Enhanced WLAN Performance with New Spectrum at 60 GHz and Visible Light

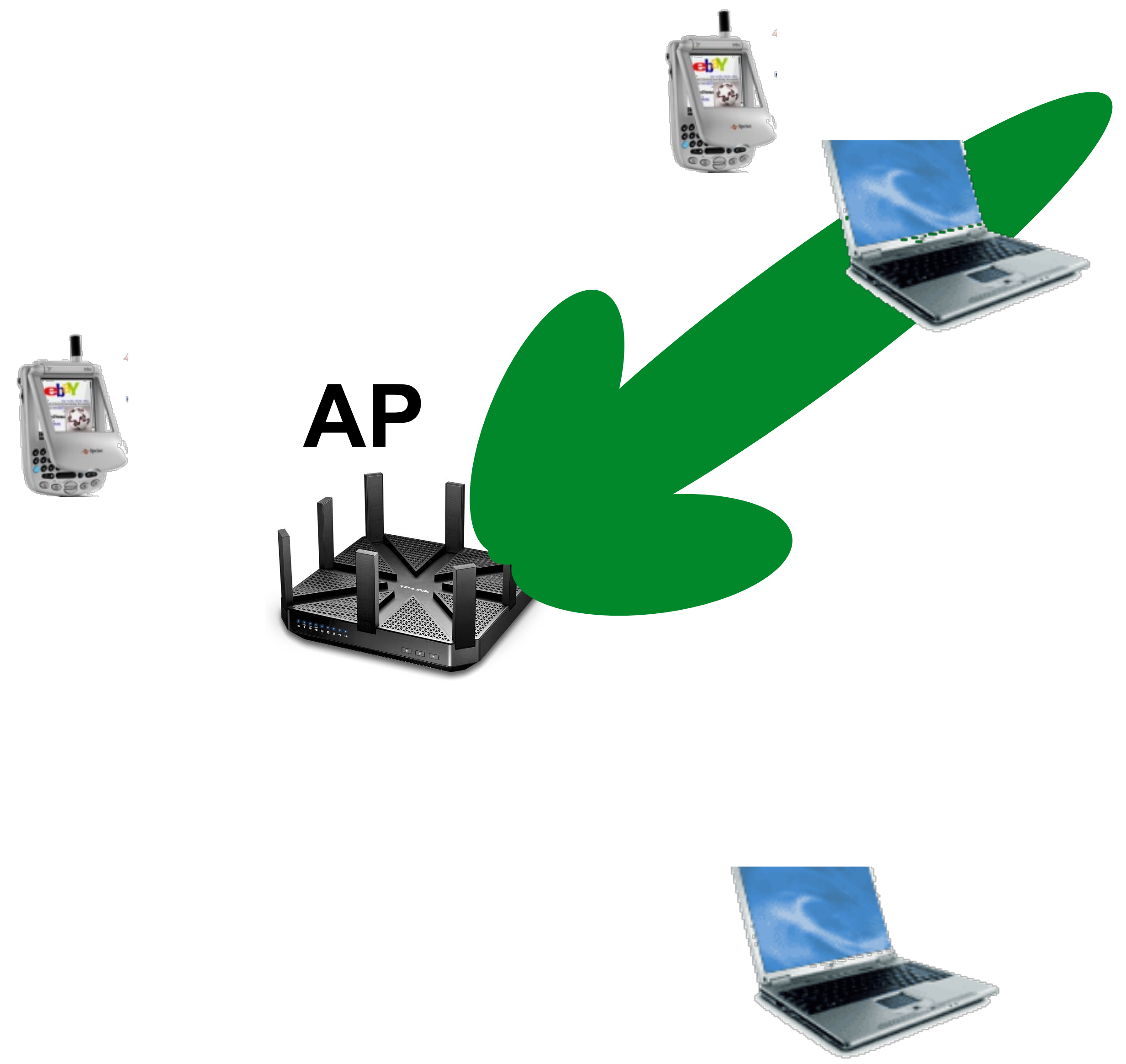
Sharan Naribole
Advisor: Dr. Edward Knightly
PhD Defense Talk

December 04, 2017

RICE

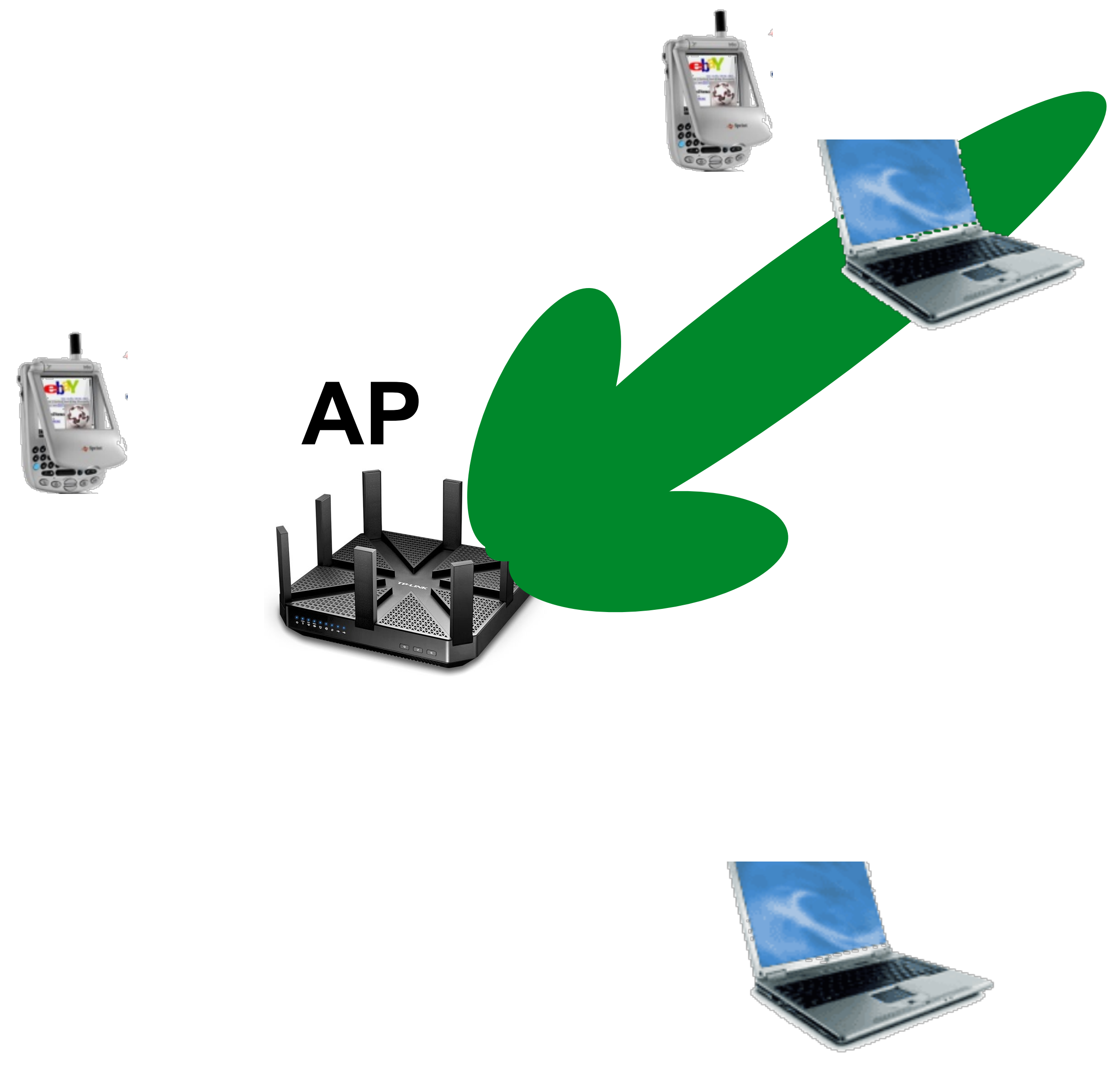
Emerging Spectrum: Properties

- **60 GHz**
  - 7-14 GHz unlicensed bandwidth
  - Up to 7 Gbps via 802.11ad
- **Propagation characteristics**
  - 20-40 dB increased attenuation
  - Highly-directional transmissions

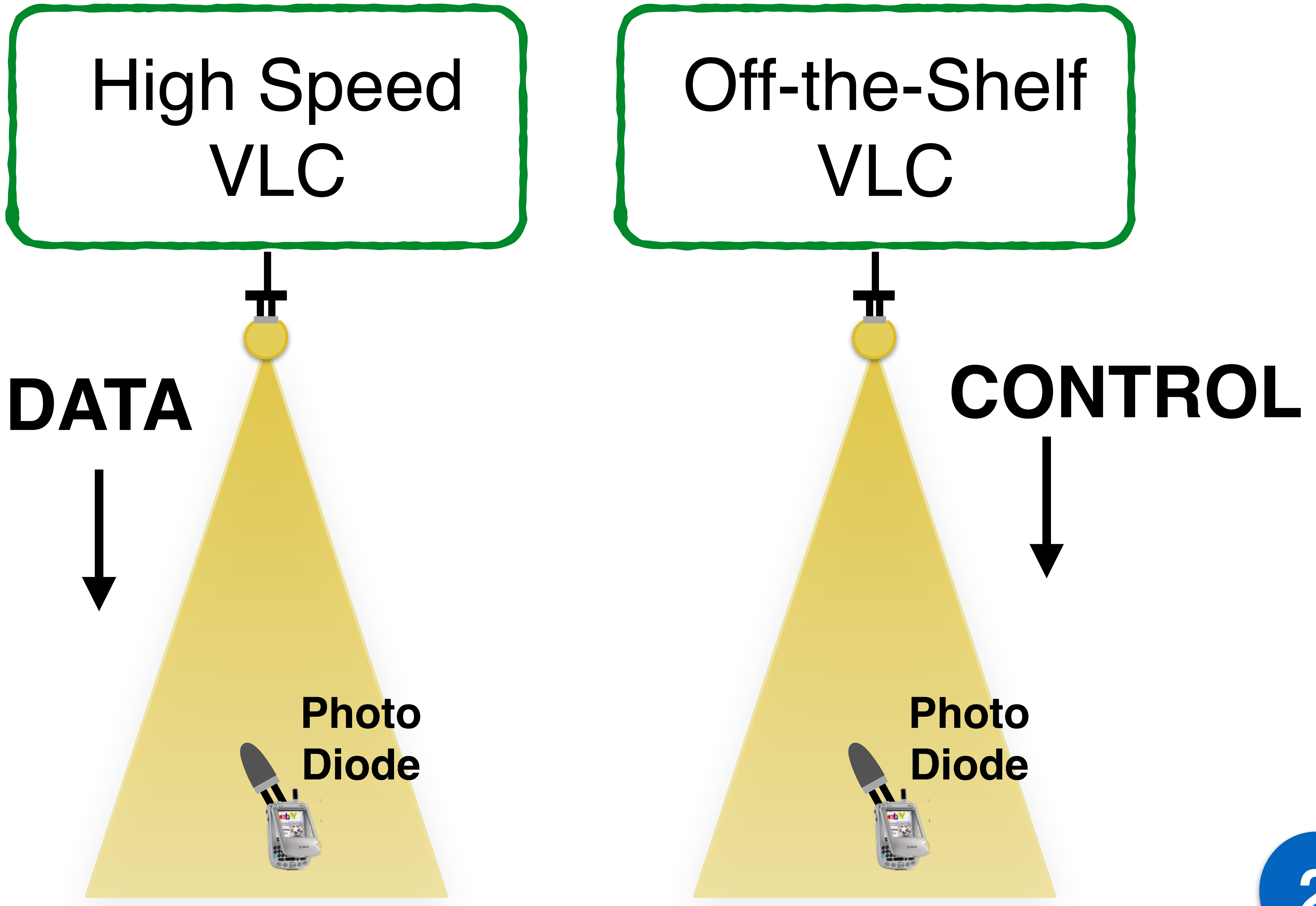


Emerging Spectrum: Properties

- **60 GHz**
  - 7-14 GHz unlicensed bandwidth
  - Up to 7 Gbps via 802.11ad
- **Propagation characteristics**
  - 20-40 dB increased attenuation
  - Highly-directional transmissions

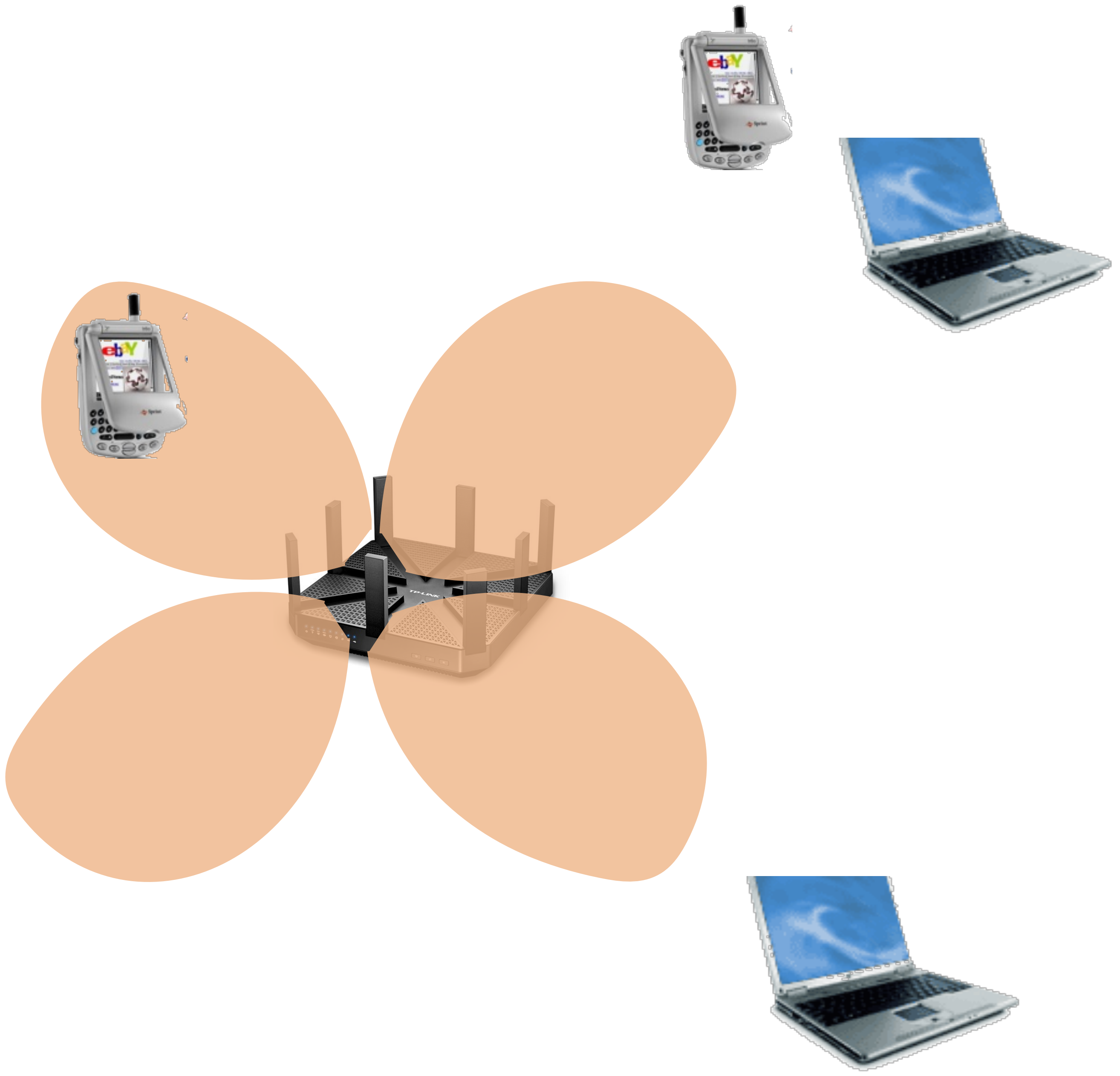


- **Visible Light Communication (VLC)**
  - Dual purpose: Illumination & communication
- **Flicker free modulation**
  - Low-cost photo diodes, cameras etc.



Emerging Spectrum: Challenges

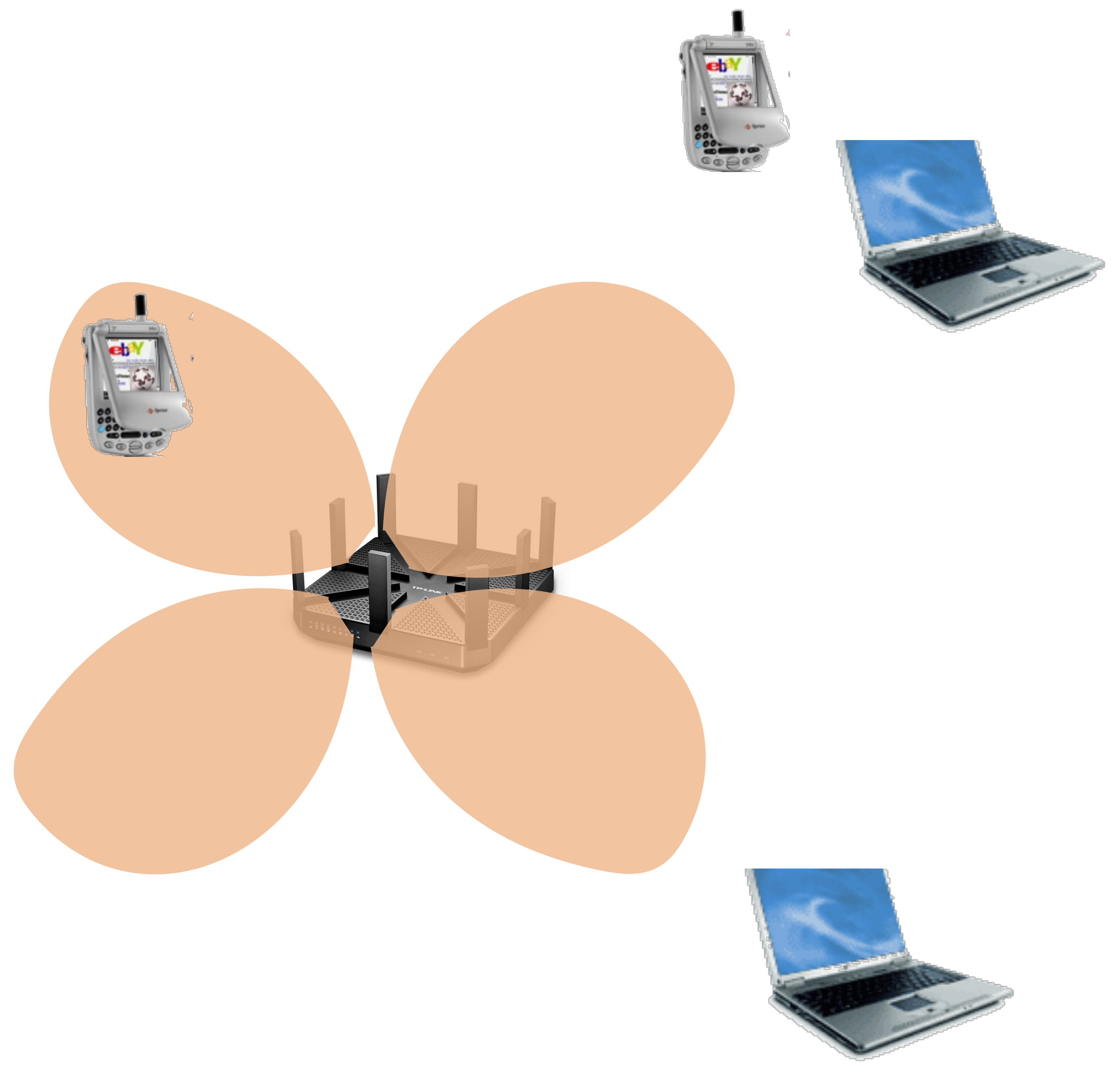
- **60 GHz Multicast**
  - Low directivity gain with wide beams



One transmission cannot reach entire group

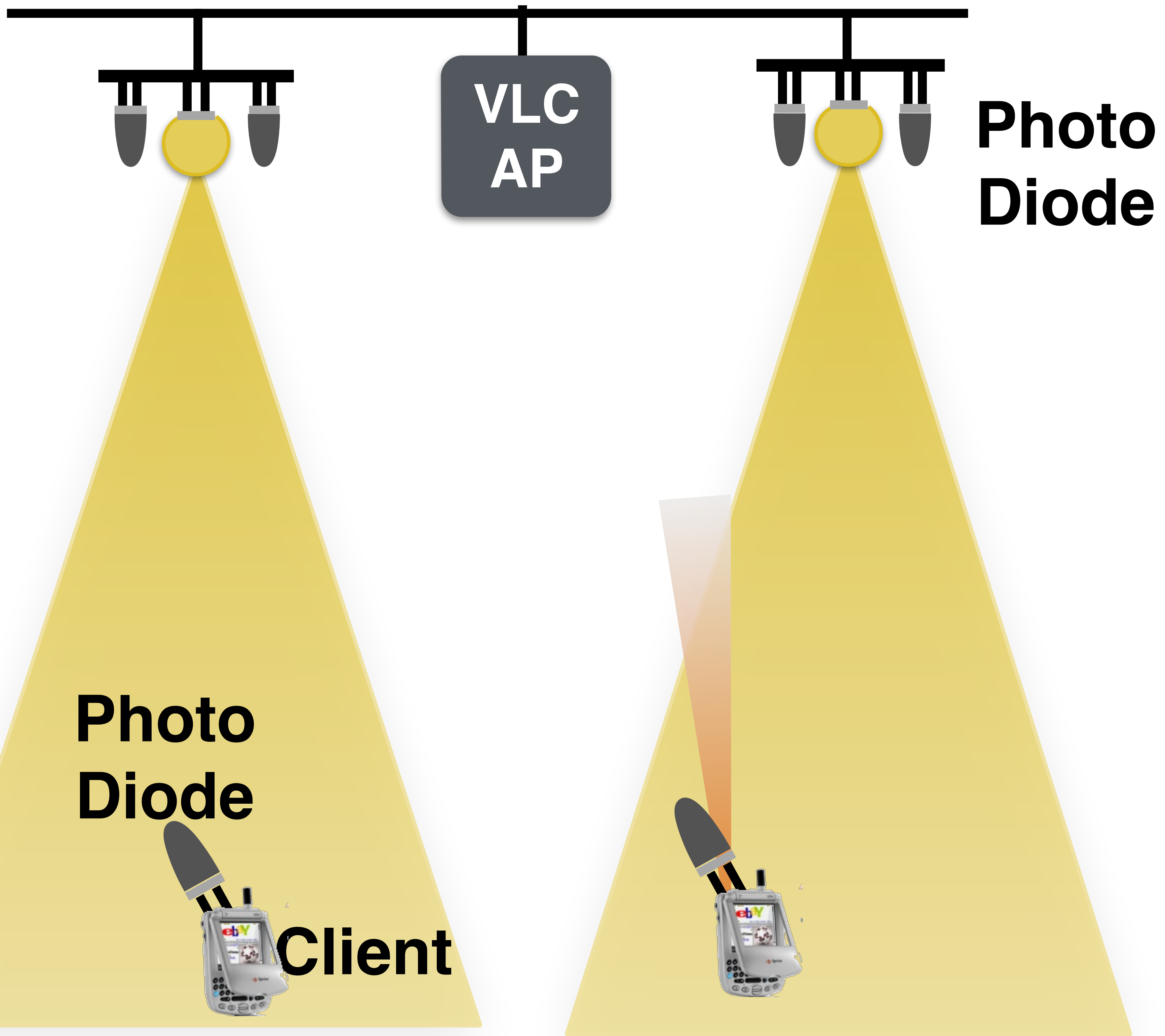
Emerging Spectrum: Challenges

- **60 GHz Multicast**
  - Low directivity gain with wide beams



One transmission cannot reach entire group

- **VLC Impractical Uplink**
  - Form factor and energy constraints

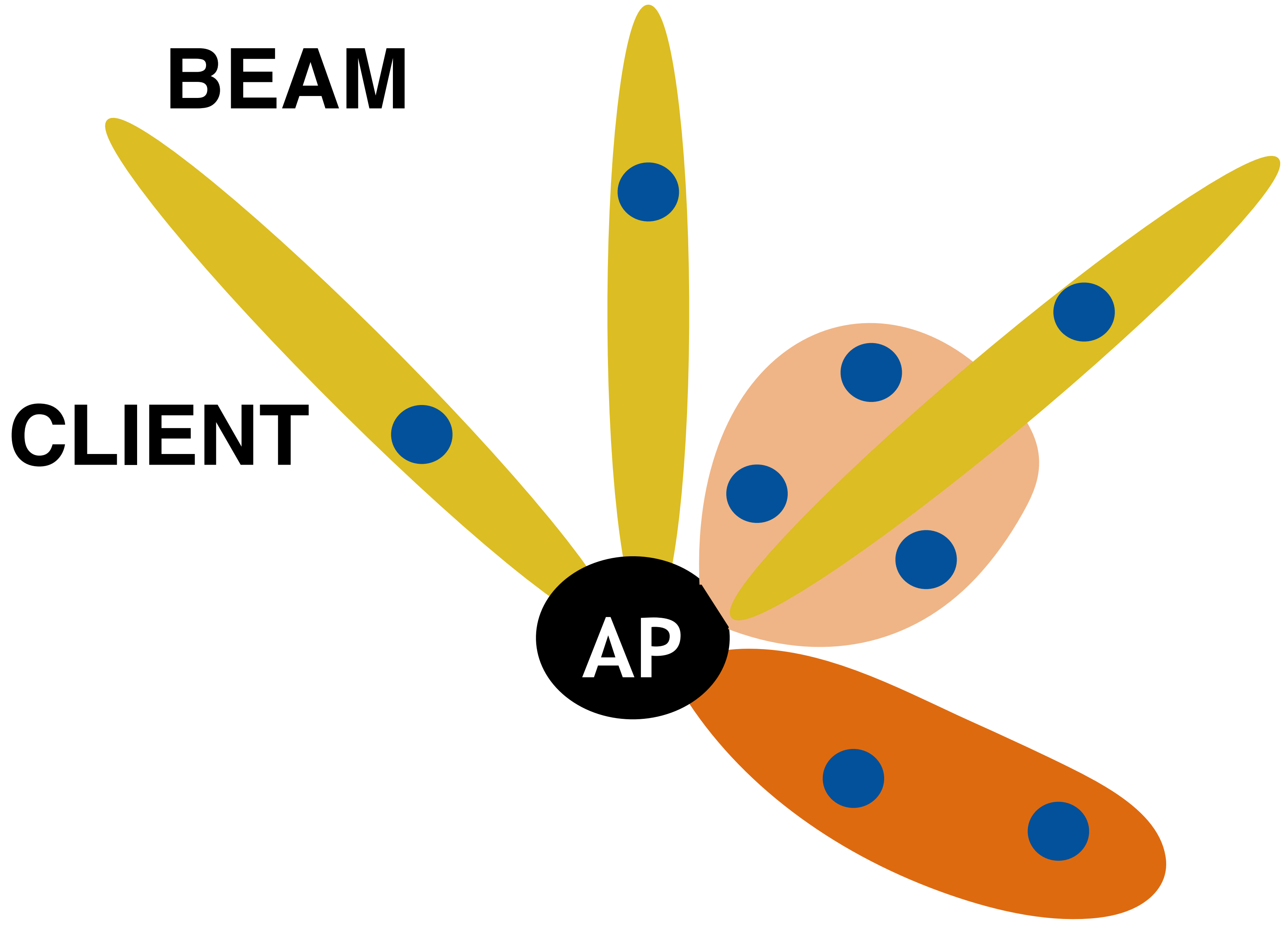


Uni-directional downlink channel

Thesis Contributions

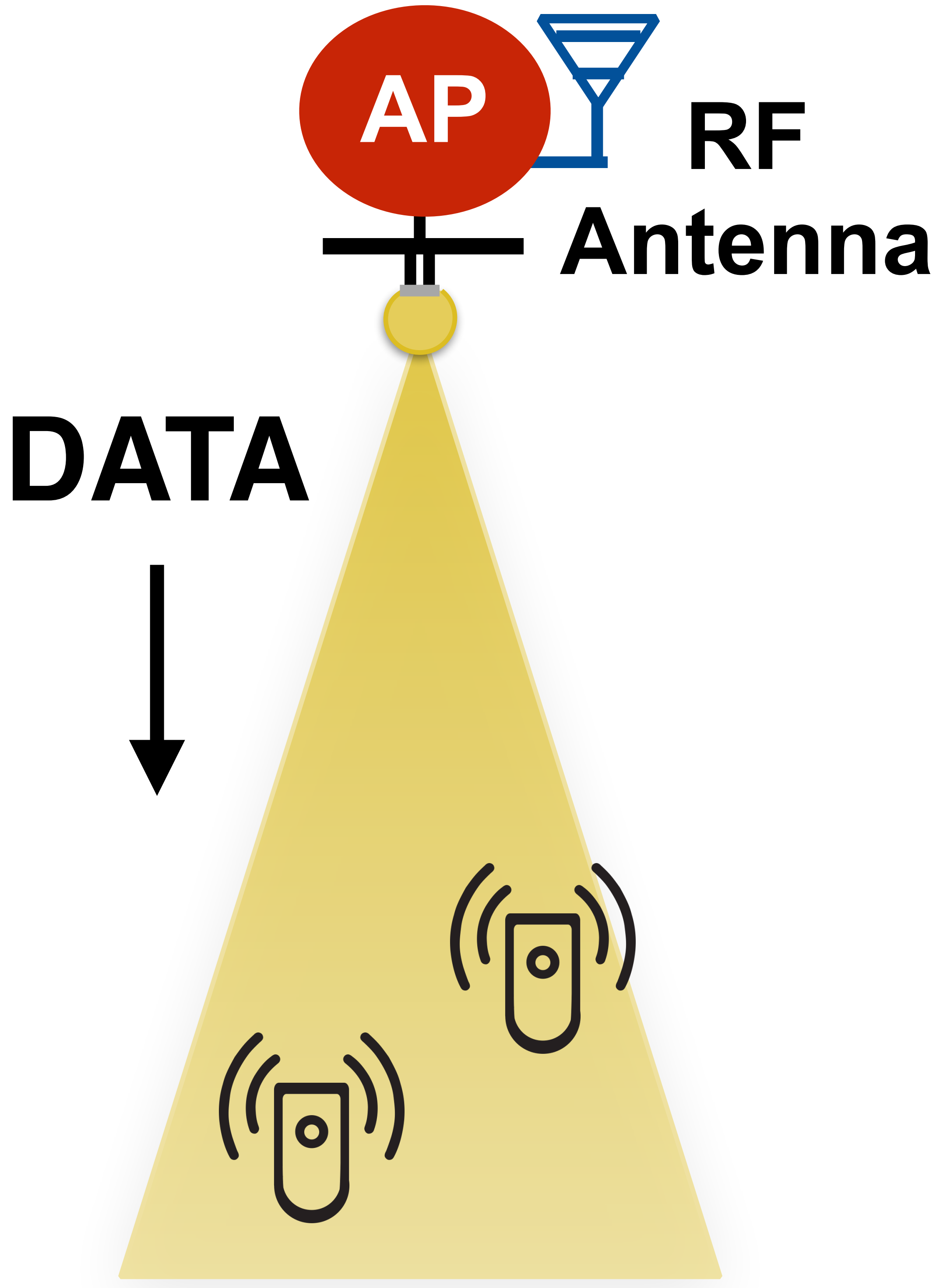
60 GHz

Scalable Directional Multicast

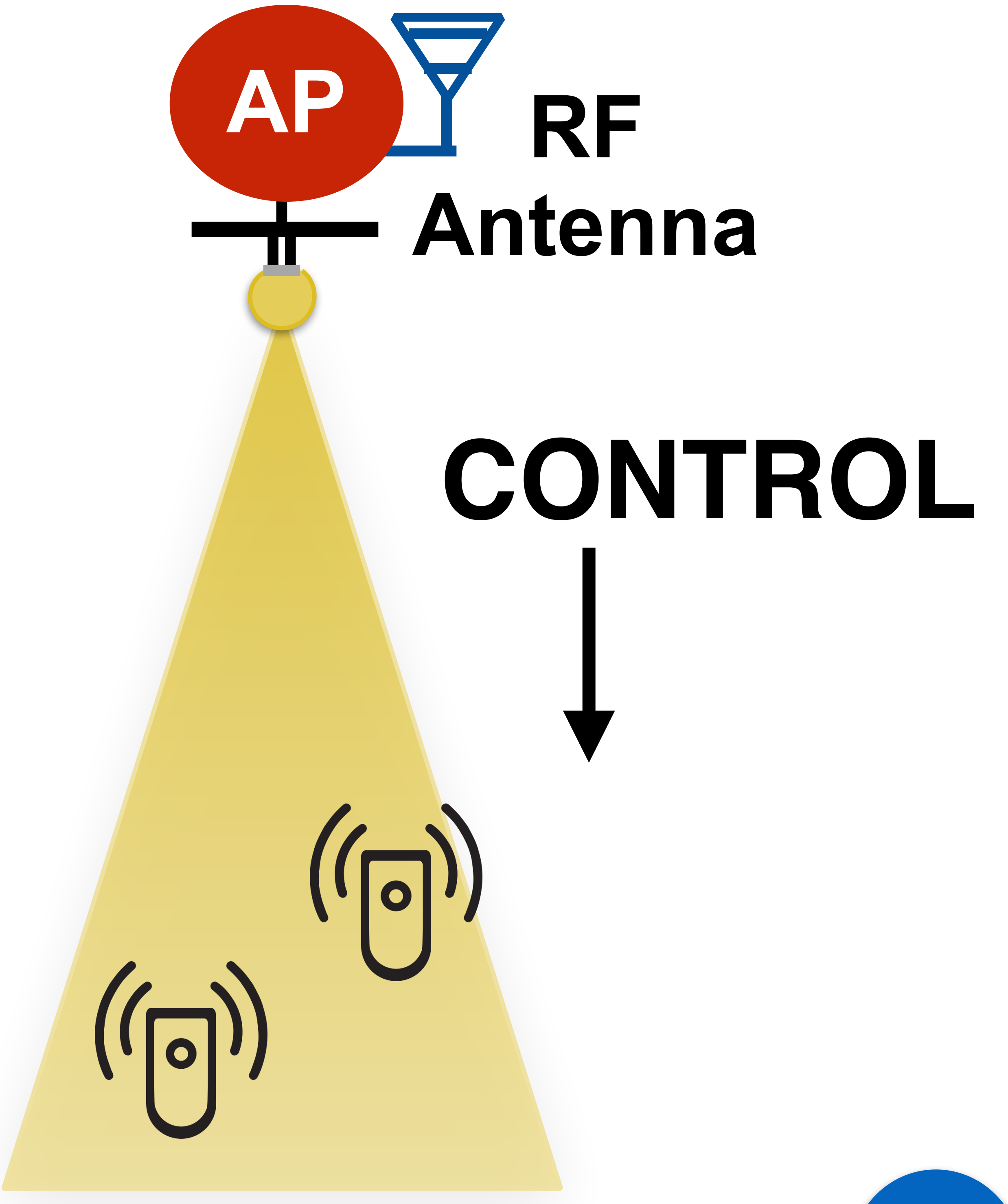


Visible Light

LiRa



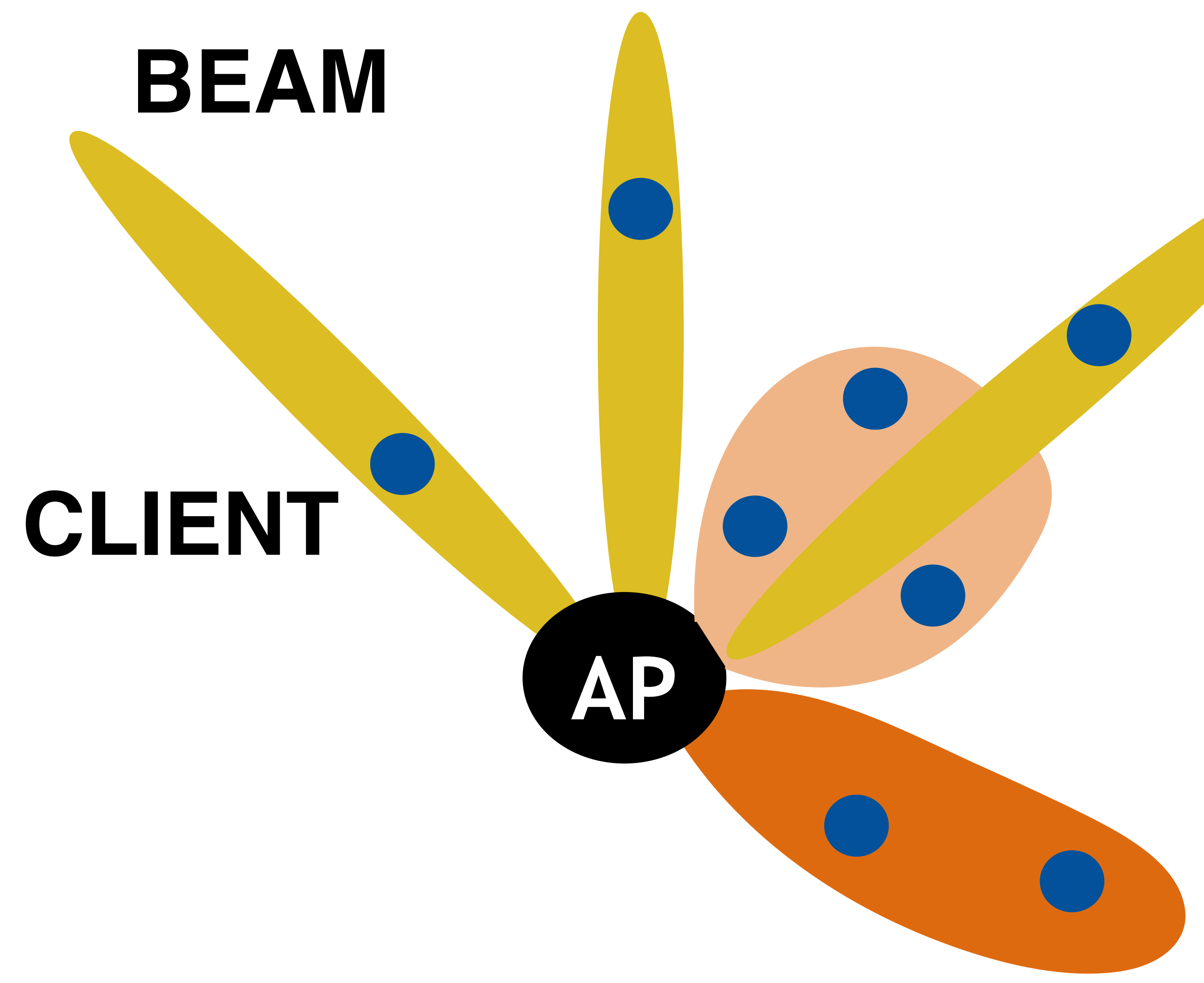
LiSCAN



Thesis Contributions

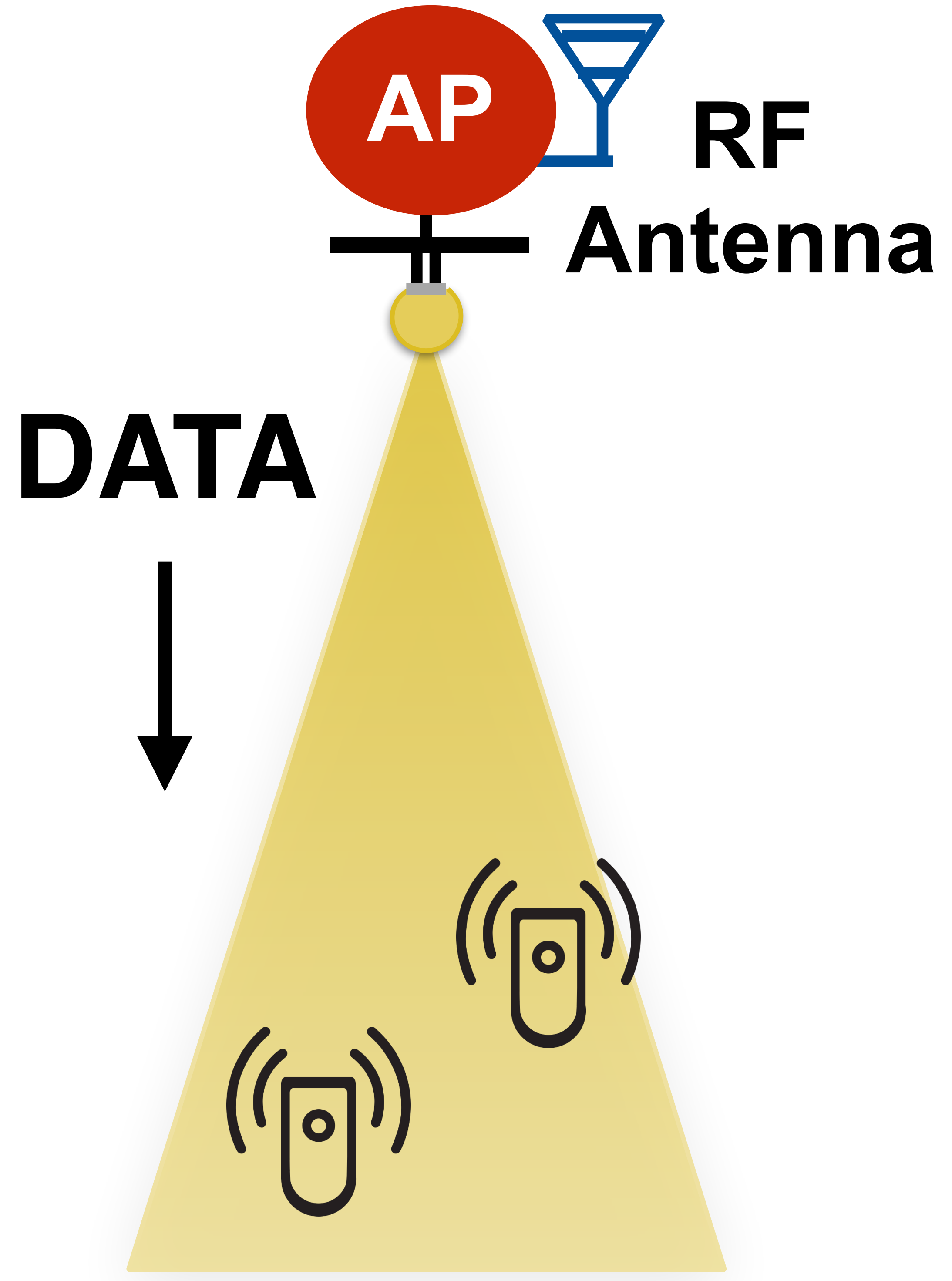
60 GHz

Scalable Directional Multicast

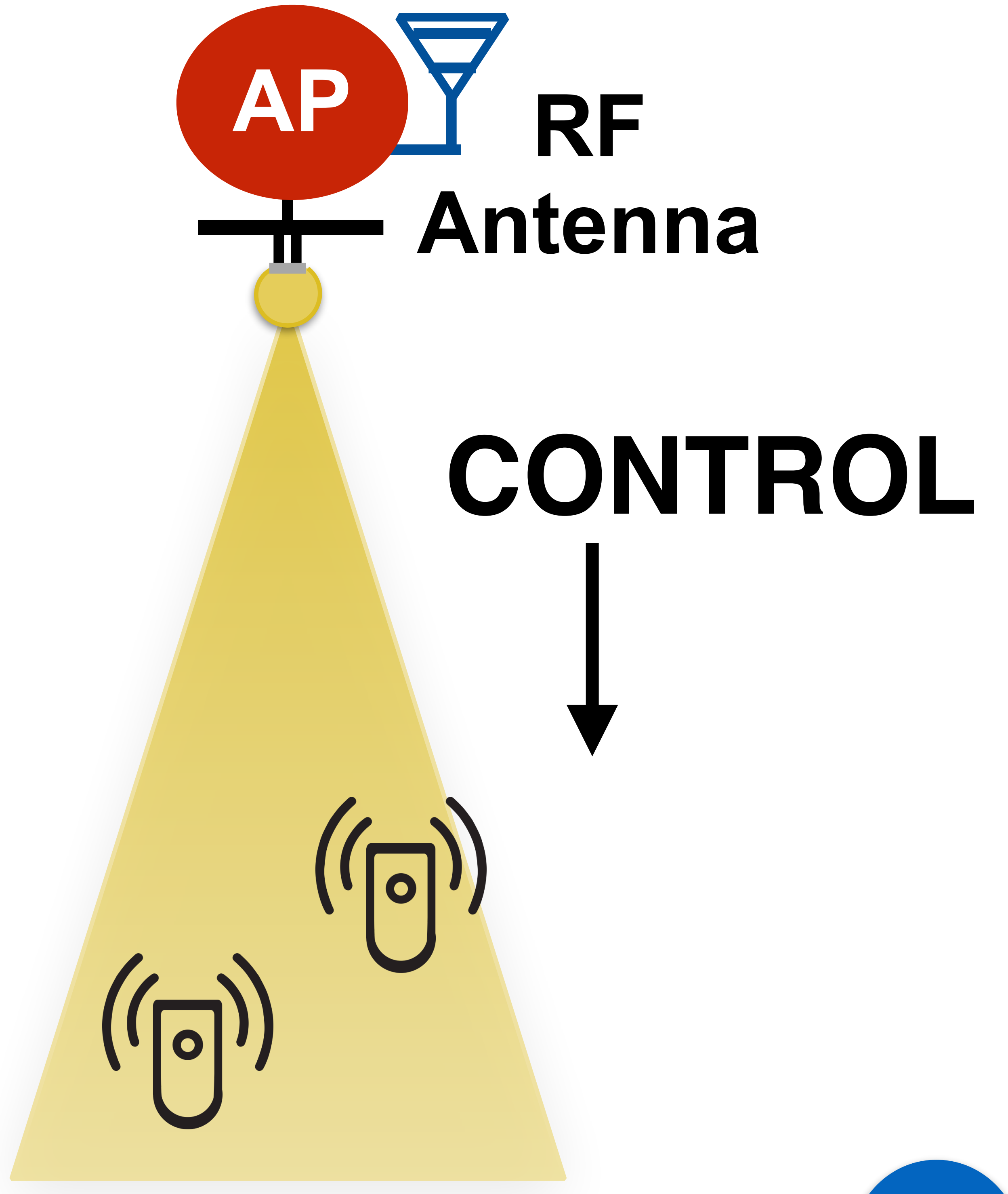


Visible Light

LiRa



LiSCAN



S. Naribole and E. Knightly, "Scalable Multicast in Highly-Directional 60 GHz WLANs," *IEEE/ACM Transactions on Networking*, October 2017.

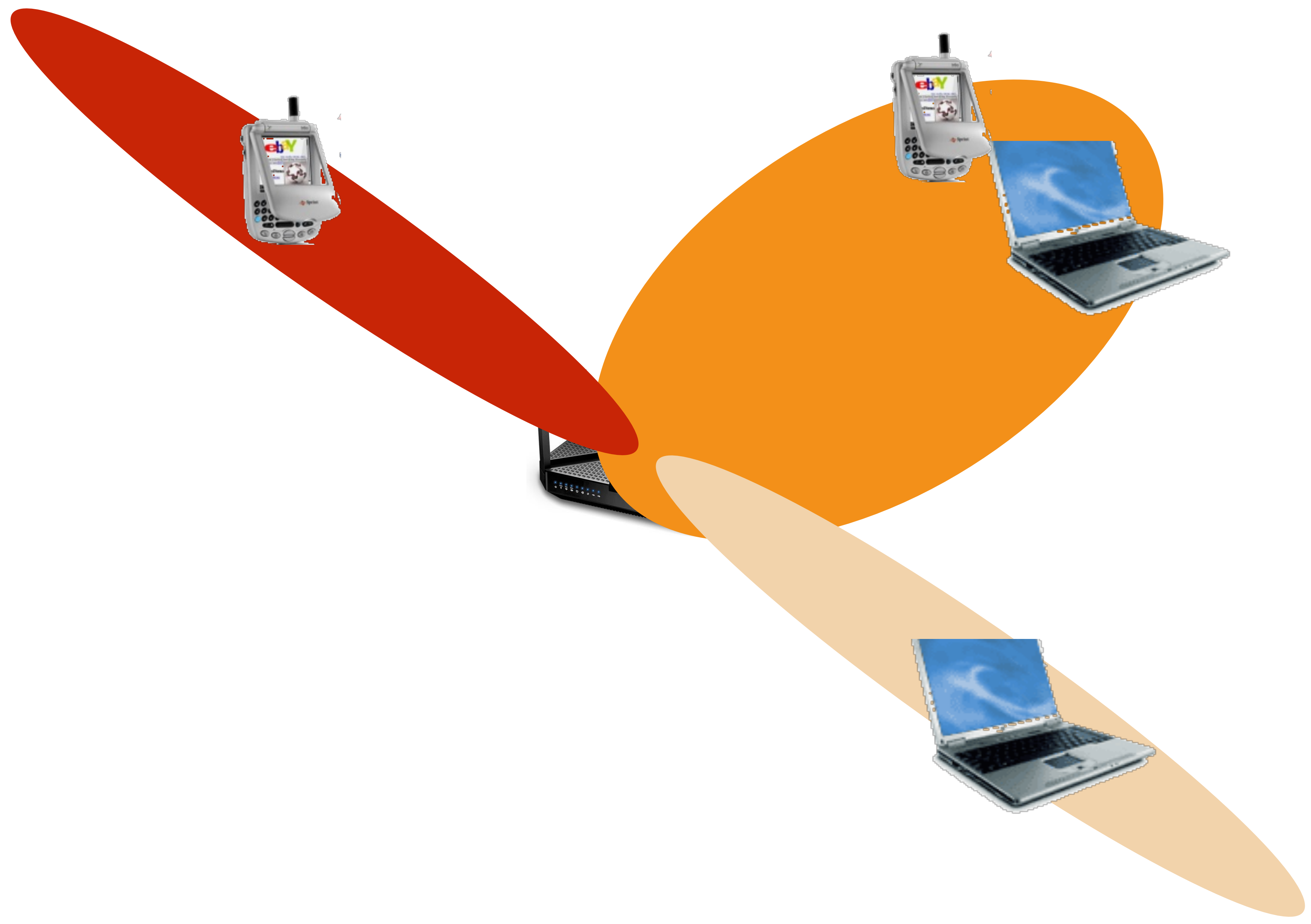
60 GHz System Model

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

- **Switched Beam**
  - Sequential transmission to cover all clients
  - TX time proportional to multicast group size

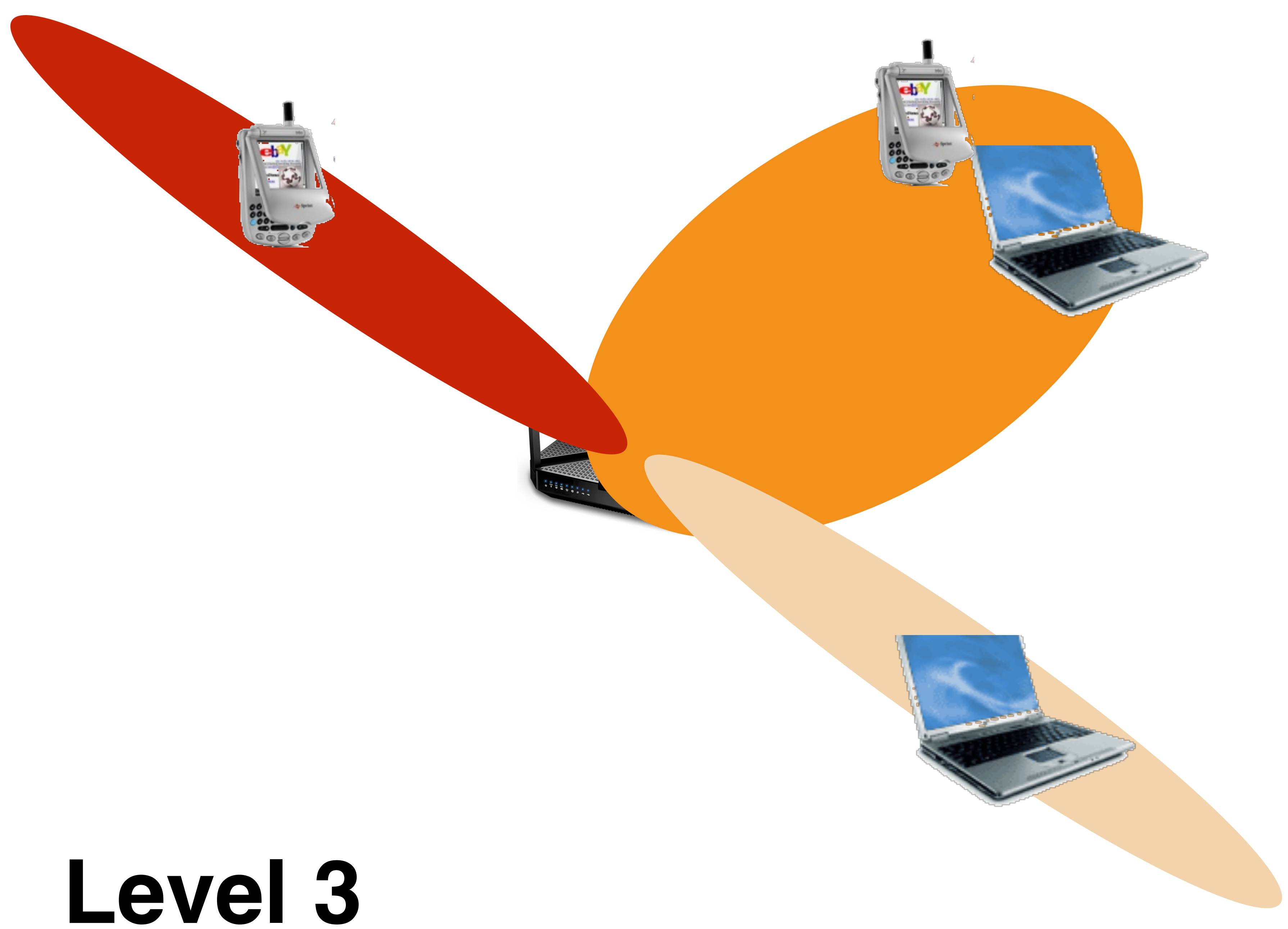
Multi-Level Codebook at AP

- **Multi-level Beams**
  - Was not required for unicast transmissions
  - Flexibility to cover multiple clients simultaneously

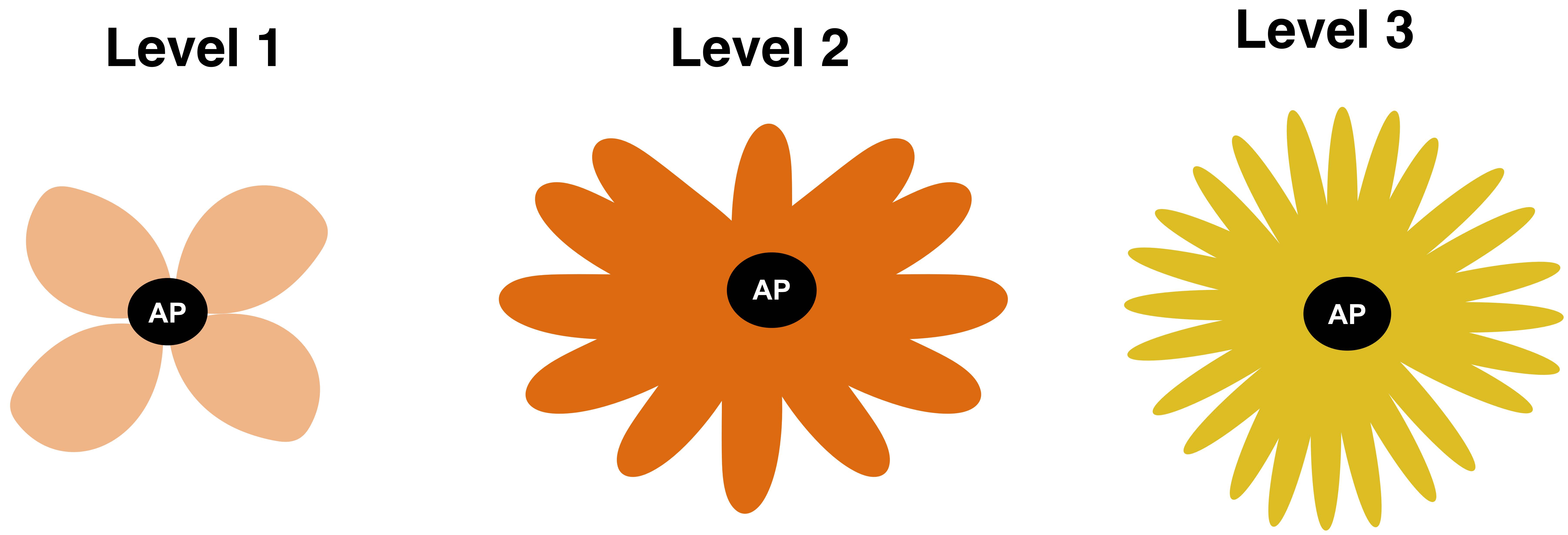


Multi-Level Codebook at AP

- **Multi-level Beams**
  - Was not required for unicast transmissions
  - Flexibility to cover multiple clients simultaneously



- **Multi-level Codebook at AP**
  - Codeword corresponds to specific beam pattern
  - Each level corresponds to specific beamwidth



Minimizing Total Transmission Time

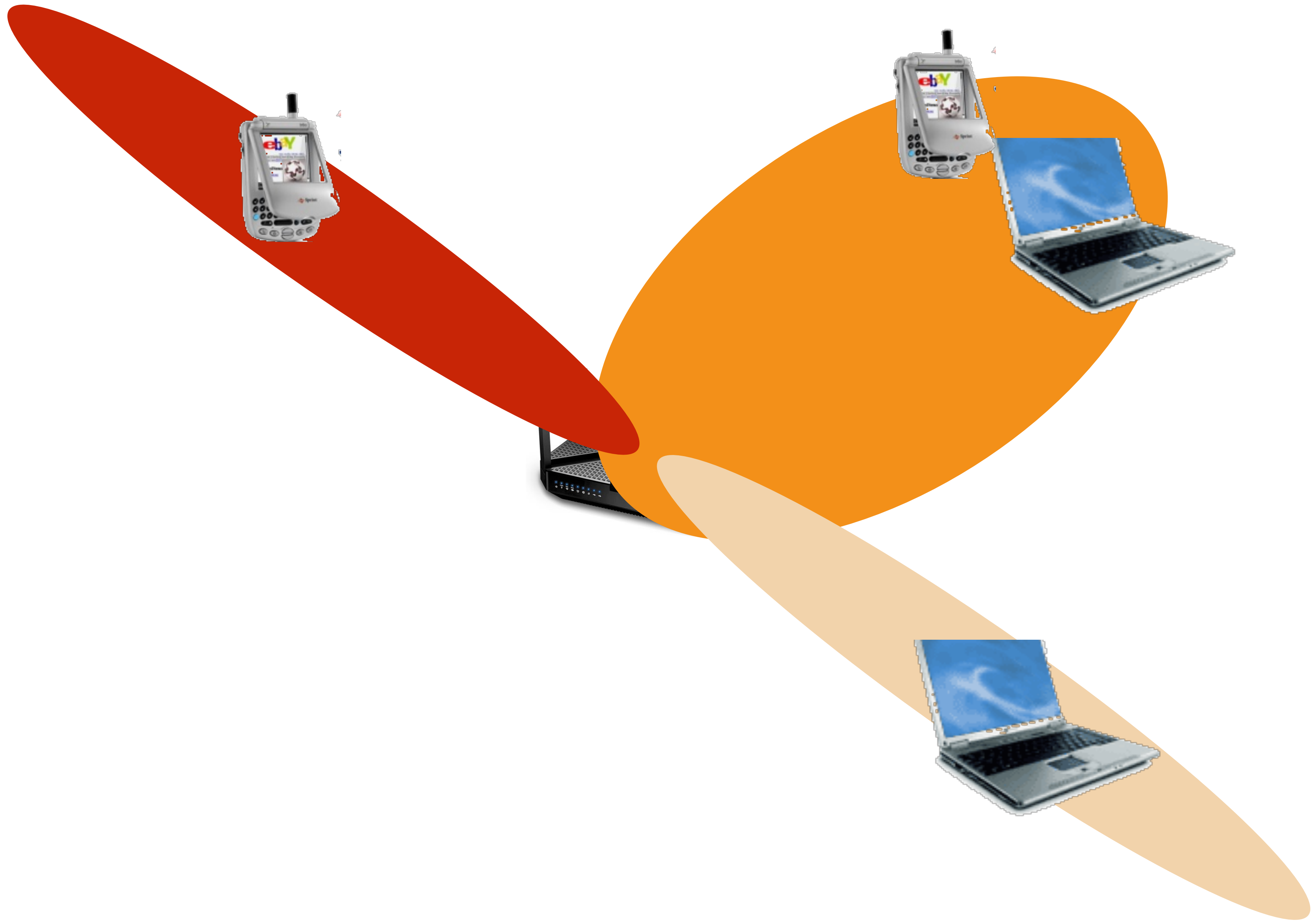
- **Servable set $C_{th}(\psi)$** for beam ψ
  - Client subset with power measure $\geq P_{min}$
- **Beam Group solution** $\{\psi_1, \psi_2, \ldots, \psi_B\}$
  - Client subset vector $\{S(\psi_1), \ldots, S(\psi_B)\}$
  - MCS vector $\{R(\psi_1), \ldots, R(\psi_B)\}$

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

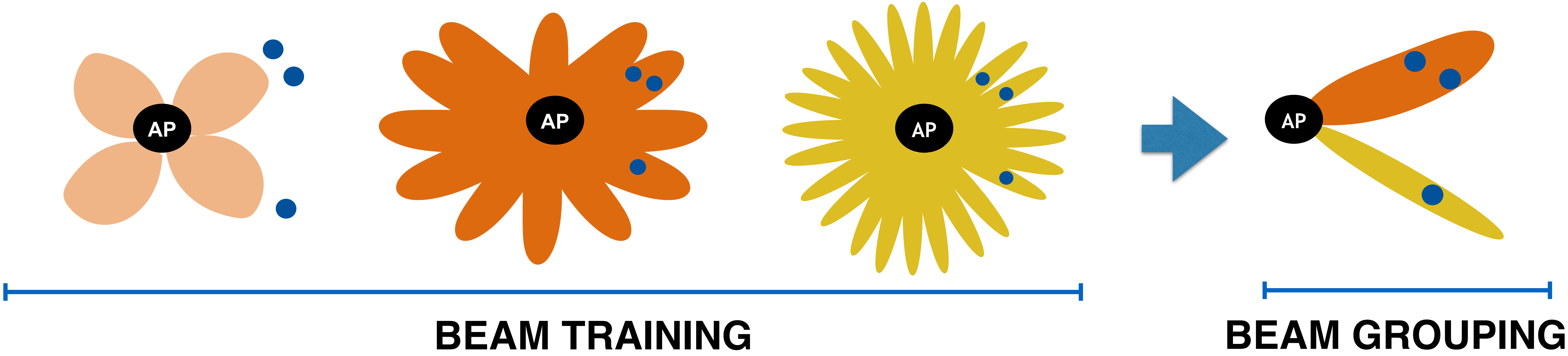
$$\text{s.t.} \bigcup_{b=1}^{B} S(\psi_b) = \mathbb{U}$$

Multicast client set

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



Overhead

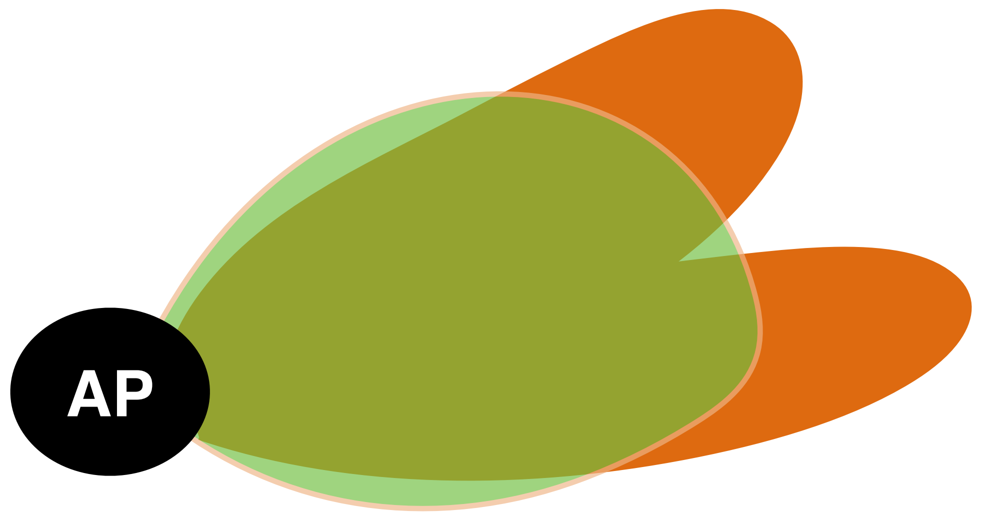


- **Exhaustive Beam Training**
  - $O(KN + c^{K})$
- **Exhaustive Beam Grouping**
  - $O(c^{K-1} N^{N/2 + 1})$

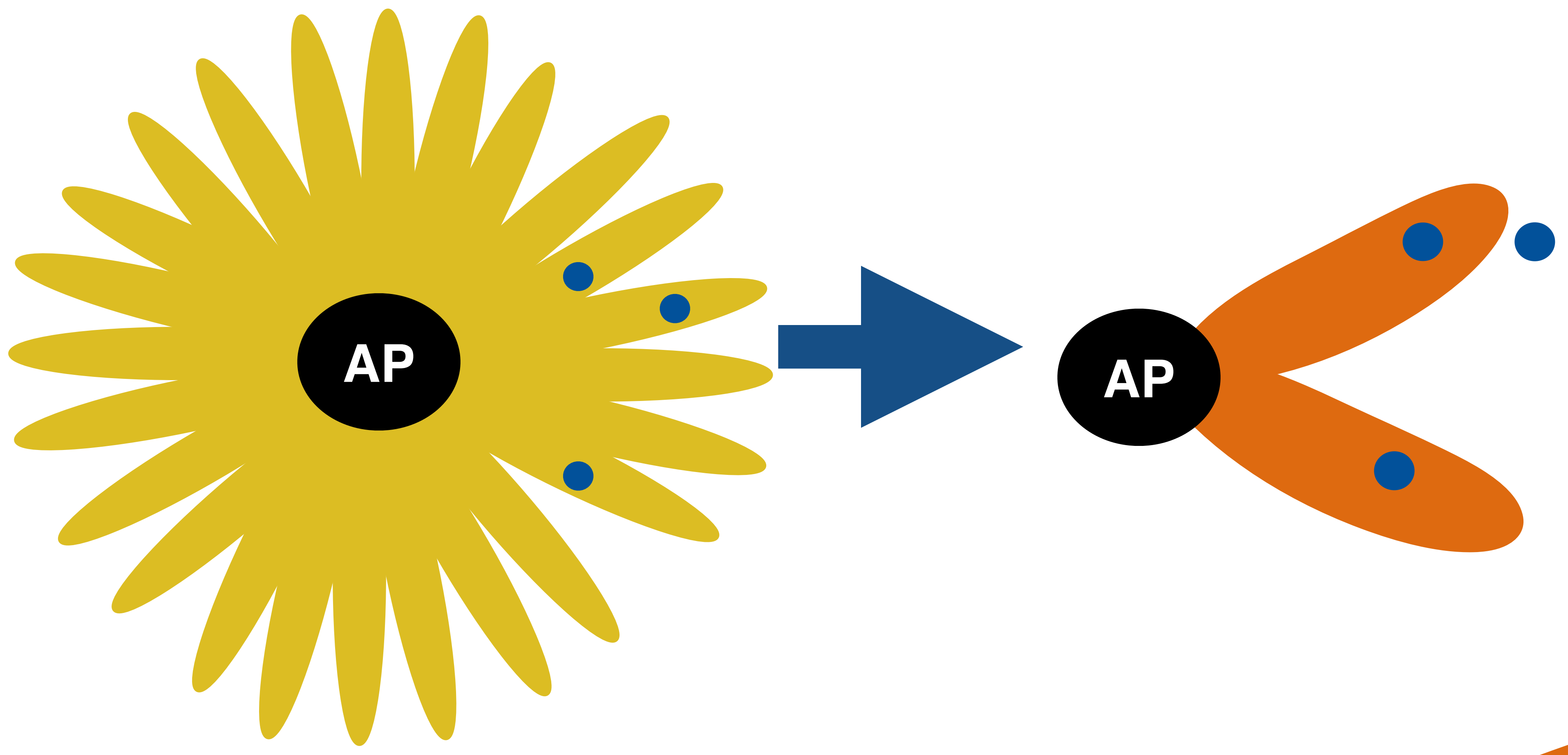
K = No. of beamwidth levels
N = multicast group size
c = No. of fine beams / No. of wide beams

SDM Design Overview

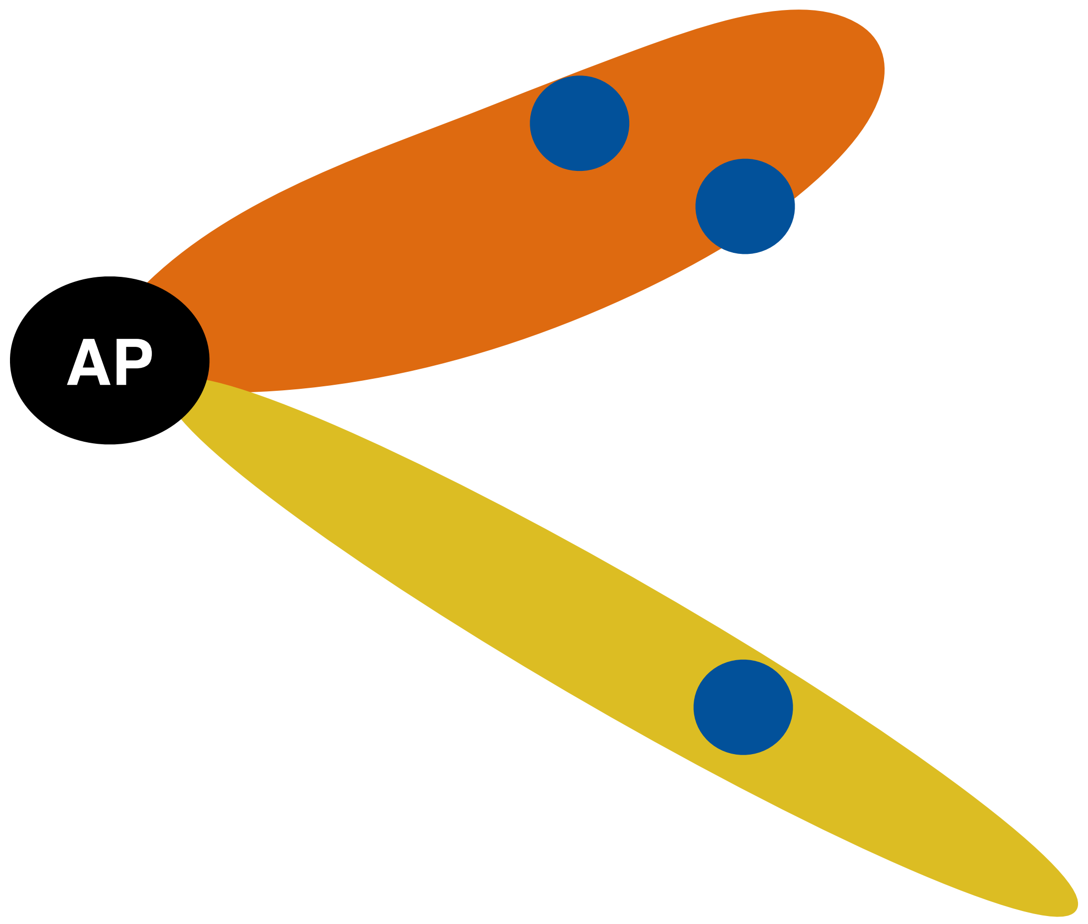
- **Multi-level Codebook Trees**
  - Prune the codebook traversal leveraging client feedback



- **Descending Order Traversal**
  - Begin training at finest beam level
  - Overhead O(KN)



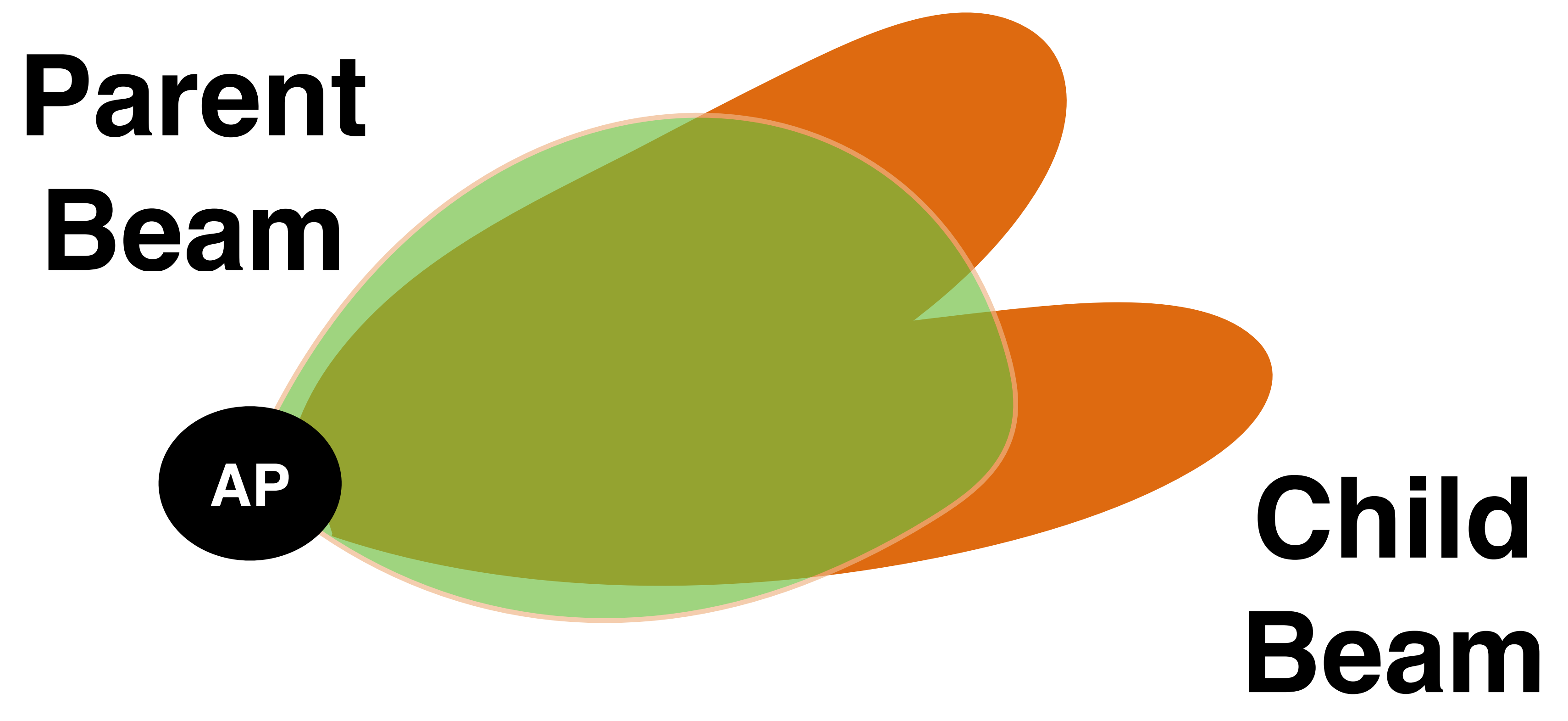
- **Wide Beam Improvement Ratio**
  - Improvement in TX time over an only finest beams solution
  - Complexity $O(KN^3)$

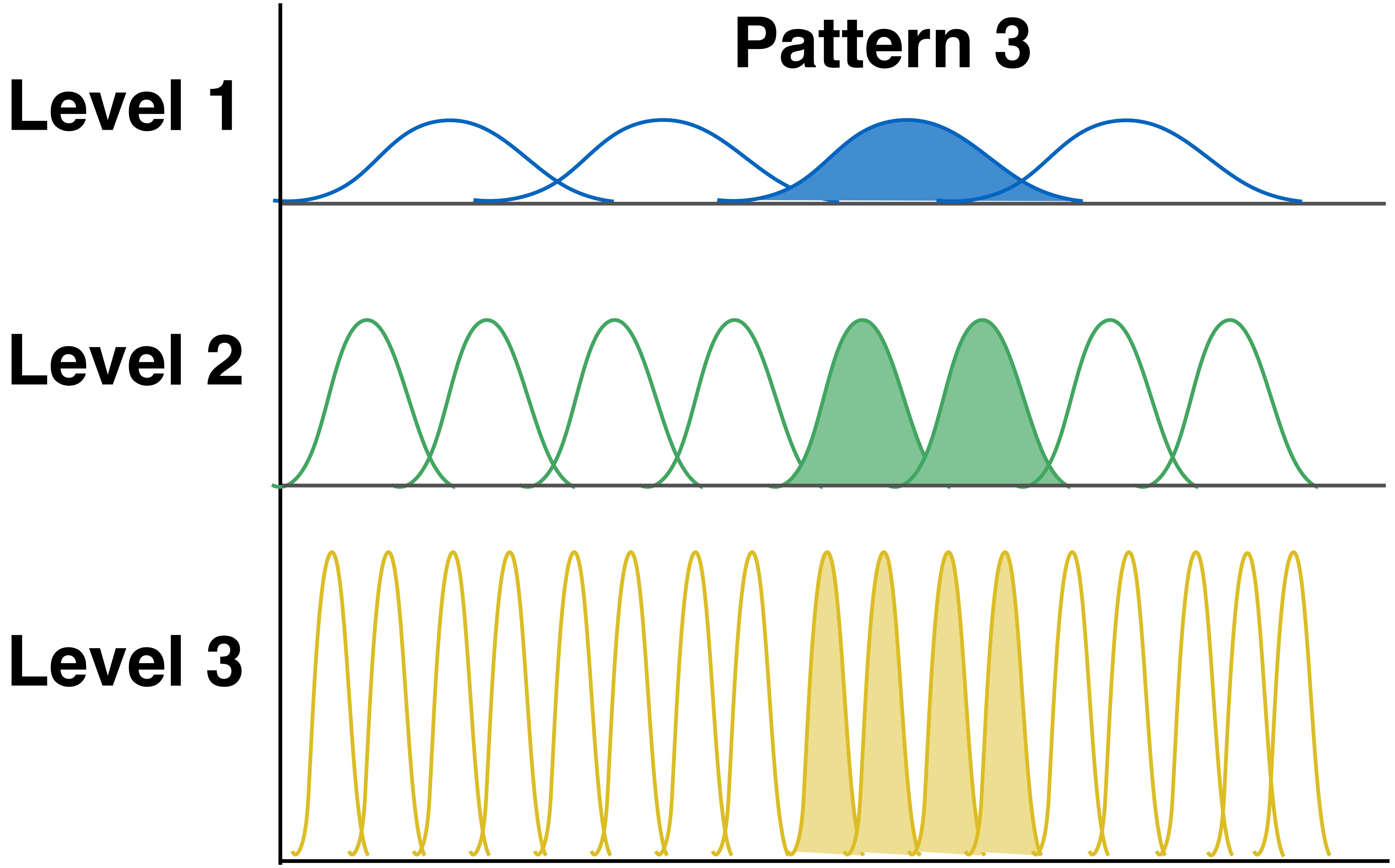


K = No. of beamwidth levels, N = multicast group size

Multi-Level Codebook Trees

- **Codebook Trees [1,2]**
  - Leverage client feedback to prune the training
  - Edges between beam patterns of adjacent levels



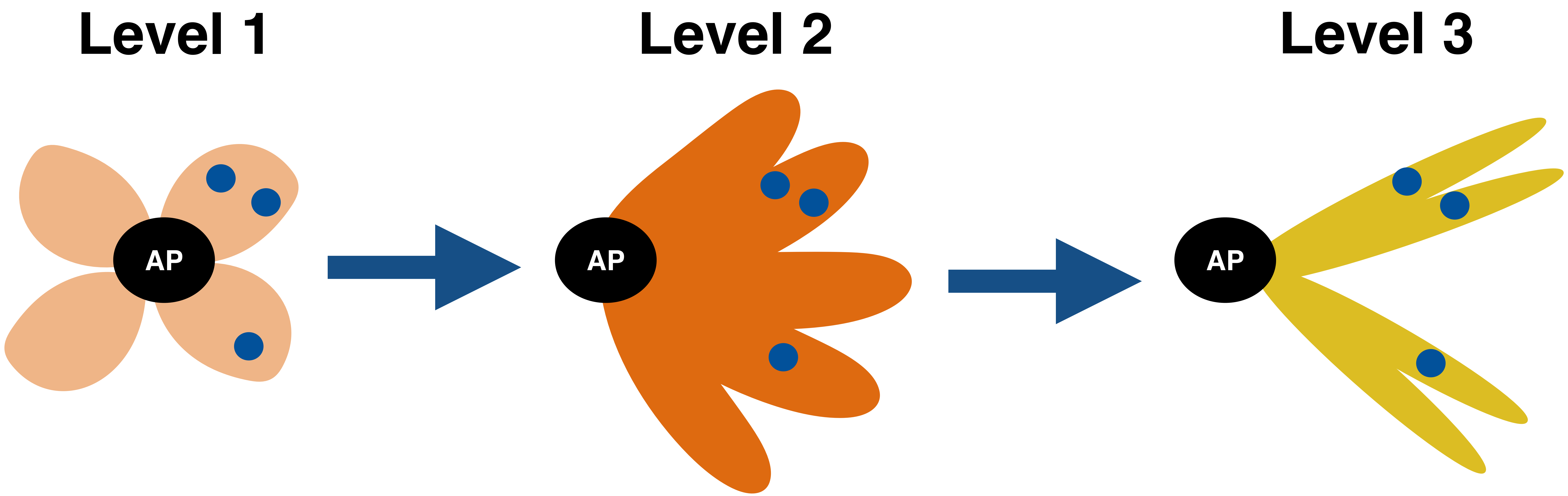


[1] Lee at al. , "Low Complexity Codebook-Based Beam- forming for MIMO-OFDM Systems in Millimeter-Wave WPAN," *IEEE Transactions on Wireless Communications*, Nov 2011.

[2] Hur et al. , "Multilevel millimeter wave beamforming for wireless backhaul," in *Proc. of IEEE GLOBECOM*, 2011.

Basic Codebook Traversal

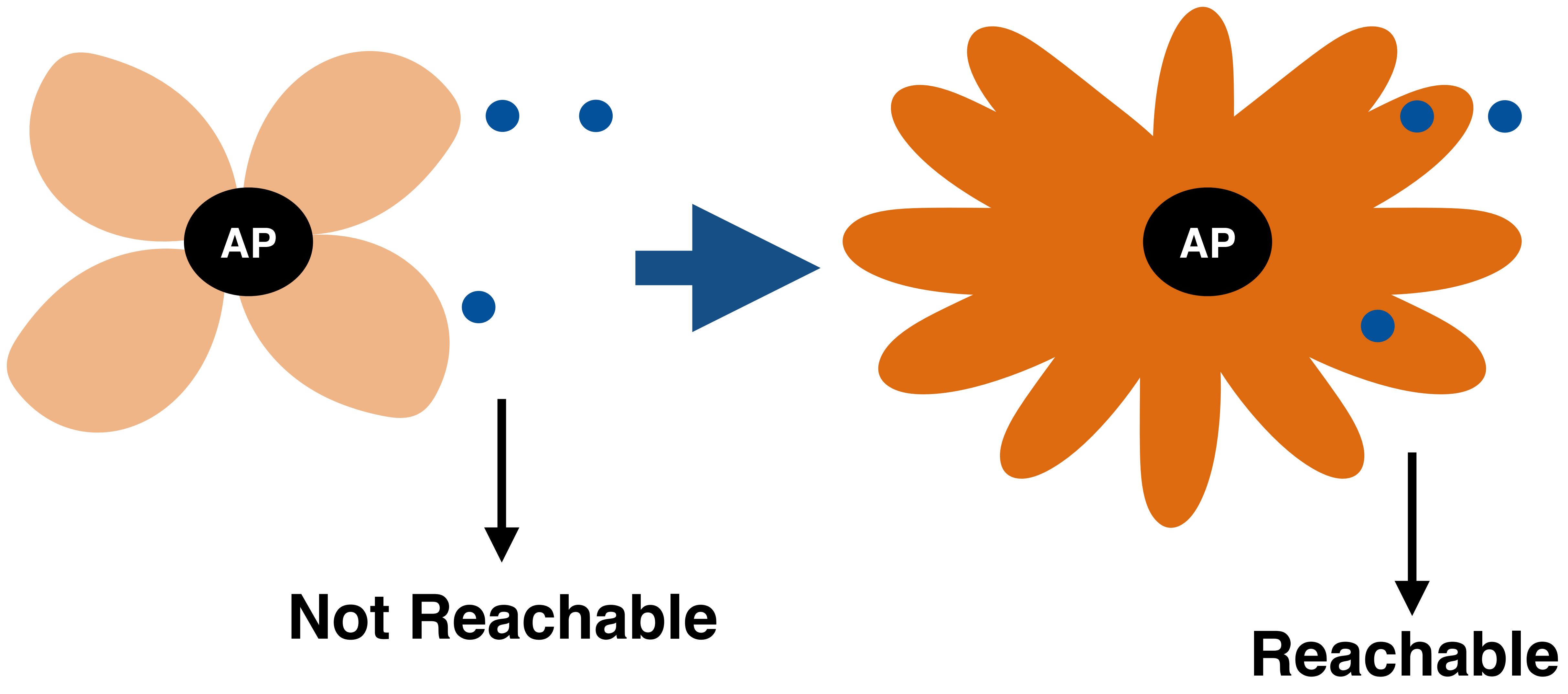
- **Minimal Training**



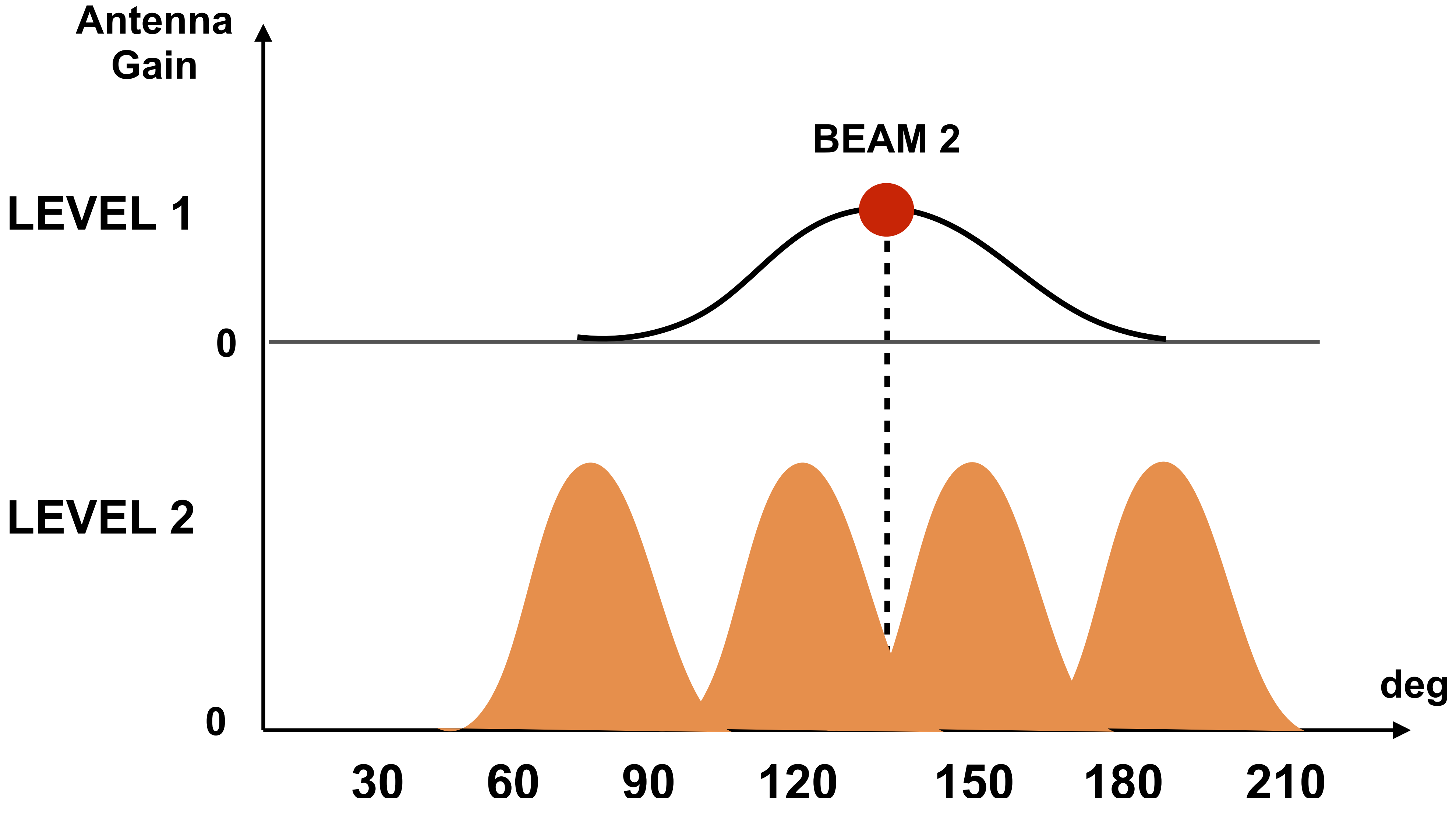
- **Client Feedback**
  - RSSI power measure vector for the beam patterns received
- **Ideal condition**
  - Best beam at any level for each client matches with exhaustive training

Multi-Level Codebook Challenges

- **Unreachability**
  - Client not reachable at every level
  - Falls back to exhaustive training



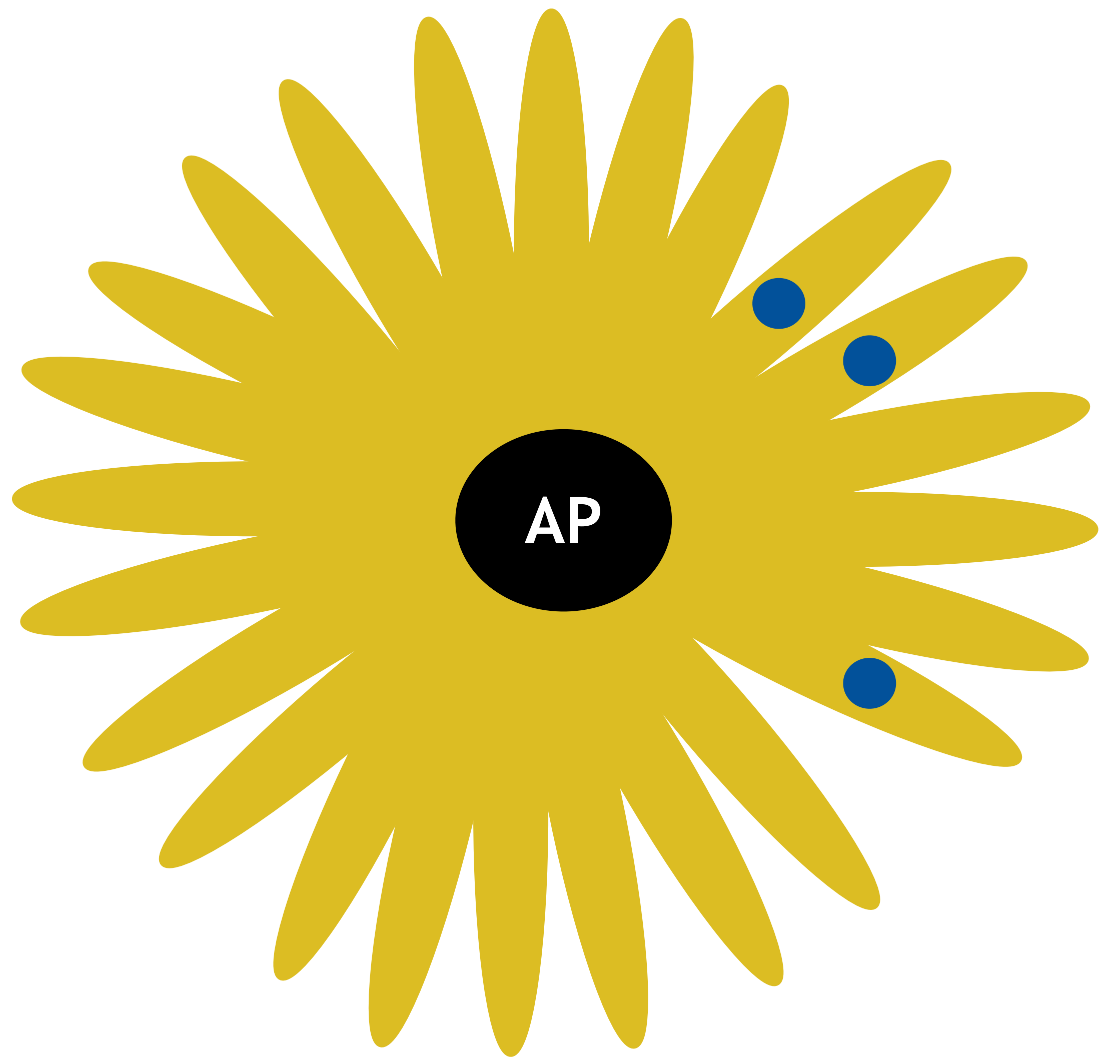
- **Imperfect Codebook traversal**
  - AP’s codebook independent of deployment
  - Reflectors/ blockage



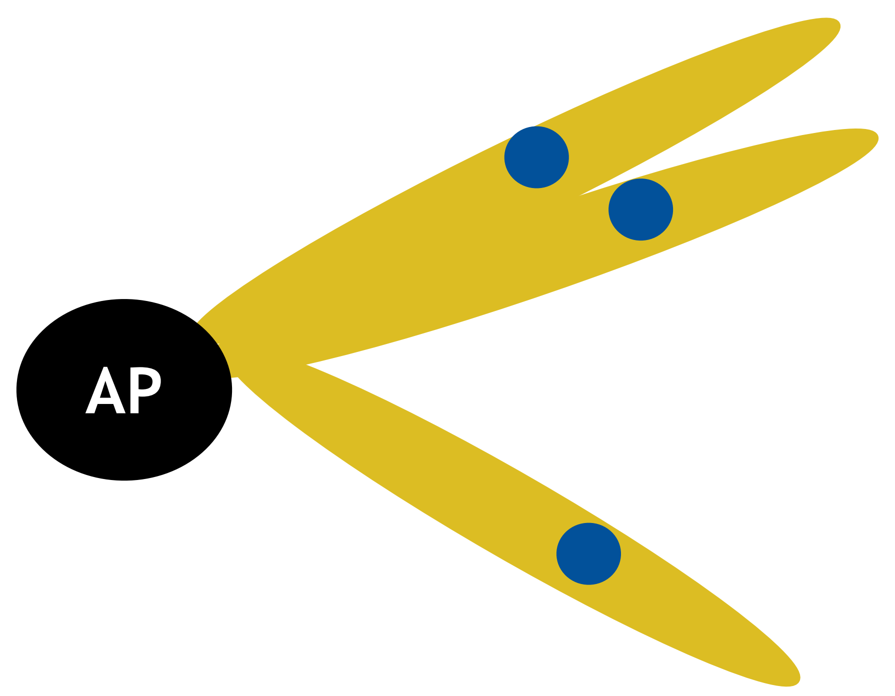
SDM's Finest Beam Training

- Exhaustive training with all the finest level beams
- Solves unreachability challenge
- Ensures at least one high directivity beam for data transmission

TRAINING



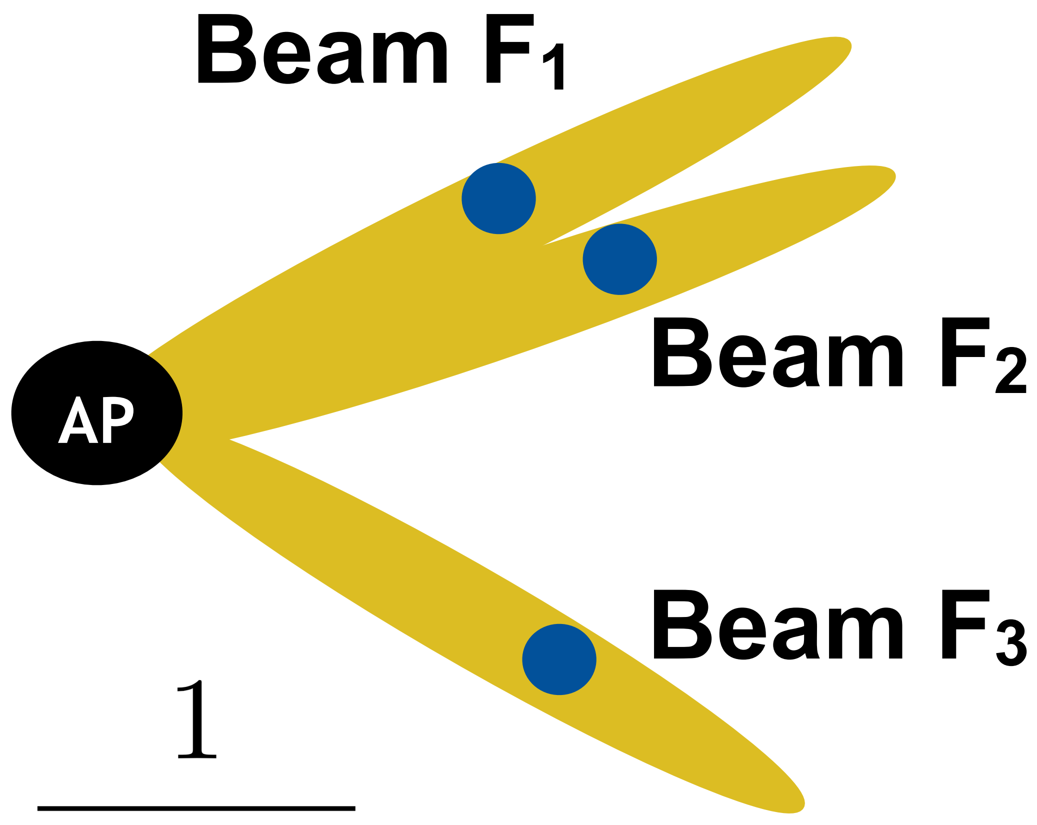
INITIAL SOLUTION



Scalable Training Overhead O(KN)

K = No. of beamwidth levels, N = multicast group size

SDM's Beam Group Selection

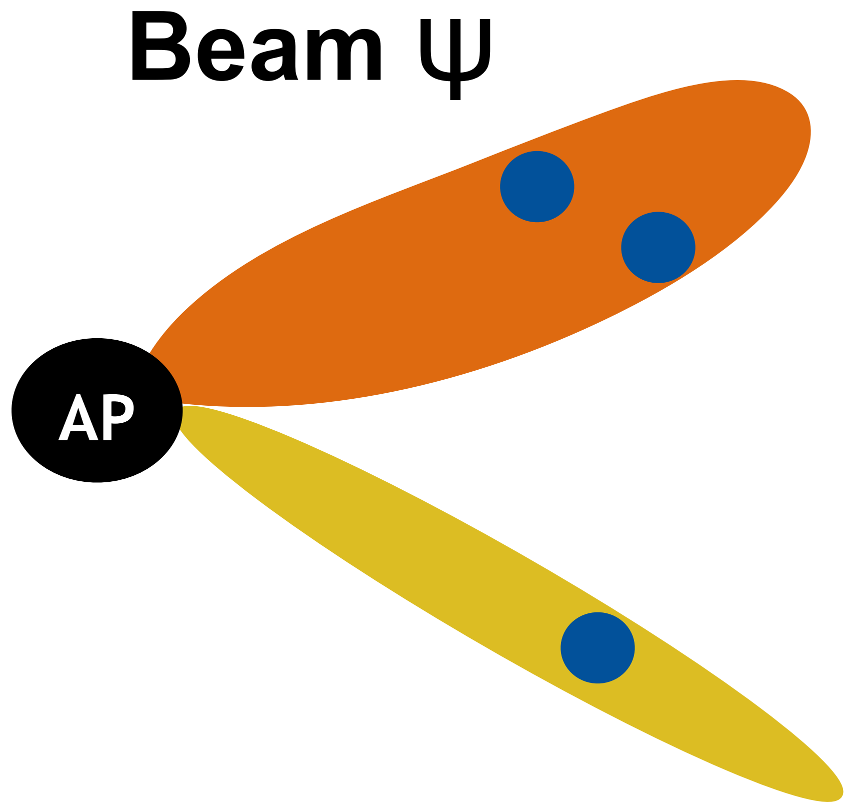


- **Wide Beam Improvement**
  - Not every wide beam improves (Beamwidth-MCS tradeoff)
  - Rate determined by client with lowest power measure

- **Wide Beam Improvement Ratio (WIR)**
  - Replace initial solution with a single wide beam

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

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

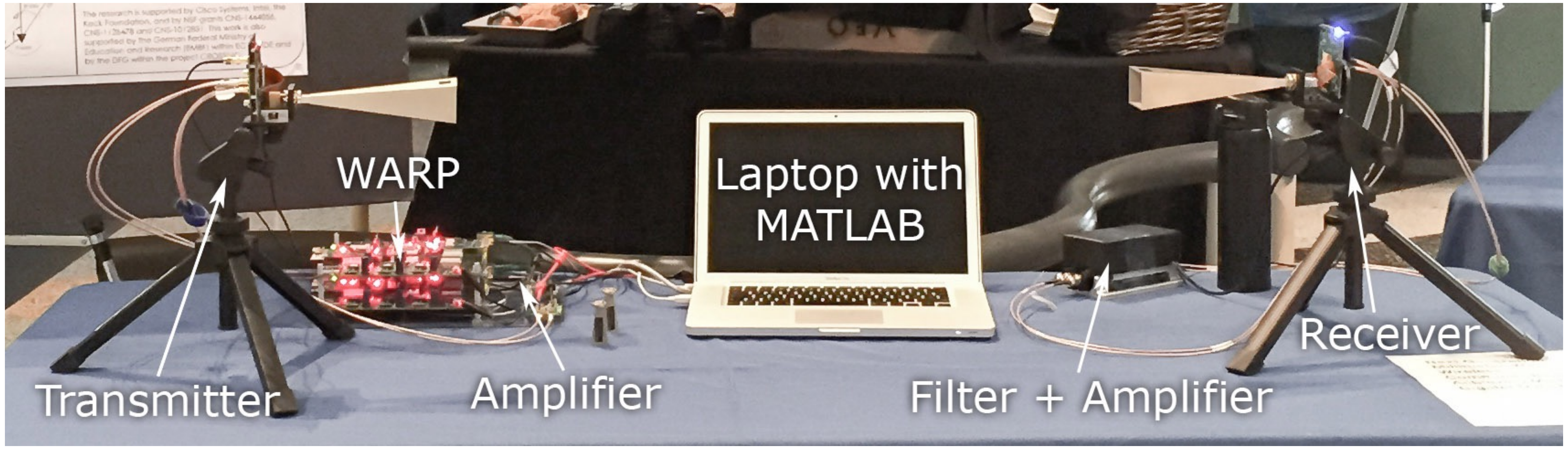


- **Final Beam Grouping Solution**
  - Descending order traversal of wide beams with WIR > 1

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

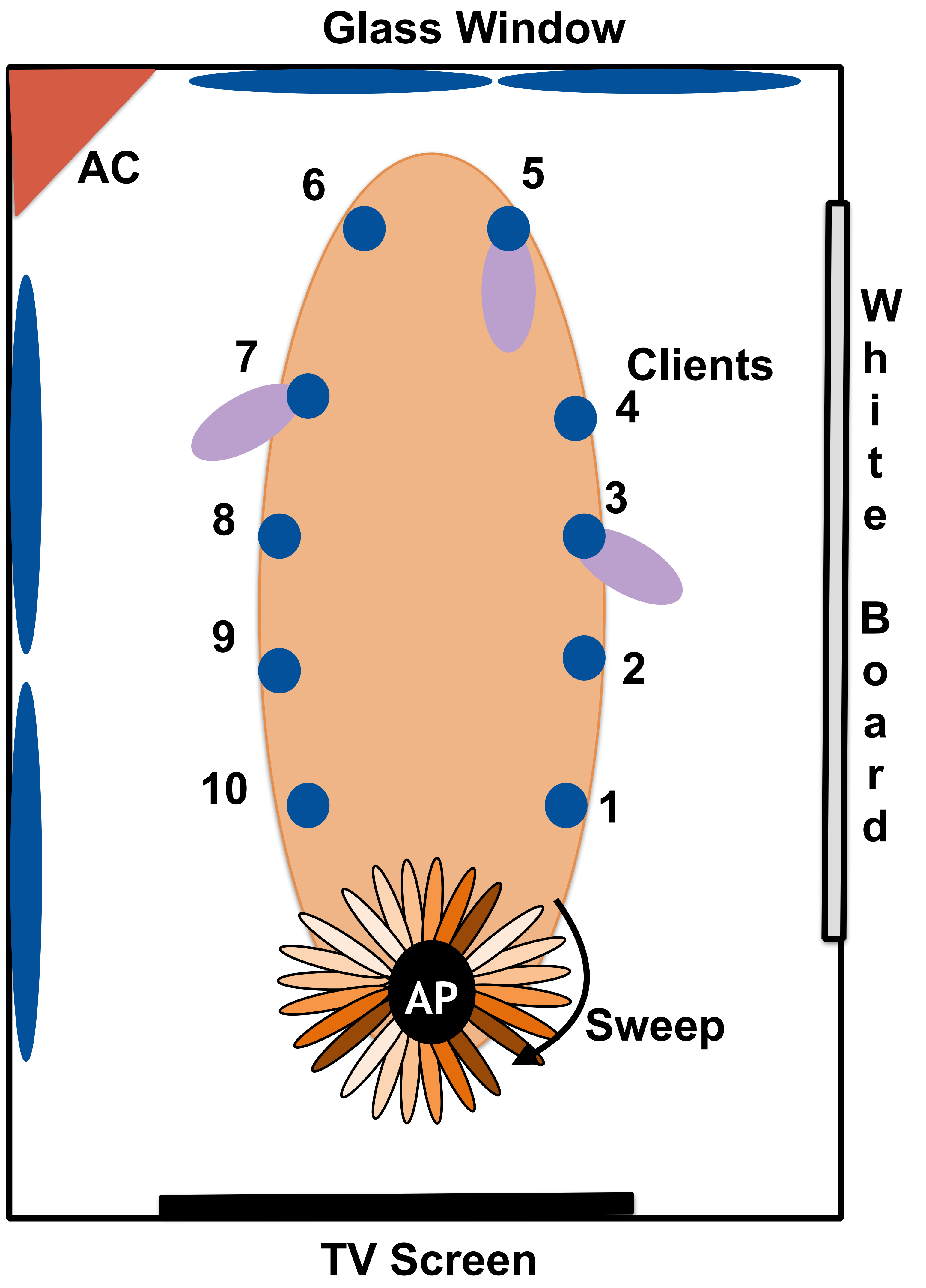
K = No. of beamwidth levels, N = multicast group size

SDM Implementation



- **Measurement Setup**
  - Horn antennas to emulate codebook levels at AP
  - Multiple 5-level codebook trees

- **60 GHz WLAN trace-driven emulator**
  - 802.11ad packet sizes and timings



Experimental Evaluation

Practical Codebook Traversal Challenge

Training Overhead

Beam Grouping Efficiency

Beam Grouping Complexity

Throughput

Experimental Evaluation

Practical Codebook Traversal Challenge

Training Overhead

Beam Grouping Efficiency

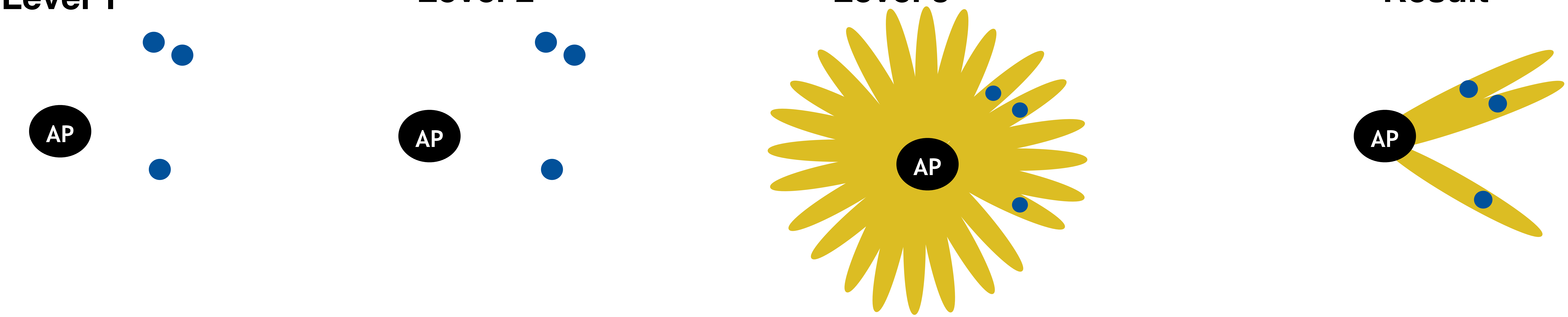
Beam Grouping Complexity

Throughput

Baseline Strategies

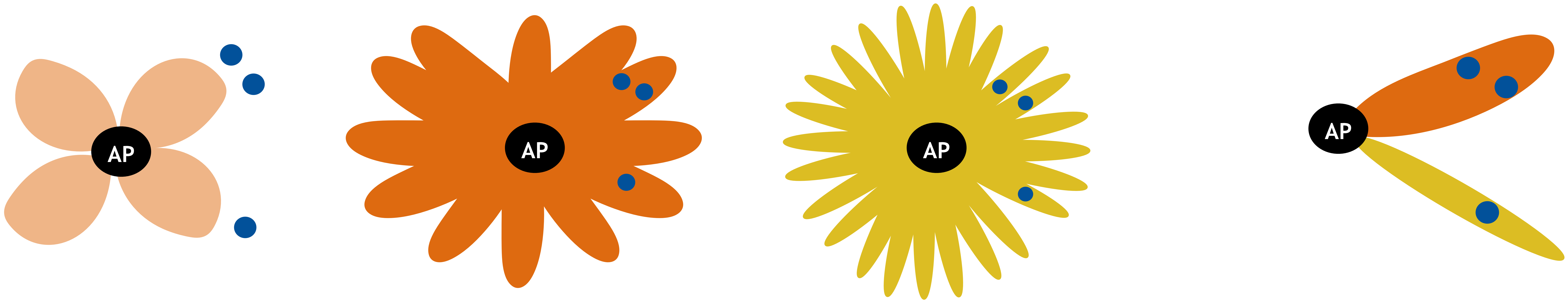
Only Finest Beams strategy : individual narrow beams to each client

Level 1 **Level 2** **Level 3** **Result**



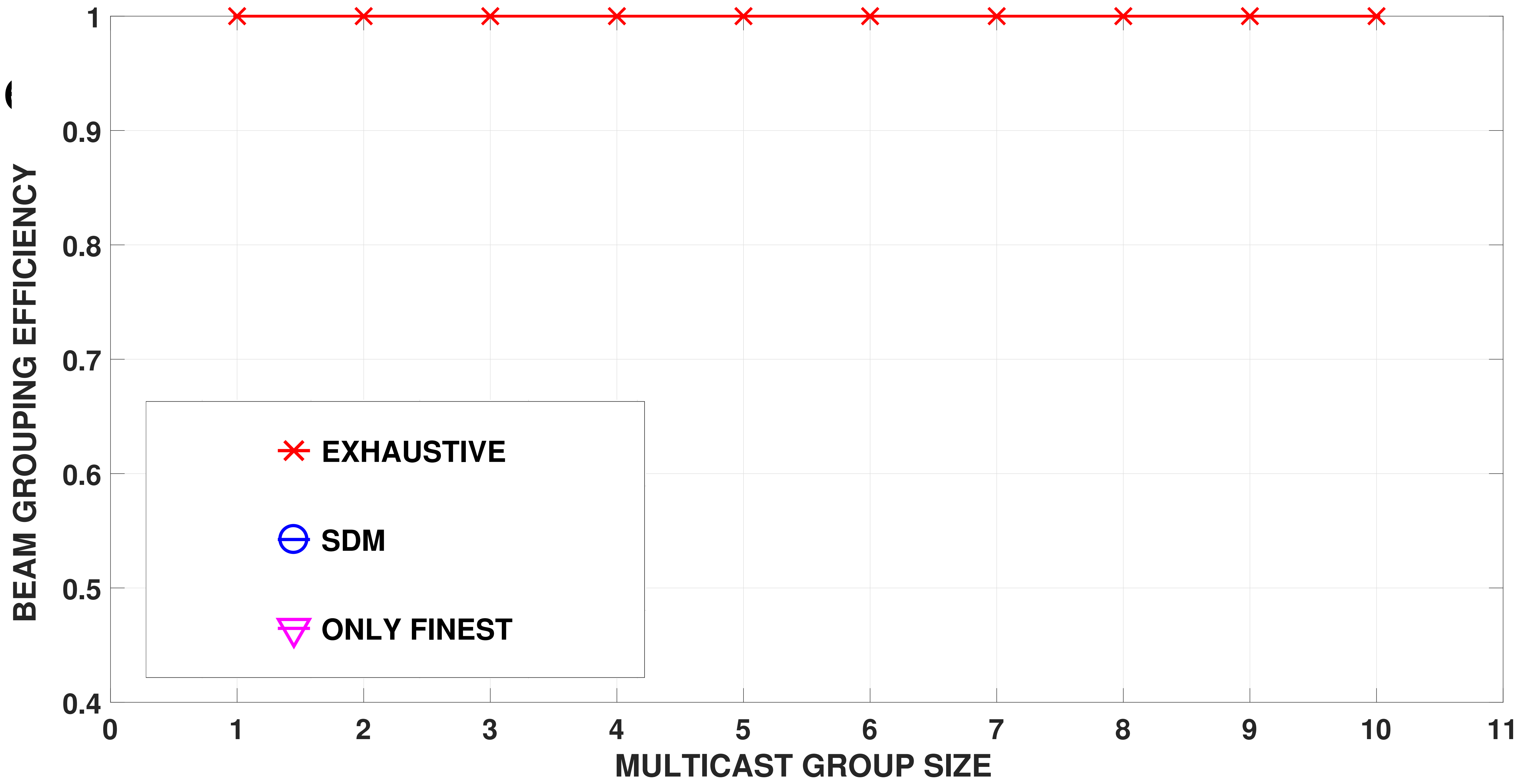
Exhaustive: Exhaustive training and optimal beam grouping

Level 1 **Level 2** **Level 3** **Result**



Beam Grouping Efficiency

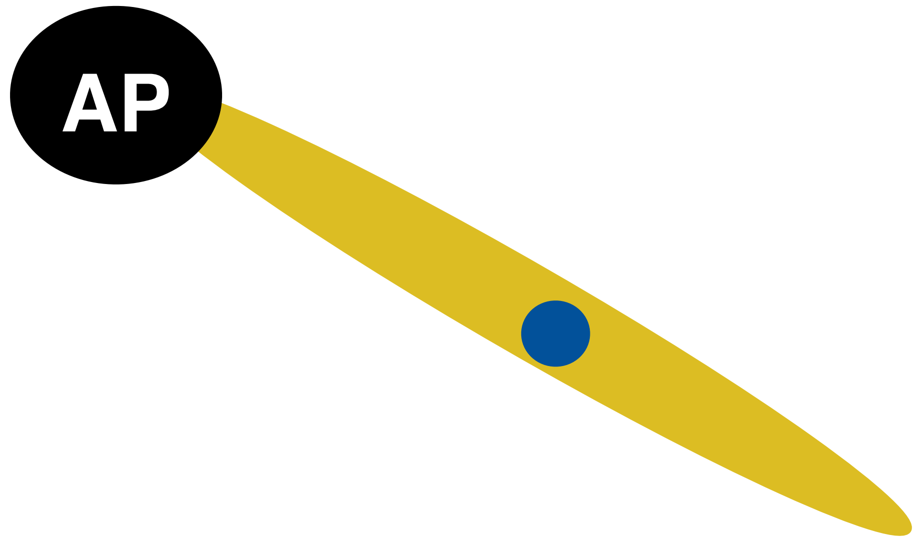
- **Experiment Setup**
  - Only data transmission
  - Training and grouping already done
- **Data Sweep Time ($T_{per\text{-}sweep}$)**
  - Time to transmit one bit of data

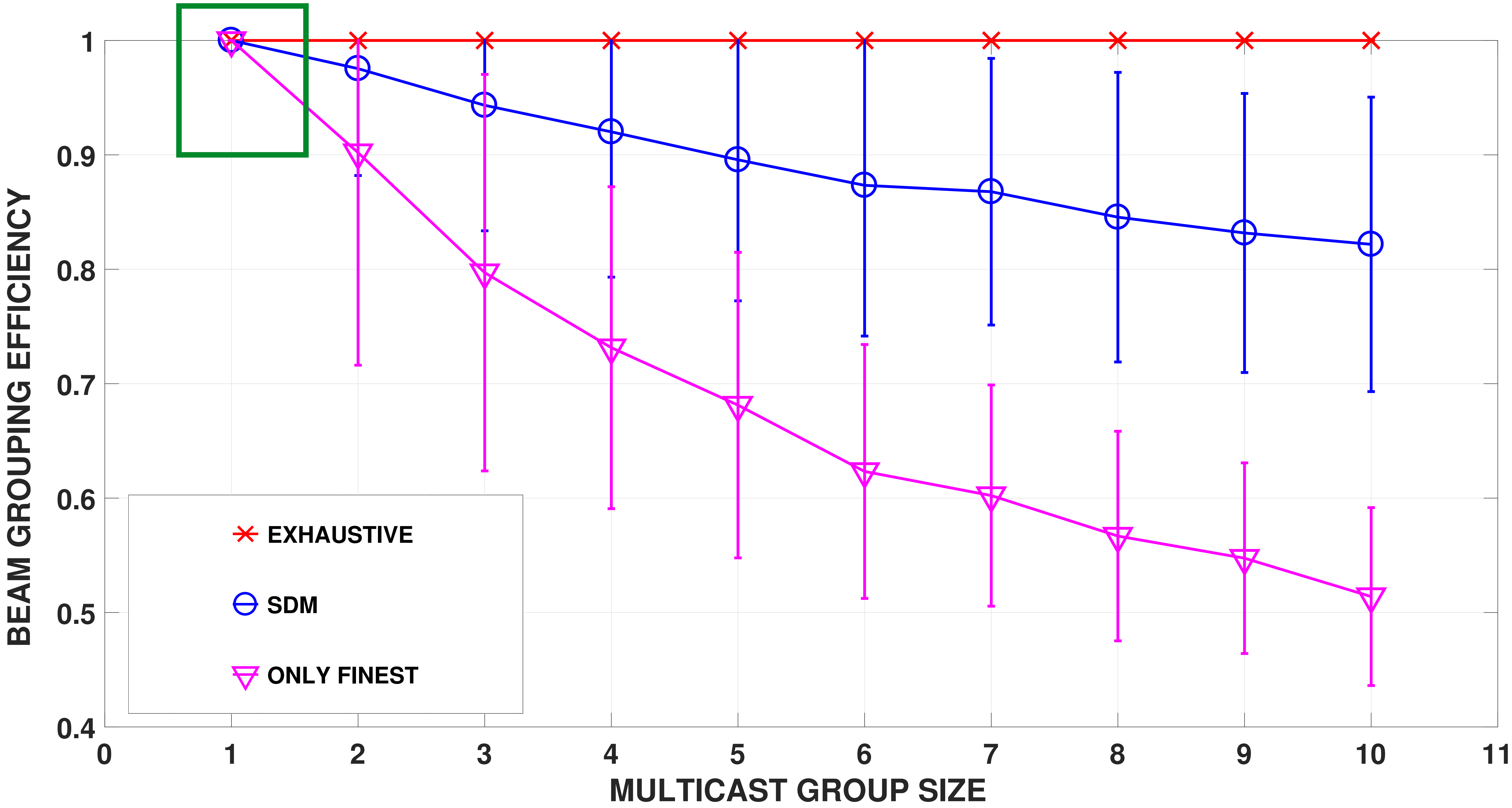


Beam grouping efficiency (strategy)

$$= T_{per\text{-}sweep}\ (\text{exhaustive}) \,/\, T_{per\text{-}sweep}\ (\text{strategy})$$

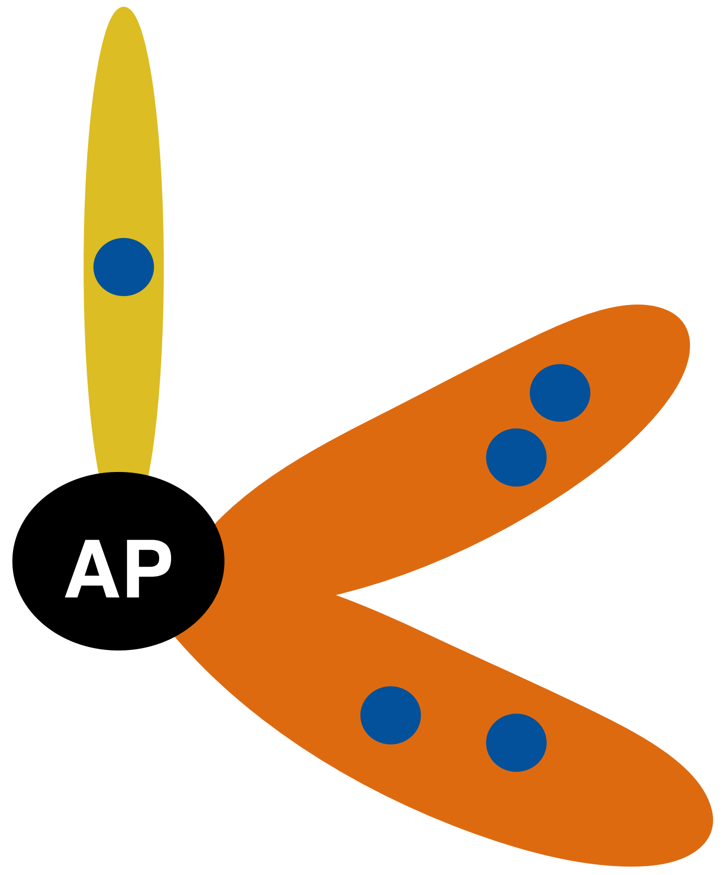
Beam Grouping Efficiency

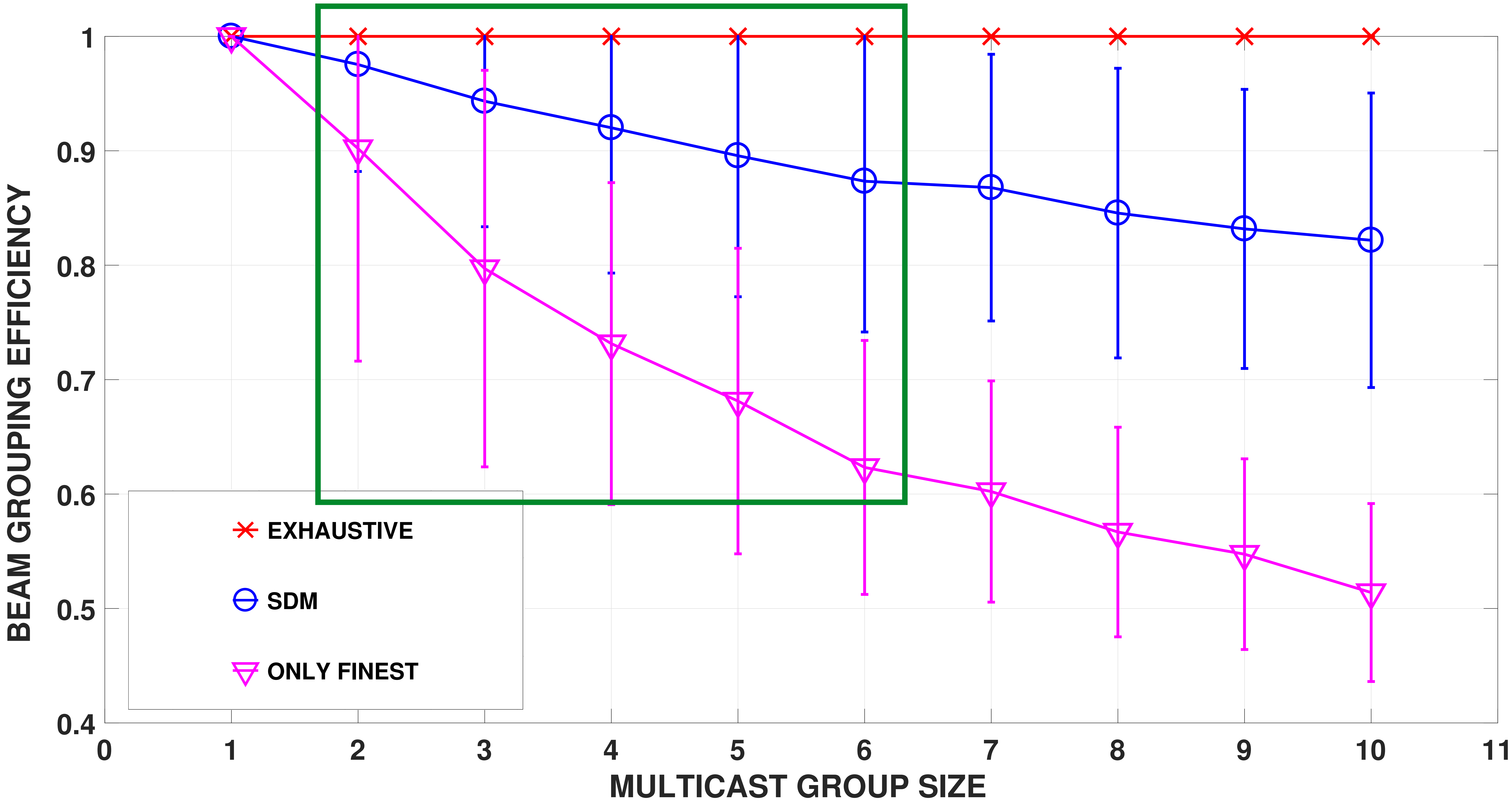




- **Single Client (unicast)**
  - Same finest beam solution

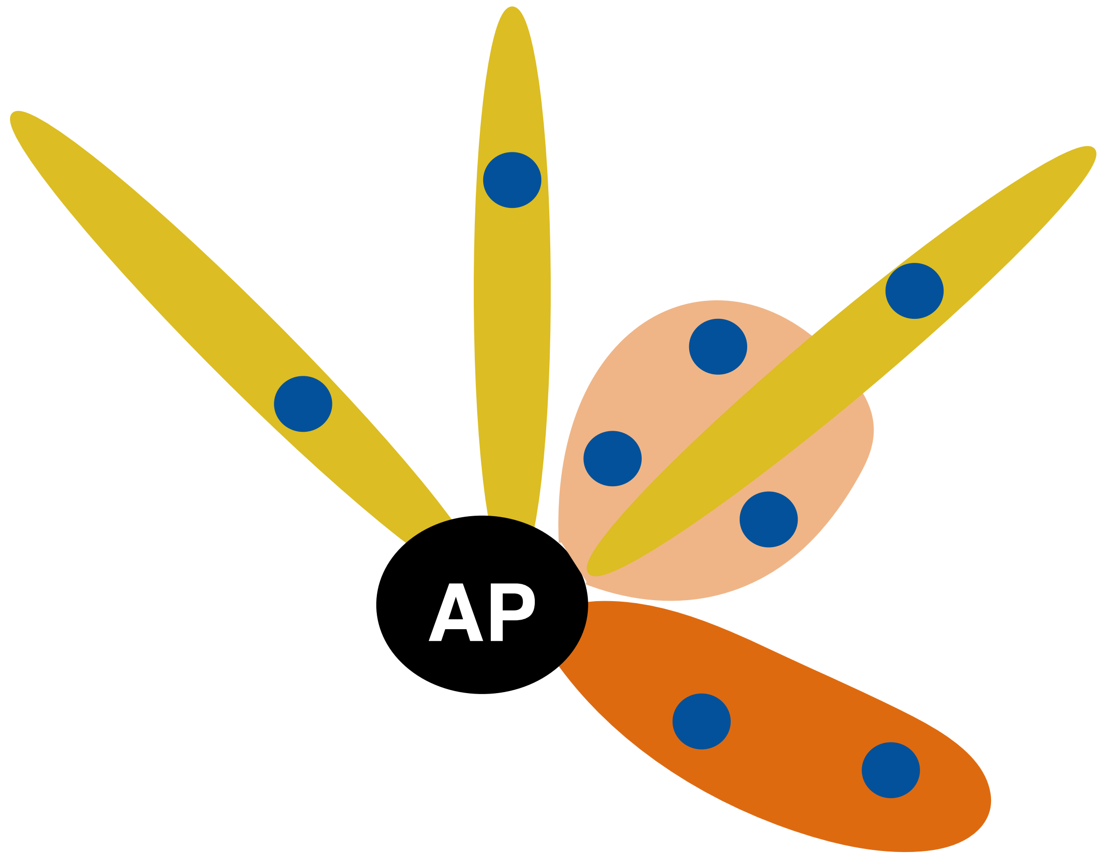
Beam Grouping Efficiency

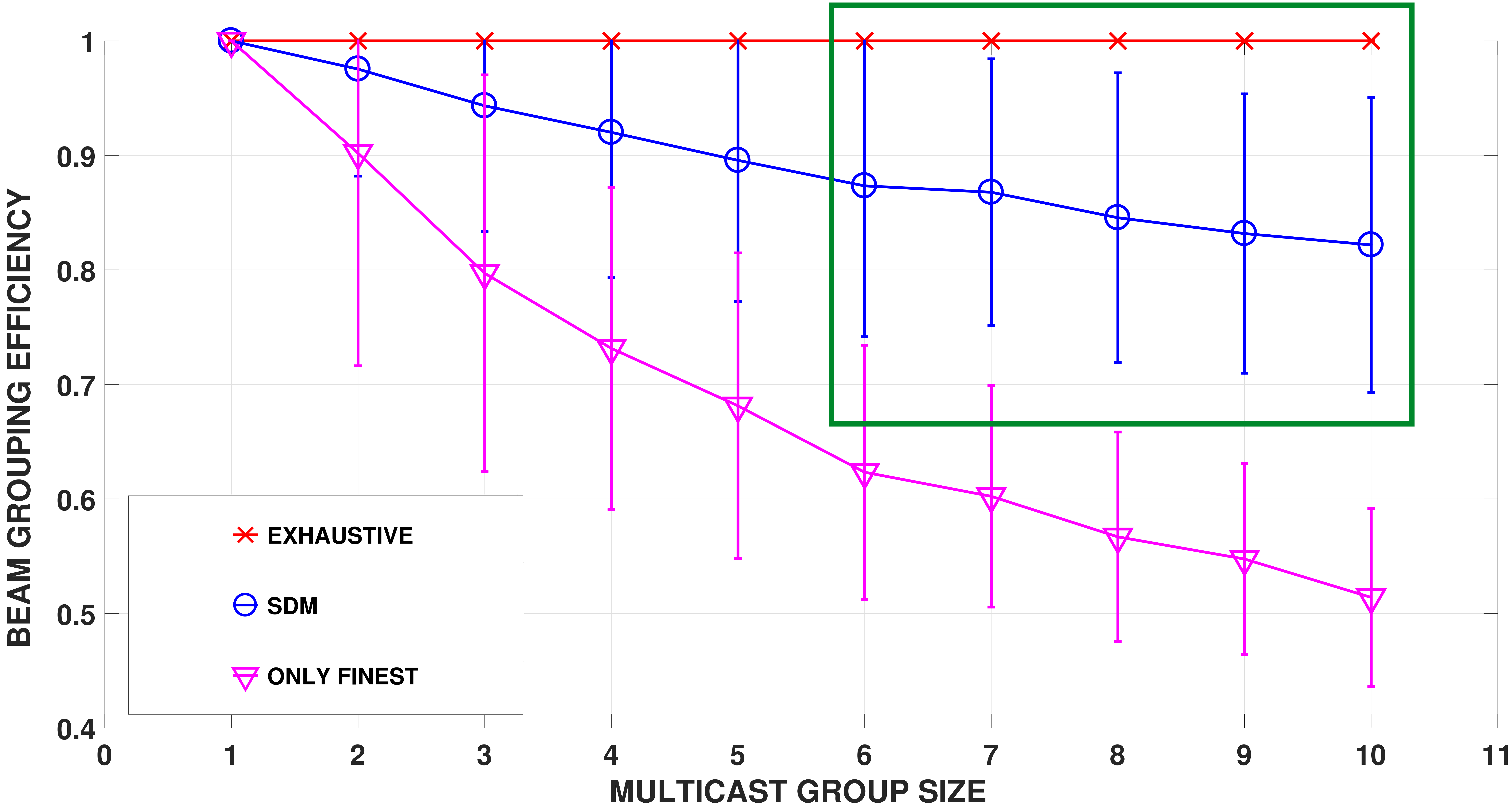




- **Medium group size**
  - Only finest doesn’t utilize wide beams

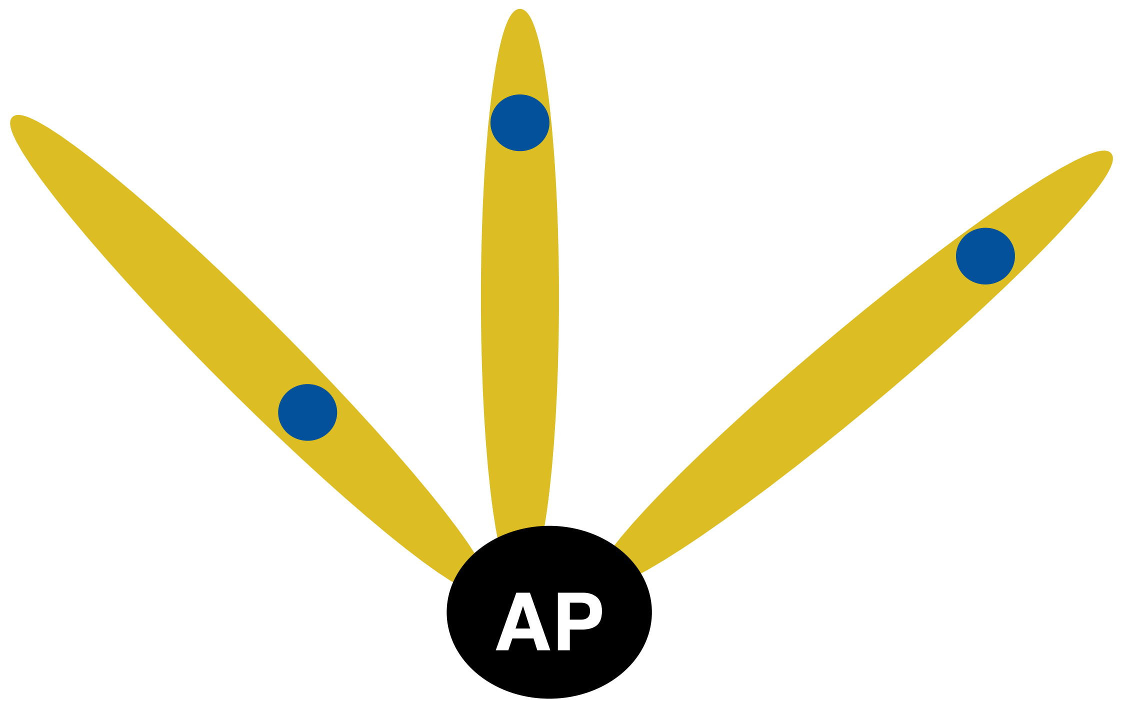
Beam Grouping Efficiency

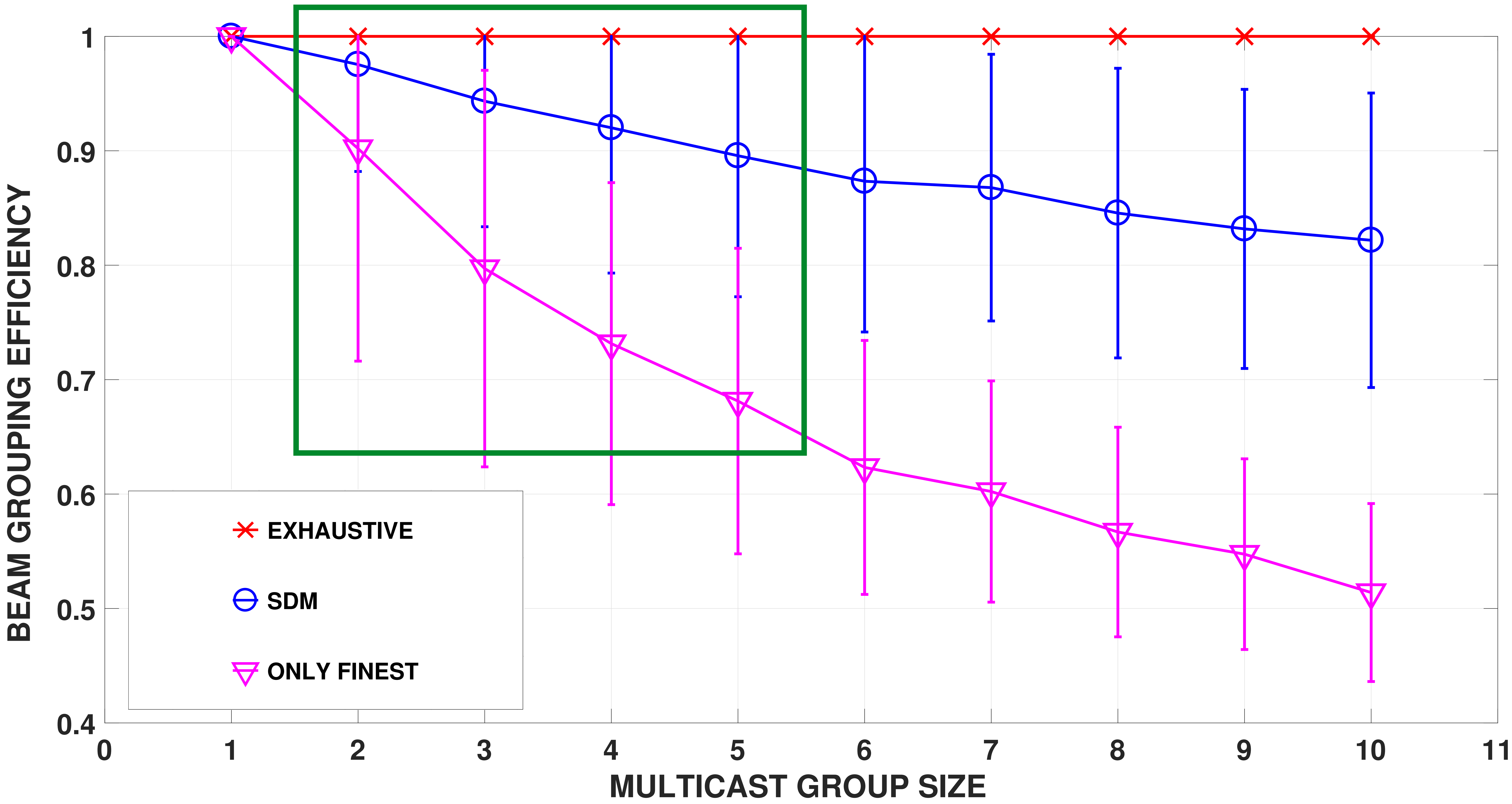




- **Large group size**
    - SDM within 80% of optimal solution

Beam Grouping Efficiency

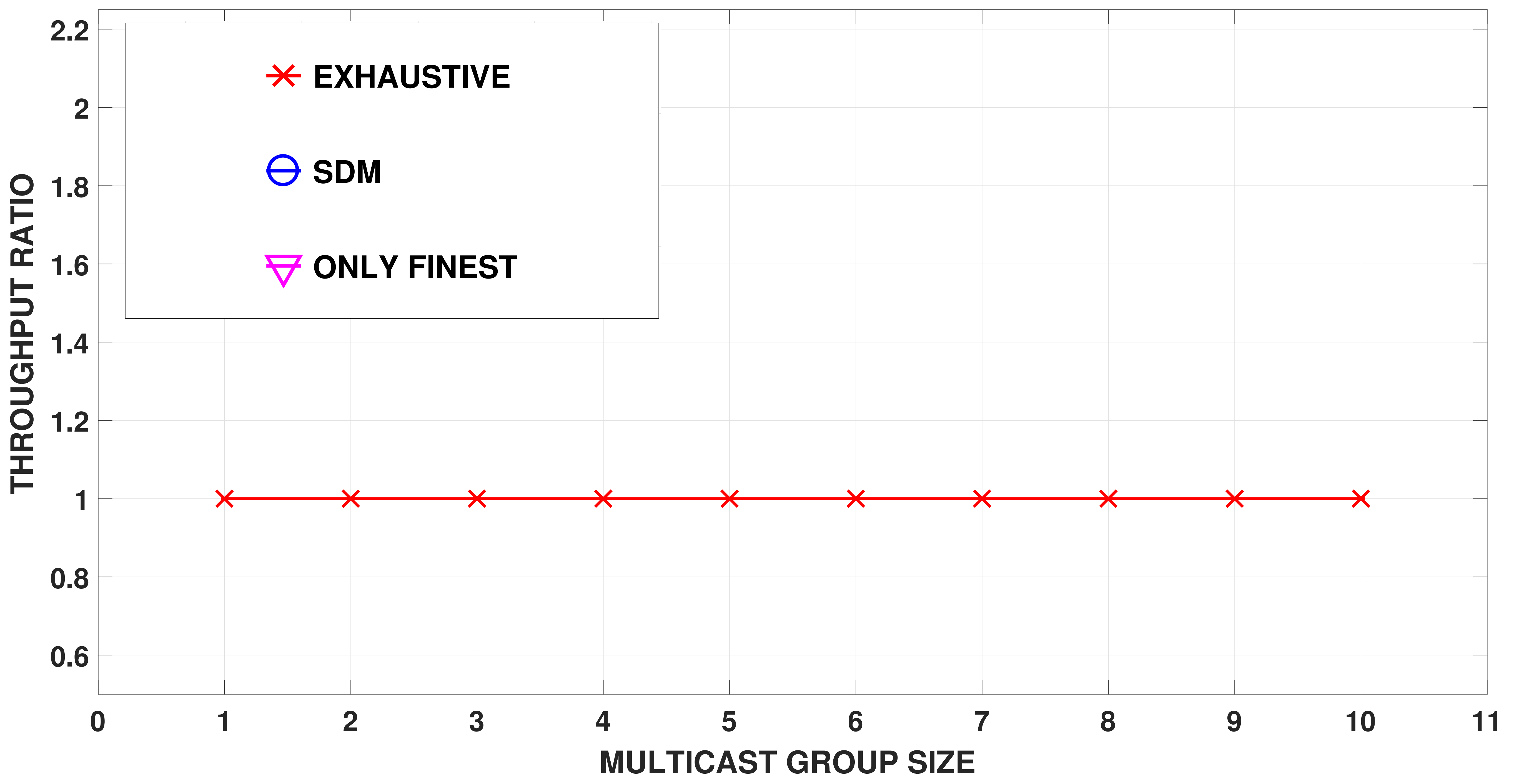


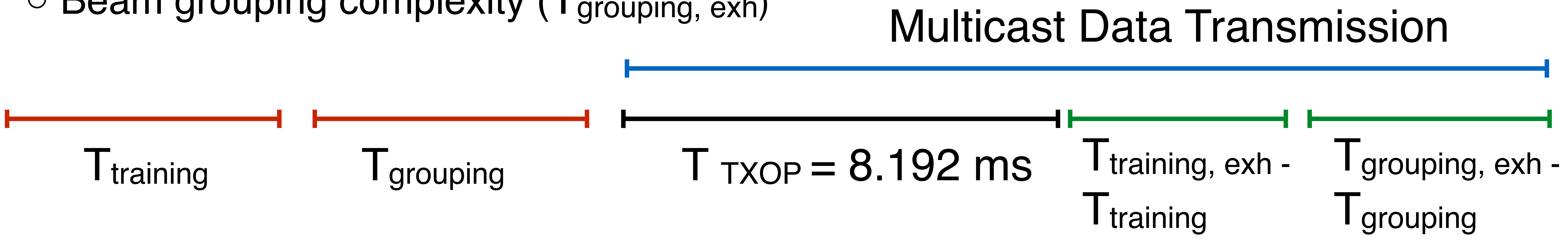


- **Only Finest Solution Variance**
  - Best solution for isolated clients
  - Probability reduces for larger groups

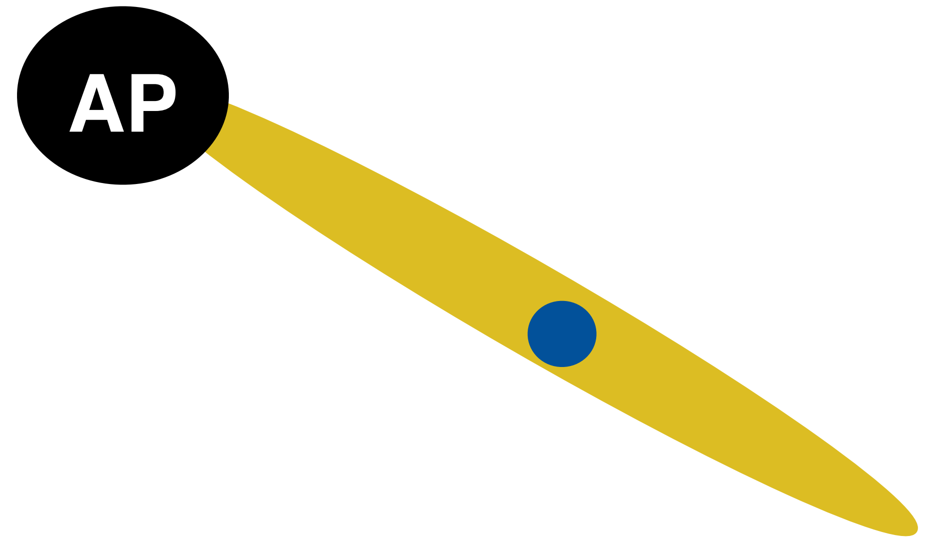
Throughput Performance

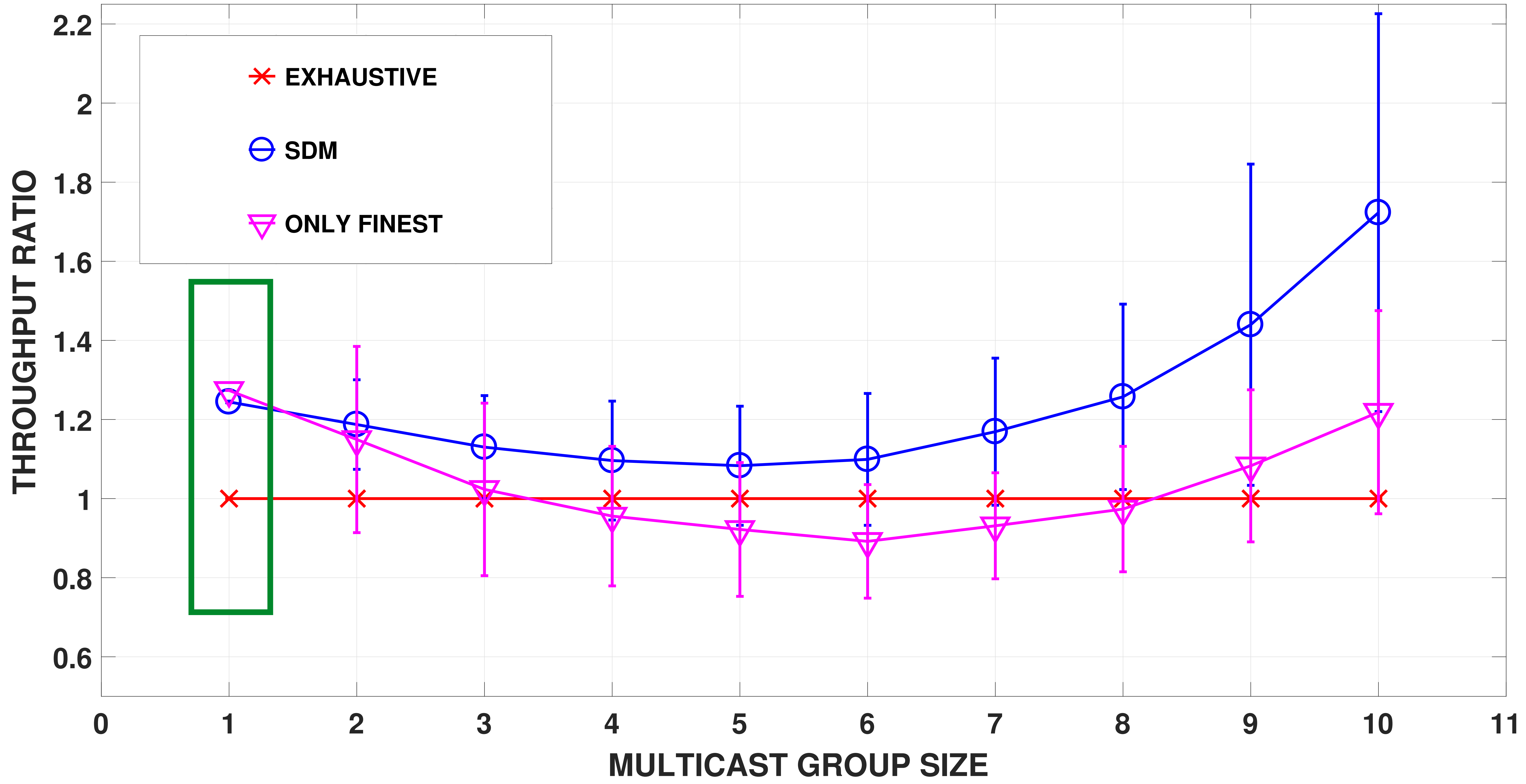
- **Factors**
  - Beam Training overhead ($T_{training}$)
  - Beam grouping complexity ($T_{grouping}$)
  - Beam grouping efficiency
- **Traffic Model**
  - Fully backlogged traffic
  - Data sweeps of 8 KB
- **Exhaustive strategy as Baseline**
  - Training overhead ($T_{training,\ exh}$)
  - Beam grouping complexity ($T_{grouping,\ exh}$)





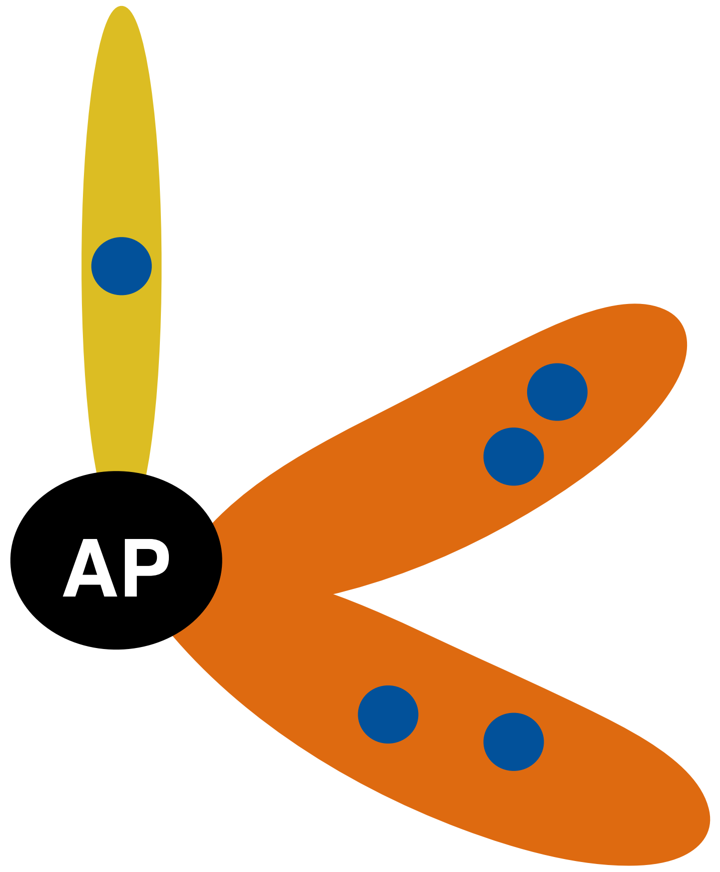
Throughput Performance

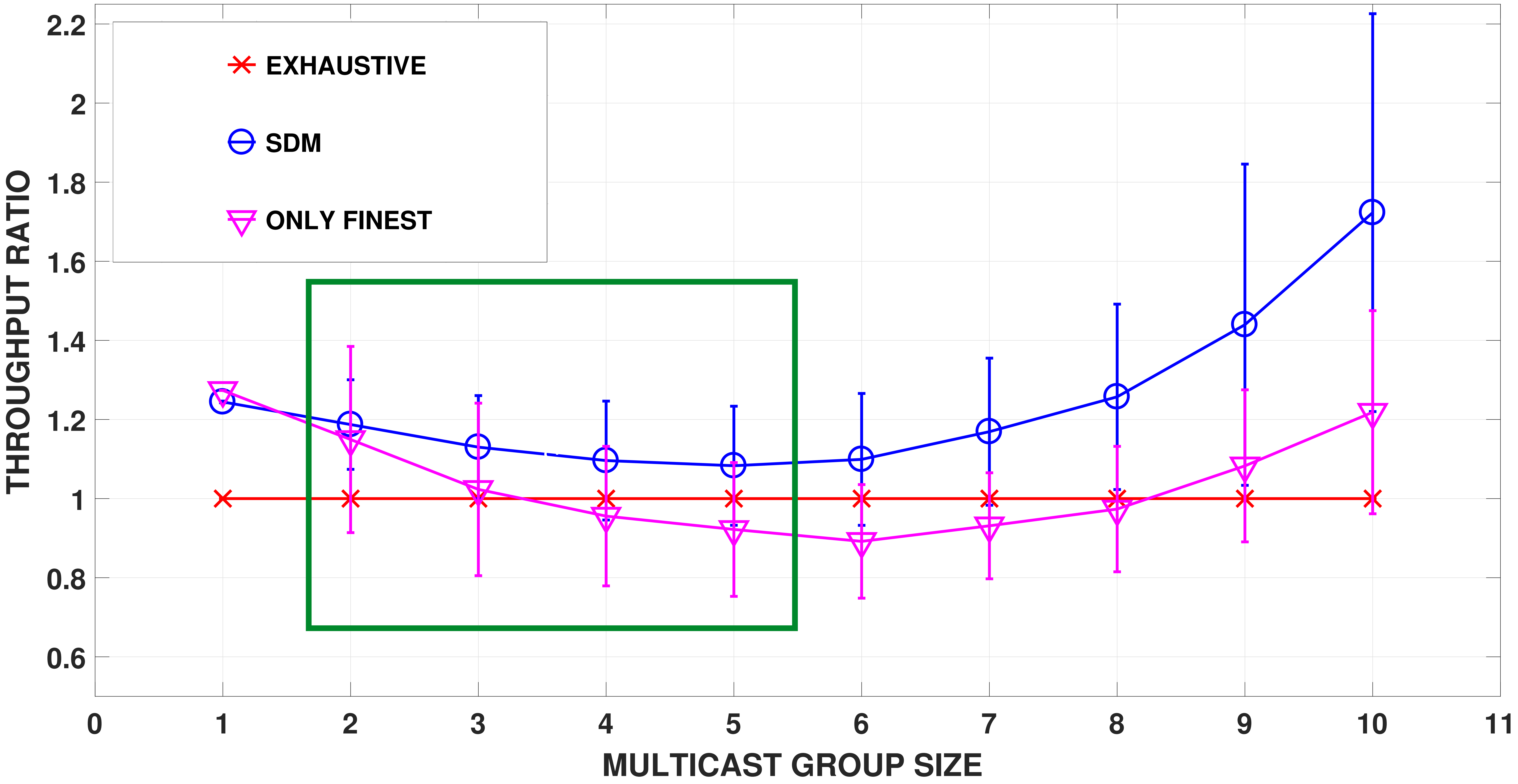




- **Single client (unicast)**
  - Same beam grouping solution
  - Only finest has lowest training

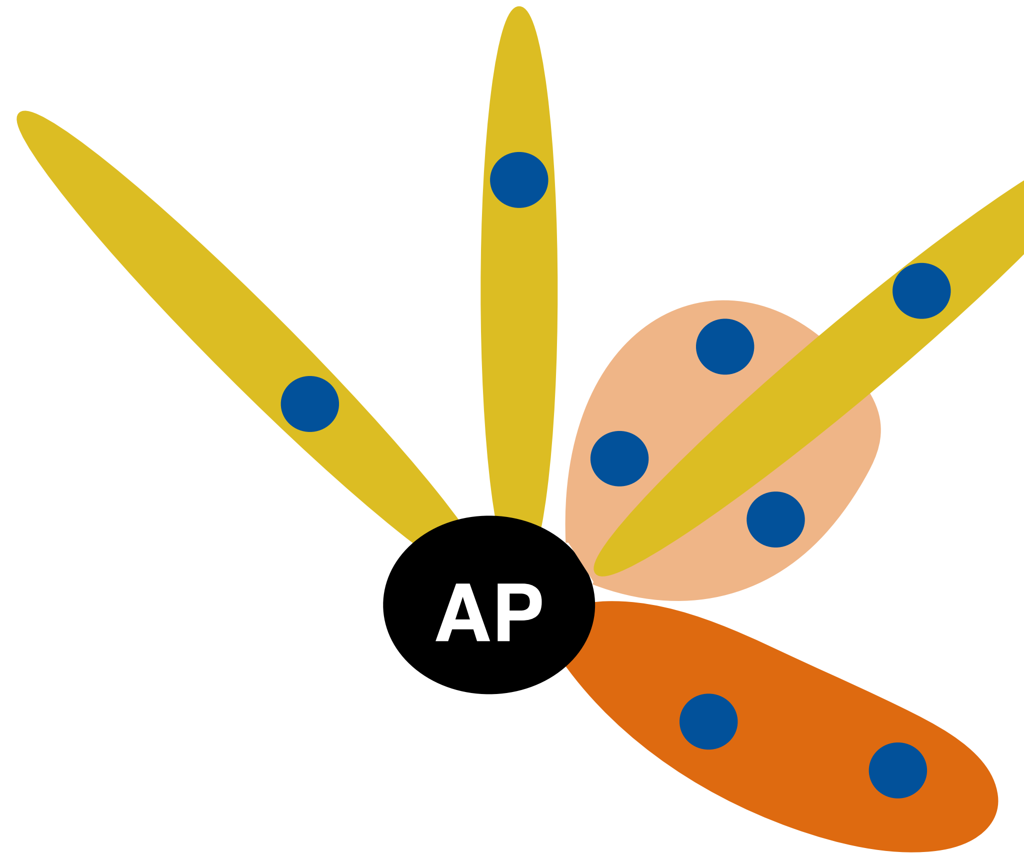
Throughput Performance

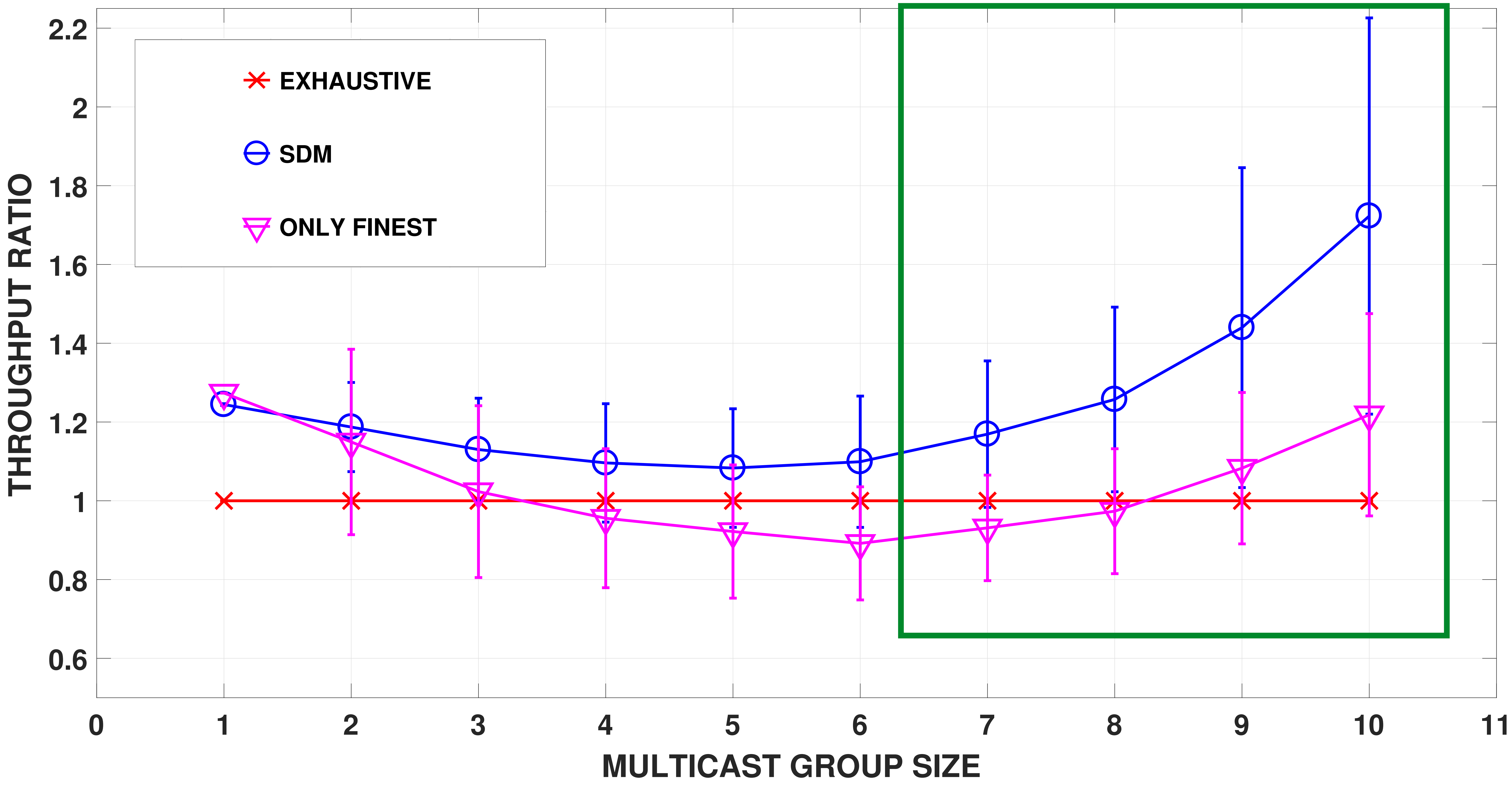




- **Medium group size**
  - Exhaustive's data transmission >> overhead
  - SDM beam grouping efficiency within 90% of Exhaustive strategy

Throughput Performance





- **Large group size**
  - Reduced overhead for SDM
  - Wide Beams unlike only Finest

Prior Work

- **Multicast Communication in sub-6 GHz bands**
  - Scheduling with idealized beam patterns [1,2]

In contrast: Multi-level codebook and beam irregularities at 60 GHz [3]

- **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

[1] Sundaresan et al., "Optimal Beam Scheduling for Multicasting in Wireless Networks," in *Proc. of ACM MobiCom*, 2009.

[2] Zhang et al., "Wireless Multicast Scheduling with Switched Beamforming Antennas," *IEEE/ACM Transactions on Networking*, 2012.

[3] Nitsche et al., "Boon and bane of 60 GHz networks: Practical insights into beamforming, interference and frame level operation," in *Proc. of ACM CoNEXT*, 2015.

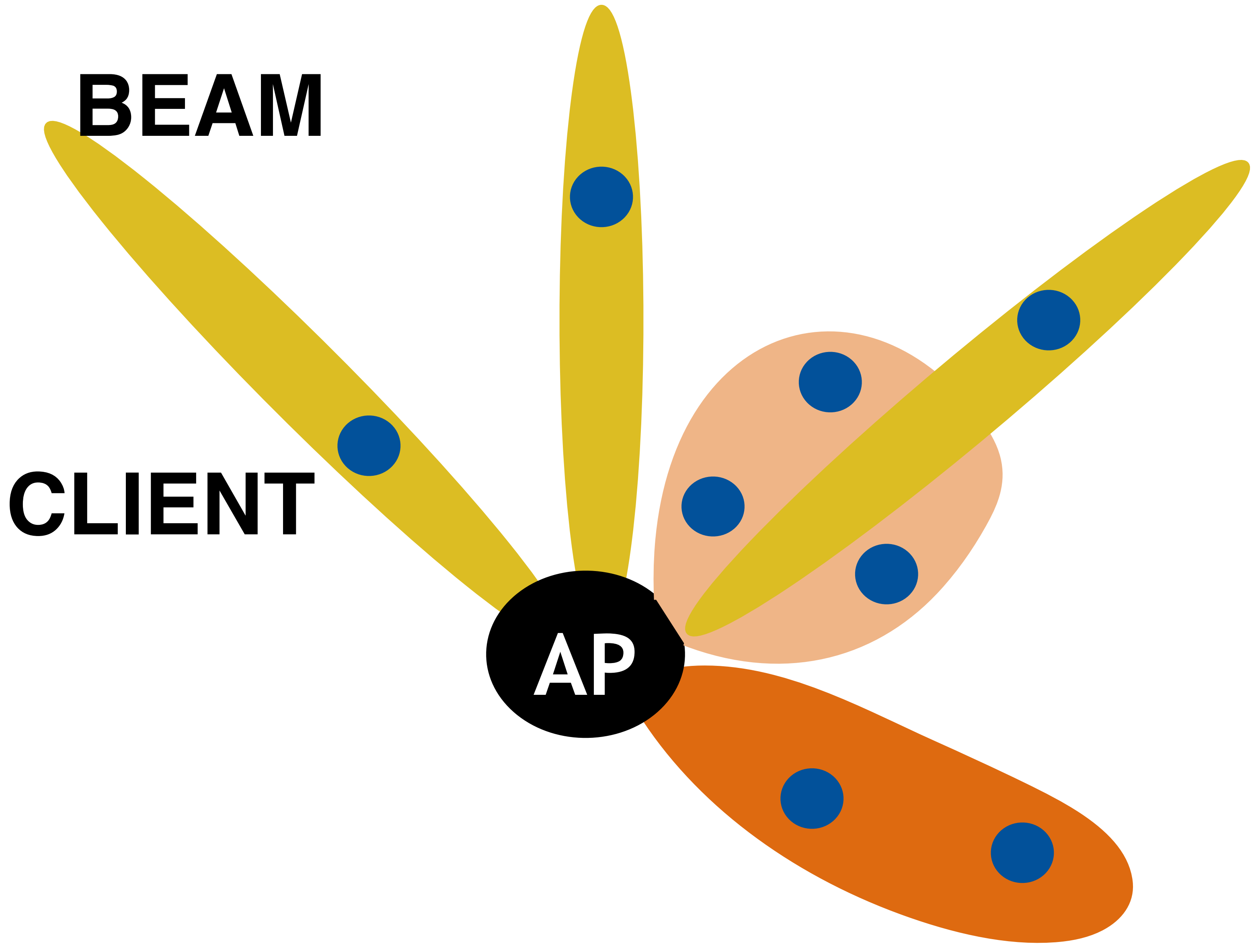
[4] Nitsche et al., "Steering with Eyes Closed: mm-Wave Beam Steering without In-Band Measurement," in *Proc. of IEEE INFOCOM*, 2015.

[5] Li et al.,"On the Efficient Beam-Forming Training for 60GHz Wireless Personal Area Networks," *IEEE Transactions on Wireless Communications*, February 2

Thesis Contributions

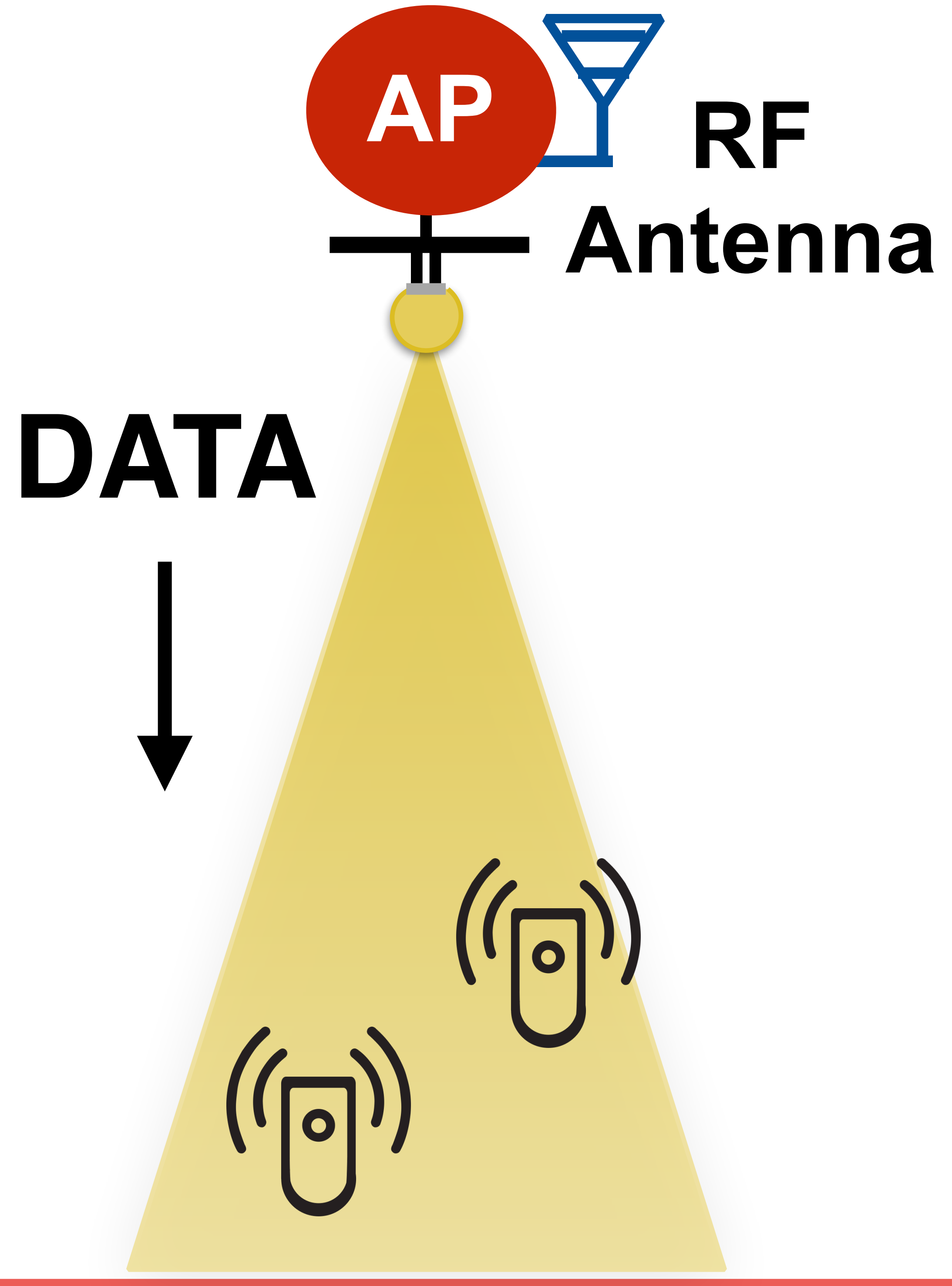
60 GHz

Scalable Directional Multicast

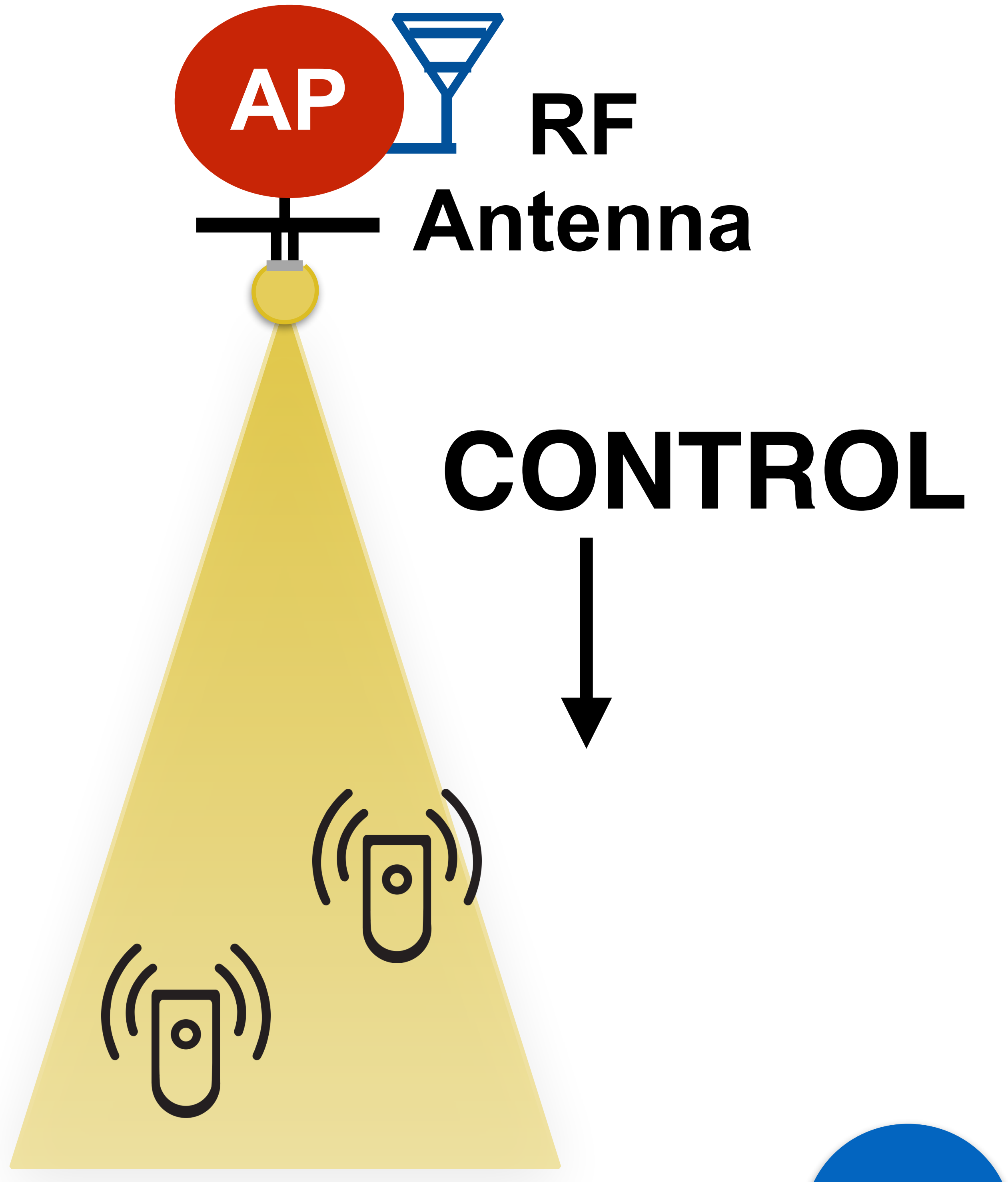


Visible Light

LiRa



LiSCAN



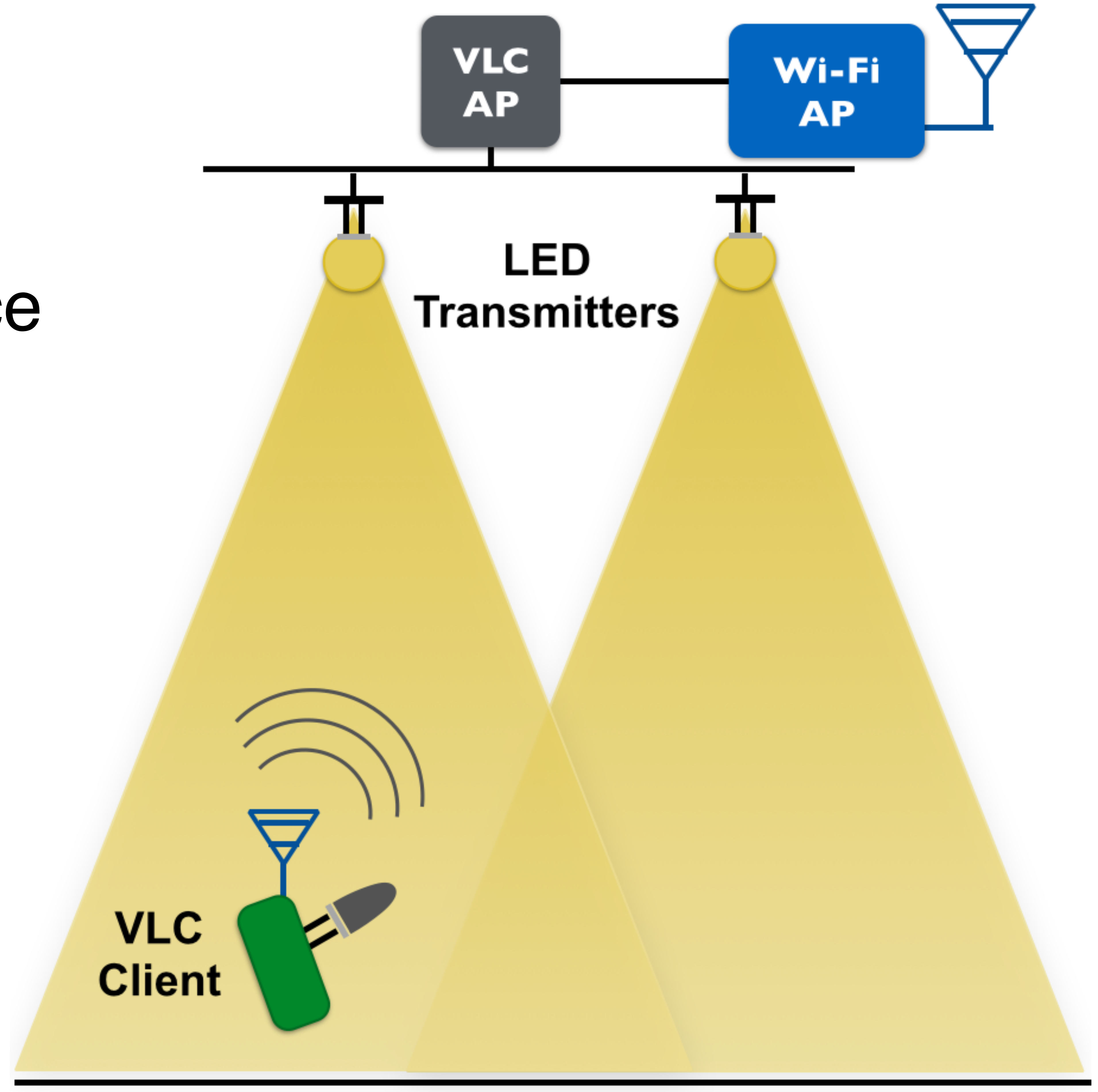
Naribole et al., "LiRa: a WLAN Architecture for Visible Light Communication with a Wi-Fi Uplink," in *Proc. of IEEE SECON*, 2017.

Objective

- **High-performance WLAN system with:**
  - VLC simplex downlink and RF uplink
  - inter-operability with legacy Wi-Fi
  - controlled impact on legacy Wi-Fi performance

- **Prior Work Focus**
  - Load balancing [1,2]
  - Wi-Fi contention for VLC downlink traffic [3]

VLC Feedback via RF for error control not addressed



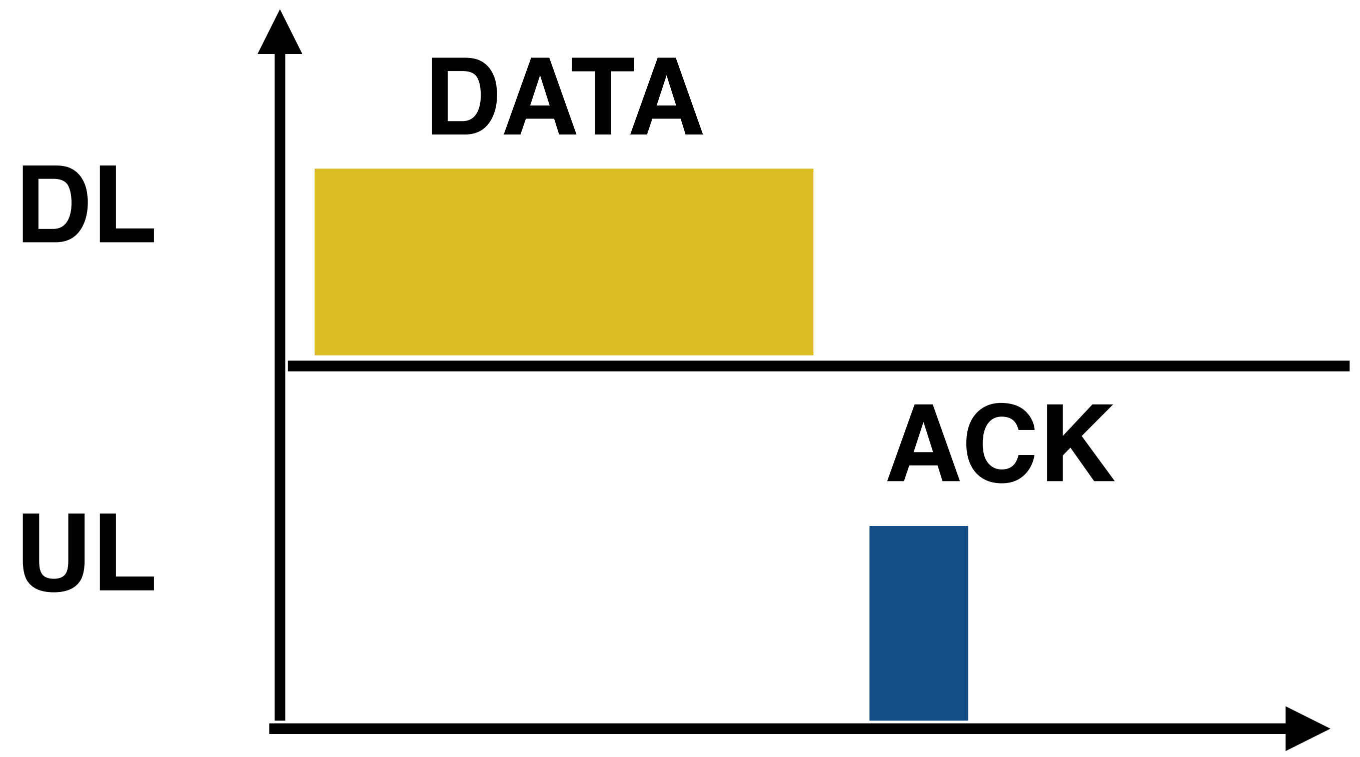
[1] Rahaim et al. , "A Hybrid Radio Frequency and Broadcast Visible Light Communication System", IEEE GLOBECOM 2011.

[2] Li et al., "Cooperative Load Balancing in Hybrid Visible Light Communications and WiFi", IEEE Transactions on Communications, 2015

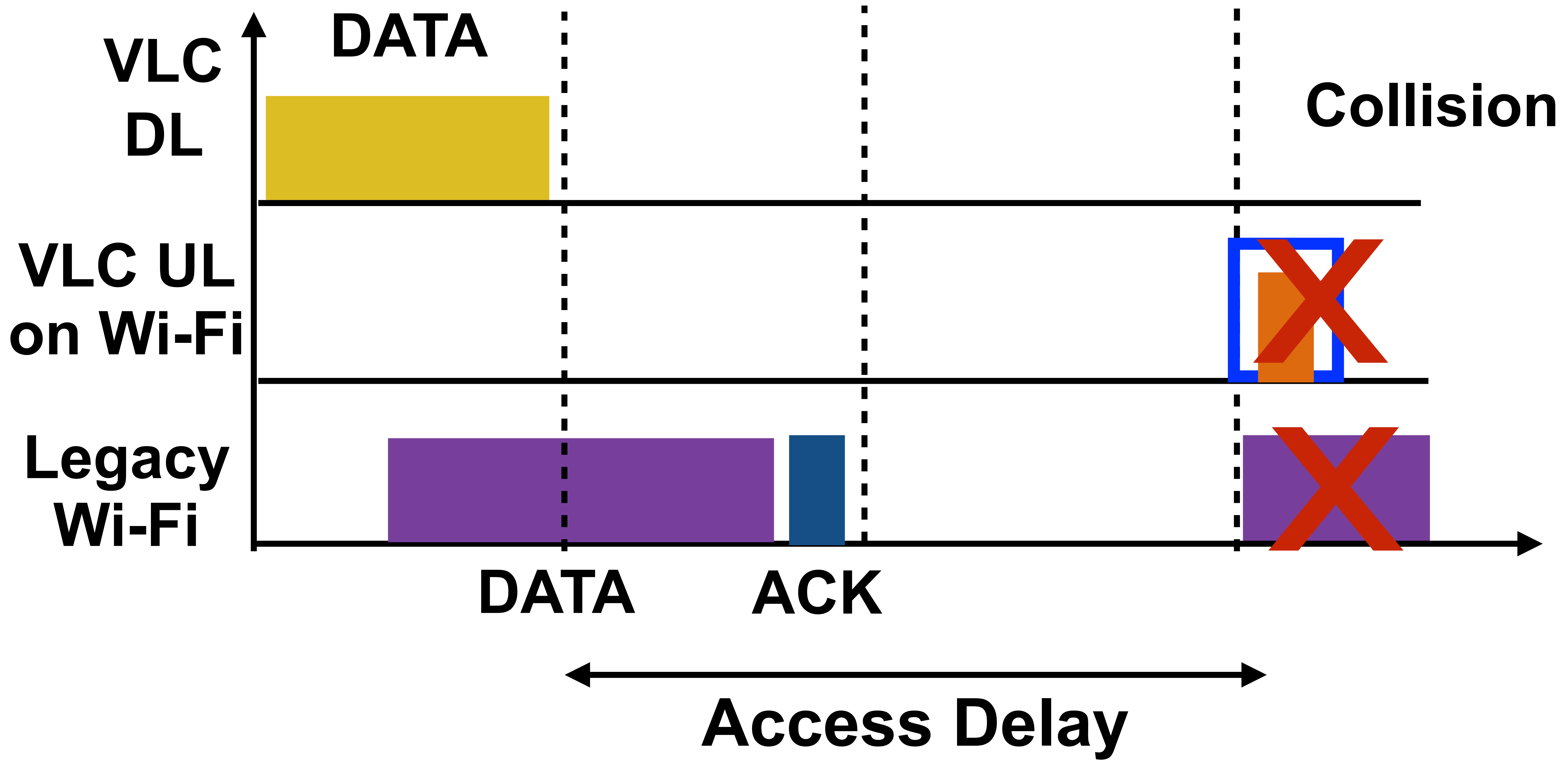
[3] W. Guo et al., "A parallel transmission MAC protocol in hybrid VLC-RF network.", Journal of Communications, 2015

Wi-Fi contention for VLC ARQ

- **Legacy WiFi:**



- **VLC-WiFi:**



Increased access delay and Wi-Fi degradation

LiRa: Light Radio WLAN

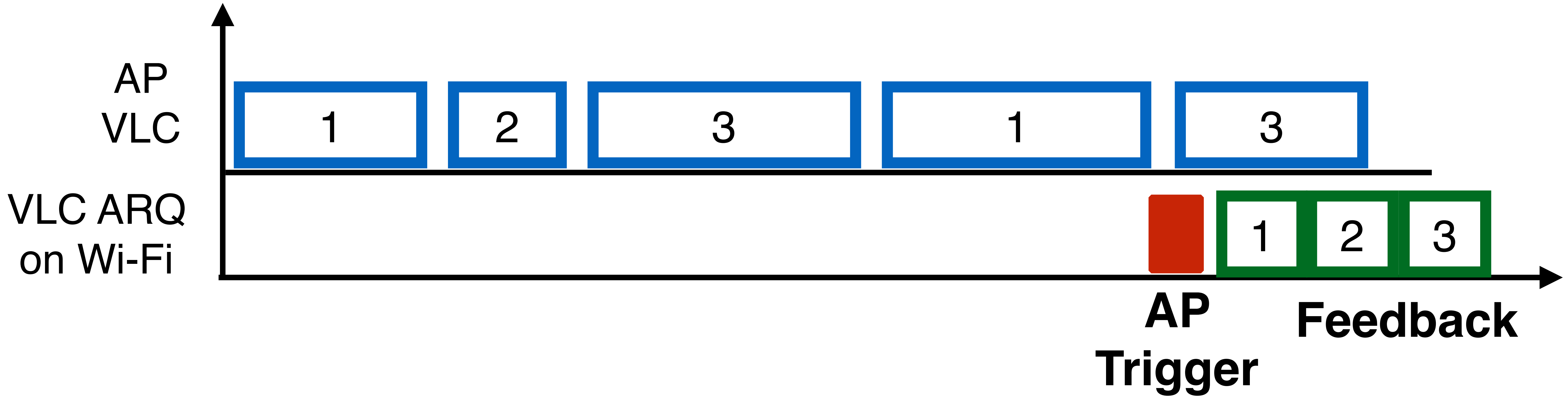
Architecture

- VLC and Wi-Fi integrated at the MAC layer
- AP-controlled feedback of VLC ARQ

LiRa: Light Radio WLAN

Architecture

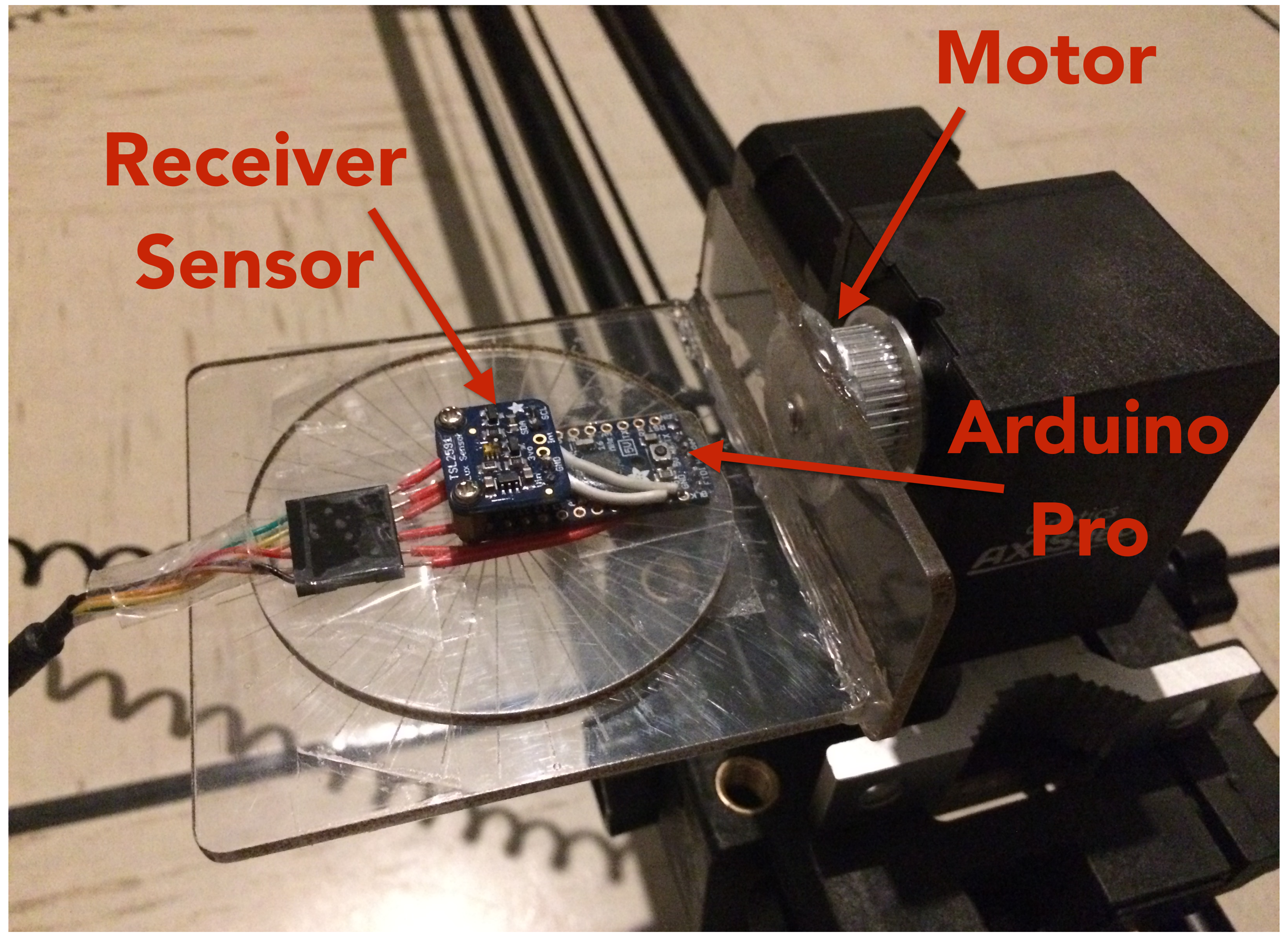
- VLC and Wi-Fi integrated at the MAC layer
- AP-controlled feedback of VLC ARQ

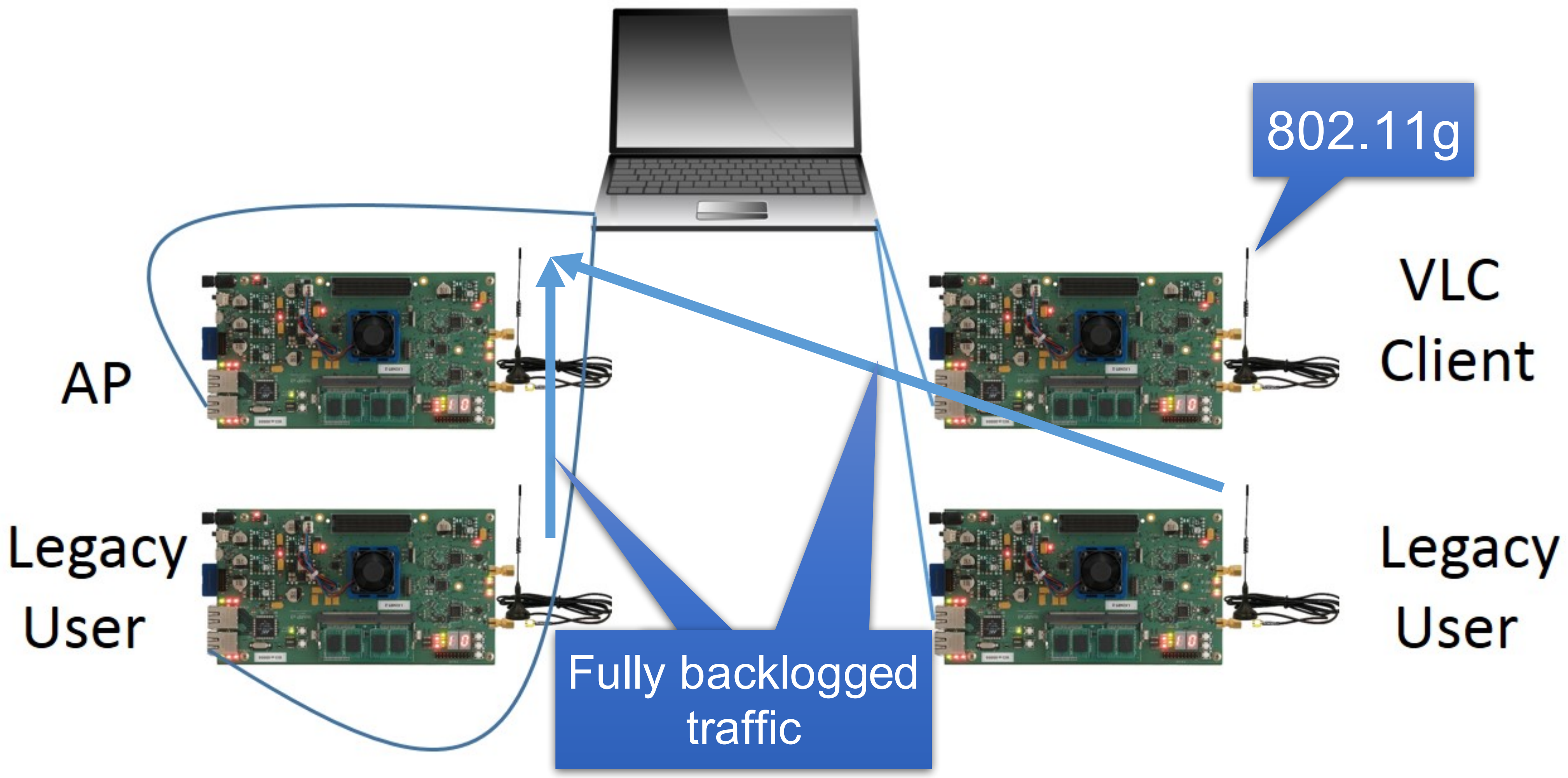


- **AP-Spoofed Multi-Client ARQ**
  - Reserve Wi-Fi medium access for entire duration of multi-client feedback
  - Eliminate the contention between VLC clients providing feedback

- **Feedback trigger time**
  - Balance the LiRa responsiveness and Wi-Fi airtime overhead

LiRa Evaluation





Response Delay

- Directly proportional to and lower than trigger time
- 15x reduction compared to per-client contention (PCC)

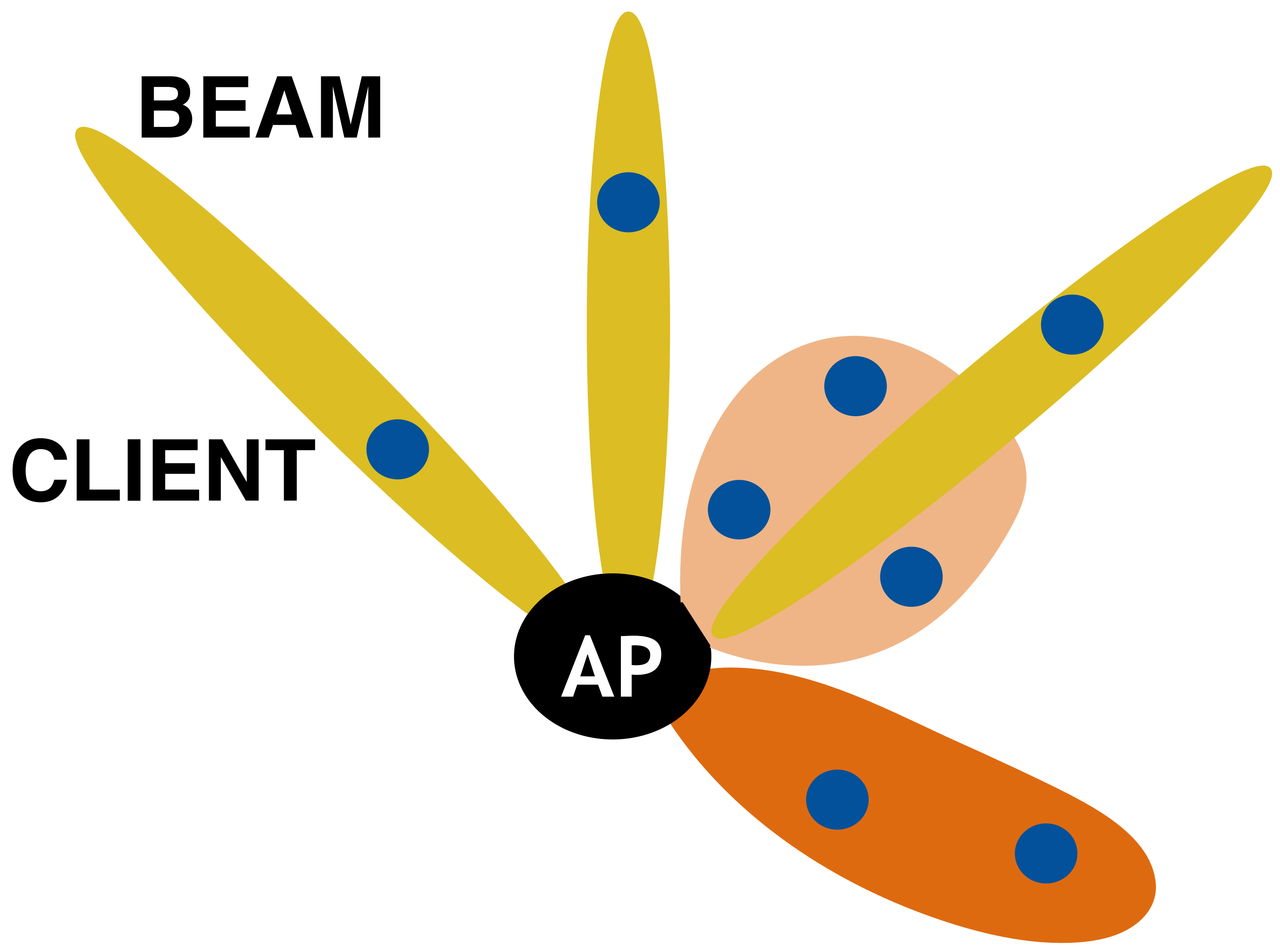
Wi-Fi Impact

- Decreases inversely proportional to trigger time
- Reduces to 3% from an excessive value of 74% in PCC

Thesis Contributions

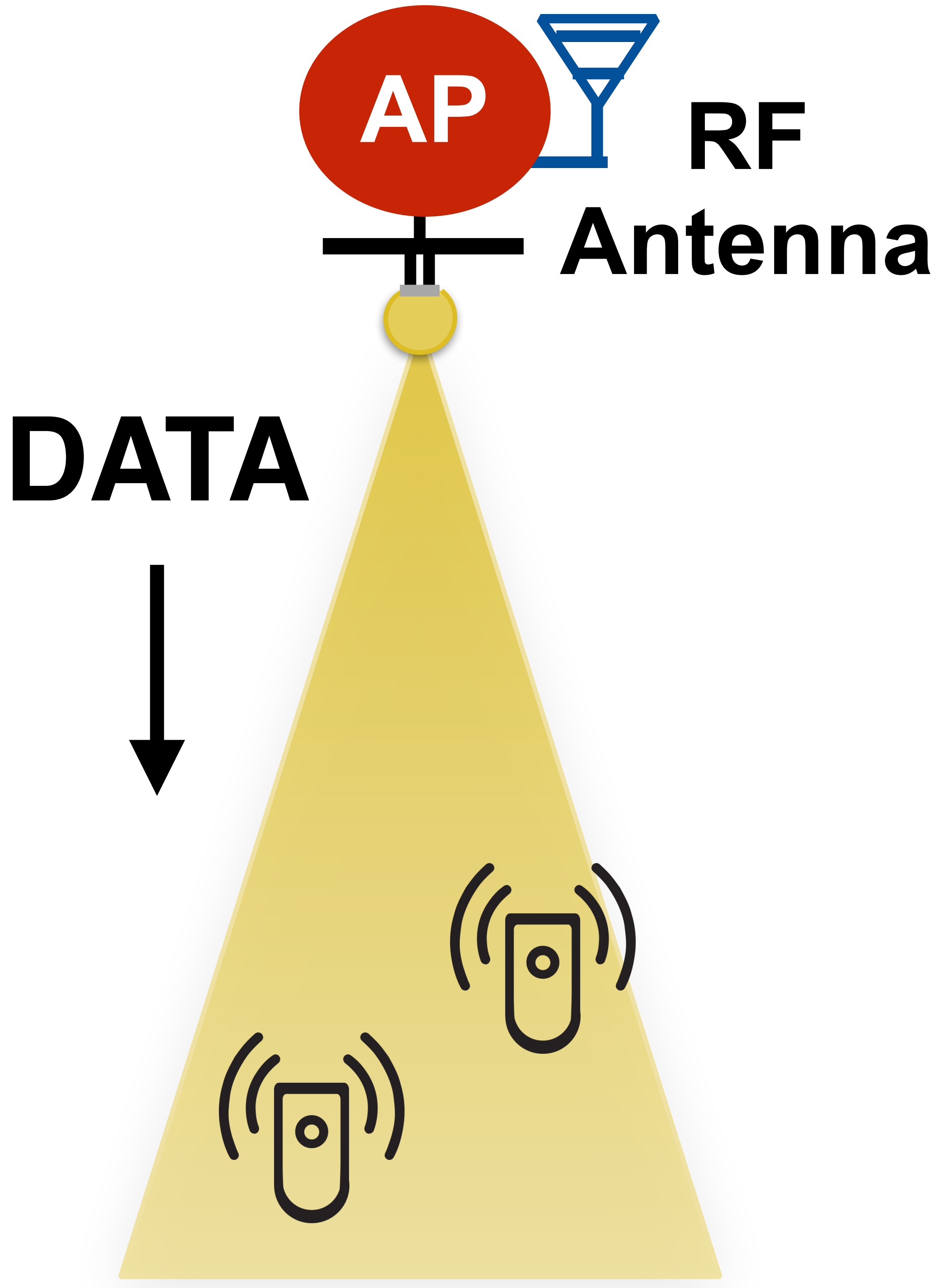
60 GHz

Scalable Directional Multicast

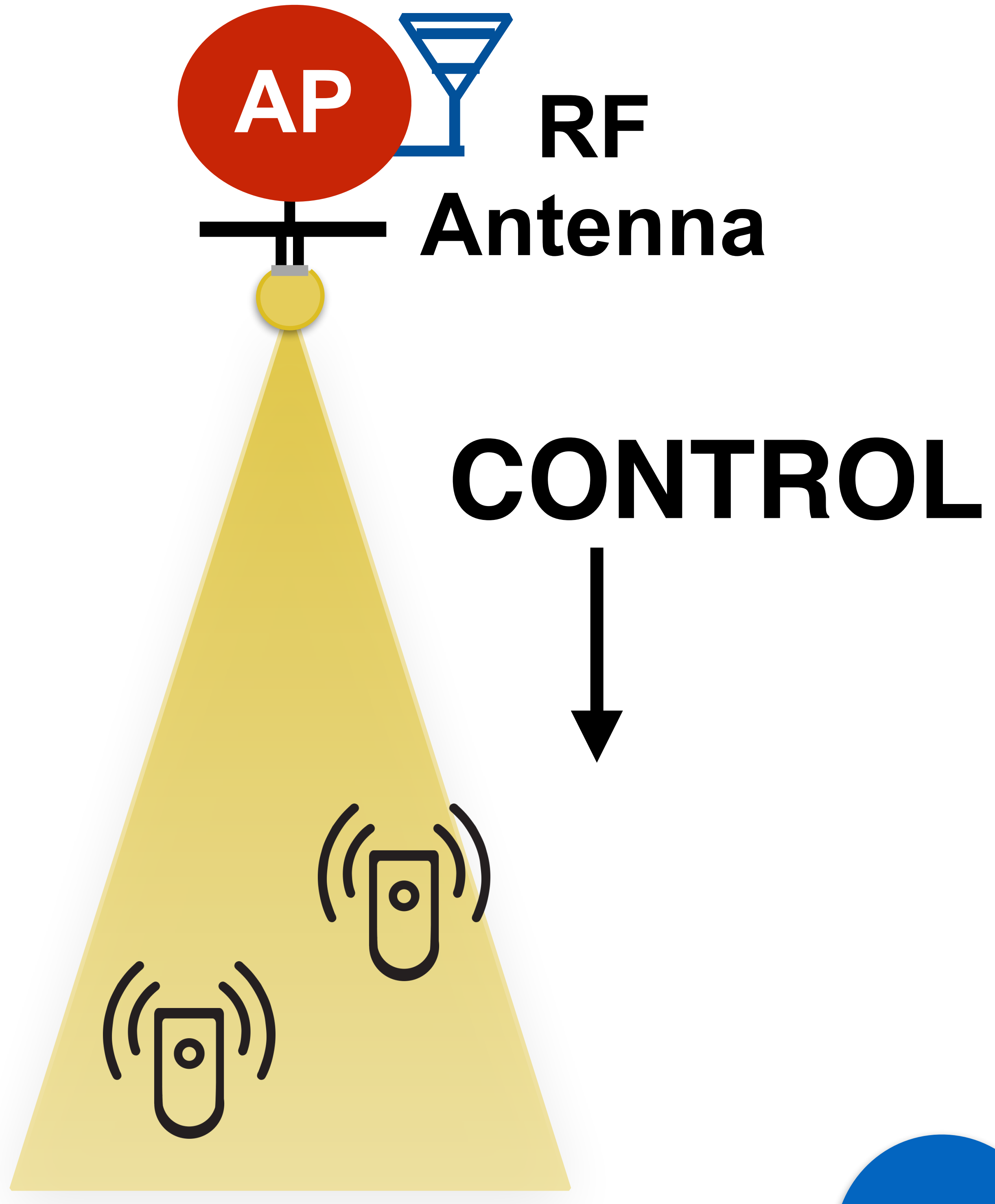


Visible Light

LiRa



LiSCAN



Dense Wireless Sensor Networks

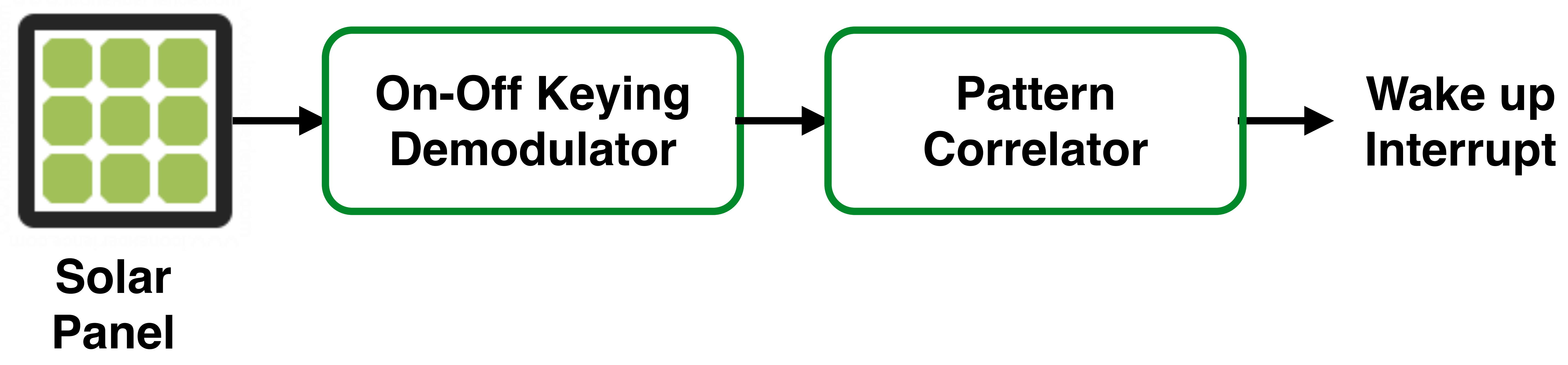
- **Network Model**
  - Hundreds of sensors [1,2]
  - Coverage ~ 100m
- **Traffic Flow**
  - Data flow in the uplink
  - Control messaging in downlink
- **Sensors**
  - Asynchronous traffic patterns
  - Low-cost, power-limited

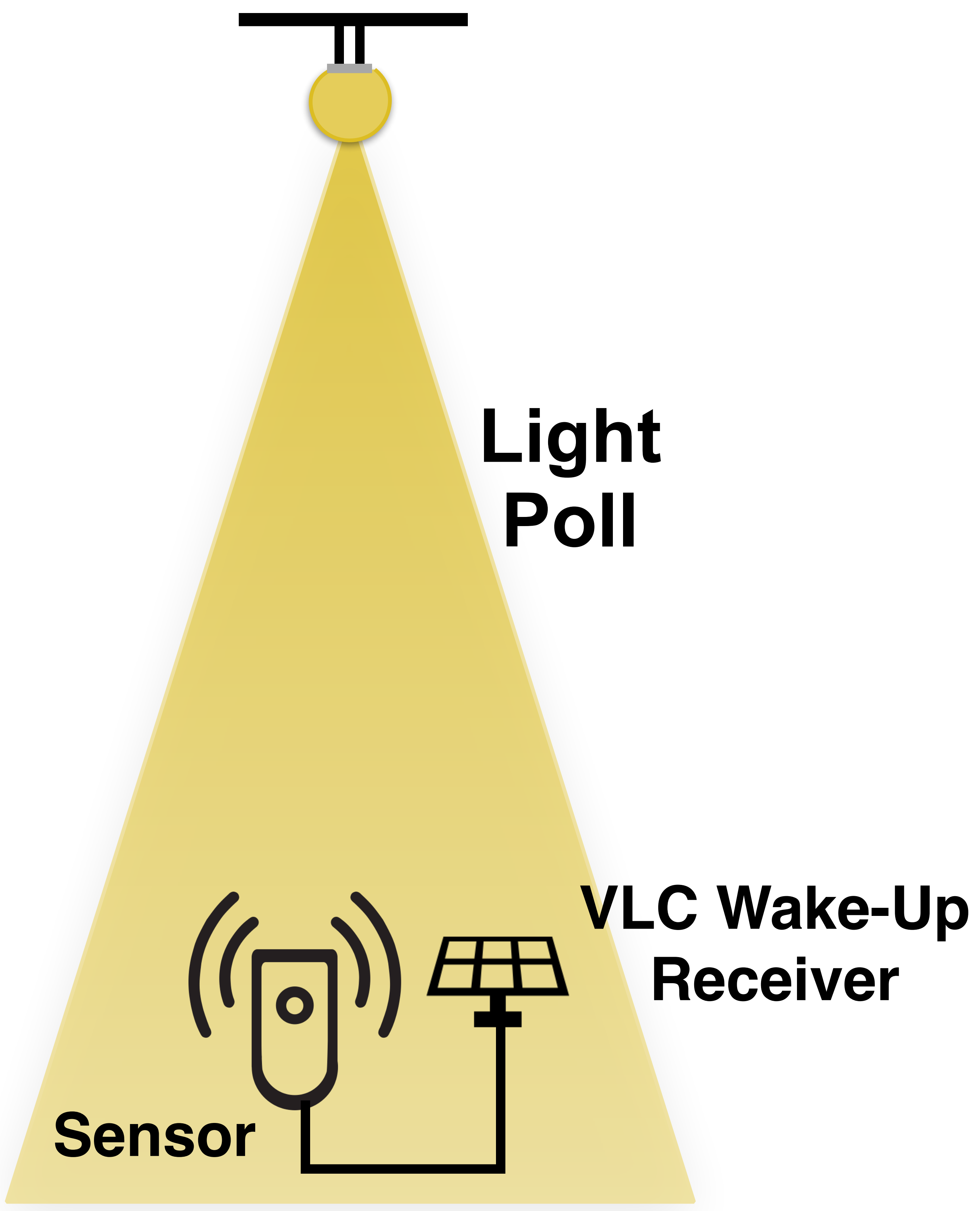
Access delay and energy consumption increase with contention

[1] Ahmed et al., "A comparison of 802.11ah and 802.15. 4 for IoT." *ICT Express*, 2016.
[2] Khorov et al., "A survey on IEEE 802.11 ah: An enabling networking technology for smart cities." *Computer Communications*, 2015.

VLC Contention Free Access

- **Inherent broadcast**
  - Distributed LED bulb luminaries for coverage
- **Energy-Autonomous Wake-up VLC receiver**
  - Tens of microwatt
  - Solar panel-based energy harvesting [1,2]

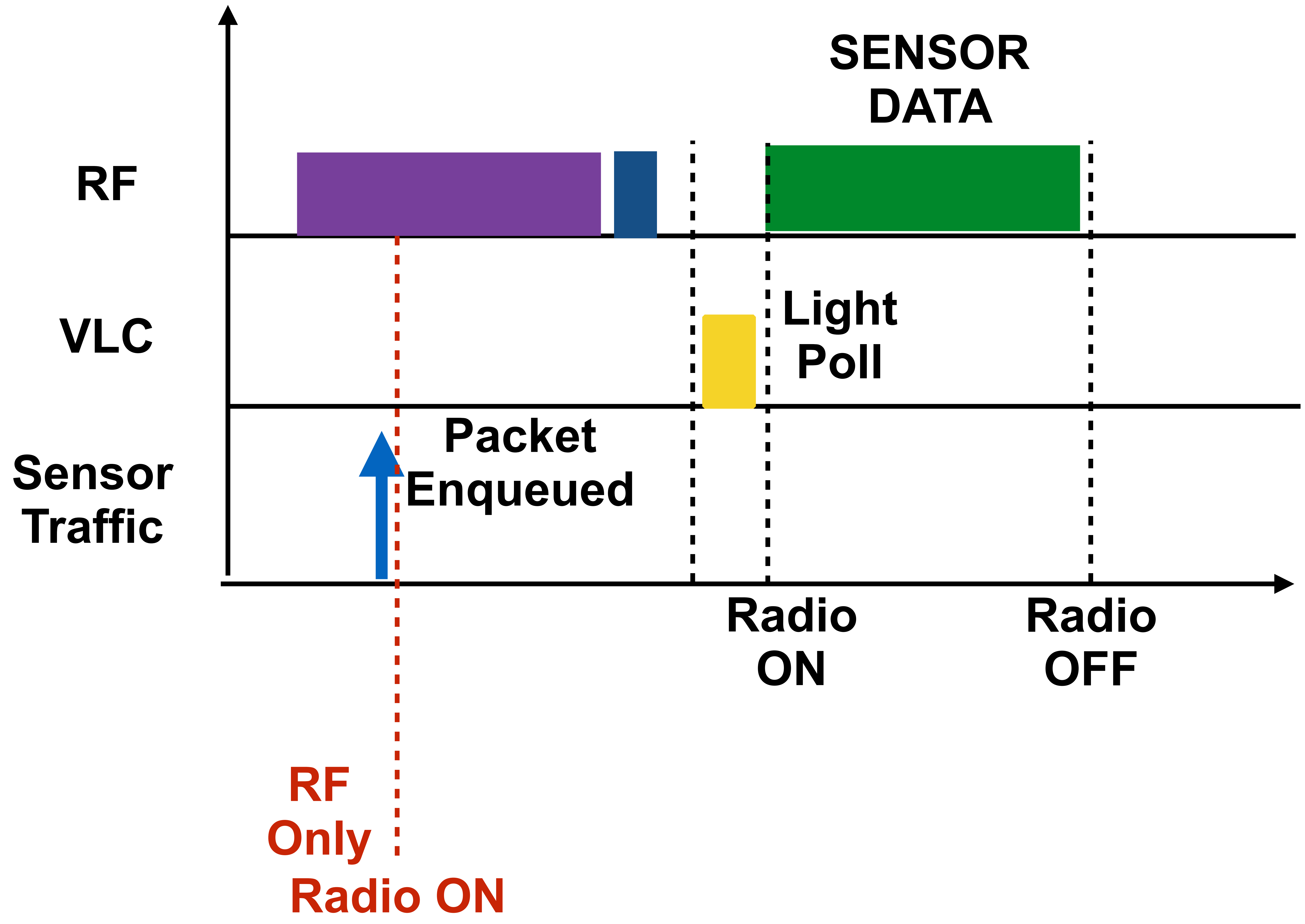




[1] Ramos et al., “Towards energy-autonomous wake-up receiver using Visible Light Communication.” in *Proc. of IEEE CCNC,* 2016.
[2] Carrascal et al., “A novel wake-up communication system using solar panel and Visible Light Communication." in *Proc. of IEEE GLOBECOM*, 2014

VLC Contention-Free Access

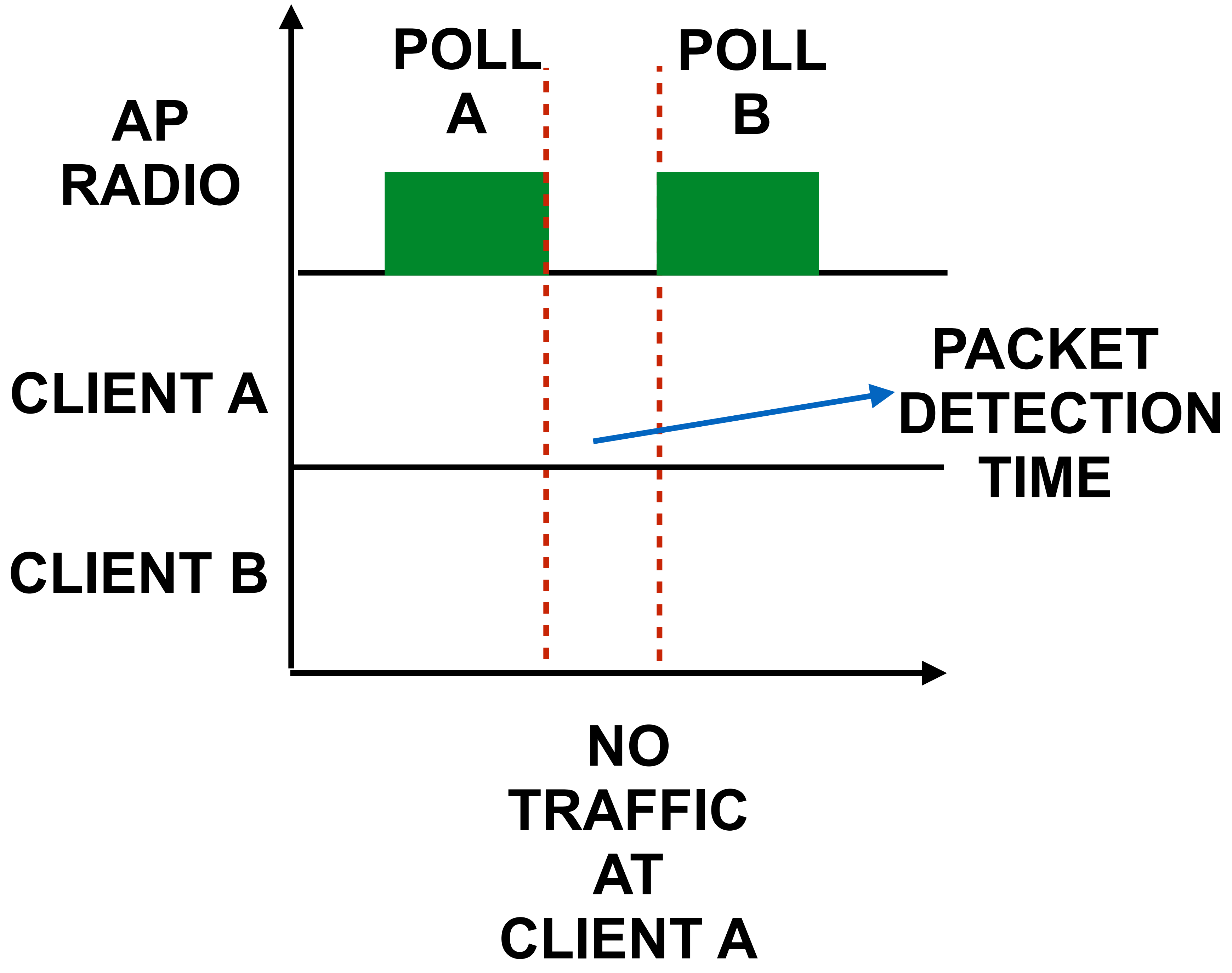
- **Minimize energy consumption**
  - VLC wake-up receiver turns on RF module only for data transmission



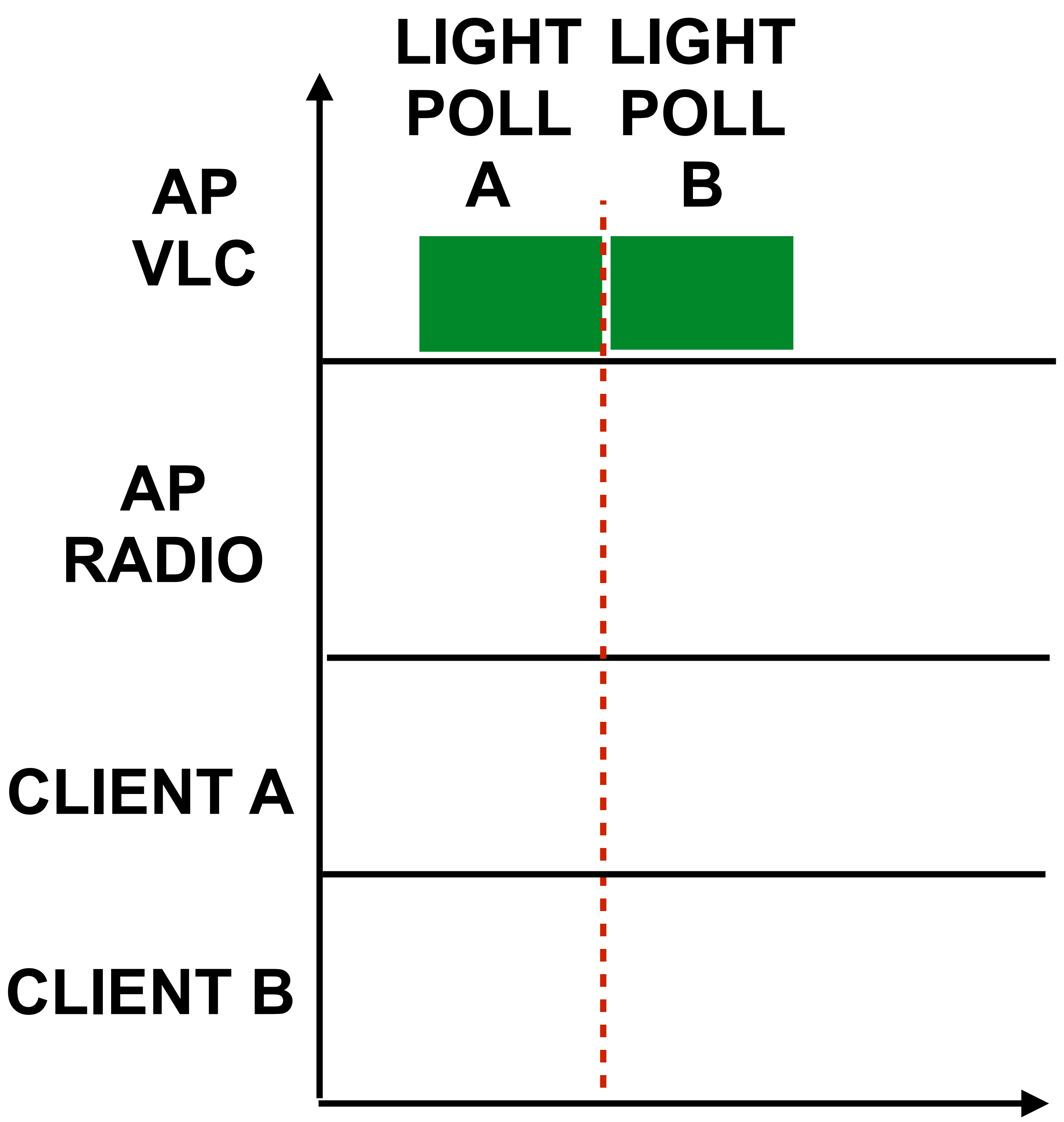
Contention-Free Access

Sensor traffic generation unknown to AP

- **RF Only:**

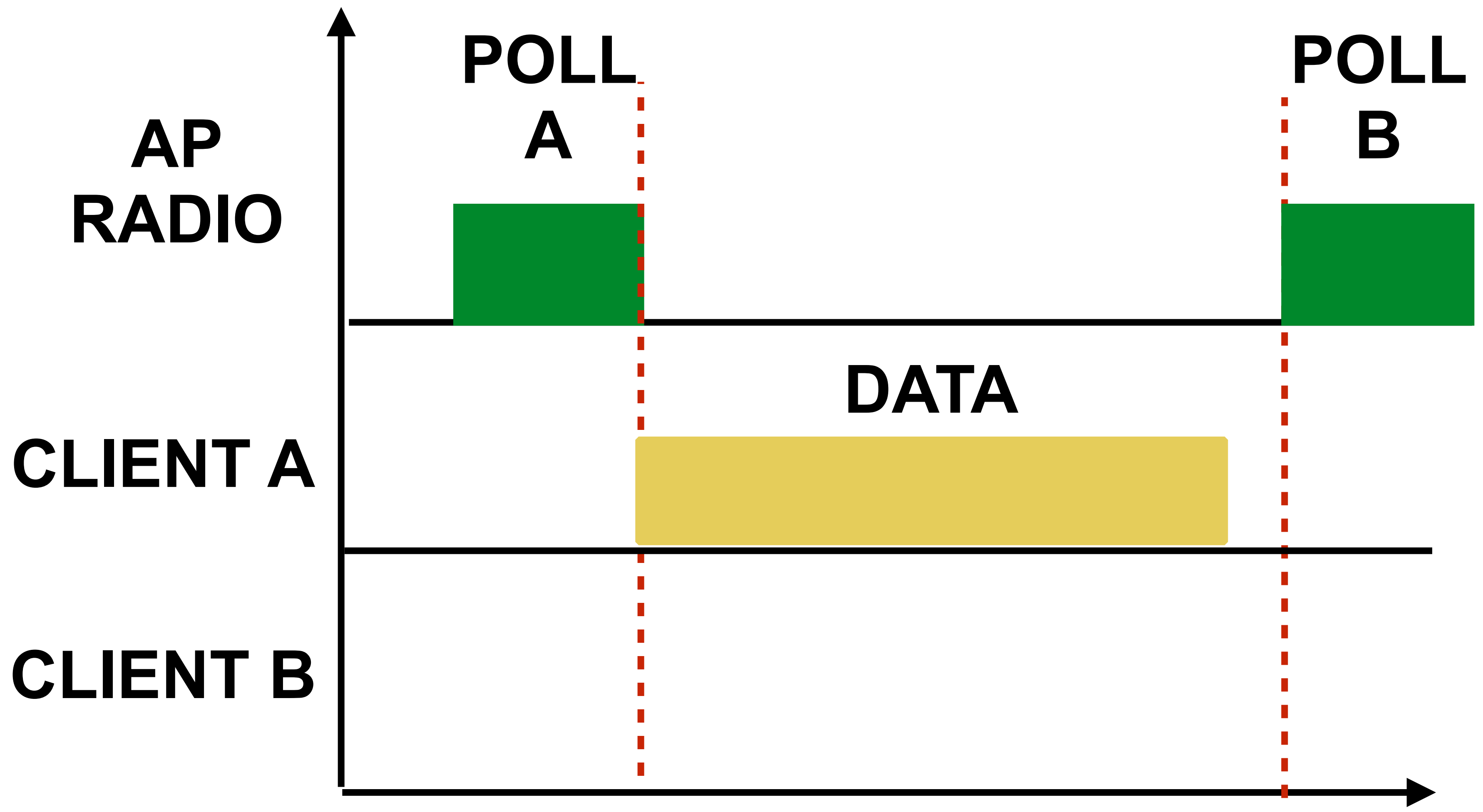


- **VLC Control:**

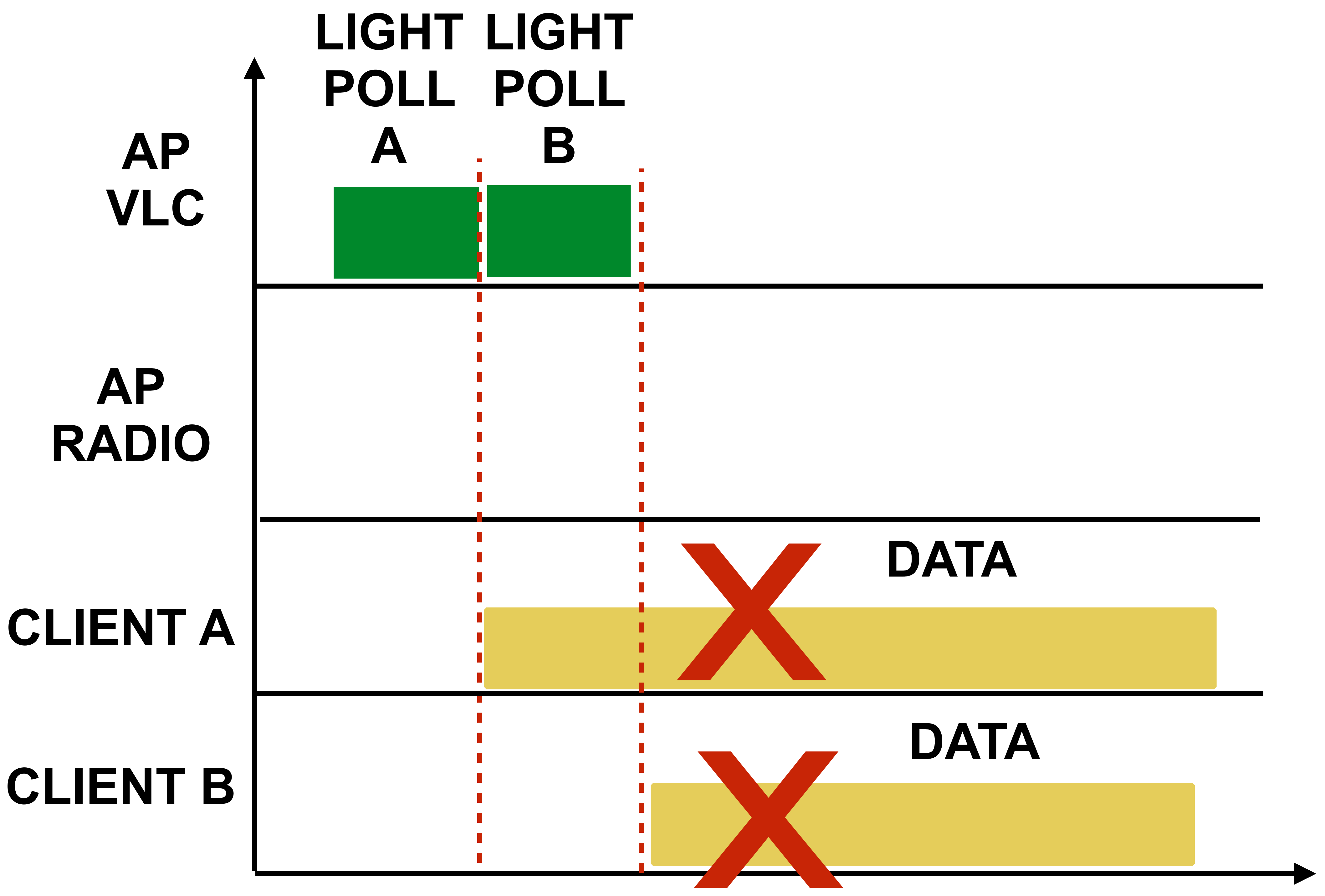


Contention-Free Access

- **RF Only:**

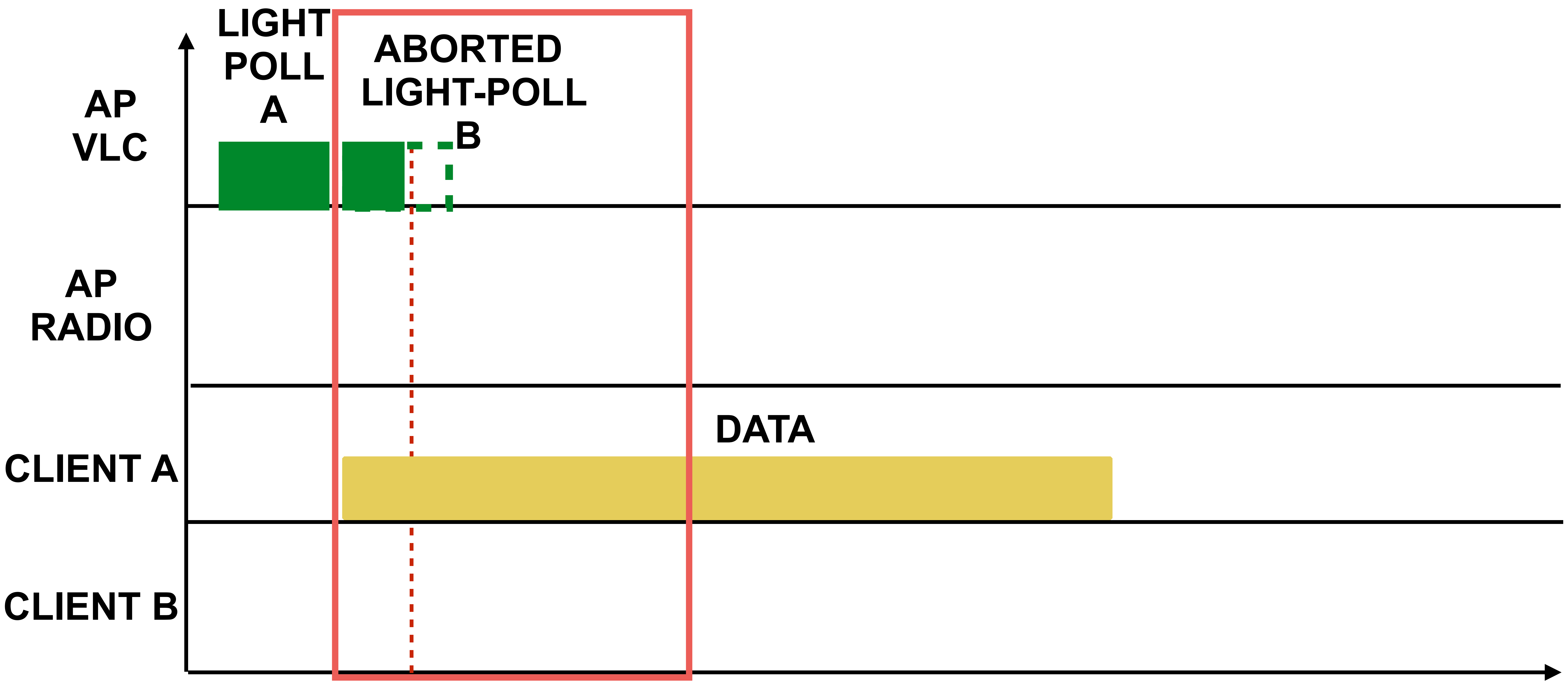


- **VLC Control:**



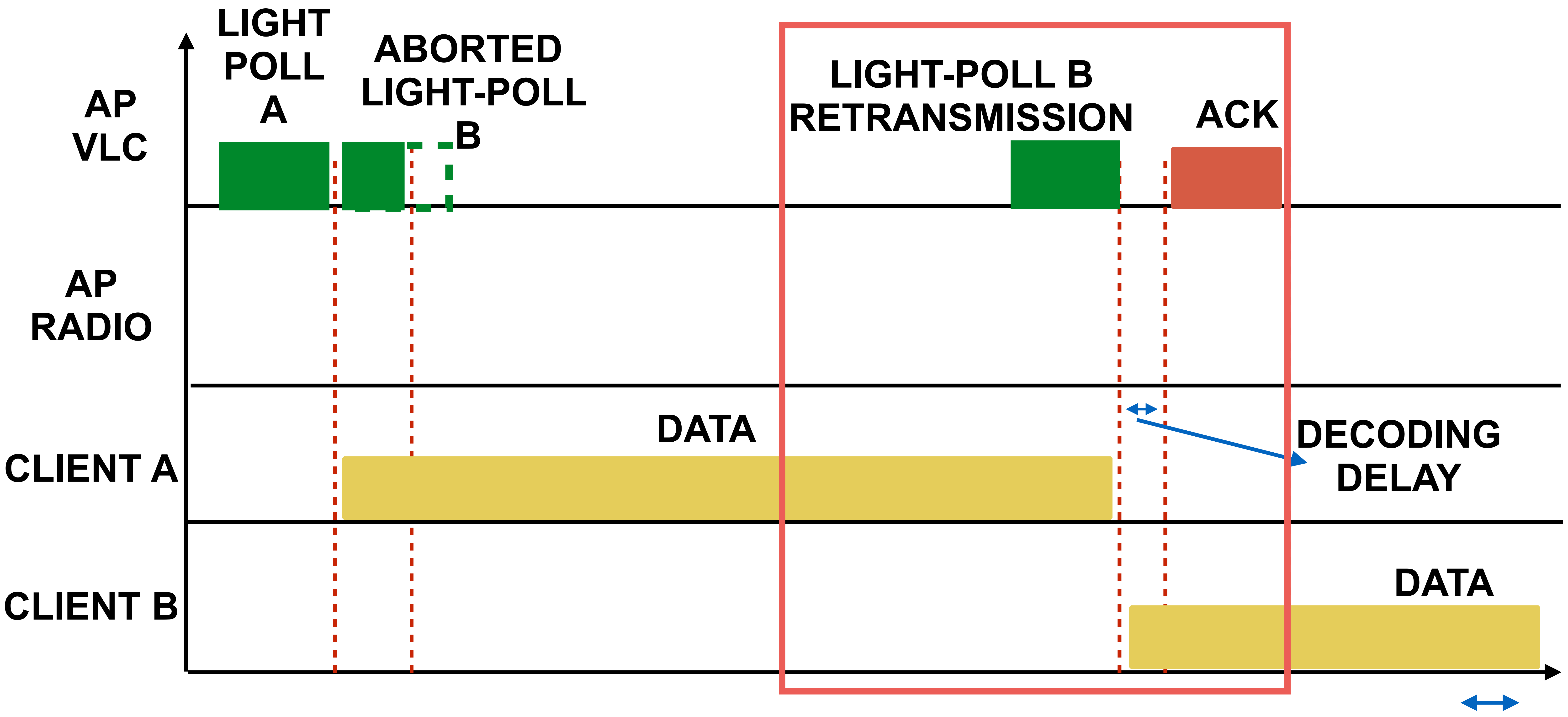
Can we perform pipelined polling and still avoid collisions?

LiSCAN Pipelined Polling



- **Light poll abortion**
  - Preemptive collision avoidance mechanism at AP

LiSCAN ACK over VLC



- **Light-Poll Retransmission Alignment**
  - Enables pipelined uplink transmissions
- **ACK over VLC**
  - Minimizes radio energy consumption

LiSCAN Evaluation

- **Protocols**
  - LiSCAN
  - Contention-based radio access
  - Contention-free radio access

ns-3
NETWORK SIMULATOR

- **Sensor traffic model**
  - Poisson Pareto burst process [1]
  - 10 ms mean burst time length with 100 kbps data generation

- **Packet Model**
  - 100 byte packet aggregation

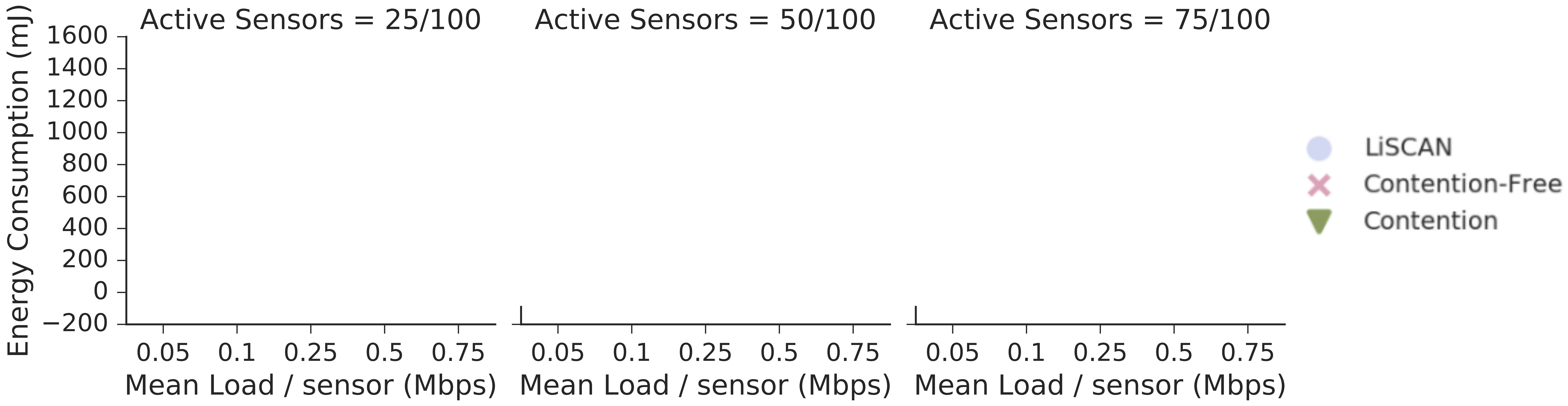
[1] Ammar et al., "A new tool for generating realistic internet traffic in ns-3," in *Proc. of International Conference on Simulation Tools and Techniques*, 2011

Simulation Setup

- **Network**
  - One hundred sensors
- **Simulation Time**
  - 1 second
- **Polling**
  - Randomized round-robin mechanism
- **Energy Consumption**
  - Typical sensor consumption states [1,2]
- **Varying Traffic**
  - Fraction of sensors generating traffic (**Active Sensors**)
  - Mean offered load per active sensor

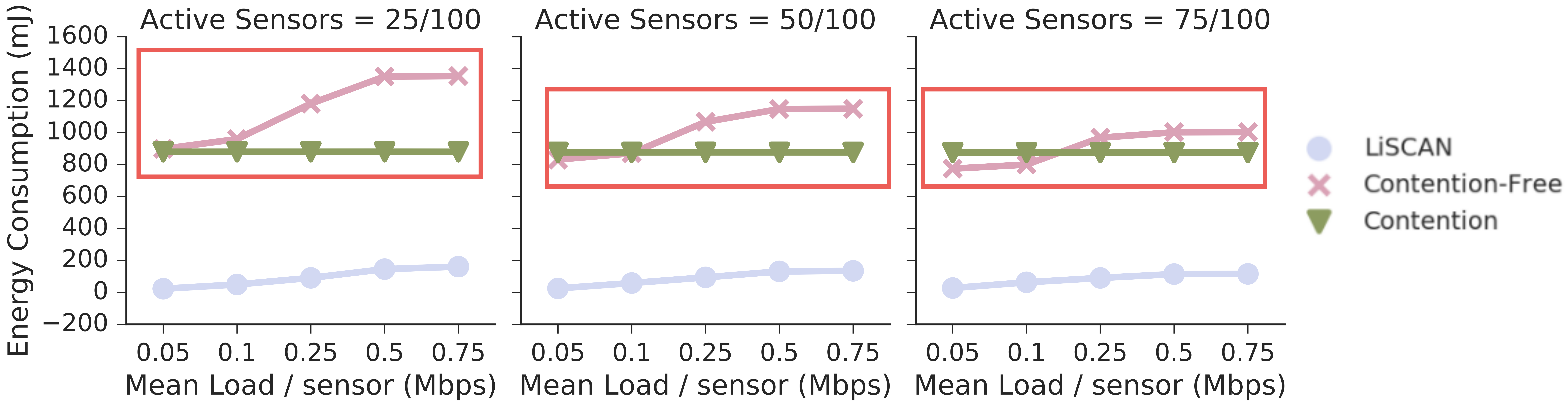
[1] Wan et al., "Modeling energy consumption of wireless sensor networks by systemc." in *Proc. of IEEE ICSNC,* 2010.
[2] Abo-Zahhad et al., "An energy consumpton model for wireless sensor networks," in *Proc. of IEEE ICEAC*, 2015.

Energy consumption



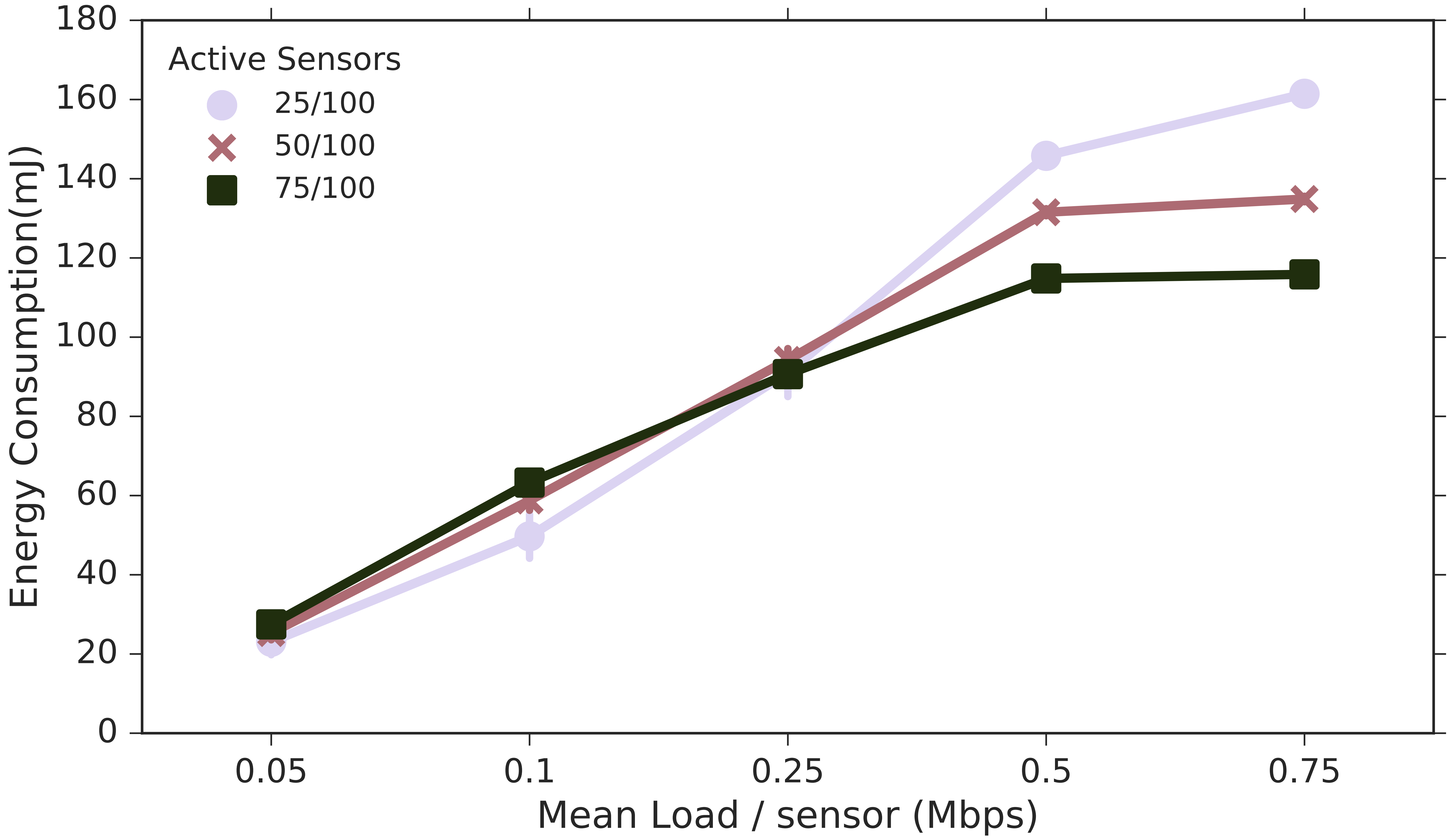
- **Metric**
  - Mean energy consumption per active sensor

Energy Consumption



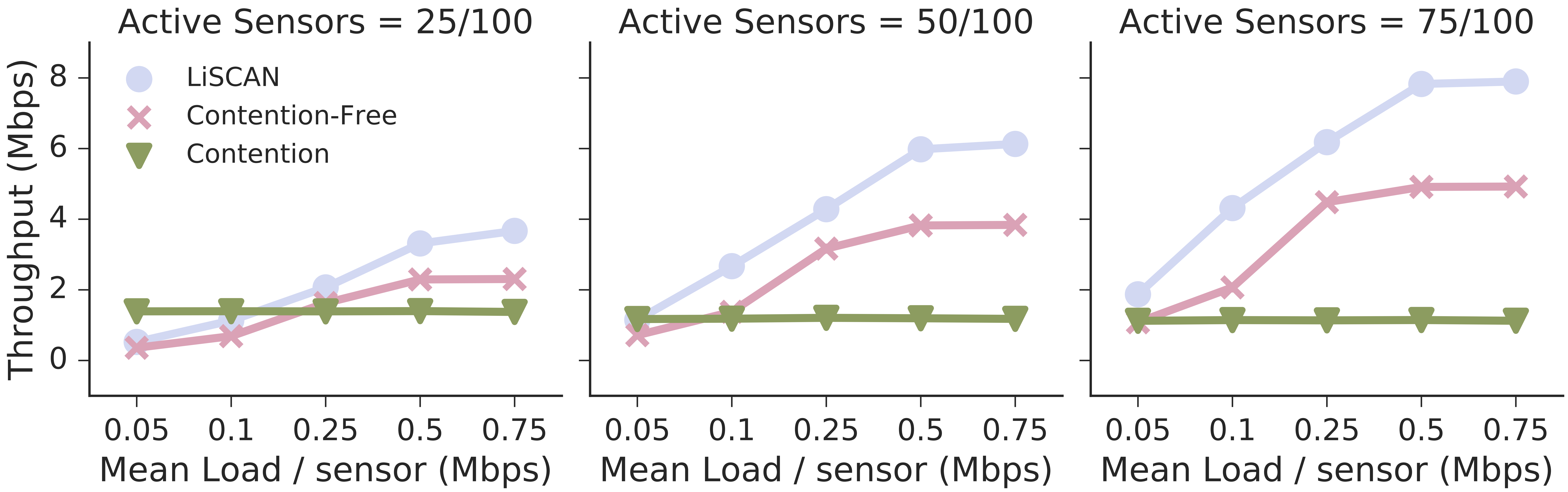
- **Contention-based strategy**
  - Negligible increase in transmission due to heavy traffic load
- **Contention-free strategy**
  - Transmission time increases with offered load before saturation
  - Transmission time per sensor decreases with increasing number of active sensors

LiSCAN Energy Consumption



- **LiSCAN**
  - Over 5x reduction in energy consumption
  - Radio awake only for data transmission
  - Consumption by VLC wake-up receiver equal to radio sleep mode

Aggregate Throughput



- **Low traffic**
  - Polling overhead dominates performance in contention-free strategies
- **Moderate-to-high traffic**
  - LiSCAN's virtual full-duplex operation doubles data transmission time

Related Work

- **Radio-based contention**
  - Bi-directional wideband radio channel [1], full-duplex radios [2]

In contrast: VLC uni-directional control channel with negligible energy consumption

- **Low-power radio**
  - Active wake-up receiver with energy shared with the sensor
  - Synchronous traffic wake-up with FM low-power radio [3]

In contrast: Energy-autonomous VLC wake-up in LiSCAN for asynchronous traffic

- **Asynchronous energy-saving MAC protocols**
  - Do not eliminate radio channel sensing [4]

In contrast: In LiSCAN, radio awake only for data transmission

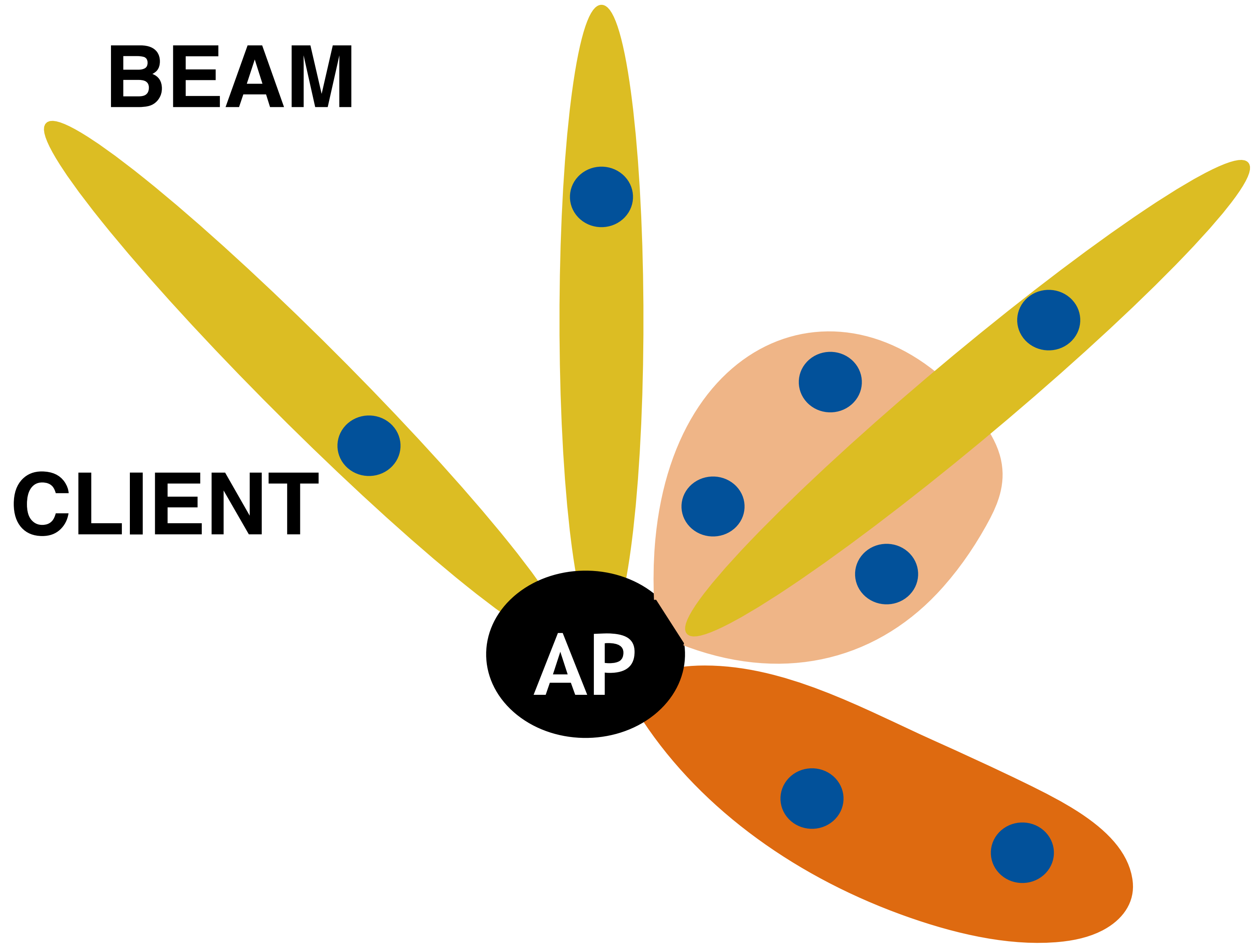
[1] Chintalapudi et al. "WiFi-NC: WiFi over narrow channels." in *Proc. of USENIX NSDI*, 2012.
[2] Magistretti et al., "WiFi-Nano: Reclaiming WiFi Efficiency Through 800 ns Slots," in *Proc. of ACM MobiCom*, 2011.
[3] Dias et al. "Green wireless video sensor networks using FM radio system as control channel," in *Proc. of IEEE/IFIP WONS*, 2016.
[4] Rault et al. "Energy efficiency in wireless sensor networks: A top-down survey," *Computer* Networks, July 2014.

Thesis Contributions

RICE

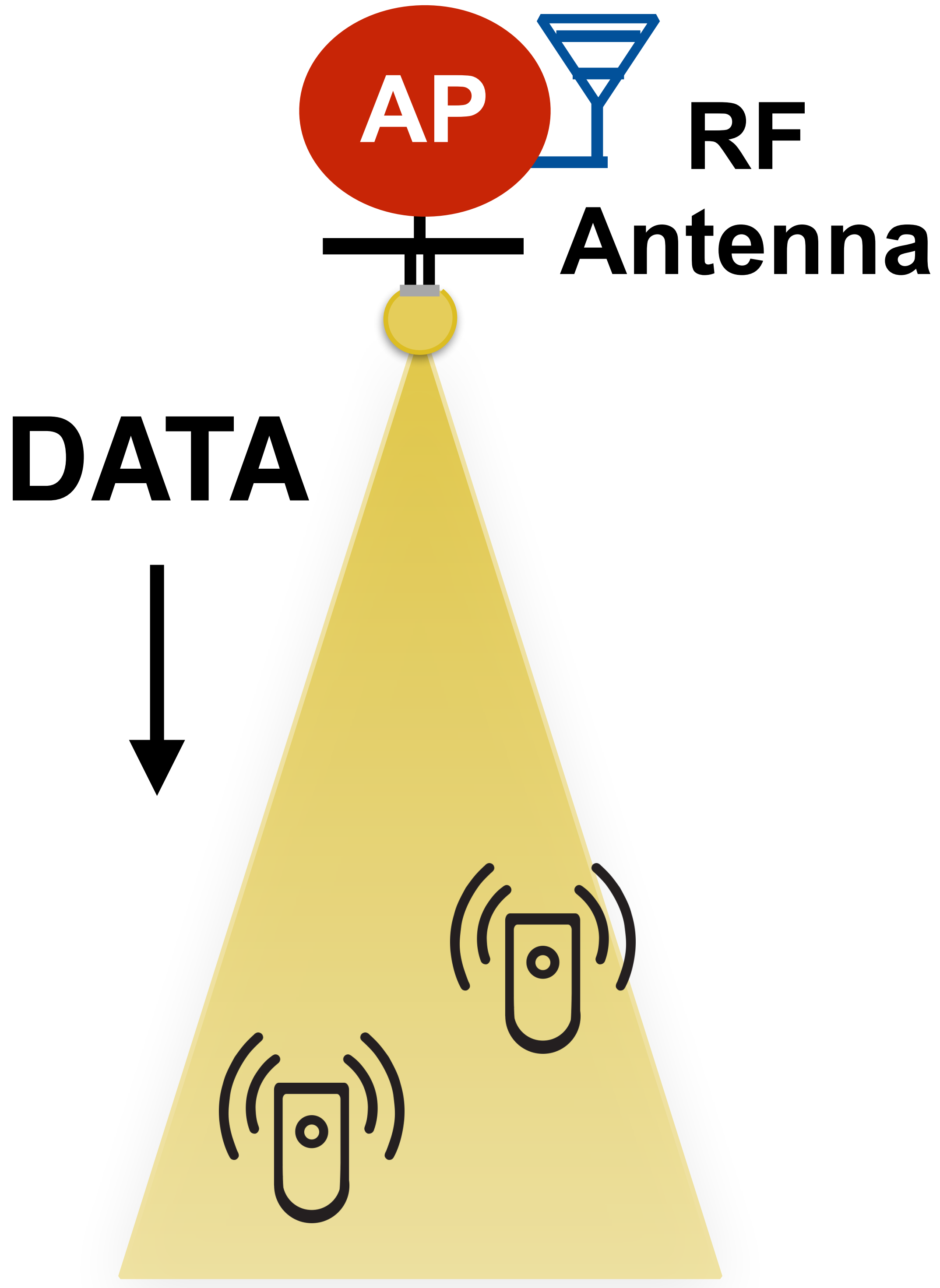
60 GHz

Scalable Directional Multicast

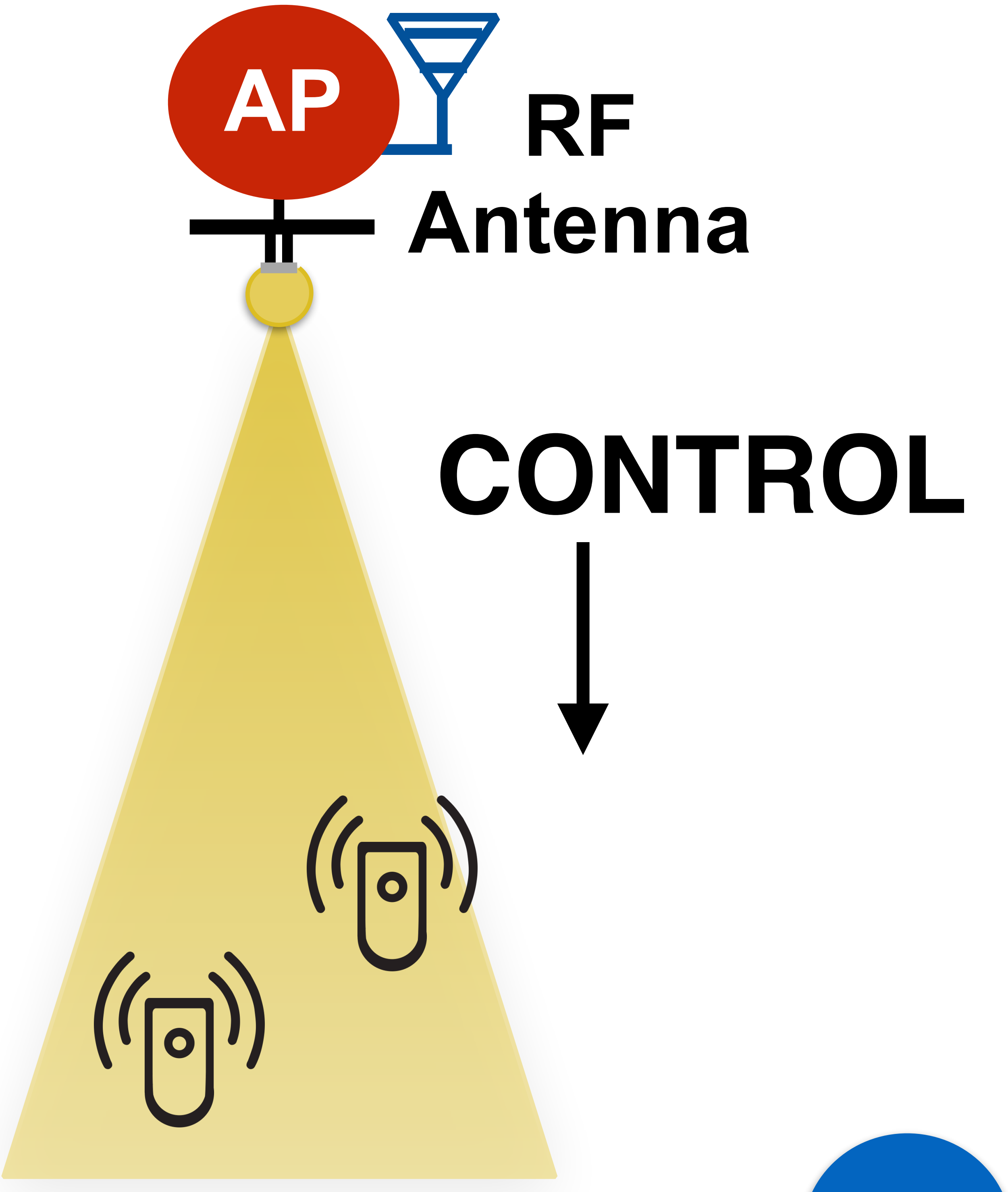


Visible Light

LiRa



LiSCAN



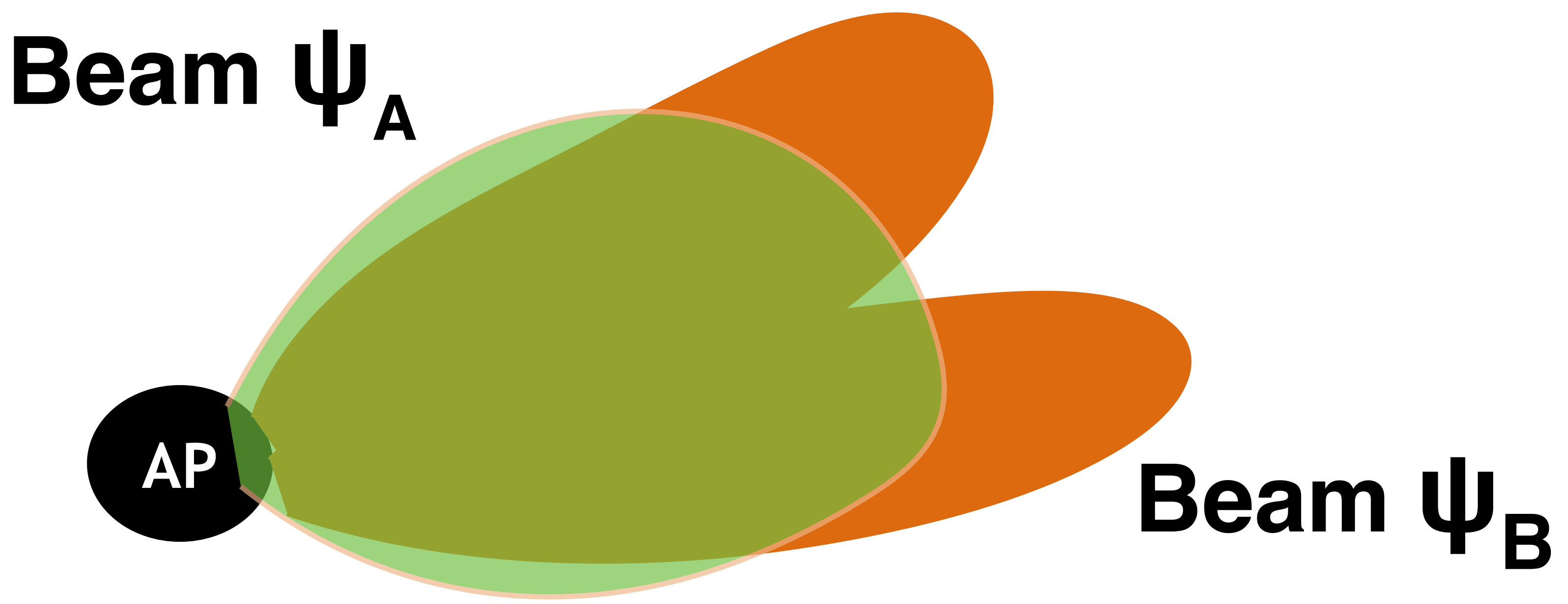
Acknowledgements

- Dr. Edward Knightly
- Dr. Behnaam Aazhang, Dr. Eugene Ng, Dr. Lin Zhong
- Rice Networks Group, Adriana, Joe, Erica, Ethan
- My family
- 8-monkeys and extd., Hike and Spike, Here Comes the Sun
- Indian Students at Rice, Rice ECE GSA, RCEL SCREECH

BACKUP

Multi-Level Codebook Trees

- **Codebook Trees [1,2]**
  - Leverage the client feedback to prune the training
  - Edges between beam patterns of adjacent levels



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

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

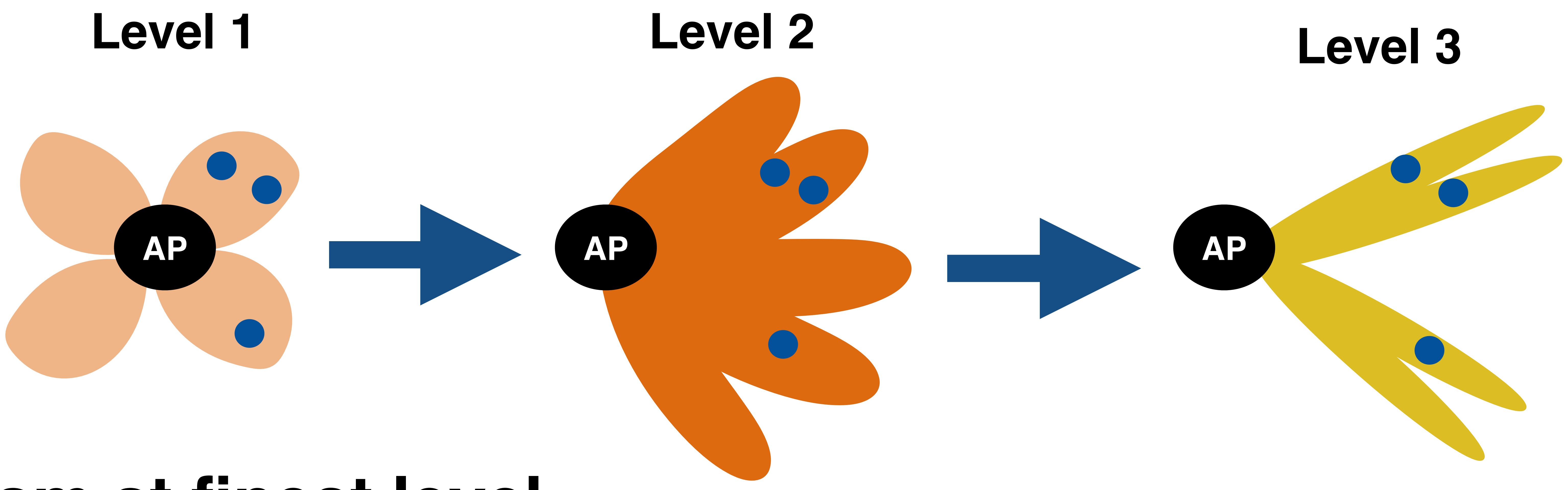
$$\text{Correlation} = |G(\psi_A)^H G(\psi_B)|$$

[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*, Nov 2011

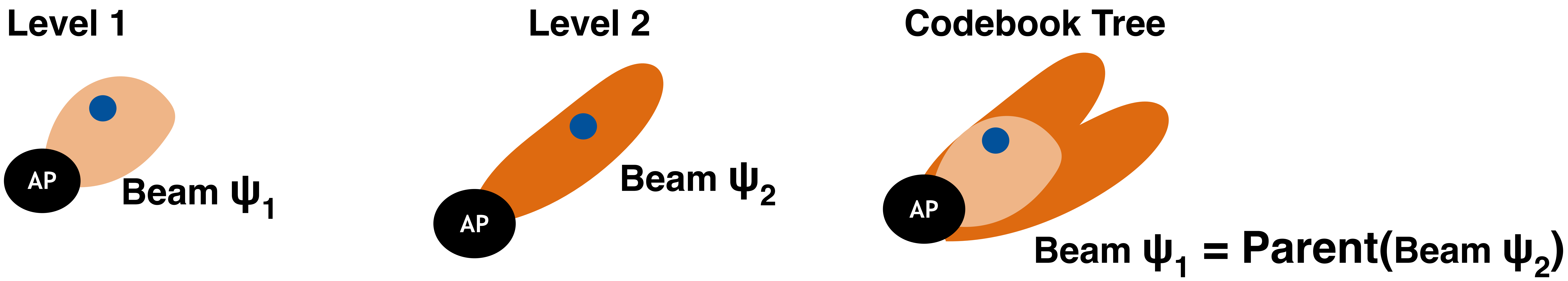
[2] S. Hur, T. Kim, D. Love, J. Krogmeier, T. Thomas, and A. Ghosh, "Multilevel millimeter wave beamforming for wireless backhaul," in *Proc. of IEEE GLOBECOM*, 2011

Basic Codebook Traversal

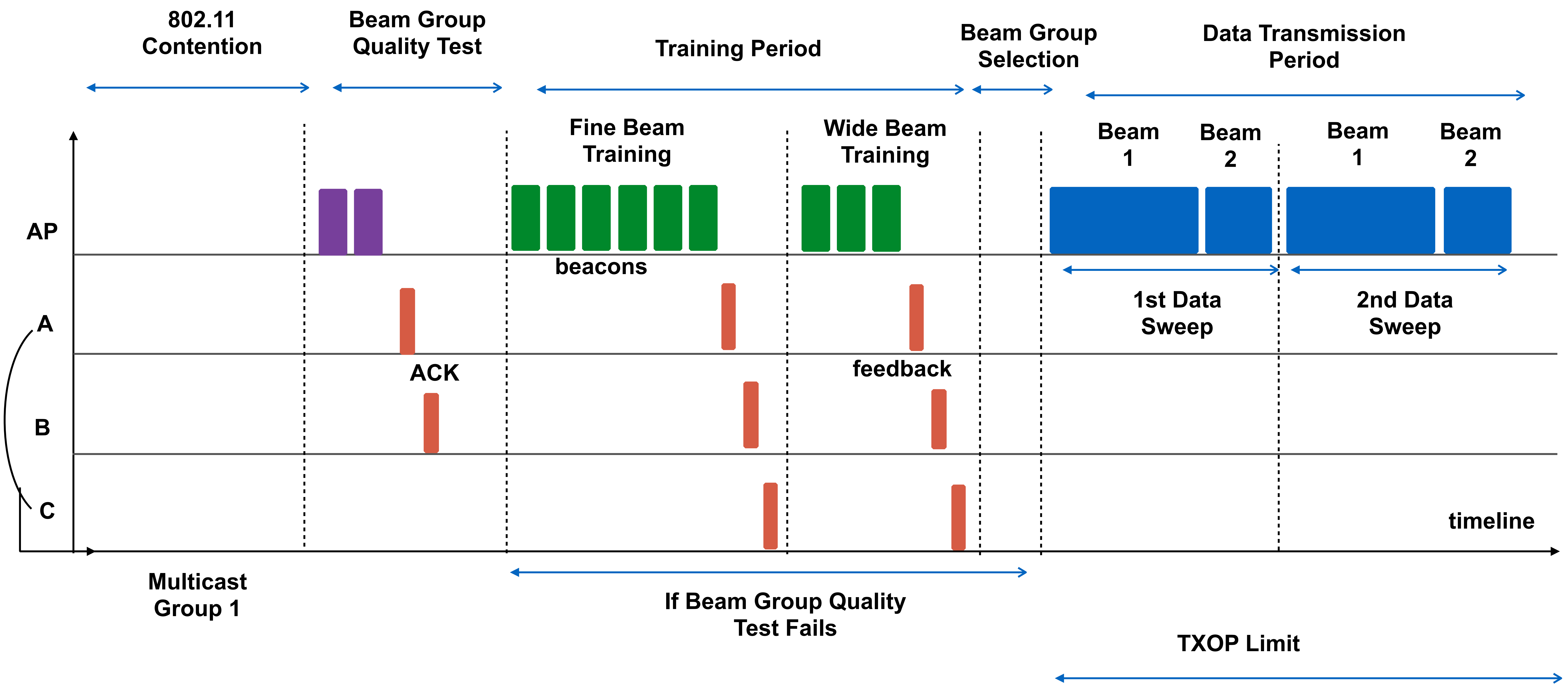
- **Minimal Training**



- **For reaching best beam at finest level**
  - Client reachable at every codebook level
  - Best beams at adjacent levels share parent-child relationship

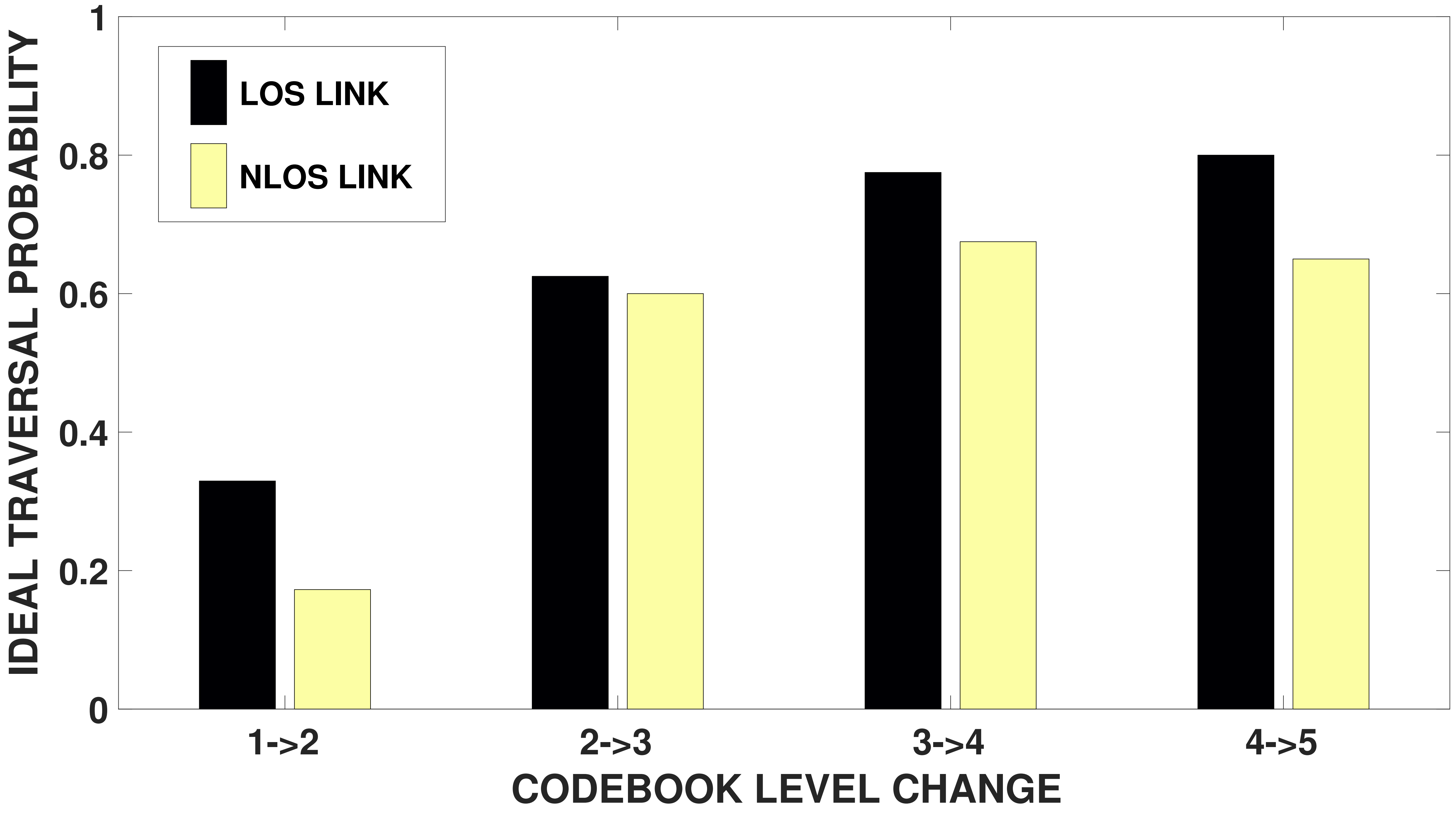


SDM Timeline



Ideal Codebook Traversal Probability

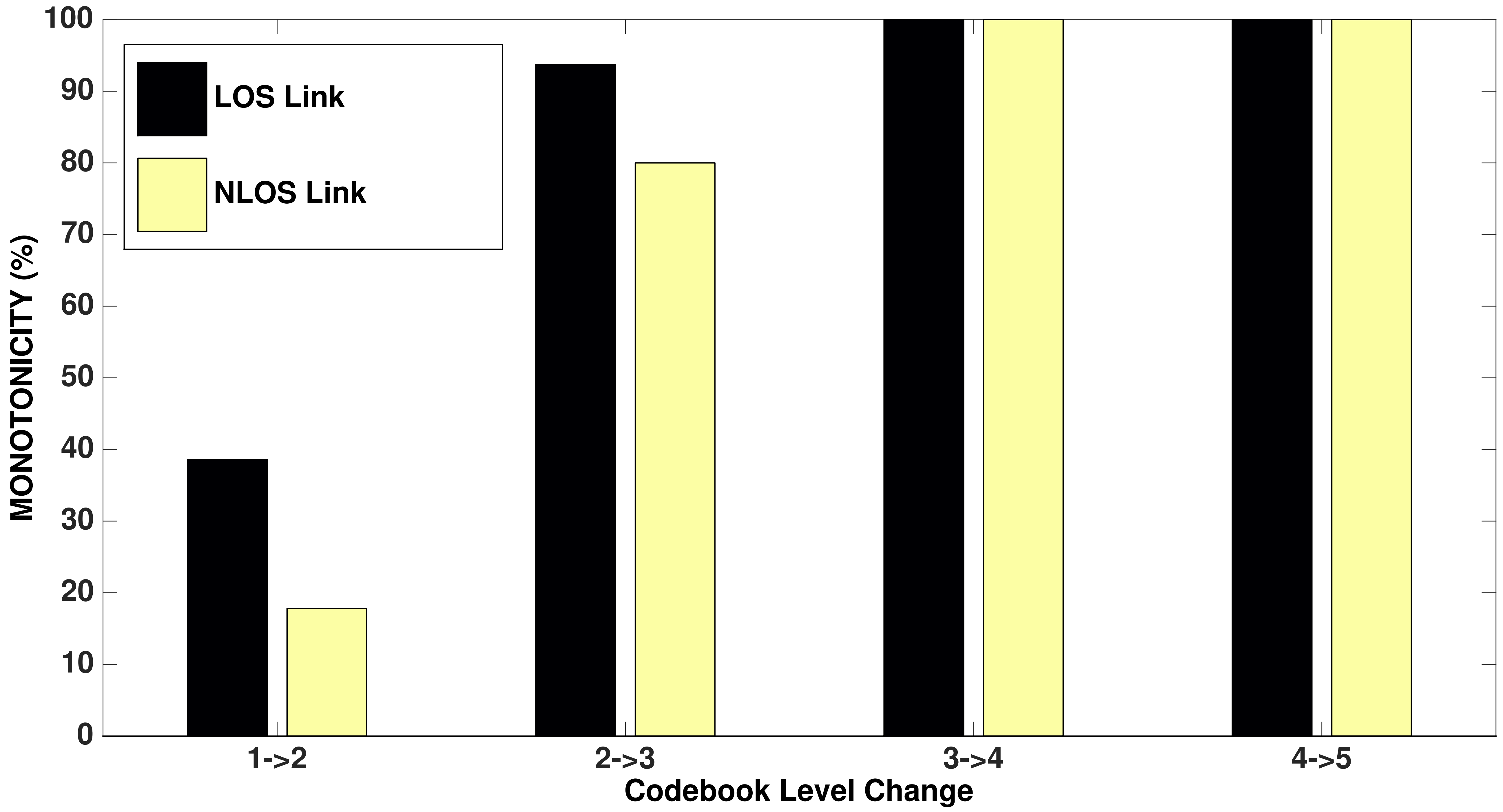
- **Dataset**
  - Each client location
  - Orientation classification
- **Non-line of sight link (NLOS)**
  - Increased path loss
- **Wide beam levels**
  - Low directivity gain



- **Transmission Performance Impact**
  - Sub-optimal beam selection at finest beam level
  - Over 40% reduction in transmission efficiency even for a single client

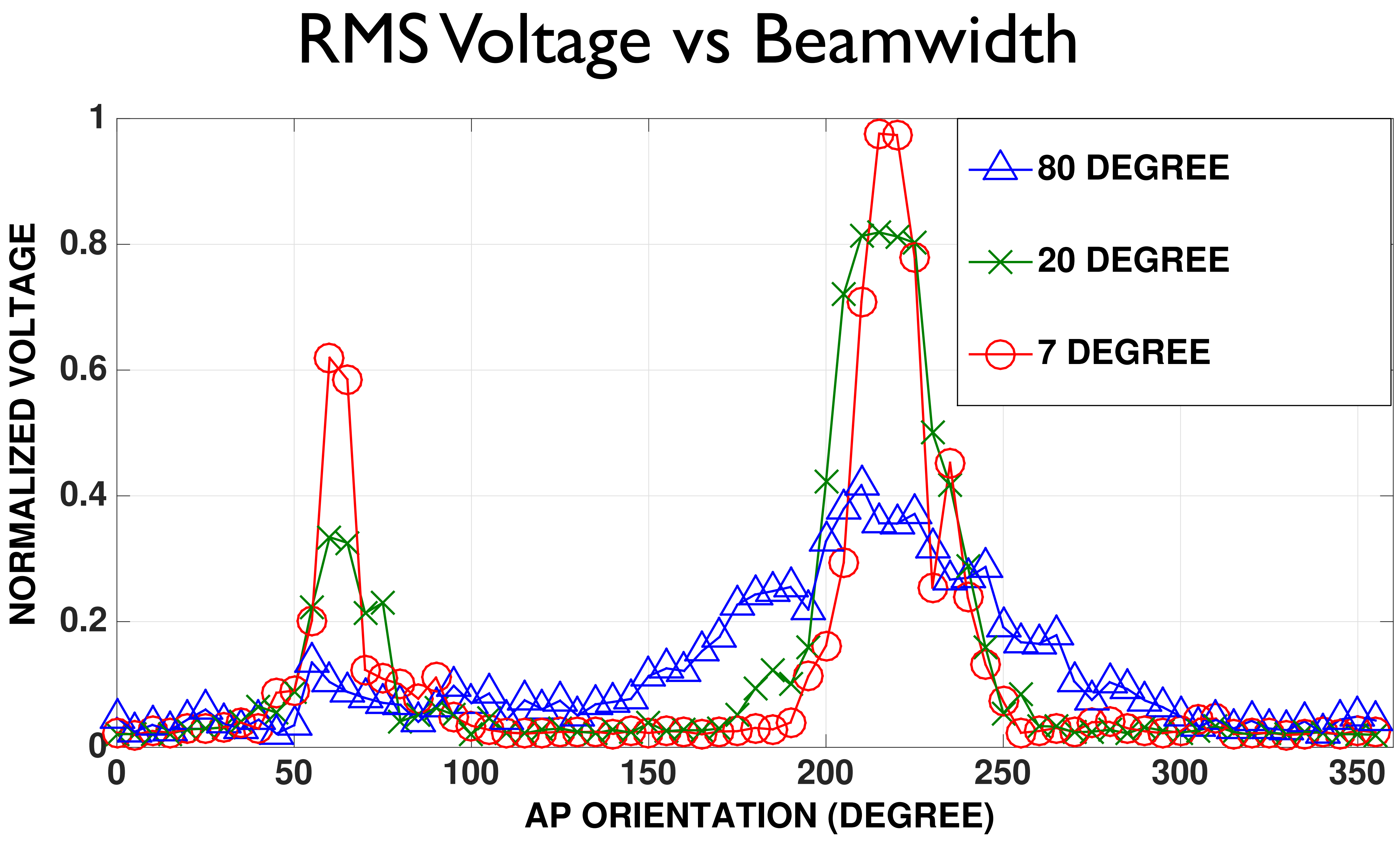
Codebook Traversal Monotonicity

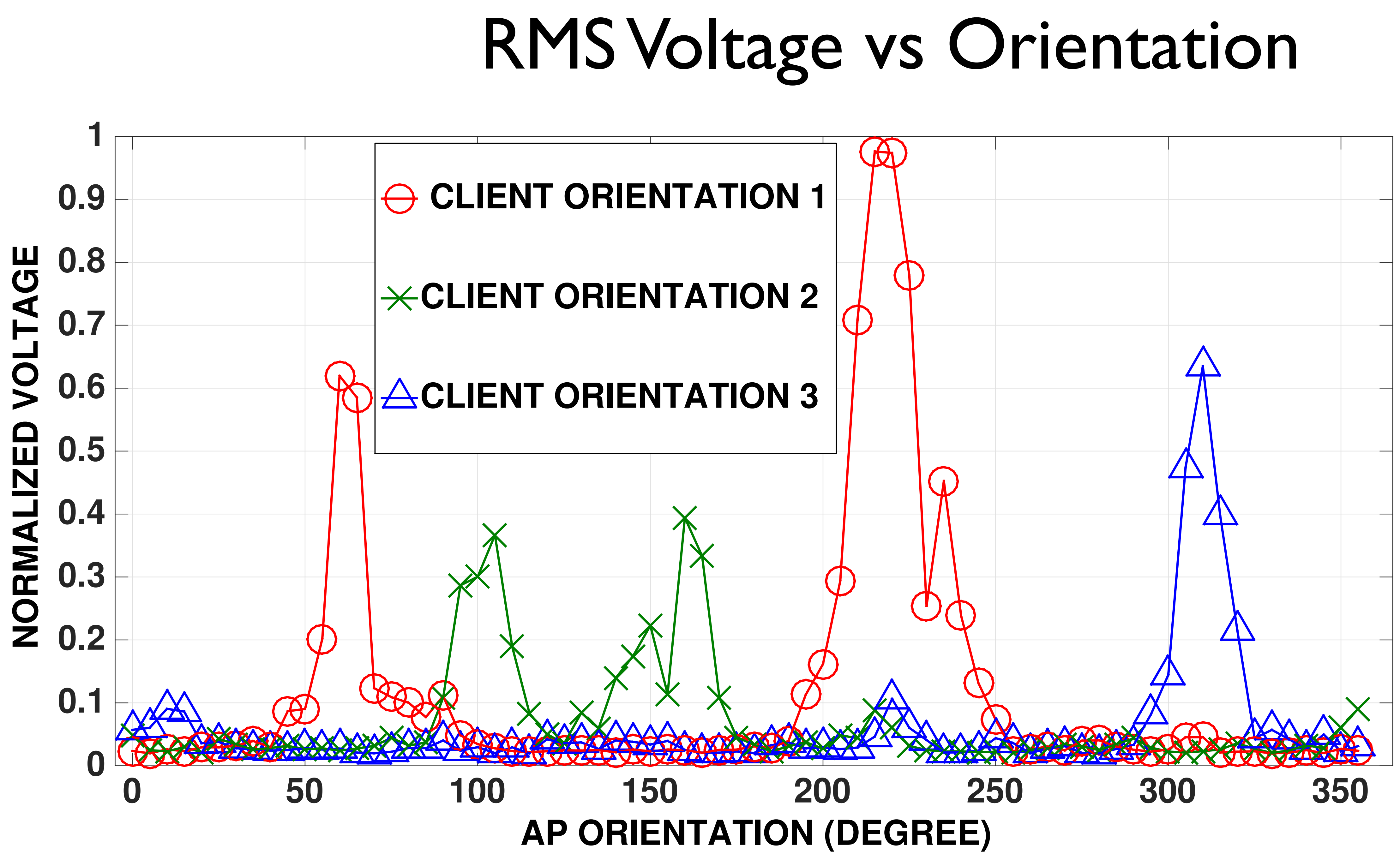
Given the best beam for a client at level “k”, can at least one of its children serve the client?



For wider beam levels, monotonicity is as low as 16%

60 GHz Testbed Measurements

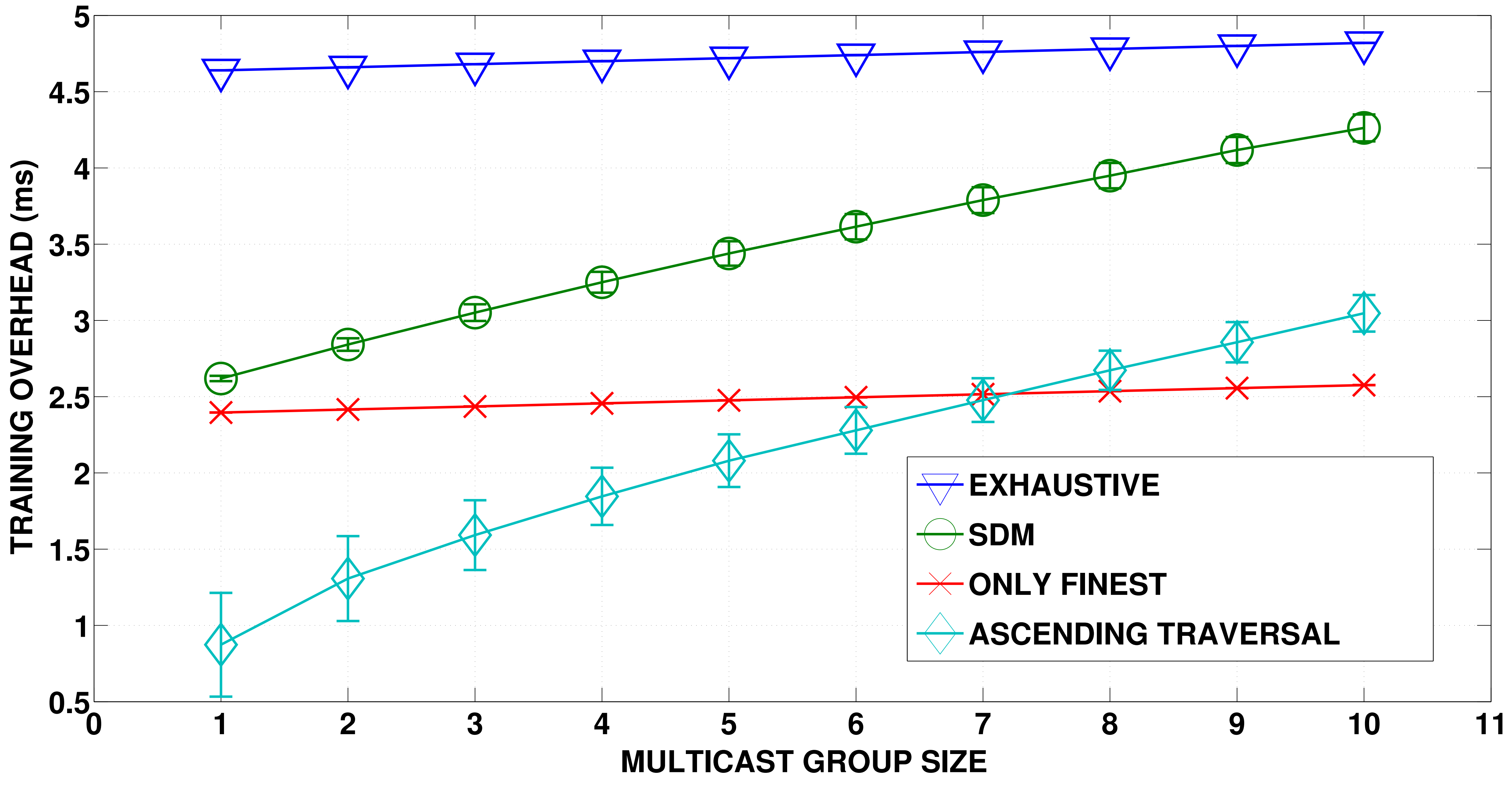




(a) The correlation in peak directions for different AP beamwidth at a fixed client location and orientation. (b) The diversity in the peak directions for different client orientations at a fixed location with 7 degree horn at the AP.

Training Overhead

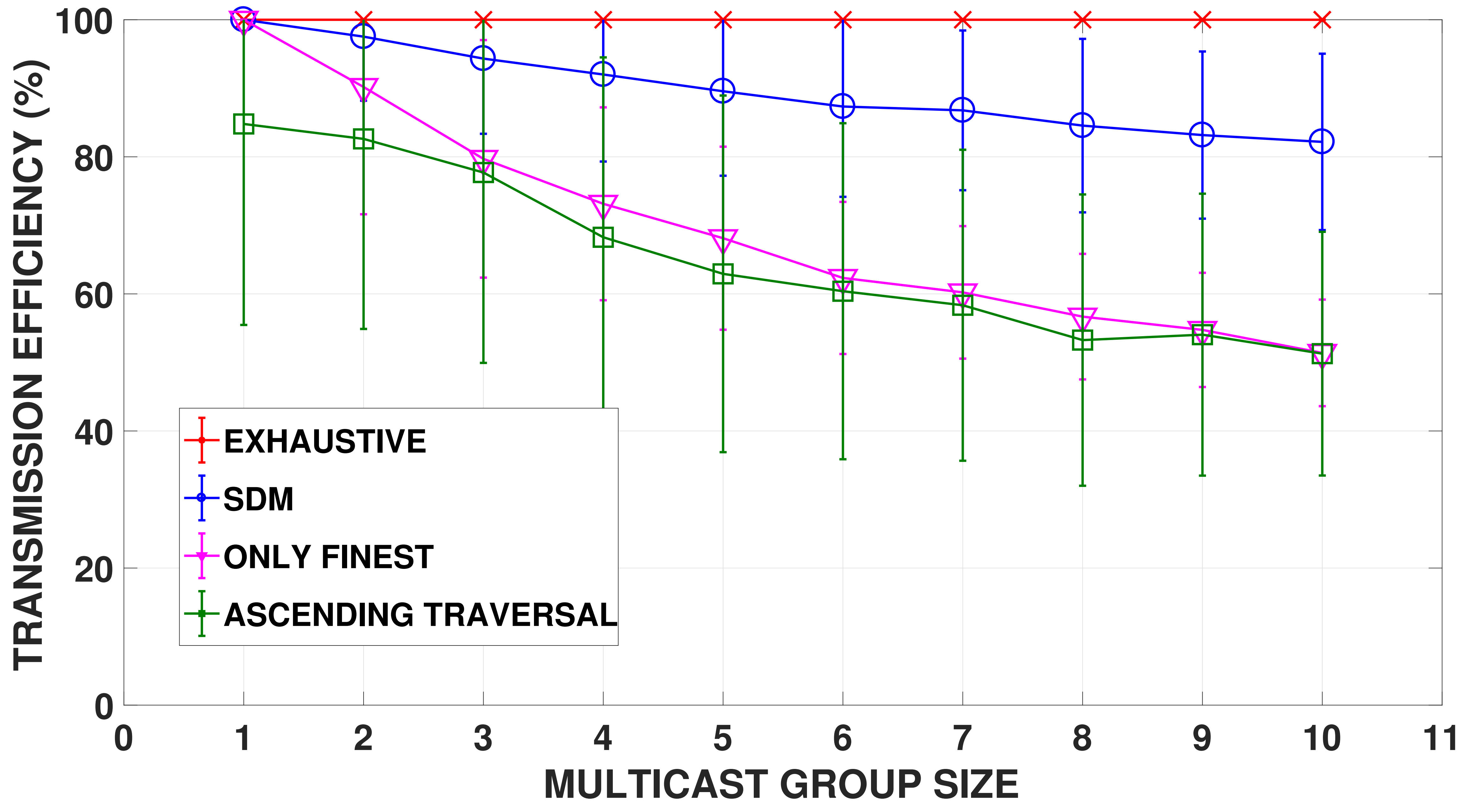
- **Exhaustive and Only Finest Beam**
  - Fixed number of beacons
  - Feedback increases with group size
- **Ascending Order Traversal**
  - Only children beams for traversal
  - Exhaustive training for unreachable clients



- **SDM**
  - Up to 44.5% reduction over exhaustive training

Beam Grouping Efficiency

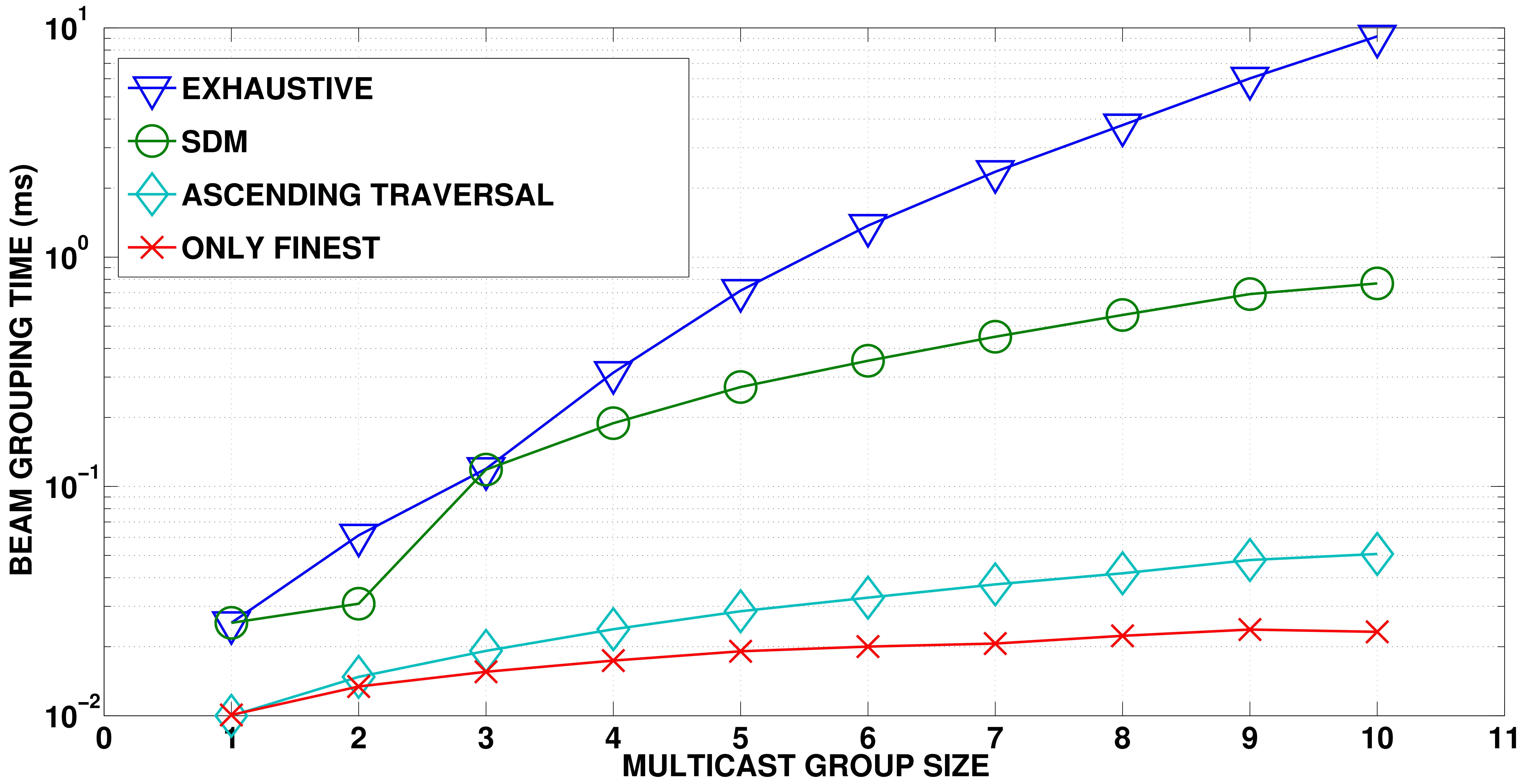
- **Beam Grouping Efficiency**
  - Equal time for data transmission
- **Single Client**
  - Sub-optimal beam for ascending traversal
  - Imperfect codebook traversal
- **Medium group size**
  - Only finest doesn't utilize wide beams



- **Large group size**
  - SDM's mean beam grouping performance within 80% of optimal solution

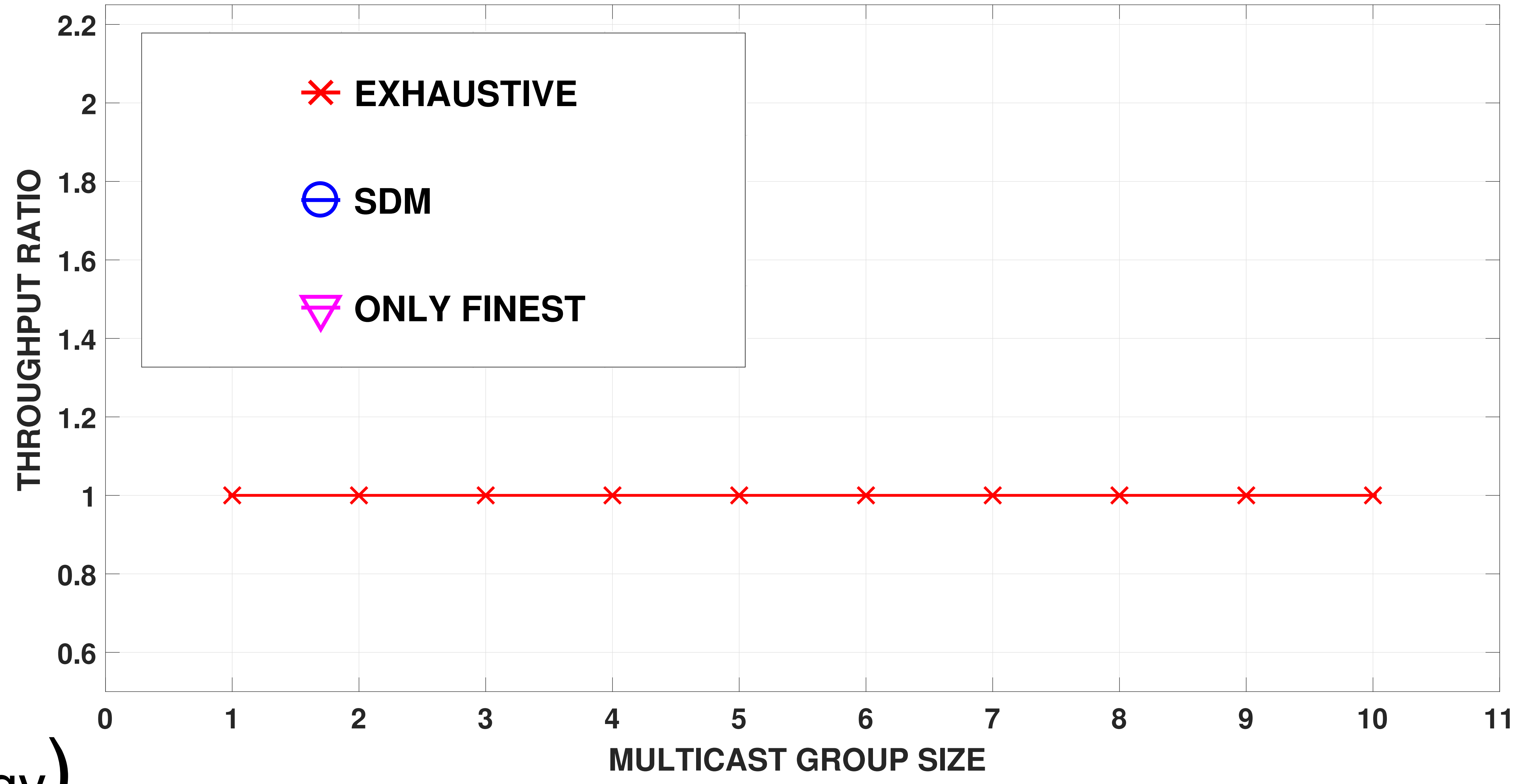
Beam Grouping Computation

- **Beam Grouping Computation**
  - 10 us for only finest beam solution computation with single client



Throughput Performance

- **Factors**
  - Beam Training overhead ($T_{overhead}$)
  - Beam grouping computation ($T_{grouping}$)
  - Beam grouping efficiency ($T_{per\text{-}sweep}$)

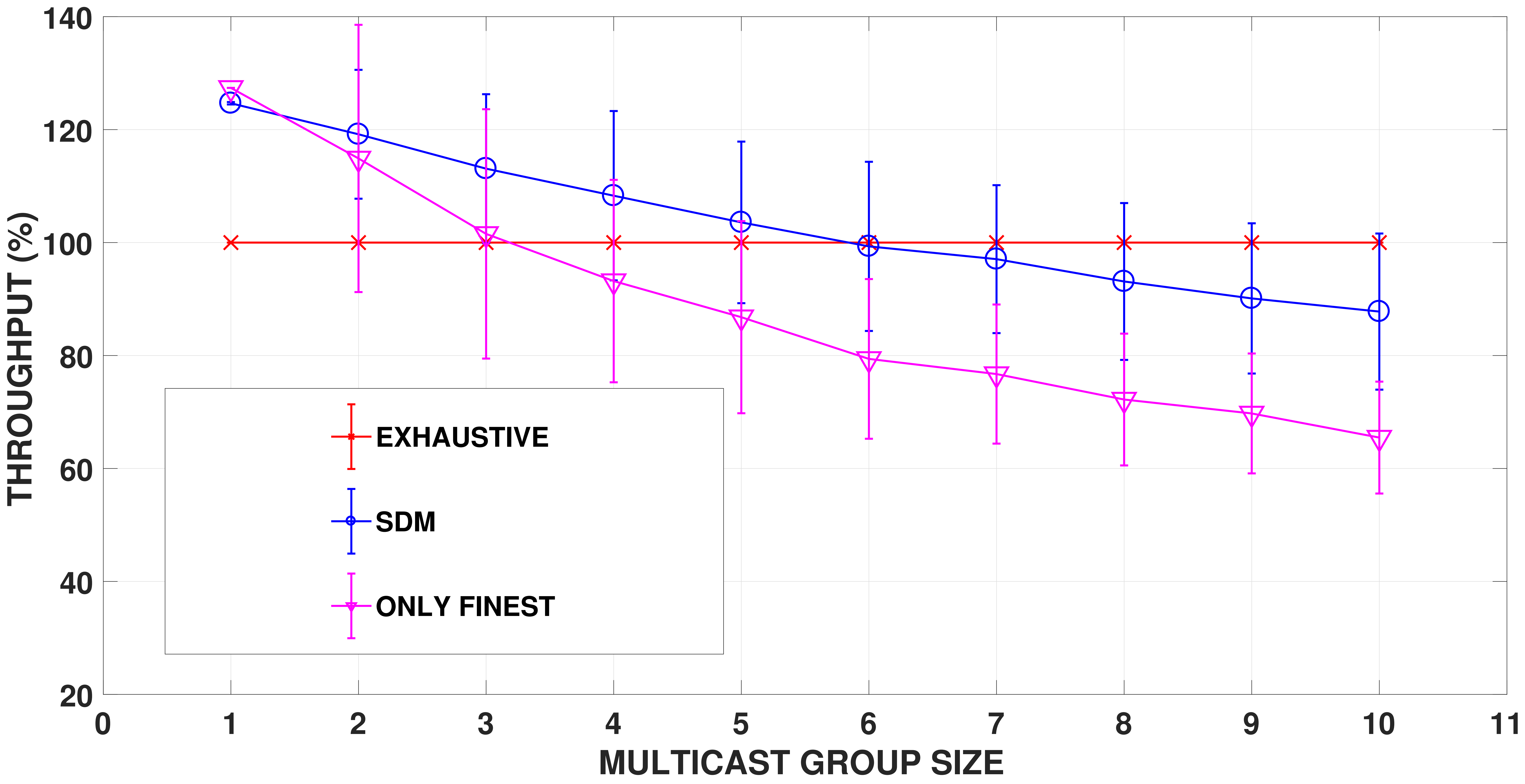


- **Data Transmission Time**

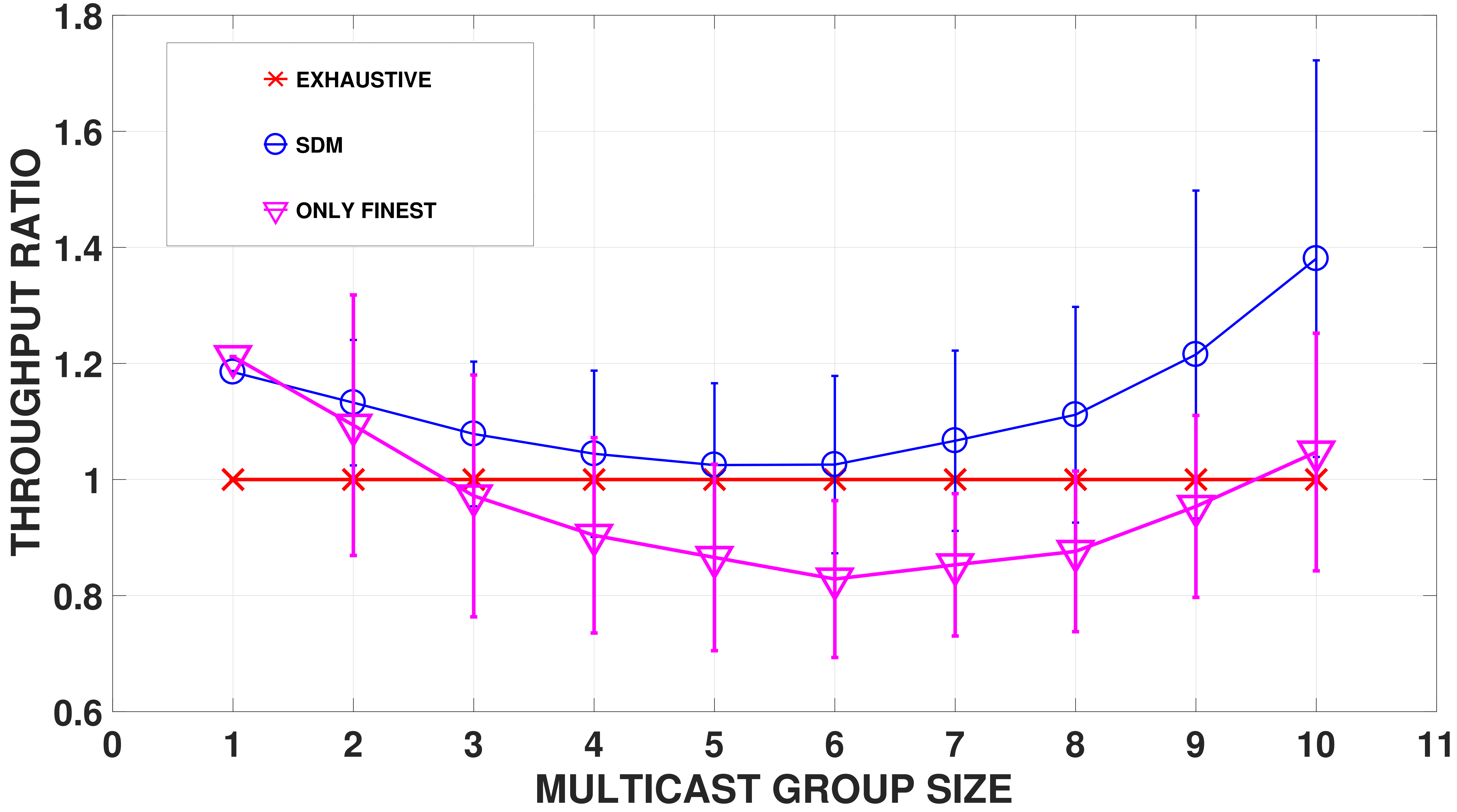
$$T_{TX,strategy} = 8.192\text{ ms} + (T_{training,\ exhaustive} - T_{training,\ strategy}) + (T_{grouping,exhaustive} - T_{grouping,\ strategy})$$

$$Throughput_{strategy} \ \alpha \ T_{TX,strategy} * T_{per\text{-}sweep,strategy}$$

Throughput w/o Grouping Complexity

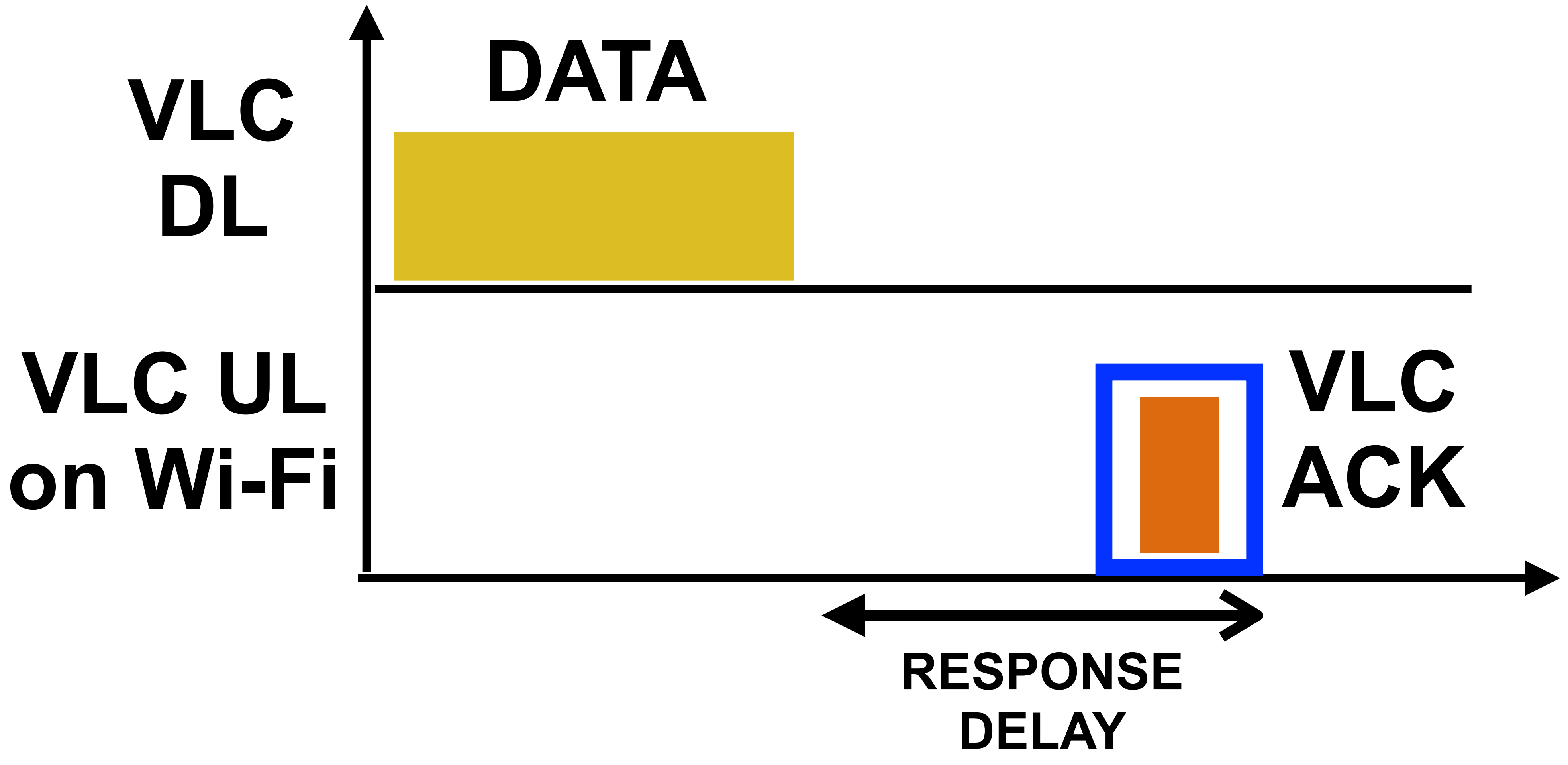


Throughput - Alternative



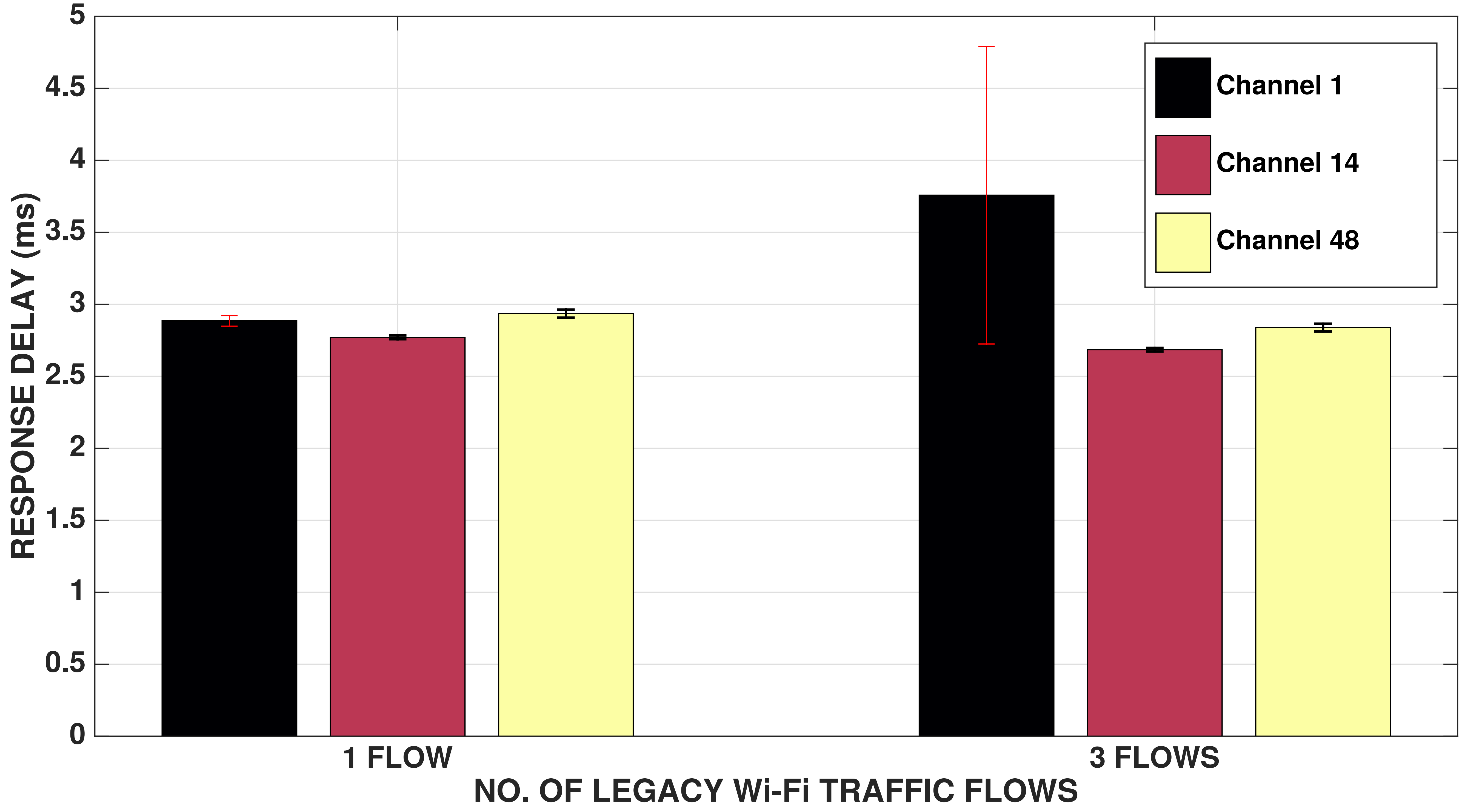
LiRa: Congested Channel Feedback Delay

- **Goal**
  - Analyze the impact of legacy Wi-Fi traffic on LiRa's feedback access delay
- **Metric**
  - Response Delay
  - Computed per VLC downlink packet



- **Experiment**
  - Single LiRa client with feedback trigger time of 4 ms
  - No. of Wi-Fi traffic flows, Wi-Fi channel
- **Hypothesis**
  - Response delay increases with number of traffic flows

LiRa: Congested Channel Feedback Delay



- **Mean response delay < Trigger Time**
  - Frames transmitted in the latter part have delay lower than feedback trigger time
- **Traffic flows**
  - Response delay increases with increase in no. of flows

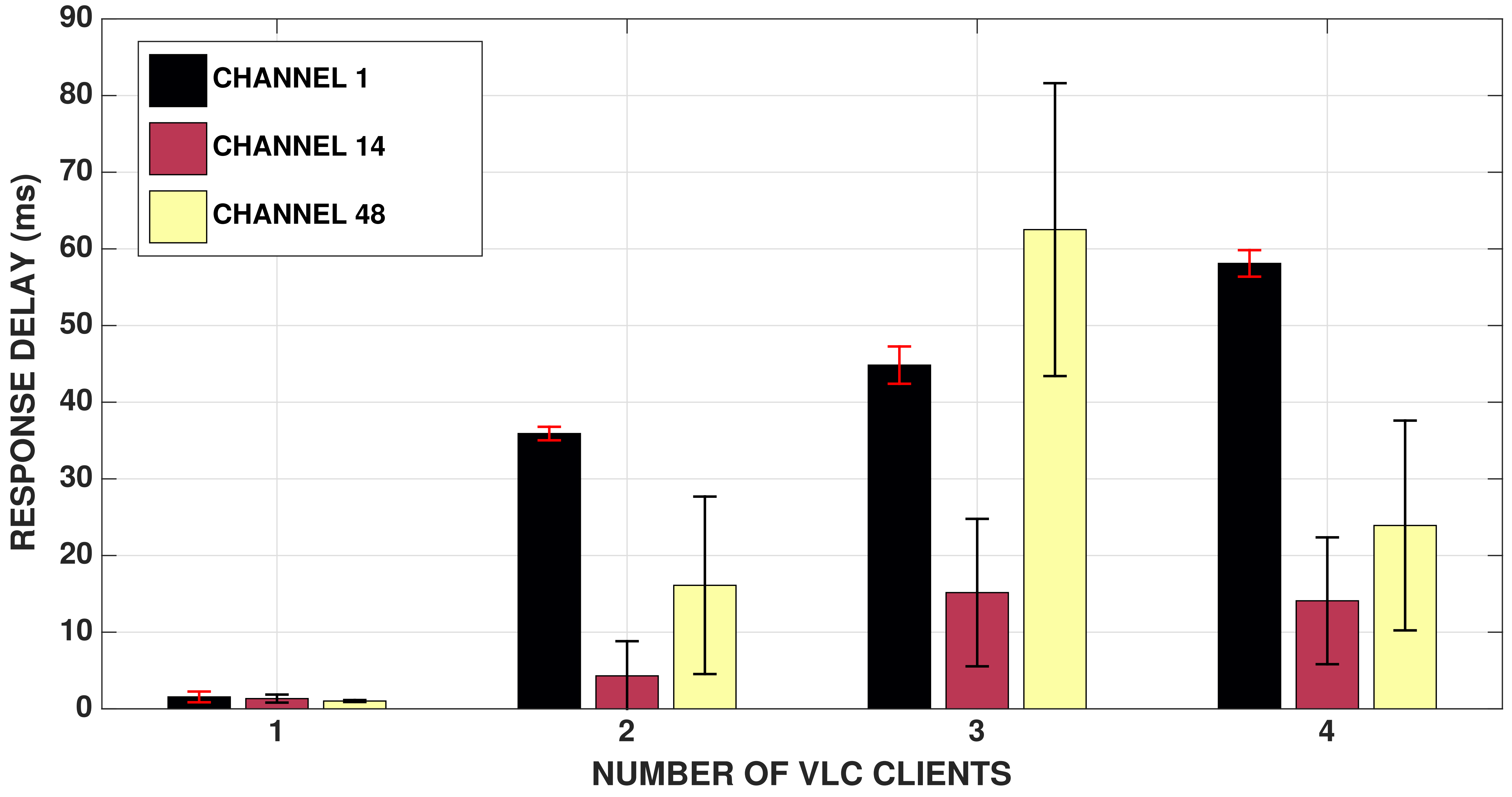
Feedback with Baseline Strategy

- **Per-client Contention (PCC) - Baseline**
  - Each client takes part in 802.11 contention independently
  - Opportunistic aggregation of VLC ACK

- **2 Clients**
  - Channel 1 delay > 35 ms
  - Co-channel interference

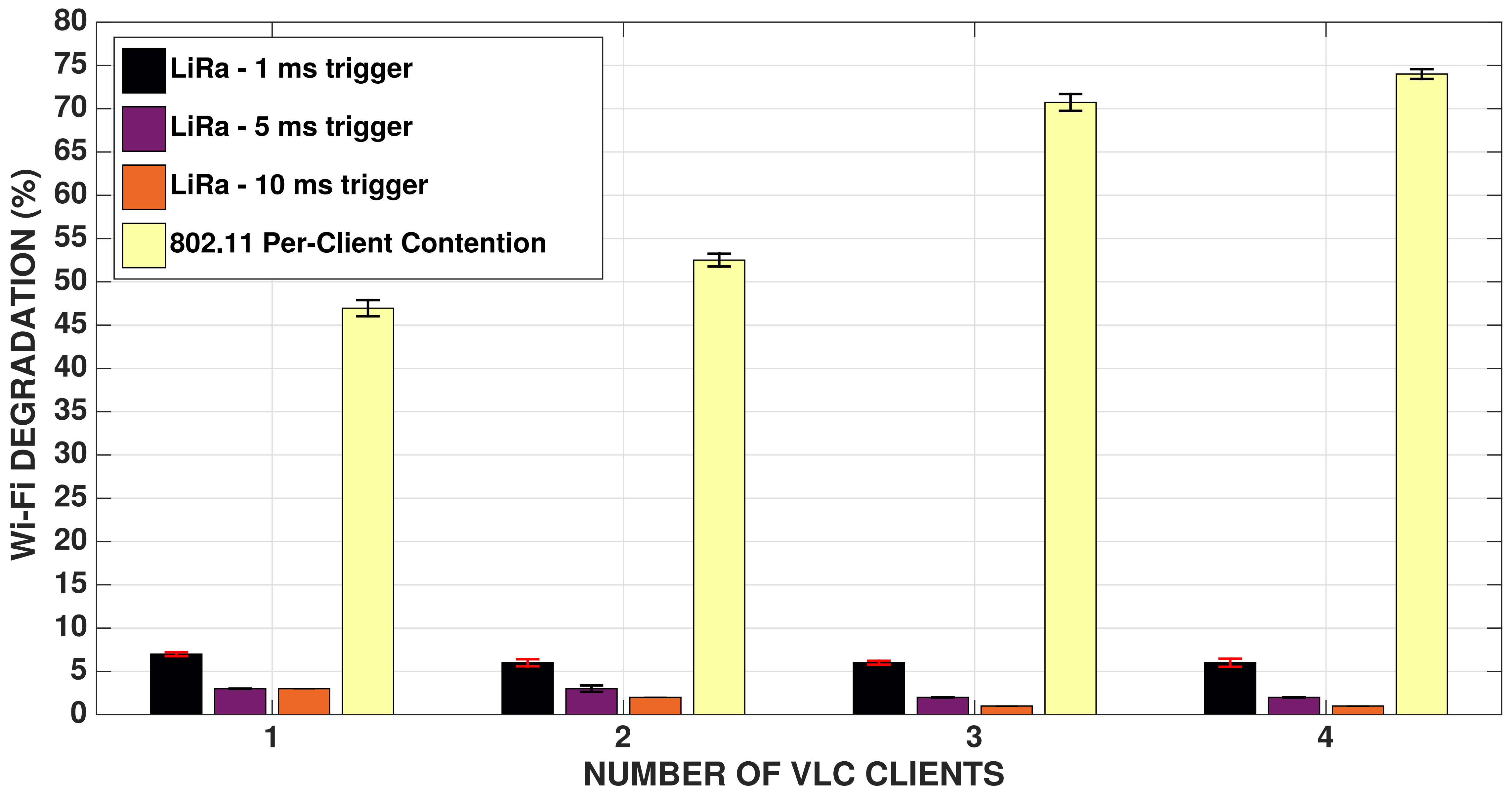
- **3 clients**
  - VLC ARQ and legacy data collide

- **4 clients**
  - Increased probability for VLC clients to win contention



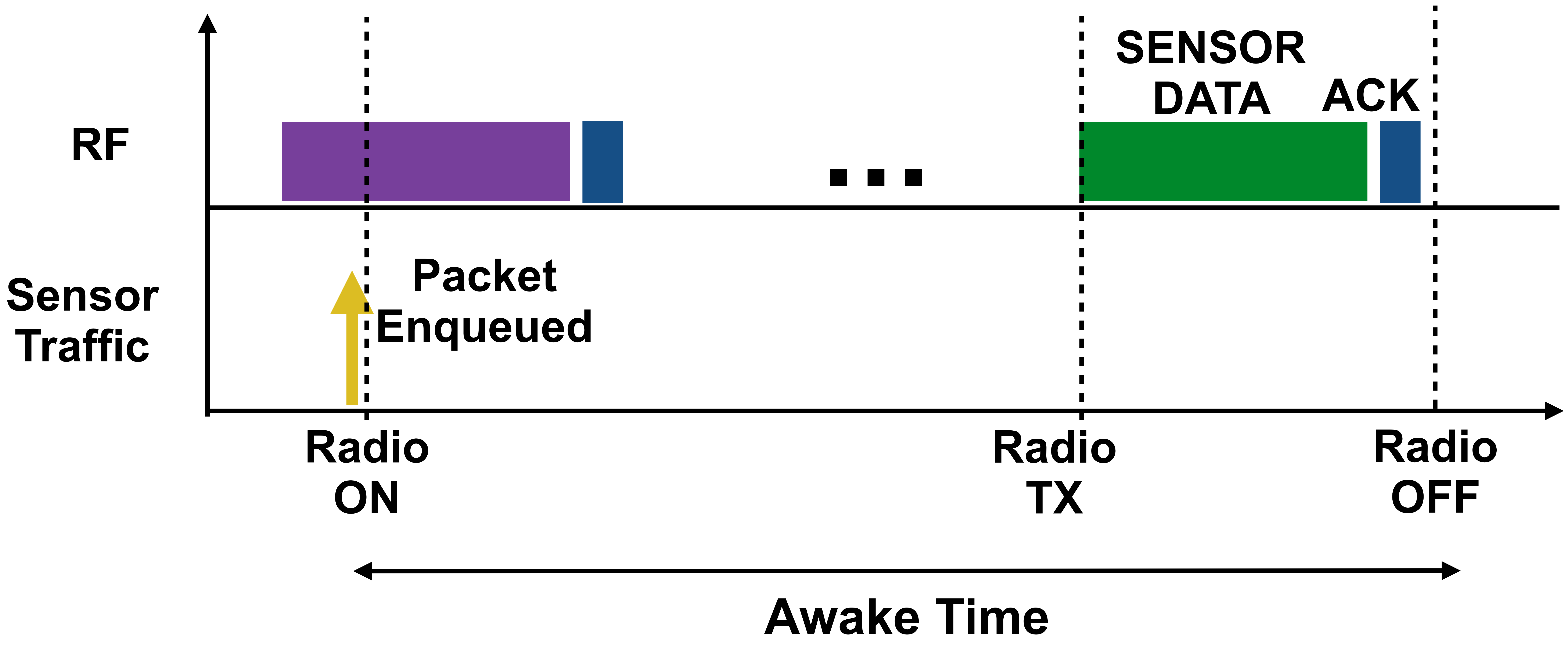
Wi-Fi Throughput Degradation

- **LiRa vs Client Size**
  - Higher variance for short trigger times
- **LiRa vs Trigger Time**
  - VLC ARQ feedback airtime slower rate



- **PCC for Single Client**
  - Client contends after first packet received since last ARQ Feedback
- **PCC for Multiple Clients**
  - Increased airtime lost in per-client contention and collisions

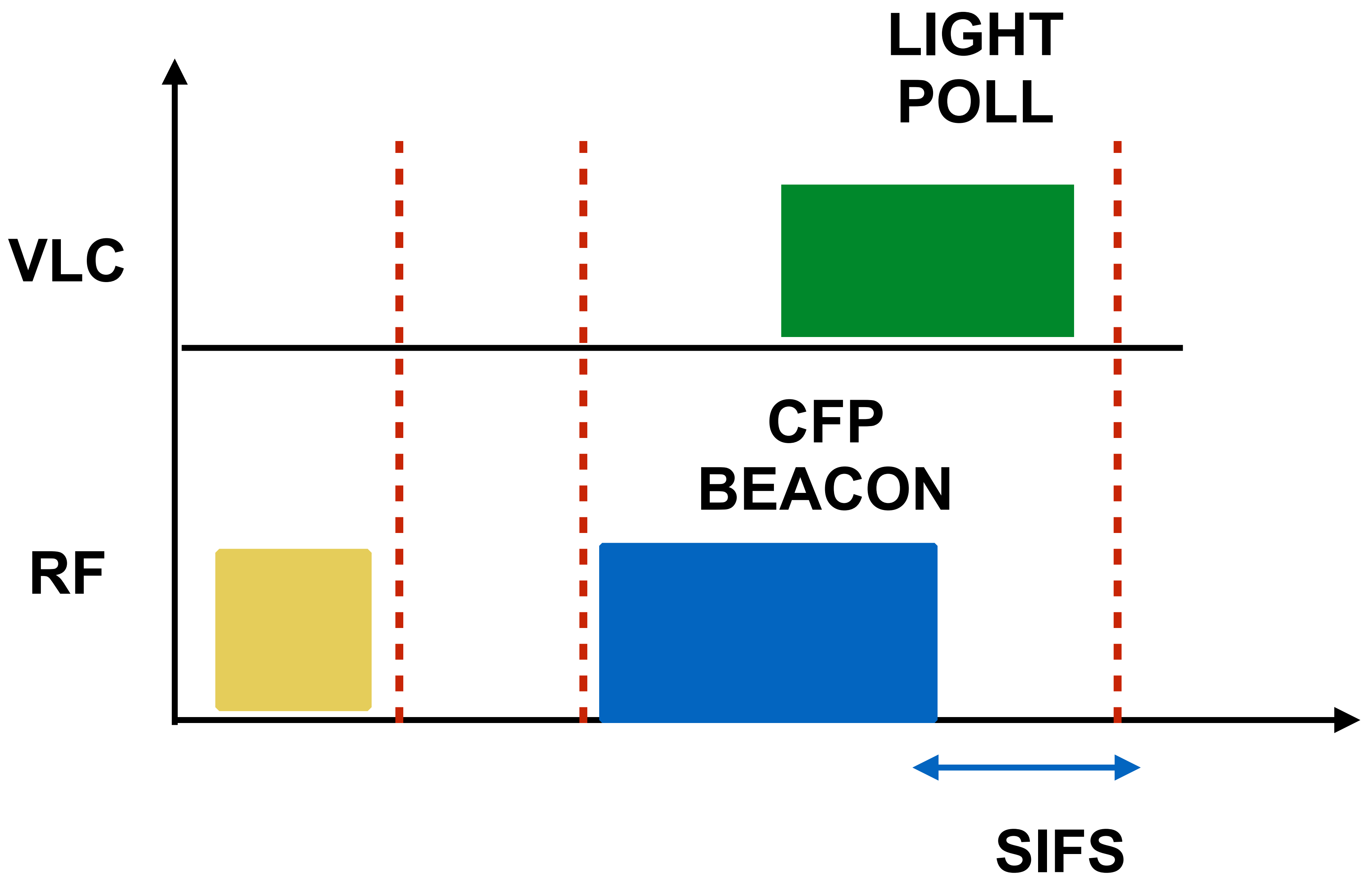
Uplink Radio Access



Access delay and energy consumption increase with contention

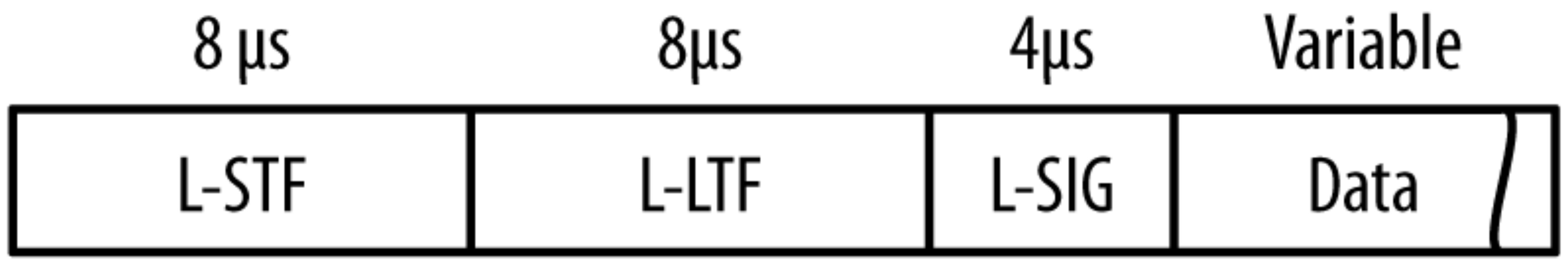
Contention-Free Period Start

- **RF channel access**
  - Beacon indicating contention-fre period start
- **VLC Channel Access**
  - No VLC downlink data prior to CFP Beacon
- **Light-poll Alignment**
  - Ends SIFS duration after end of CFP start beacon

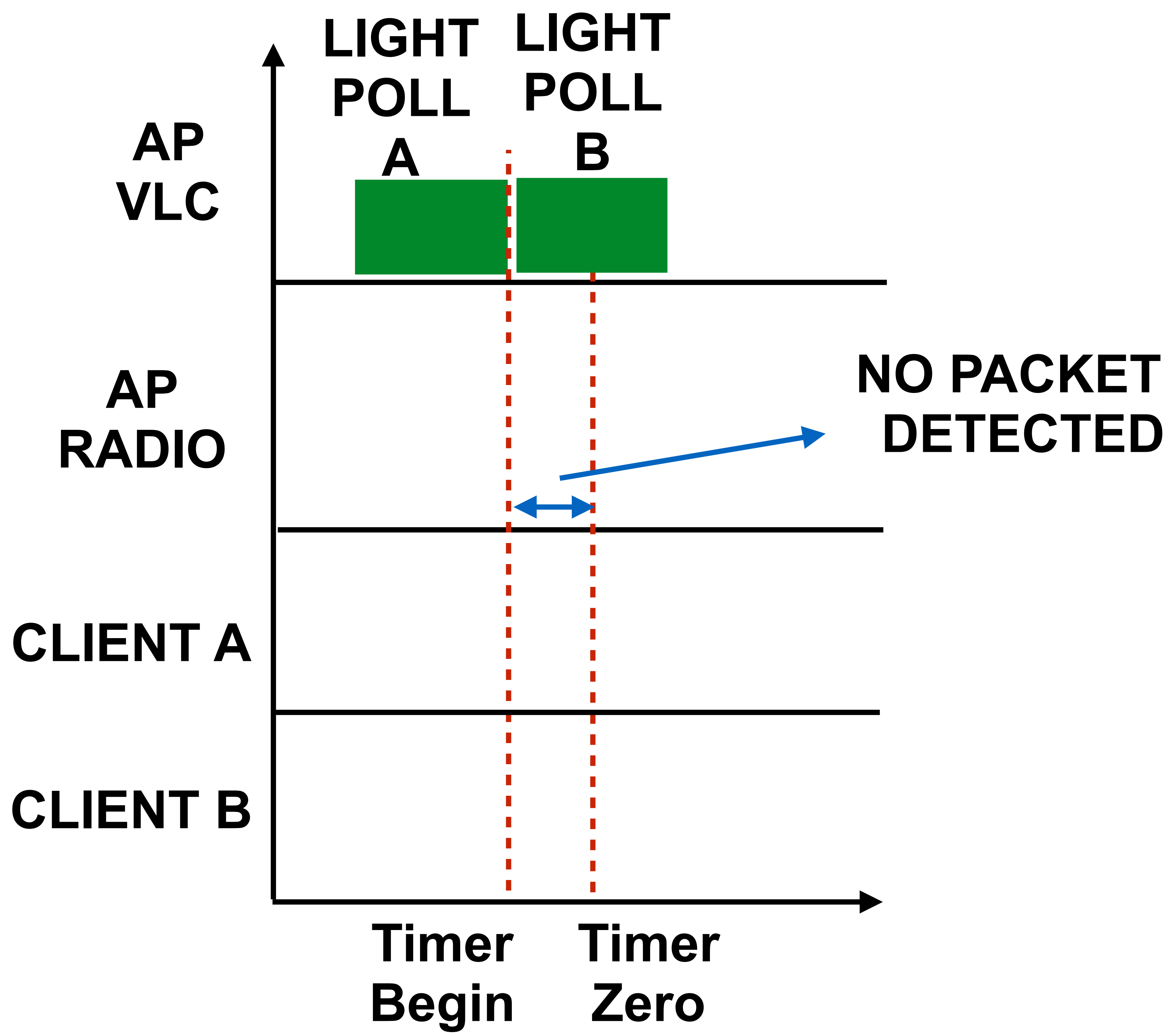


LiSCAN Packet Detection Timer

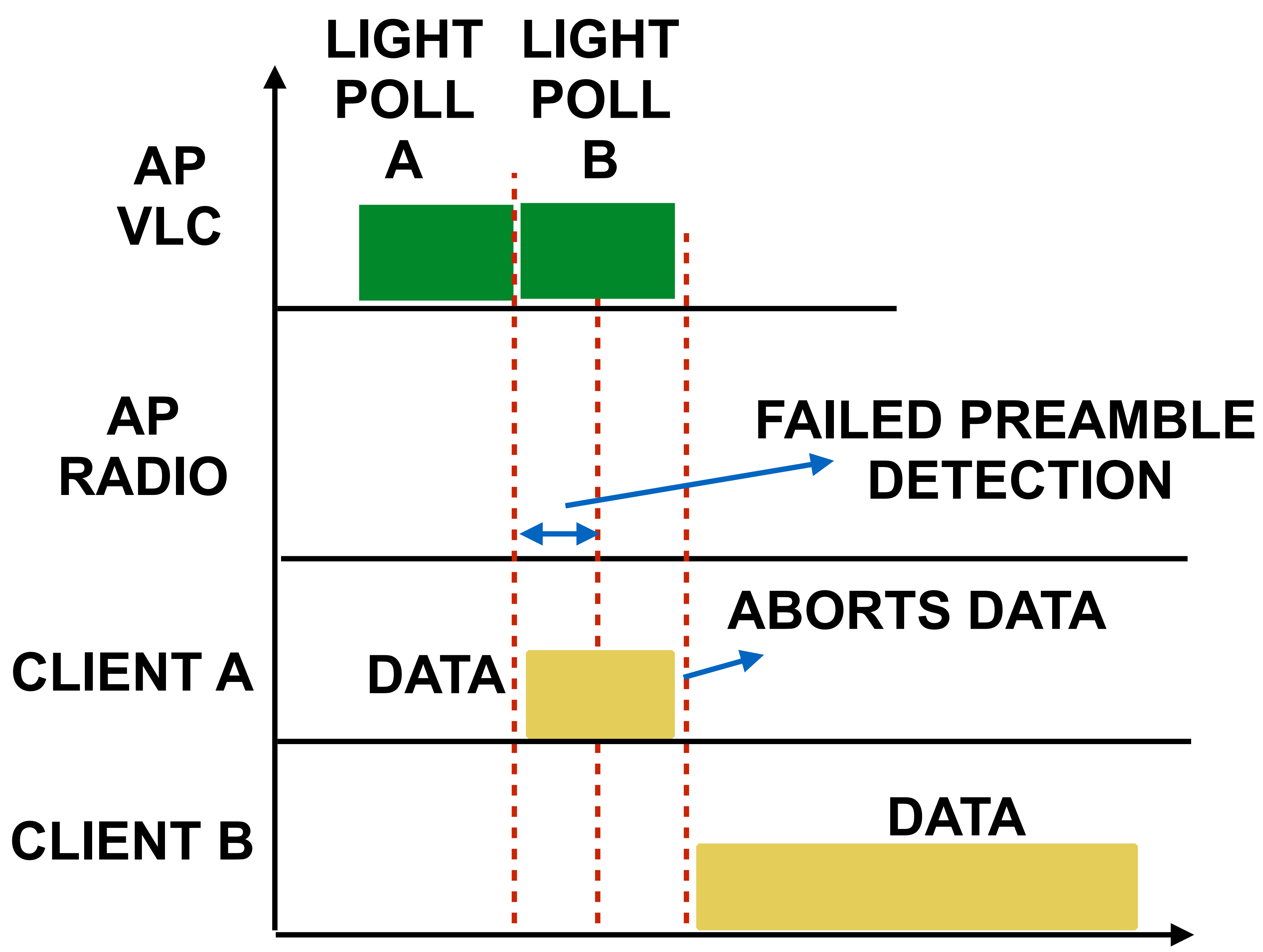
- **Packet Detection Timer**
  - Begin countdown after light-poll transmission



- **No Packet Detected**
  - Light-poll longer than packet detection time
  - Complete light-poll transmission for next client

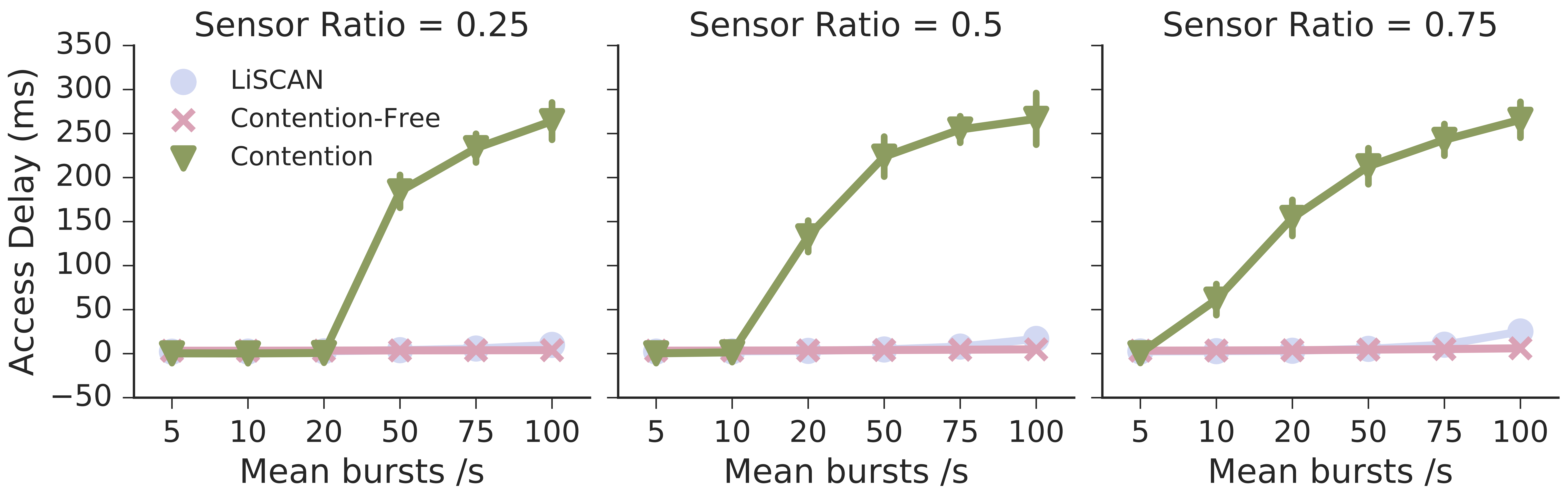


Pre-emptive Collision Avoidance



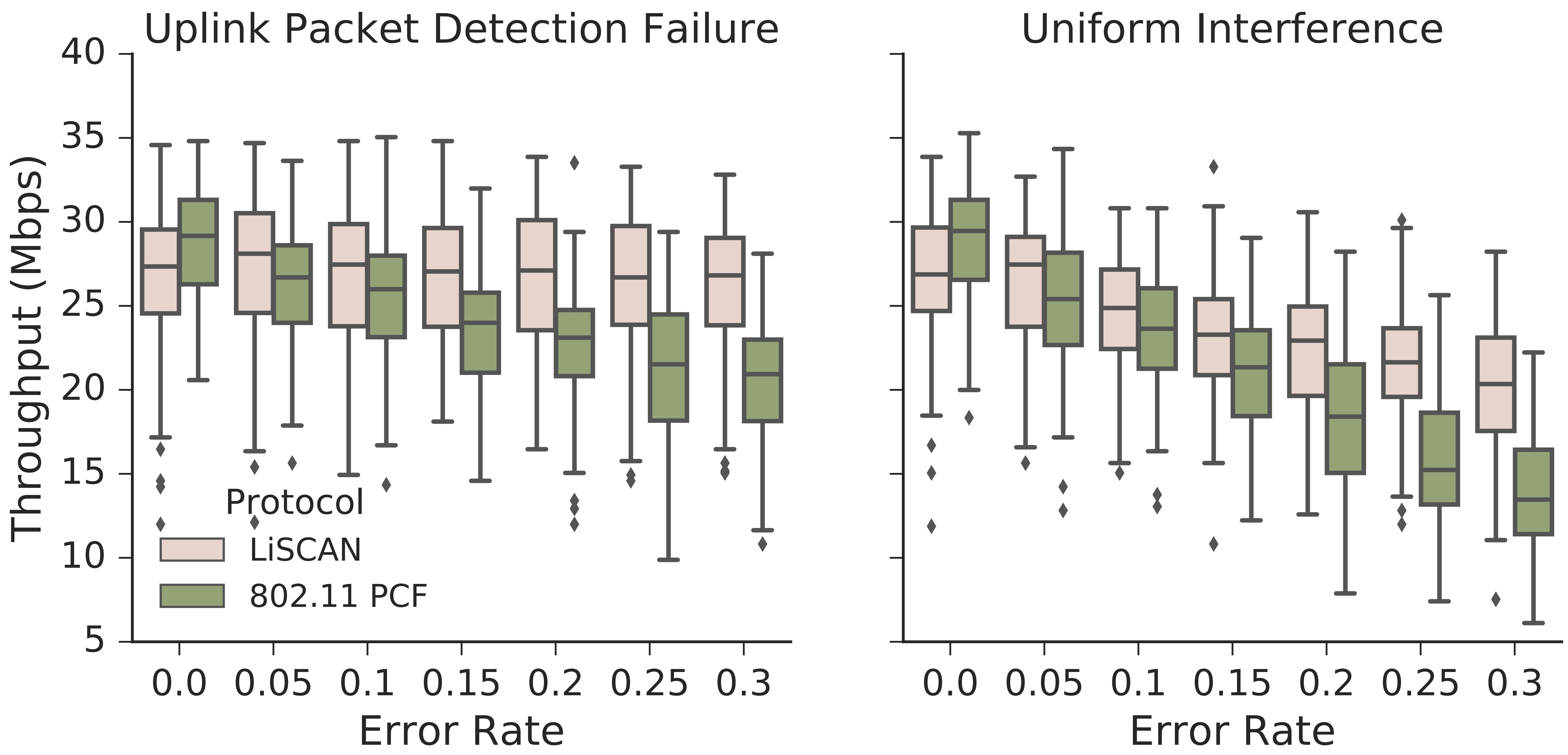
- **Pre-emptive Collision Avoidance**
  - Client A decodes Light-poll B
  - Learns it's packet wasn't detected by AP

Radio Access Delay



- **Low traffic**
  - Polling overhead dominates performance in contention-free strategies
- **Moderate-to-high traffic**
  - Increase in collisions and retransmissions in contention-based strategy

Radio Interference



Thesis Contributions

- **SDM**
  - Directional communication challenge at 60 GHz for multicast
  - Scalable training and beam grouping with near-optimal transmission efficiency
- **LiRa**
  - Integrated visible light and radio WLAN system architecture
  - Scalable VLC feedback over Wi-Fi with controlled impact on legacy Wi-Fi
- **LiSCAN**
  - VLC uni-directional control channel for uplink radio access
  - Virtual full-duplex operation with near-zero radio energy consumption