Decoupling Beam Steering and User Selection for Scaling Multi-User 60 GHz WLANs

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60 GHz WLANs

- **Capabilities and propagation characteristics**
  - 7-14 GHz available unlicensed bandwidth
  - 20-40 dB increased signal attenuation

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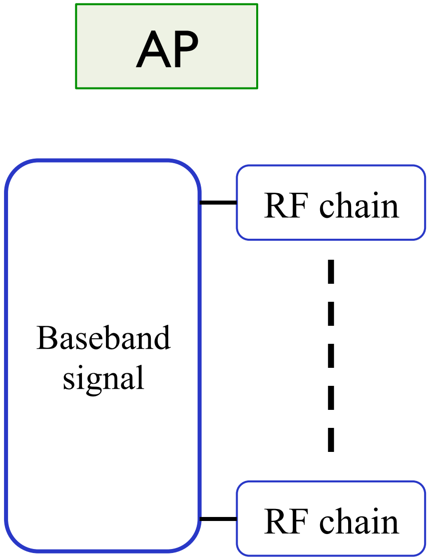
- **Directional transmission**
  - Small form factor with mm-scale antennas
  - Standardized via IEEE 802.11ad
  - Up to 7 Gbps data rate

Goal

- **Enabling multi-user directional transmission**
  - Opportunity for spatial reuse
  - Simultaneous downlink transmission
  - Scaling total throughput
  - Which users and which beams (directions)?

Multi-user 60 GHz system model

- Multi-RF chain AP



AP

Baseband signal

RF chain

RF chain

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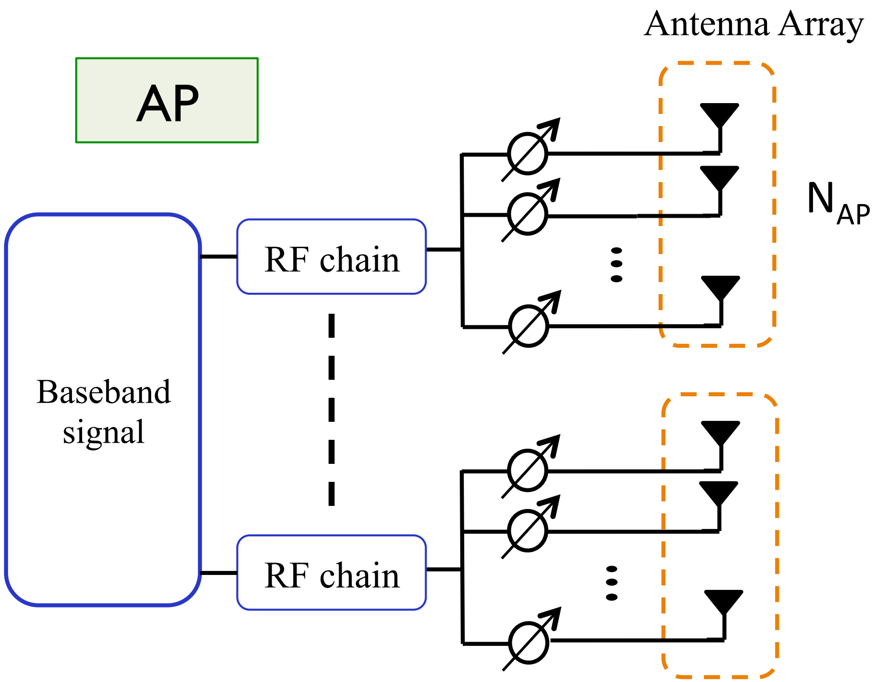
- Each RF chain is connected to multiple antennas (vs. one in 2.4/5 GHz)



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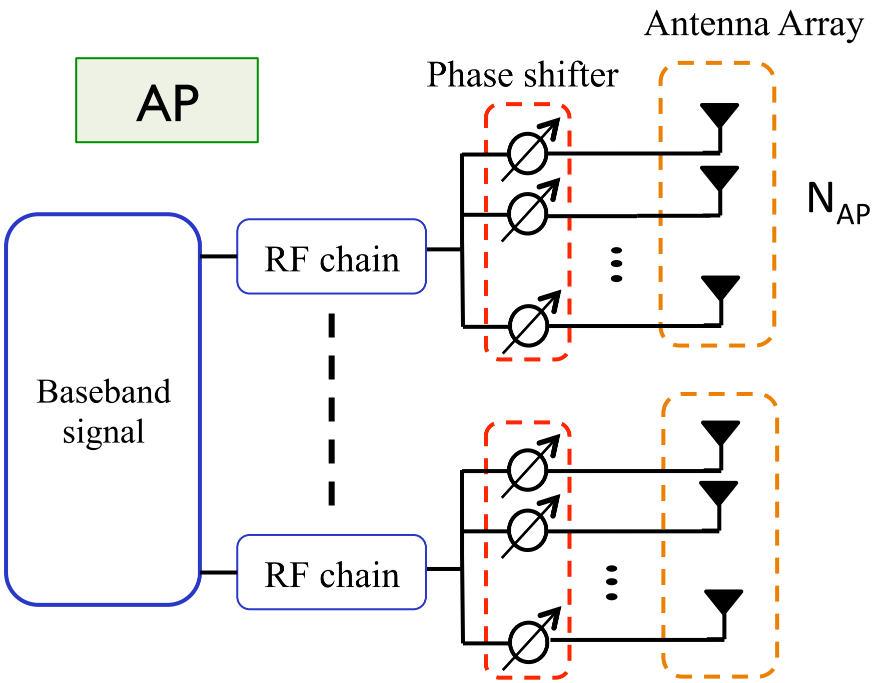

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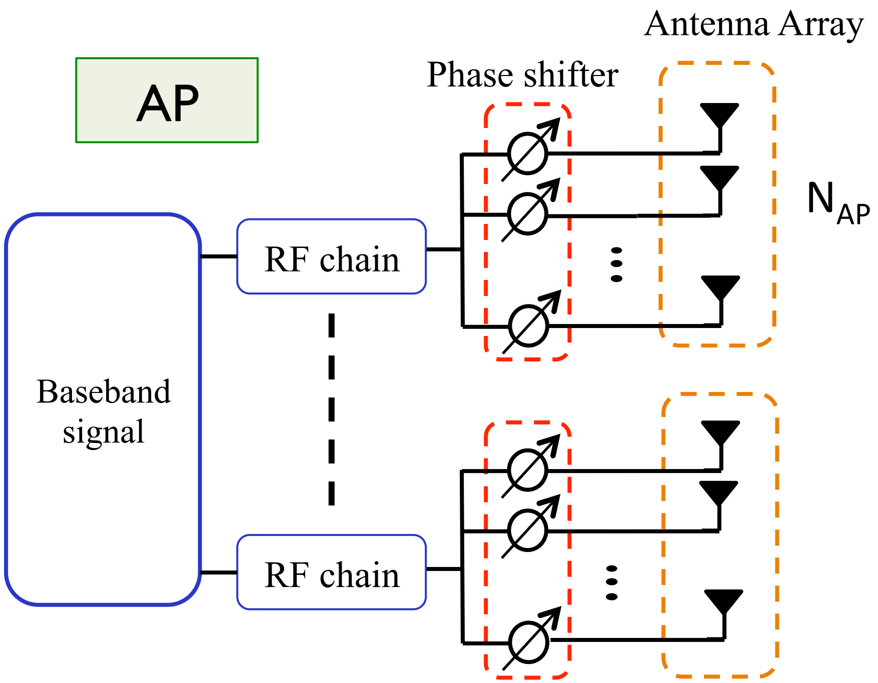

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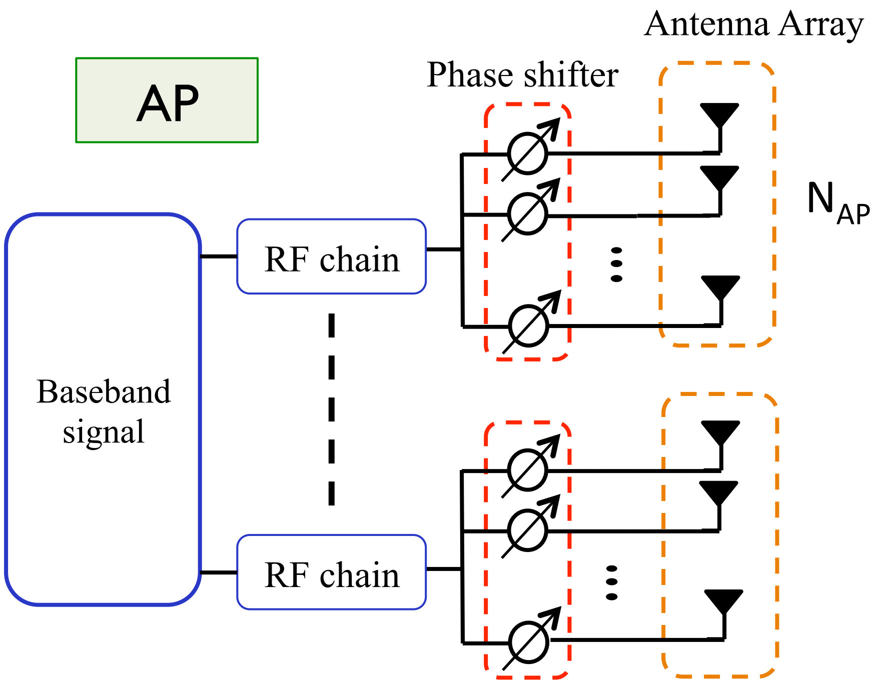

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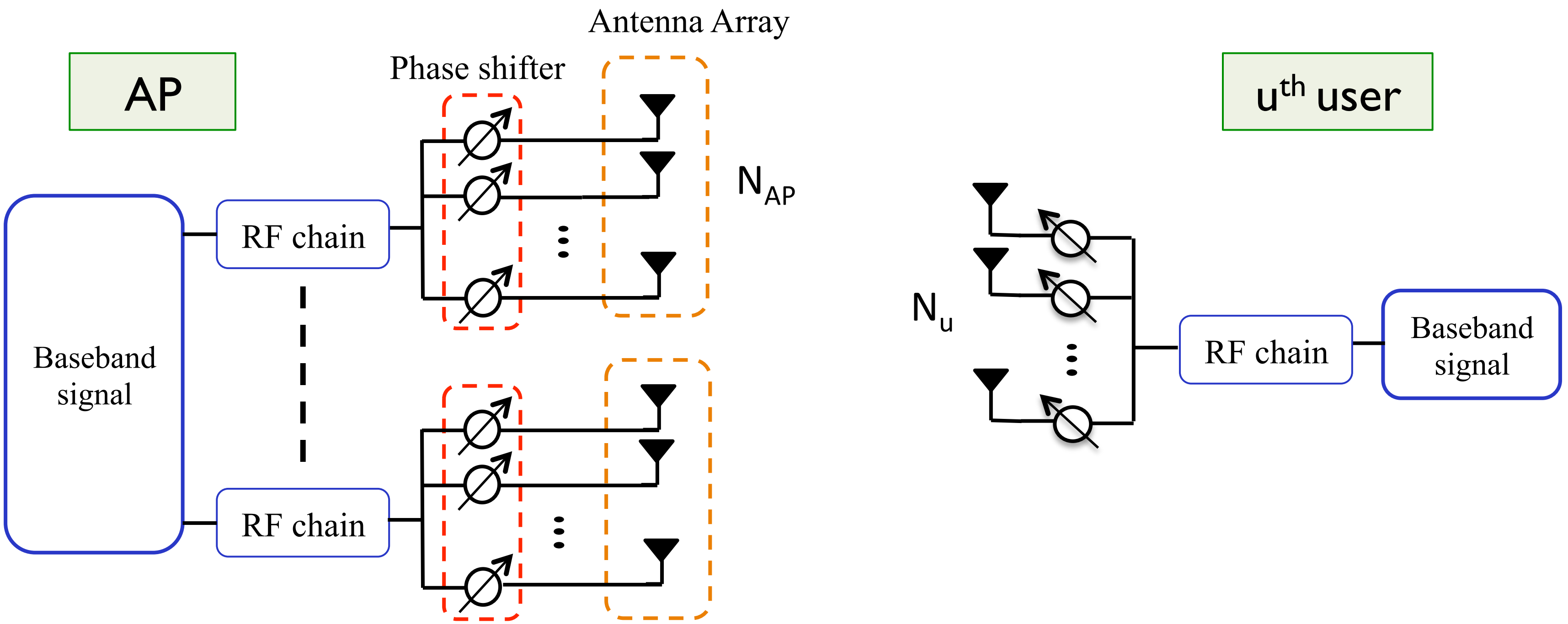

Key steps before a MU transmission

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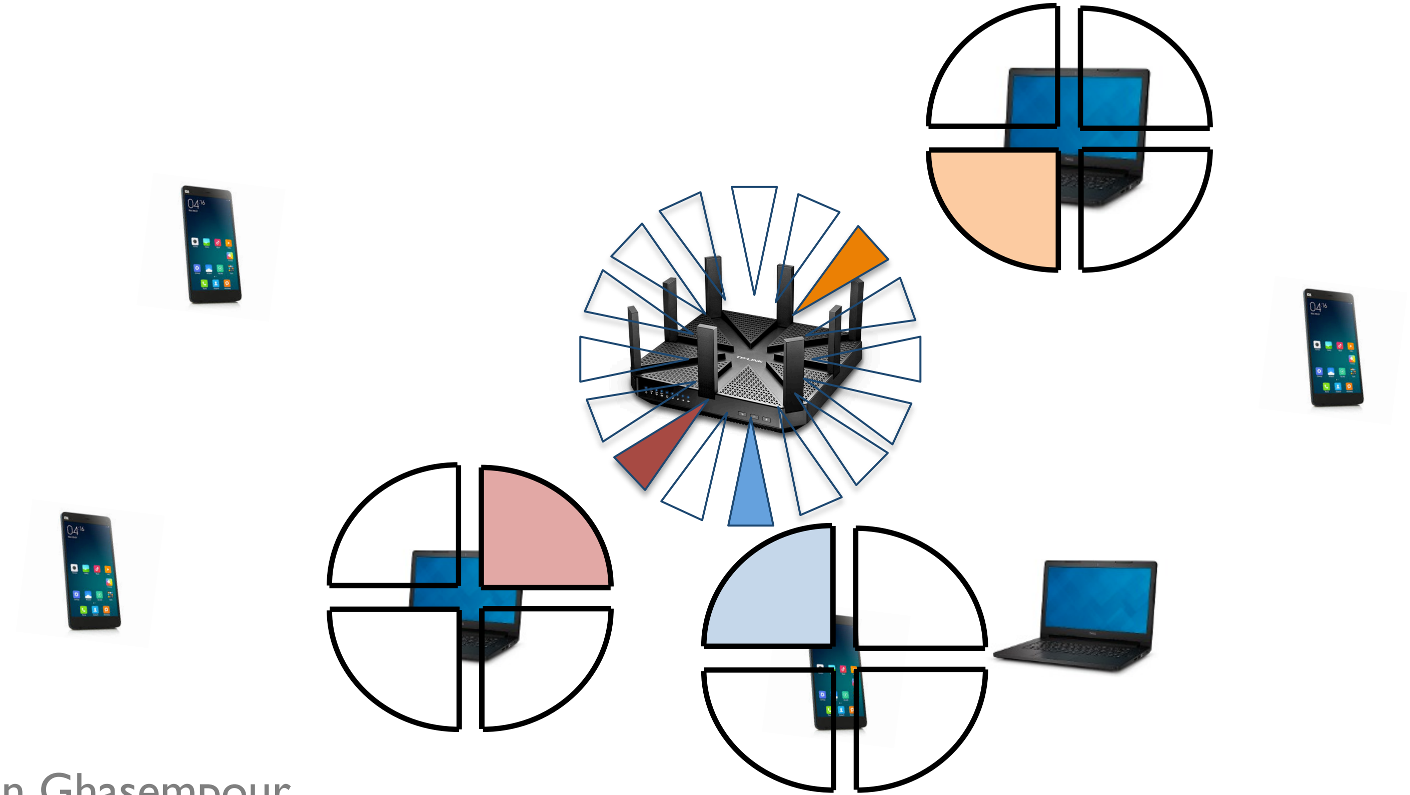
- Transmit and receive analog beamforming vectors
- Digital beamforming weights (F_{BB})

$$\left\{ \begin{array}{l} w_{u,tx} \in C^{N_{AP} \times 1} \\ w_{u,rx} \in C^{N_u \times 1} \end{array} \right.$$



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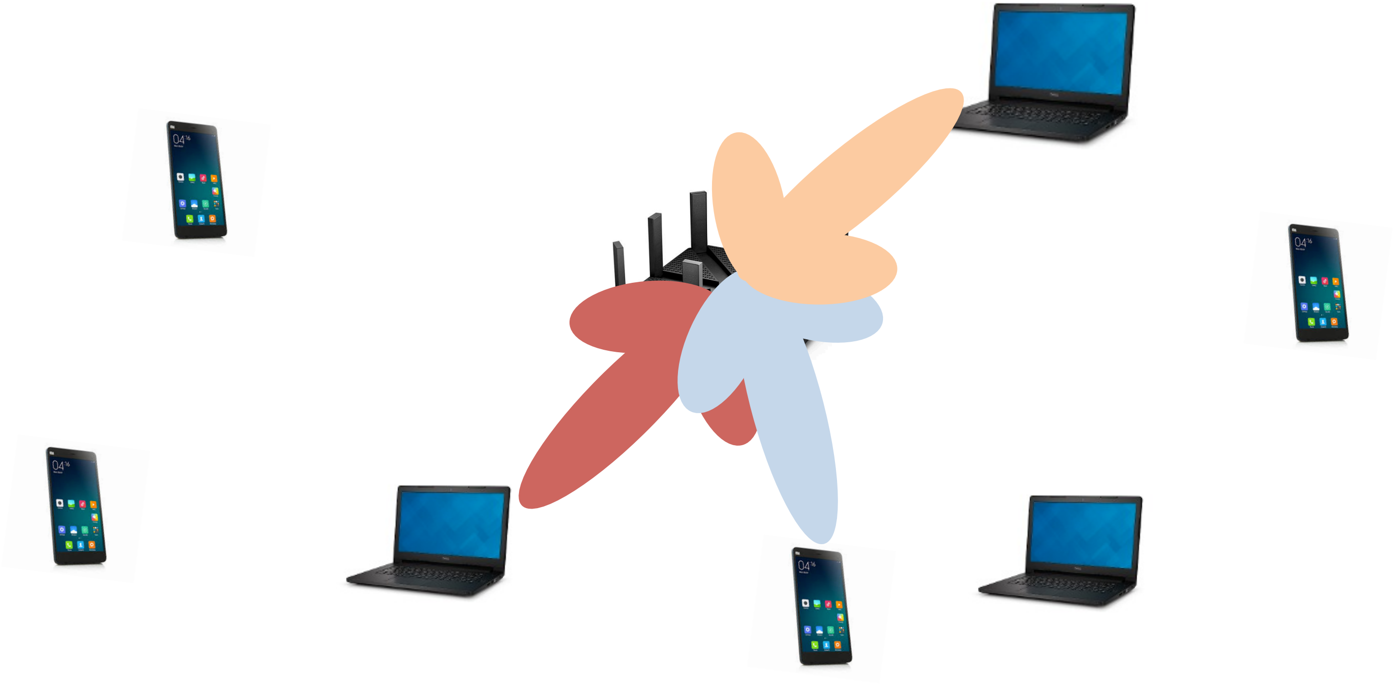

Achievable data rate

$$R_{sum}(G) = \sum_{u=1}^{U} R_u(G, w_{u,tx}, w_{u,rx}, F_{BB})$$

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- Constraints:
  - Analog beams limited to a codebook
  - No. of users limited to no. RF chains

$$w_{u,tx} \in F, u = 1, 2, \ldots, U,$$

$$w_{u,rx} \in W, u = 1, 2, \ldots, U,$$

$$|G| \leq N_{RF.}$$

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- Requires channel sate info of every client (channel size : N_{AP} x N_u)
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Not Practical

- Maximizing sum-rate

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Prior Work

Hybrid beamforming for 60 GHz MU transmissions[1, 2]

- For a given group of users → no user grouping
- Developing low-complexity algorithms for hybrid analog and digital beamforming
  Maximizing sum-rate considering the hardware limitation and channel specification with limited feedback

➢ No protocol for user selection

MU-MIMO in sub 6 GHz

- One antenna per RF chain → no analog beam steering, smaller channel size
- User grouping based on channel state info [3]
- User grouping without channel info exploiting the rich scattering propagation environment below 6 GHz [4]

➢ In contrast, we consider a different frequency band and node architecture

[1] A. Alkhateeb, et. al. Limited Feedback Hybrid Precoding for Multi-User Millimeter Wave Systems. IEEE Transactions on Wireless Communications (2015).

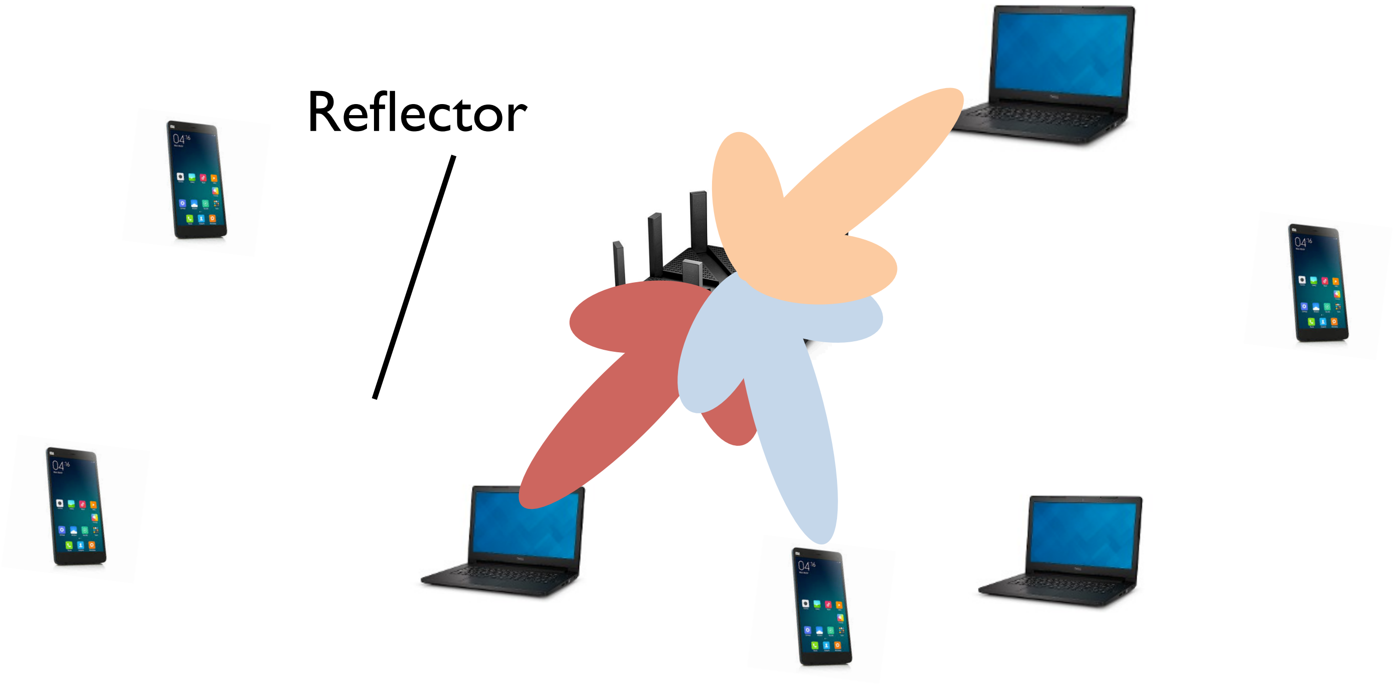
[2] R. A. Stirling-Gallacher, et. al. Multi-user MIMO strategies for a millimeter wave communication system using hybrid beam-forming. ICC'15.

[3] S. Sur, et. al. Practical MU-MIMO user selection on 802.11ac commodity networks. MobiCom 2016

[4] N. Anand, et. al., Mode and user selection for multi-user MIMO WLANs without CSI. INFOCOM 2015.

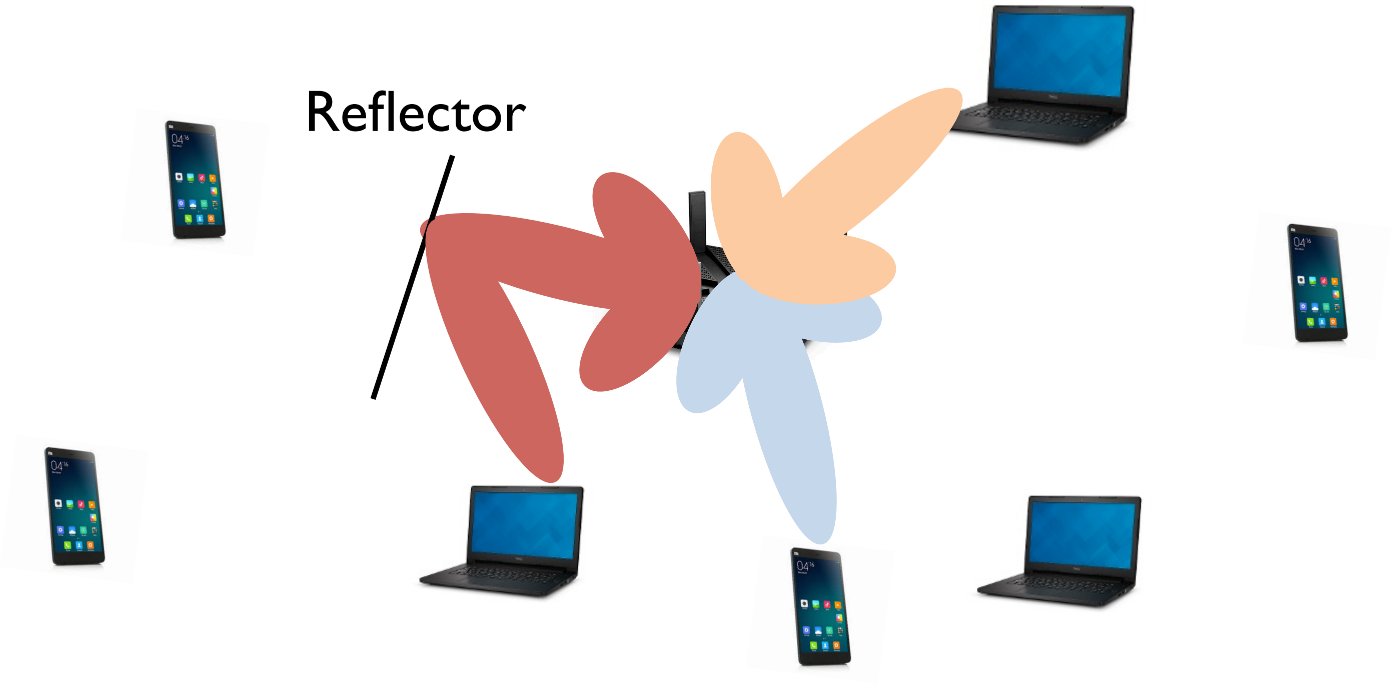
Decoupling User and Beam Selection

- Choosing analog beams independent from potential user selection



Decoupling User and Beam Selection

- Choosing analog beams independent from potential user selection
- sub-optimal approach



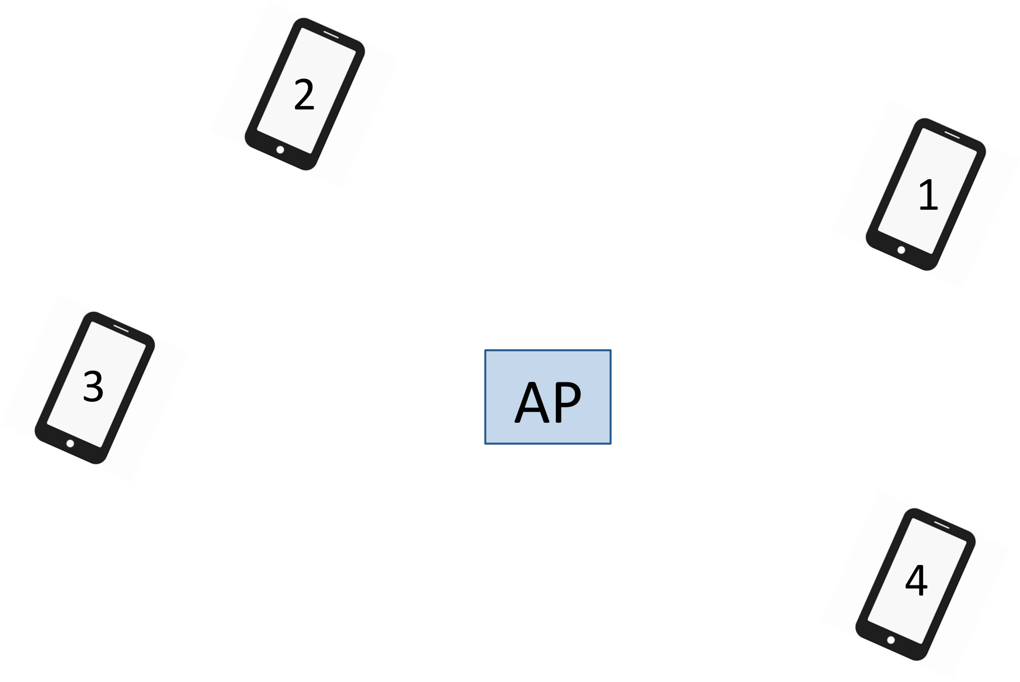
Decoupling User and Beam Selection

- Single-User beam Training (SUT):
  - Training every user individually
  - Repeat only when the old transmit/receive beams are not reliable
- User selection
  - Selecting a set of users
  - Right before a multi-user transmission

SUT U. S. Data U. S. Data . . . SUT U. S. Data

Single-User beam Training (SUT)

- The AP and each user discover the best analog beam to communicate
- Beams are selected from a pre-determined codebook
- E.g. 802.11ad beam training



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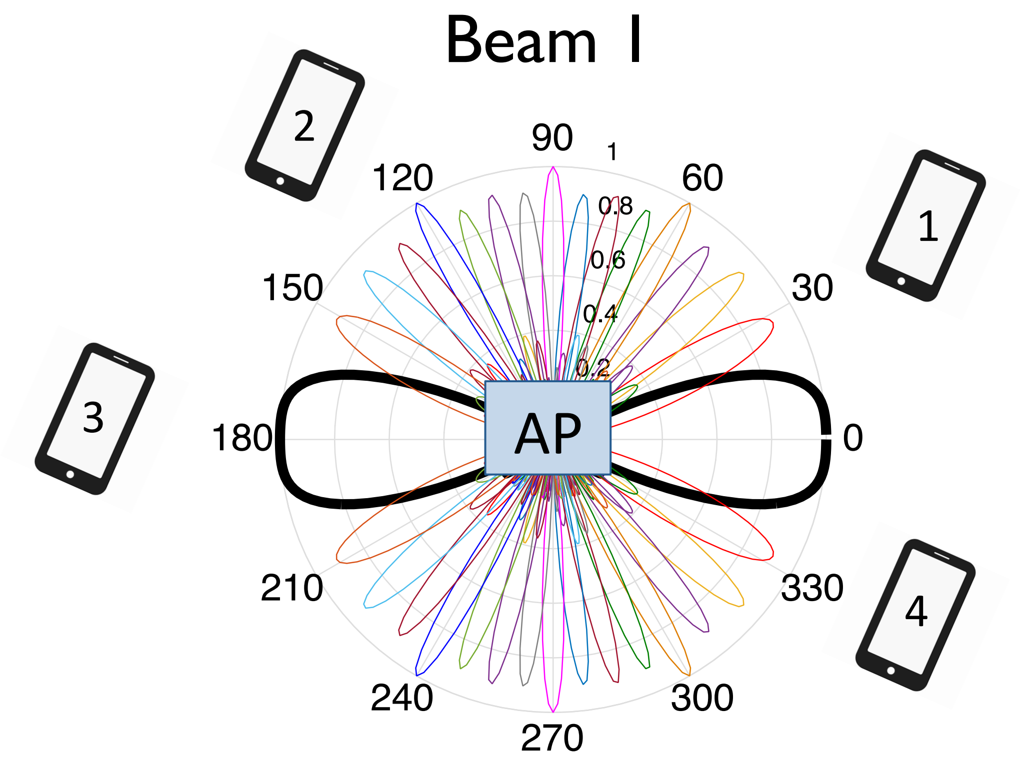

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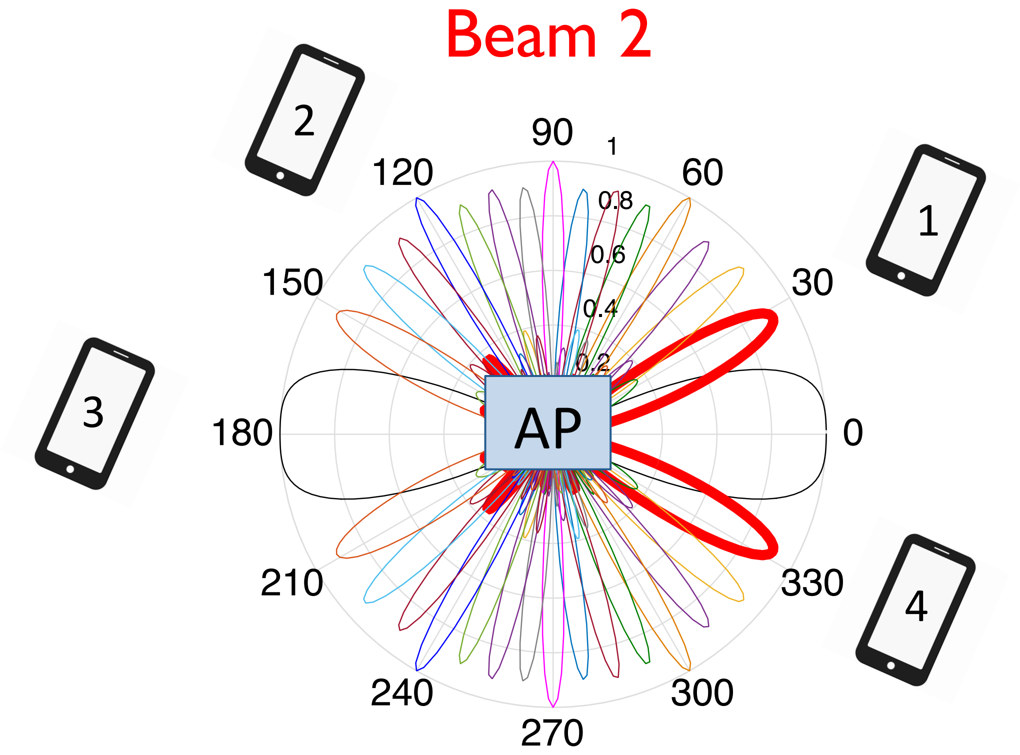

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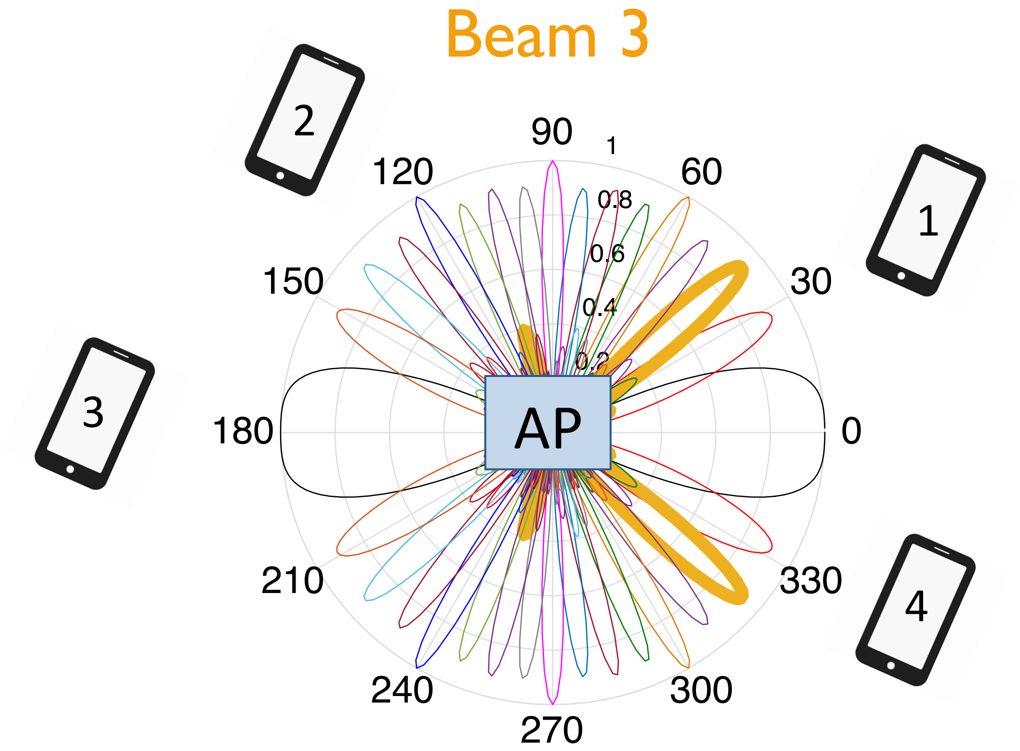

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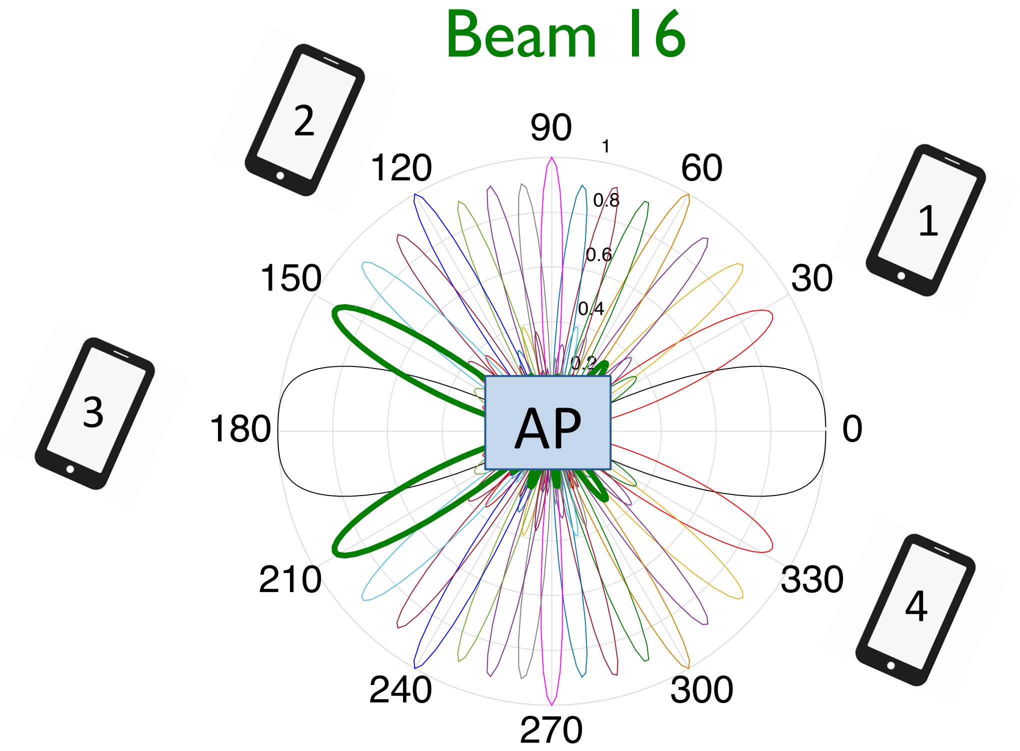

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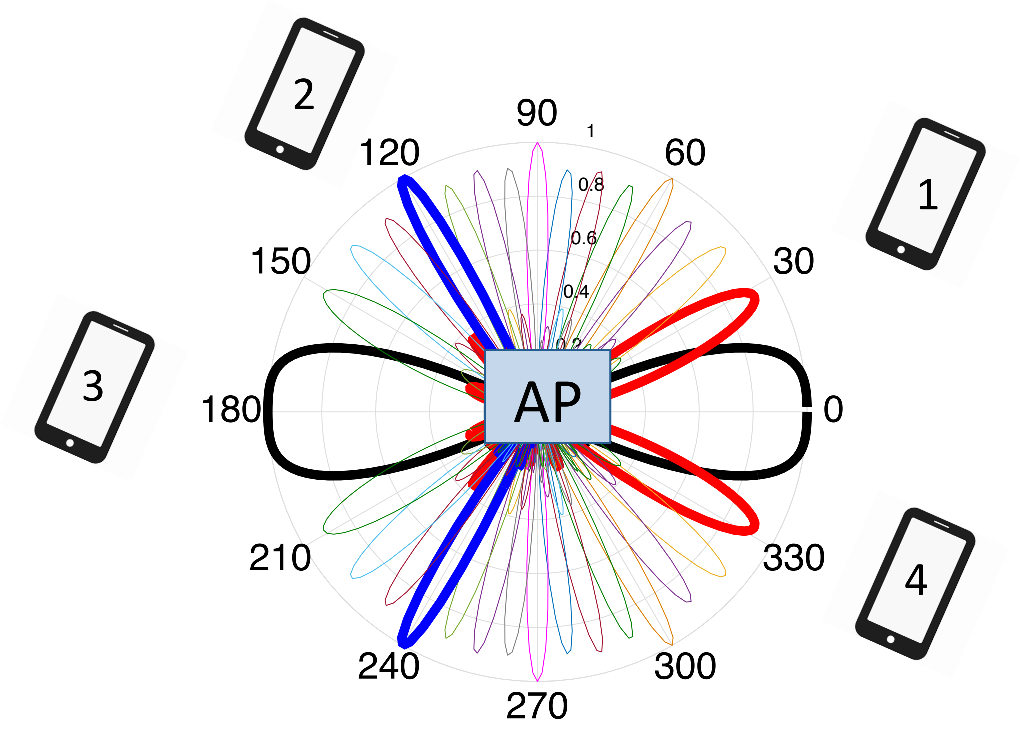
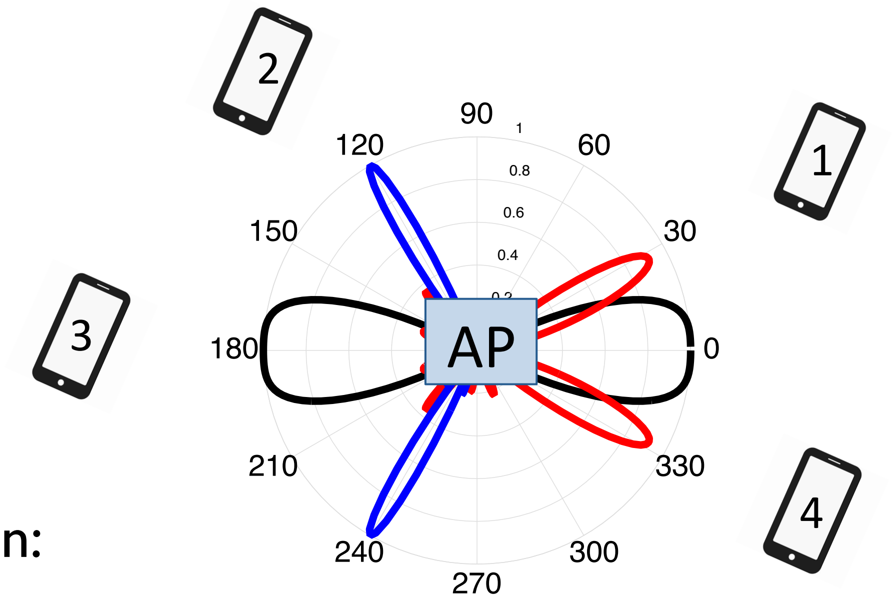


User ID	TX beam ID
1	Beam 2
2	Beam 13
3	Beam 1
4	Beam 2

User Selection Framework



- Available info after SUT:
  - Beam ID selected for all users
  - Received SNR of SU transmission

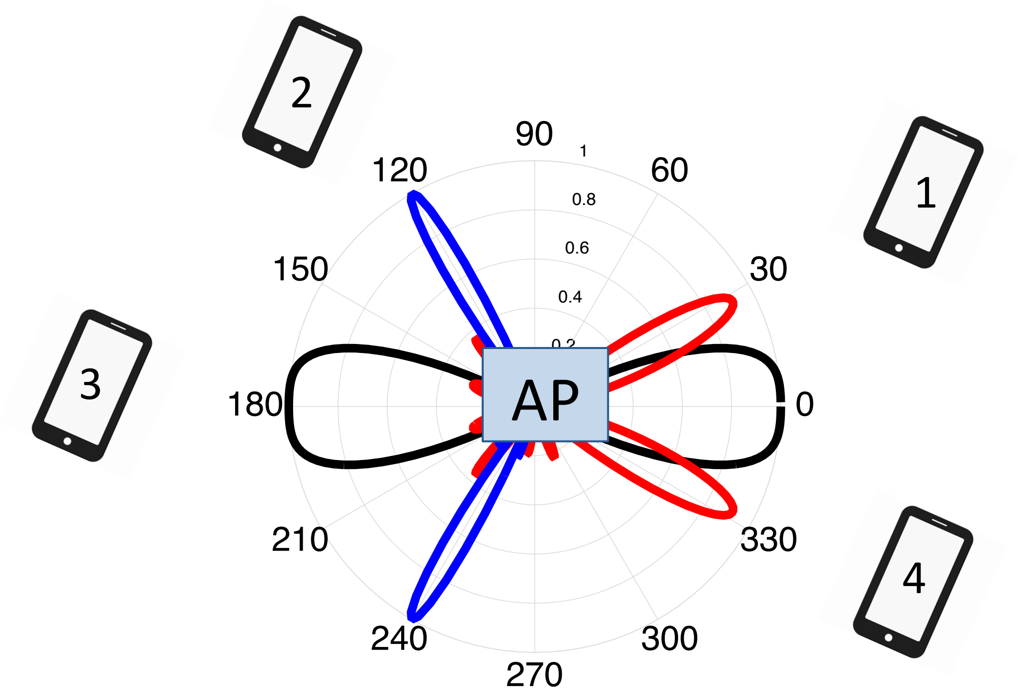
- Two general classes for user selection:

Class I : Only based on information acquired in SUT → Single-Shot (S^2)

Class II: Collecting further info before choosing users

Single-Shot (S^2) user selection example

- Maximum beAm Separation (S^2-MAS)
  - Choosing users with maximum beam separation
  - Which user should be grouped with user 1?



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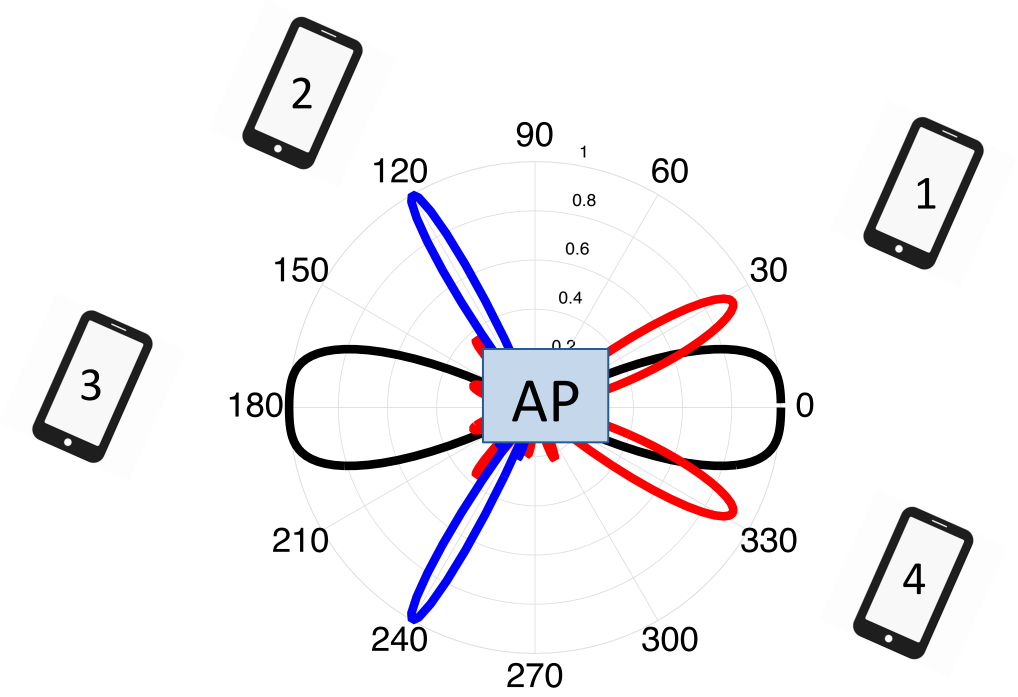

User ID	TX beam ID	
1	2	
2	13	→ 11
3	1	→ 1
4	2	→ 0

Single-Shot (S^2) user selection example

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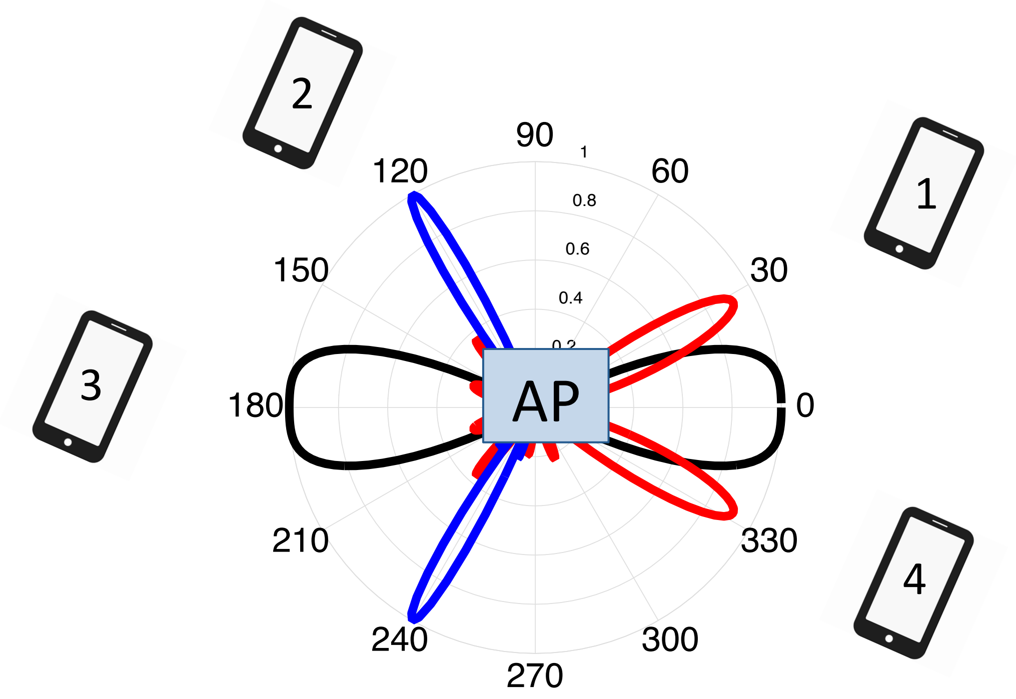

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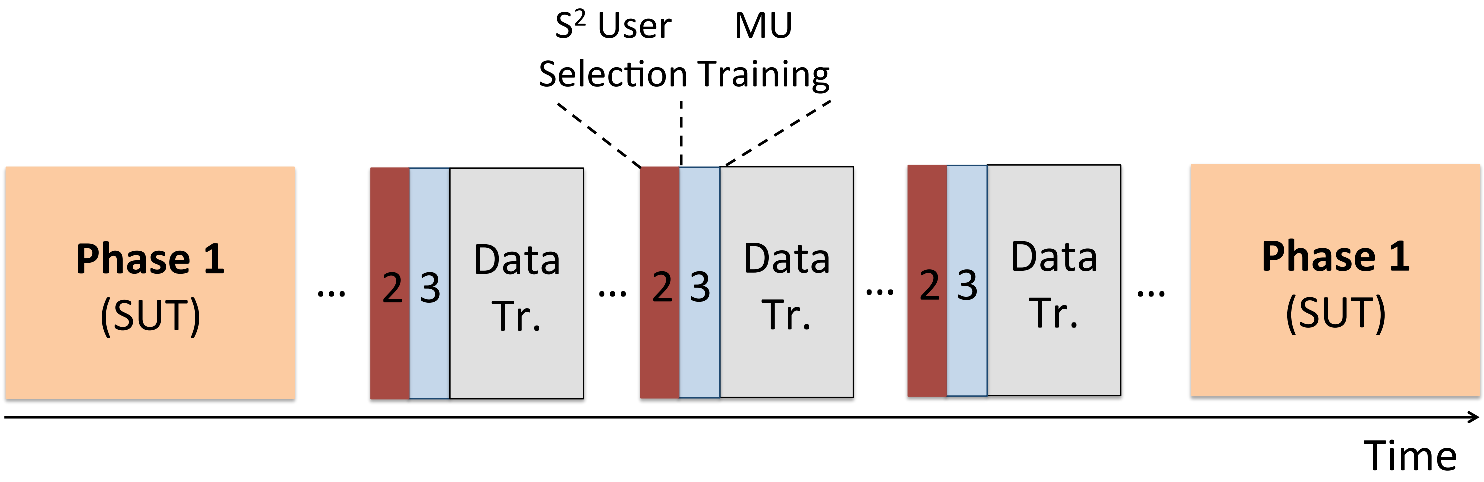
Single-Shot (S^2) timeline

- Phase 1: SUT
- Phase 2: Single-shot user selection
- Phase 3: digital precoding, e.g. zero-forcing, to cancel any residual inter-user interference between selected users



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- We call this class, Interference-aware Incremental (I^2) user selection

I^2 user selection example

- Example: I^2-Partitioned multi-test (I^2-PM)
  - Assume $U=9$, $N_{RF}=3$

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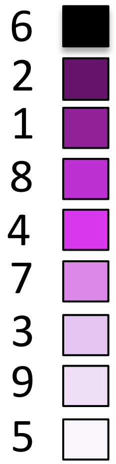

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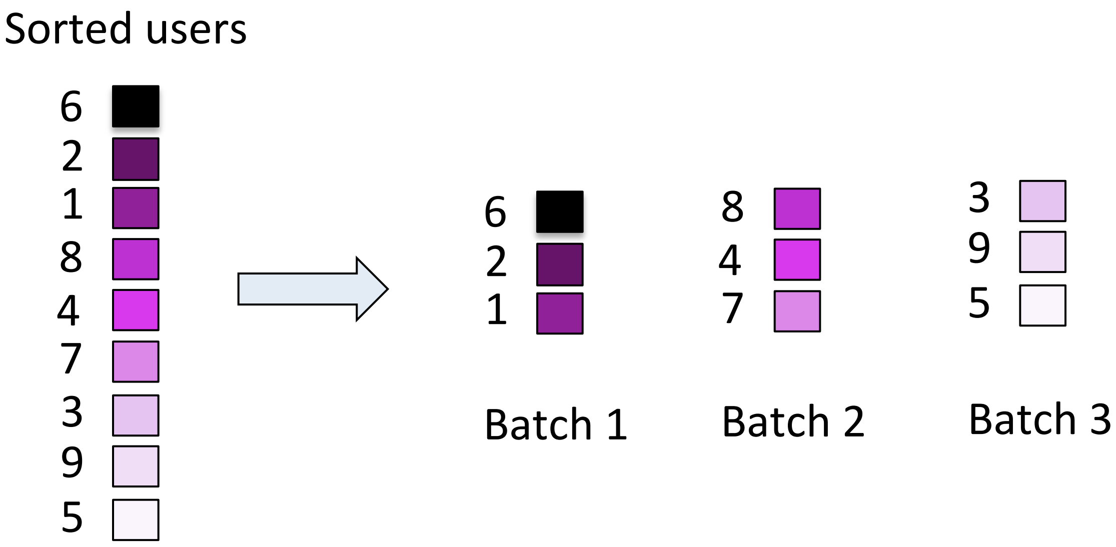
Sorted users

6
2
1
8
4
7
3
9
5

6
2
1

Batch 1

8
4
7

Batch 2

3
9
5

Batch 3

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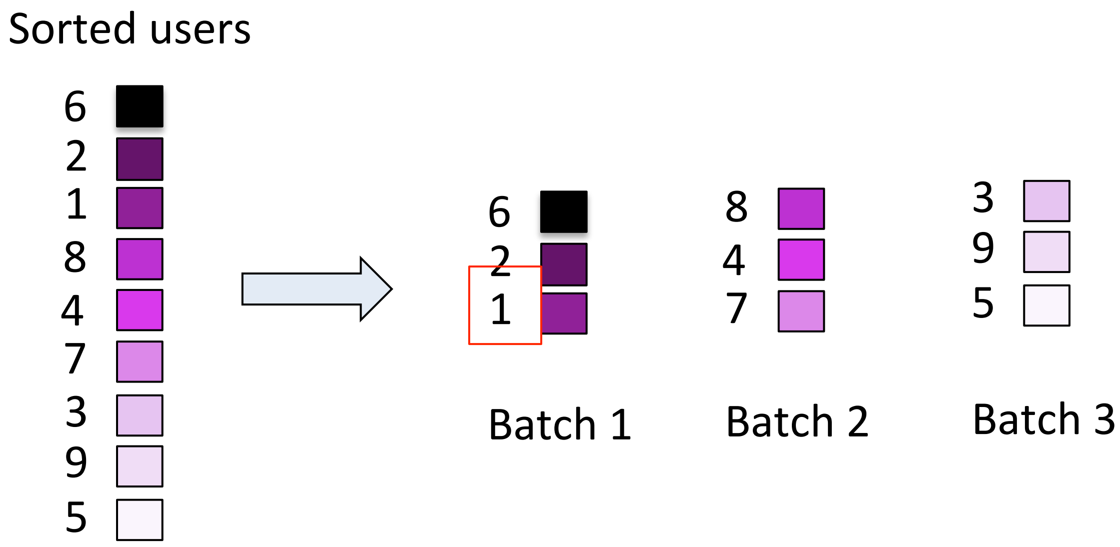

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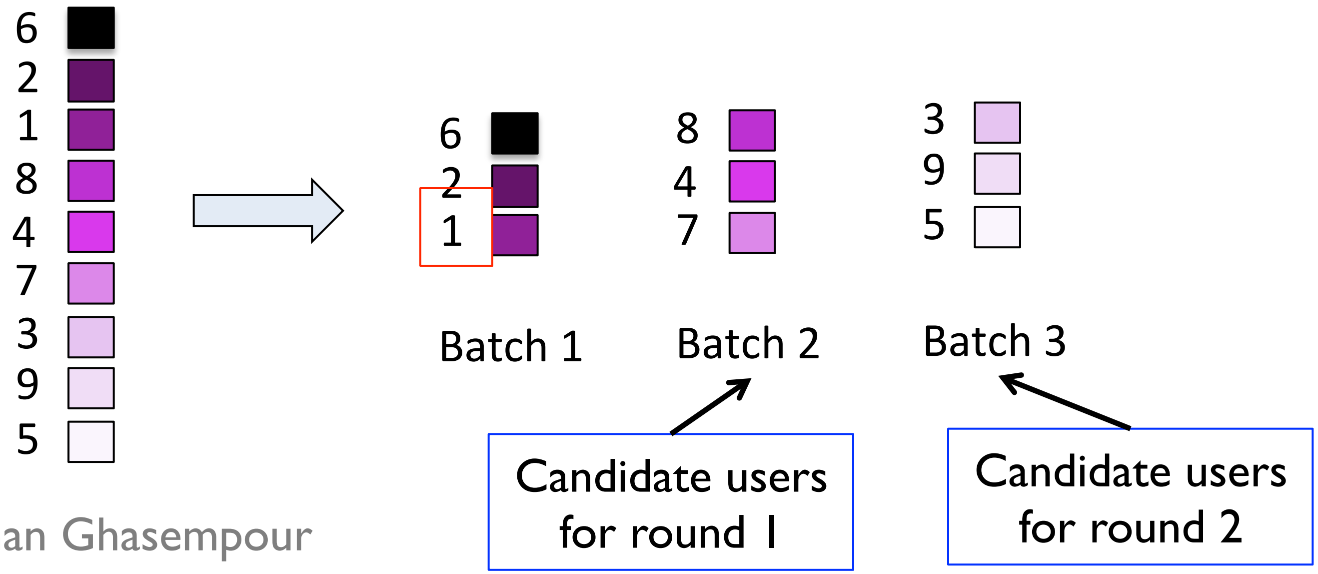

Sorted users

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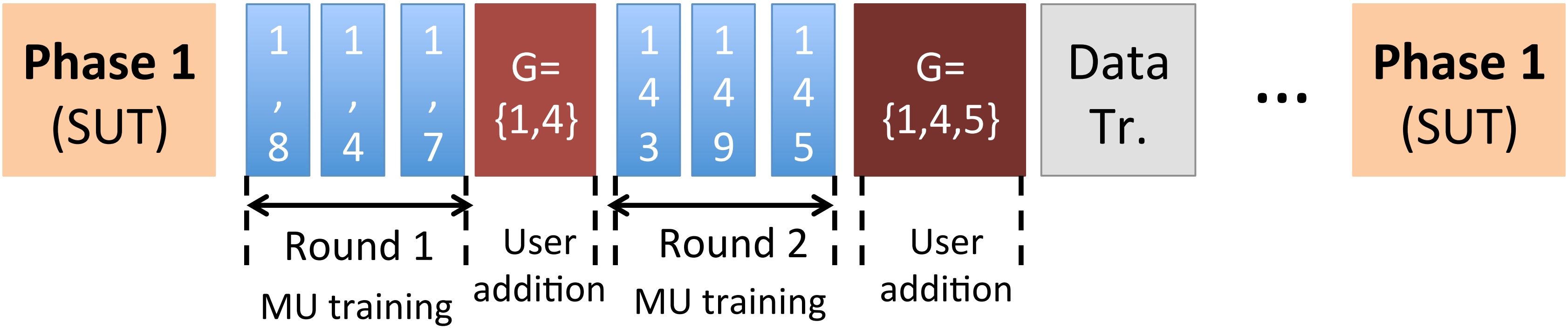
Batch 2

Batch 3

Candidate users for round 1

Candidate users for round 2

I^2 user selection timeline



Phase 1 (SUT)

1,8

1,4

1,7

G={1,4}

1 4 3

1 4 9

1 4 5

G={1,4,5}

Data Tr.

…

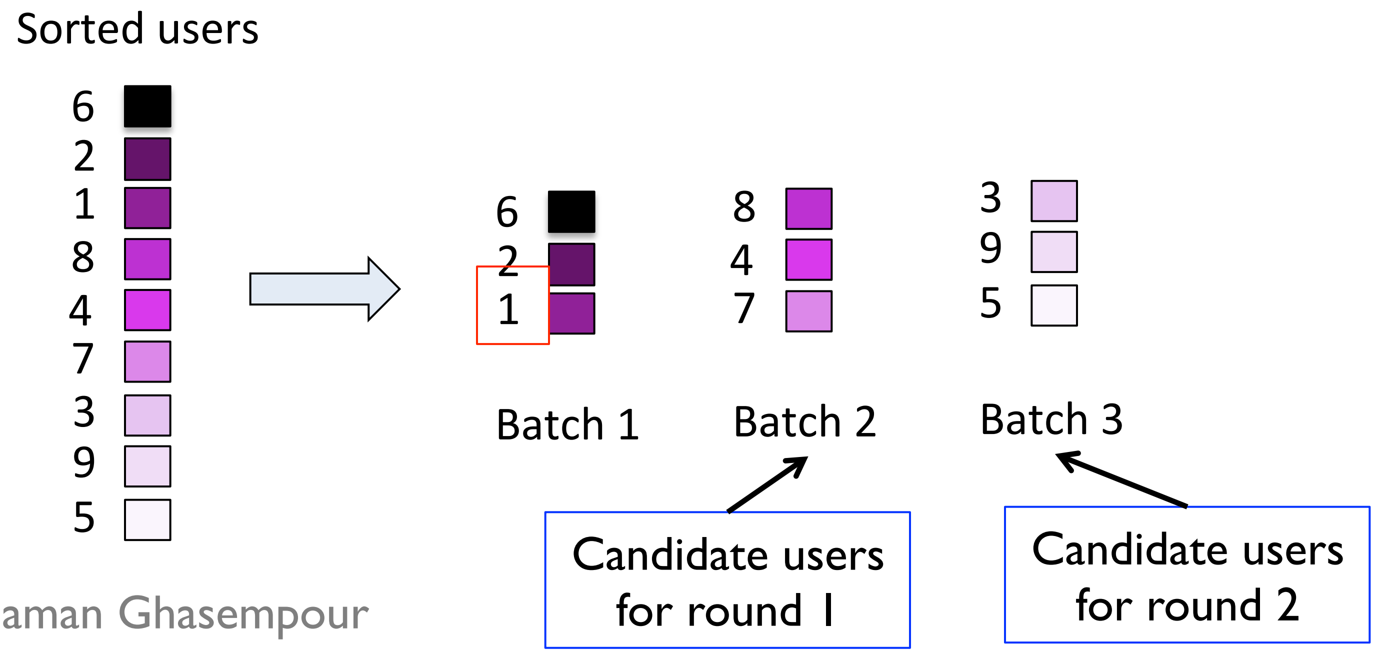
Phase 1 (SUT)

Round 1 MU training

User addition

Round 2 MU training

User addition



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6
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Batch 1

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Batch 3

Candidate users for round 1

Candidate users for round 2

User Selection Framework- Summary

Single-Shot (S^2)

- Only based on info acquired in SUT
- Interference estimation
- One-shot
  - Lower complexity
  - Zero grouping overhead

- Example: S^2-MAS

Interference-aware Incremental (I^2)

- Collecting further info
- Interference measurements
- Multi-round incremental
  - Higher complexity
  - Higher overhead

- Example: I^2-PM

Benchmarking algorithms

- Exhaustive Joint: Exhaustively test all user-beam combinations
- Exhaustive Decoupled:
  - SUT for beam selection
  - Exhaustively test all user combinations

	Beam selection	User selection	Total
Exhaustive joint			$\sum_{m=1}^{N_{RF}} \binom{U}{m} (F^m \times W^m)$
Exhaustive decoupled	$U \times (F \times W)$	$\sum_{m=1}^{N_{RF}} \binom{U}{m}$	$U \times (F \times W) + \sum_{m=1}^{N_{RF}} \binom{U}{m}$
S²-MAS			
I²-PM			

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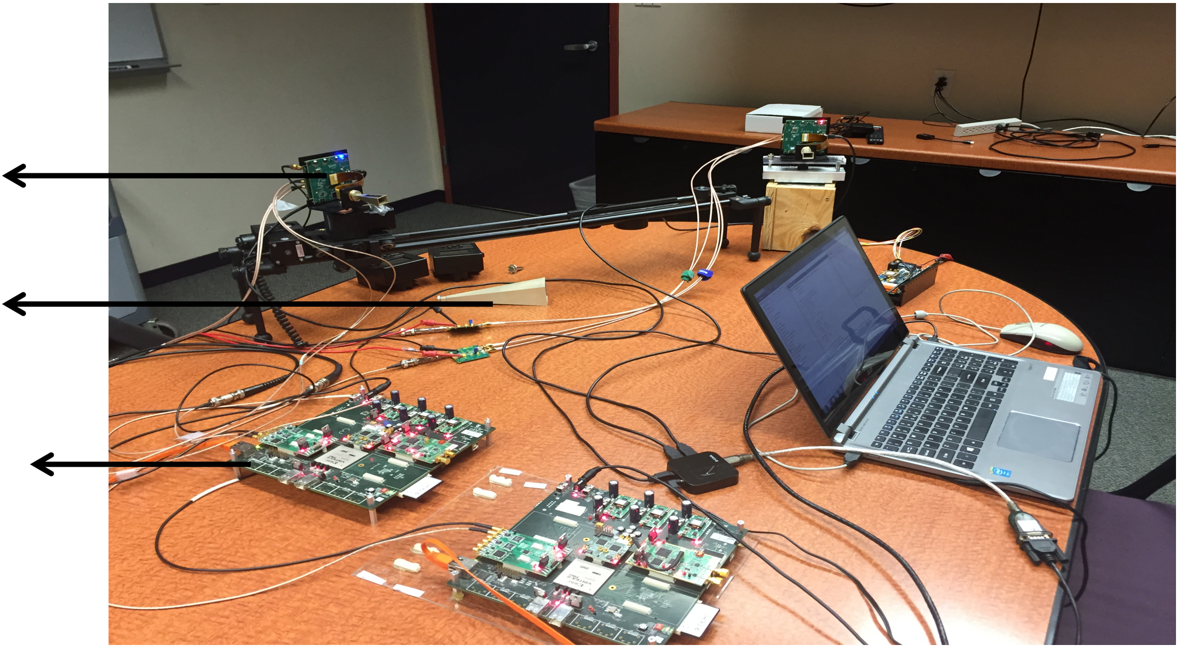
Exhaustive decoupled	$U \times (F \times W)$	$\sum_{m=1}^{N_{RF}} \binom{U}{m}$	$U \times (F \times W) + \sum_{m=1}^{N_{RF}} \binom{U}{m}$
S2-MAS	$U \times (F \times W)$	0	$U \times (F \times W)$
I2-PM	$U \times (F \times W)$	$(\frac{U}{N_{RF}}) \times (N_{RF} - 1)$	$U \times (F \times W) + (\frac{U}{N_{RF}}) \times (N_{RF} - 1)$

Testbed

- Commercial 60 GHz VubIQ transceivers
- WARP v1 boards with only one RF chain
- Horn antennas instead of phased array
- Using NYU channel model to validate RSS with over the air measurements
- Extensive measurements: over 10000 measurements varying receiver location, antenna orientation, antenna beamwidth



VubIQ transceiver

Horn antenna

WARP v1 board

Performance loss due to decoupling

- Comparing "exhaustive joint" and "exhaustive decoupled" algorithms
- Scenario : U=20, |F|=24, N_{RF}=2,3,4, |W|=1
- Two different extremes: all users having LOS or NLOS connectivity
- R_j : Achievable sum-rate via Exhaustive joint algorithm
- R_d : Achievable sum-rate via Exhaustive decoupled algorithm

- Metric 1: R_d/R_j%

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Scenario	R_d/R_j %
$N_{RF}=2$, LOS	98.26
$N_{RF}=2$, NLOS	98.22
$N_{RF}=3$, LOS	98.06
$N_{RF}=3$, NLOS	97.44
$N_{RF}=4$, LOS	95.79
$N_{RF}=4$, NLOS	95.19

Joint User-Beam Selection vs. Decoupled

- R_d/R_j %> 95
- R_d/R_j % slightly decreases with increasing number of RF chains
- Increasing no. RF chains → group size increases → higher inter-user interference

Scenario	R_d/R_j %
N_{RF}=2, LOS	98.26
N_{RF}=2, NLOS	98.22
N_{RF}=3, LOS	98.06
N_{RF}=3, NLOS	97.44
N_{RF}=4, LOS	95.79
N_{RF}=4, NLOS	95.19

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- Increasing no. RF chains → group size increases → higher inter-user interference

Decoupling beam steering and user selection results in 5% capacity loss with 4 streams. The capacity loss increases in NLOS case and as the group size increases.

Scenario	R_d/R_j %
N_{RF}=2, LOS	98.26
N_{RF}=2, NLOS	98.22
N_{RF}=3, LOS	98.06
N_{RF}=3, NLOS	97.44
N_{RF}=4, LOS	95.79
N_{RF}=4, NLOS	95.19

S^2 and I^2 user selection comparison

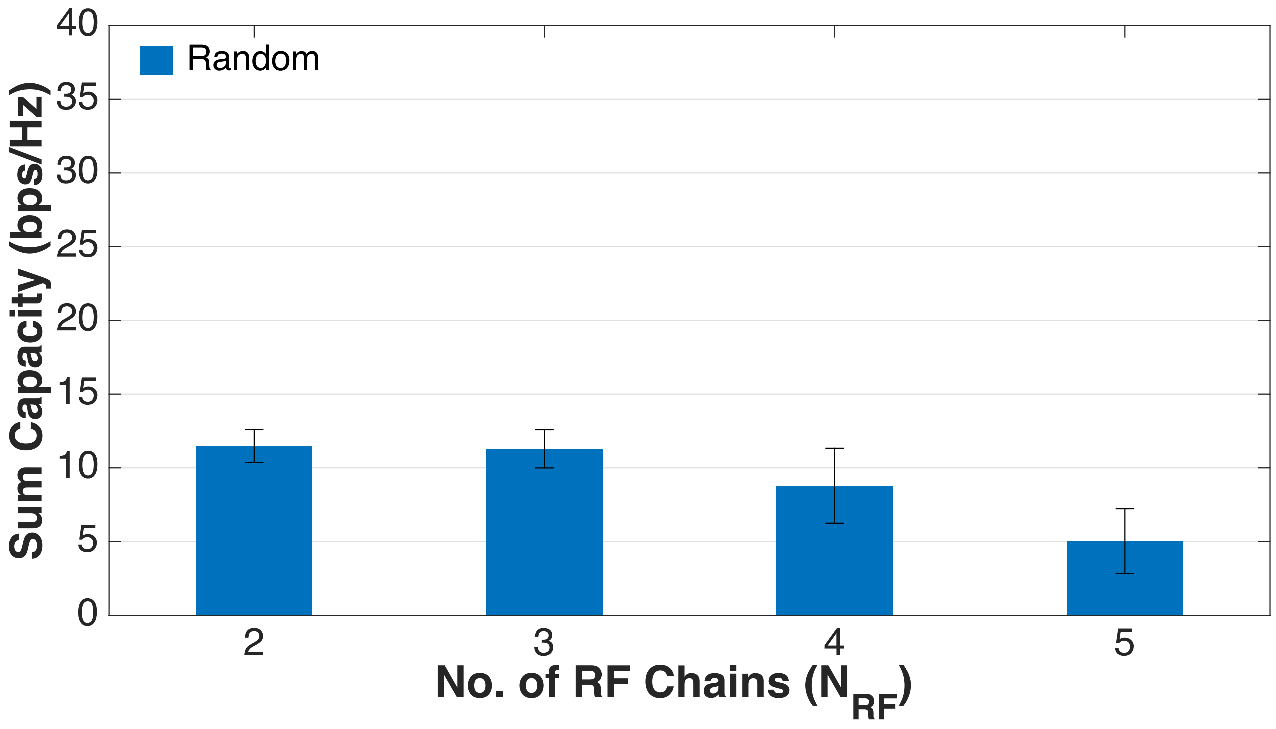
- Scenario: U=40, N_{RF}=2,3,4,5, |F|=32, |w|=4
- LOS connectivity

S^2 and I^2 user selection comparison

- Scenario: U=40, N_{RF}=2,3,4,5, |F|=32, |w|=4
- LOS connectivity
- SUT for beam selection
- S^2-MAS, I^2-PM for user selection
- Random and Exhaustive decoupled user selection strategies for comparison
- Zero-forcing as digital precoding scheme

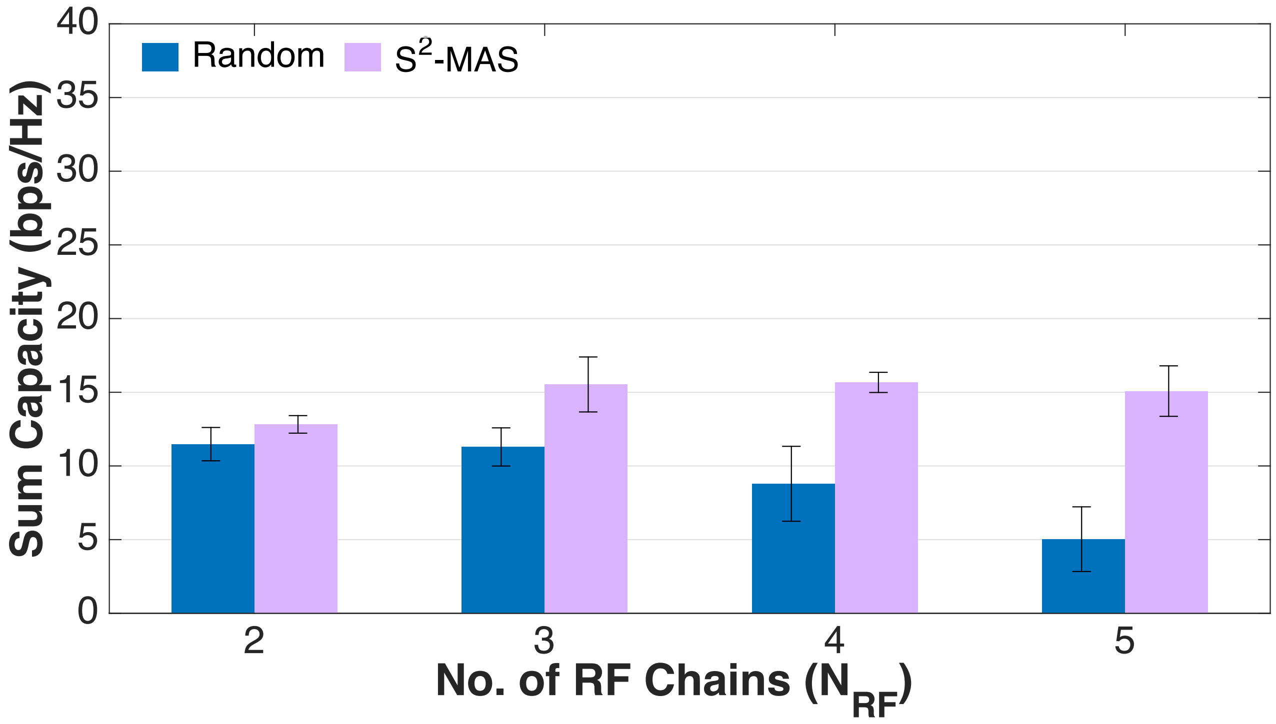
S^2 and I^2 user selection comparison

- Random selection can yield to choosing users with significant overlapping beam



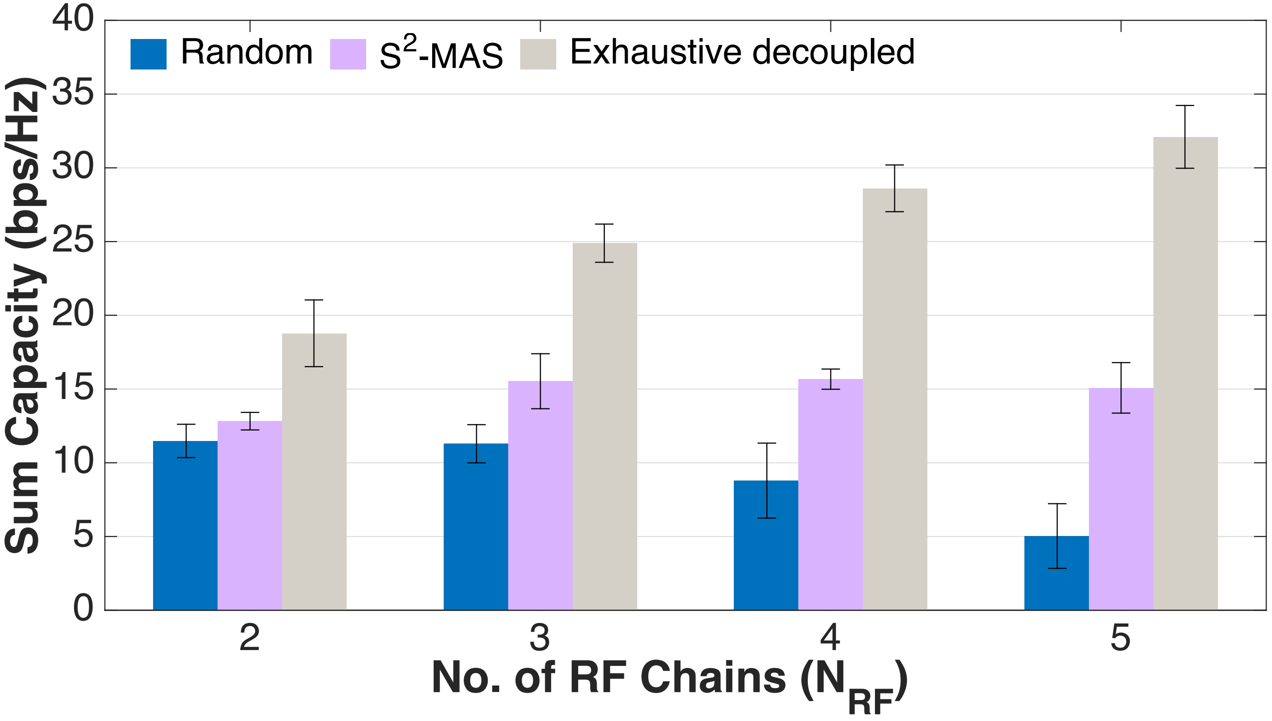
S^2 and I^2 user selection comparison

- Random selection can yield to choosing users with significant overlapping beam
- MAS makes sure that users with separated beams are chosen



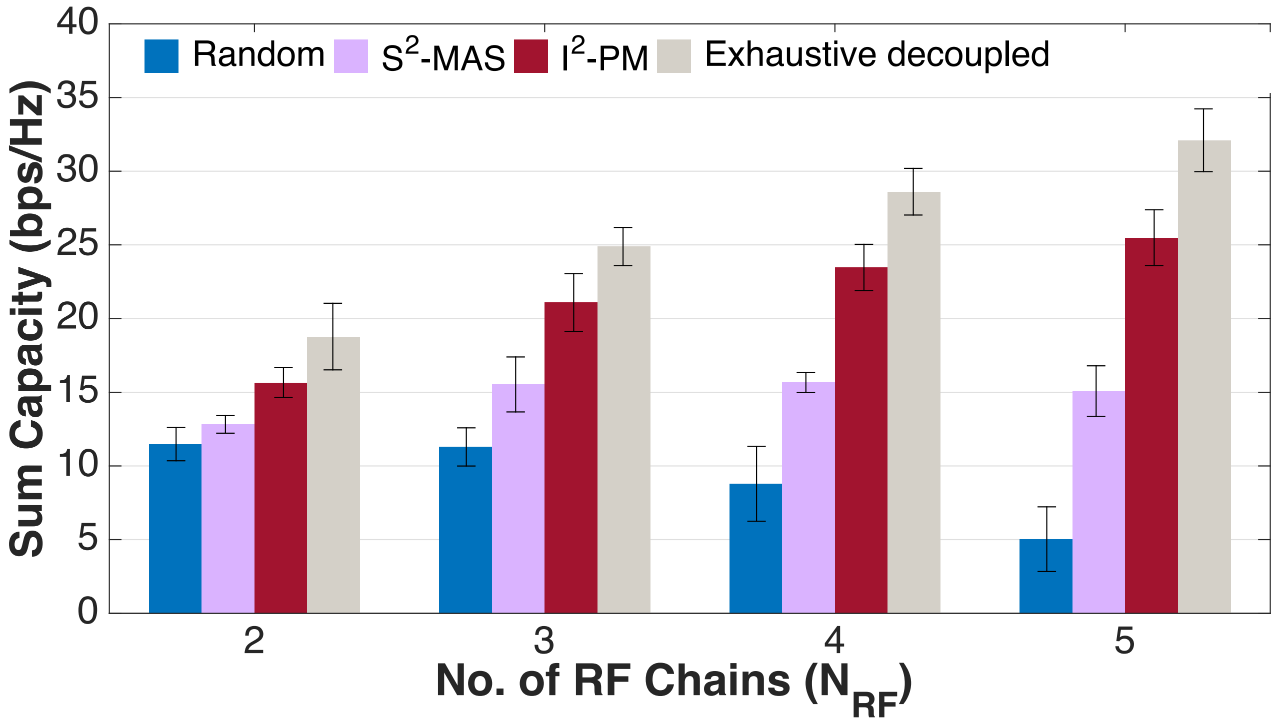
S^2 and I^2 user selection comparison

- Random selection can yield to choosing users with significant overlapping beam
- MAS makes sure that users with separated beams are chosen
- With N_{RF}=2 , MAS >70 % of Exhaustive approach
- With N_{RF}=5 , MAS <50 % of Exhaustive approach



S^2 and I^2 user selection comparison

- Random selection can yield to choosing users with significant overlapping beam
- MAS makes sure that users with separated beams are chosen
- With $N_{RF}=2$, MAS >70 % of Exhaustive approach
- With $N_{RF}=5$, MAS <50 % of Exhaustive approach
- I^2-PM never loses capacity due to an additional RF chain at the AP



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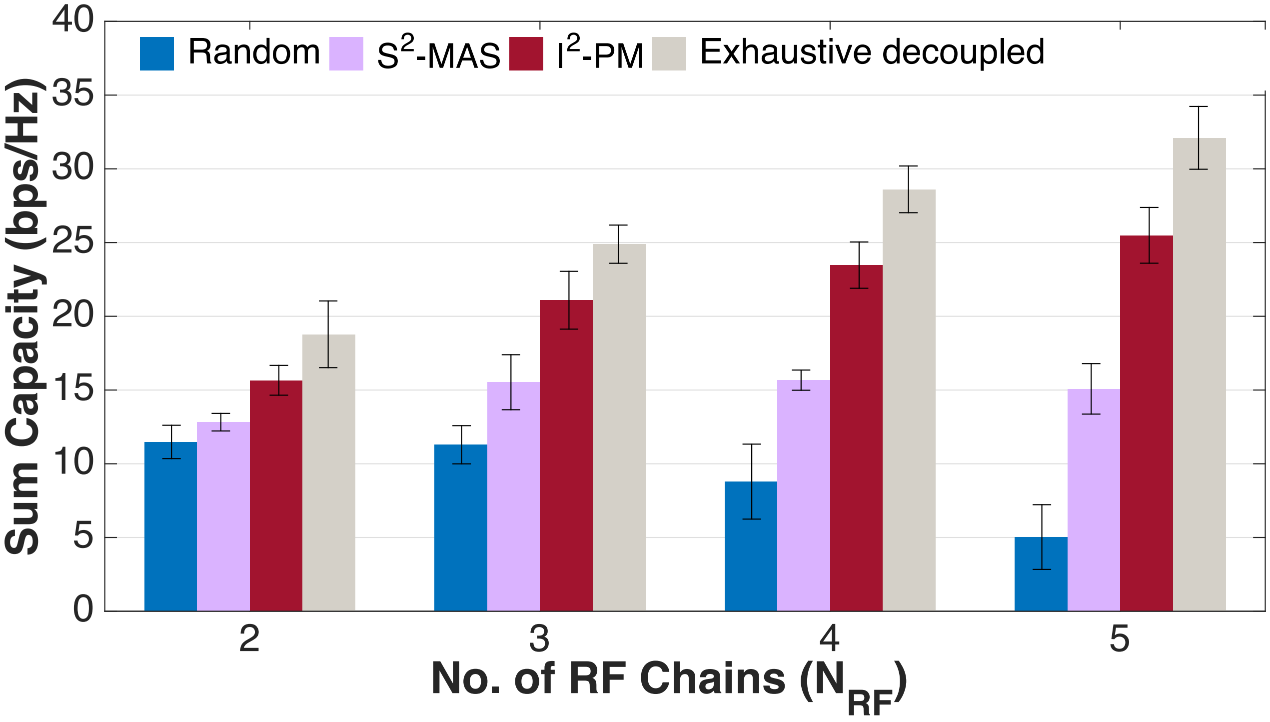
S^2 and I^2 user selection comparison

For smaller group size, the single-shot user selection policies can provide around 70% of the maximum possible PHY capacity with zero grouping overhead.



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Conclusion

- Joint selection of users and beams requires prohibitively large training and feedback overhead

- We introduced decoupling user and beam selection for multi-user 60 GHz WLANs.

- Decoupling beam steering and user selection results in 5% capacity loss with 4 streams. The capacity loss increases in NLOS case and as the group size increases.

- We introduced and evaluated two structures, S^2 and I^2 for user selection in the decoupled framework.

- For smaller groups, the single-shot user selection policies can provide around 70% of the maximum possible capacity with zero grouping overhead.

If you have any questions, email me at ghasempour@rice.edu