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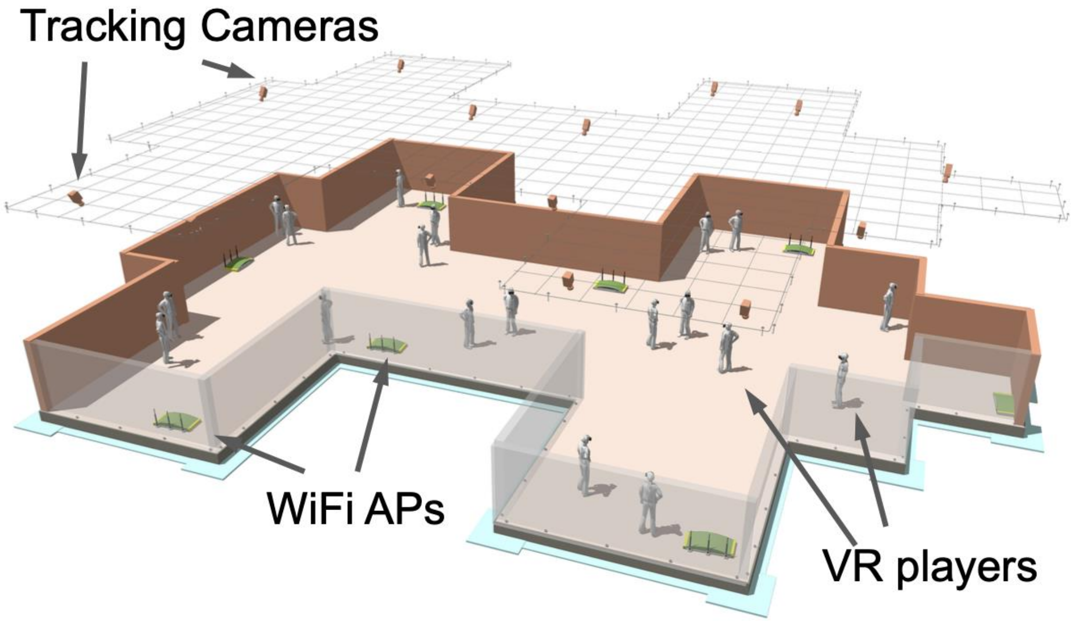
Roaming Free in the VR World with MP^2

Yifei Xu, Xumiao Zhang, Yuning Chen, Pan Hu, Xuan Zeng, Zhilong Zheng, Xianshang Lin, Yanmei Liu, Songwu Lu, Z. Morley Mao, Wan Du, Dennis Cai, Ennan Zhai, Yunfei Ma

UCLA Alibaba Cloud UC Merced Uber University of Michigan

Presenter: Yifei Xu July 8, 2025

What’s Free-Roaming VR



- Gaming, virtual tourism, training, education, etc.
- Wireless streaming is preferred due to the weight, battery, and temperature considerations of the headset

What's needed for Free-Roaming VR Streaming

- **Mobility:** Allows users to roam across multiple access points (APs)
- **Scalability:** Supports up to tens of users
- **Efficiency:** Meets bandwidth (e.g., 100 Mbps) & latency (e.g., 20 ms) requirements for VR applications

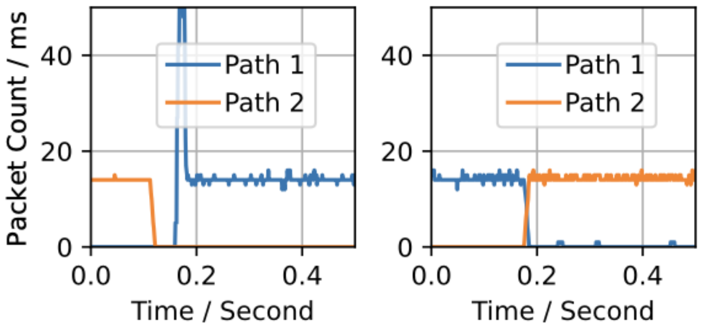
Wi-Fi becomes the go-to choice: cost and throughput

Does Existing Solutions Work Well?

A case study with:

- Steam VR platform
- ALVR (popular open-source VR streaming solution)
- XLINK (SOTA multipath transport protocol)
- ROG Rapture GT-AXE11000 (high-end gaming Wi-Fi router)

Does Existing Solutions Work Well?



(a) High handover latency

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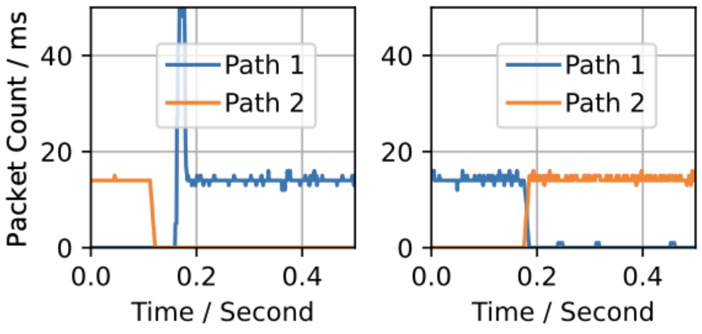

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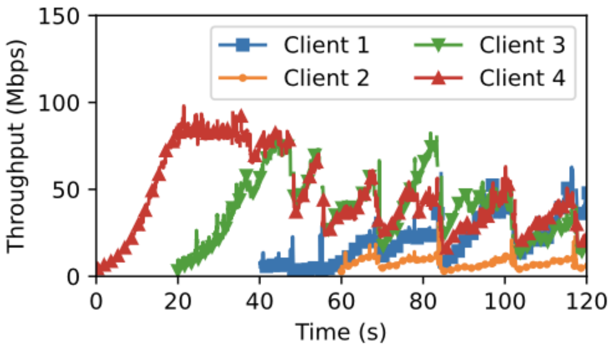

(b) Unstable bitrate

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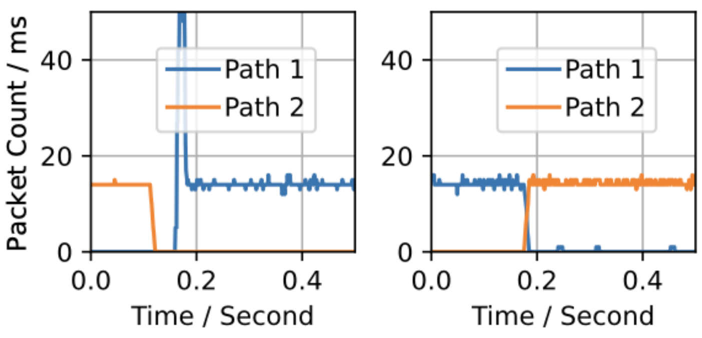

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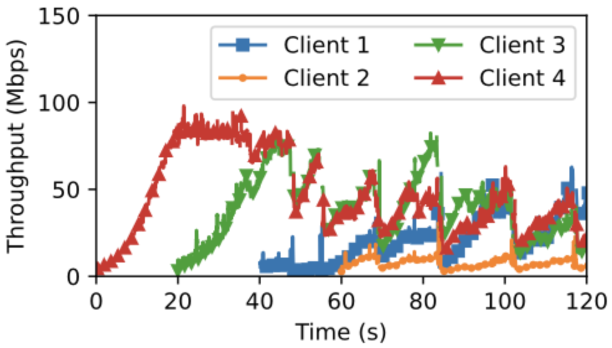

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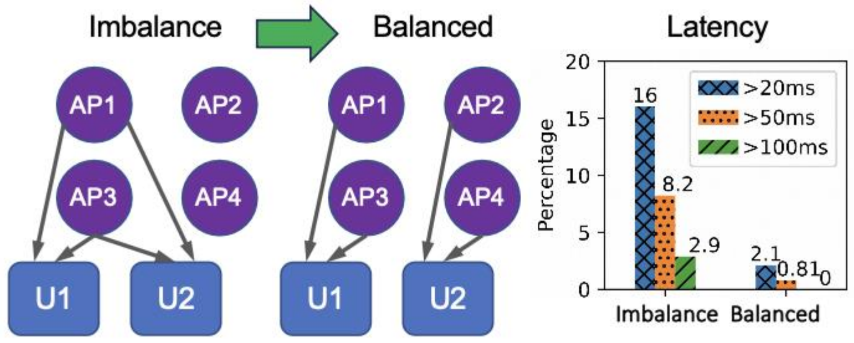


(c) Imbalanced loads

Our Answer: MP^2 (Multi-Path for Multi-Player)

A centralized overlay system that

- *has a global view of the entire stack, and*
- *coordinates link / path / bitrate decisions across users on different APs*

Observations

#1 - Centralization beats decentralization

- Coordinate decisions across (i) users and (ii) network layers

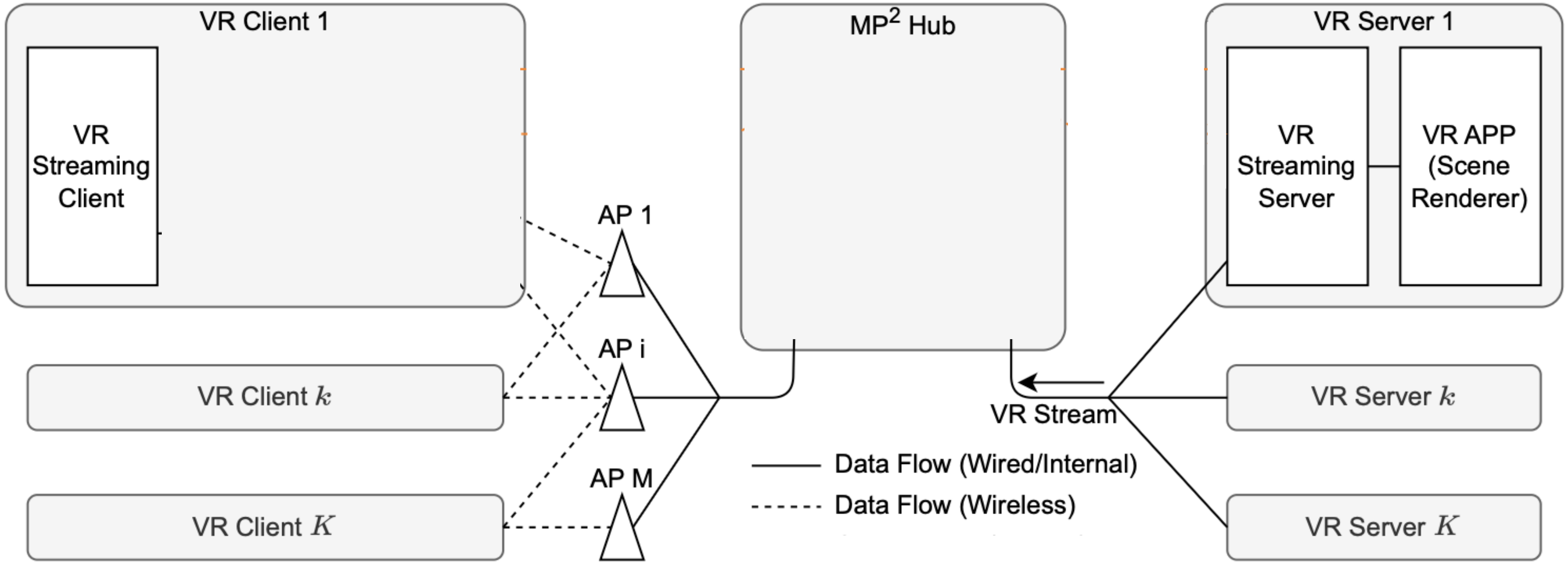
#2 - Single Wi-Fi is insufficient

- Hundred-ms level network outage upon handover
- Interference, congestion, and signal degradation

#3 - User-space implementation simplifies deployment

- OS kernel modifications and special hardware are undesired
- Easier adaptation to evolving wireless technologies

System Overview



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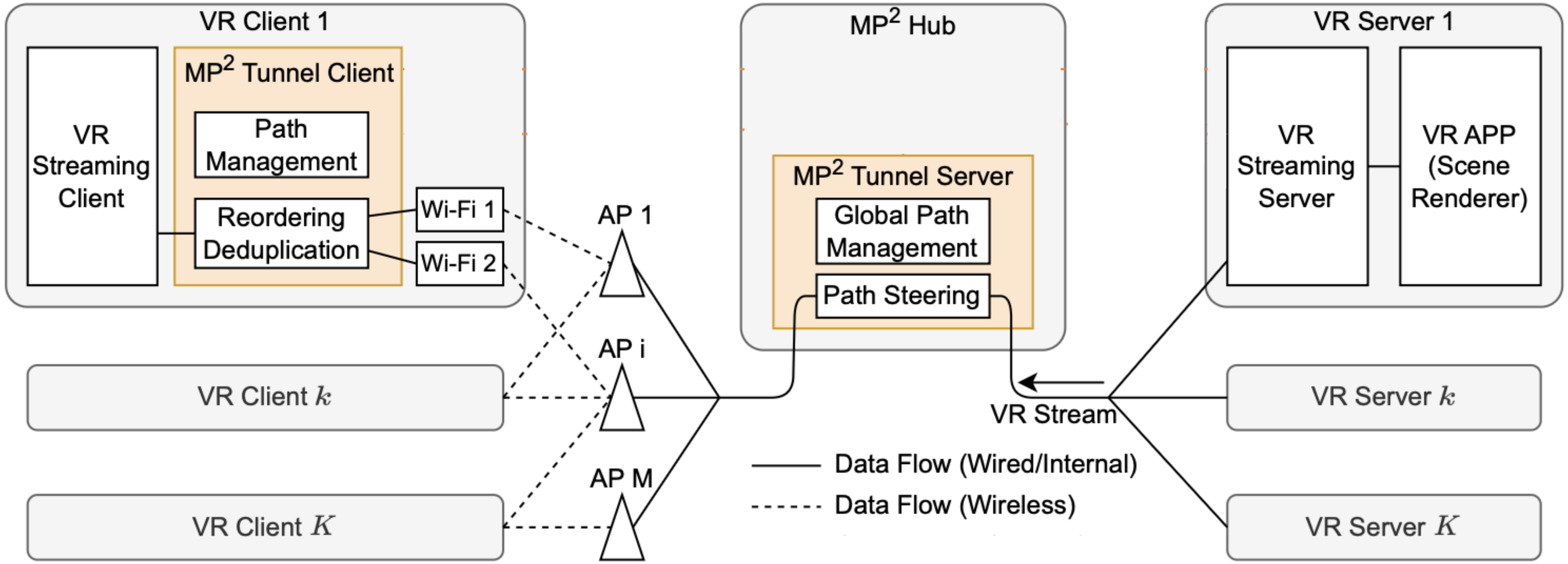
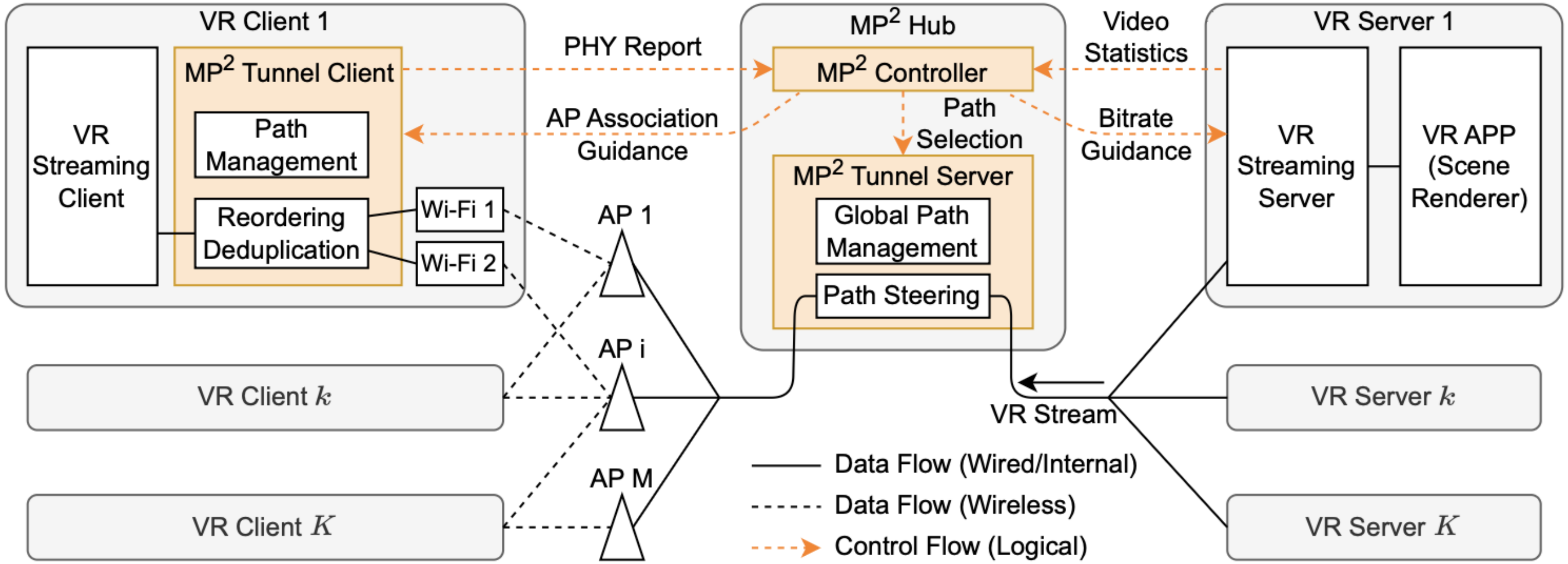


Data Plane: MP^2 Tunnel Client / Server

- Built on top of multipath QUIC tunnels, leveraging 2 Wi-Fi interfaces
- Mask the complexity of path/AP management & packet delivery
- Route VR traffic according to the decisions from the control plane

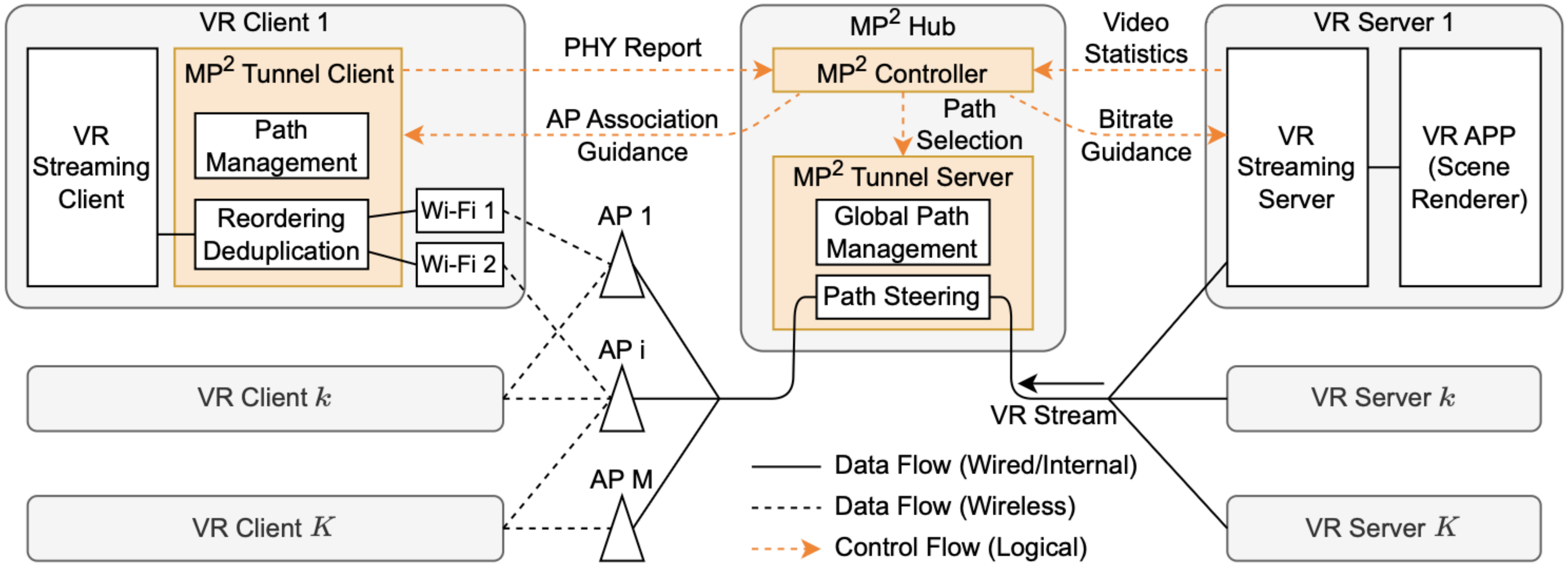
System Overview



Control Plane: MP^2 Controller

- Collects global cross-layer information: Wi-Fi PHY and VR application data
- Orchestrates cross-layer decisions to optimize global QoE: AP association (link-layer), path selection (transport-layer), and bitrate guidance (application-layer)
- Coordinates streams to ensure smooth enforcement

System Overview



All in the user space!

- No modification to the kernel
- Can be implemented with low-cost commercial Wi-Fi hardware

Coordinated Seamless Migration

- **Path Warmup**
  - Before migrations, MP^2 sends a small probing traffic over the target link
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- **Bitrate "Guidance"**
  - After migrations, the ABR algorithms can take > 10 sec to converge
  - MP^2 proactively enforces a maximum bitrate **cap** for all users on that involved AP
    -> Faster convergence
    -> ABR continues to adapt: MP^2 can coexist seamlessly with non-VR traffic

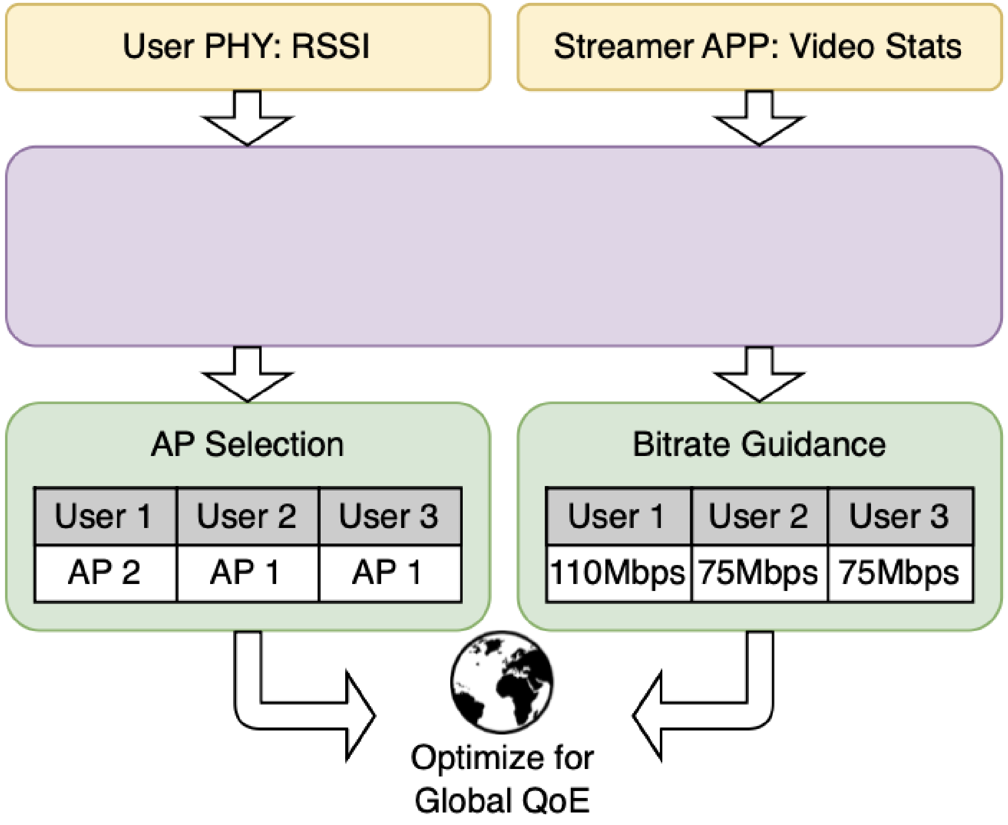
Control Problem Formulation

- **Control Inputs**
  - RSSI from clients
  - Statistics of VR frames from servers
- **Control Outputs**
  - **AP selection:** which AP (path) should each stream be routed through
  - **Bitrate guidance:** what bitrate should each stream run at
- **Optimization Goal**

$$\boldsymbol{Q} = \sum_{k=1}^{K} \boxed{\boldsymbol{B}_k} * (1 - \sum_{i=1}^{3} w_i * \boxed{\boldsymbol{P}_{k,i}})$$

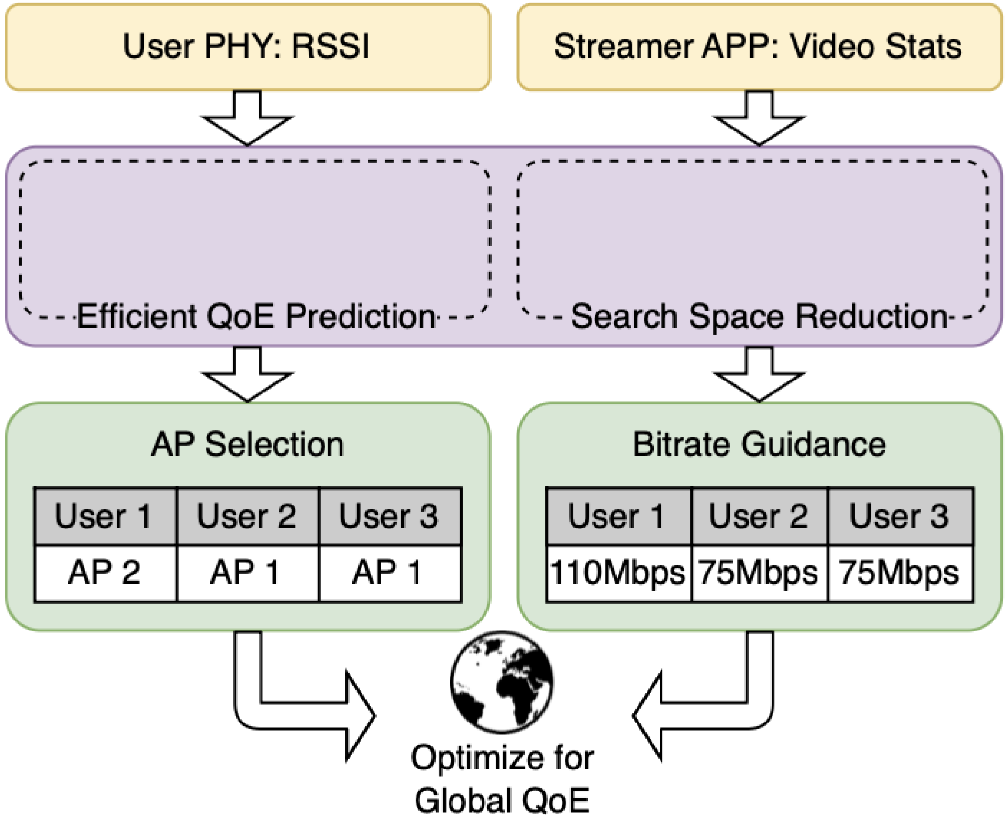
Bitrate for stream *k*

Lag rate of stream *k*



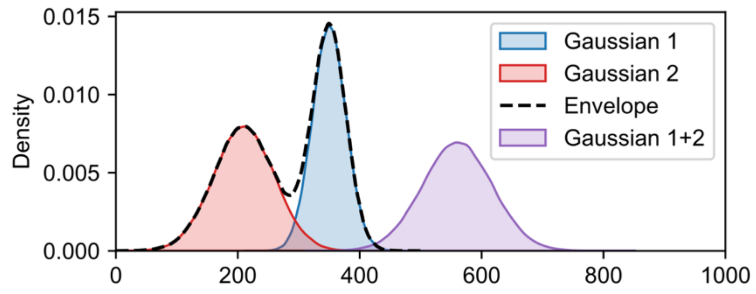
Challenges for the Controller

- **Closed-form prediction of tail latency**
  - Without this, the tail latency has to be obtained from simulation with recorded video traces: inefficient
- **Intractable search space**
  - Search space grows exponentially as the number of user grows
  - 4 APs, 12 users, 10 bitrate levels to search, 0.1 sec per simulation -> 1.7×10^{18} sec!



MP^2 Controller: Frame Size Modeling

- **When *k* streams compete for the same AP**
  - Worst case: frames from all streams collide
    - worst_latency = $\sum_{i=1}^{k}$ frame_size$_k$ / link_rate
  - If sizes all follow Gaussian distribution: $\sum_{i=1}^{k}$ frame_size$_k$ is still Gaussian
  - Closed-form worst-case tail latency available



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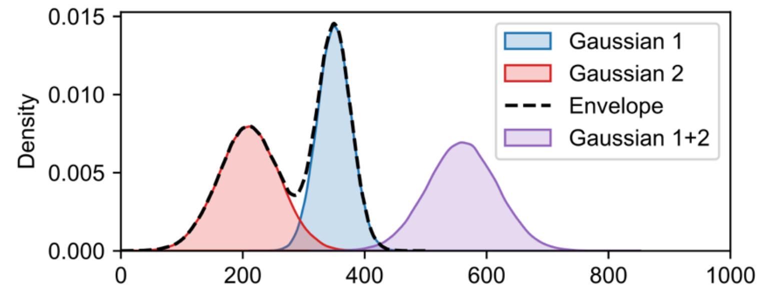
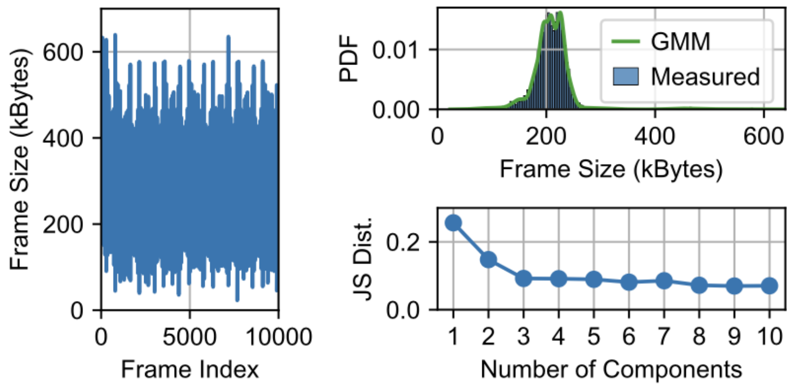


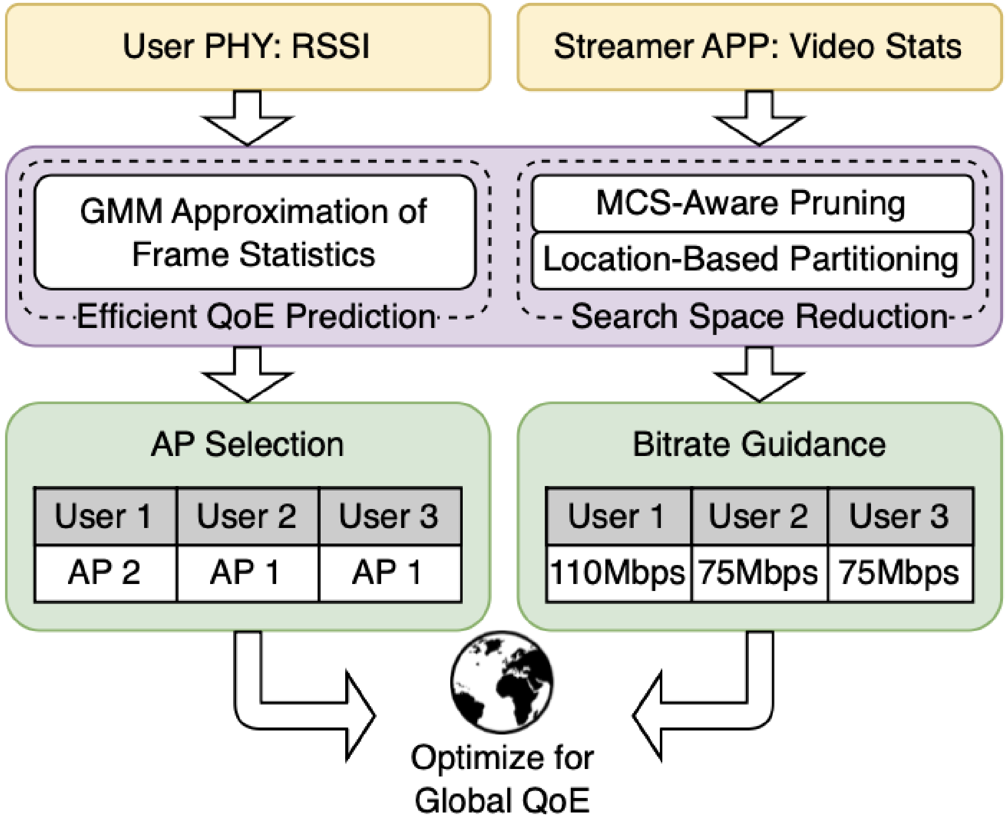
- **Mixed frame types?**
  - Gaussian Mixture Modeling can closely track the mixed distribution
  - The above still hold



MP^2 Controller: Pruning and Partitioning

- **Link quality-based pruning**
  - Skip bottom *p* percent of poor links
- **Location-based partitioning**
  - Partition users into location-based cells
  - Optimize arrangement locally within each cell
  - With bounded cell size, search space grows linearly with user count

Less than 1-sec compute for 48 users, 16 APs

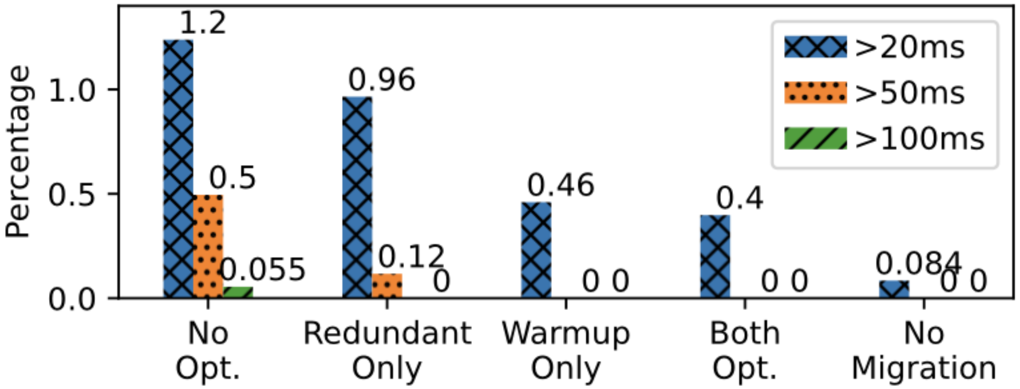


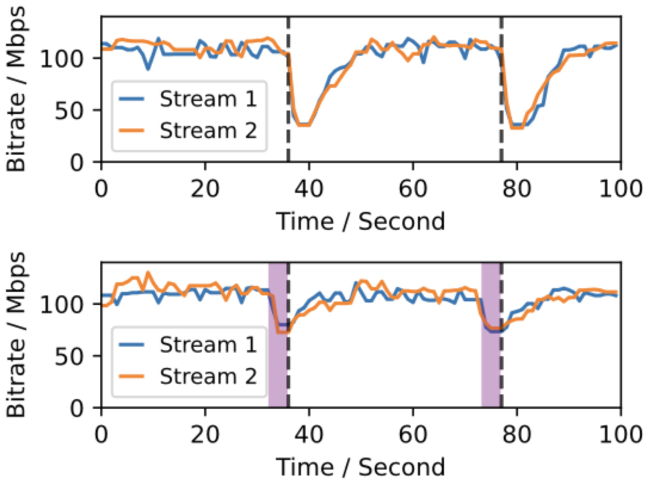
Implementation

- **VR Streaming Platform**
  - **GPU Servers:** Linux PC + Steam VR + ALVR server
  - **Headsets:** Linux PC + Monado (cross-platform XR runtime) + ALVR client

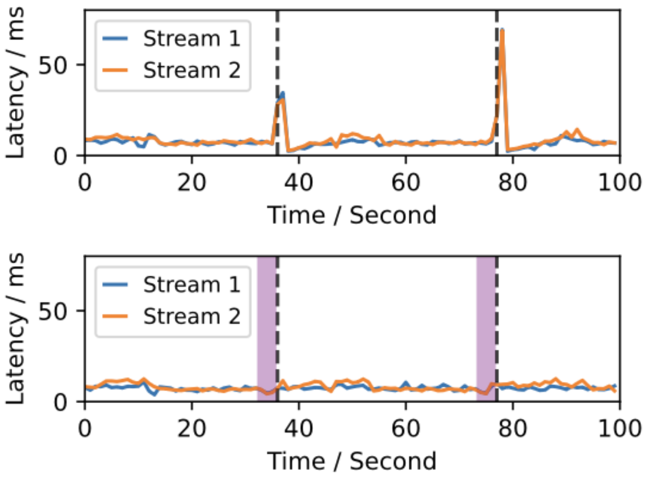
- **MP^2 Components**
  - **MP^2 Controller:** run on any one of the servers
  - **MP^2 Tunnel Server:** run on any one of the servers
  - **MP^2 Tunnel Client:** run on every headset
  - All portable applications for Linux PC

Evaluation: Seamless Migration

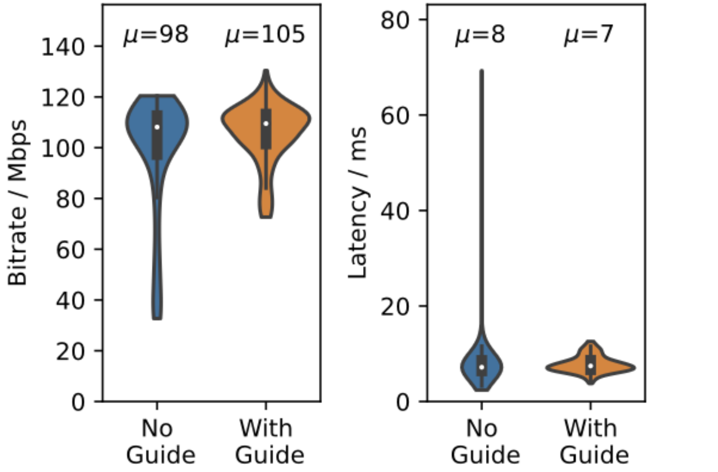




(a) Bitrate of two streams without (top) and with (bottom) guidance.



(b) Latency of two streams without (top) and with (bottom) guidance.



(c) Distribution of bitrate (left) and latency (right).

Evaluation: Large-Scale Emulation

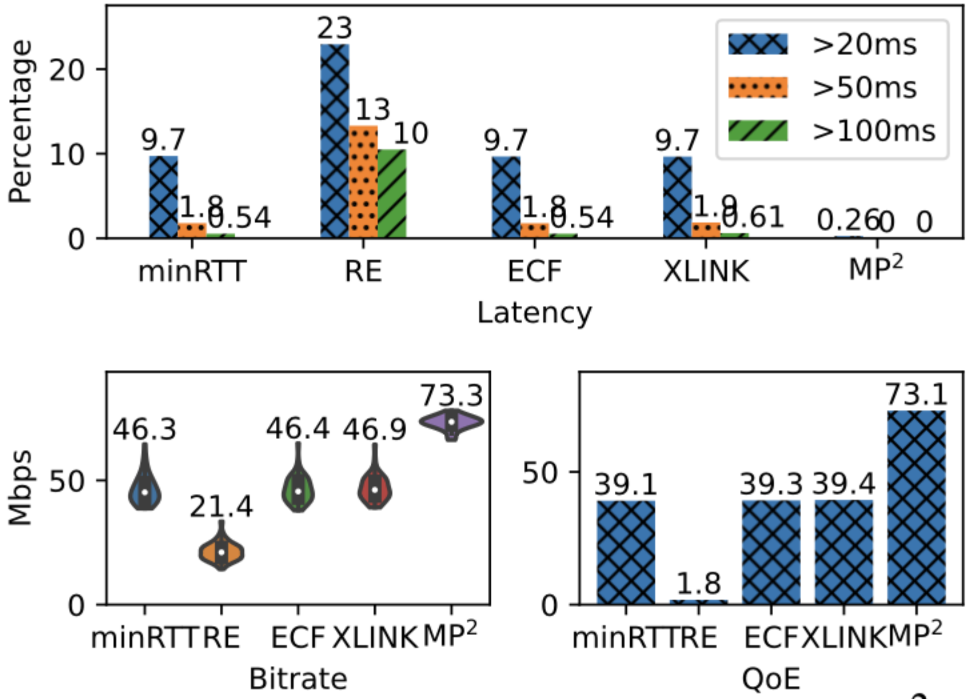


Figure 10: 16 AP × 48 client Emulation. MP^2 significantly outperforms XLINK + ALVR and different flavors of MPQUIC (MinRTT, RE, ECF) + ALVR on both latency (35× improvement over 2nd place), bitrate (1.56×), and QoE (1.86×).

Evaluation: User Study

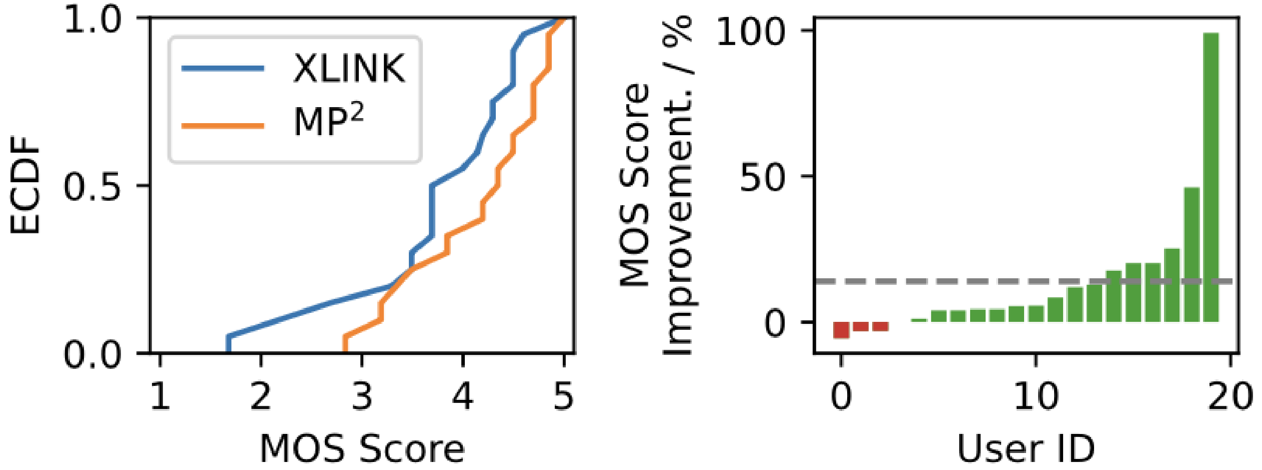


Figure 15: Perceptual quality of experience score for MP^2 and XLINK + ALVR, the higher the better. MP^2 consistently outperforms the baseline and is significantly preferred by the vast majority of users.

Summary

- Handover latency, bitrate fluctuation, and imbalanced loads are three roadblocks to multiplayer free-roaming VR

- MP^2 introduces a user-space, centralized overlay system that:
  - has a global view of the entire stack, and
  - coordinates link / path / bitrate decisions across users on different APs

- Yes, the only hardware gap is a second Wi-Fi interface on the headset!

Thank you!