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OPTIMIZED LIVE 4K VIDEO MULTICAST STREAMING ON COMMODITY WIGIG DEVICES






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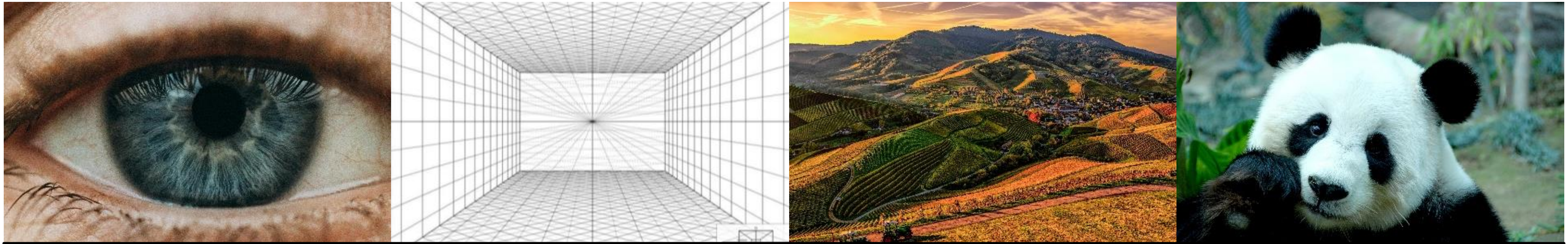
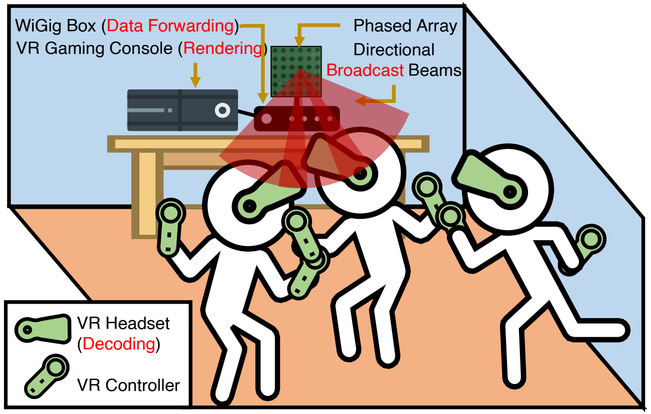
Motivation

- 4K videos gives



Finer Details	Better image depth	More natural colors	More realistic objs

- Wireless 4K streaming needs large bandwidth.
  - mmWave is a perfect fit.
- Applications call for video multicast, such as
  - AR/VR gaming
  - Live sports/concert streaming



Challenges

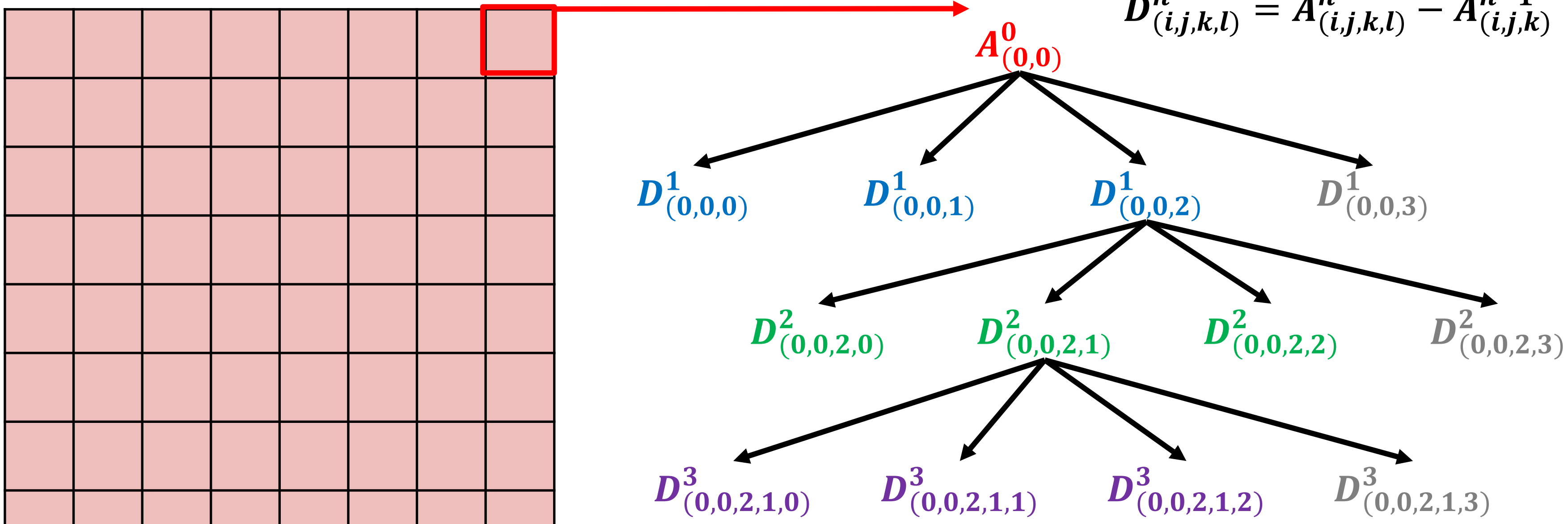
- Users with different SNRs may receive different amounts of data.
  - Can not directly apply unicast algorithms, e.g., DASH[1], to multicast
- mmWave throughput fluctuates severely with movements.
  - Calls for beamforming and swift adaptation.
- Video quality depends on the transmission strategy
  - How to assign users into multicast groups
  - How to beamform towards each multicast group
  - How to allocate time across multicast groups
  - How to avoid redundancy across multicast groups
  - How to provide resilience and avoid congestion in multicast

[1] Stockhammer, Thomas. "Dynamic adaptive streaming over HTTP-- standards and design principles." Proceedings of the second annual ACM conference on Multimedia systems. 2011.

Our Approach – Jigsaw[2]

- Jigsaw – a layered coding strategy designed for live 4K video streaming.

$$D^{n}_{(i,j,k,l)} = A^{n}_{(i,j,k,l)} - A^{n-1}_{(i,j,k)}$$



Gracefully degrade video quality for users with bad wireless channel conditions without impacting others.

[2] Baig, Ghufran, et al. "Jigsaw: Robust live 4k video streaming." The 25th Annual International Conference on Mobile Computing and Networking. 2019.

Our Approach – Optimize Resource Allocation

- Problem formulation

$$\max_{T_{G,j}} \quad \sum_i Q(D_{i,1}, D_{i,2}, D_{i,3}, D_{i,4}) - \lambda \sum_i D_{i,j}$$

$$\text{subject to} \quad D_{i,j} = \sum_{i \in G} T_{G,j} R_G, \forall i, j$$

$$\sum_{G,j} T_{G,j} \leq \frac{1}{FR}$$

$Q(\cdot)$: Utility function

$D_{i,j}$: Data at layer j received by user i

FR: Frame rate

$T_{G,j}$: Transmission time allocated to multicast group G

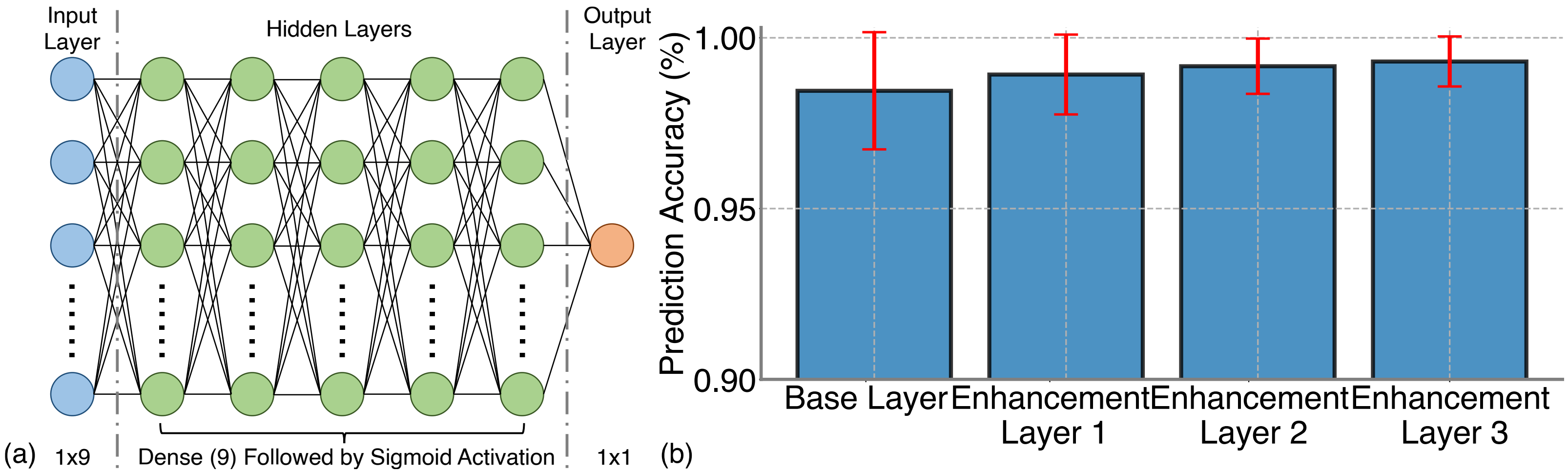
R_G: Data rate of multicast group G

λ: regularization term

Optimization Goal: maximizing the overall video quality and minimize the amount of traffic
We solve this problem using fmincon.

Our Approach – DNN-based Utility Function

- $Q(\cdot)$ Map amount of received data to video quality.



Inputs:

(1) number of packet received at each layer
(2) SSIM if everything up to the i-th layer is received
(3) SSIM value of the blank frame

Output: SSIM

Our Approach – RaptorQ[3]

- RaptorQ – a rateless fountain source code that effectively eliminates redundancy.

(a) Unicast

TS Assigned	User-1	User-2	User-3
Group(1)	Data/3		
Group(2)		Data/3	
Group(3)			Data/3
Data/User			Data/3

(b) Multicast-w/o Source Coding Case 1

TS Assigned	User-1	User-2	User-3
Group(1)	Data/2		
Group(2,3)		Data/2	Data/2
Data/User			Data/2

(c) Multicast-w/o Source Coding Case 2

TS Assigned	User-1	User-2	User-3
Group(1,2)	Data(1)	Data(1)	
Group(2,3)		Data(1)	Data(1)
Group(1,3)	Data(2)		Data(2)
User(1,3)	2/3Data	User-2	1/3Data

(d) Multicast – w/ RaptorQ

TS Assigned	User-1	User-2	User-3
Group(1,2)	Data/3	Data/3	
Group(2,3)		Data/3	Data/3
Group(1,3)	Data/3		Data/3
Data/User			2/3Data

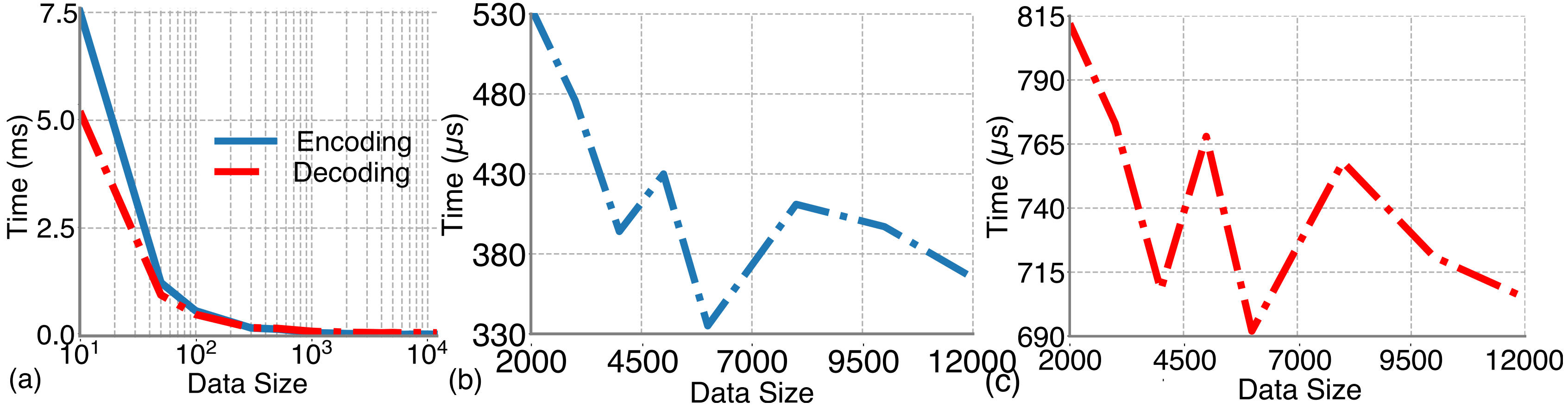
(e) Multicast – Optimal Case

TS Assigned	User-1	User-2	User-3
Group(1,2,3)		Data	
Data/User			Data

[3] Shokrollahi, Amin. "Raptor codes." IEEE transactions on information theory 52.6 (2006): 2551-2567.

Our Approach – RaptorQ

- To use RaptorQ rateless coding, we need to determine
  - the symbol size
  - number of symbols for coding.



Set symbol size to 6000B yields the shortest encoding and decoding time

Our Approach – Packet Scheduling

Traffic allocation across layers and multicast group → **Traffic allocation across coding groups**

- Problem formulation

$$\max \sum_i \sum_u ss(u,i,j)$$

$$\text{subject to } \forall G, j : \sum_i sss(G,i,j) \leq S(G,j)$$

$$\forall u : ss(u,i,j) = \begin{cases} size(i,j), & \sum_{u \in G} sss(G,i,j) \geq size(i,j) \\ 0, & o.w. \end{cases}$$

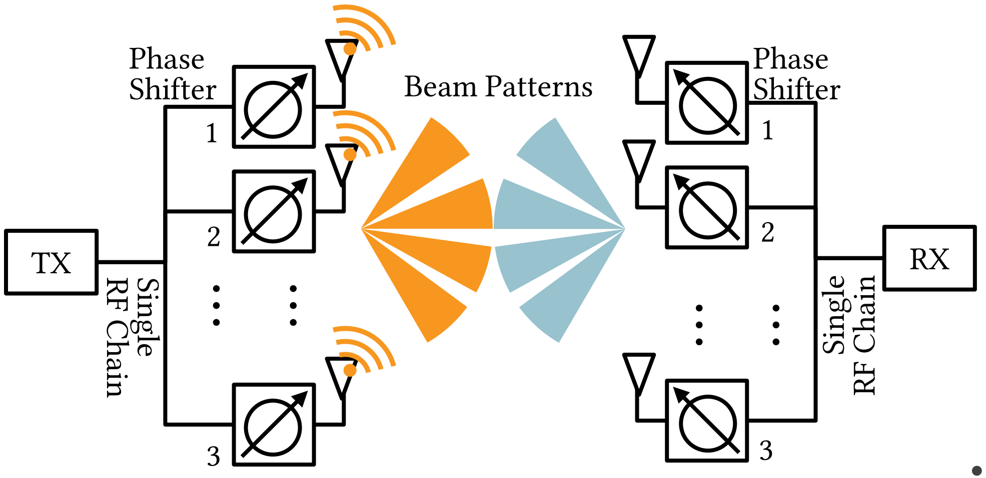
Solved by using greedy heuristic

$S(G,j)$: traffic size allocated to multicast group G at layer j

$sss(G,i,j)$: traffic size allocated to multicast group G at i-th coding group in layer j

$ss(u,i,j)$: decoded traffic by user u at i-th coding group in layer j

mmWave and Beamforming



- Adjust the phase & amplitude of the signals at each antenna to make them constructively combined

Channel

$$b = \boldsymbol{w}^T \boldsymbol{H} \boldsymbol{f}\ \gamma + \sigma$$

Rx combiner   Tx precoder

- To set the correct combiner and precoder, one need to estimate channel, i.e., How the wave propagates.

Beam-training on commercial 802.11ad/ay devices

- Override Rx-side beam-training, i.e., Rx uses a quasi-omnidirectional beam.
- AP performs sector-level sweeping (SLS) and selects the precoder yielding strongest received signal strength (RSS)
- Pros: Simple and fast
- Cons:
  - No CSI estimation – Only reports RSS
  - Coarse and not optimal – impossible to exhaustively try codebooks
  - No multicast beamforming

60 GHz Wi-Fi
Access Point (AP)

60 GHz Wi-Fi
Station (STA)

Our Approach – Multicast Beamforming

- We use ACO[4] to extract the CSI.
- The data rate of a multicast group is determined by the worst user. We have to find Tx precoder **f** that maximizes the minimum received signal strength (RSS) across users.

$$\max_{\mathbf{f}} \min \mathbf{b} = |\mathbf{f}[(\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_N)]| \qquad (1)$$

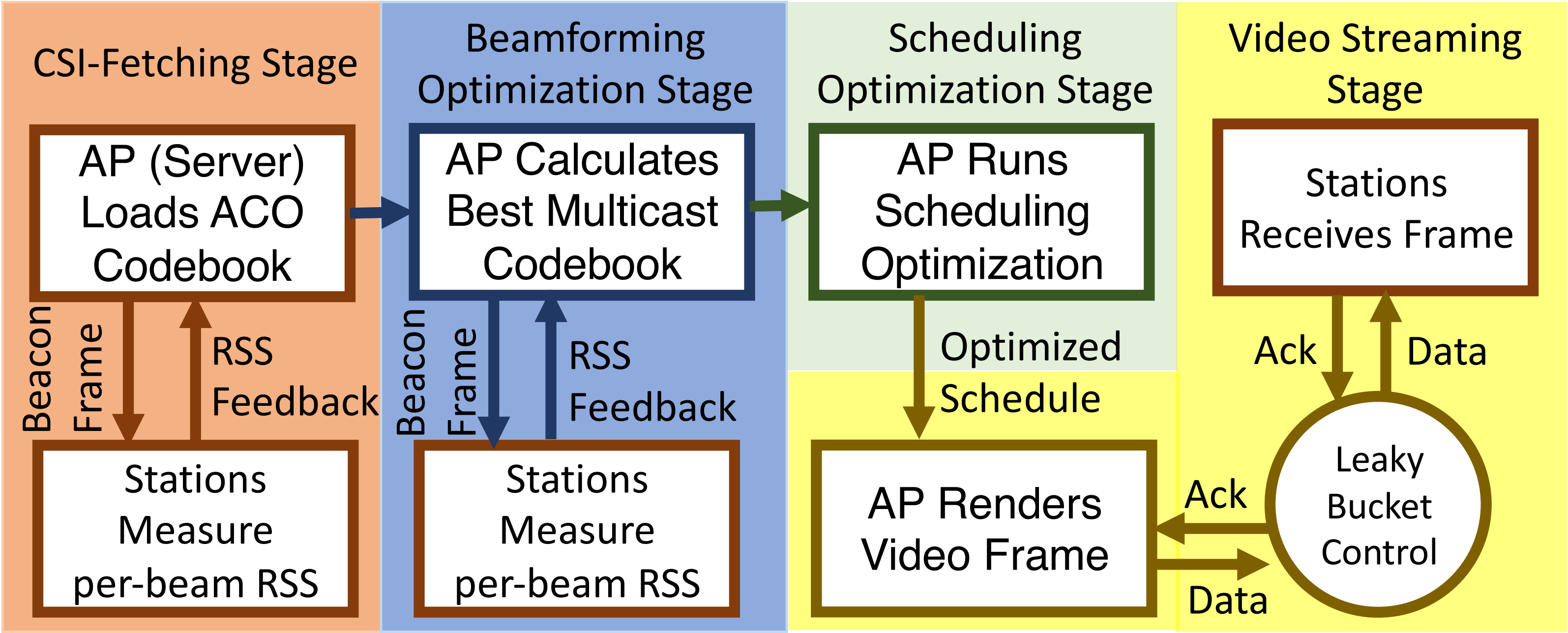
- However, the max-min problem is NP-hard[5]. Instead of solving (1), we solve

$$\max_{\mathbf{f}} \quad \sum \mathbf{b}$$
$$\text{where} \quad \sum \mathbf{b} = \|\mathbf{H}\mathbf{F}'\|^2$$
$$\mathbf{H} = [\mathbf{h}_1; \mathbf{h}_2; \cdots \mathbf{h}_n]$$

- The multicast precoder is the first column of V', where $\mathbf{H} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}'$

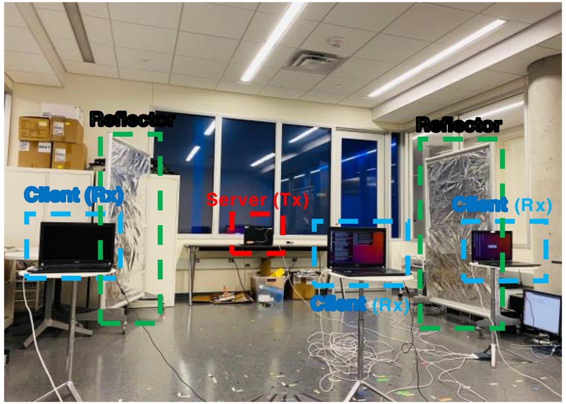
[4] Palacios, Joan, et al. "Adaptive codebook optimization for beam training on off-the-shelf ieee 802.11 ad devices." Proceedings of the 24th Annual International Conference on Mobile Computing and Networking. 2018.
[5] Lopez, Michael J. Multiplexing, scheduling, and multicasting strategies for antenna arrays in wireless networks. 2004.

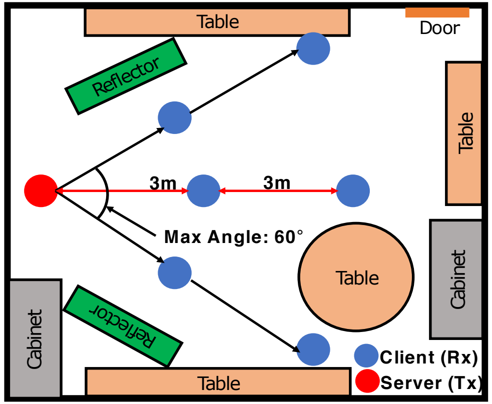
Our Approach - System Workflow

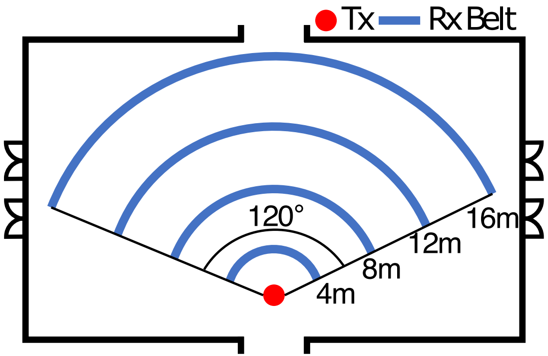


Experiment Setup

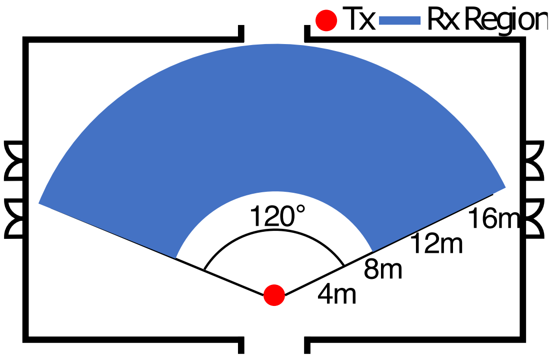
- Experiment + Emulation
- 4 laptops with Qualcomm QCA6320 802.11ad network card
- One as AP, 3 as STA
- Homogeneous placement + Heterogeneous placement







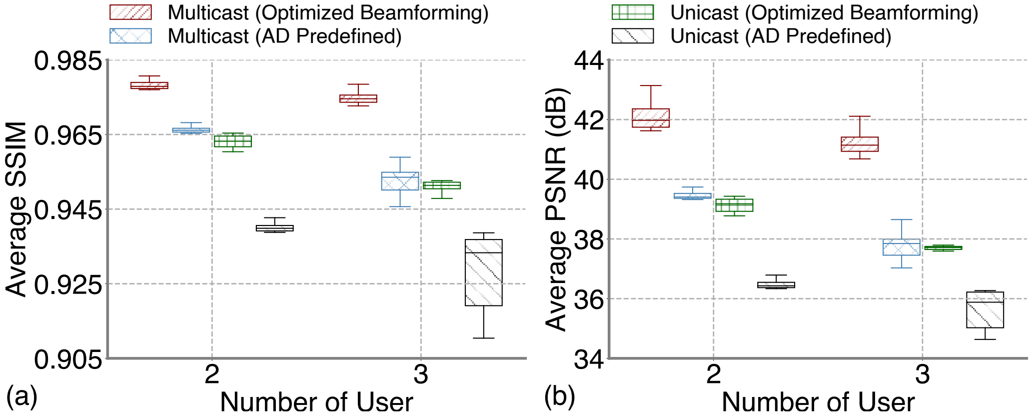
Homogeneous



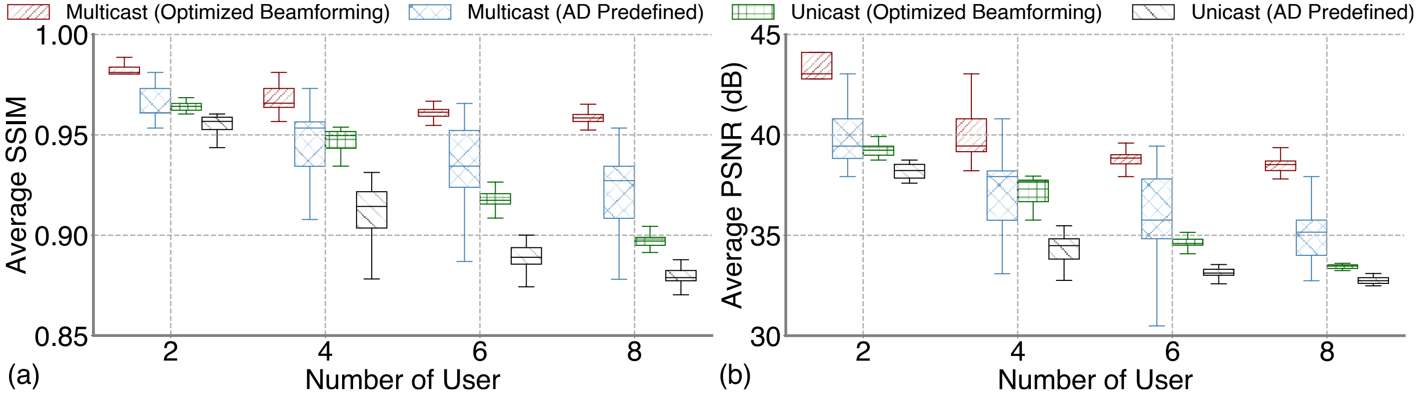
Heterogeneous

Results – Impact of Number of Users

- Experiment

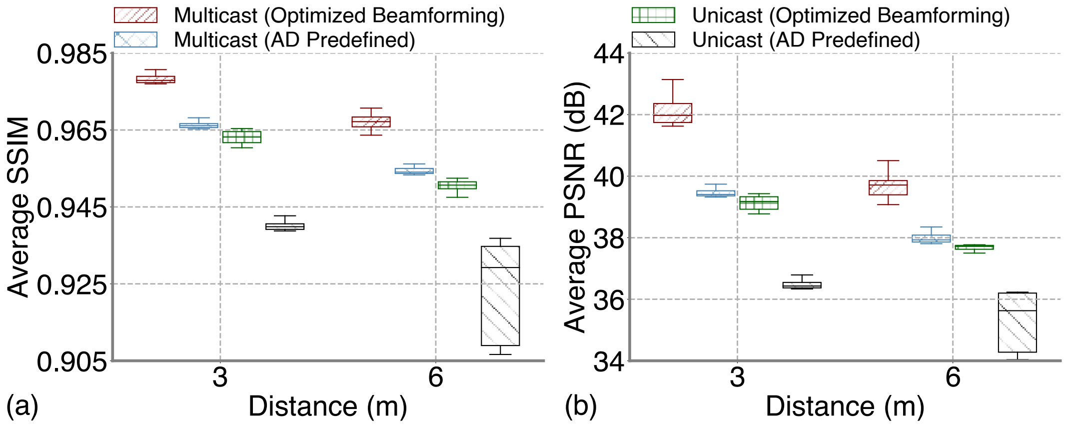


- Emulation

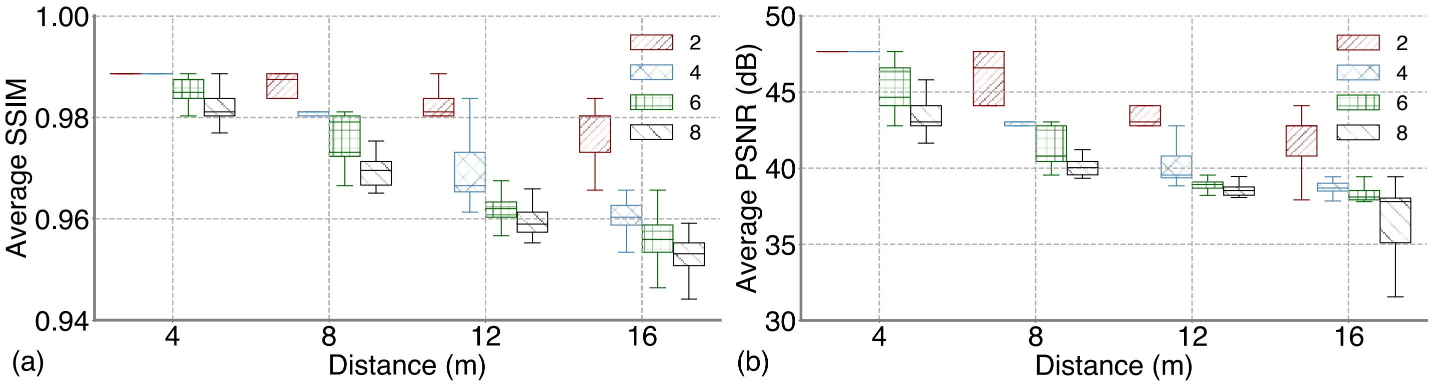


Results – Impact of Distance

- Experiment

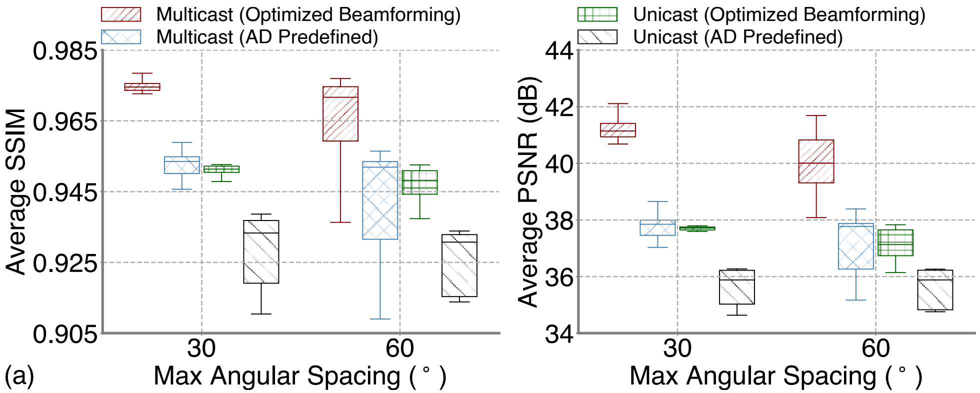


- Emulation

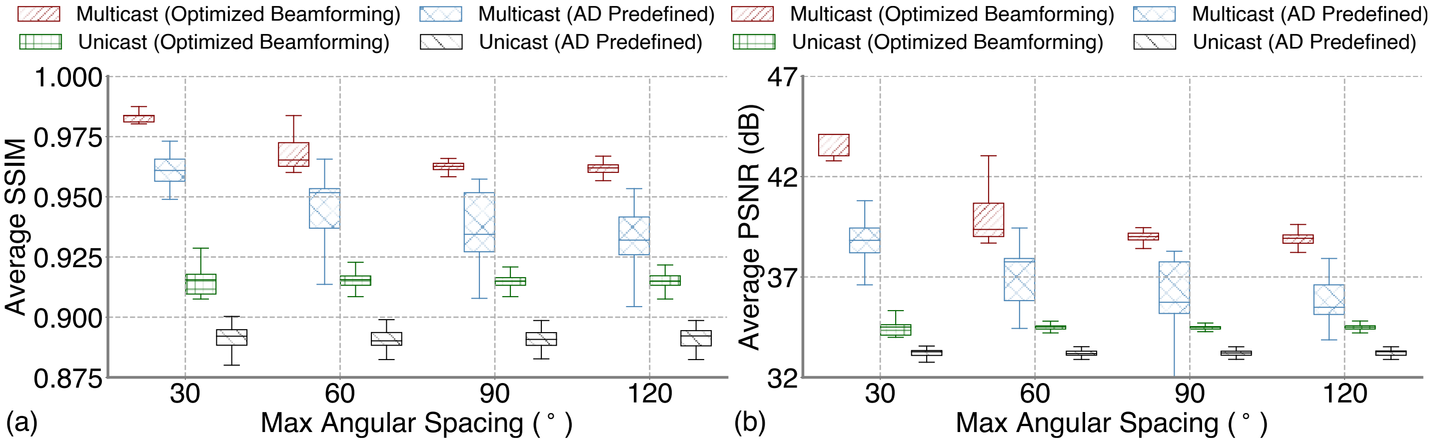


Results – Impact of Maximum Angular Spacing (MAS)

- Experiment

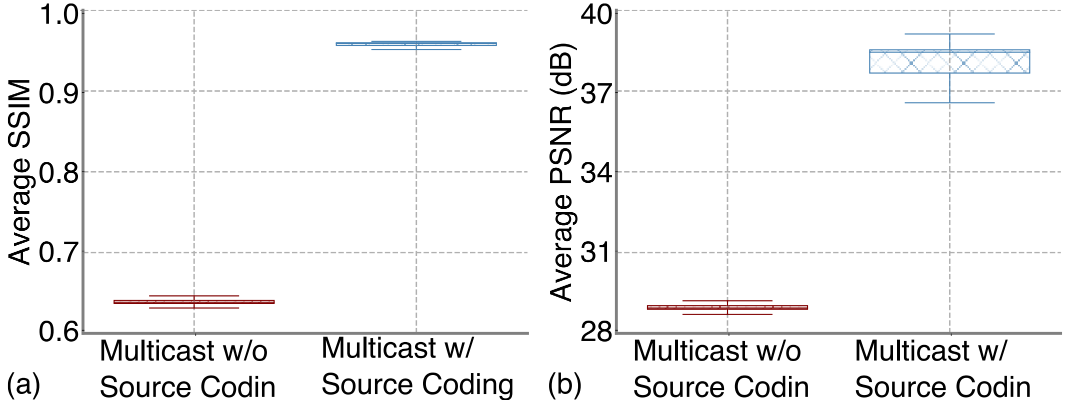


- Emulation

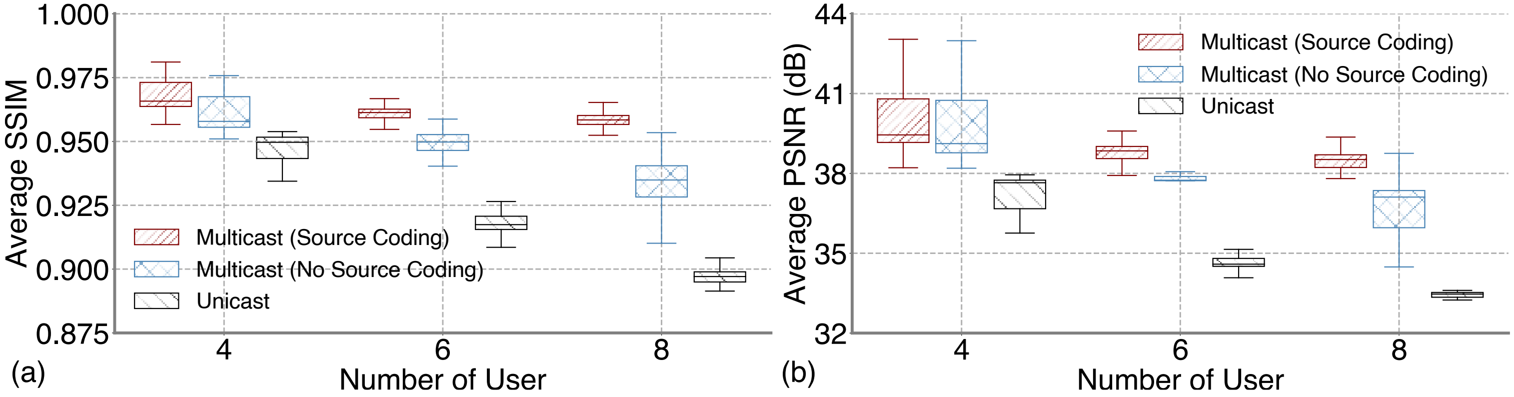


Results – Impact of Source Coding

- Experiment

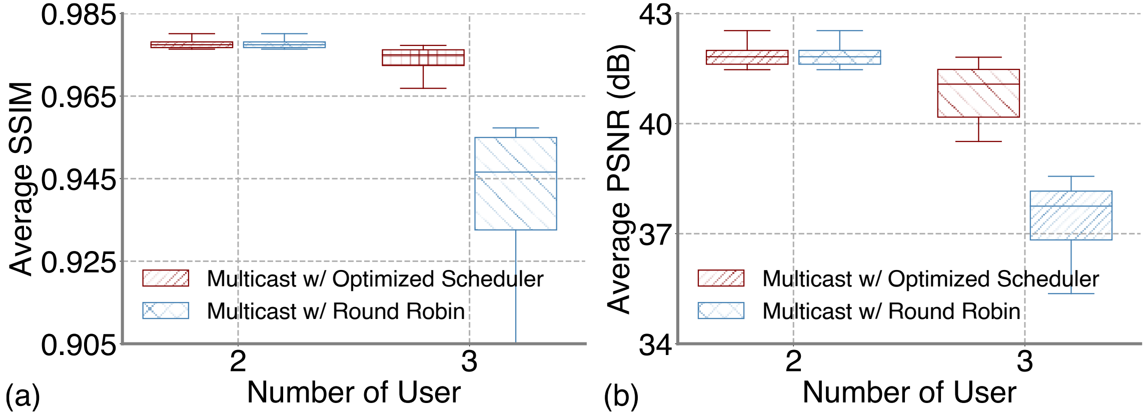


- Emulation

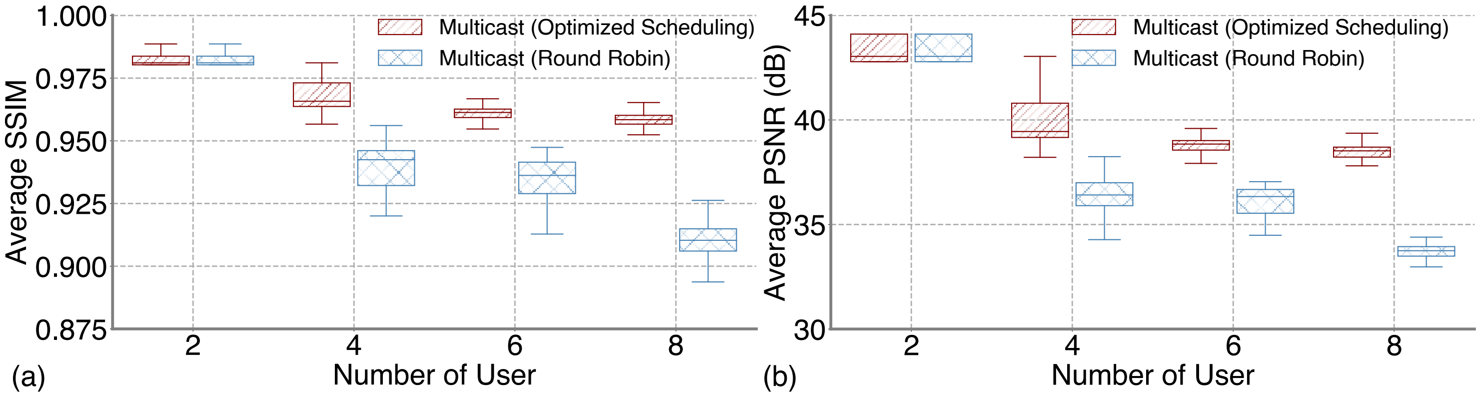


Results – Impact of Packet Scheduling Algorithm

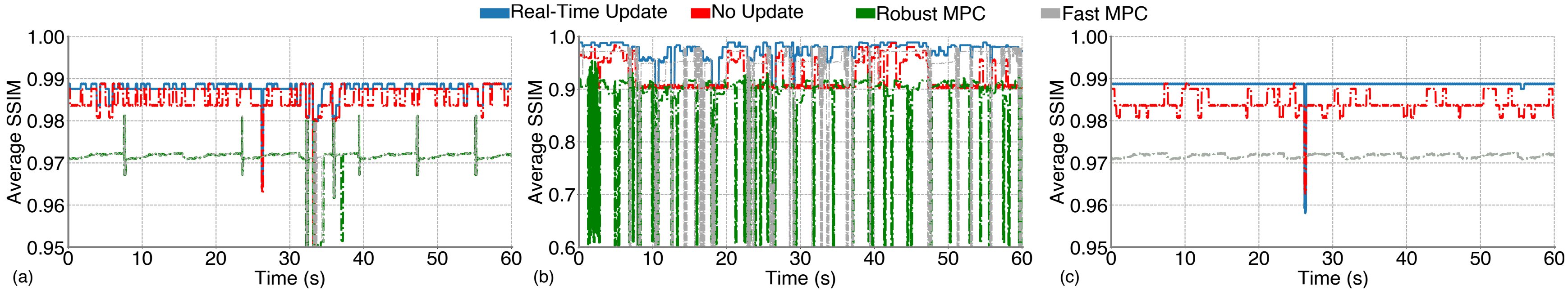
- Experiment



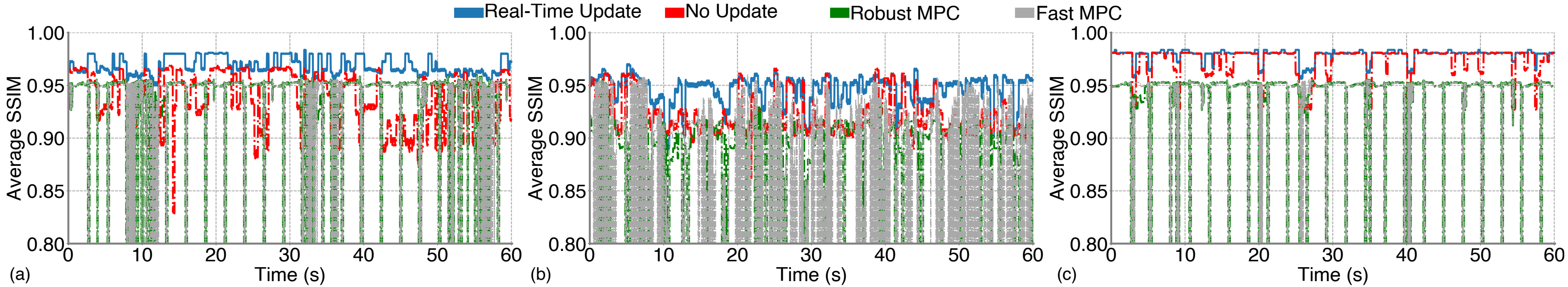
- Emulation



Results – Mobile Experiment



Emulation result of serving 1 receiver when (a) receiver is moving under High RSS (>-61dBm), (b) receivers are moving under Low RSS (<-61dBm), and (c) environment is moving.



Emulation result of serving 3 receivers when (a) two receivers are moving under High RSS (>-61dBm), (b) two receivers are moving under Low RSS (<-61dBm), and (c) environment is moving.

Conclusion

- Develop an end-to-end live 4K video multicast system, which
  - models video quality
  - optimizes traffic allocation and packet scheduling
  - addresses redundancy issues via source coding
  - avoids congestion via rate control
  - adapts to dynamic wireless channels via beamforming.

- Our extensive experiments demonstrate its effectiveness.

Acknowledgement

This work is supported in part by NSF Grant CNS-2008824 and CNS-2107037. We appreciate the insightful feedback from IEEE ICDCS 2024 anonymous reviewers.

Ethical Concern

The personnel involved in the experiment are fully insured and paid. No personally identifiable information (PII) was collected during the exploration. This work does not raise any ethical concern.

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Thank You!

Questions?

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