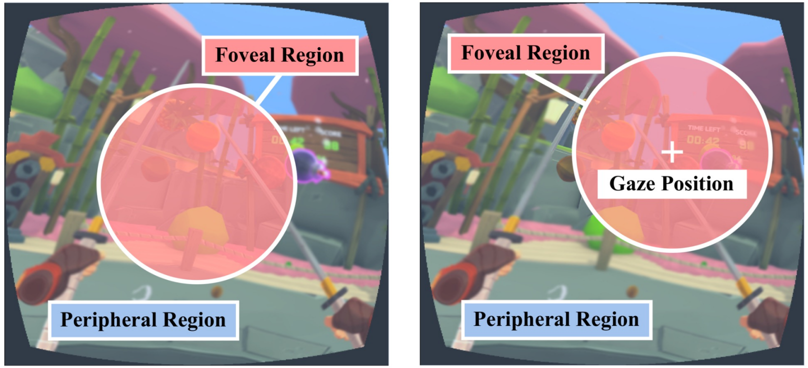
# Optimizing Dynamic Foveation for a Cloud VR Gaming Platform




Jia-Wei Fang (nthu107062121@gapp.nthu.edu.tw)

Network and Multimedia Systems Lab
Department of Computer Science
National Tsing Hua University

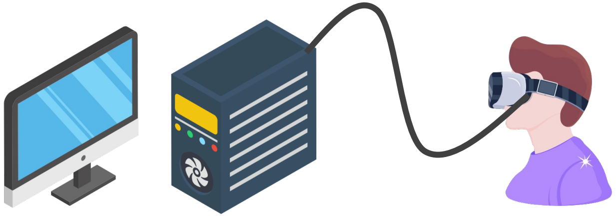
# Outline

- Introduction
- Related Work
- System Overview
- Dynamic Foveation in a Cloud VR Gaming Platform
- Optimization of the Foveation Module
- Subjective Evaluations
- Conclusion & Future Work

# Cloud VR Gaming

### Tethered VR

Cumbersome Wires : (



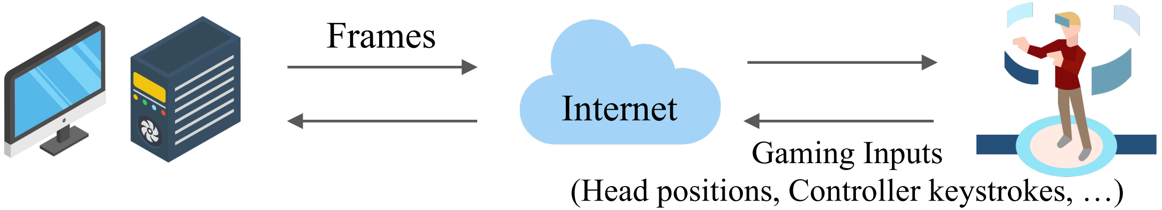
Powerful Rendering Resources!

### Mobile VR

Limited Rendering Resources : (

Full Mobility!

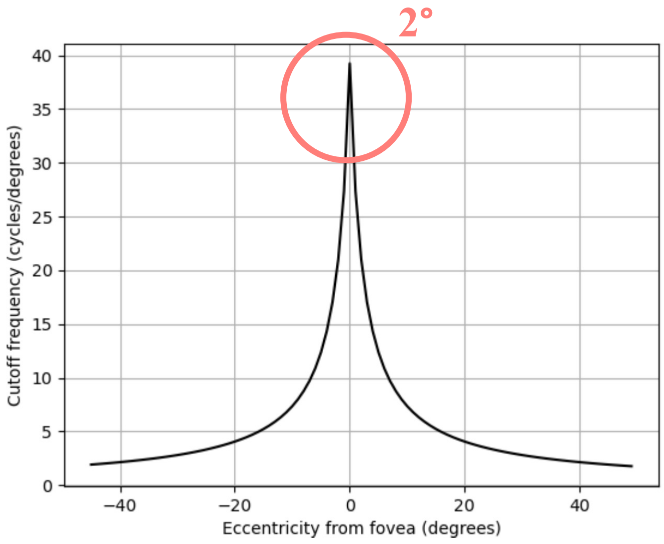
## **Cloud VR**



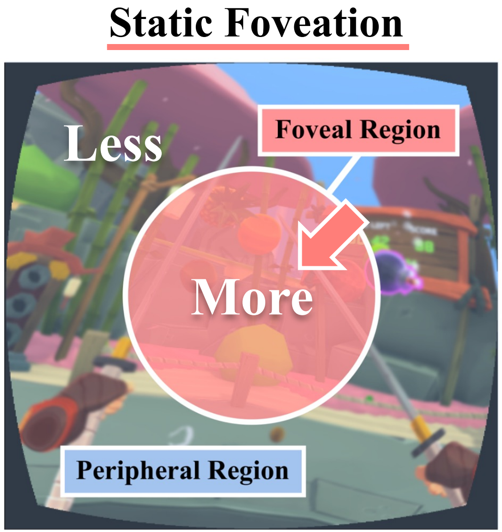

**But…High quality ➔ High bandwidth requirement**

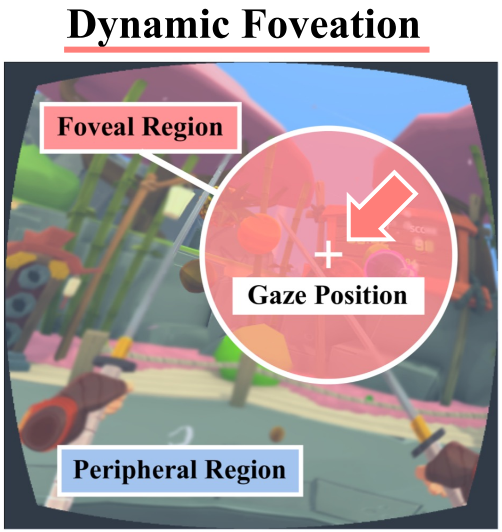
# Foveation

The phenomenon of **non-uniform visual acuity** of human eyes:



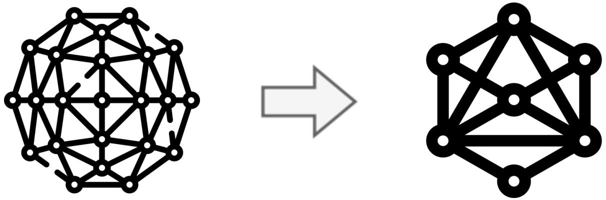

[G.Illahi et al, MMSys'21]



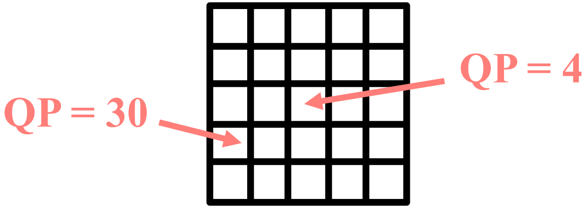



# Foveation Types

- **Foveated Rendering**: reduce the computing workload, e.g., downsampled 3D meshes



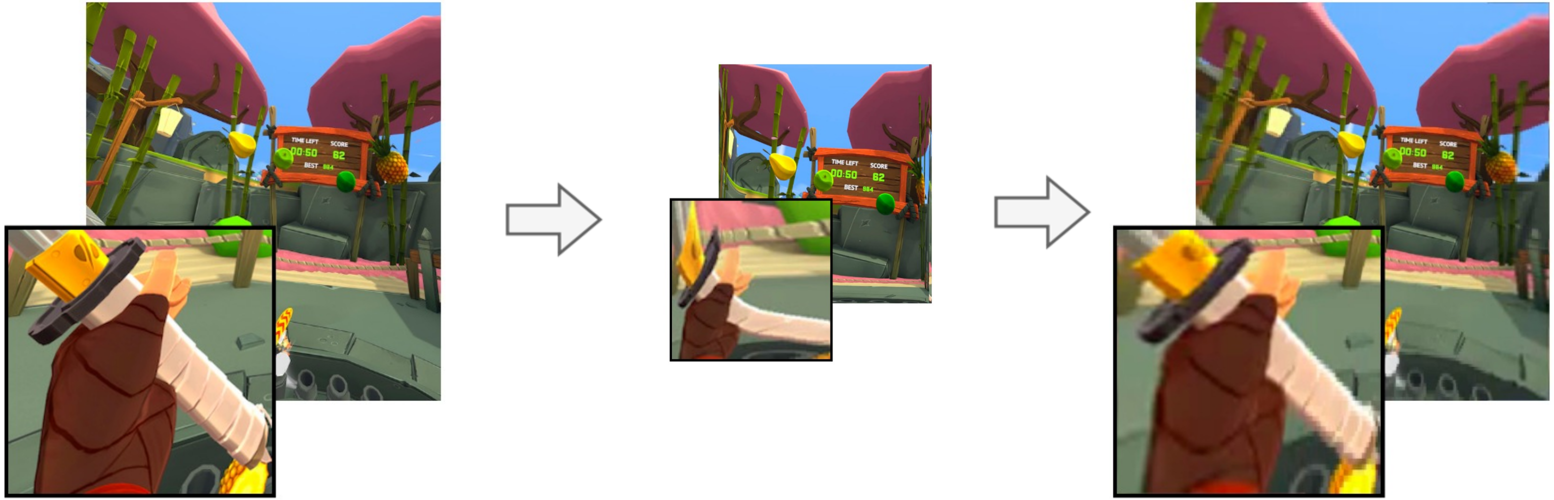
- **Foveated Encoding**: adjust the video encoding parameters, e.g., quantization parameters




- ✓**Foveated Warping**: non-uniformly downsample the rendered viewports before encoding

# Foveated Warping

**Original** **Warped** **Unwarped**



# Quality of Experience (QoE)

**QoE** serves as a **multifaceted metric** encompassing **the overall satisfaction and perception of users** while engaging with a particular system or service.

**Influencing Factors:**

**Human**

**(Age, Gender, …)**

**✓System**

**(Visual quality, Latency, …)**

**Context**

**(Task, Time, Location, …)**

# Research Questions

- **RQ1: Does dynamic foveation boost cloud VR gaming experience?**
- **RQ2: How to effectively support dynamic foveation in cloud VR gaming?**
- **RQ3: How much QoE improvement can we achieve after optimizing the platform?**

**Goal**
Enable Dynamic Foveation in Cloud VR Gaming Platform

**RQ1**
Conduct a User Study to Evaluate Dynamic Foveation

**RQ2**
Optimize the Foveation Module in the Platform

**RQ3**
Conduct another User Study to Evaluate the Optimized Platform

# Reality and Challenges

**As of Today**

- Mobile HMDs with eye trackers had not been widely adopted
- Existing remote VR gaming systems **only support static foveation** at best

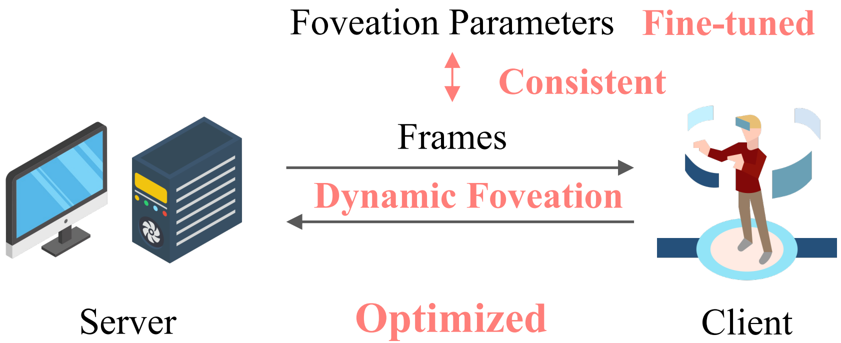
**Challenges**

- Foveation parameters must be **consistent** at the frame level
- Foveation parameters must be **fine-tuned** through time-consuming user studies
- The foveation module must be **optimized** to achieve ideal system performance (low latency and high frame rate)

Few Mobile HMD with Eye-tracking

Pico Neo 3 Pro Eye

Meta Quest Pro



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# Related Work

**Remote rendering systems**

- GamingAnywhere [MMSys'13]
- CloudXR [Nvidia]
- Cloud gaming foveation prototypes [TOMM'20]

**None of these studies realized real-time remote rendering VR systems with dynamic-foveation supports**

**Unequal rate allocation**

- Content-aware [MMSys'19]
- Object-aware [ICMEW'21]
- Foveation-based [TOMM'20]

**These studies need the ROIs and object information from VR applications / Foveation-based systems do not support VR contents**

## Gaze-driven adaptations

- Adjust the encoding parameters of each macroblock [TMM'20]
- Encode the video in multiple-resolution tiles [MM'16]
- Deliver high-quality VR content around the gaze in 360° videos [VRW'18]

**Our work realizes an interactive cloud VR platform rather than one-way video streaming**

## VR user studies with foveation

- Investigate the relationship between response time and bitrate [SIGCOMM'22]
- Evaluate the HVS acuity [TOG'16]
- Evaluate different subjective metrics [MM'17]

**None of these studies conducted user studies with eye-tracking-enabled HMDs to assess the performance of dynamic foveation**

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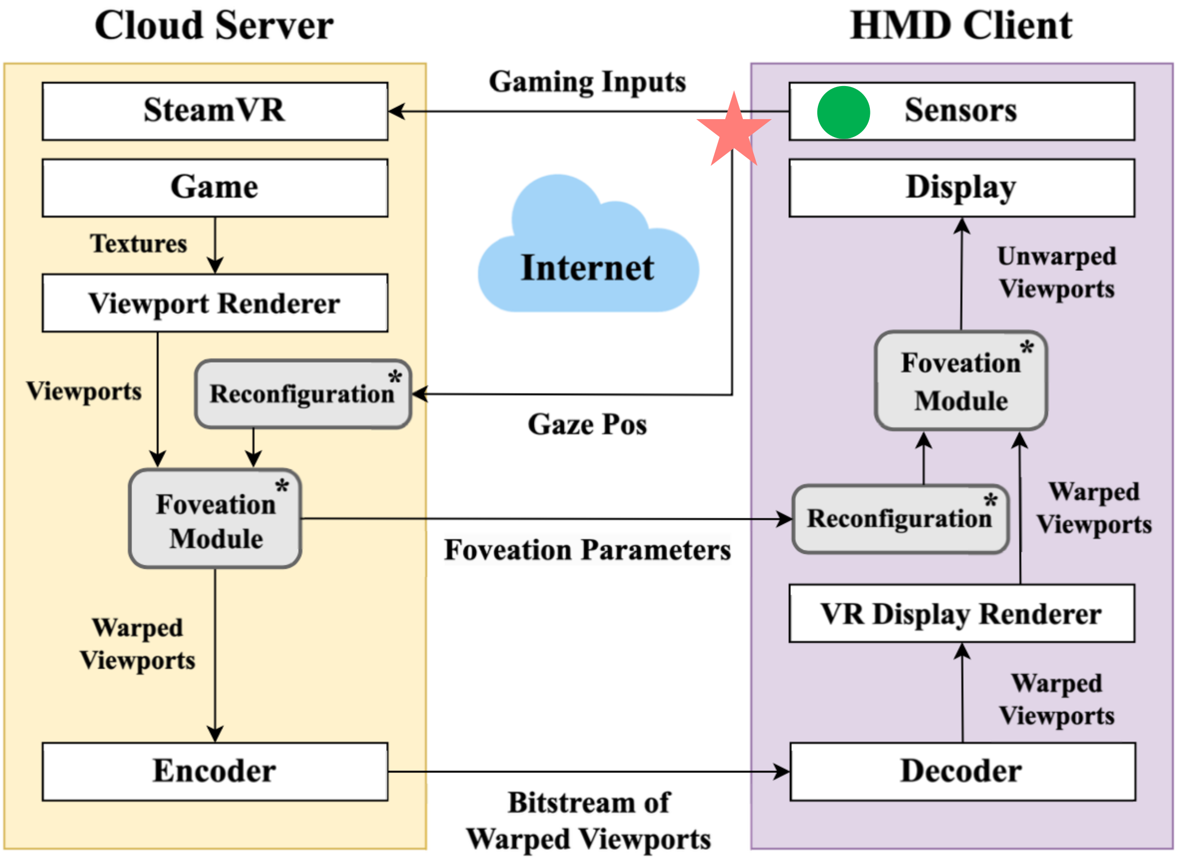
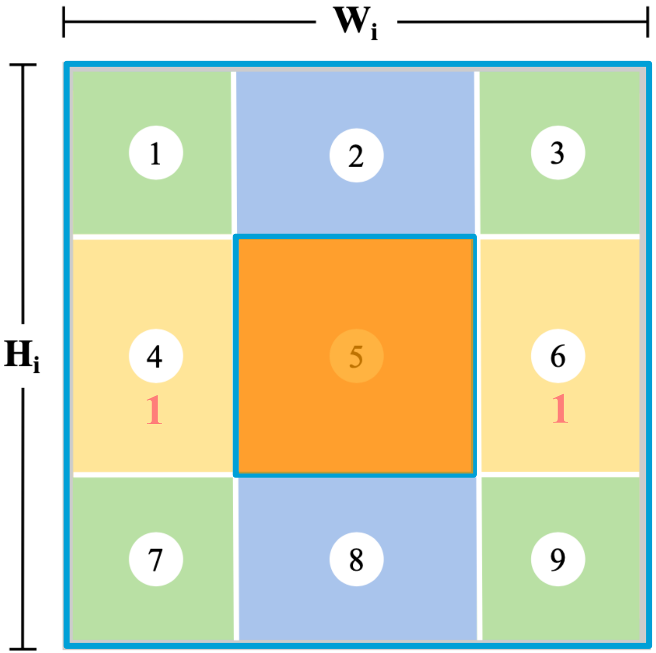
# Interaction between the Server and Client

Warped



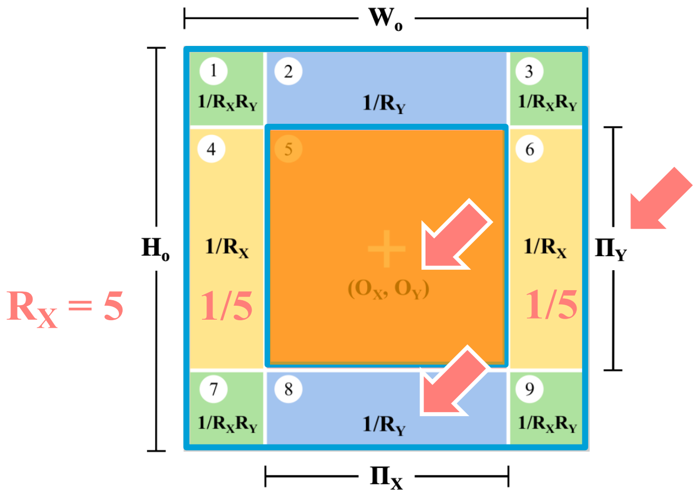

Unwarped

# AADT Warp (Axis-Aligned Distortion Transmission)




**The sizes of peripheral region are squeezed**

**The sizes of foveal region are the same**




$$W_o = W_i \times [\Pi_X + (1 - \Pi_X)/R_X];$$
$$H_o = H_i \times [\Pi_Y + (1 - \Pi_Y)/R_Y],$$

- Original viewport width and height: $W_i$, $H_i$
- Warped viewport width and height: $W_o$, $H_o$
- Foveal region size: $\Pi_X, \Pi_Y \in \{0, 1\}$
- Foveal region center: $O_X, O_Y \in \{-1, 1\}$
- Compression ratios: $R_X, R_Y \in \{1, 10\}$

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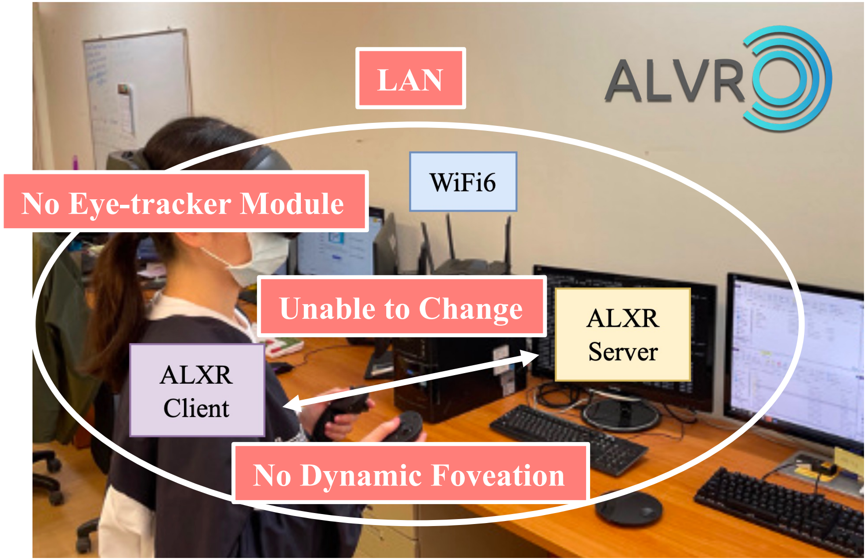
# ALXR (https://github.com/korejan/ALVR)

An **open-source project** that streams VR games from PC to HMD via WiFi

Limitations:

1. Implemented in LAN streaming
2. No eye-tracker support
3. Only supports static foveation
4. Foveation parameters are manually-selected



# Enhancement on ALXR

- Modify ALXR to make the client initiate a session with a user-specific server IP address → to **support WAN streaming**
- Invoke head- and eye-tracking APIs through OpenXR SDK

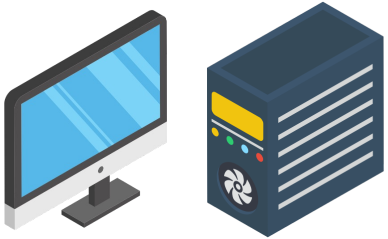
  → to **track gamers' head and gaze positions** in real-time
- Develop **dynamic foveation mechanism**

  → to **support dynamic foveation**

  → to **adjust foveation parameters** in real-time

# Dynamic Foveation Mechanism

ALXR Server



ALXR Client

`gazePos(x, y)`

`renderingTime`

1. Client sends gaze positions and timestamp to server

# Dynamic Foveation Mechanism

ALXR Server


ALXR Client

`New Foveation Parameters`

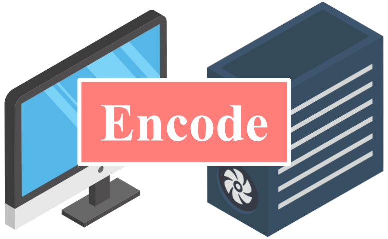
`Current time ≥ renderingTime`

2. Server warps the frame with new foveation parameters when the current time is close to the timestamp

# Dynamic Foveation Mechanism

ALXR Server

ALXR Client



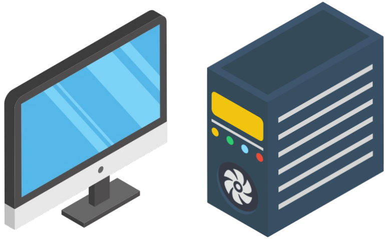

`New Foveation Parameters`

`displayTime`

3. Server encodes the warped frame and sends it with new foveation parameters and its anticipated playout timestamp

# Dynamic Foveation Mechanism

ALXR Server



ALXR Client

`New Foveation Parameters`

`displayTime`

4. Client stores the received timestamp and foveation parameters

# Dynamic Foveation Mechanism

ALXR Server

ALXR Client


New Foveation Parameters

Current time ≥ displayTime

5. When current time is equal to the timestamp,
client unwarps the frame with the corresponding foveation parameters

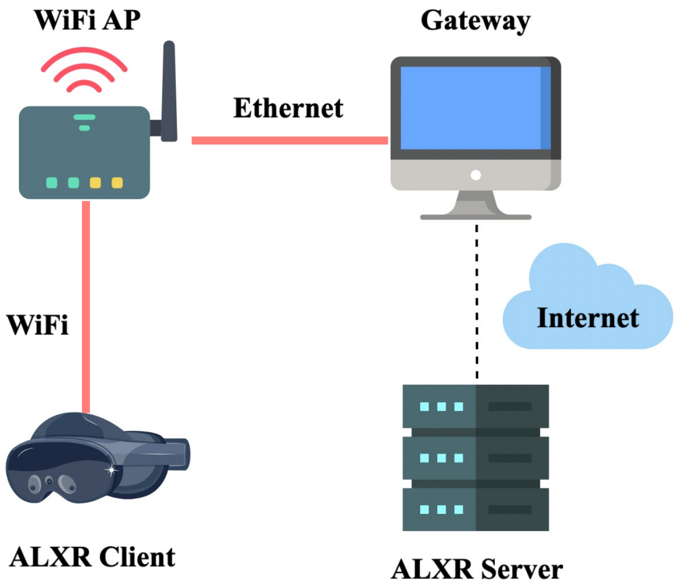
# Dynamic Foveation Mechanism

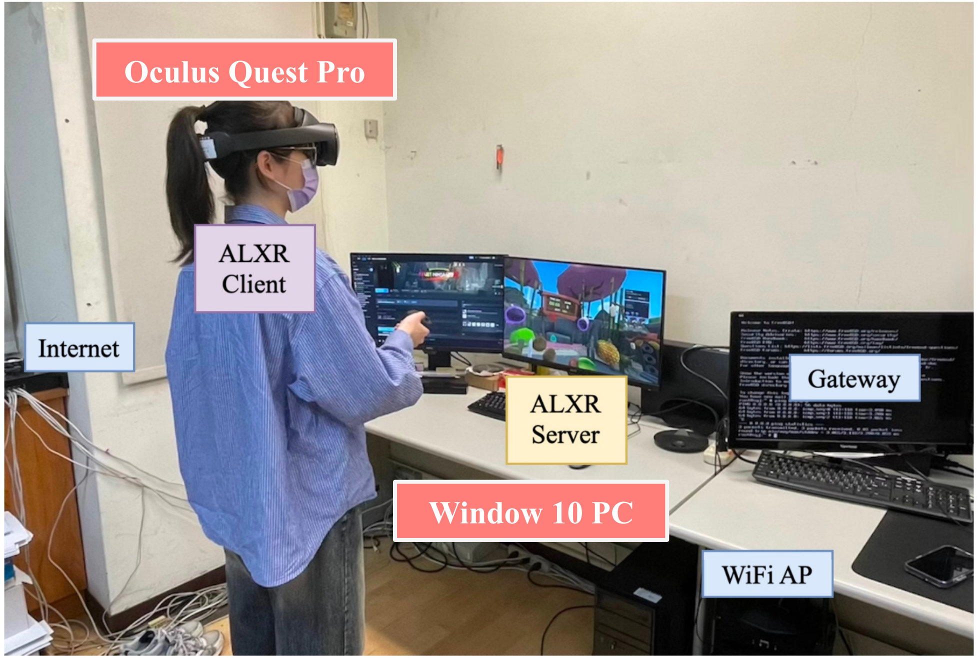
ALXR Server

ALXR Client


6. Client finally displays the frame

# Experimental Testbed



# User Study Setup

**Game**: Fruit Ninja VR 2

**Encoder**: Nvidia H.264

**Target bitrate**: 5 Mbps (CBR)

**Frame rate**: 72 FPS

**Gaze update frequency**: 10 Hz

**13 Scenarios**:

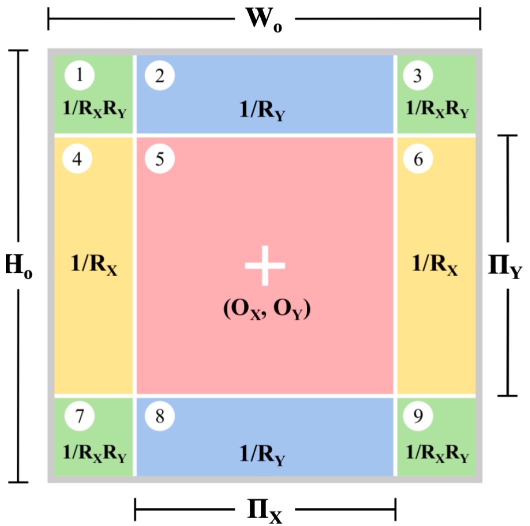
- (**D**, Π, *R*),
  Π ∈ {0.2, 0.5, 0.8}, *R* ∈ {2, 5, 8}
- (**S**, Π, *R*),
  ***Aggressive*** (**S**, 0.2, 8),
  ***Balanced*** (**S**, 0.5, 5),
  ***Safe*** (**S**, 0.8, 2)
- (**N**, -, -)

**Foveal region size: $\Pi_X, \Pi_Y \in \{0, 1\}$**

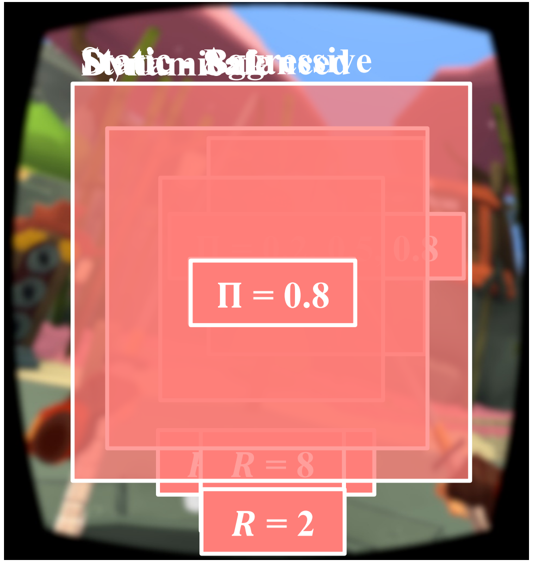
0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9

**Compression ratios: $R_X, R_Y \in \{1, 10\}$**

1, 2, 3, 4, 5, 6, 7, 8, 9



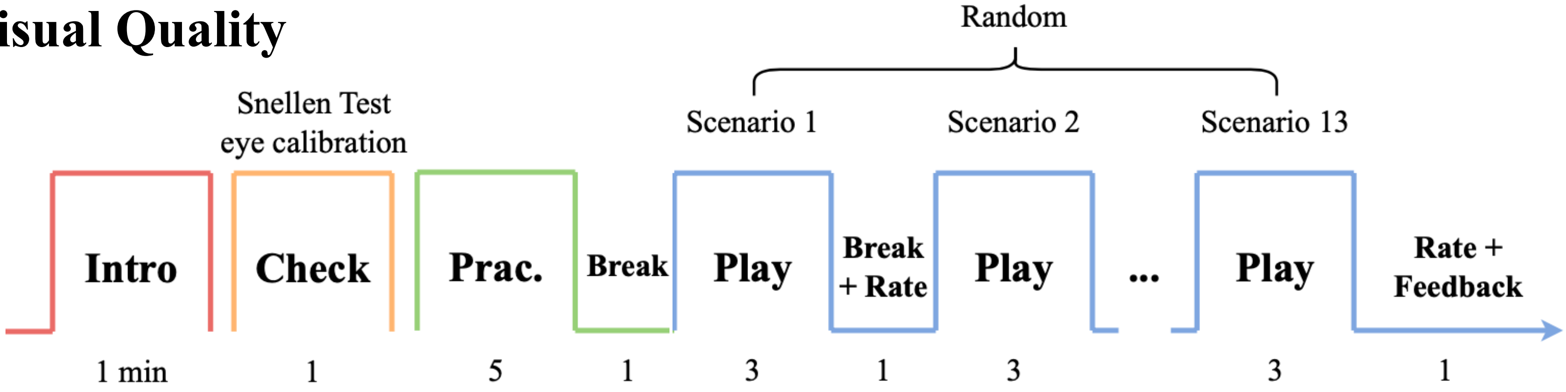




RQ1

# Procedure

- **15 subjects** (9 males)
- **Age**: 22 – 25 years old
- **Time**: 60 – 90 minutes
- Single-stimulus **ACR** (Absolute Category Rating) [1] on a scale of **1 – 5** in **Visual Quality**




[1] T. Installations and L. Line. 1999. Subjective video quality assessment methods for multimedia applications. Networks 910, 37 (1999), 5.

# Optimal Parameters for Dynamic Foveation

- (S, 0.5, 5) and (D, 0.5, 5) are the best foveation parameters
- Foveal region should not be too small or too large
- Compression ratio should not be too low or too high
- Subjects are less tolerant to small foveal regions

| | No Foveation | Static Foveation | | | Dynamic Foveation | | |
|---|---|---|---|---|---|---|---|
| Π / *R* | - | **0.2** | **0.5** | **0.8** | **0.2** | **0.5** | **0.8** |
| **2** | 3.47 (± 0.22) | - | - | 2.87 (± 0.25) | 3.60 (± 0.14) | 3.80 (± 0.23) | 3.00 (± 0.18) |
| **5** | | - | **4.07** (± 0.19) | - | 2.50 (± 0.25) | **4.67** (± 0.13) | 3.80 (± 0.18) |
| **8** | | 1.20 (± 0.11) | - | - | 1.87 (± 0.17) | 2.80 3.07 (± 0.12) | 3.13 (± 0.25) |

# Dynamic Foveation Significantly Improves Gaming Experience

RQ1

***Aggressive* (*F*, 0.2, 8)** where $F \in$ (D, S)

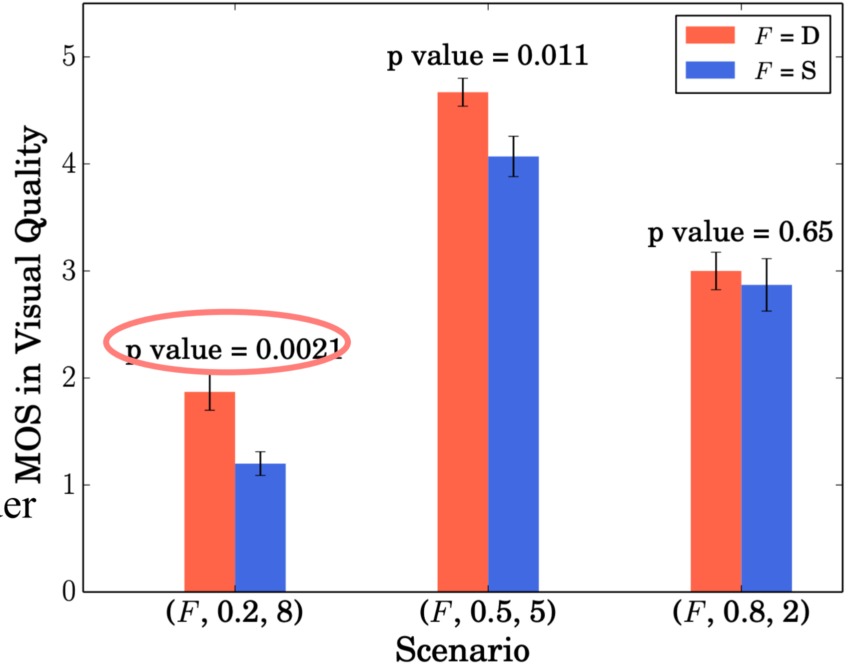
- p value < 0.05 (D is better than S)
- ($F$ = S) Hard to see the items at the viewport edge
- ($F$ = S) Hard to see the remaining time and score

***Balanced* (*F*, 0.5, 5)** where $F \in$ (D, S)

- p value < 0.05 (D is better than S)
- ($F$ = D) less likely to notice the foveal region border

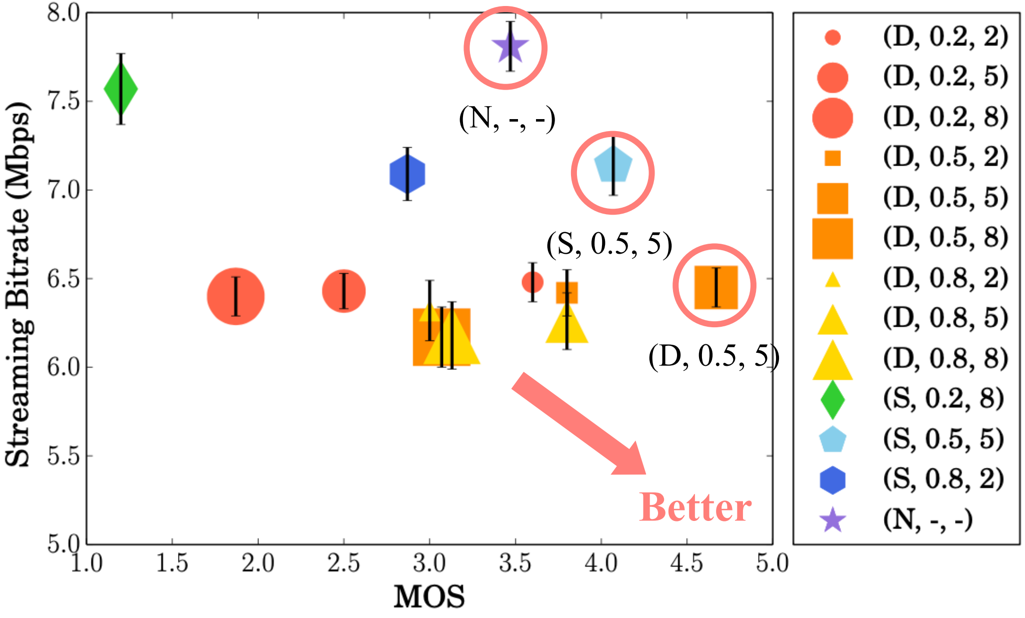
***Safe* (*F*, 0.8, 2)** where $F \in$ (D, S)

- Foveated effect is difficult to perceive



# Dynamic Foveation Can Maximize the Resource Allocation

RQ1




**Static compared to no foveation**

- The foveal region of no foveation is blurrier
- MOS increase of 0.60
- bitrate reduction of 8.71%

**Dynamic compared to static foveation**

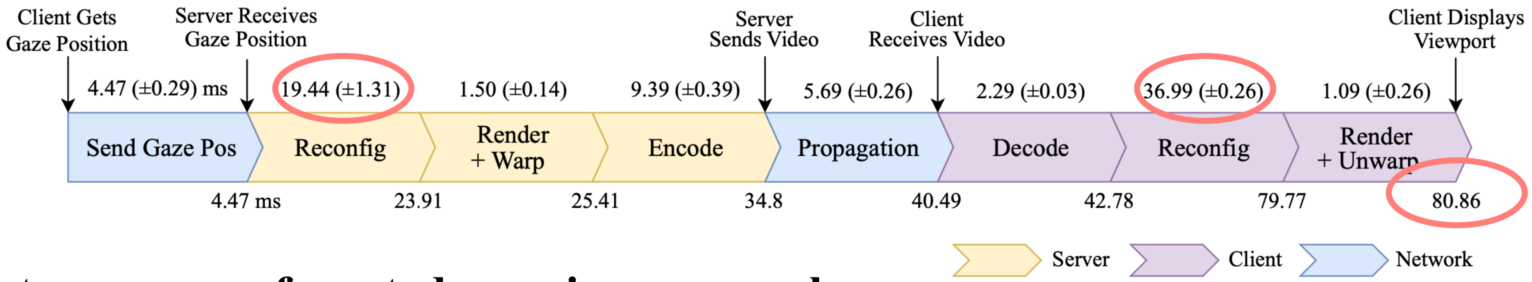
- Dynamic foveation with the optimal parameters leads to the highest MOS
- MOS increase of 0.60
- bitrate reduction of 9.81%

➔ Answer **RQ1**:

Dynamic foveation efficiently improves the gaming experience in visual quality

# Limitations

- **Reconfiguration overhead**
  - **Average total latency** of 80.86 ms (50—70 ms is tolerated [1])
  - **Average frame rate** of 24.47 (±0.23) FPS




- **Heterogeneous foveated warping approaches**
  - ALXR platform only supports AADT Warp
  - It is not clear if AADT Warp is the best foveated warping approach



[1] R. Albert, A. Patney, D. Luebke, and J. Kim. 2017. Latency requirements for foveated rendering in virtual reality. ACM Transactions on Applied Perception 14, 4 (2017), 1–13.

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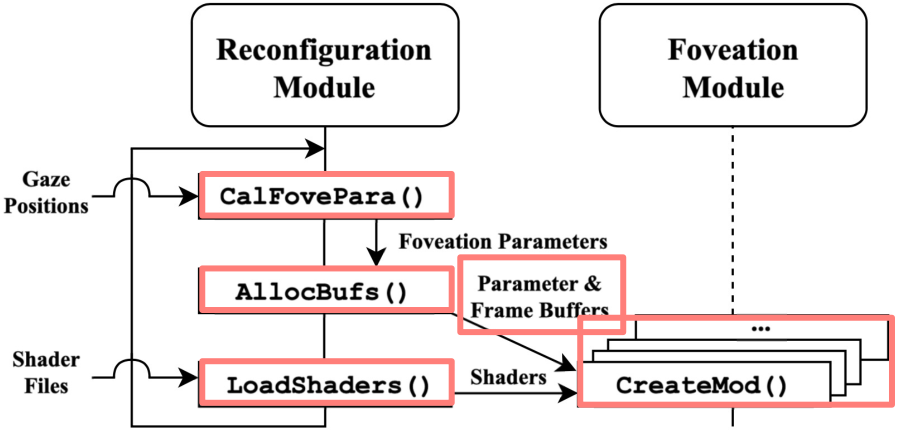
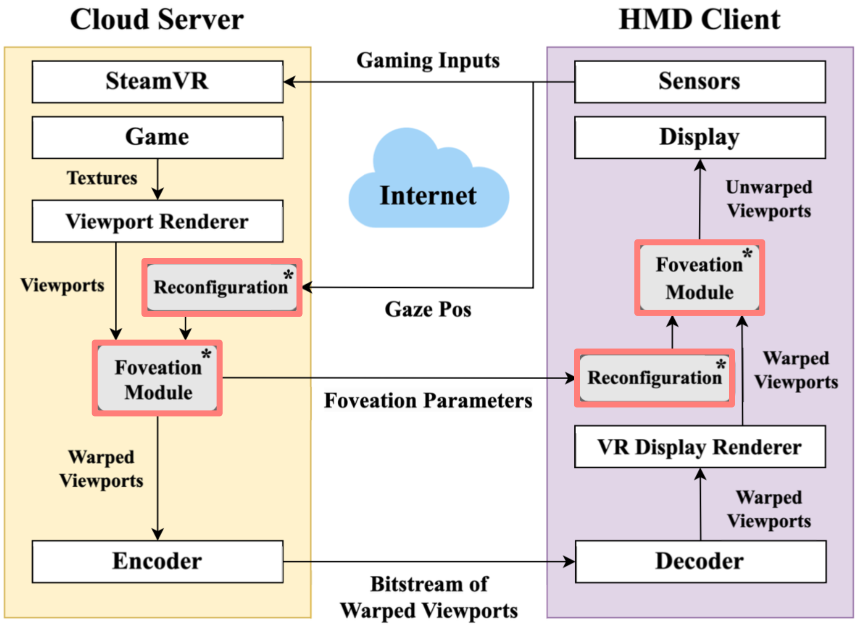
RQ2: How to effectively support dynamic foveation in cloud VR gaming?

# Creating a Foveation Module



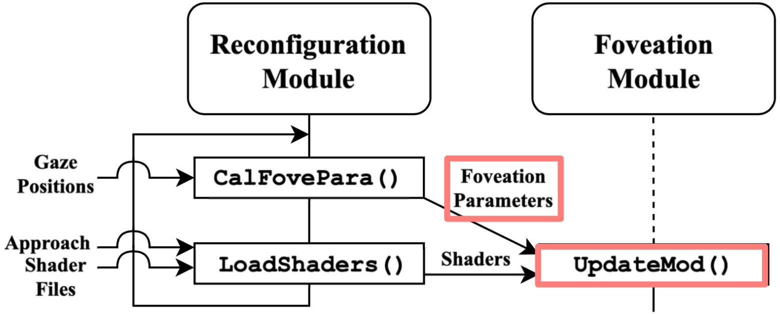



RQ2

# Updating Foveation Parameters

Frequently updated

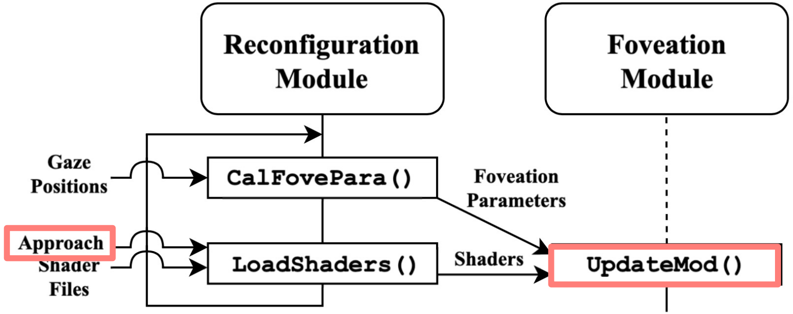
- **Server** – buffer type
  - ***Default***: for static data that is infrequently modified
  - ✓ ***Immutable***: for static data that remains unchanged after initialization
  - ***Dynamic***: for frequently updated data; efficient modification in CPU
  - ***Staging***: for rapid data transfer between CPU and GPU
- **Client** – constant type
  - ✓ ***Specialization***: create shaders with **certain constants** embedded during compilation
  - ***Push***: allow the CPU to some data directly to the shaders



RQ2

# Heterogeneous Foveated Warping Approaches

- Introduce **an argument** to configure the foveated warping approach
- **Server**
  - Loads/Updates shaders according to **the foveated warping approach**
  - Sends **the foveated warping approach** to the client
- **Client**
  - Gets **the foveated warping approach** from the server
  - Loads/Updates shaders according to **the foveated warping approach**



RQ2

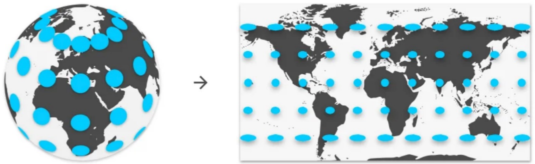
# Alternative Foveated Warping Approach

| | 1 Region | 2 Regions |
|---|---|---|
| **Non-uniform** | Foveated Radial Warp | AADT Warp |
| **Uniform** | No foveation | - |

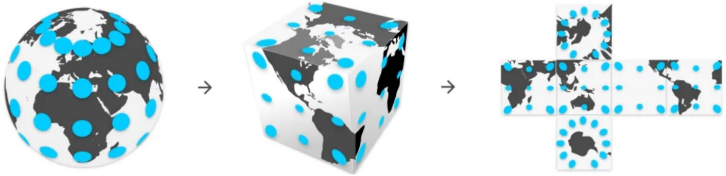
**A single region with a non-uniform warping function** centered at the gaze position, **mimicking the characteristics of the HVS**

## 360° Video Projection (https://blog.google/products/google-ar-vr/bringing-pixels-front-and-center-vr-video/)

- Equirectangular projection

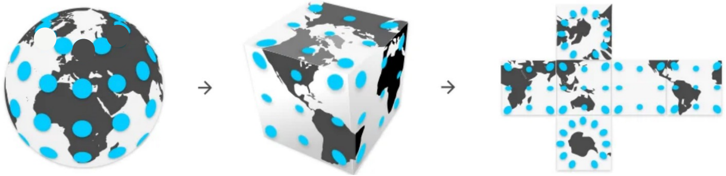


- Traditional cubemap



- **Equiangular cubemap (EAC) by Google [1]**

$$p = E(q) = (\frac{2}{\pi})\tan^{-1}(4q)$$



[1] 2017. EAC used by Google in Youtube. https://reurl.cc/qrG6Wq.

RQ2

# Foveated Radial Warp [1]

EAC: $p = E(q) = (\frac{2}{\pi})\tan^{-1}(4q)$

[-1, 1] [-1, 1]

Given (i) the ease of implementation and (ii) the ability to be conveniently adjusted to emphasize the gaze point, we adopt **the modified version of EAC, *Foveated Radial Warp***.

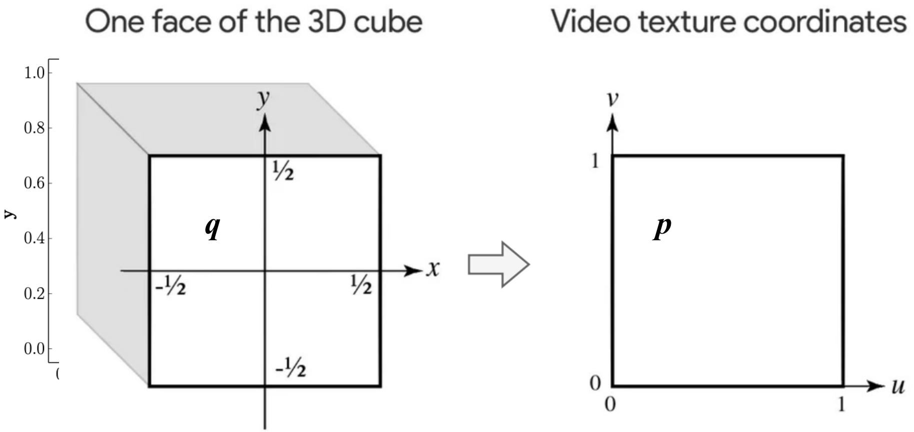
$$p = E(q) = (\frac{2}{\pi})\tan^{-1}(Mq)$$

→ Inverse warping function

$$p = E(q) = \frac{1}{\tan^{-1}M}\tan^{-1}(Mq)$$

Inverse

$$q = F(p) = \frac{\tan(\tan^{-1}(M)p)}{M}$$




[1] T. Kämäräinen and M. Siekkinen. 2023. Foveated spatial compression for remote rendered virtual reality. In Proc. of Workshop on Metaverse Systems and Applications (MetaSys'23). 7–13.

RQ2

# Objective Evaluations

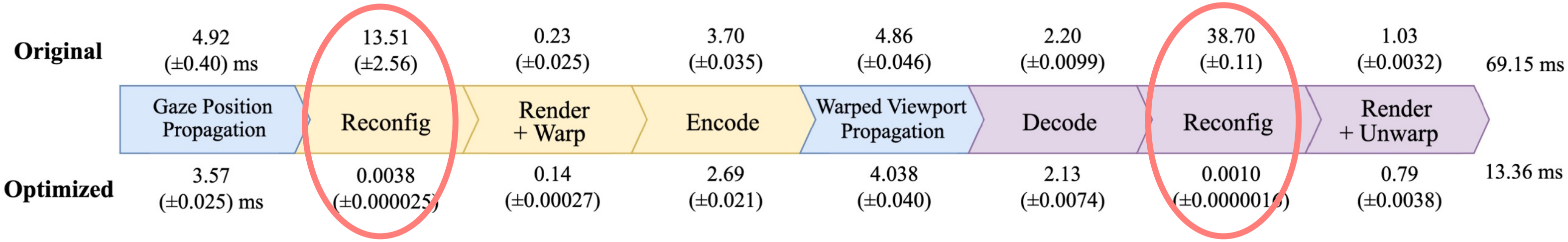
Setup: follow the previous user study testbed and settings (15 people played Fruit Ninja)

Scenarios [1]:

| Scenario | Platform | Foveated Warping Approach | Π | R | M |
|---|---|---|---|---|---|
| **Unopt** | Unoptimized | AADT Warp | 0.5 | 5 | - |
| **$\mathbf{Opt}_{4.7}$** | Optimized | Foveated Radial Warp | - | - | 4.7 |

Results:

| Platform | Latency (ms) | Frame Rate (FPS) |
|---|---|---|
| **Unoptimized** | 69.15 (± 0.73) | 25.64 (± 0.15) |
| **Optimized** | 13.36 (± 0.52) | 68.78 (± 0.05) |
| **Improvement** | 5.18X | 2.68X |




➔ Answer **RQ2**: We can effectively support dynamic foveation

[1] T. Kämäräinen and M. Siekkinen. 2023. Foveated spatial compression for remote rendered virtual reality. In Proc. of Workshop on Metaverse Systems and Applications (MetaSys'23). 7–13.

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RQ3: How much QoE improvement can we achieve after optimizing the platform?

# User Study Setup

**Game**: Fruit Ninja VR 2

**Encoder**: Nvidia H.264

**Target bitrate**: 5Mbps (CBR)

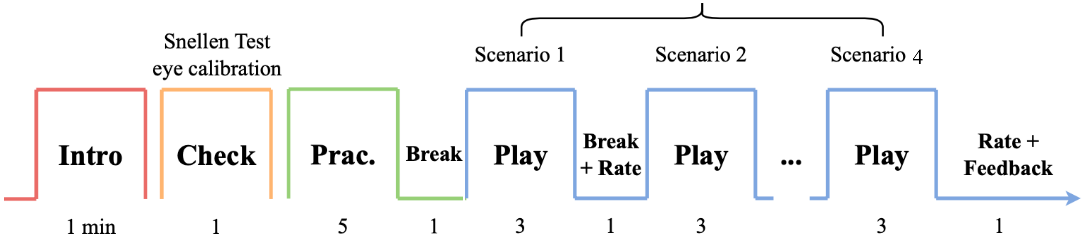
**Frame rate**: 72 FPS

**4 Scenarios [1]**:

| Scenario | Platform | Foveated Warping Approach | Π | R | M |
|---|---|---|---|---|---|
| **Unopt** | Unoptimized | AADT Warp | 0.5 | 5 | - |
| **$Opt_{4.7}$** | Optimized | Foveated Radial Warp | - | - | 4.7 |
| **$Opt_{6.3}$** | Optimized | Foveated Radial Warp | - | - | 6.3 |
| **$Opt_{7.9}$** | Optimized | Foveated Radial Warp | - | - | 7.9 |

**Procedure**:

- 15 subjects (9 males)
- Age: 22 – 26 years old
- Time: 20 – 30 minutes



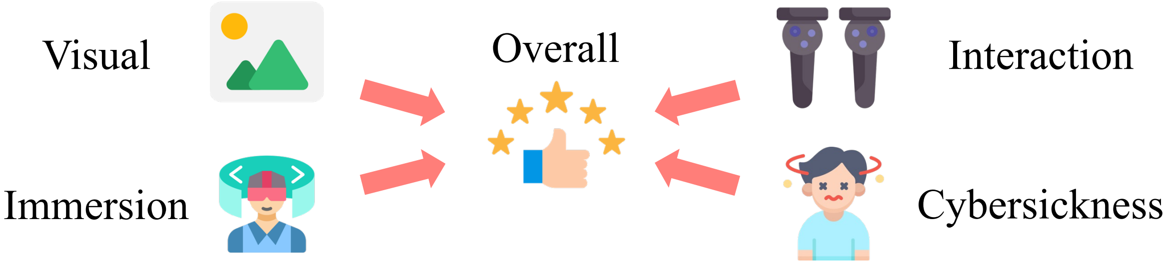



[1] T. Kämäräinen and M. Siekkinen. 2023. Foveated spatial compression for remote rendered virtual reality. In Proc. of Workshop on Metaverse Systems and Applications (MetaSys'23). 7–13.

RQ3

# QoE Questionnaire

- Single-stimulus **ACR** [1][2] on a scale of **1 – 5**




| Question | Description | Score |
|---|---|---|
| **Overall Quality** | How would you rate the overall quality of this gaming scenario? | 1 (Bad) – 5 (Excellent) |
| **Visual Quality** | How would you rate the visual quality of this gaming session? | 1 (Bad) – 5 (Excellent) |
| **Immersive Level** | How is your assessment about the sense of immersion during this gaming scenario? | 1 (Low) – 5 (High) |
| **Interaction Quality** | How responsive was the environment to actions that you performed? | 1 (Not responsive) - 5 (Completely responsive) |
| **Cybersickness** | Are you feeling any sickness or discomfort now? | 1 (Unbearable) – 5 (No problem) |

[1] T. Installations and L. Line. 1999. Subjective video quality assessment methods for multimedia applications. Networks 910, 37 (1999), 5.
[2] P. Pérez, N. Oyaga, J. Ruiz, and A. Villegas. 2018. Towards systematic analysis of cybersickness in high motion omnidirectional video. In Proc. of International Conference on Quality of Multimedia Experience (QoMEX'18).

# The Optimized System Achieves Higher QoE Scores

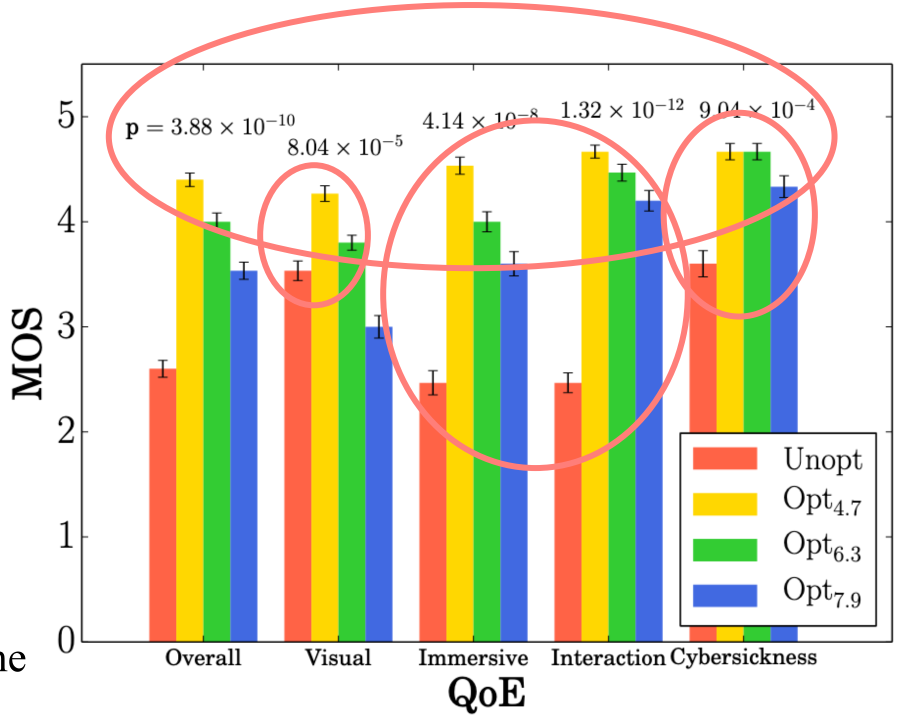
RQ3

**Observation**

- $p$ value < 0.05: significantly different
- $Opt_M$ generally achieves higher MOS in all QoE aspects

**Subjects' Feedback**

- Higher latency and lower frame rates contribute to a reduction in visual quality scores
- The scores of immersive level and interaction quality drop to 2.47 in Unopt
- Subjects reported a sense of nausea, leading to the lowest score of 3.60 in cybersickness in Unopt



# Different *M* in Foveated Radial Warp

$M$ = 4.7

$M$ = 7.9

| Scenario | Overall | Visual | Immersive | Interaction | Cybersickness |
| --- | --- | --- | --- | --- | --- |
| Unopt | 2.60 (± 0.08) | 3.53 (± 0.09) | 2.47 (± 0.12) | 2.47 (± 0.09) | 3.60 (± 0.12) |
| $Opt_{4.7}$ | **4.40** (± 0.06) | **4.27** (± 0.07) | **4.58** (± 0.58) | **4.67** (± 0.06) | **4.67** (± 0.08) |
| $Opt_{6.3}$ | 4.00 (± 0.08) | 3.80 (± 0.07) | 4.00 (± 0.10) | 4.47 (± 0.08) | **4.67** (± 0.08) |
| $Opt_{7.9}$ | 3.53 (± 0.58) | 3.00 (± 0.11) | 3.60 (± 0.11) | 4.20 (± 0.10) | 4.33 (± 0.10) |

**$M$ = 4.7**

- Achieves the highest QoE scores
- Subjects can hardly notice the foveated artifacts

**$M$ = 6.3**

- Achieves slightly lower QoE scores
- Some subjects were unable to discern a noticeable difference from $M$ = 4.7

**$M$ = 7.9**

- Achieves the lowest QoE scores
- The blurring effect becomes pronounced

➔ Answer **RQ3**:

The optimized platform achieves an MOS increase of

- **1.80 in overall**
- 0.74 in visual
- **2.11 in immersive**
- **2.2 in interaction**
- 1.07 in cybersickness

# Outline


- Introduction
- Related Work
- System Overview
- Dynamic Foveation in a Cloud VR Gaming Platform
- Optimization of the Foveation Module
- Subjective Evaluations
- Conclusion & Future Work

# Conclusion

- **Goal** **Developed the first cloud VR gaming system with dynamic foveation supports**
- Answered the three RQs
  1. **RQ1** : **Dynamic foveation** effectively improves the gaming experience in visual quality
  2. **RQ2** : The **optimization** in the foveation module leads to **low latency and high frame rate** compared to the unoptimized system
  3. **RQ3** : The optimized cloud VR gaming platform achieves **the best gaming QoE**
- Other observations for future developers of cloud VR games
  1. Gamers are intolerant to the sudden quality jumps between the foveal and peripheral regions, which are more **noticeable when the foveal regions are smaller**
  2. **Latency and frame rate** significantly affect the gaming experience

# Future Work

## Cloud VR Gaming Platforms

- Study the implications of different network conditions and game genres in gaming QoE
- **Develop methods to adapt the system parameters [1]**

## Other Applications

- Apply our developed techniques to a wider range of applications



| System \ Property | Bidirectional | Cloud Rendering | Extended Reality | Quality Sensitive | Latency Sensitive | Bandwidth Sensitive |
|---|---|---|---|---|---|---|
| 360° Video Streaming | ○ | ○ | ● | ◐ | ○ | ◐ |
| VR Teleconferencing | ● | ○ | ● | ◐ | ◐ | ◐ |
| AR Rendering | ○ | ● | ● | ○ | ● | ○ |
| Cloud Gaming | ● | ● | ○ | ◐ | ● | ◐ |
| Cloud VR Gaming | ● | ● | ● | ● | ● | ● |

| | |
|---|---|
| ○ | No |
| ◐ | Partially Yes |
| ● | Yes |



[1] K. Lee, J. Fang, Y. Sun, and C. Hsu. 2023. Modeling gamer Quality-of-Experience using a real cloud VR gaming testbed. In Proc. of International Workshop on Immersive Mixed and Virtual Environment Systems (MMVE'23).

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Publications:

[1] J. Fang, K. Lee, T. Kamarainen, M. Siekkinen, and C. Hsu, "Optimizing dynamic foveation for a cloud VR gaming platform.", in preparation for a submission to ACM Transactions on Multimedia Computing, Communications, and Applications, 2024.

[2] J. Fang, K. Lee, T. Kamarainen, M. Siekkinen, and C. Hsu, "Will dynamic foveation boost the gaming experience in cloud VR?" in Proc. of ACM International Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV'23), Vancouver, Canada, June 2023.

[3] K. Lee, J. Fang, Y. Sun, and C. Hsu, "Modeling gamer quality-of-experience using a real cloud VR gaming testbed," in Proc. of ACM International Workshop on Immersive Mixed and Virtual Environment Systems (MMVE'23), Vancouver, Canada, June 2023.

[4] S. Tang, Y. Sun, J. Fang, K. Lee, and C. Hsu, "Optimal camera placement for 6 Degree-of-Freedom immersive video streaming without accessing 3D scenes", in Proc. of ACM International Workshop on Interactive eXtended Reality (IXR'22), Lisbon, Portugal, October 2022.

[5] T. Fan, F. Liu, J. Fang, N. Venkatasubramanian, and C. Hsu, "Enhancing situational awareness with adaptive firefighting drones: leveraging diverse media types and classifiers.", in Proc. of ACM Multimedia Systems Conference (MMSys'22), Athlone, Ireland, June 2022.

# Q & A