Scalable Multicast in Highly-Directional 60 GHz WLANs

Sharan Naribole and Edward Knightly

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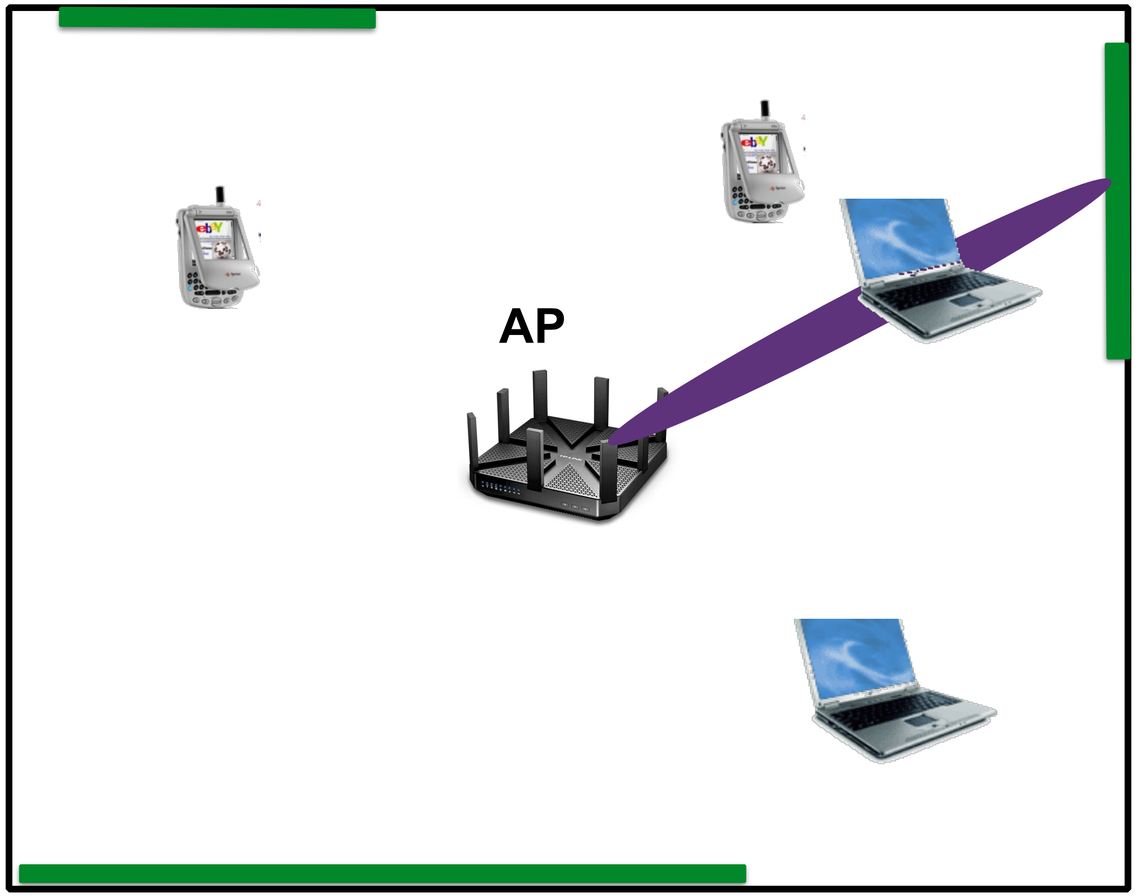
RICE

60 GHz Multicast

- **Multicast Service**
  - AP provides same data to multiple clients
  - For e.g., live HD video streaming
- **60 GHz**
  - 7-14 GHz for unlicensed operation
  - 20-40 dB increased signal attenuation
- **Unicast transmission**
  - Beams as narrow as 3 degree
  - Maximize directivity gain



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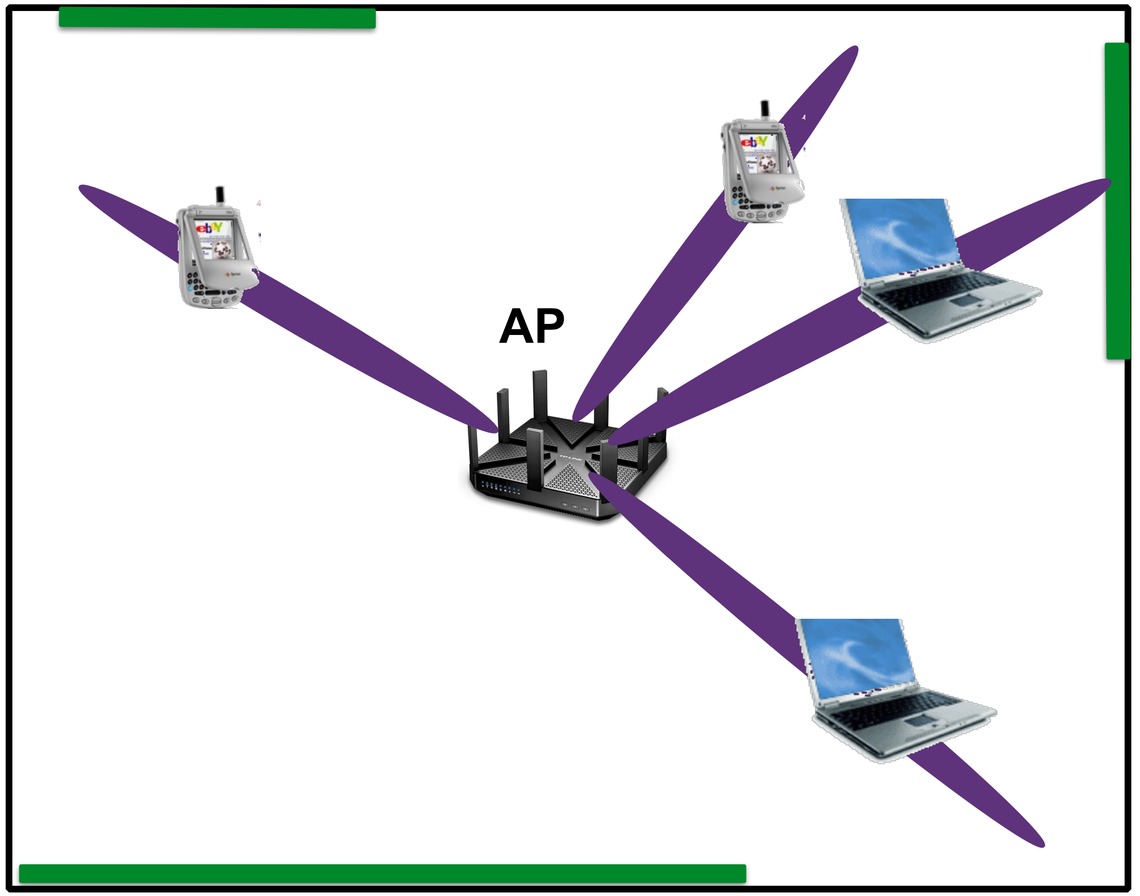
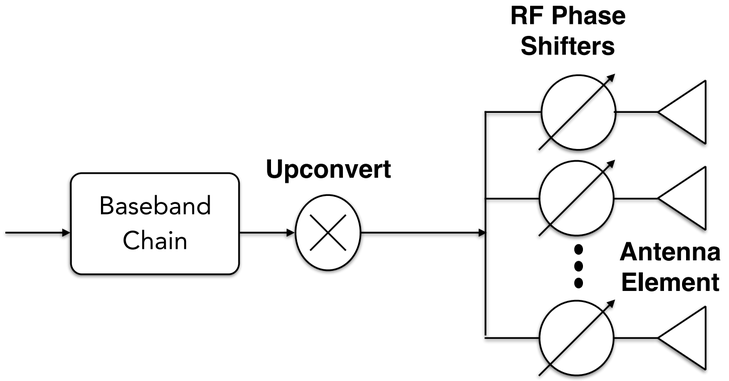
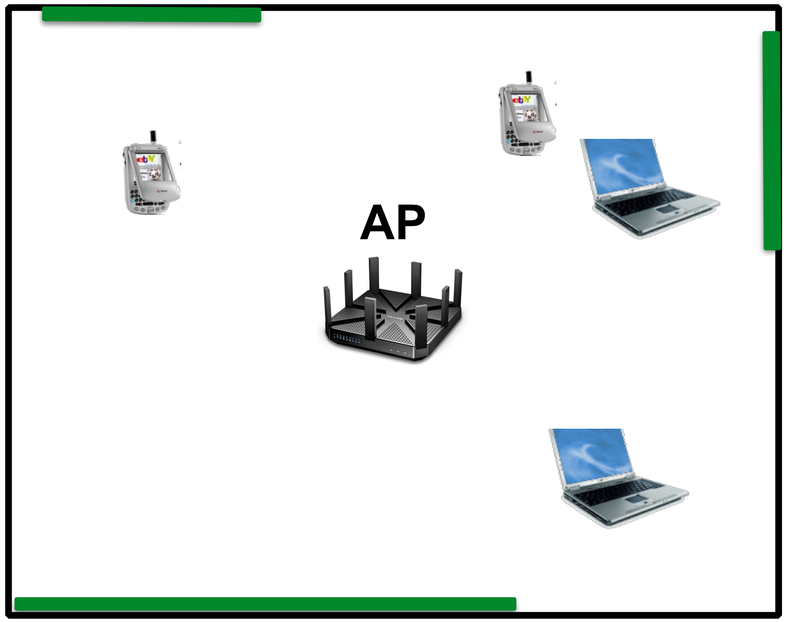


60 GHz Multicast = Simple Extension to Unicast?

- **Single RF Chain**
  - State-of-the-art systems (unlike 2.4/5 GHz MIMO)
  - Single beam at any time



- **Switched Beam System**
  - Sequential transmission of multicast data to cover all clients
  - Transmission time linearly increases with no. of clients



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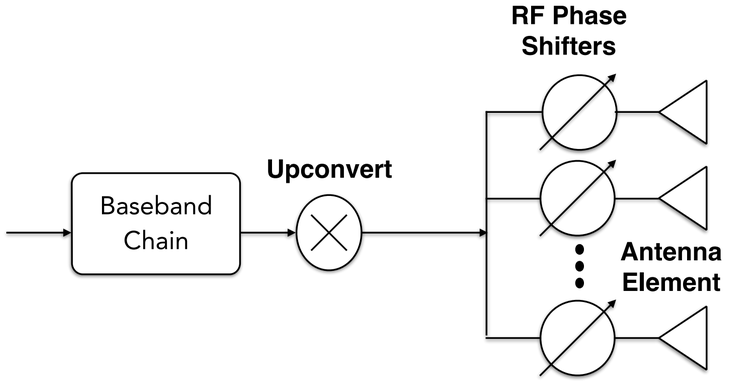

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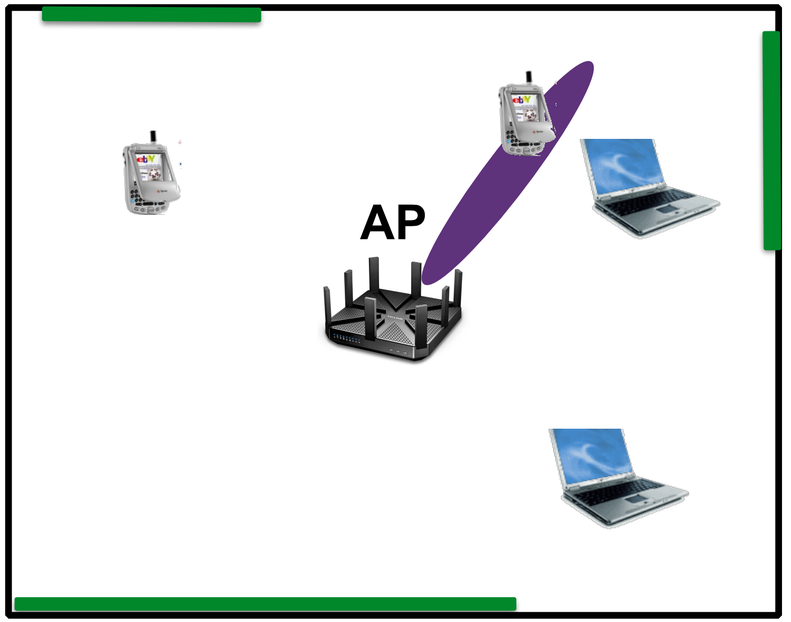

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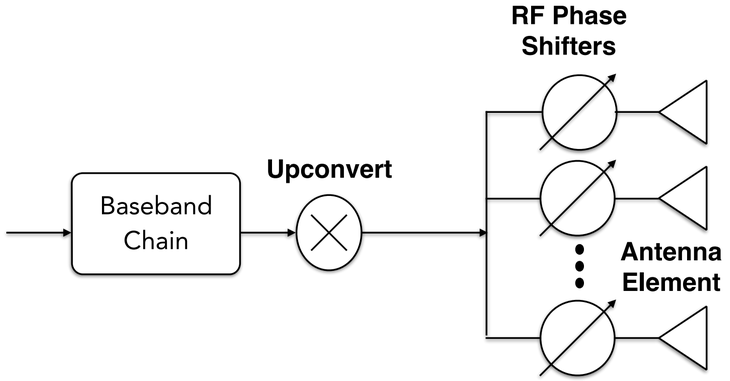

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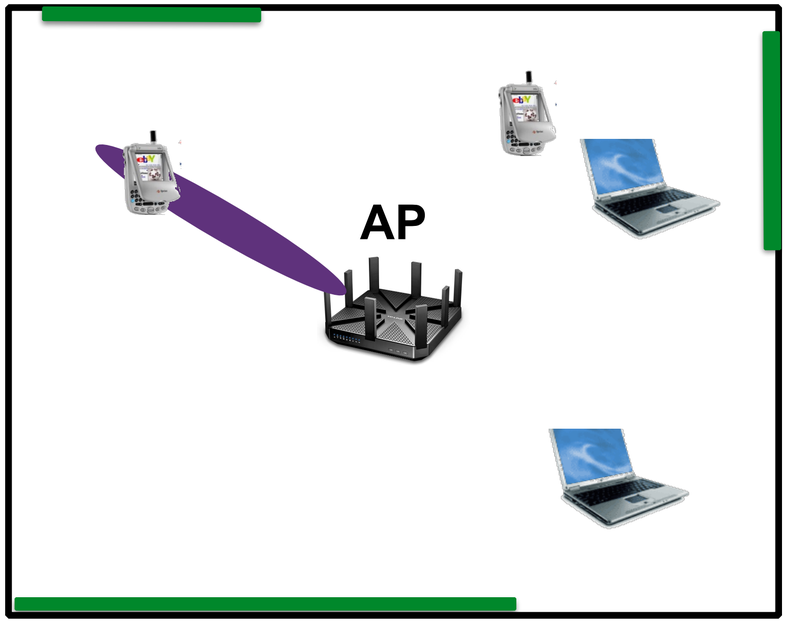

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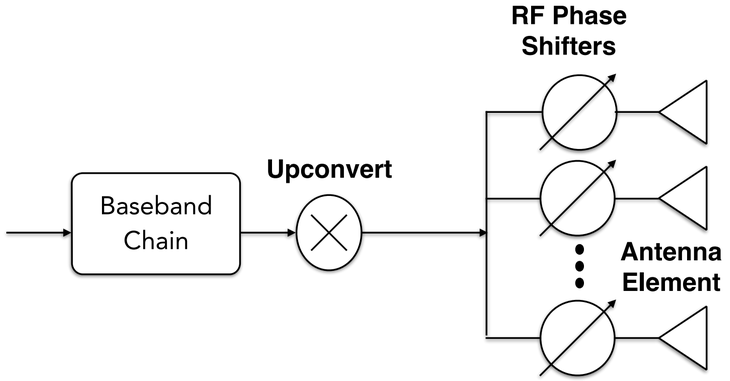

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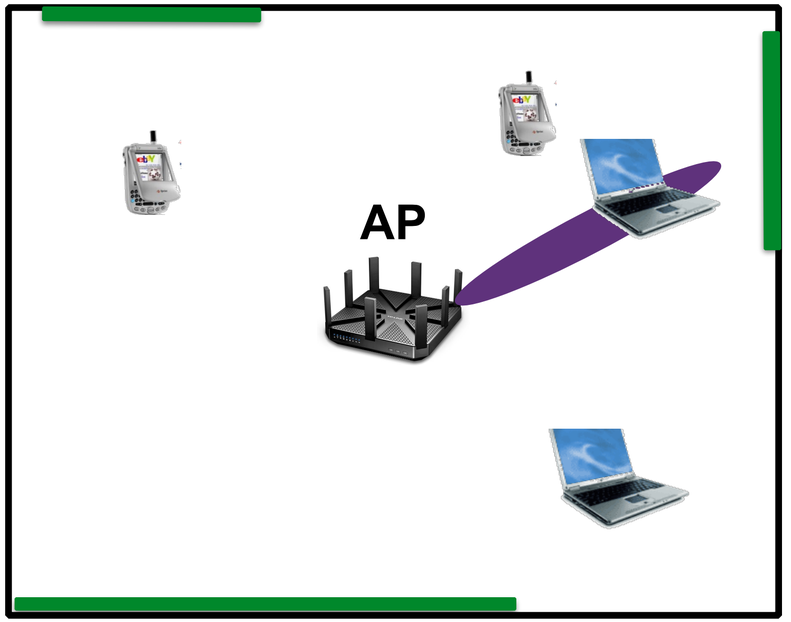

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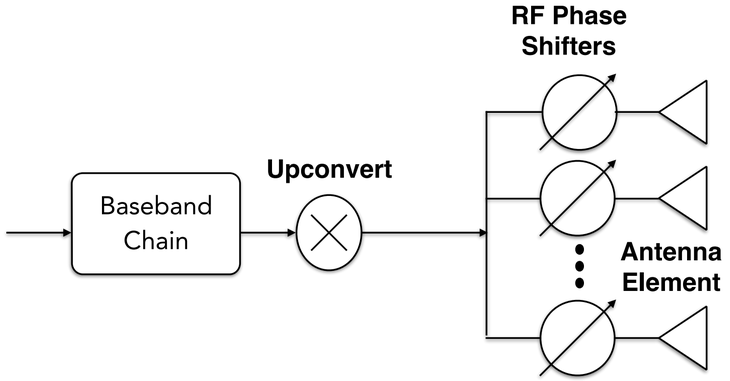

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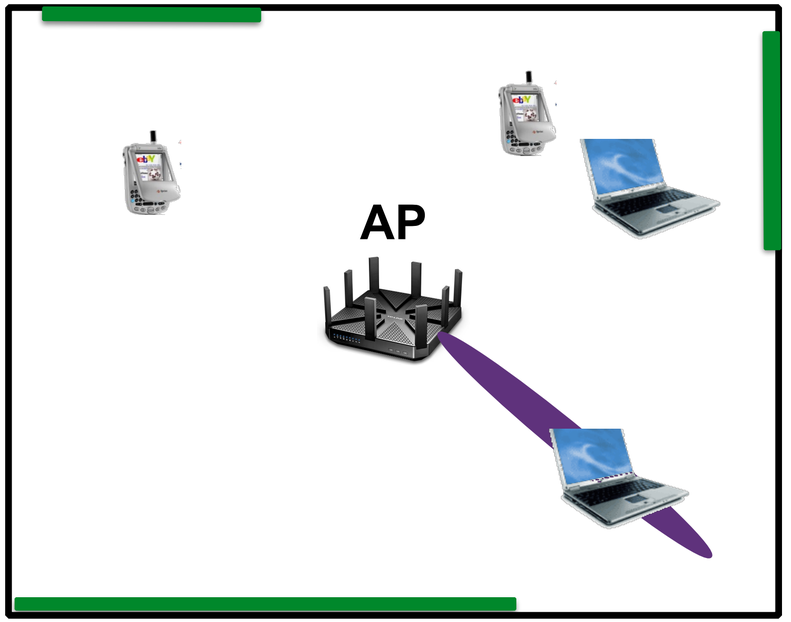
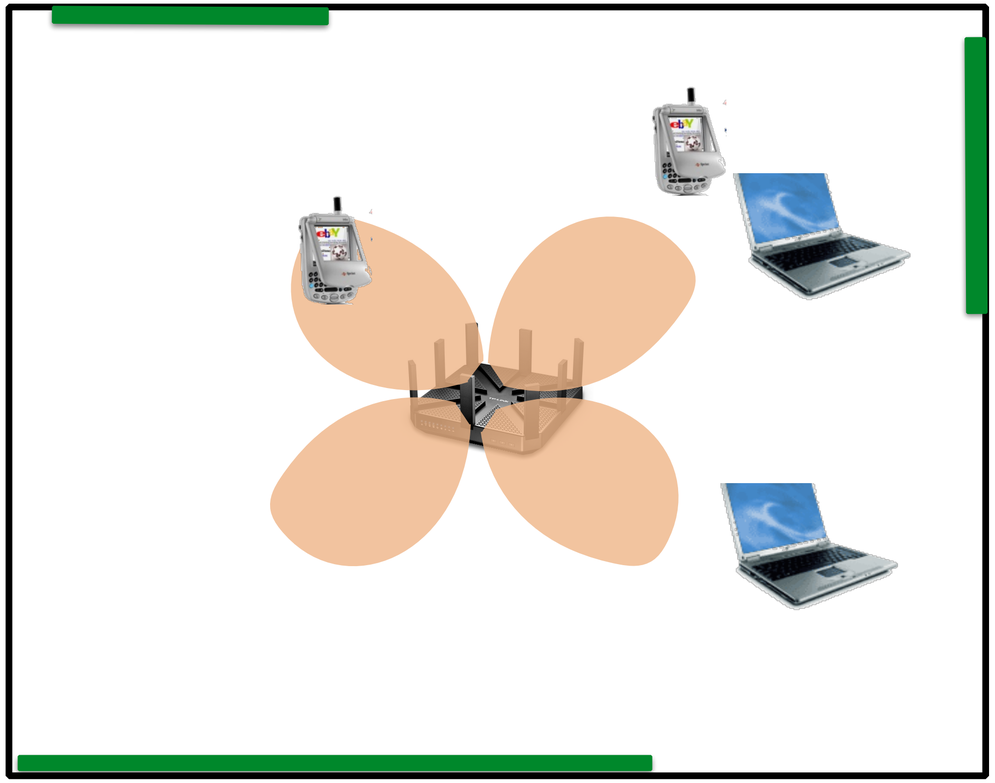


Wide Beams

- **Reachability**
  - Low directivity gain
  - Clients might be unreachable

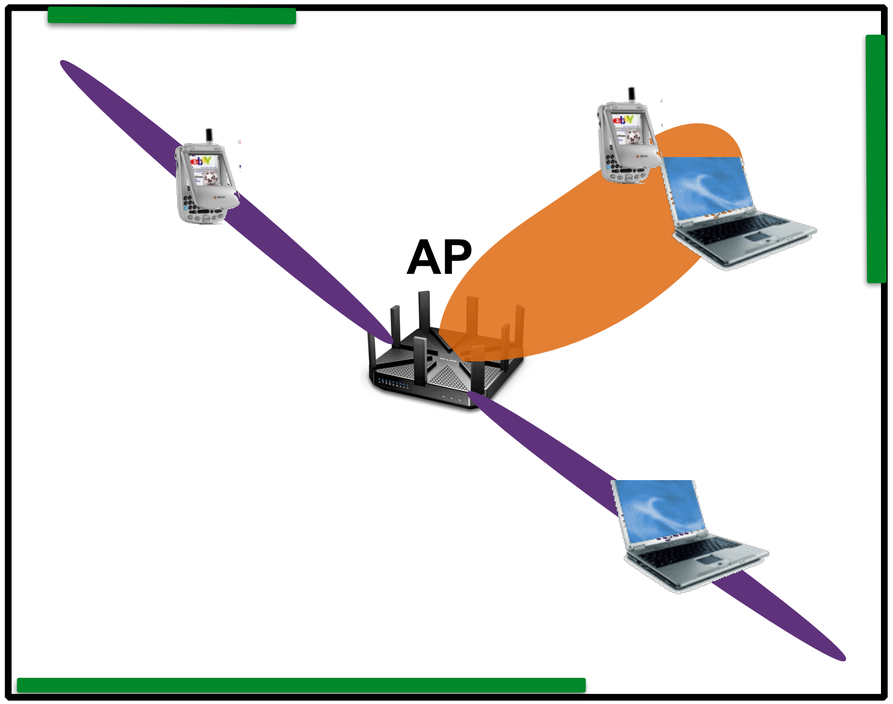
- **Low MCS**
  - Beamwidth-MCS Tradeoff
  - Big hit on the data rate



Only narrow beams or only wide beam strategies might lead to inefficient multicast transmission

Minimizing Total Transmission Time

- **Servable set $C_{th}(\psi)$** for beam ψ
  - Client subset with power measure $\geq P_{min}$
- **Beam Group solution** $\{\psi_1, \psi_2, \ldots, \psi_B\}$
  - Client subset vector $\{S(\psi_1), \ldots, S(\psi_B)\}$
  - MCS vector $\{R(\psi_1), \ldots, R(\psi_B)\}$



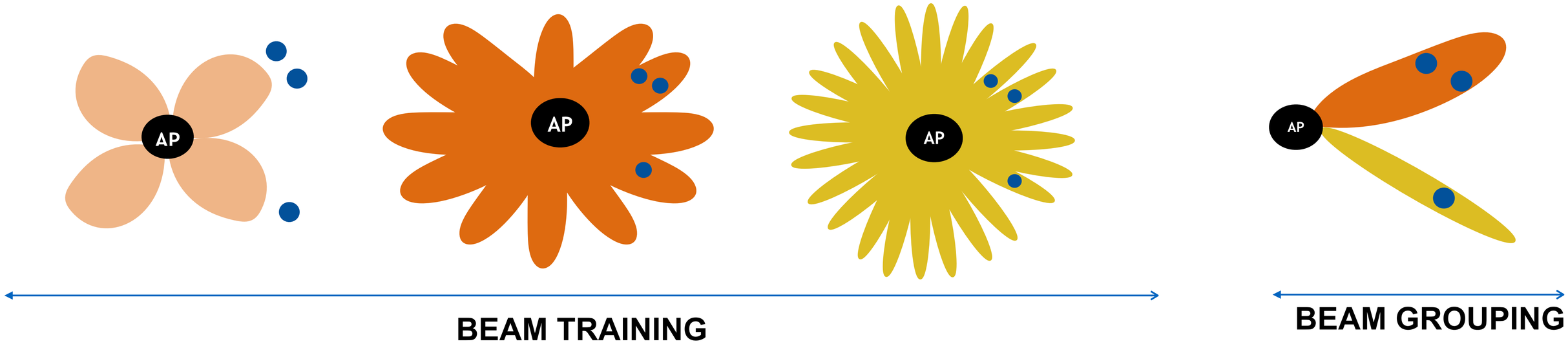
$$\min_{B,\psi_1,\ldots,\psi_B,S(\psi_1),\ldots,S(\psi_B)} \sum_{b=1}^{B} \frac{1}{R(\psi_b)}$$

$$\text{s.t.} \bigcup_{b=1}^{B} S(\psi_b) = \mathbb{U}$$

Multicast client set

$$S(\psi_b) \subseteq C_{th}(\psi_b), \ 1 \leq b \leq B$$

Overhead

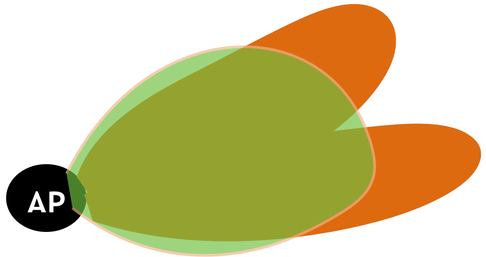


- **Exhaustive Beam Training**
  - $O(KN + c^K)$ for K beamwidth levels, N clients
- **Exhaustive Beam Grouping**
  - $O(c^{K-1} N^{N/2 + 1})$

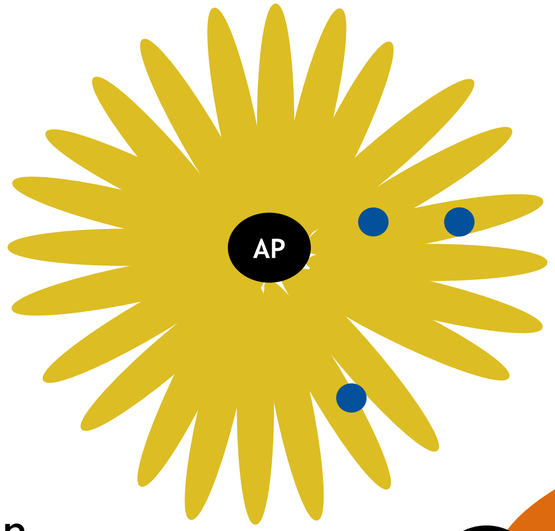
Scalable Directional Multicast Protocol (SDM)

SDM Overview

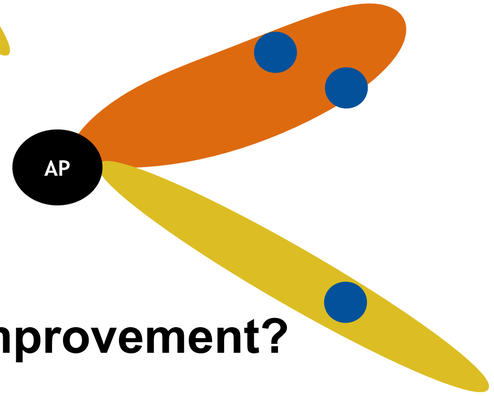
- **Multi-level Codebook Trees**
  - Link beams of different beamwidth levels using spatial similarity
  - Prune the codebook traversal leveraging client feedback



- **Descending Order Traversal for Beam Training**
  - Begin training at finest beam level to address unreachability
  - Only partial set of parent beams for wider beam levels



- **Wide Beam Improvement Ratio**
  - Improvement in transmission time over an only finest beams solution
  - Replace the only finest beams solution in descending order of wide beam improvement



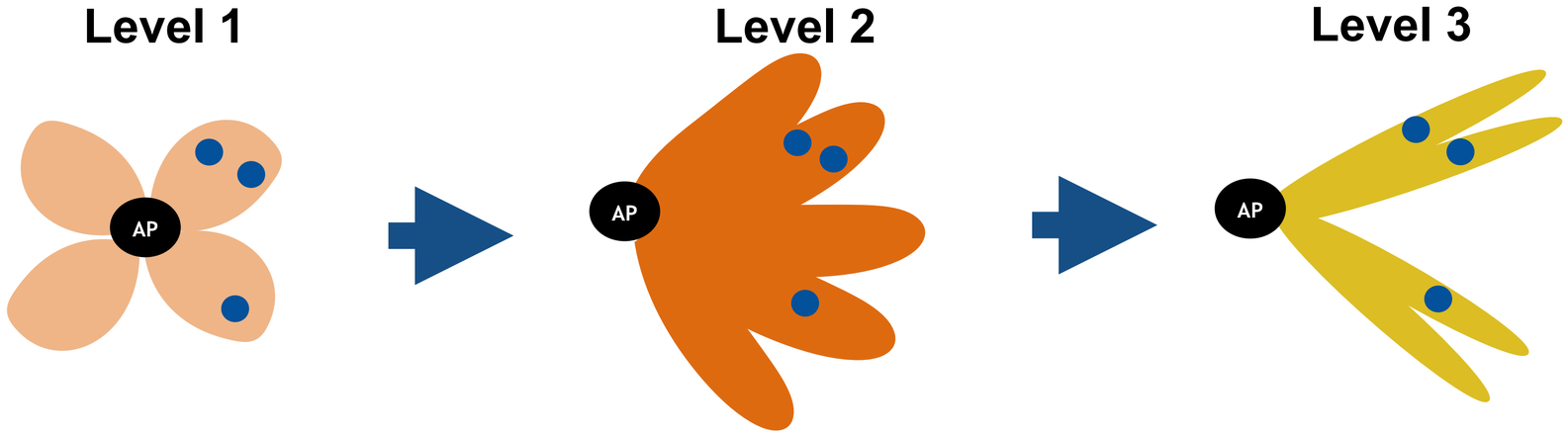
Multi-Level Codebook Trees

- **Multi-level Codebook**
  - Was not required for unicast transmissions
  - Flexibility for AP to cover multiple clients simultaneously
- **Codebook Trees**
  - Leverage the client feedback to prune the training
  - Edges between beam patterns of adjacent levels
- **Spatial Similarity [1,2]**

Array factor $AF(\psi, \theta) = \sum_{u=1}^{U} w(u) e^{j2\pi/\lambda(u-1)dcos(\theta)}$

$G(\psi) = [AF(\psi, 0),\ ...,\ AF(\psi, 2\pi - 360/2\pi)]^T$

$\text{Correlation} = |G(\psi_A)^H G(\psi_B)|$

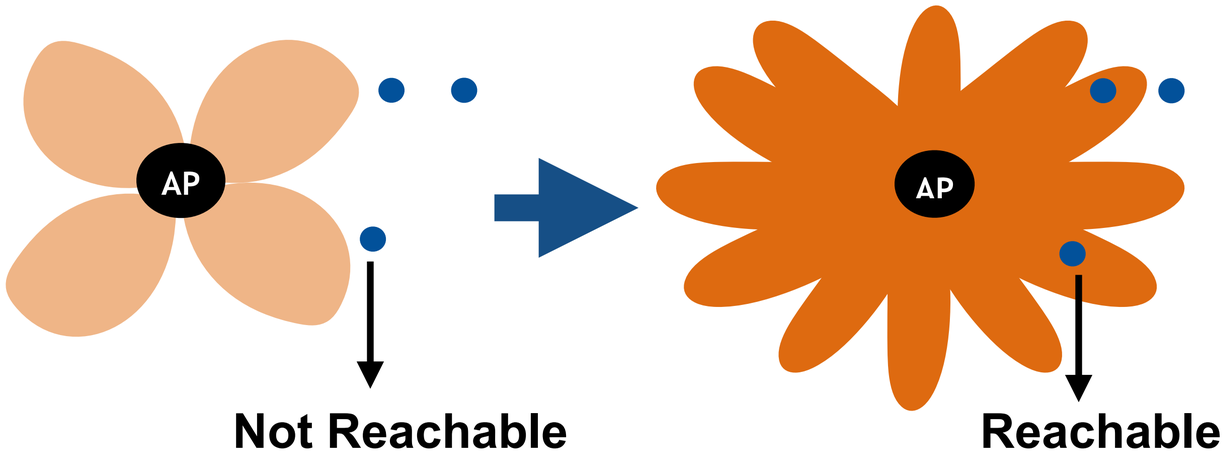


[1] H.-H. Lee and Y.-C. Ko, "Low Complexity Codebook-Based Beam- forming for MIMO-OFDM Systems in Millimeter-Wave WPAN," *IEEE Transactions on Wireless Communications*, November 2011

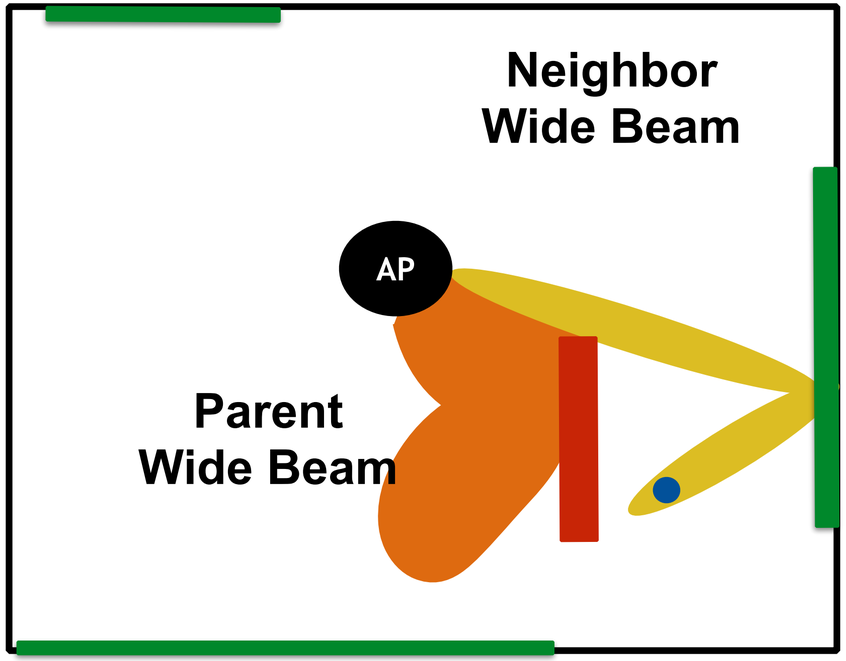
[2] S. Hur, T. Kim, D. Love, J. Krogmeier, T. Thomas, and A. Ghosh, "Multilevel millimeter wave beamforming for wireless backhaul," in *Proc. of IEEE GLOBECOM*, 2011

Challenges

- **Unreachability**
  - Every client might not be reachable at every level
  - Falls back to exhaustive training



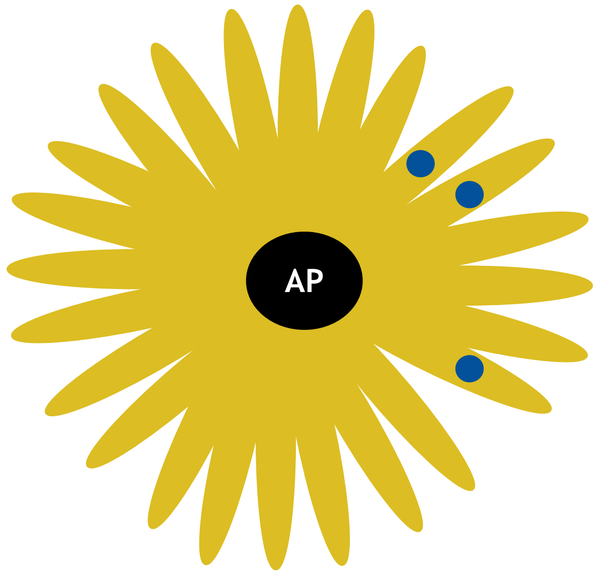
- **NLOS and Blockage**
  - AP's codebook independent of deployed environment
  - Reflectors/ blockage
  - Imperfect codebook tree traversal



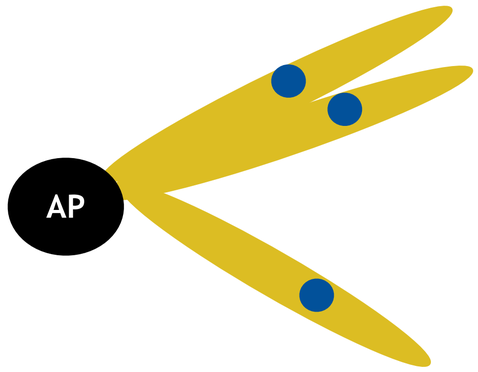
SDM's Finest Beam Training

- Exhaustive training with all the finest level beams
- Highest directivity gain
- Solves unreachability challenge
- Initial solution of only finest beams

TRAINING

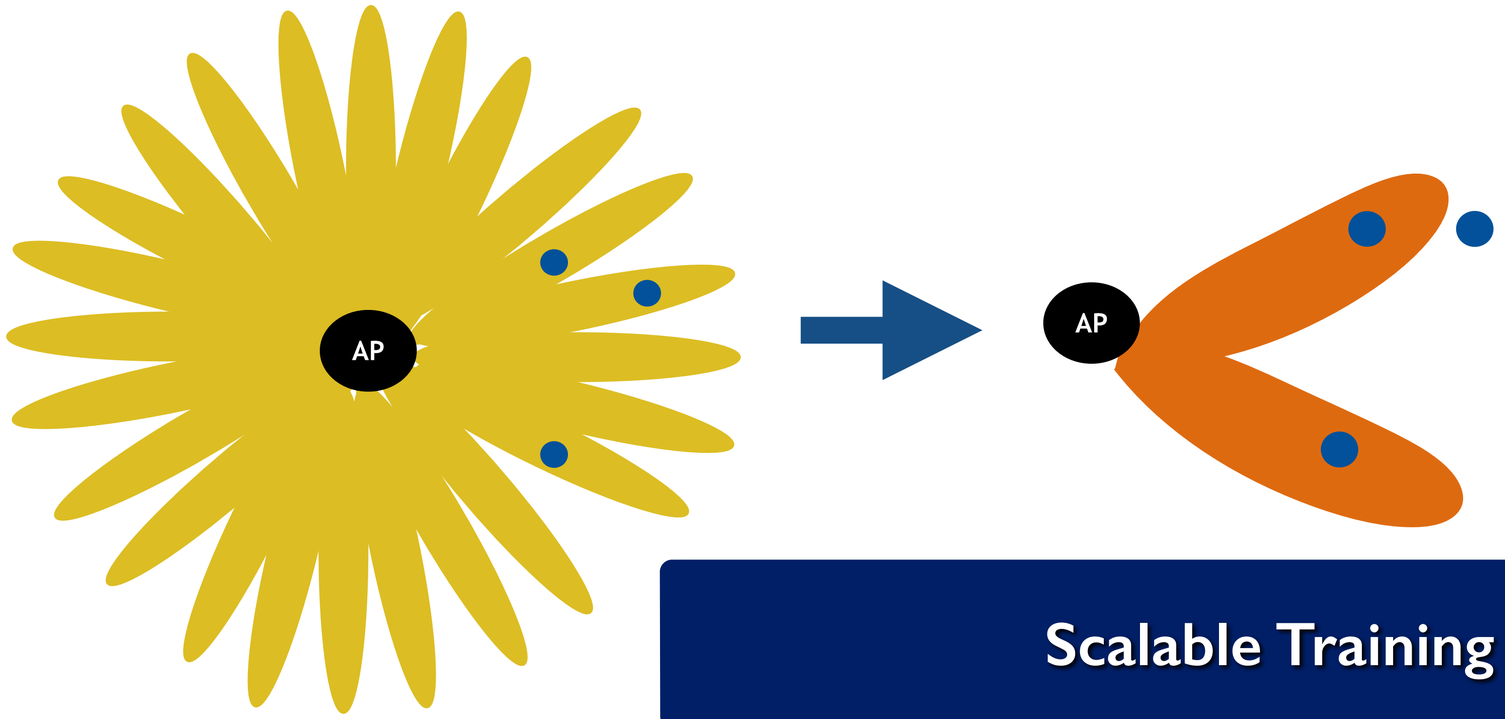


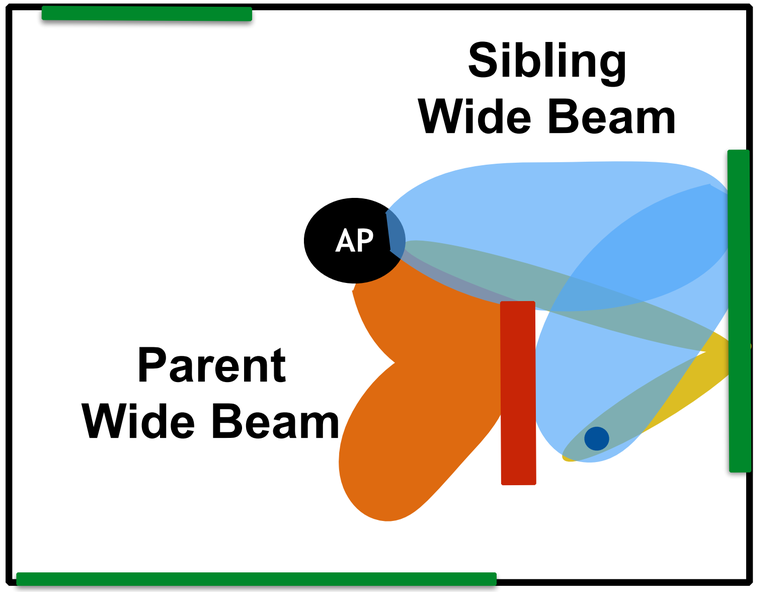
INITIAL SOLUTION



SDM's Wide Beam Training

- **Wide Beam Training**
  - Only parent beams in codebook tree leveraging client feedback
  - Sibling beams in codebook tree to address NLOS scenarios



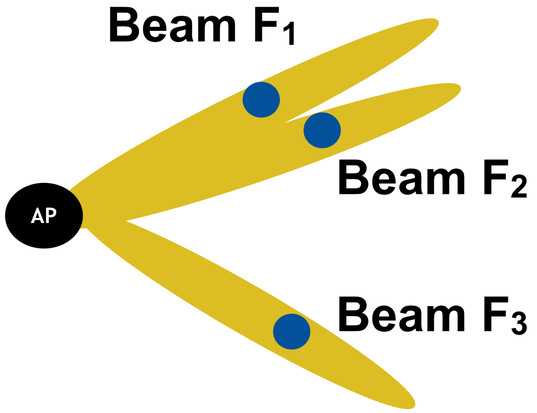


Scalable Training Overhead O(KN)

Which Wide Beams can be used?

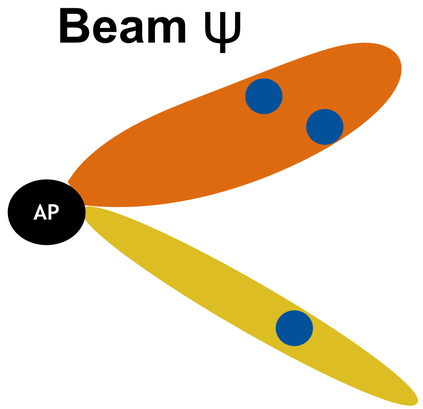
- **Wide Beam Improvement**
  - Identify every wide beam Ψ that can improve upon the only finest beams solution
  - Not every wide beam necessarily improves (Beamwidth-MCS tradeoff)

$$\frac{1}{R(\psi)} < \sum_{f=1}^{2} \frac{1}{R(F_f)}$$



- **Wide Beam Improvement Ratio (WIR)**
  - Replace initial solution with a single wide beam
  - Ratio of transmission time of only finest beams solution over the new solution
  - Traverse the beams that have WIR > 1 in descending order

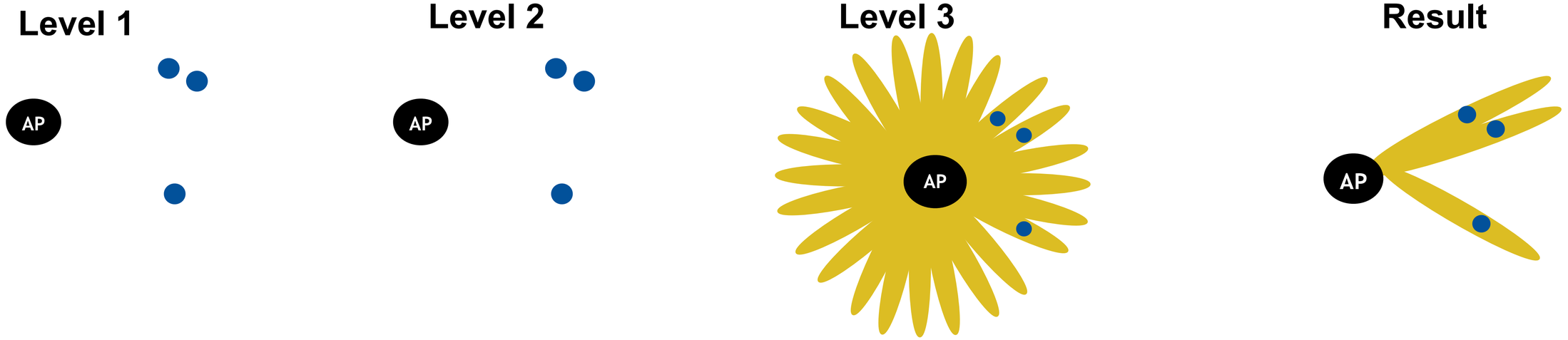
$$\mathrm{WIR}(\psi) = \sum_{f=1}^{3} \frac{1}{R(F_f)} / \left(\frac{1}{R(\psi)} + \frac{1}{R(F_3)}\right)$$



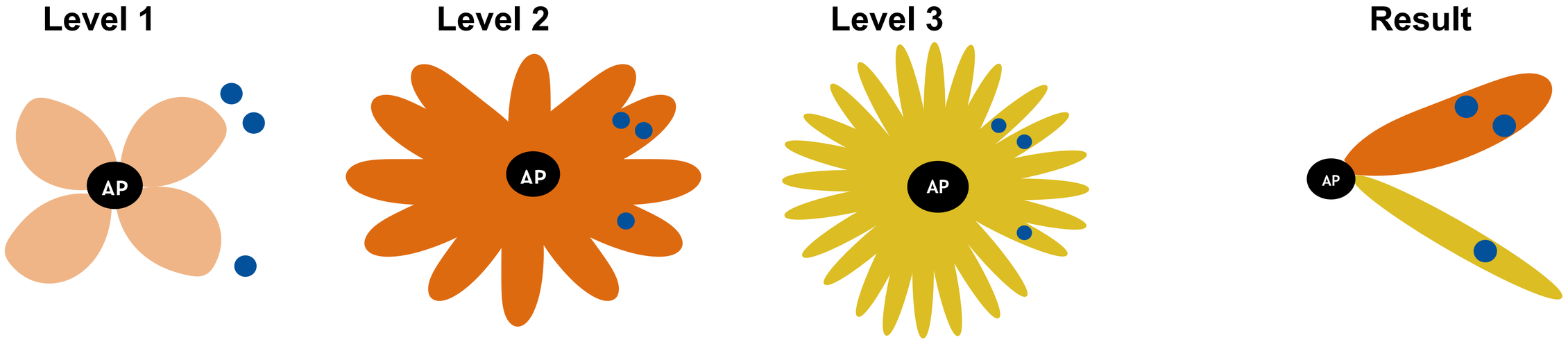
Scalable Beam Grouping Overhead $O(KN^3)$

Alternative Strategies

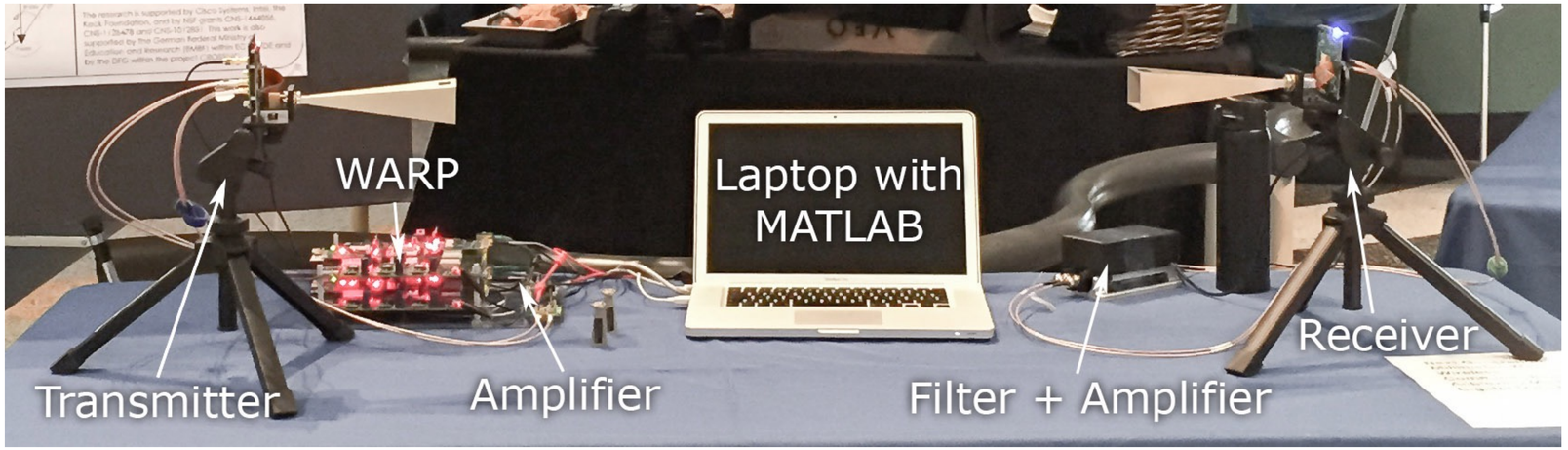
Only Finest Beams strategy : individual narrow beams to each client

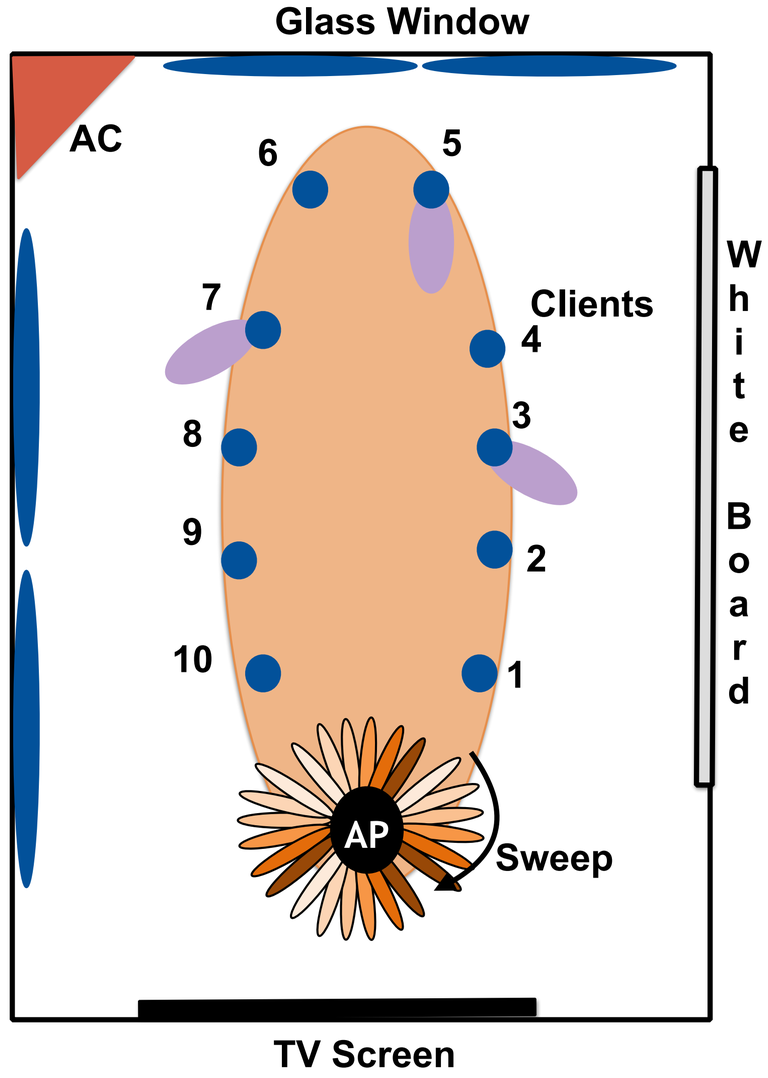


Exhaustive: Exhaustive training and optimal beam grouping



Experimental Evaluation

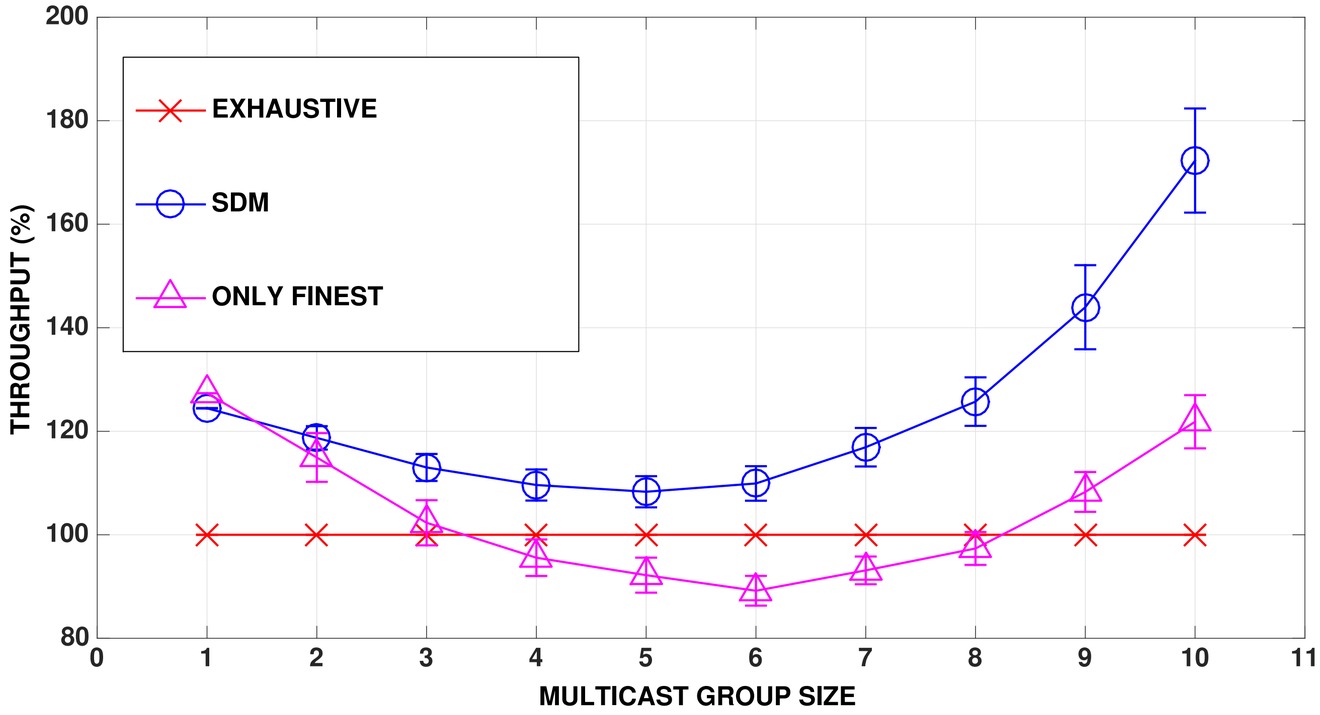




- **Measurement Setup**
  - Typical conference room environment
  - Horn antennas to emulate codebook levels at AP
  - Multiple 5-level codebook trees
- **60 GHz WLAN trace-driven emulator**
  - MATLAB
  - 802.11ad packet sizes and timings

Throughput Performance

- **Single client (unicast)**
  - All strategies have same beam grouping solution
  - Only finest performs the best - Lowest training
- **Medium group size**
  - Exhaustive's data transmission dominates overhead
  - SDM's beam grouping solution within 90% of Exhaustive solution
- **Large group size**
  - Reduced training and beam grouping overhead
  - Wide Beams unlike only Finest



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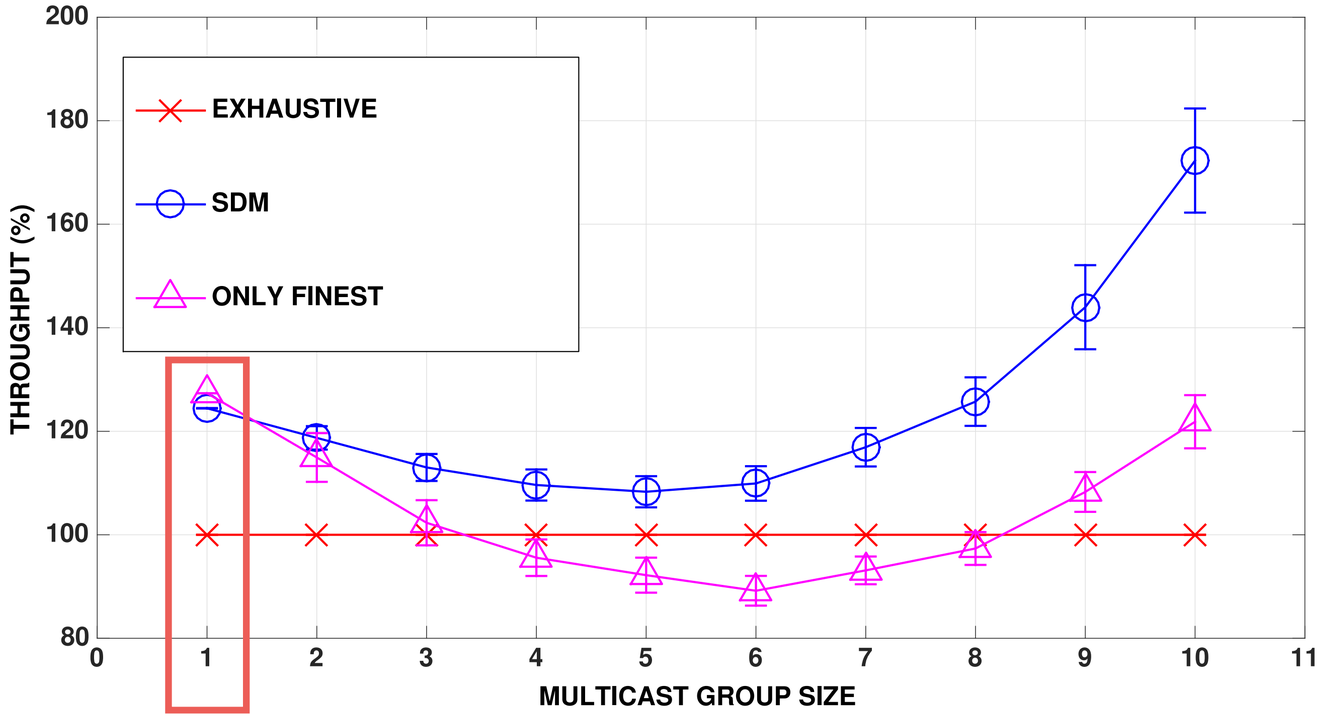

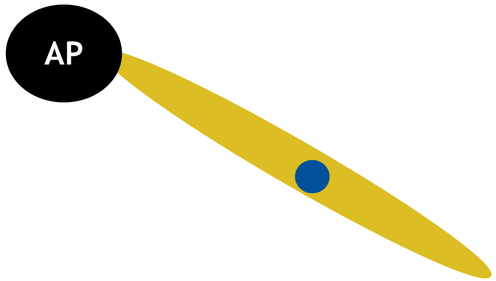

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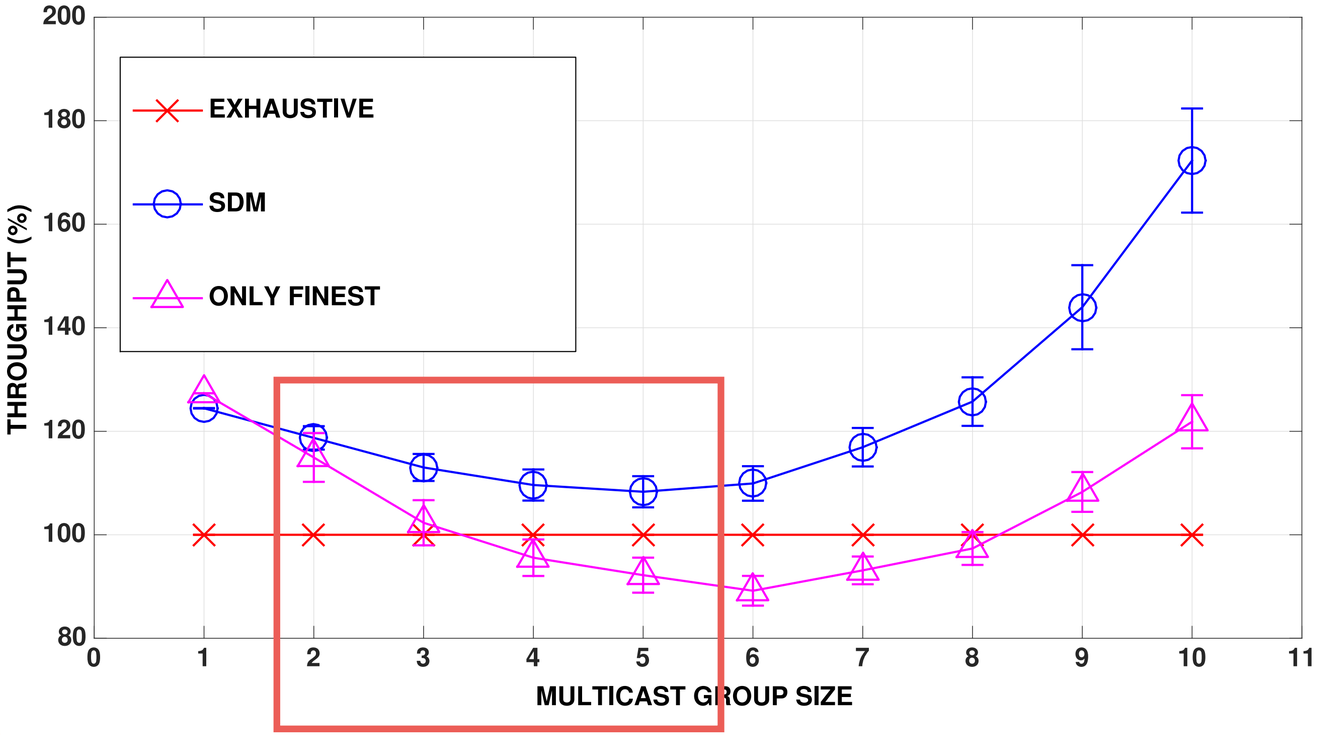

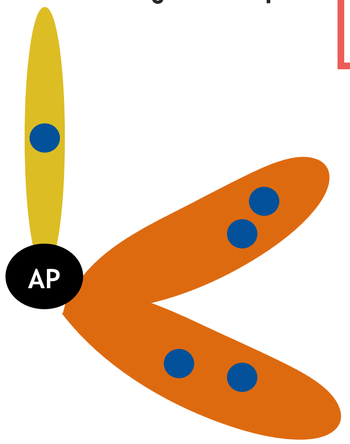

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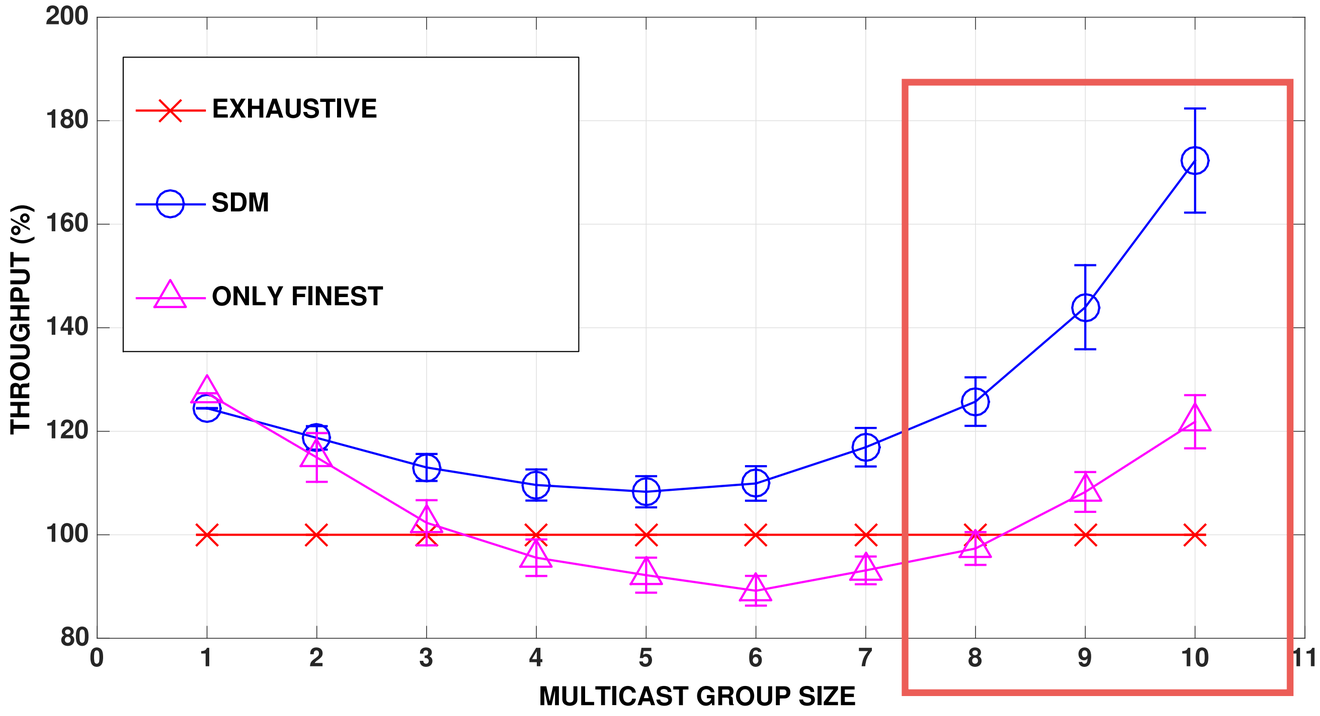

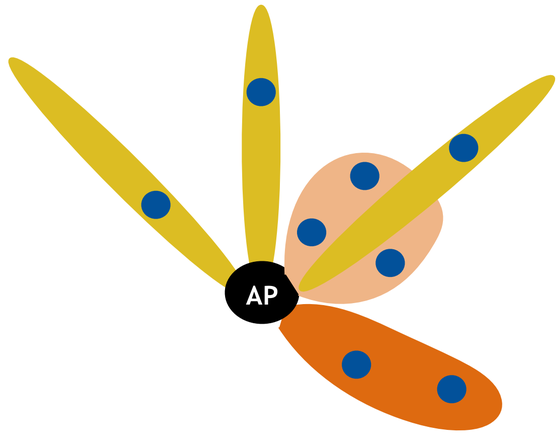

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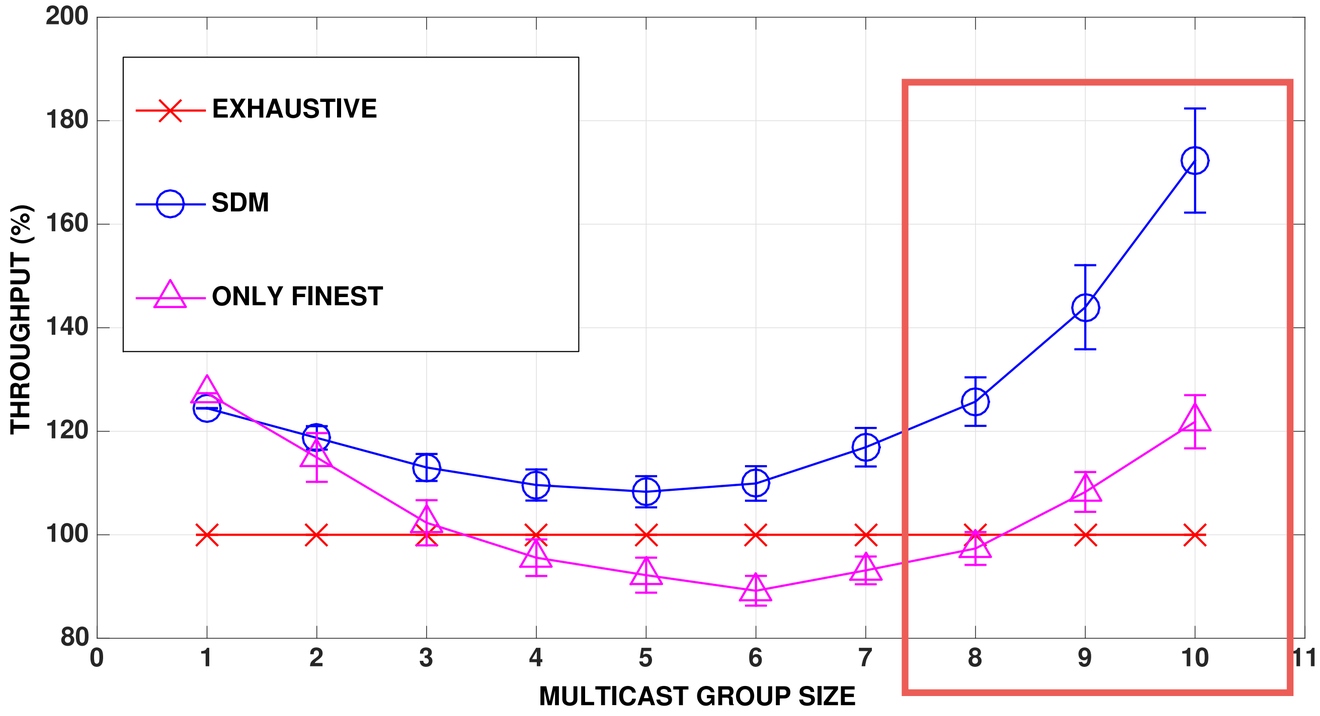
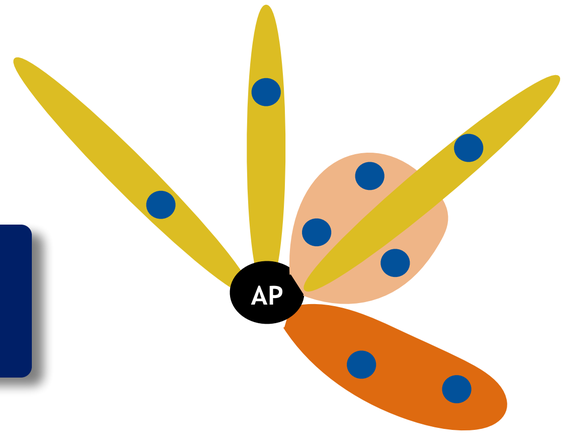




SDM provides over 80% throughput gains over the exhaustive approach

Related Work

- **Multicast Communication**
  - Optimal beam scheduling with Multi-lobe pattern [3]

  In contrast: Single RF chain solution

- **Unicast Beam Training Overhead**
  - Narrowest beams used for data transmission
  - Wider levels skipped by out-of-band solution [4] or gradient-based optimization [5]

  In contrast: For multicast, wider beams cover multiple clients simultaneously

[3] Sundaresan et al., "Optimal Beam Scheduling for Multicasting in Wireless Networks", ACM MobiCom 2009.

[4] Nitsche et al., "Steering with Eyes Closed: mm-Wave Beam Steering without In-Band Measurement," IEEE INFOCOM 2015.

[5] Li et al., "On the Efficient Beam- Forming Training for 60GHz Wireless Personal Area Networks," IEEE Transactions on Wireless Communications, February 2013

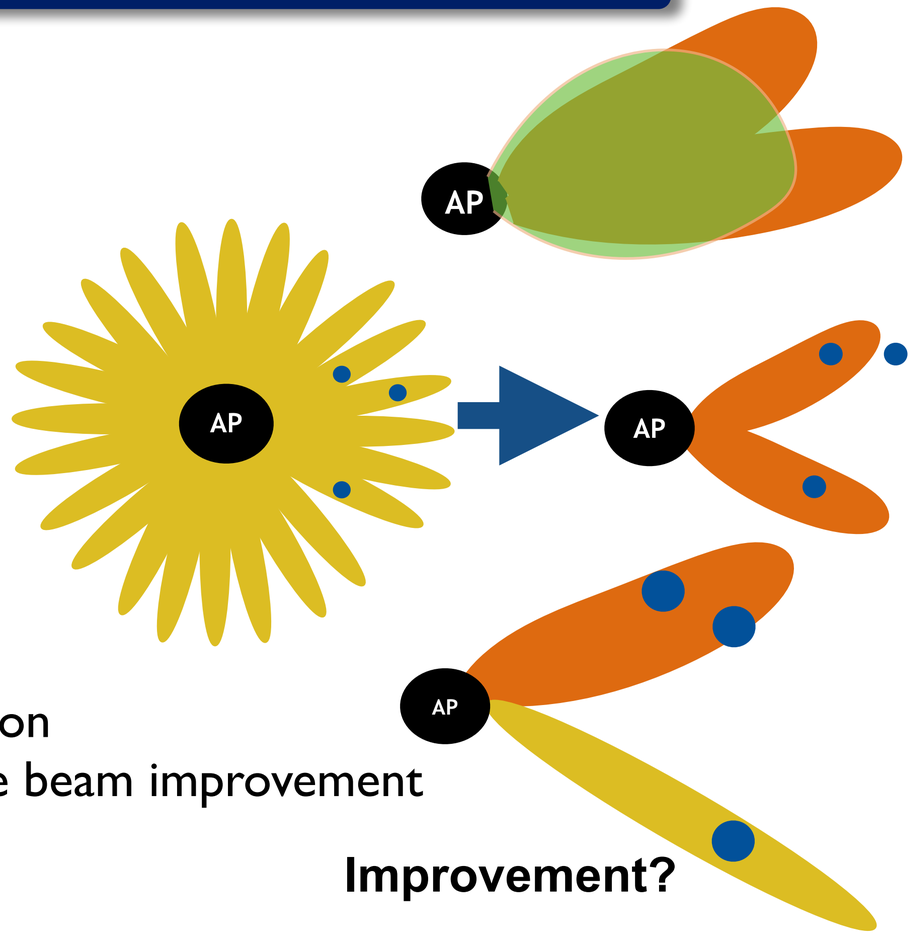
Conclusion

SDM - First 60 GHz Multicast protocol to incorporate training and beam grouping overhead

- **Multi-level Codebook Trees**
  - Link beams of different beamwidth levels using spatial similarity
  - Prune the codebook traversal leveraging client feedback

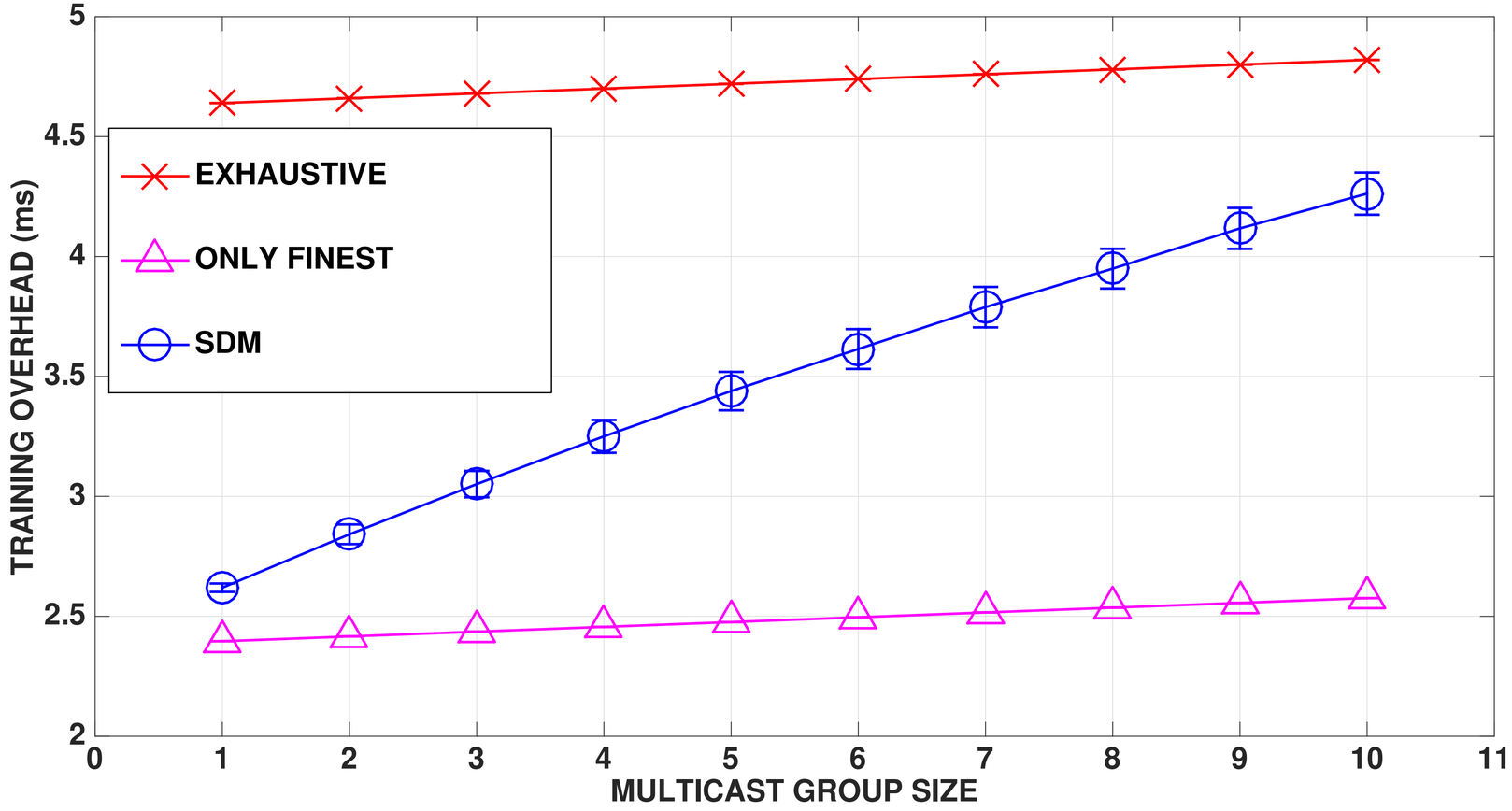
- **Descending Order Traversal for Beam Training**
  - Begin training at finest beam level to address unreachability
  - Only partial set of parent beams for wider beam levels

- **Wide Beam Improvement Ratio**
  - Improvement in transmission time over an only finest beams solution
  - Replace the only finest beams solution in descending order of wide beam improvement



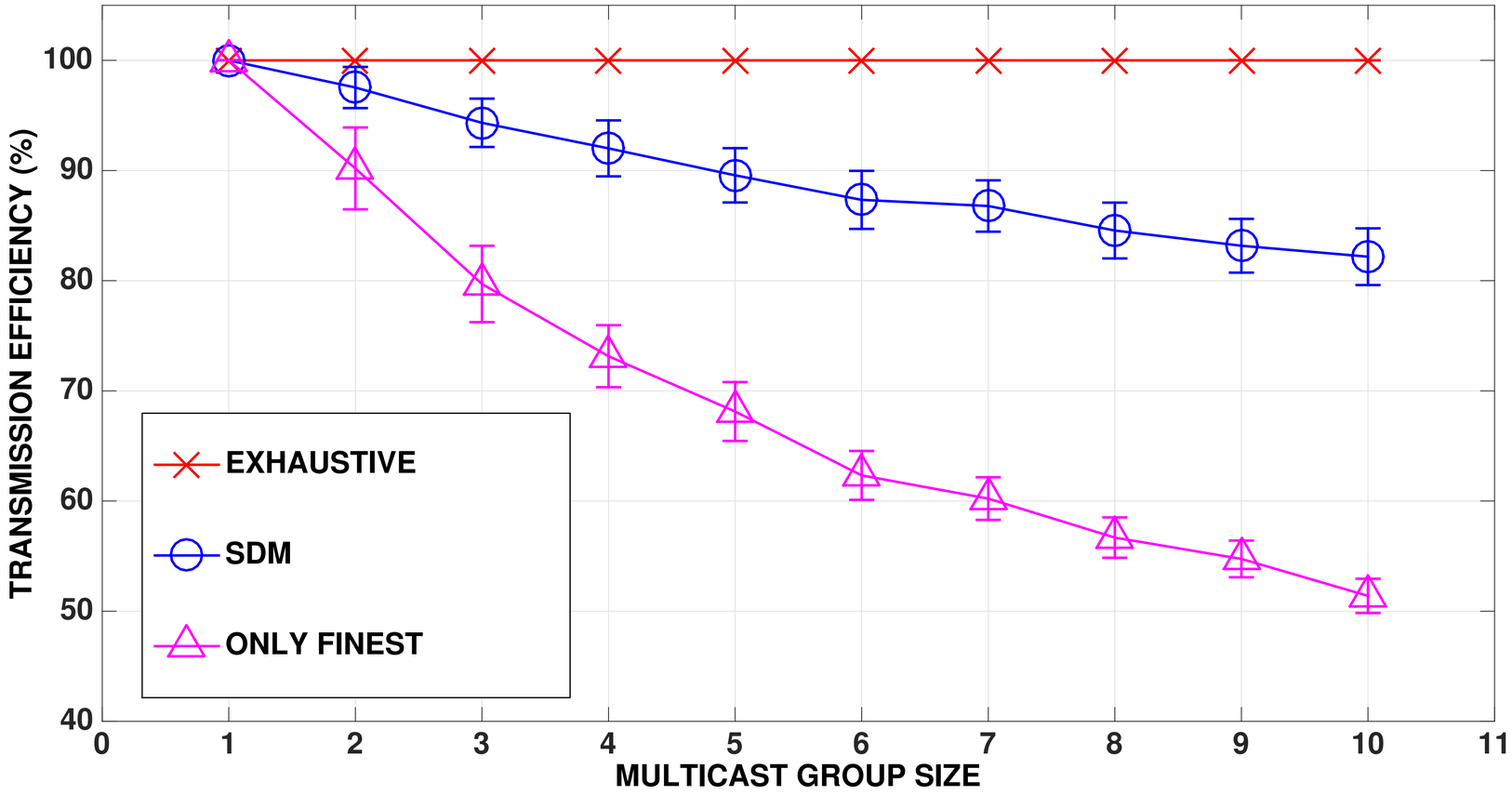
BACKUP

Training Performance



Up to 44.5% reduction in training overhead by SDM

Beam Grouping Performance



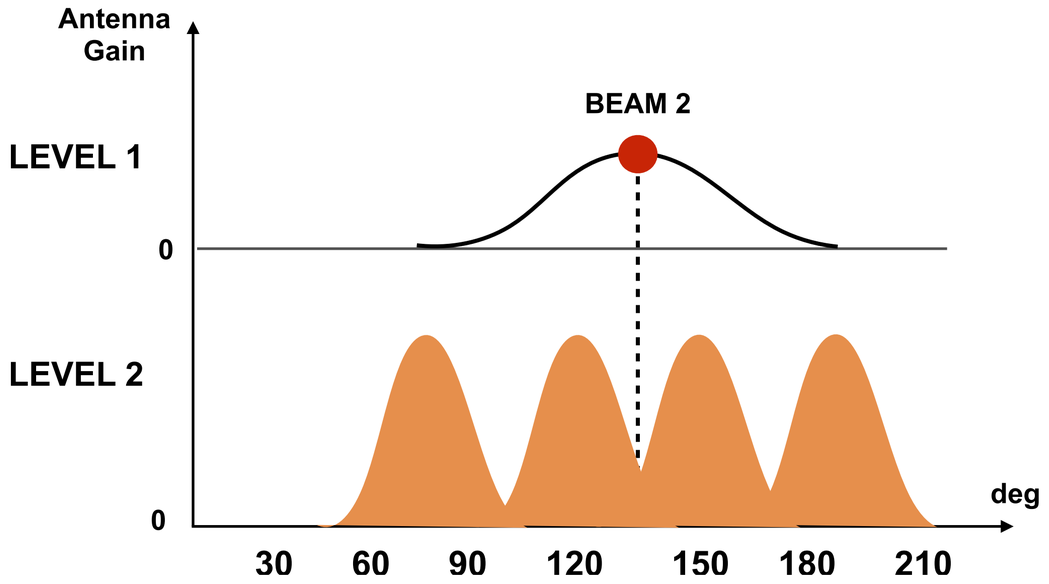
SDM has a performance within 80% of exhaustive search and grouping solution.

Non-Monotonicity

Link budget = P_{TX} + G_{AP} + G_{client} - PL - $L_{reflection}$

- **G_{AP} : AP's transmit beam directivity gain**
  - Theoretically, antenna gain inversely proportional to beamwidth
  - In multi-level codebooks, gain statistically increases with increase in codebook level

- **Exhaustive Training**
  - Every codeword at each level used for training
  - O(KN + c^K) for K levels and N clients

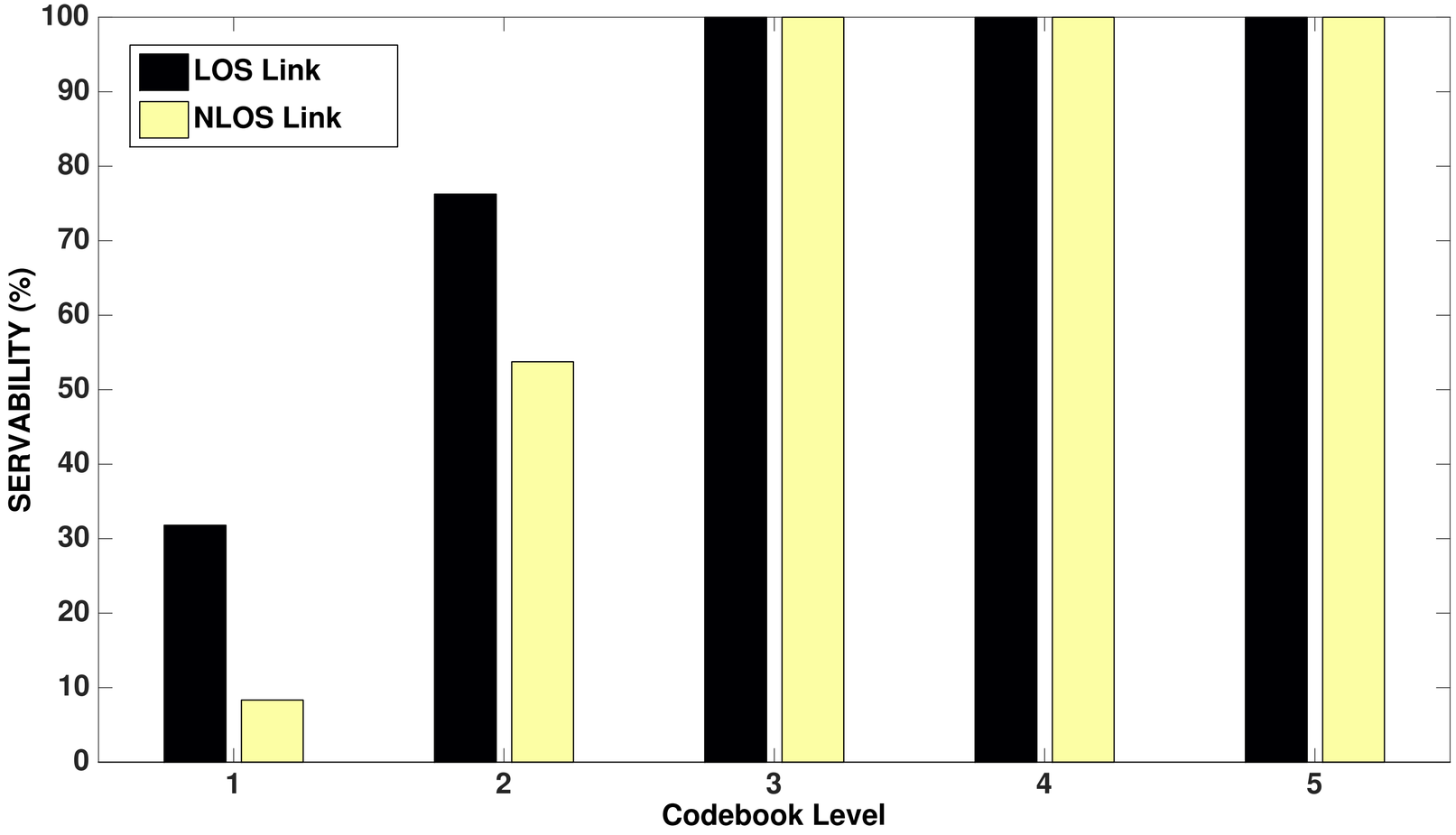


Directivity Gain does not necessarily increase with codebook level

[1] H.-H. Lee and Y.-C. Ko, "Low Complexity Codebook-Based Beam- forming for MIMO-OFDM Systems in Millimeter-Wave WPAN," *IEEE Transactions on Wireless Communications*, November 2011

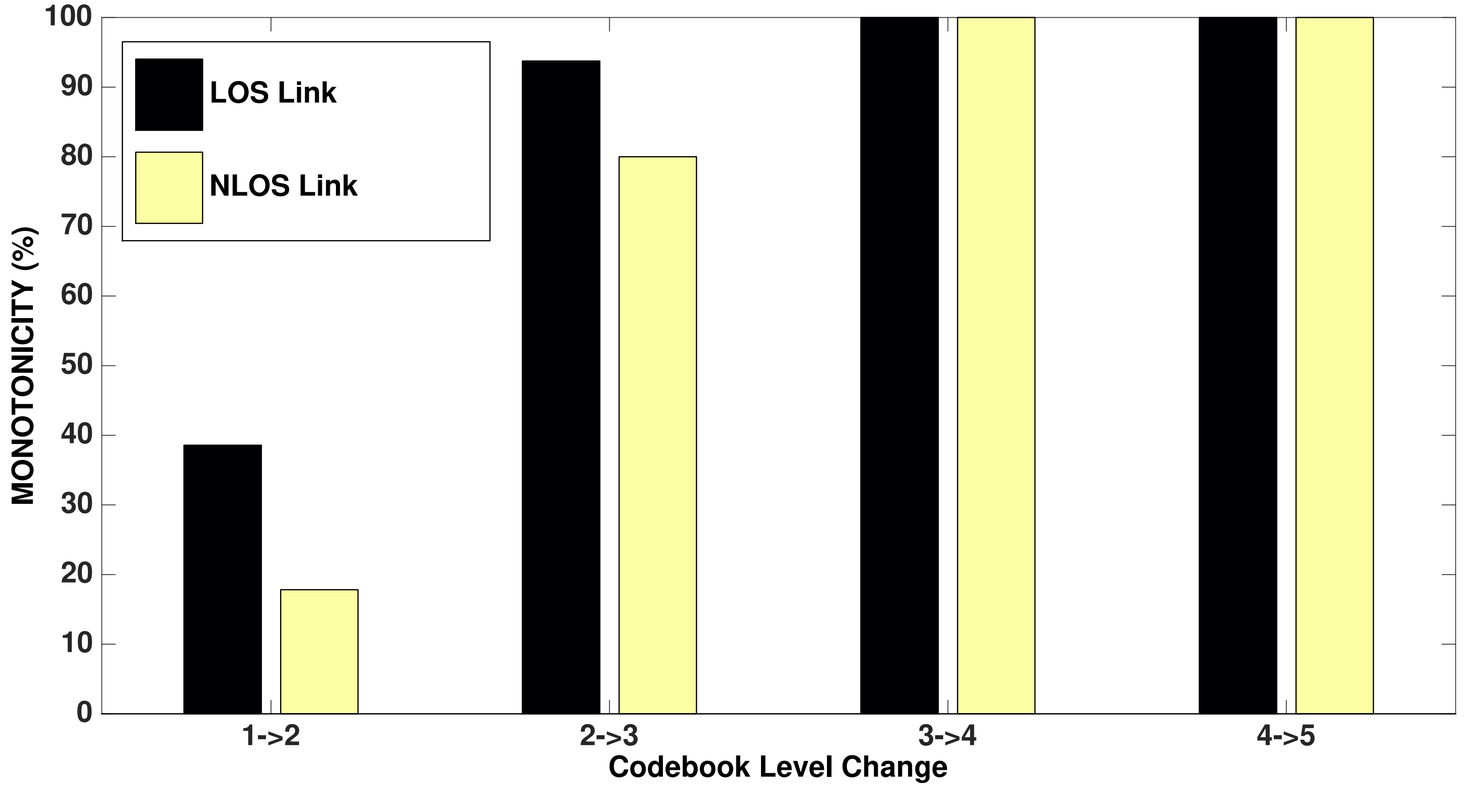
[2] S. Hur, T. Kim, D. Love, J. Krogmeier, T. Thomas, and A. Ghosh, "Multilevel millimeter wave beamforming for wireless backhaul," in *Proc. of IEEE GLOBECOM*, 2011

Servability Analysis



Monotonicity Analysis

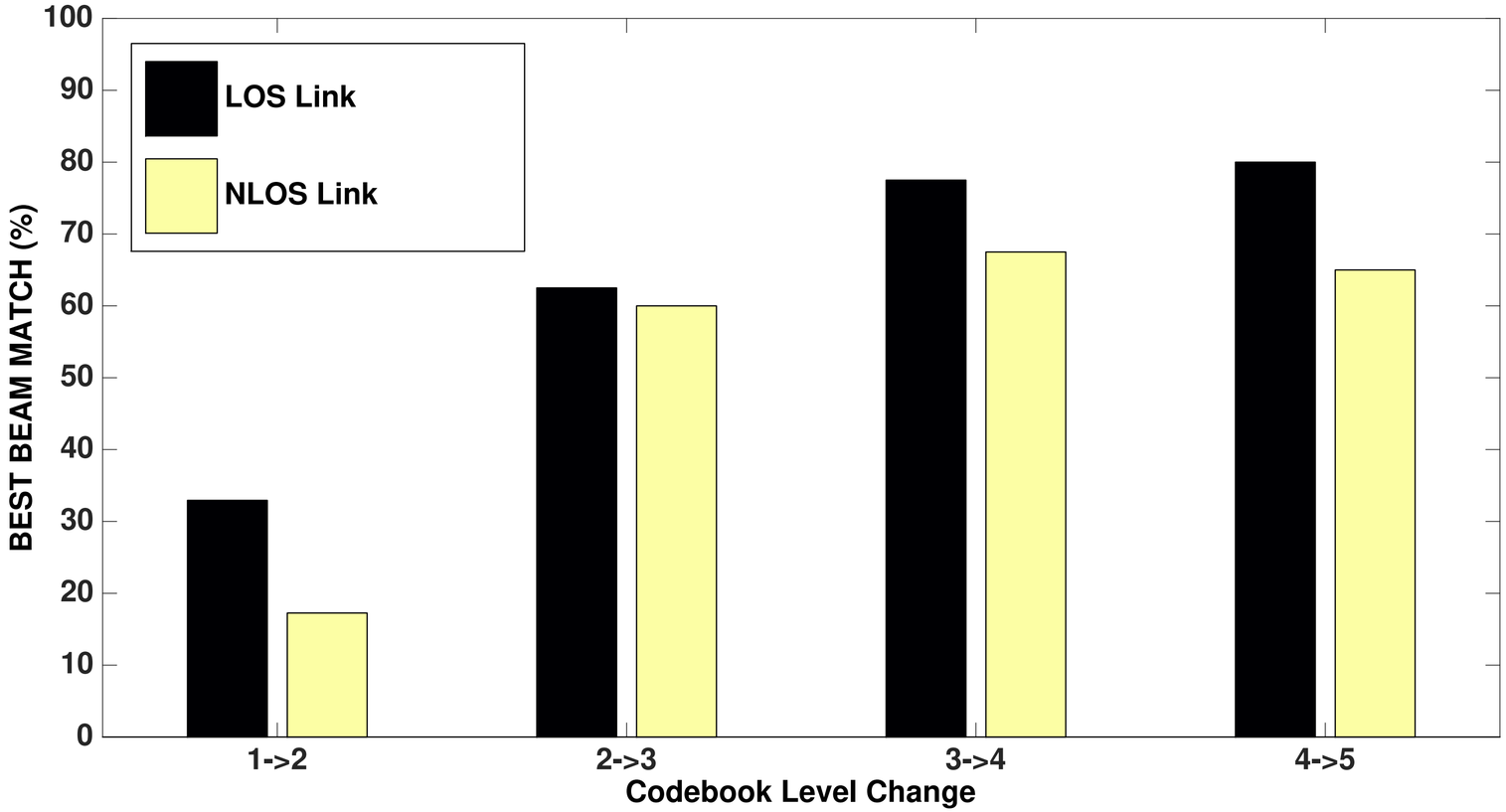
Given the best beam for a client at level "k", can at least one of its children serve the client?



For wider beam levels, the monotonicity in adjacent codebook levels is as low as 16%

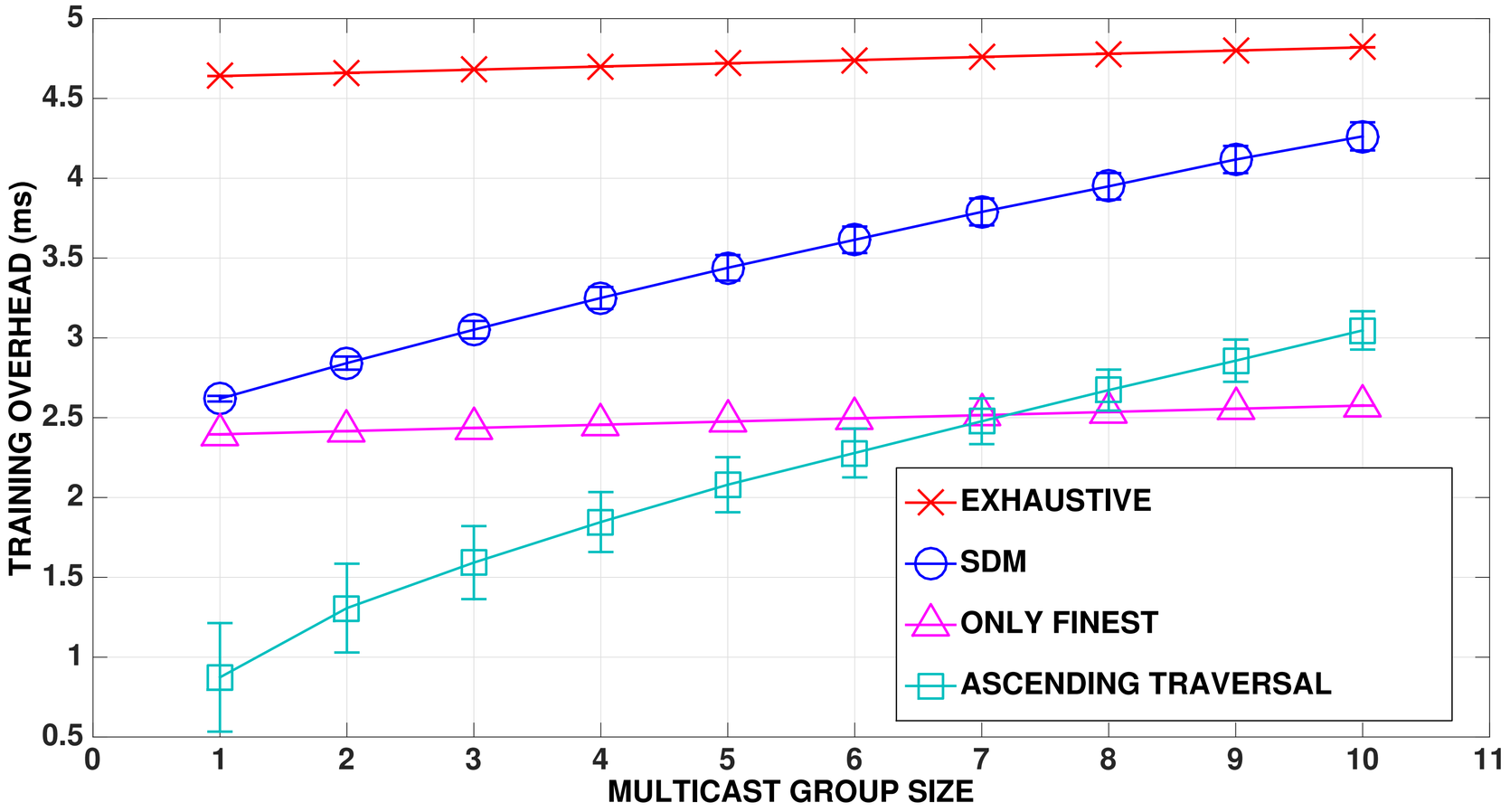
Deviation from Best Beam

Is the best beam for a client at level “k +1” a child of best beam at level “k”

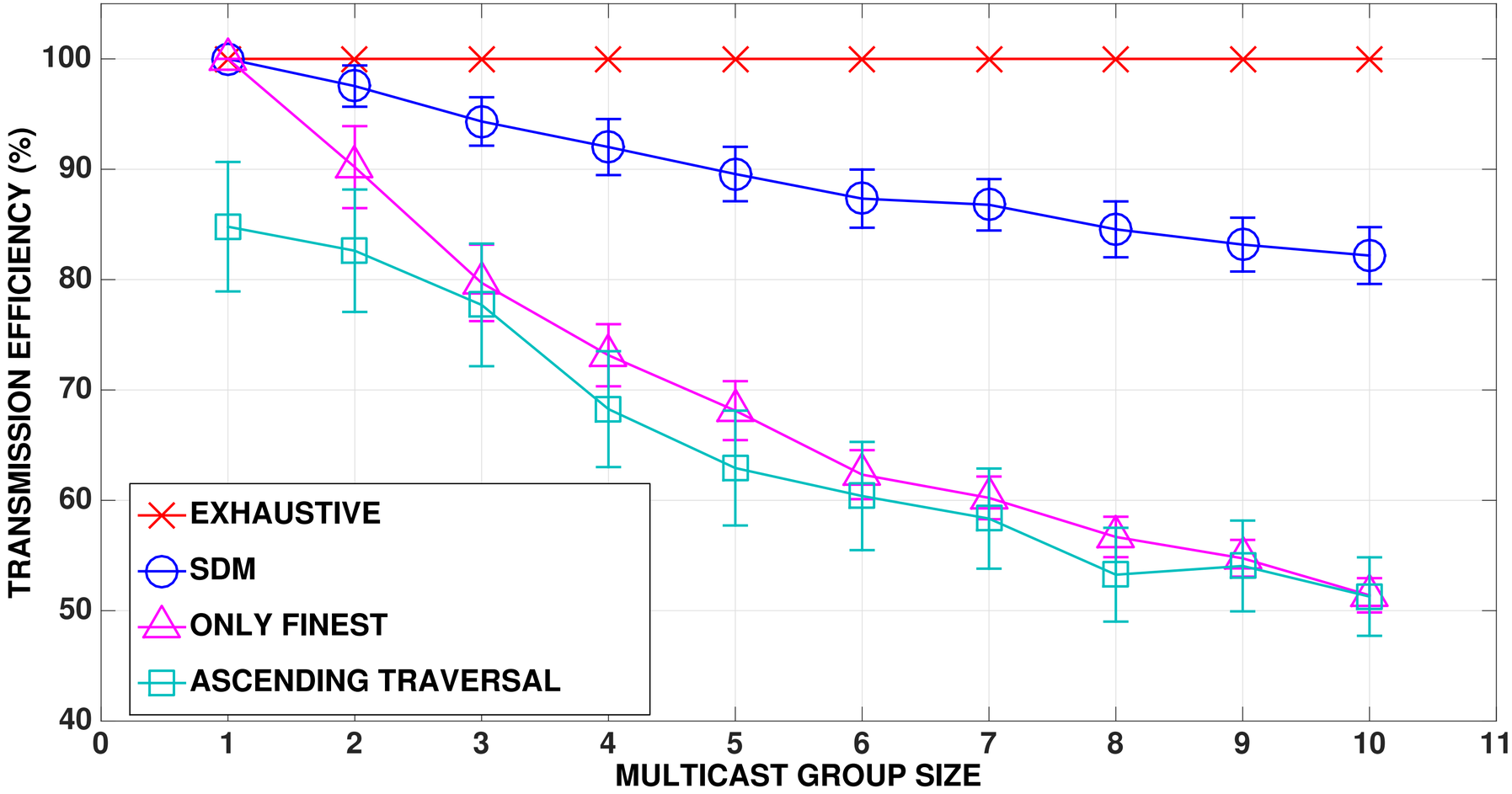


Significant mismatch with the match percentage as low as 12% for wider beams

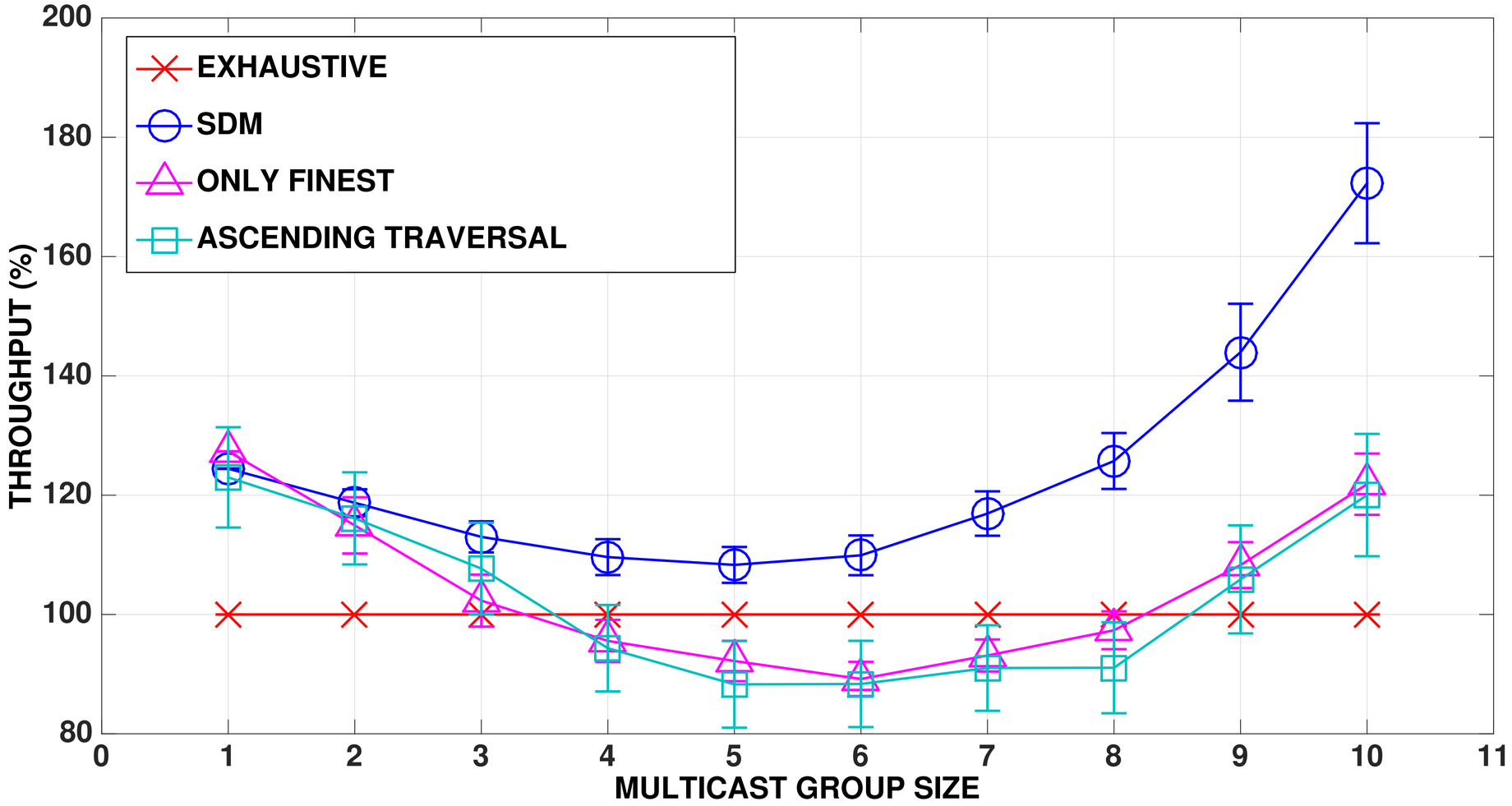
Training Performance



Beam Grouping Performance



Throughput Performance

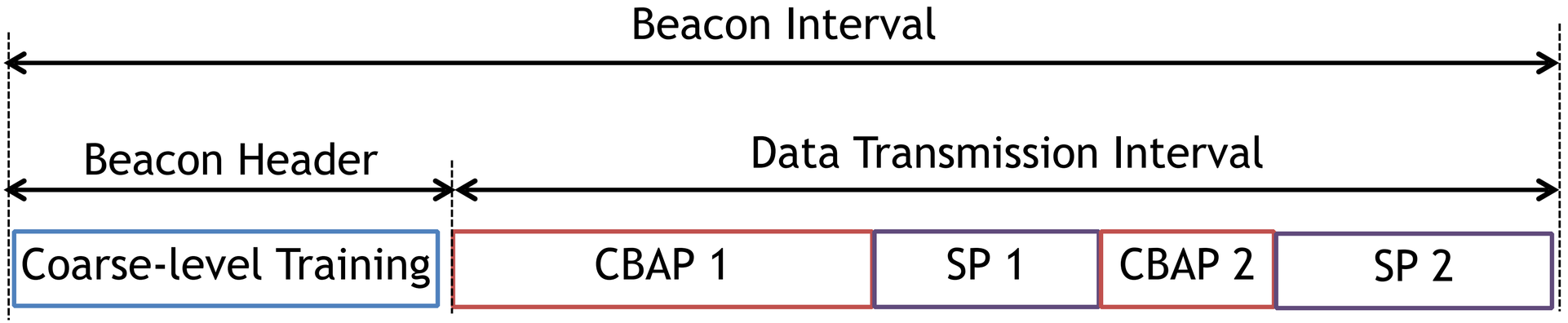


802.11ad MCS Table

RICE

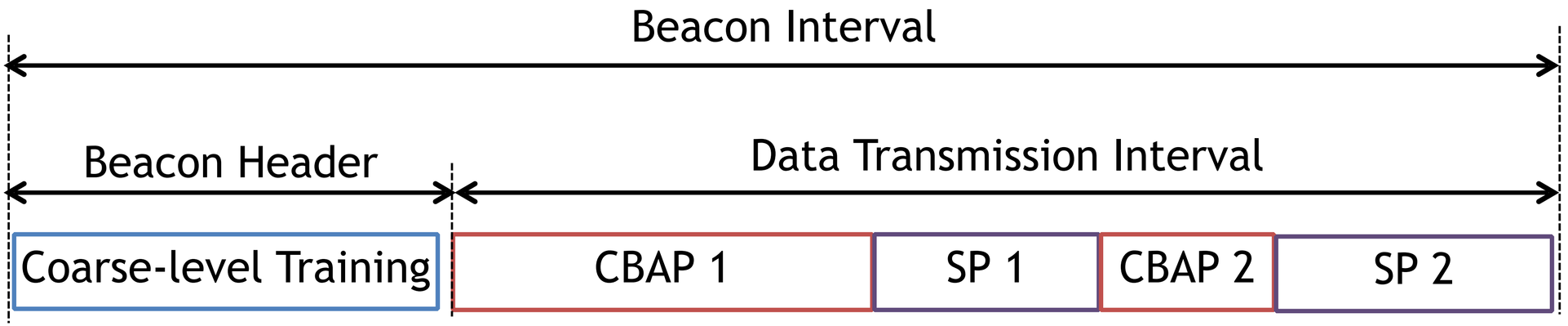
MCS Index	Receive sensitivity (dBm)	Data Rate (Mbps)
0	-78	27.5
1	-68	385
2	-66	770
3	-65	962.5
4	-64	1155
5	-62	1251.5
6	-63	1540
7	-62	1251.5
8	-61	1540
9	-59	2502.5
10	-55	3080
11	-54	3850
12	-53	4620

802.11ad Timeline



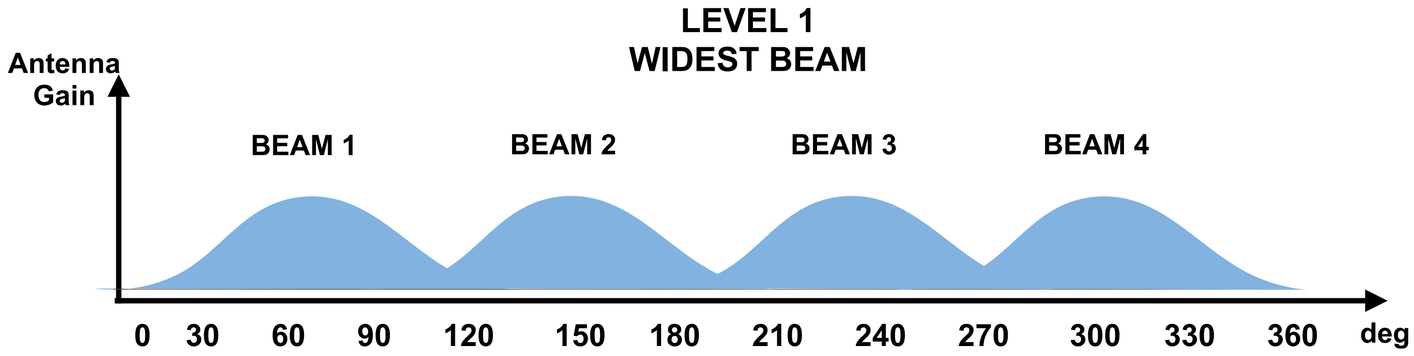
CBAP = 802.11 contention-based access
SP = Service Period

802.11ad Timeline

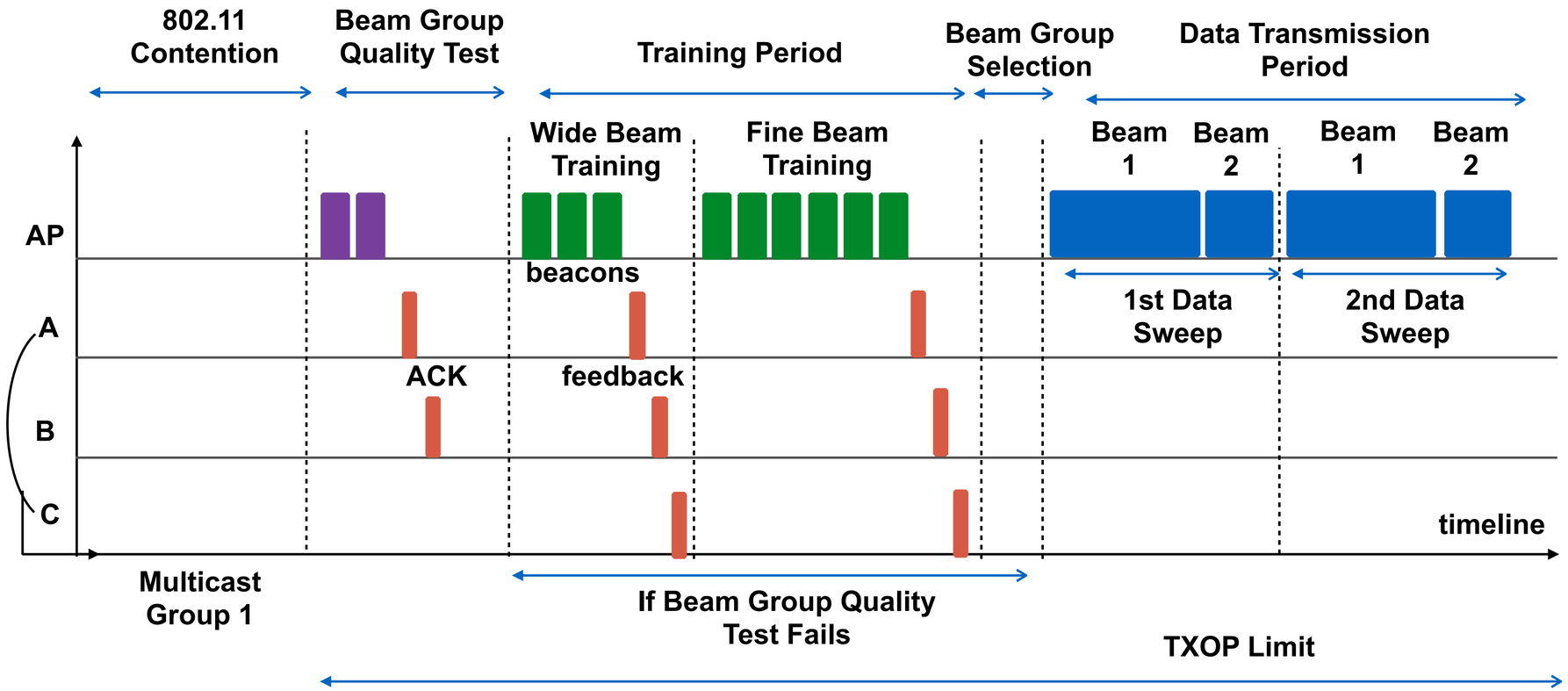


CBAP = 802.11 contention-based access
SP = Service Period

- **Coarse-level Training**
  - AP Widest beam level Training
  - Control messages at Base Rate (MCS 0)
  - Client-side beam training

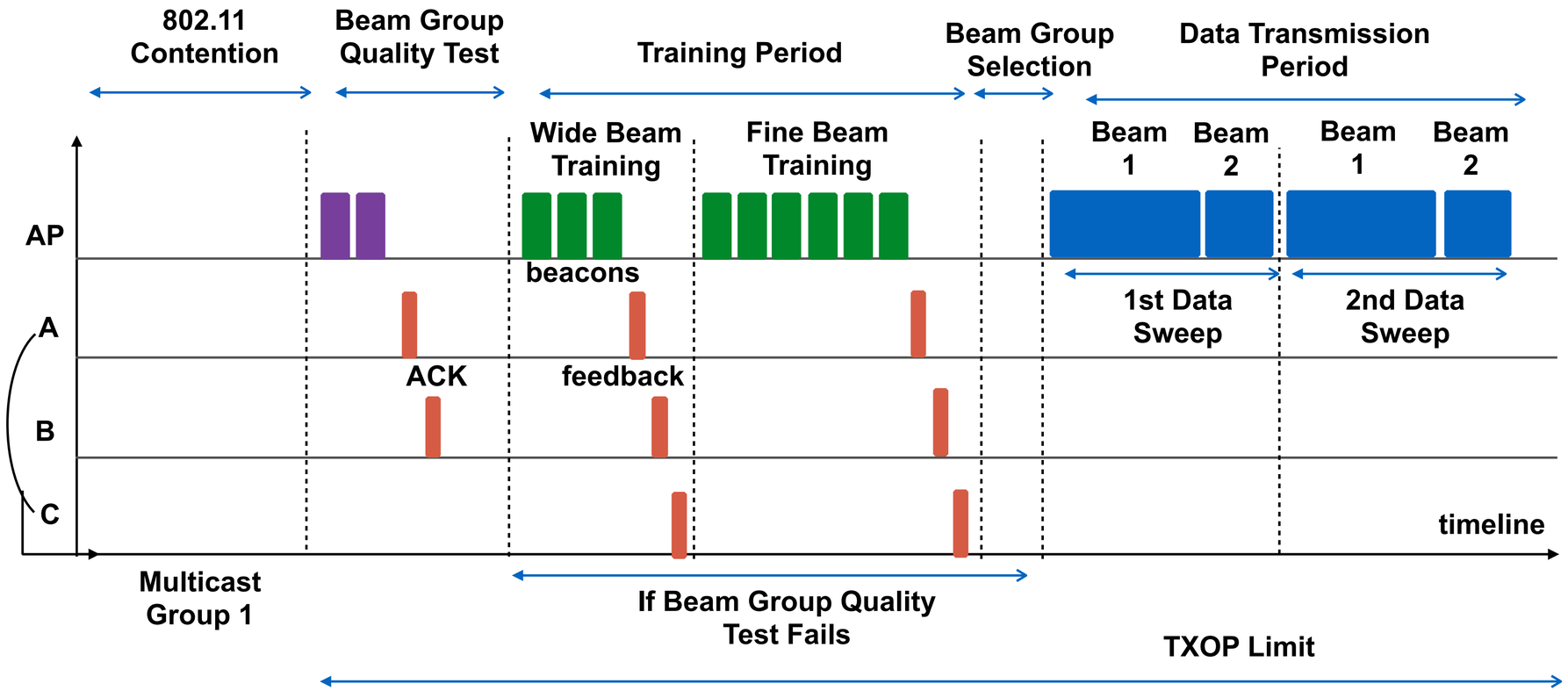


SDM Timeline



- Beam specs: Codebook entry, client subset and data rate
- Data sweep; multiple times during TXOP

SDM Timeline



- Beam specs: Codebook entry, client subset and data rate
- Data sweep; multiple times during TXOP

To minimize the Data Sweep time, the exhaustive search is order $O(c^{K-1}N^{N/2+1})$