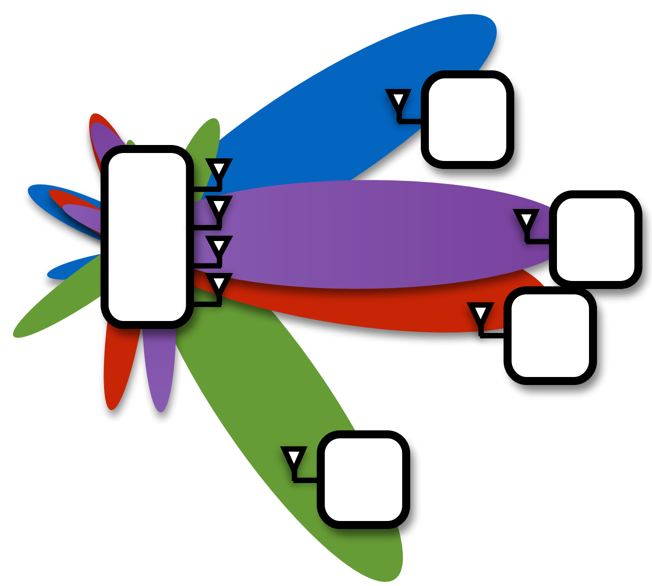
Topology

One 4-antenna AP

30 single-antenna users

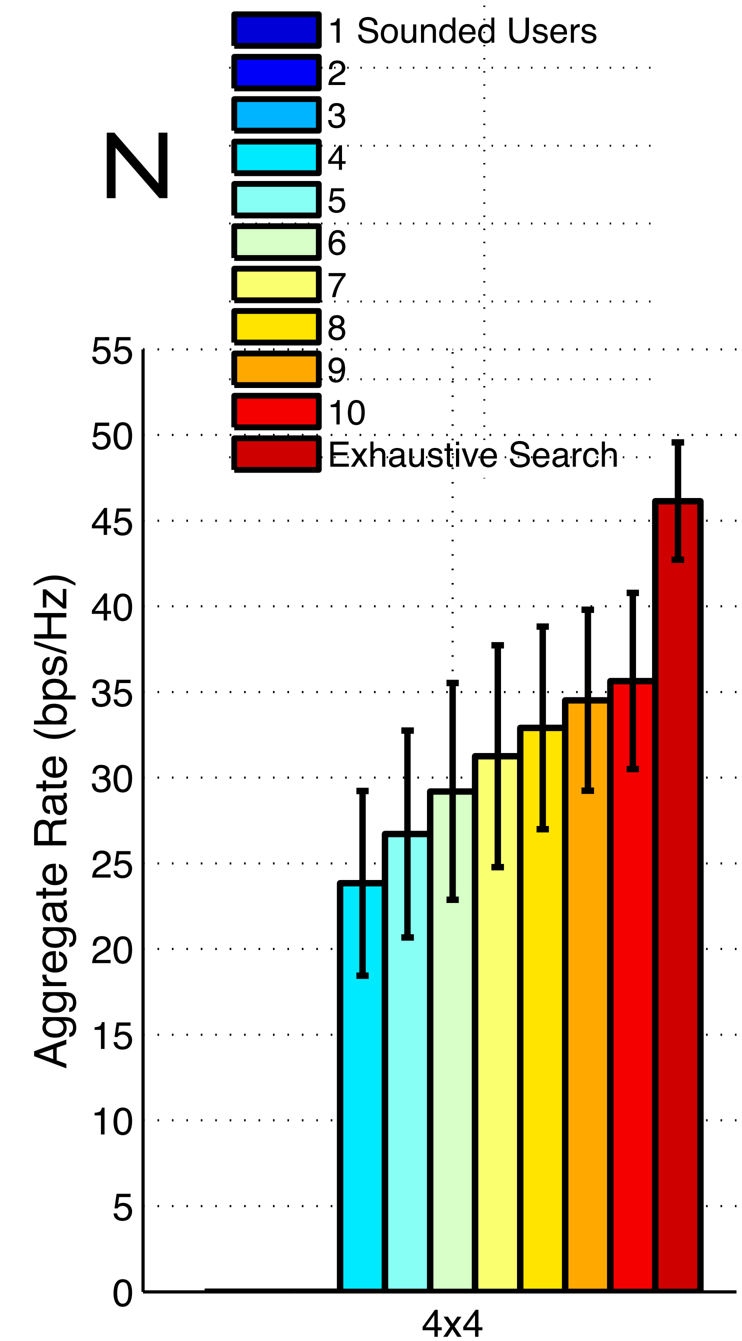
Experiment

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



K = 4
N = 4 to 10

N



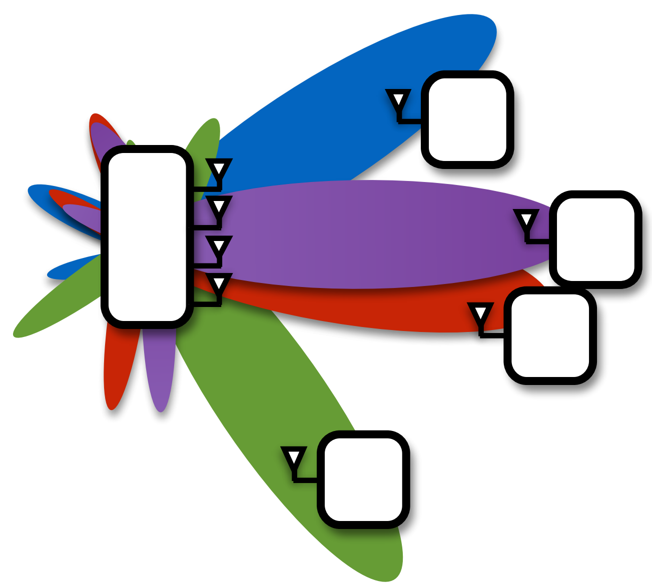
Sounding Inhibition (*MUTE*)

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

Topology

One 4-antenna AP

30 single-antenna users

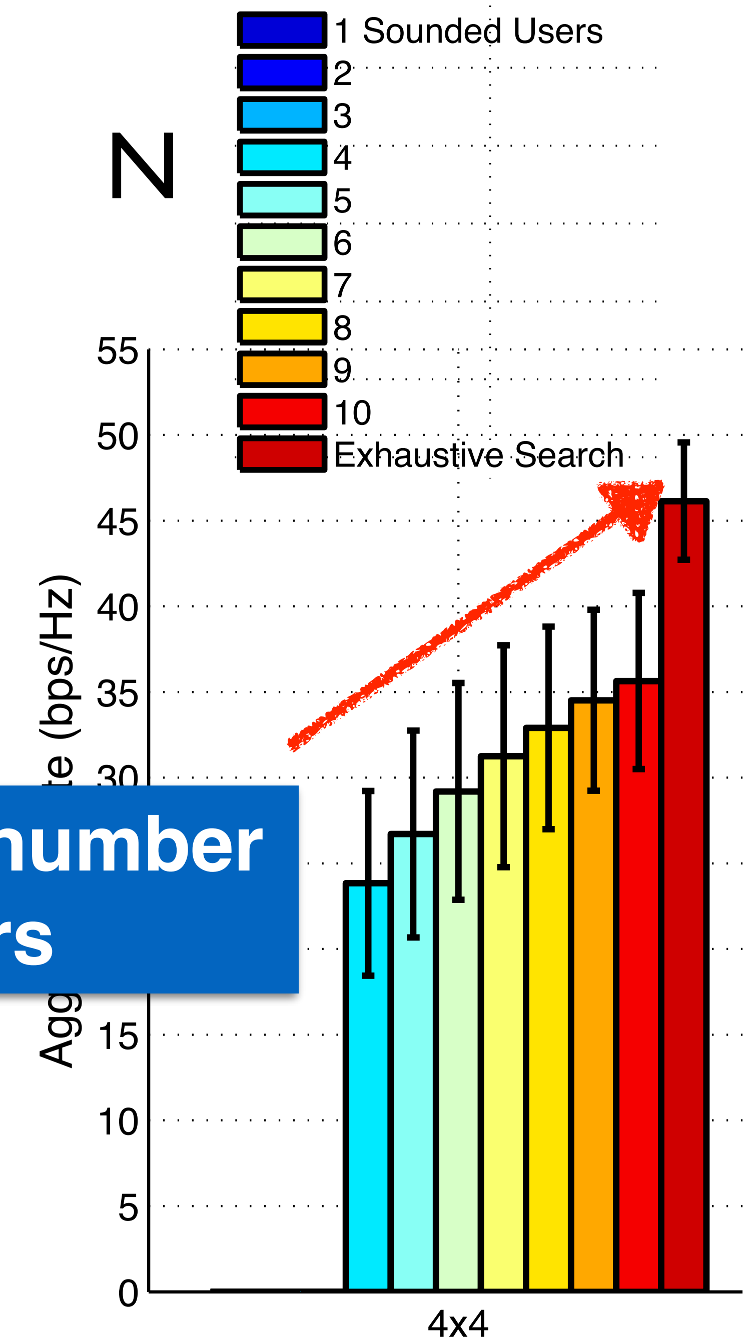


Experiment

1) Sound N ran
(uniform dist

2) Choose the K users that maximize rate

N = 4 to 10



Clear benefit from an increased number of monitored/sounded users

Sounding Inhibition (*MUTE*)

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*)

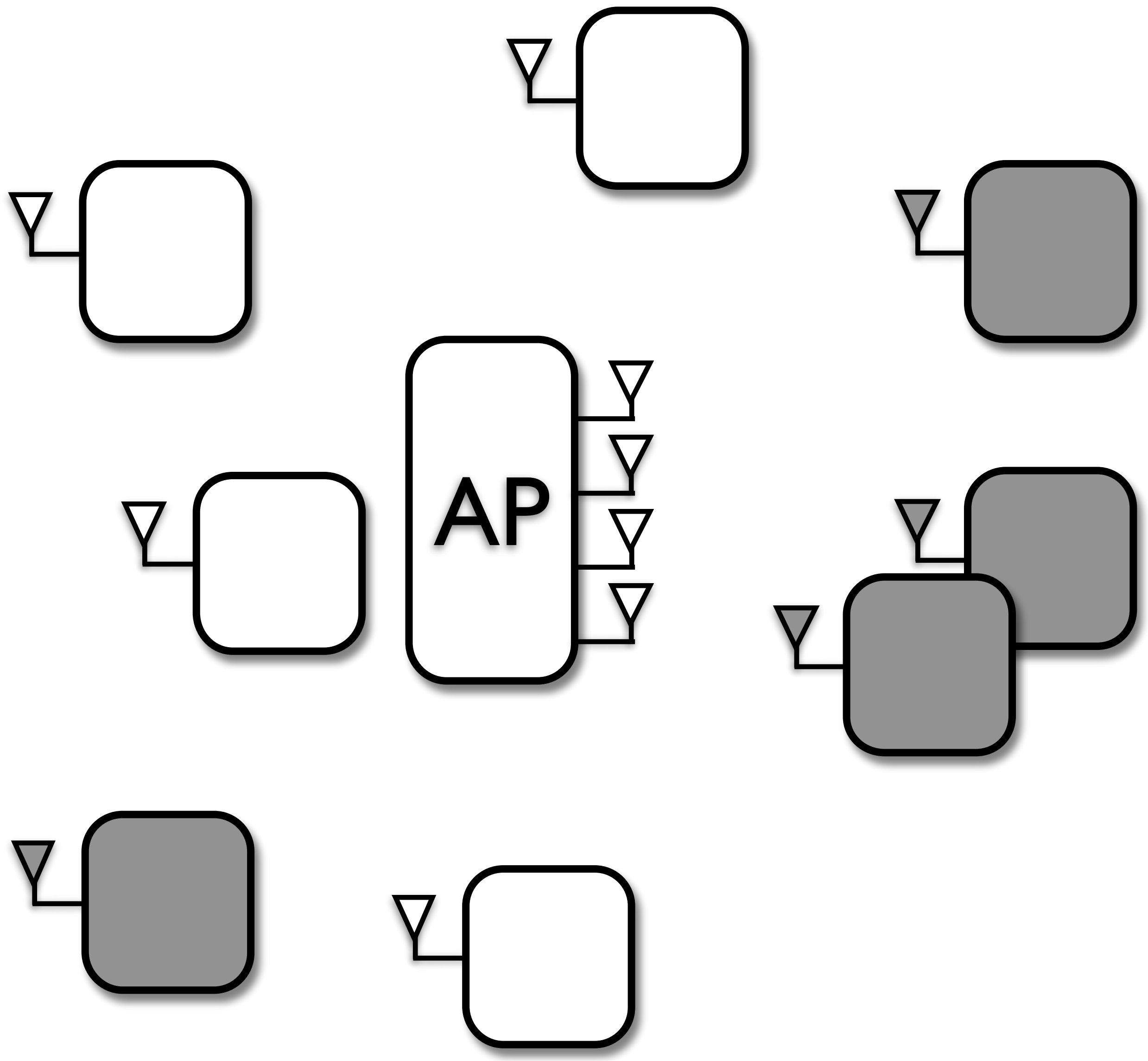
Who to sound?

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

Who to serve?

Sounding Inhibition (*MUTE*)

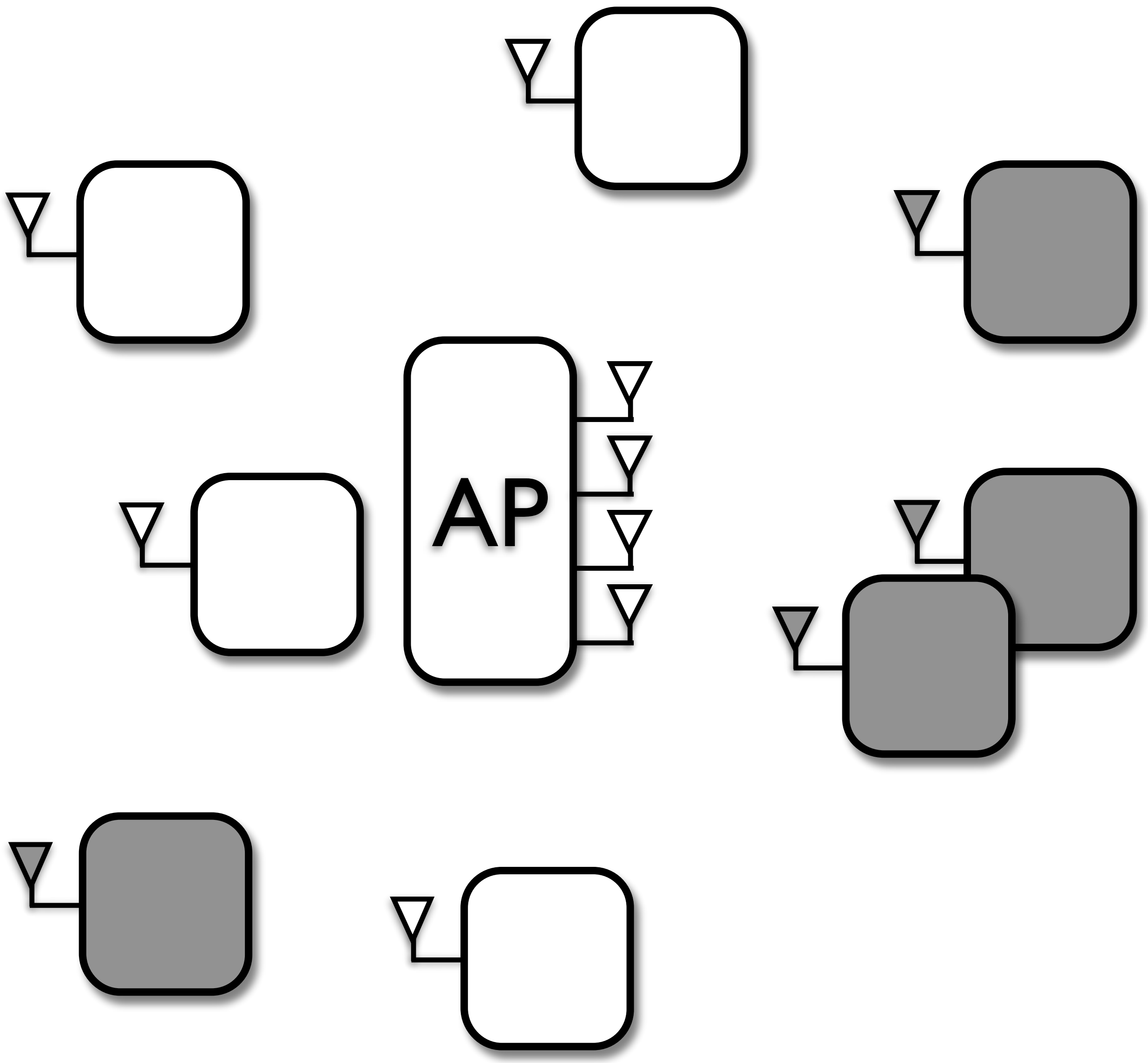
Traditional system - sounding user set selection coupled with transmission user set selection



Schedule transmissions for 4 users

Sounding Inhibition (*MUTE*)

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

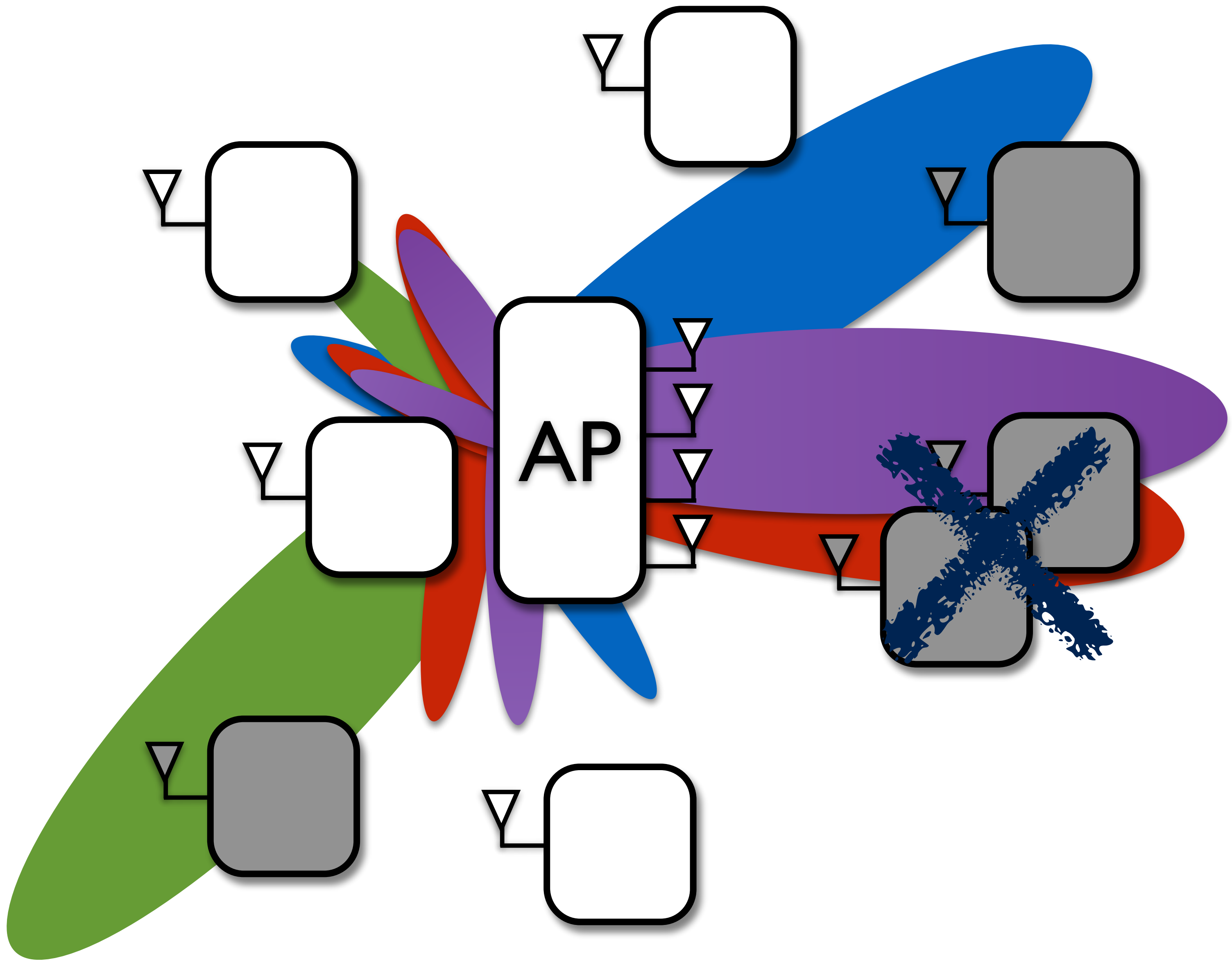


Sound all same 4 users

High overhead

Sounding Inhibition (*MUTE*)

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



Serve all same 4 users

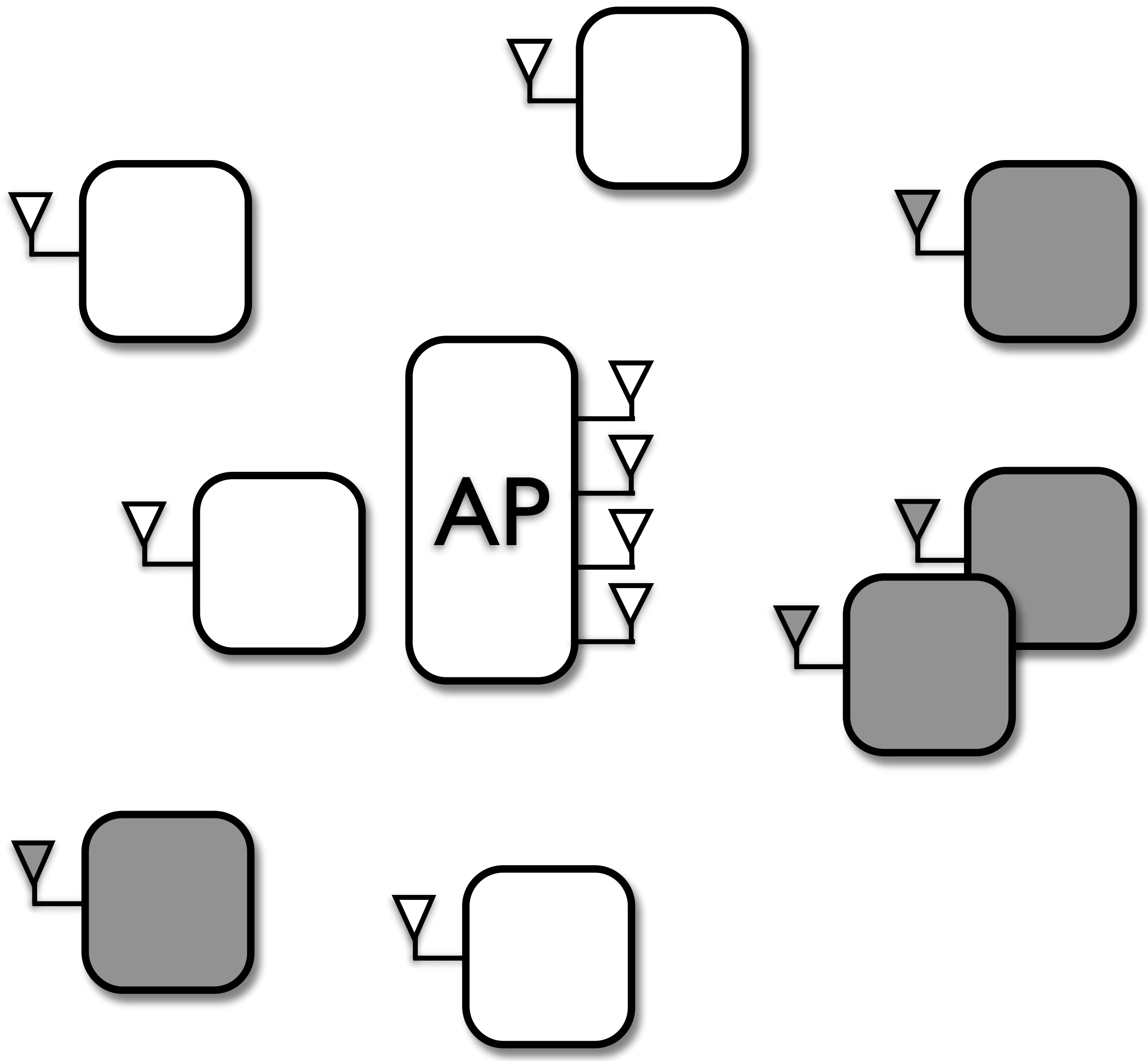
Poor user grouping

Sounding Inhibition (*MUTE*)

In contrast…

Sounding Inhibition (*MUTE*)

MUTE ~~Traditional~~ system - sounding user set selection ~~coupled~~ decoupled from ~~with~~ transmission user set selection

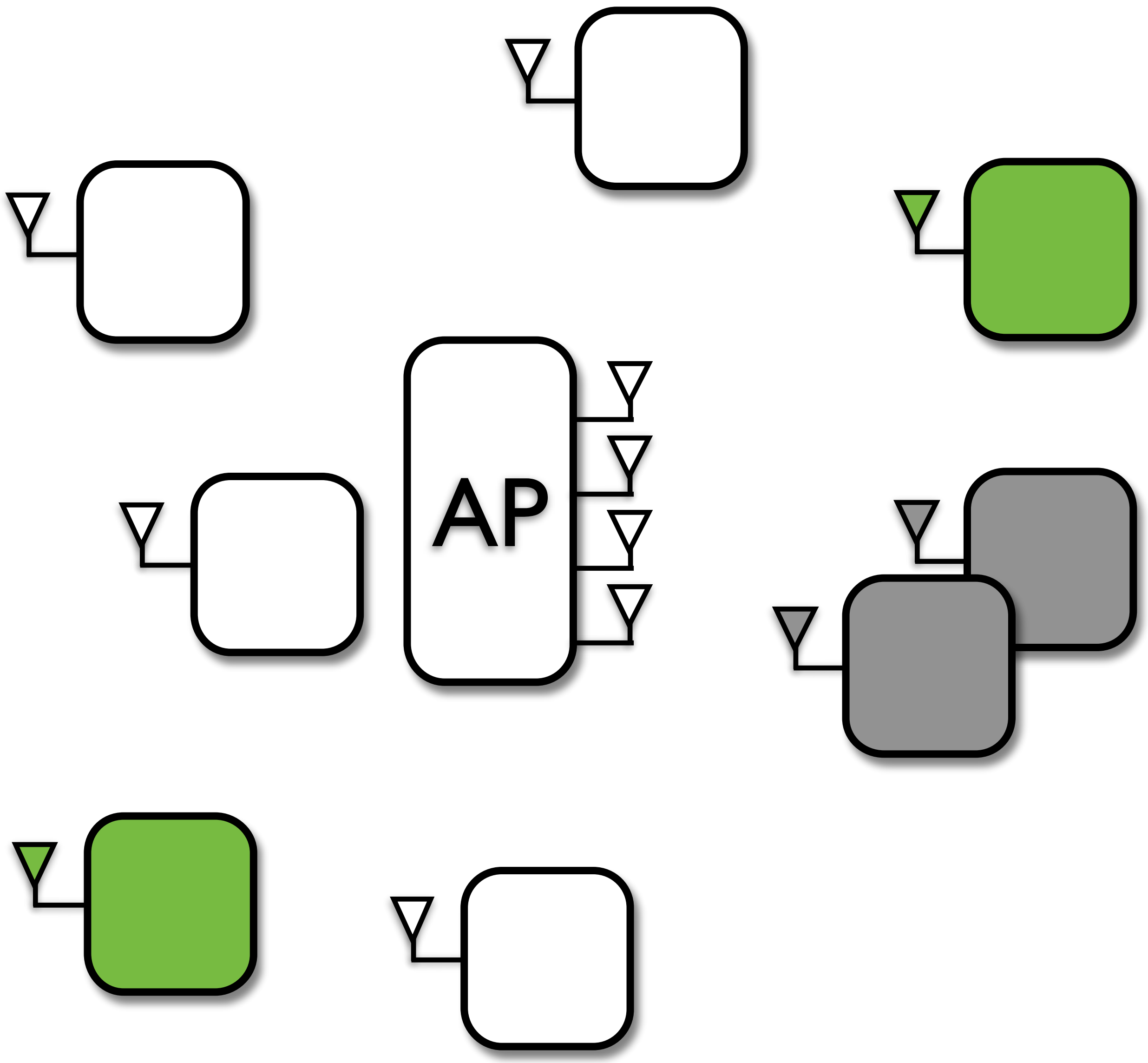


Schedule transmissions for 4 users

Sounding Inhibition (*MUTE*)

MUTE   decoupled from

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



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

Low overhead

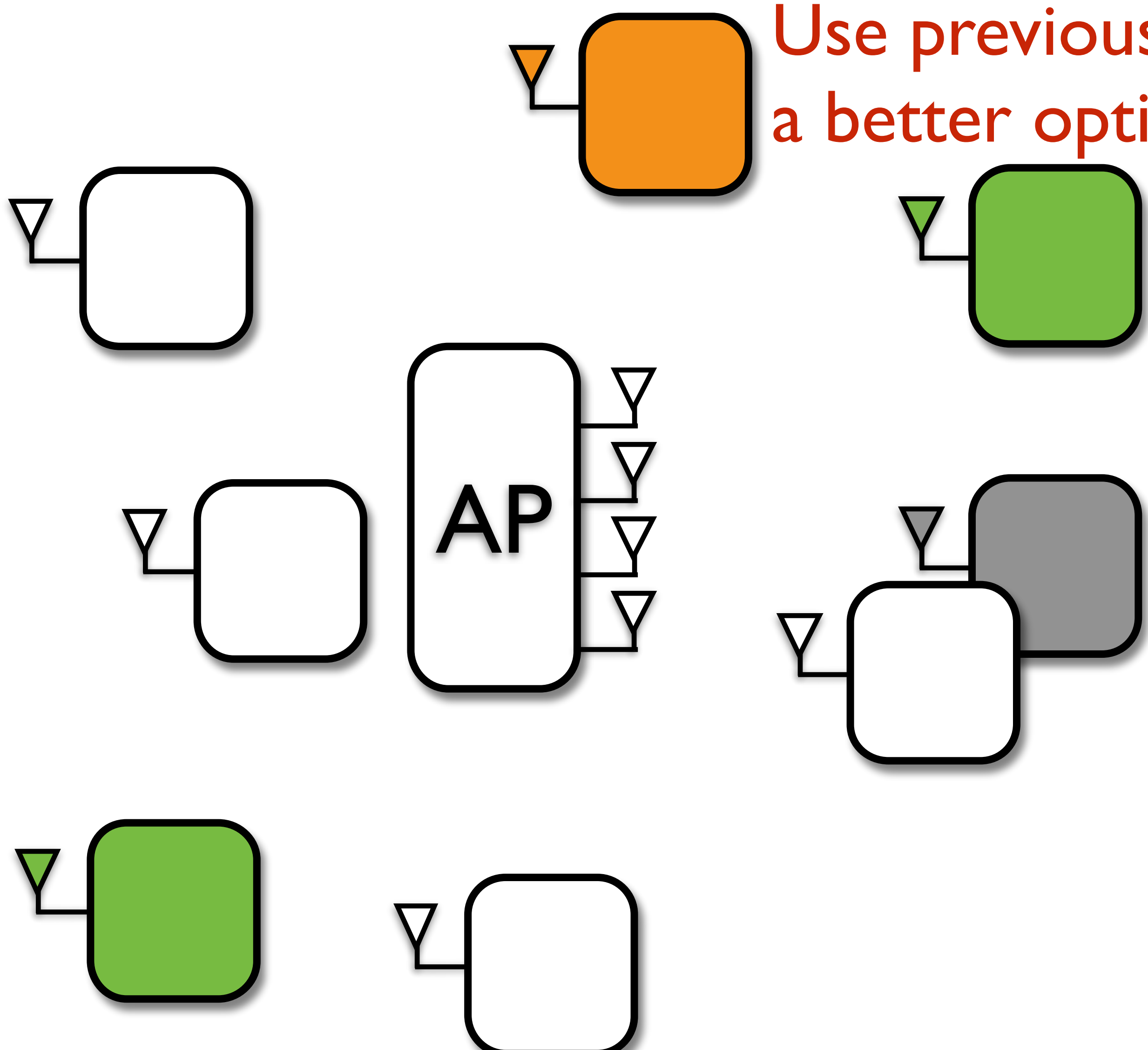
Sounding Inhibition (*MUTE*)

MUTE

decoupled from

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

Use previously collected channel statistics to select a better option



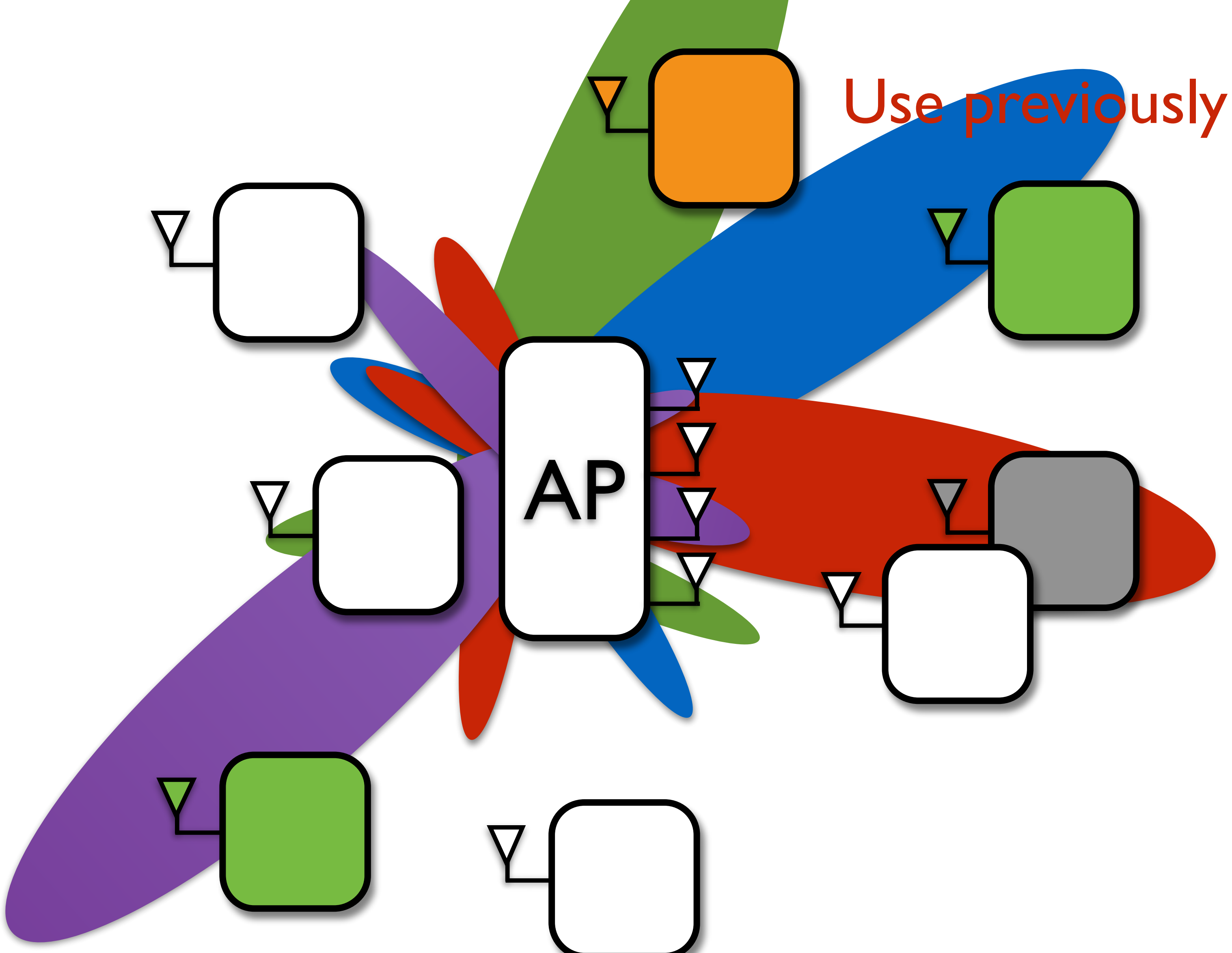
Serve a new set of users. Leverage user diversity based on historical information the AP already has

Rate Maximization

Sounding Inhibition (*MUTE*)

MUTE ~~Traditional~~ system - sounding user set selection decoupled from ~~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

Sounding Inhibition (*MUTE*)

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

[1] Shen, Zukang, Jeffrey G. Andrews, and Brian L. Evans. "Short range wireless channel prediction using local information." Signals, Systems and Computers, 2004. Conference Record of the Thirty-Seventh Asilomar Conference on. Vol. 1. IEEE, 2003.

[2] Duel-Hallen, Alexandra. "Fading channel prediction for mobile radio adaptive transmission systems." Proceedings of the IEEE 95.12 (2007): 2299-2313.

[3] Gesbert, David, et al. "Outdoor MIMO wireless channels: Models and performance prediction." Communications, IEEE Transactions on 50.12 (2002): 1926-1934.

[4] Halperin, Daniel, et al. "Predictable 802.11 packet delivery from wireless channel measurements." ACM SIGCOMM Computer Communication Review 41.4 (2011): 159-170.

[5] Phillips, Caleb, Douglas Sicker, and Dirk Grunwald. "A survey of wireless path loss prediction and coverage mapping methods." Communications Surveys & Tutorials, IEEE 15.1 (2013): 255-270.

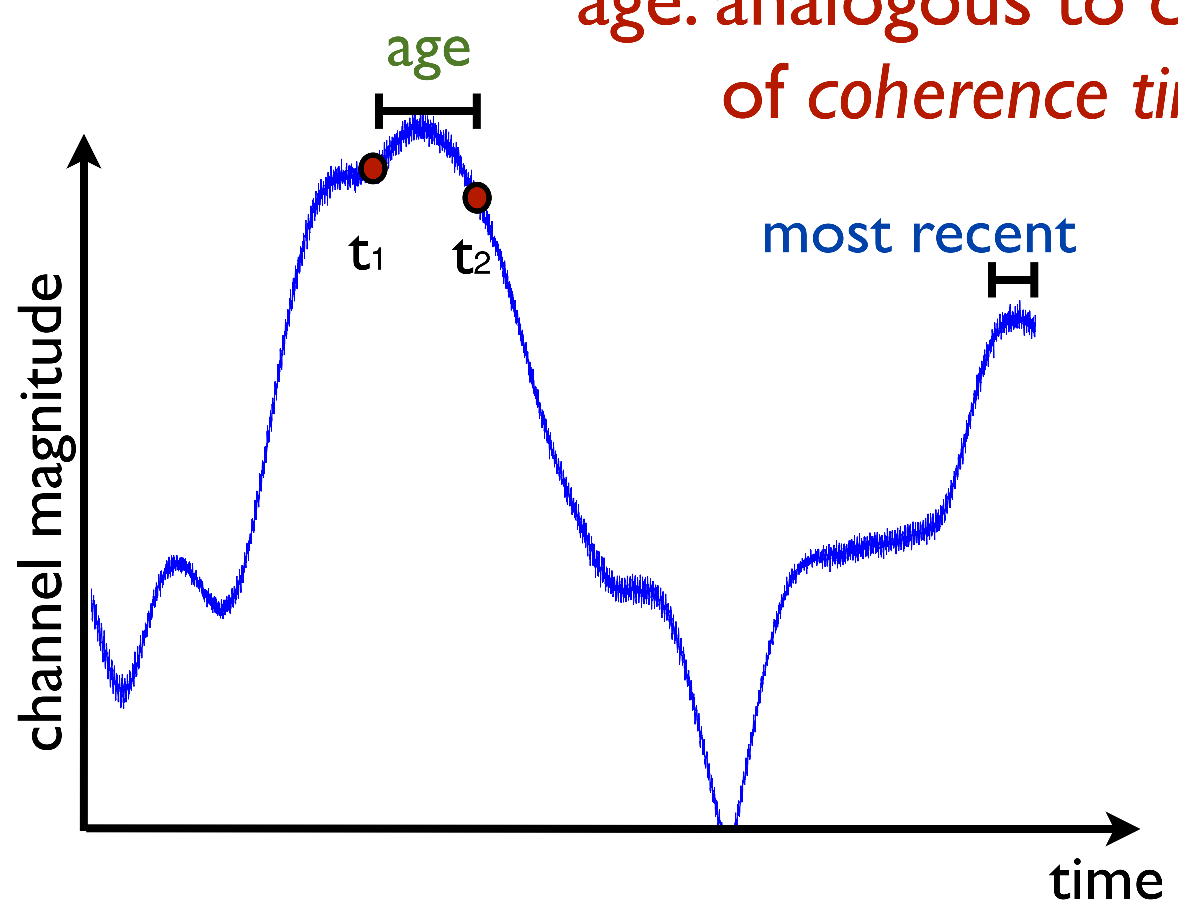
Sounding Inhibition (*MUTE*)

Two Empirical Observations:

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

Collected samples in static channels degrade similarly with time

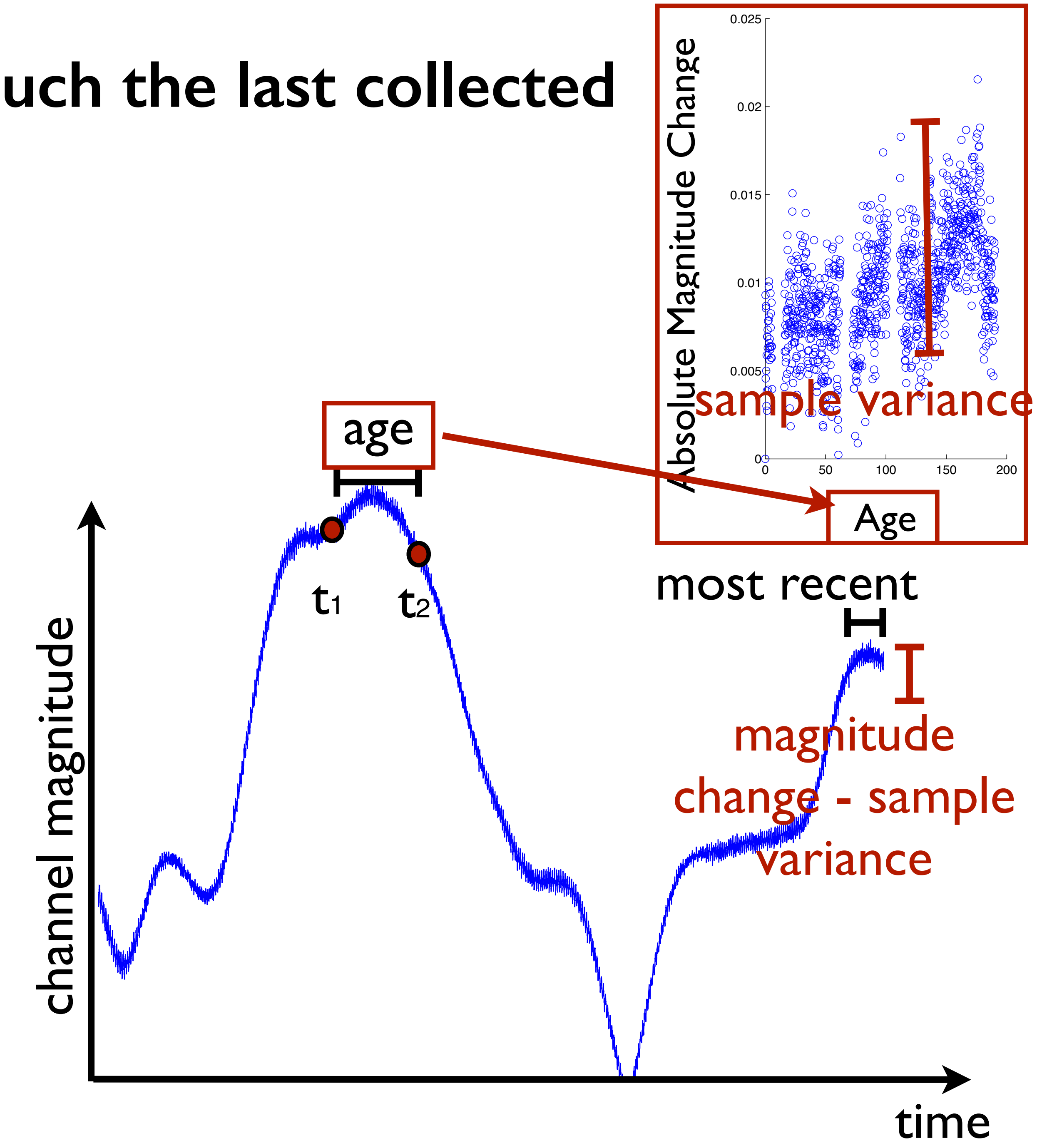
age: analogous to concept of *coherence time*



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

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

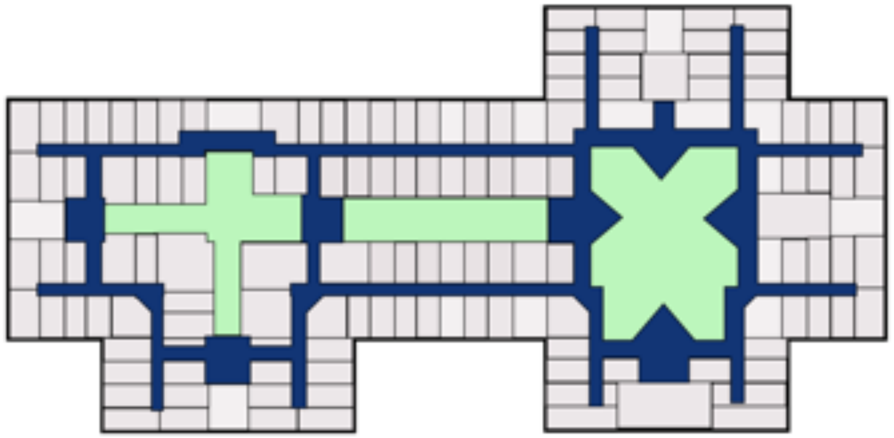
Experimental Evaluation of MUTE

Our evaluation answers the following question:

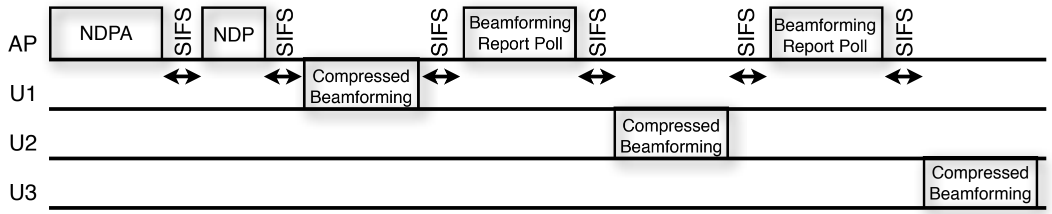
Can MUTE strike a balance between *overhead suppression* and *rate penalty* due to inaccurate channel estimates?

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

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

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

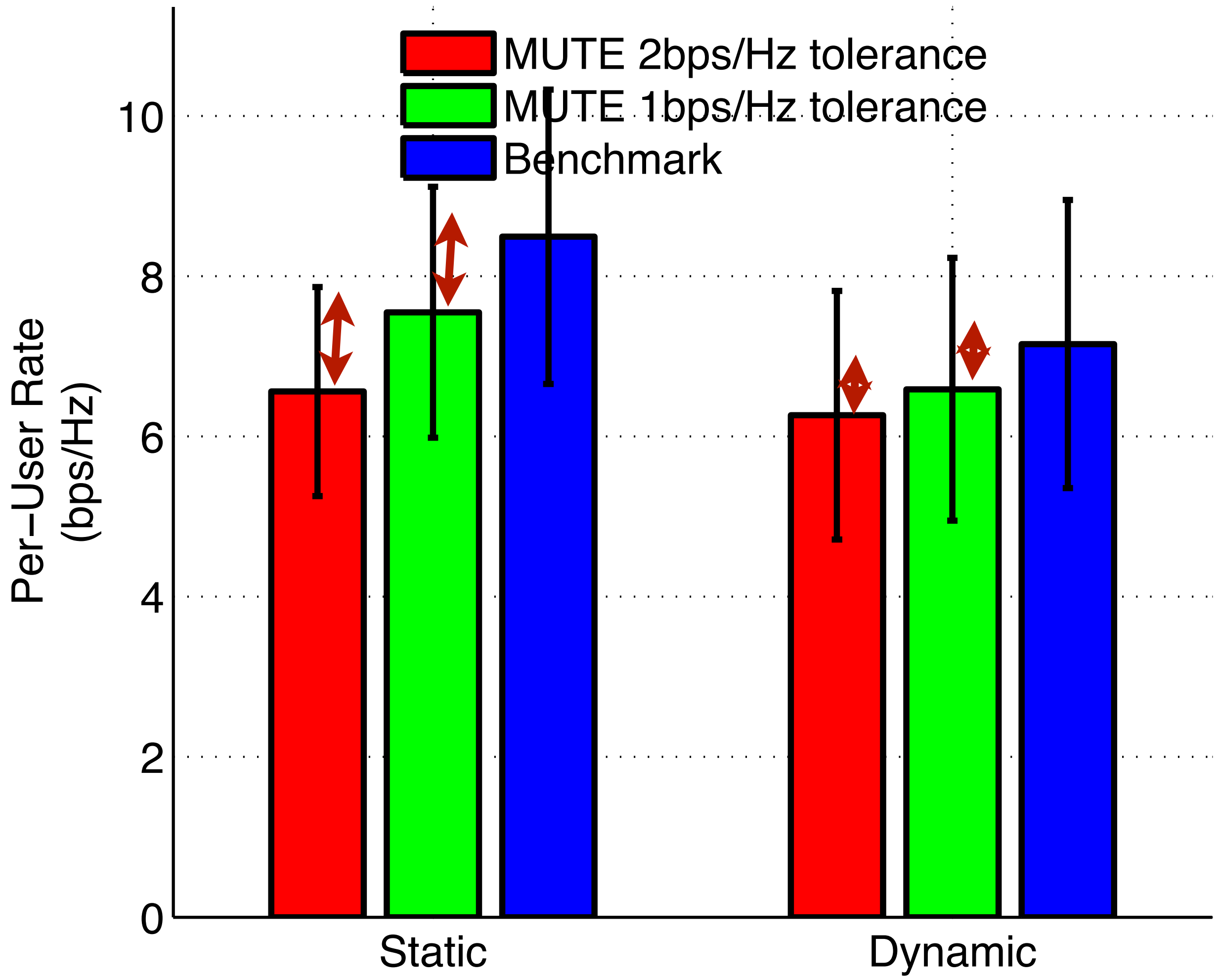
Evaluation of rate penalty due to infrequent sounding

- Setup
  - Overhead **not** considered
  - 4x4 system
  - 30-user topology
  - Compute rate loss

Experimental Evaluation of MUTE

Evaluation of rate penalty due to infrequent sounding

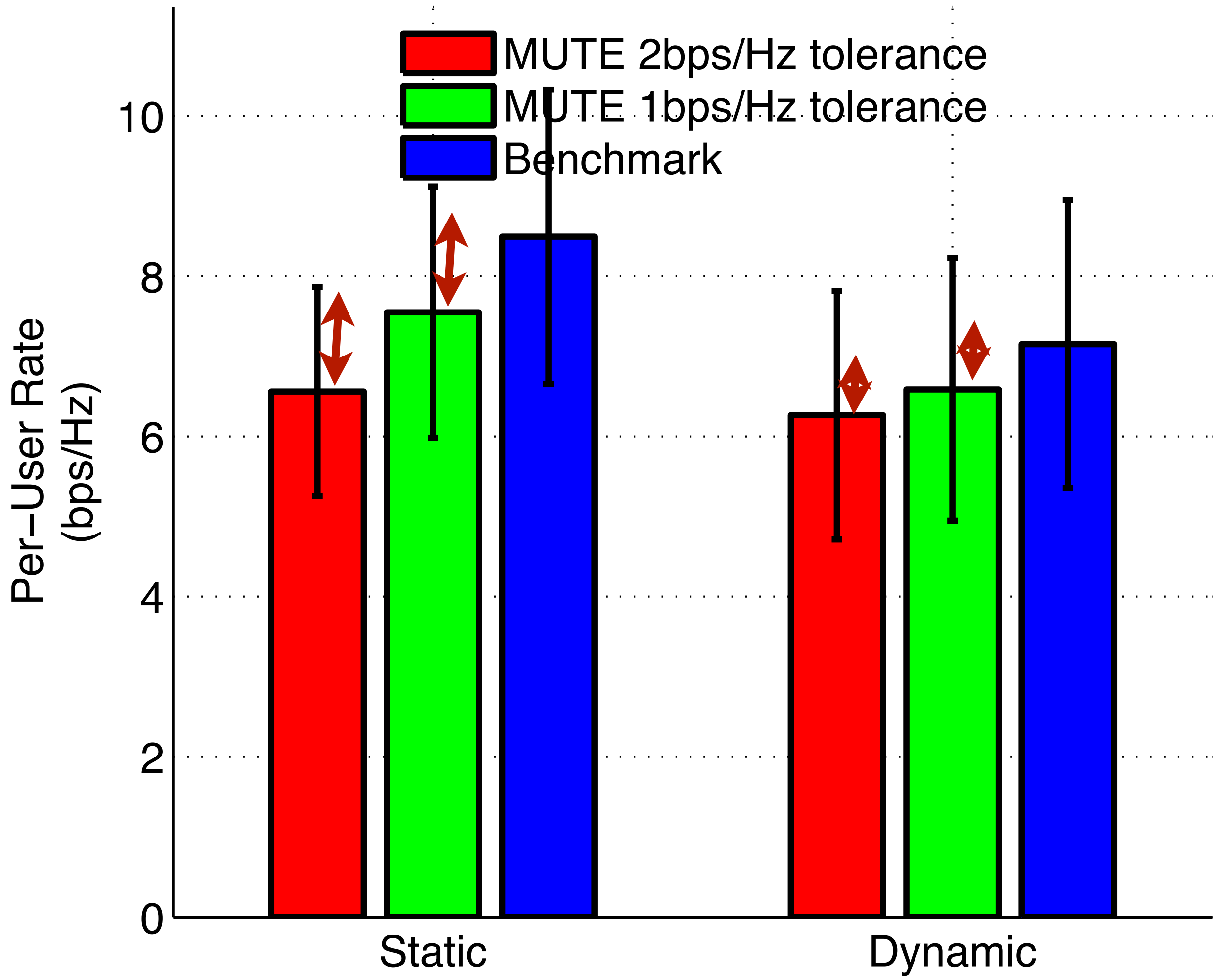
- Setup
  - Overhead **not** considered
  - 4x4 system
  - 30-user topology
  - Compute rate loss



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

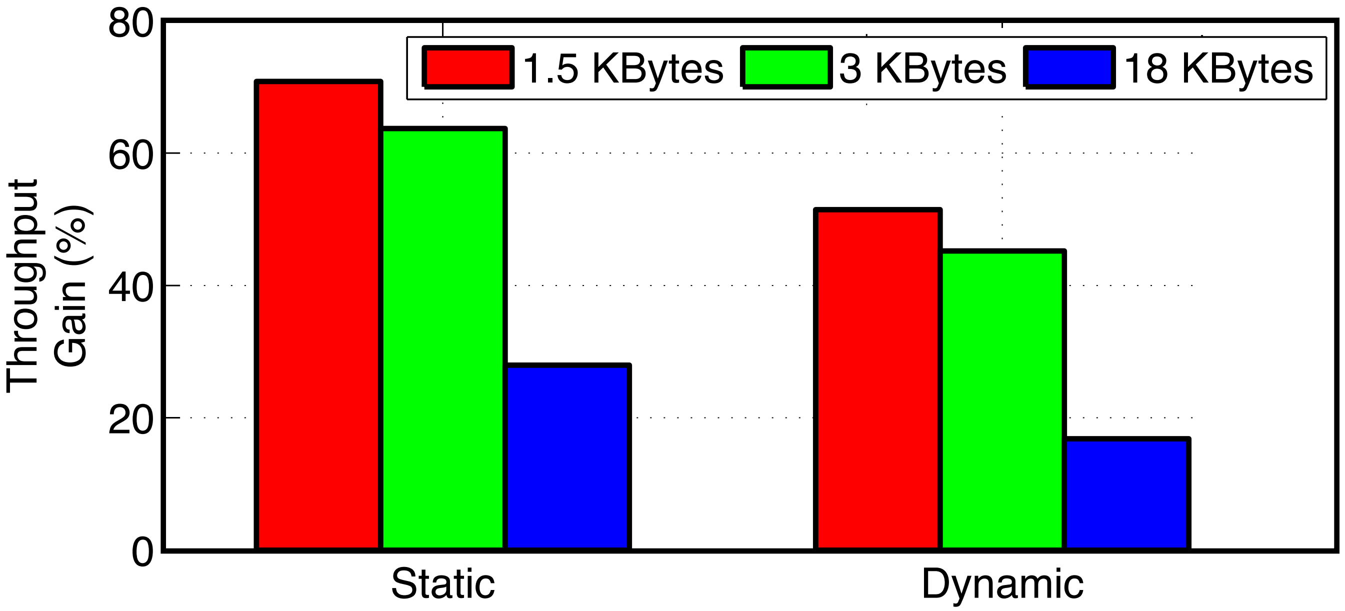
Evaluation of overall throughput performance

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

Experimental Evaluation of MUTE

Evaluation of overall throughput performance

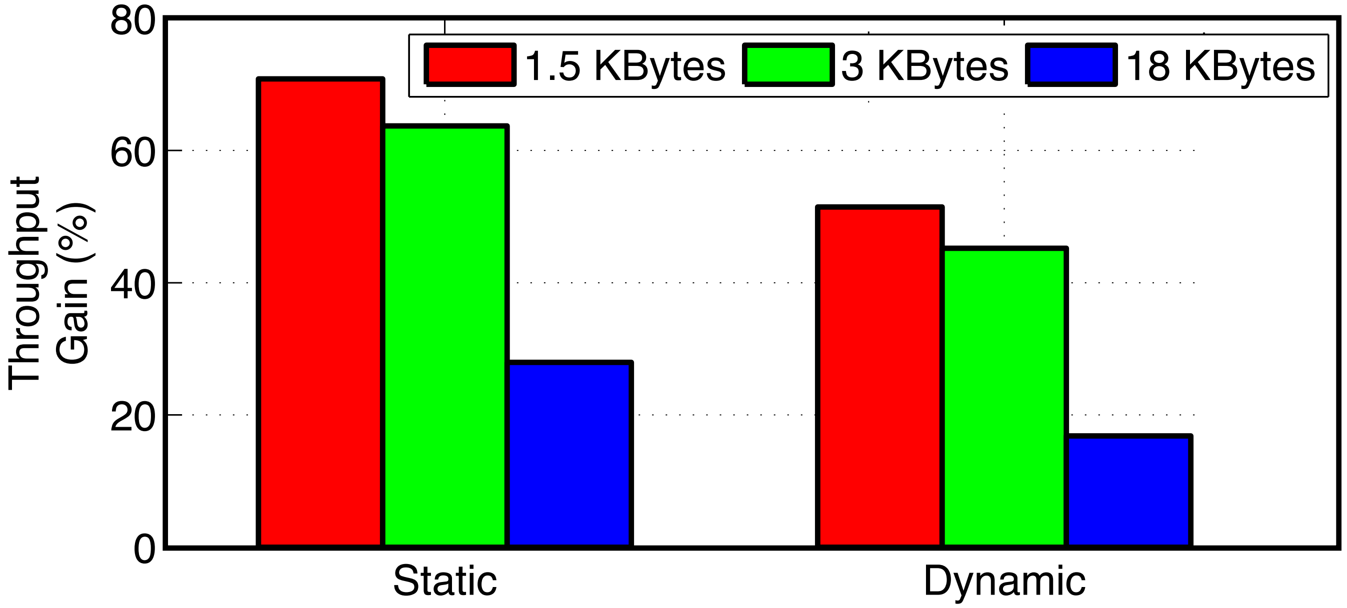
- Setup
  - Overhead considered
  - 4x4 system
  - 30-user topology
  - 1.5 to 18 kBytes aggregation
  - Compute xput gain compared to benchmark



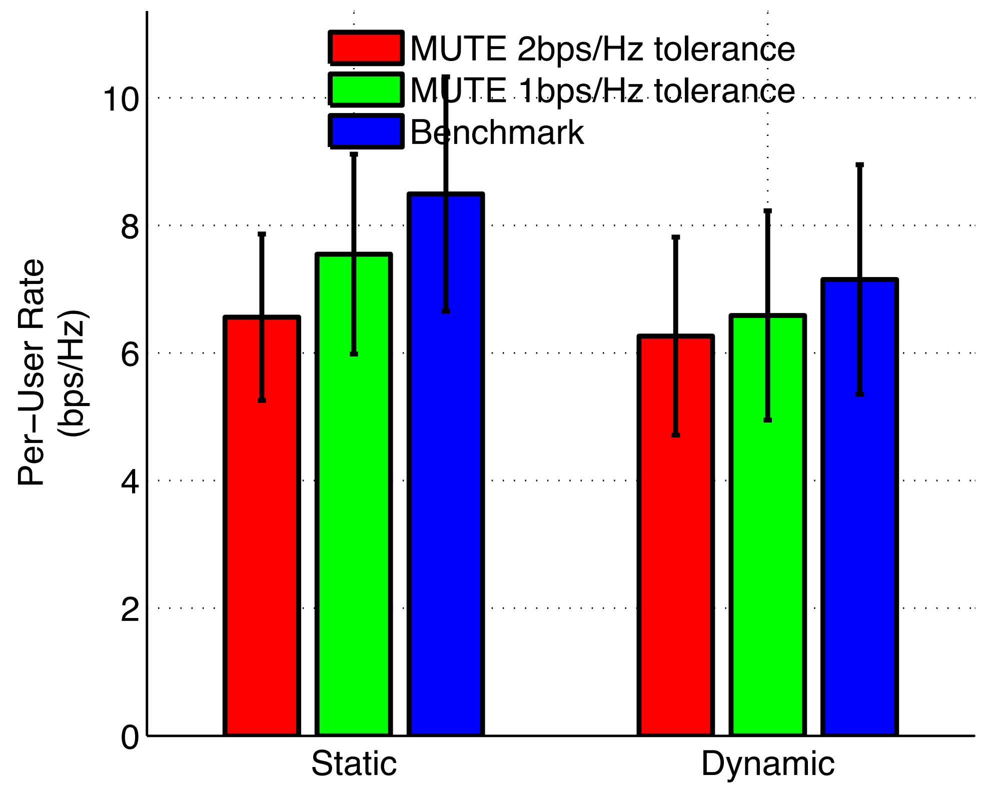
Experimental Evaluation of MUTE

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

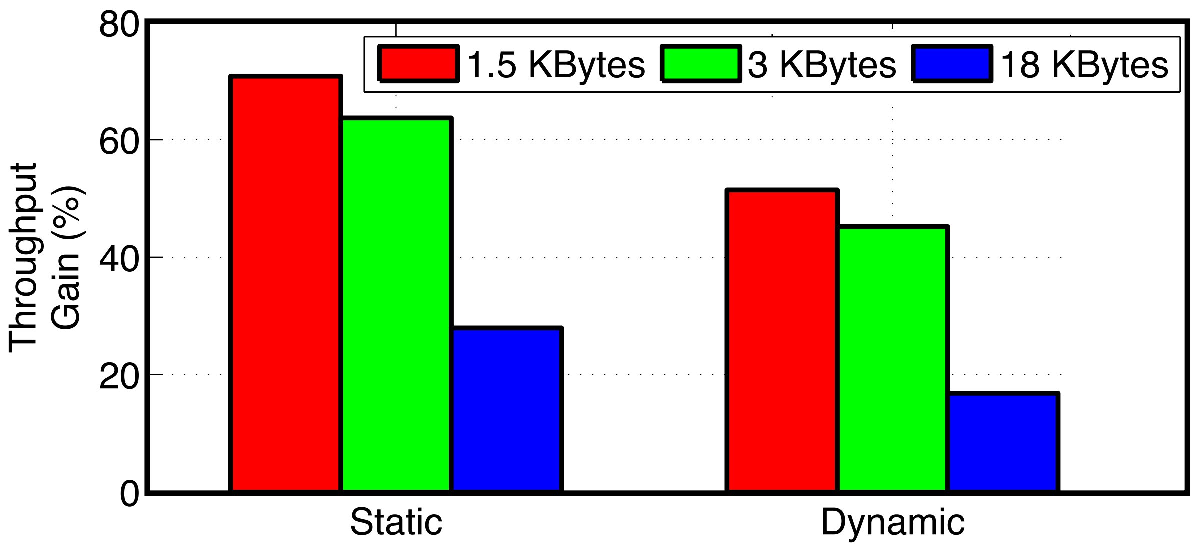


Experimental Evaluation of MUTE



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

Conclusion

Thank you!