EECE5512
Networked XR Systems

Lecture Outline for Today

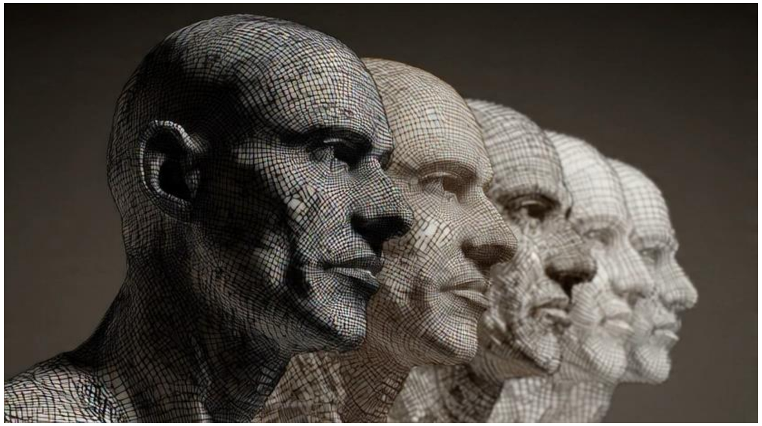
- Homework3
- Mesh Streaming

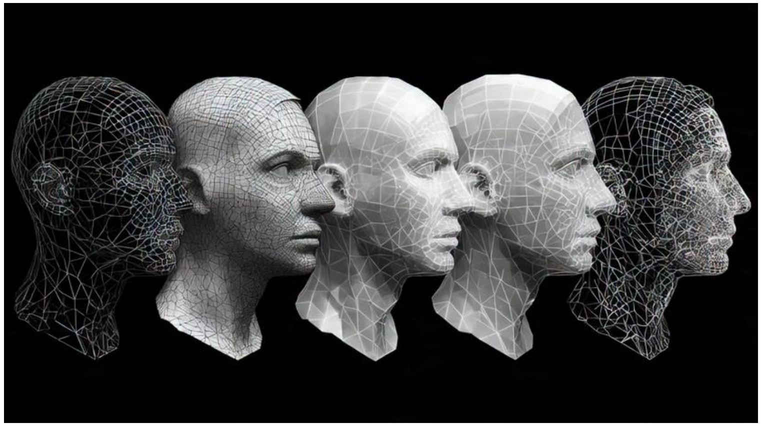
Recap: Mesh

- Data representation
  - Each frame has vertices and connectivity
  - Color texture is stored independently, so there is also mapping information from texture to polygons

4D Mesh Sequence

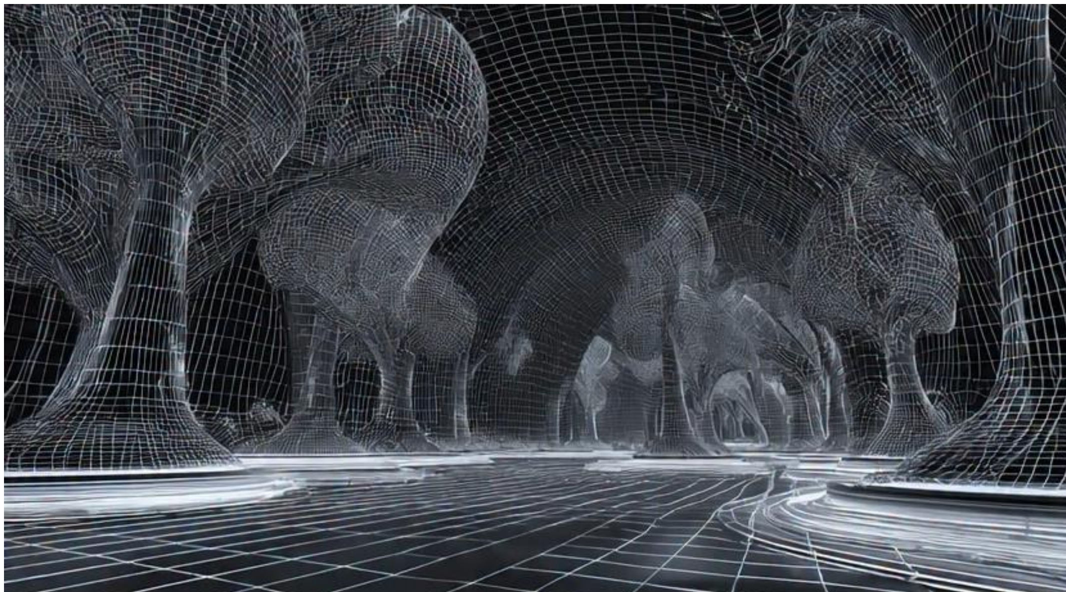
Think of a 6-DoF, free viewpoint, volumetric video





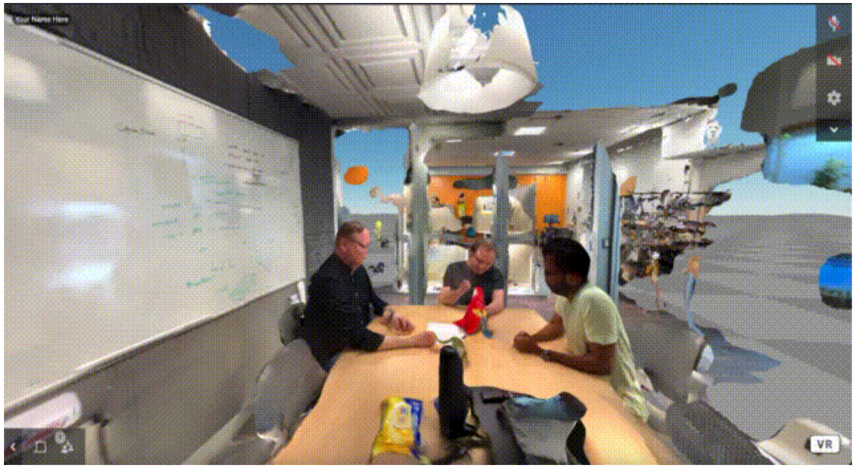
4D Mesh Sequence

Think of a 6-DoF, free viewpoint, volumetric video



Mesh Streaming

- Bandwidth and latency are a function of the scale of the scene captured.

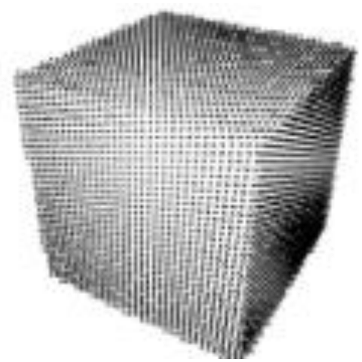


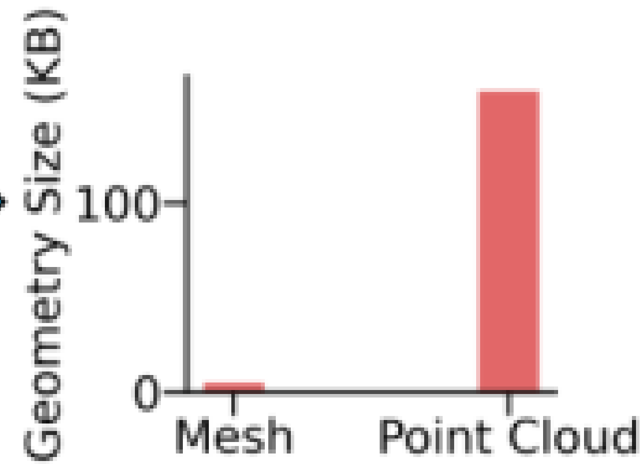
Requirements in 4D Mesh Streaming

- **Low Latency**: For interactive live streaming, we expect latencies on the order of 2D video conferencing systems (<100ms).
- **Scalable**: 3D video quality is often a function of number of cameras and scene size. An ideal capture solution should support dozens of sensors with commodity hardware.
- **Adaptive Streaming**: The system must operate given practical bitrates for Internet streaming, and the quality of the system should adapt to bandwidth availability.

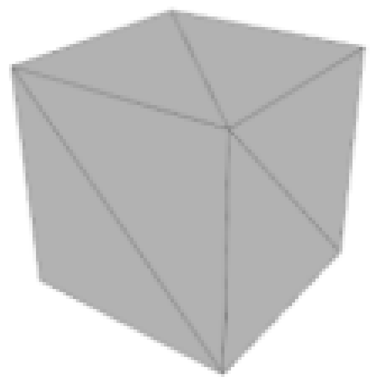
Implications of 3D Representations

Point Cloud Representation





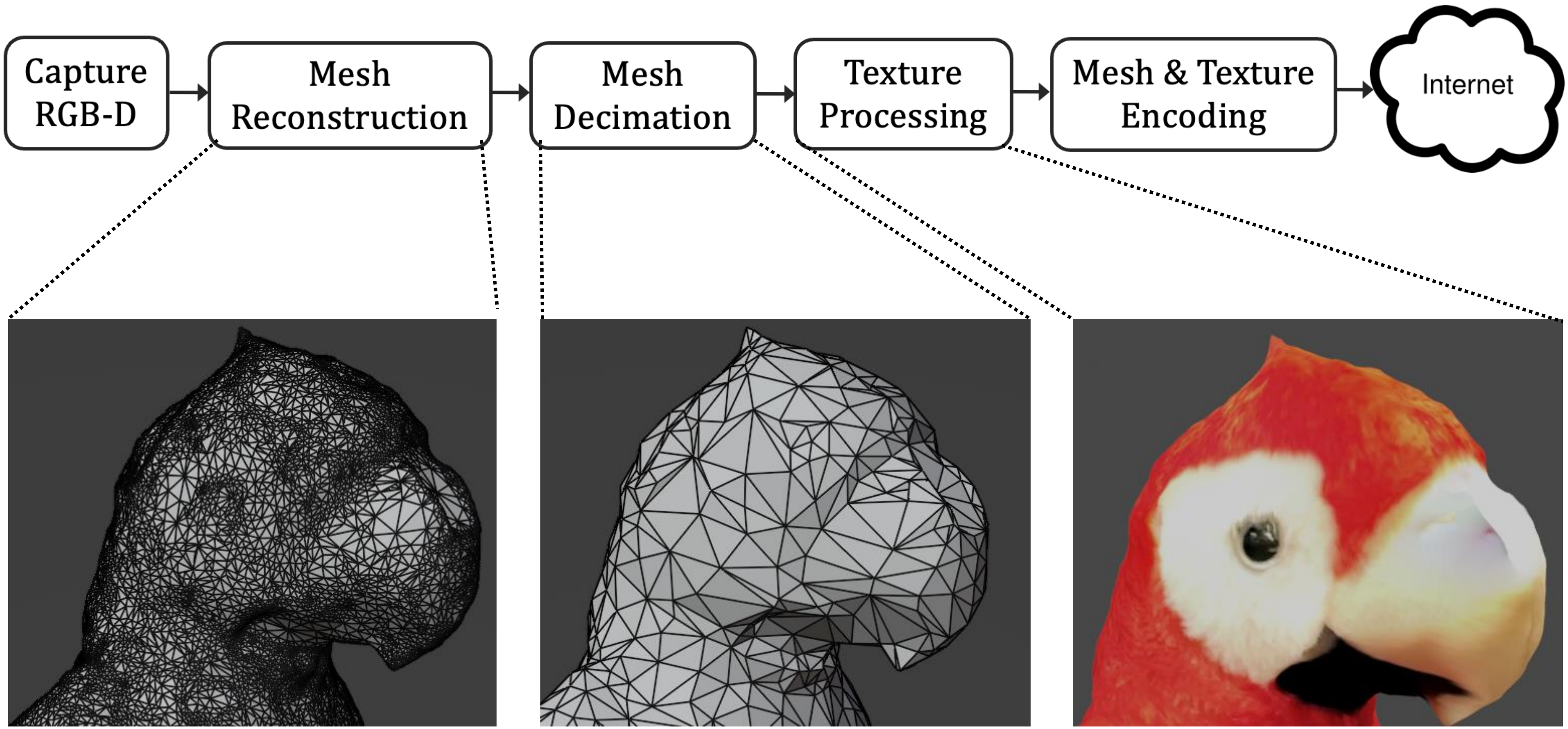
Mesh Representation



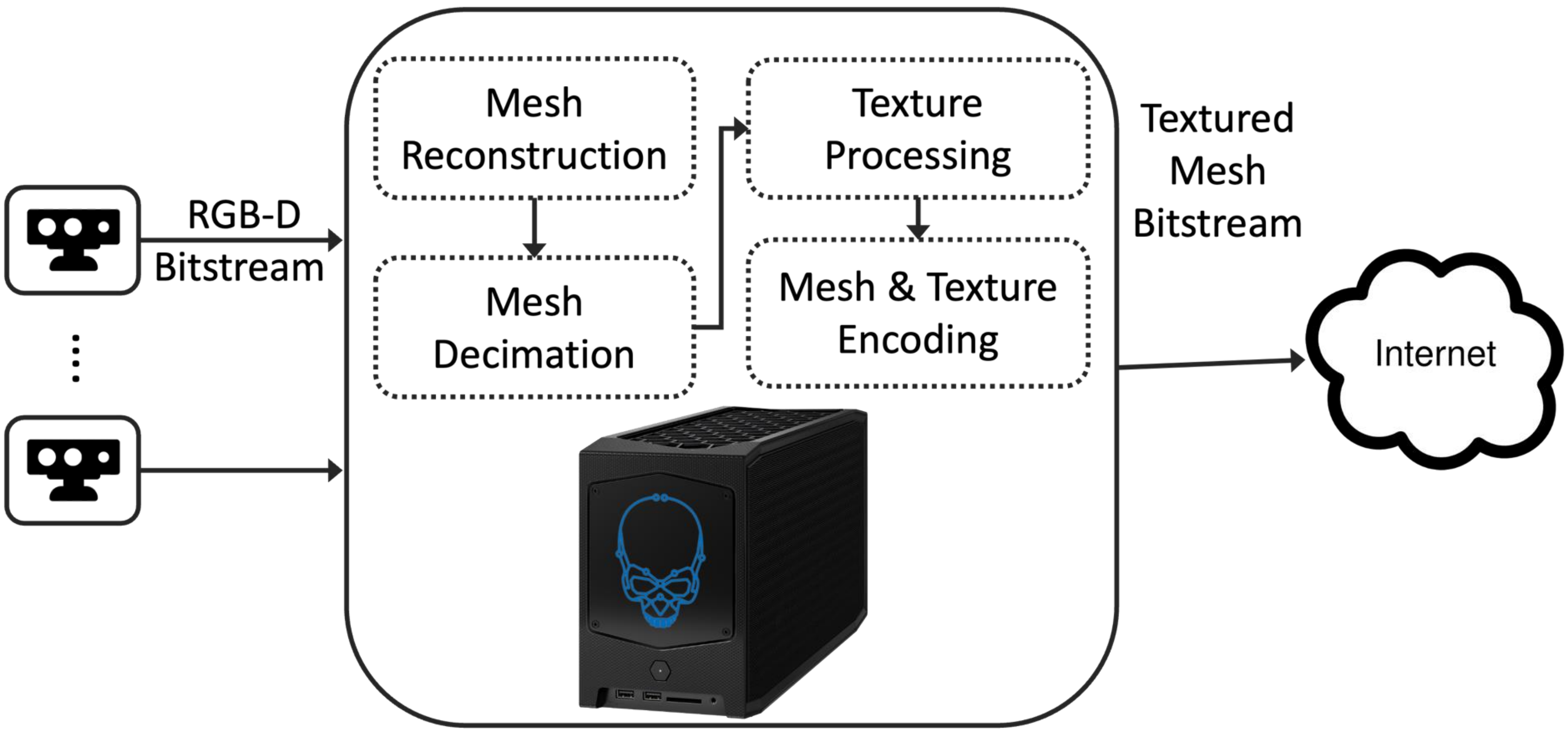
Mesh is not natively available in sensors

Mesh requires significantly less data rate but poses numerous computational challenges

Mesh Capture

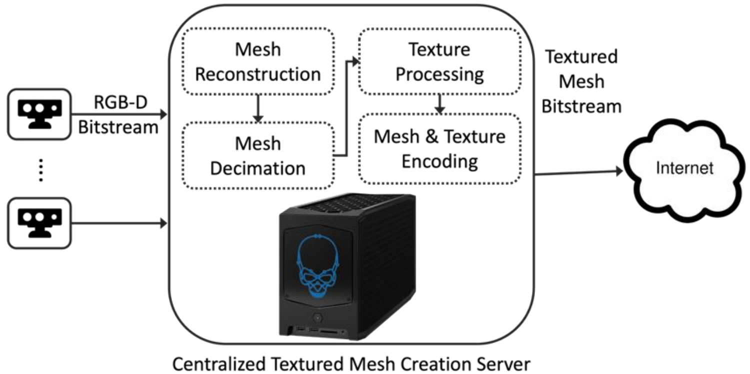


Mesh Capture

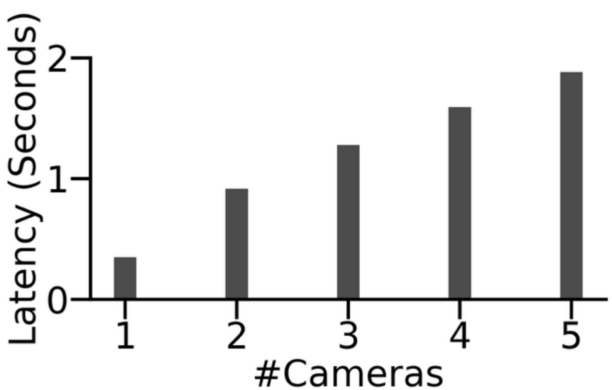


Centralized Textured Mesh Creation Server

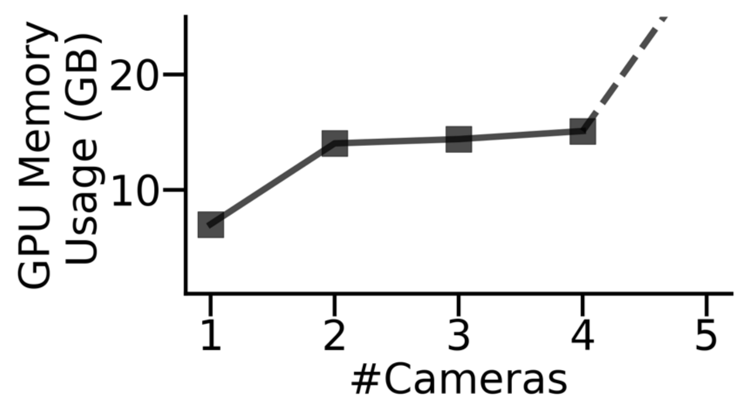
Mesh Capture



Decimation is computationally expensive task

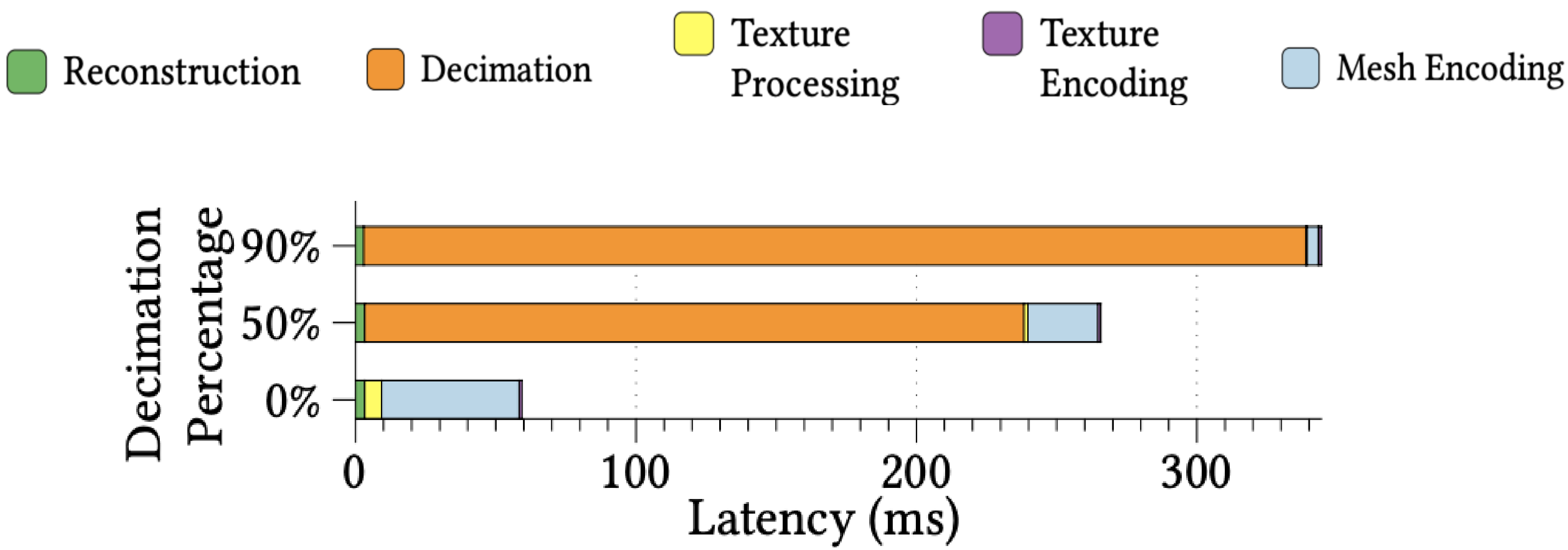


Reconstruction is GPU memory intensive



Not scalable with #cameras, scene size, and high quality

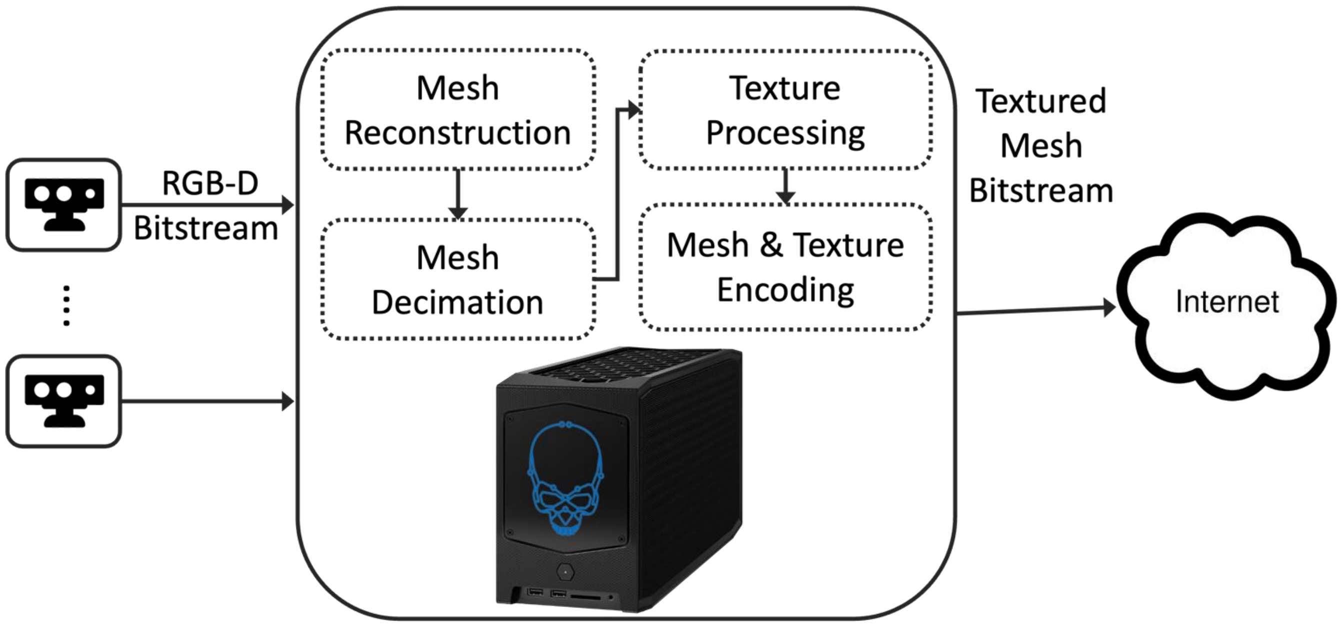
Root Cause Analysis



Decimation is computationally expensive task

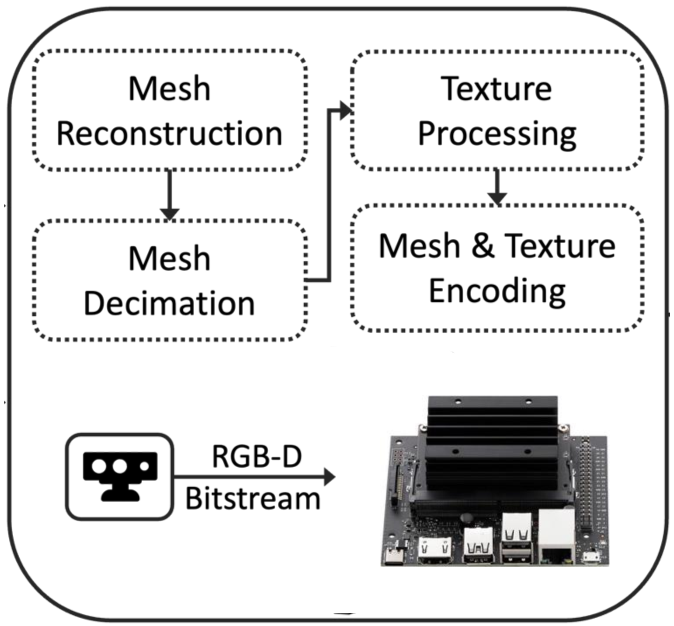
Reconstruction is fast but GPU memory intensive

Distributed Capture

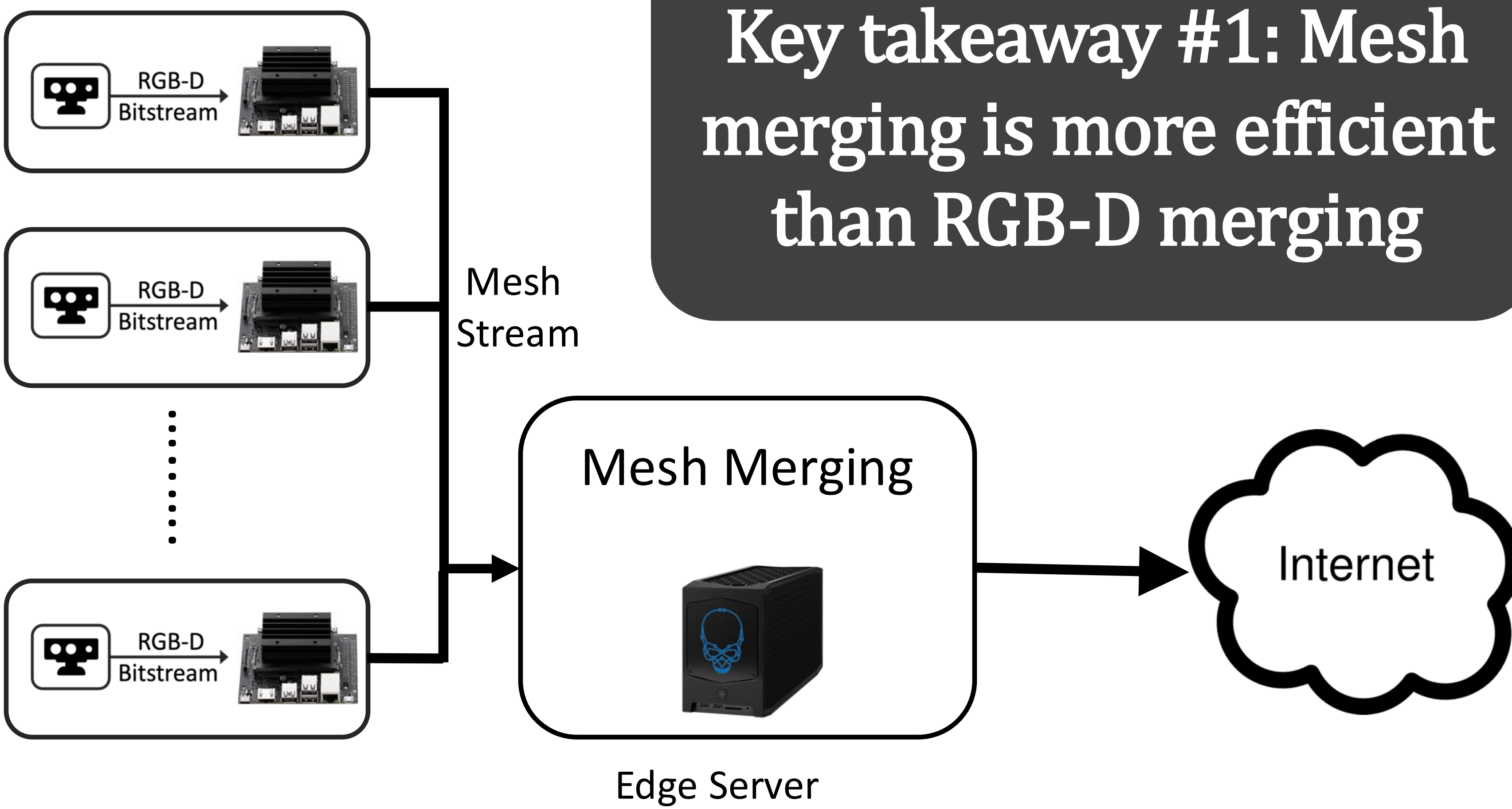


Centralized Textured Mesh Creation Server

Distributed Capture

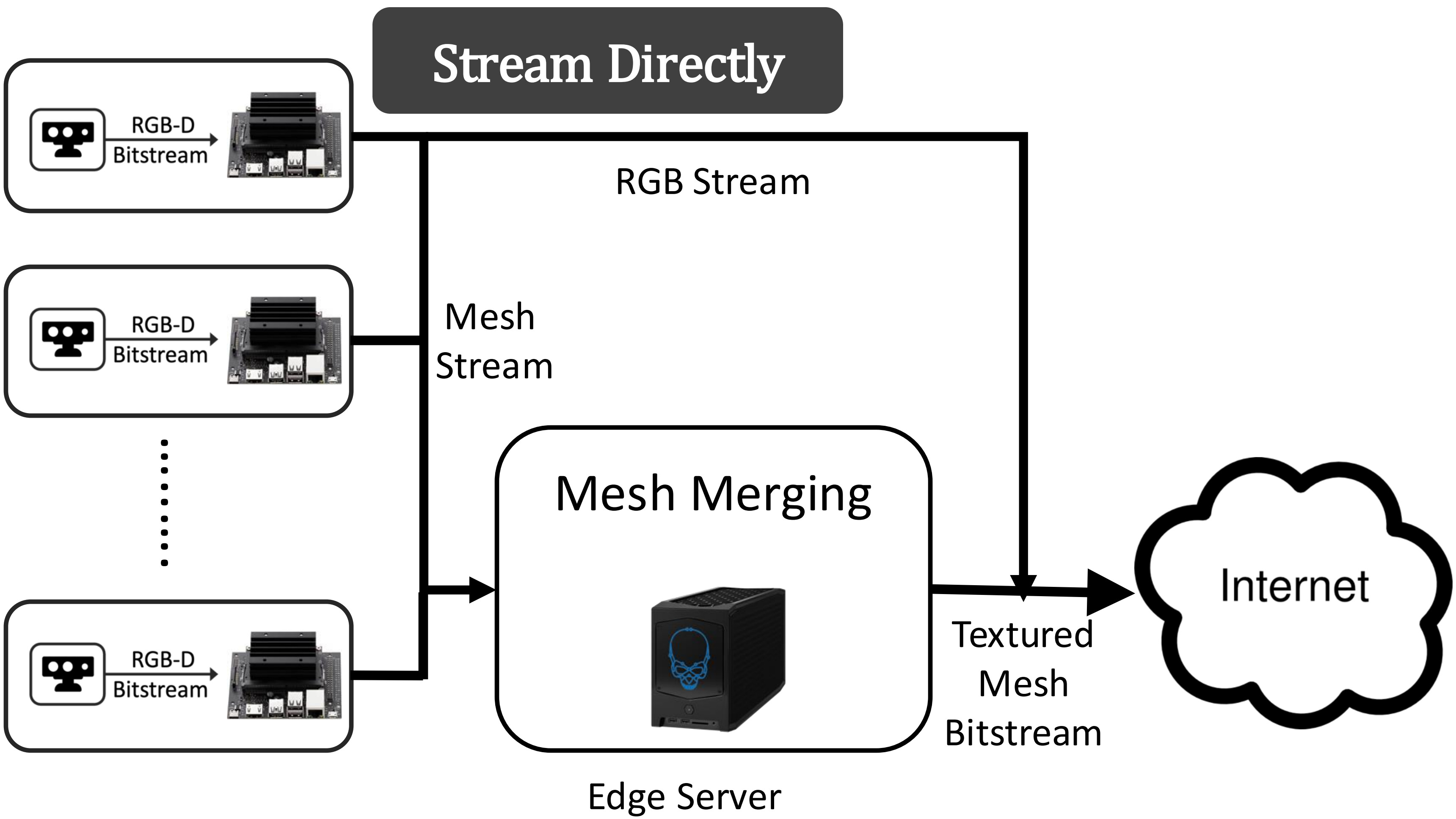


Distributed Capture

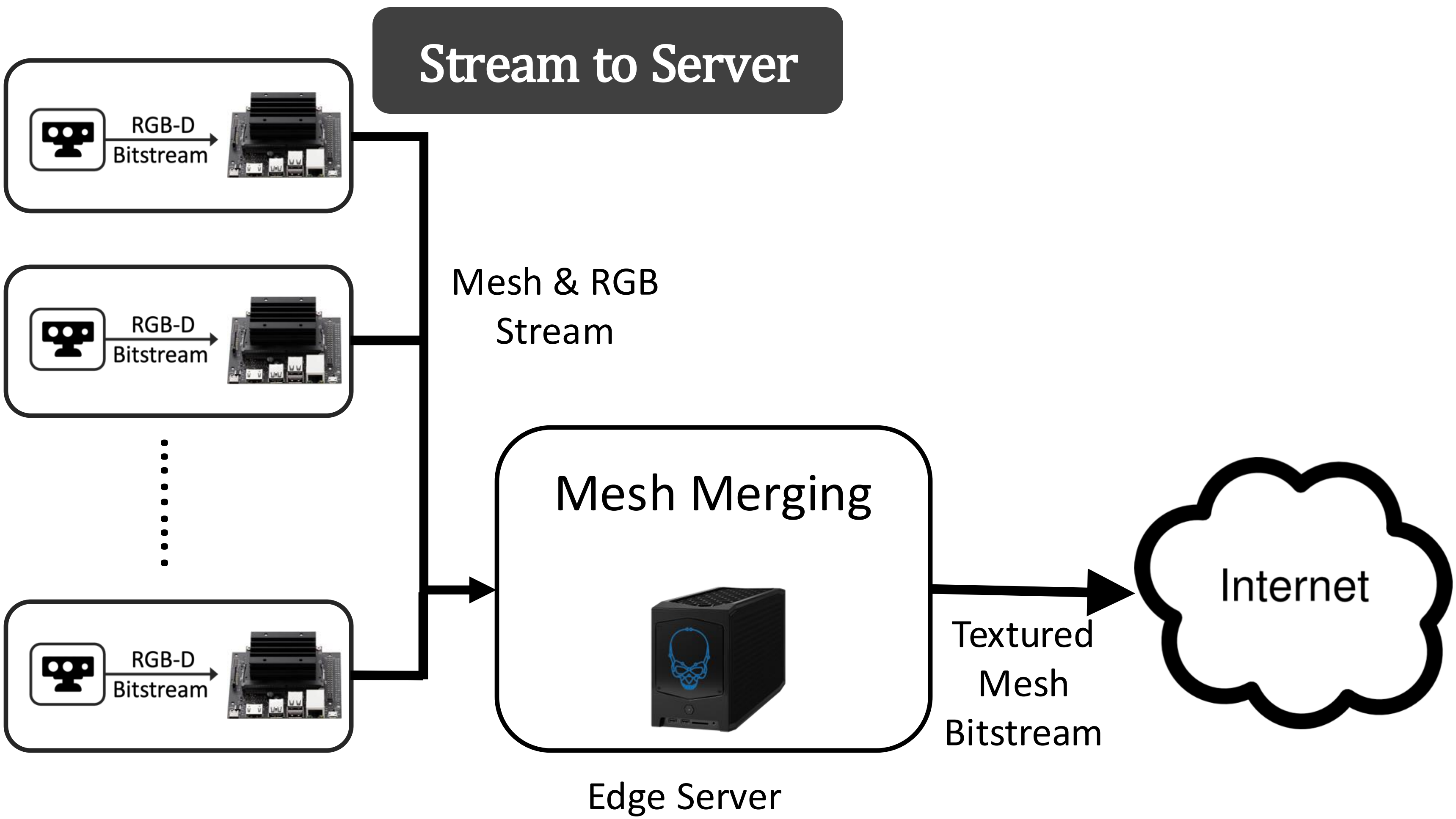


Key takeaway #1: Mesh merging is more efficient than RGB-D merging

Distributed Capture



Distributed Capture



Texture Processing

Compact Packing

NxN

NxN

Texture Processing

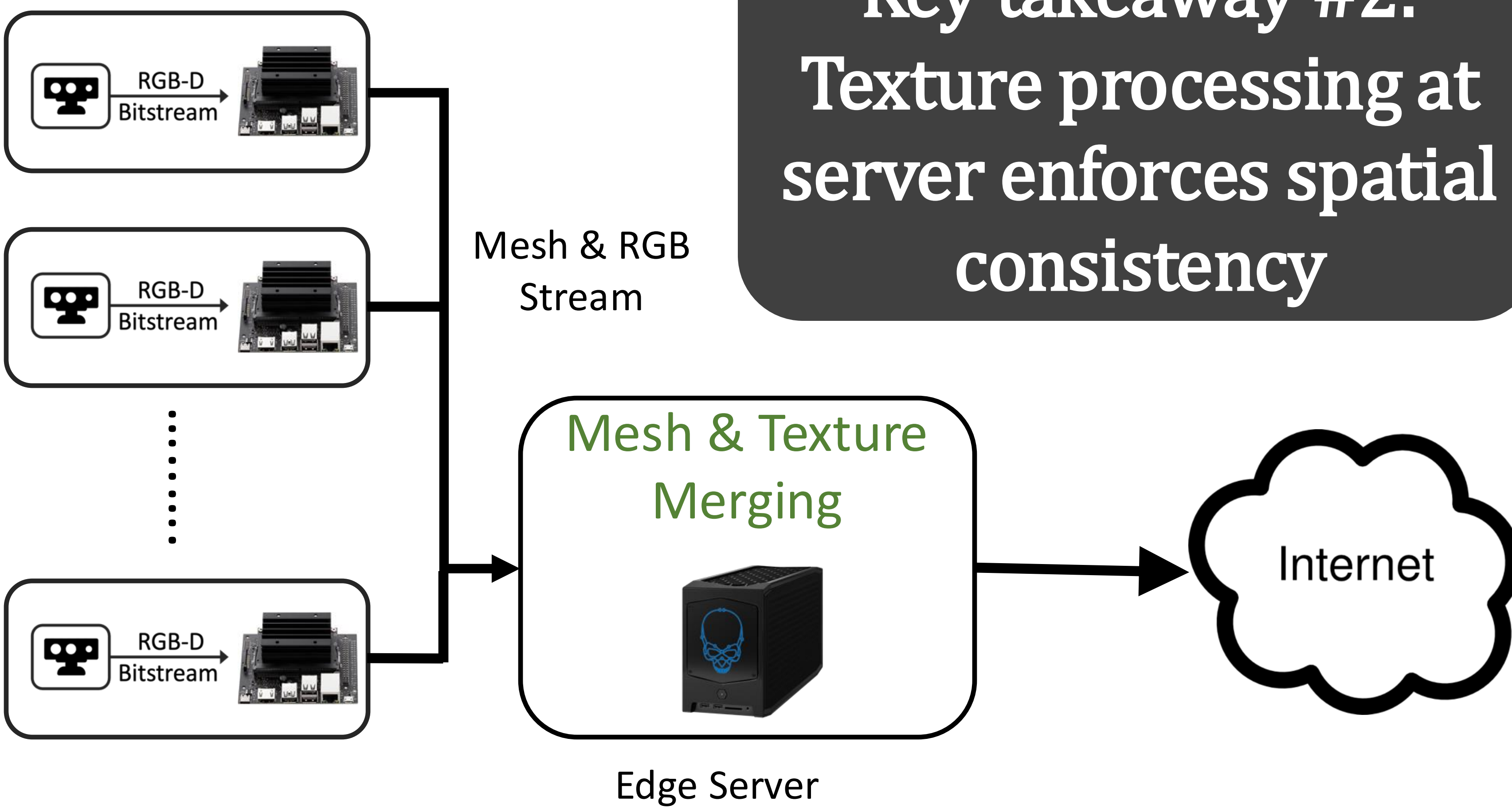
Nx2N

Compact Packing

< Nx2N

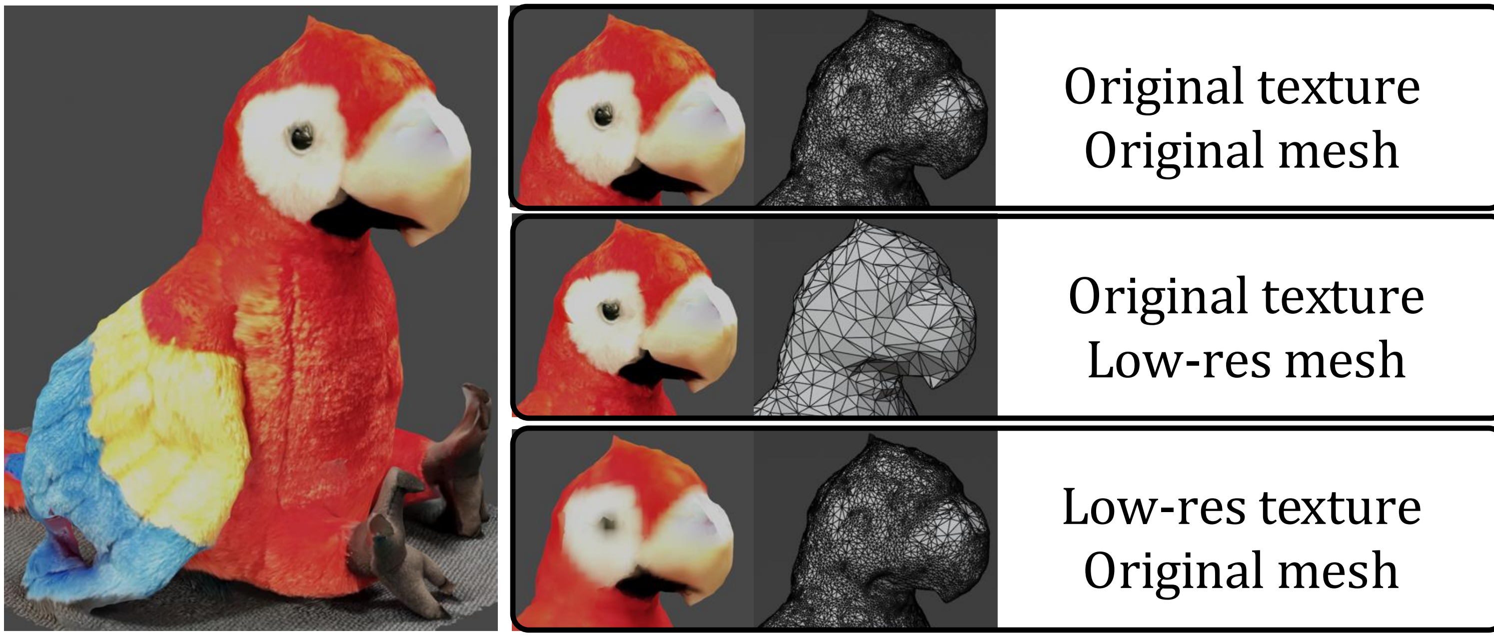
Codec/Bandwidth Efficient Packing

Distributed Capture



Key takeaway #2: Texture processing at server enforces spatial consistency

3D Rate control Problem



164MB

8.2MB

8.2MB

Texture has more impact on final rendered quality. It should be allocated more bits.

3D Rate control Problem

Texture vs. Geometry

$$\mathcal{L} = \mathcal{D} + \underbrace{\lambda_t \mathcal{R}_t + \lambda_g \mathcal{R}_g}$$

Rate distortion Function

Distortion

Bitrates for texture and mesh geometry with tuning parameters

How to split the bandwidth between texture and mesh?

How to select optimal coding parameters for both texture & mesh?

3D Rate control Problem

- Total bitrate: $R_{\text{total}} = 2000$ kbps
- Texture constant: $A_t = 400$
- Geometry constant: $A_g = 100$
- Lagrange multiplier: λ is same for both (so we can equate derivatives)

Question

1. Derive the relationship between R_t and R_g using:

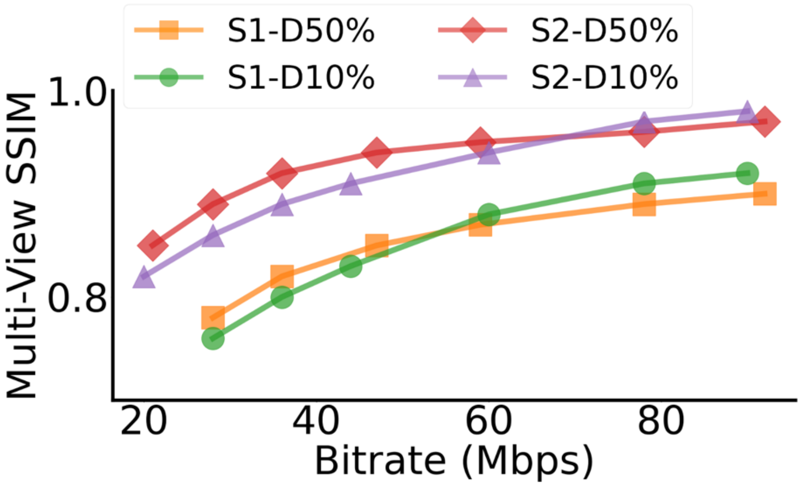
$$\frac{A_t}{R_t^2} = \frac{A_g}{R_g^2}$$

2. Compute the ratio R_t/R_g.
3. Find the values of R_t and R_g given $R_t + R_g = 2000$.

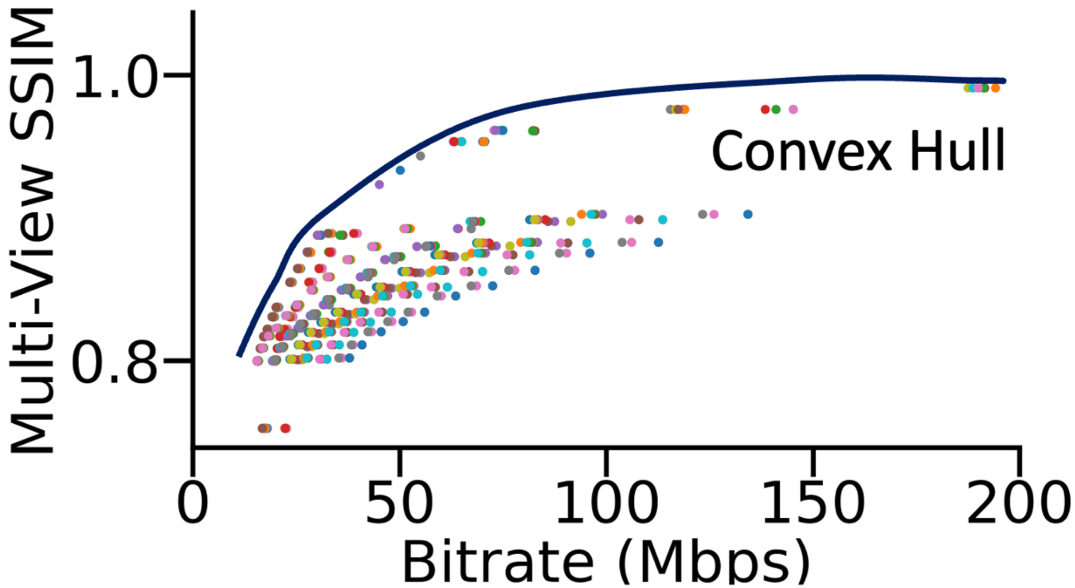
Streaming Texture vs. Mesh Geometry

- Rate distortion with two scenes (S1, S2) with two decimation levels (10%, 50%) encoded at different bitrates.

- For the same bitrates, S1 and S2 produce different qualities, and hence they need different coding parameters to produce same bitrates at same quality.



Streaming Texture vs. Mesh Geometry



Set of bitrate vs. quality points generated with different coding parameters.

Streaming Texture vs. Mesh Geometry

How to split the bandwidth between texture and mesh?

How to select optimal coding parameters for both texture & mesh?

RGB-D frames →

Bandwidth history →

Predictive Model

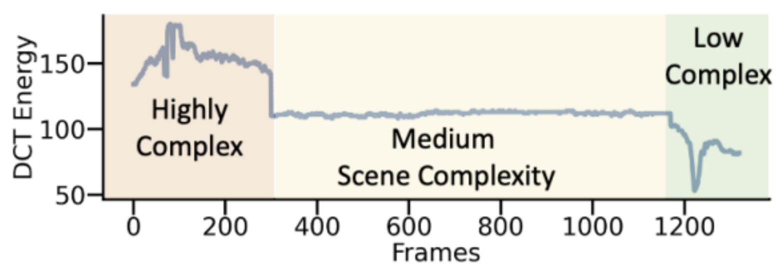
→ Coding Parameters for Texture & Mesh

Scene Complexity Metric

- DCT Energy

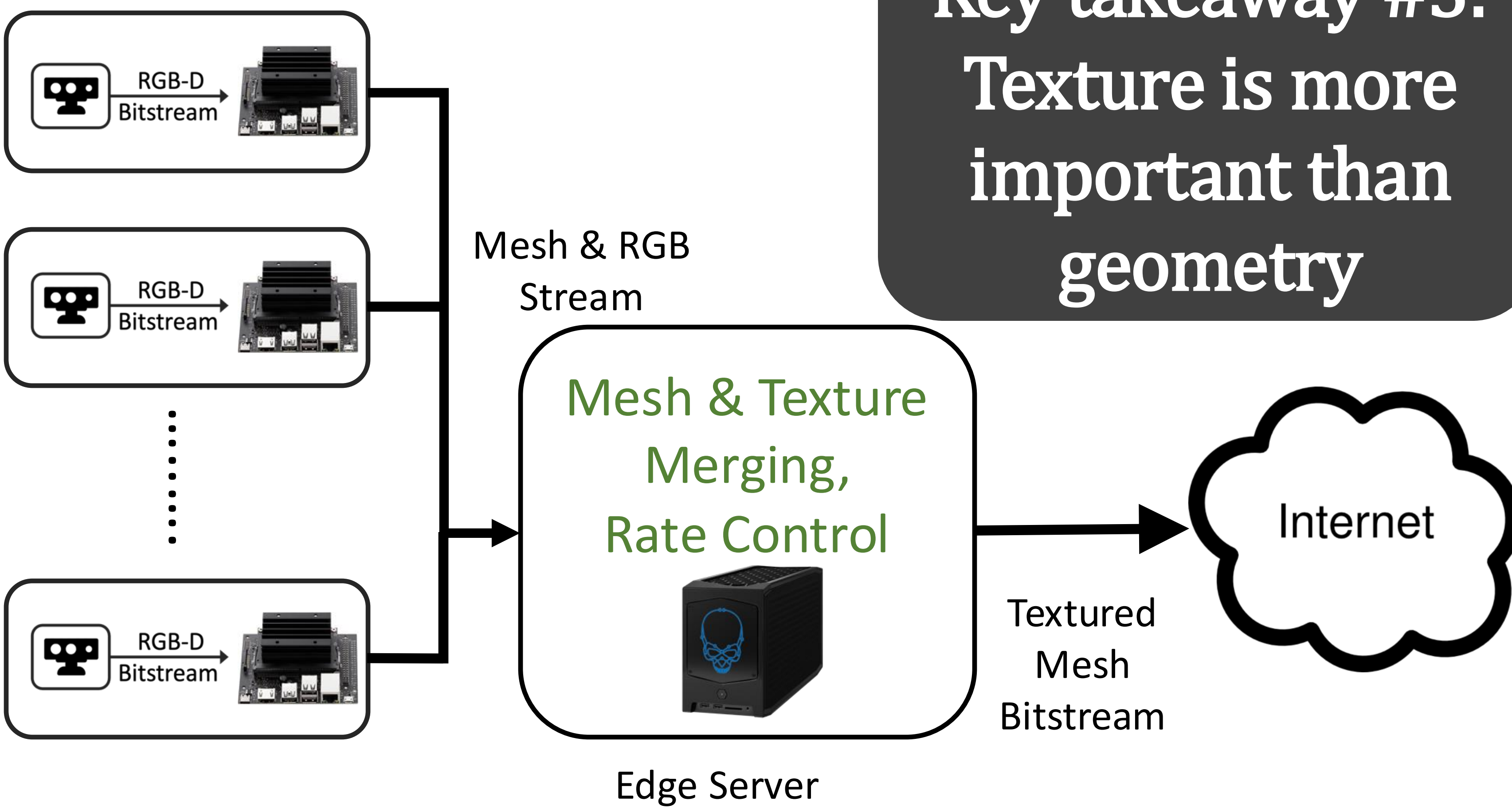
$$\mathscr{E}_{dct} = \sum_{i=w}^{j=h} e^{[(\frac{ij}{wh})^2 - 1]} |DCT(i-1, j-1)|$$

where, where w and h are the width and height of each block, and $DCT(i, j)$ is the $(i, j)^{th}$ DCT component when $i + j > 2$, and 0 otherwise



Distributed Capture

Key takeaway #3: Texture is more important than geometry



Adapting Texture and Mesh Streams

The scene is segmented into N objects: $1...N$.

q_i is the perceived quality of of the object i.

the quality q is a function of the texture video bitrate t_r, mesh polygon distortion ratio (m_r), and the texture mapping distortion (t_d).

We can model the function q in the following way.

$q = f(t_r \oplus m_r) - t_d$

where, $f(t_r \oplus m_r)$ is the perceived quality of rendered quality using the texture quality at t_r bitrate, and mesh quality at m_r bitrate.

Adapting Texture and Mesh Streams

$f(t_r \oplus m_r)$ can be computed in the following ways.

1. A linear function: $f(t_r \oplus m_r) = t_r + m_r$
2. A ratio: $f(t_r \oplus m_r) = \frac{t_r + m_r}{max_{t_r} + max_{m_r}}$
3. An index into a table of $t_r + m_r$ estimated through rate distortion curves of t_r and m_r

Adapting Texture and Mesh Streams

Given the above quality function for each object in the scene, we can model the overall expected perceptual quality of rendered final scene as

$E(Q) = \sum_{i=1}^{N} p_i \times r_{i,d} \times q_i$

where p_i is the view probability of object i, and $r_{i,d}$ is an integer variable denoting object being downloaded.

If an object is missed i.e., not downloaded, it results in loss of quality. We represent this loss in quality as

$E(O_m) = \sum_{i=1}^{N} p_i \times r_{i,m}$

where $r_{i,m}$ is an integer variable denoting object being missed.

Thus, the overall QoE can be modeled as

QoE = $E(Q) - \sigma E(O_m)$

Our objective is to maximize the above QoE function subject to the following constraints.

Adapting Texture and Mesh Streams

Constraints.

The following constraints ensure the feasibility of the solution. The quality of an object can only be positive if the object is downloaded, i.e.,

$q_i \geq r_{r,d}$

also, every object must be either downloaded or missed.

$r_{i,d} + r_{i,m} = 1, \forall i = 1...N$

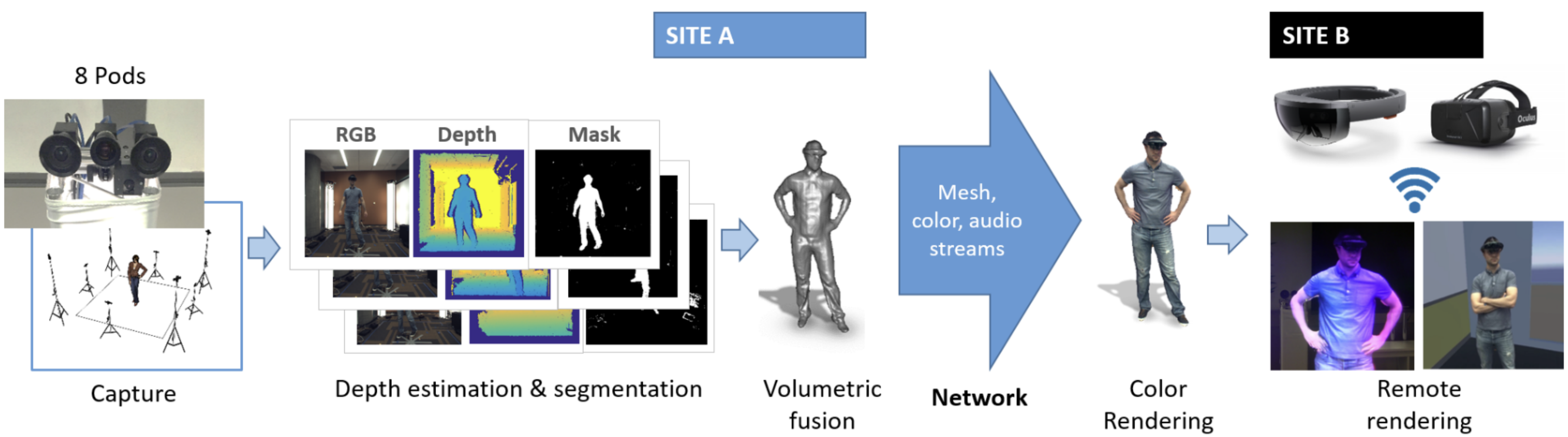
Finally, the downloading must complete before some time δ before the playback time P_t. Let $d(q_i)$ be the download time of object i at quality q_i. Then this constraint can be represented as.

$\sum_{i=1}^{N} d(q_i) \times r_{i,d} + \delta \leq P_t$

This represents the bandwidth constraint, which can also be written as follows, $t_r + m_r \leq C$, where C is the predicted bandwidth.

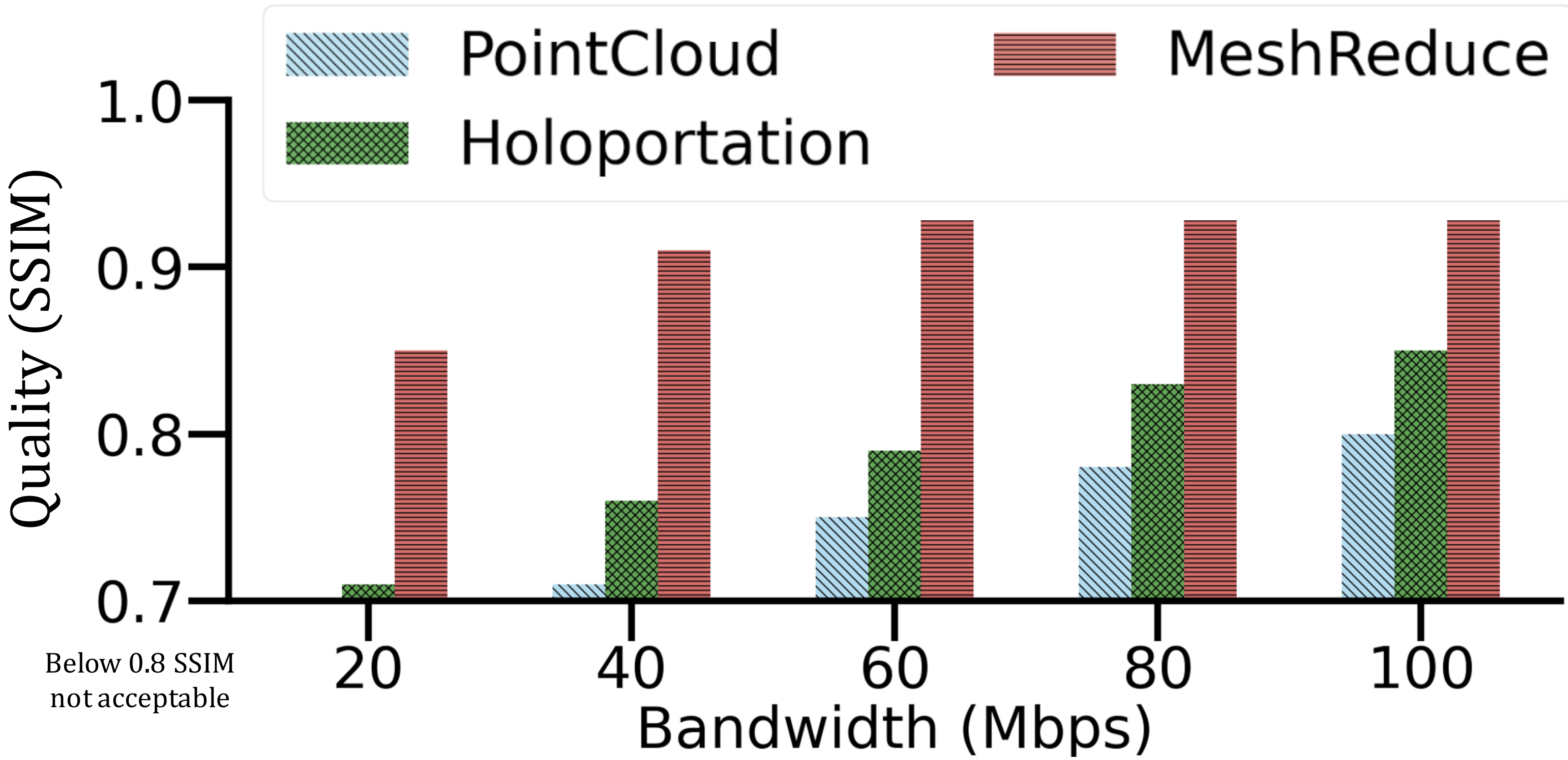
Distributed Capture Performance

- Comparison
  - MeshReduce
  - Holoportation
  - Point Cloud based streaming



Holoportation

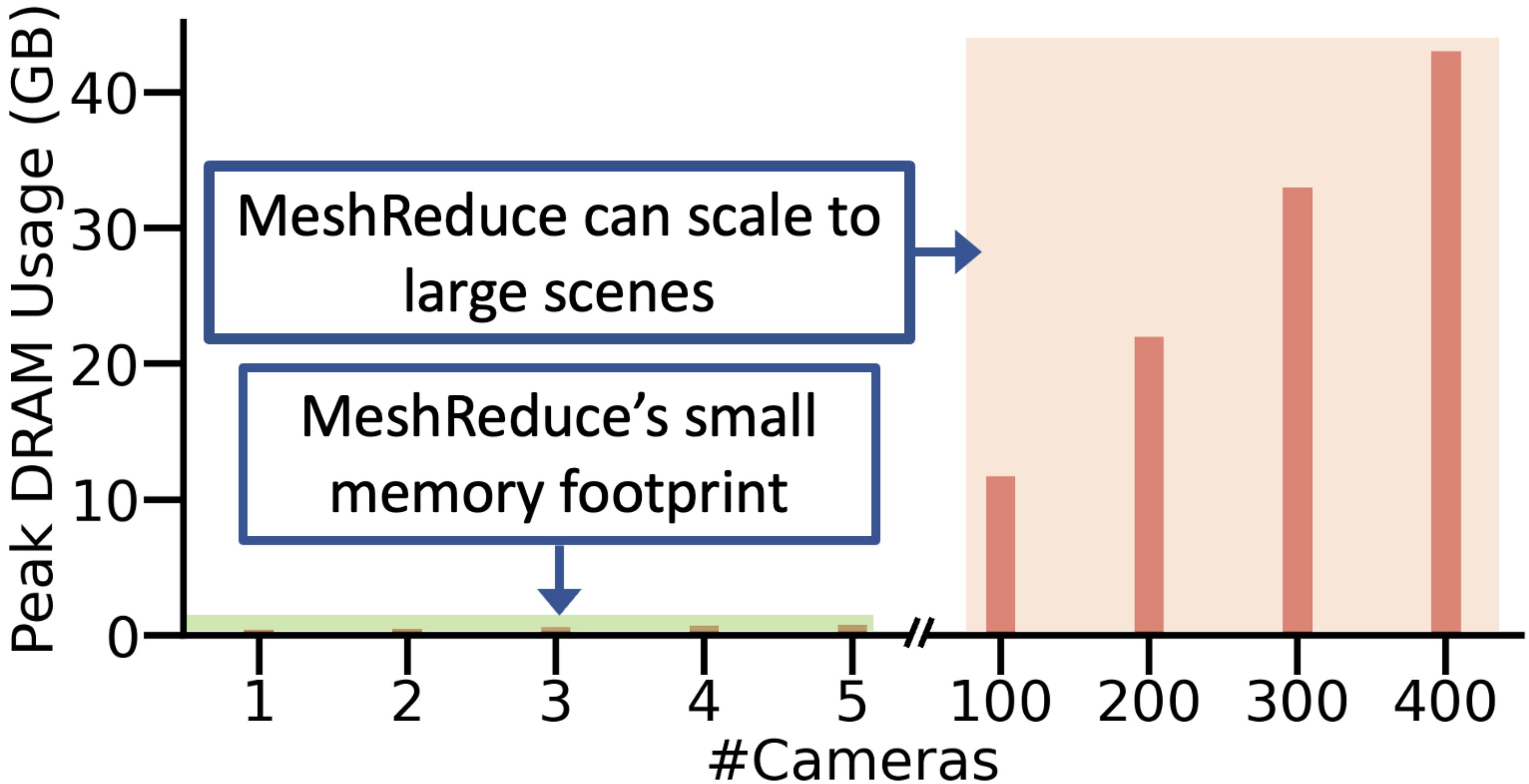
Distributed Capture Performance



Below 0.8 SSIM
not acceptable

Significantly better quality under lower bitrates

Scalability of Distributed Capture



Not GPU bottlenecked; DRAM is abundant and scalable

Visual Quality

Color inconsistency Depth holes Occlusion

Deep Learning based in-fill

Color Texture | Depth/Geometry | Texture Mapped Mesh | Mesh Diffusion in-Fill

Traditional textured mapped mesh vs. genAI/Diffusion in-filled upsampling.

Summary of the Lecture

- Mesh streaming
- Distributed Capture
- Adaptation of texture and mesh streams

Next up: XR Experiences