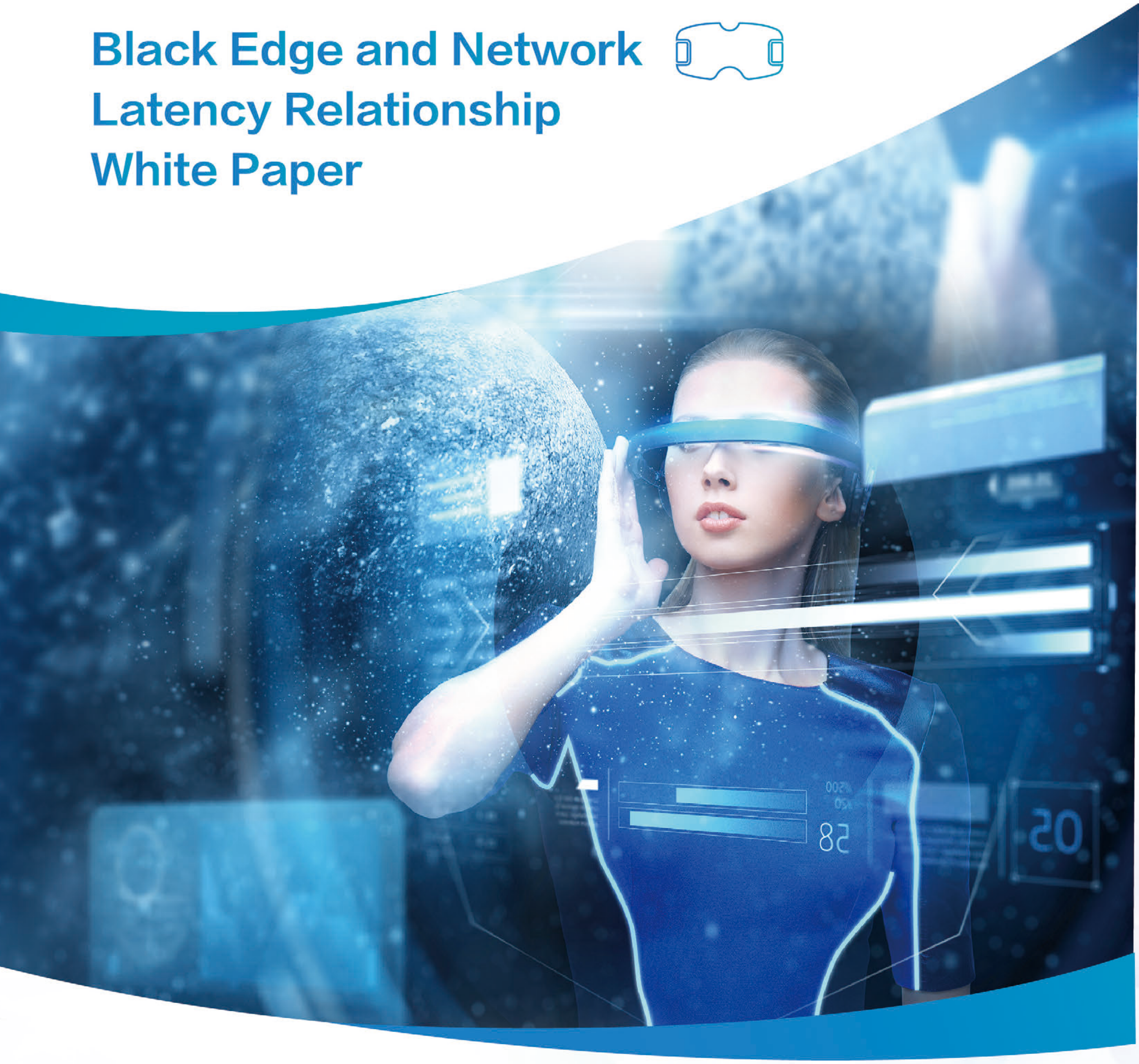
iLab VR OPEN LAB

Cloud VR

Black Edge and Network Latency Relationship White Paper



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Foreword

Black edges are a common issue in strong-interaction Cloud VR services, and are key factors that affect user experience.

By examining the current industry situation, this white paper aims to launch an industry-wide discussion about the requirements black edges and network latency must meet to ensure good cloud VR experience.

The white paper describes what black edges look like and how they are generated. The size of a black edge is mainly dependent on network latency and head angular velocity. Therefore, based on the characteristics of real service content, this white paper examines strong-interaction services that have typical head motion experience requirements. Specifically, this paper quantifies the impact of black edges on user experience, researches the relationship between black edge size and network latency, and provides suggestions on network latency to ensure optimal Cloud VR experience.

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01 Introduction to Black Edges

1.1 What Is a Black Edge?

When using strong-interaction Cloud VR services (such as games), users generally need to move their heads. While the user moves, a black area or a trailing smear often appears at the edges of the Field of View (FOV). These are black edges, as shown in the following figure.

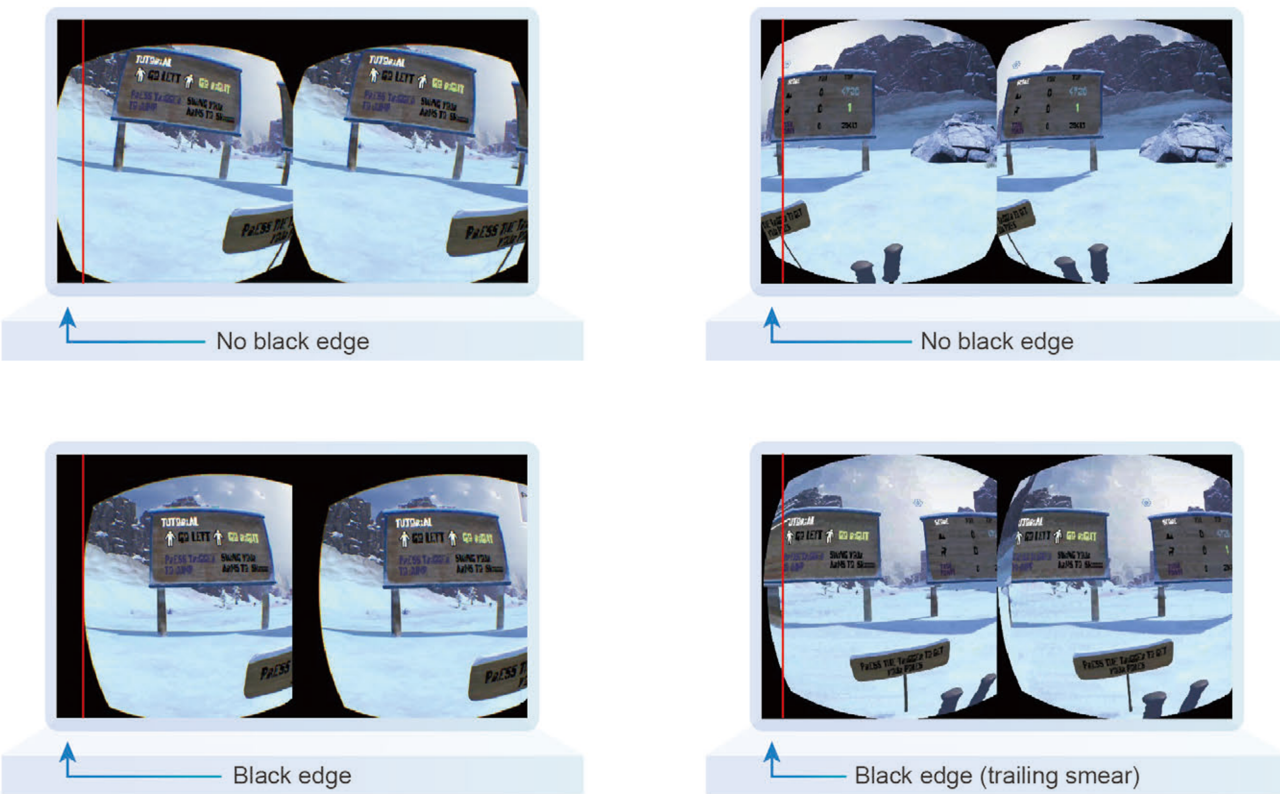


Figure 1-1 Appearance of black edges

Source: VR game *Skiing II*

1.2 How Is a Black Edge Generated?

In strong-interaction Cloud VR services, terminal-cloud asynchronous rendering is used to alleviate motion sickness. Black edges are a side effect of this technology.

1.2.1 Core Technology for Cloud VR Rendering: Terminal-Cloud Asynchronous Rendering

• The key constraint involved in Cloud VR solutions is that motion-to-photon (MTP) latency must be less than or equal to 20 ms.

Like local VR, the primary problem facing Cloud VR is motion sickness. Motion sickness occurs when a person's visually perceived motion is inconsistent with the motion sensed by the person's vestibular system. According to the mainstream view in the industry, motion sickness can be avoided if the MTP latency of a VR terminal does not exceed 20 ms (that is, if the time difference between a person's head motion and the corresponding image change seen by the person's eyes is 20 ms or less). Therefore, ensuring an MTP latency of 20 ms or less has become a key constraint involved in Cloud VR solutions.

• Terminal-cloud asynchronous rendering makes an MTP latency of 20 ms or less achievable for Cloud VR services.

Cloud VR processing includes motion capturing and reporting, cloud rendering and streaming, and terminal screen refreshing and display. Cloud rendering and streaming is a process in which cloud VR terminal motion information is transmitted from a terminal to a cloud through a network, and a video stream is transmitted to the terminal through the network for decoding after logical computation, real-time rendering, encoding, and compression in the cloud.

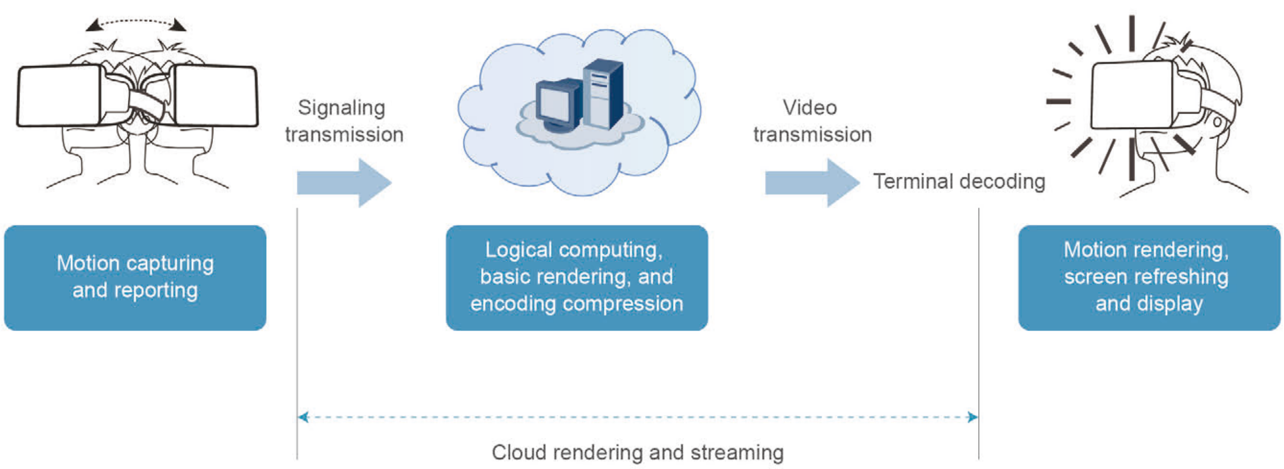


Figure 1-2 Cloud VR service process

Local VR terminals need to perform a series of operations, such as motion capturing, logical computation, image rendering, and screen refreshing and display, which makes it difficult to meet the MTP latency requirement. If Cloud VR still uses the serial processing of cloud rendering and streaming, and terminal screen refreshing and display, it will be difficult to ensure an MTP latency of 20 ms or less due to network transmission, encoding, and decoding in the cloud rendering and streaming process.

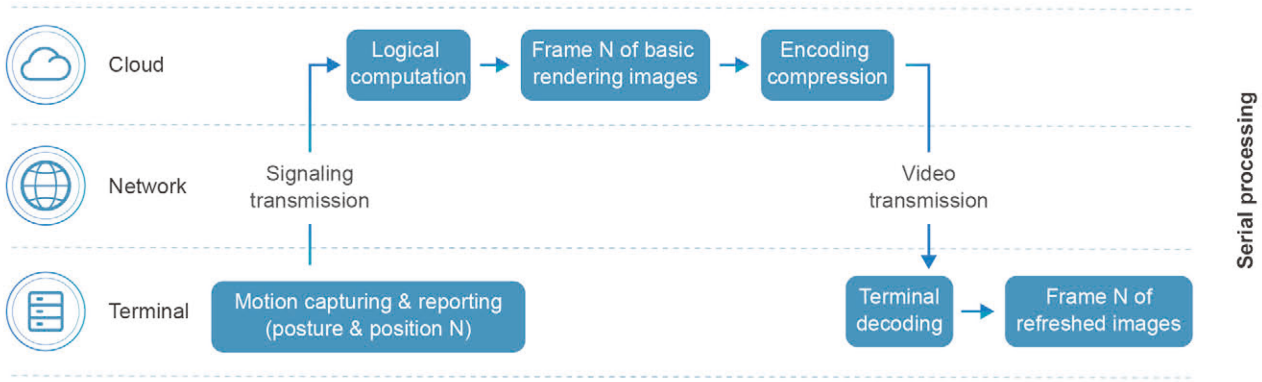


Figure 1-3 Solution that cannot guarantee satisfactory MTP latency

The core of terminal-cloud asynchronous rendering is to implement parallel processing of cloud rendering, streaming, and terminal refreshing and display. Specifically, the cloud performs basic rendering, performs logical computation based on the posture and location information sent by the terminal in real time, and renders basic images. At the same time, the terminal renders head motions, and performs secondary rendering (such as rotation, translation, and warp on locally rendered images according to real-time posture and location information) to generate real-time display images. In this process, the MTP latency is determined by the terminal, and refreshing of terminal display images is not dependent on cloud rendering. As a result, an MTP latency of 20 ms or less is achievable.

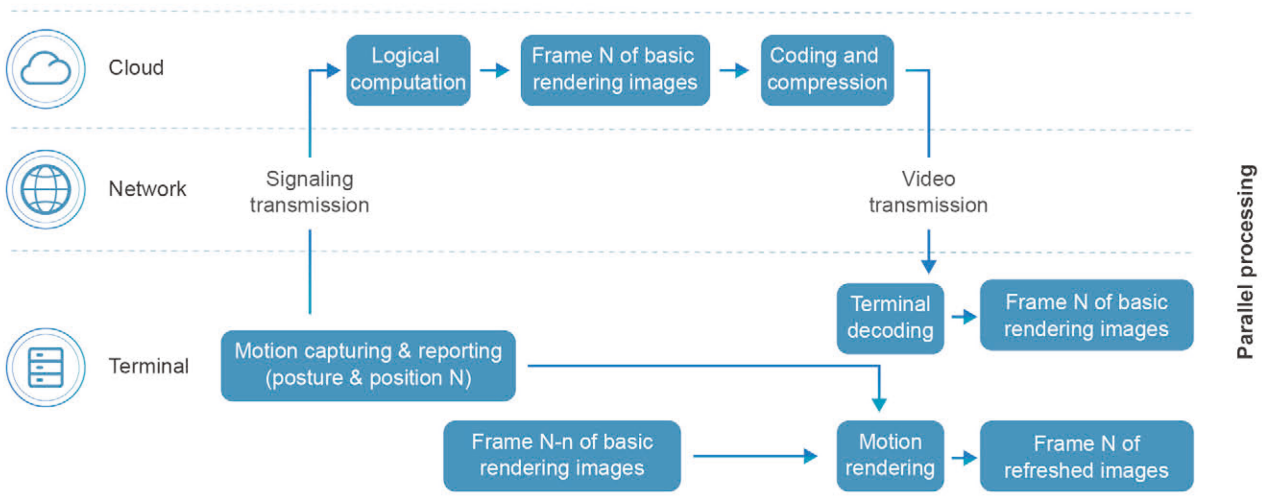


Figure 1-4 Schematic diagram of terminal-cloud asynchronous rendering (guaranteeing MTP latency)

Note:

Secondary rendering is the process of rotating, translating, and warping rendered images of postures and positions based on changes of postures and positions. Typical secondary rendering algorithms include Asynchronous Timewarp (ATW) and Asynchronous Space-warp (ASW). ATW is used to process head posture changes, and ASW is used to process head position changes.

1.2.2 Terminal-Cloud Asynchronous Rendering Introduces Black Edges, Affecting User Experience

When terminal-cloud asynchronous rendering is used, if a VR terminal uses motion rendering to warp basic rendered images to a new angle of view (AOV) based on head posture changes, no image will be displayed in the new FOV. As a result, black edges will be formed, as shown in the following figure. The shape of black edges varies depending on the motion rendering algorithm used by the VR terminal. Some algorithms fill the typical black edges with pixels. This introduces a trailing smear like the one shown in Figure 1-1. This impact on the quality of Cloud VR images affects user experience.

To minimize the impact of black edges on user experience, hyper-view image rendering can be performed on the cloud. That is, the angle of basic images to be rendered on the cloud can be increased to ensure that images can be displayed in the angle of view even when the user moves their head. However, this increases rendering and encoding costs, and prolongs cloud rendering and streaming latency. If FOV is 101° and 5° is added to each direction of basic rendering images on the cloud, cloud resource consumption will be increased by 21%. Therefore, the angle to be increased for hyper-view image rendering is generally small.

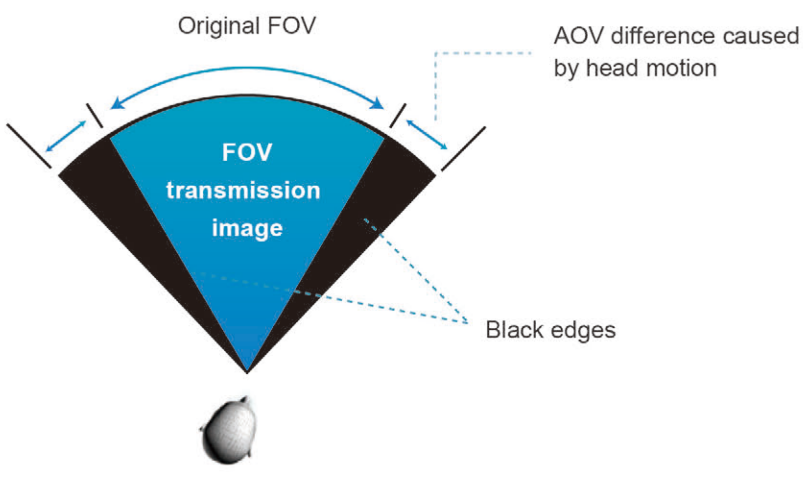


Figure 1-5 Schematic diagram of black edges

1.3 Black Edge Size Is Mainly Dependent on Network Latency and Head Angular Velocity

In terminal-cloud asynchronous rendering, images displayed on terminals are always the production of basic cloud-rendered images that are generated after motion rendering based on the posture information before a latency period, as shown in the following figure. Therefore, the difference between the current posture and the posture before a latency period determines the angle that needs to be offset for basic rendering images (that is, the angle of view of black edges). The black edge angle is essentially the head motion angle of a user within a latency period. The research conducted for this paper used a fixed model of head-mounted displays (HMDs). The motion capturing and sending latency and the head motion rendering latency were basically fixed and relatively small. Therefore, the research focused on the cloud rendering and streaming latency. If hyper-view image rendering is performed on the cloud, the black edge angle should not include the angle of hyper-view image rendering in a single direction.

In sum, the angle of a black edge is mainly affected by the cloud rendering and streaming latency and the user's head angular velocity. Theoretically:

Angle of black edge ≈ Cloud rendering and streaming latency x Head motion angular velocity – Angle increased for hyper-view image rendering (single direction)

In current industry solutions, the FOV of cloud-rendered images is generally the same as the FOV of images on terminals, and no angle for hyper-view image rendering is added.

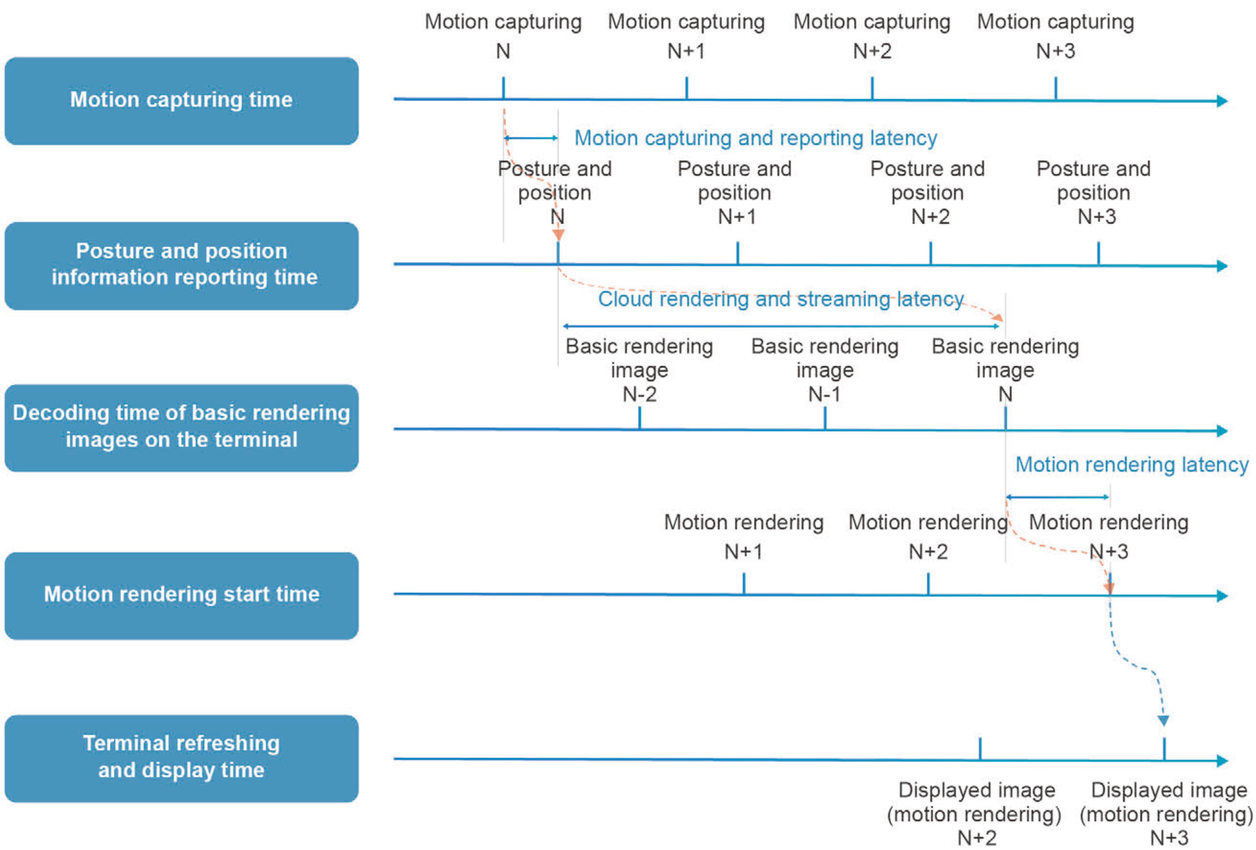


Figure 1-6 Relationship between the processing time of each Cloud VR phase

Cloud rendering and streaming latency consists of cloud processing latency, network transmission latency, and terminal processing latency. This white paper focuses on the impact of network latency on black edges. Network latency affects instruction and video transmission latency, and further affects cloud rendering and streaming latency. To study the relationship between network latency and black edges, we tried to keep cloud processing latency and terminal processing latency as stable as possible in this research. Based on the capability of the industry's Cloud VR cloud rendering solutions, the cloud rendering and streaming latency can be 50-60 ms, ignoring network latency.

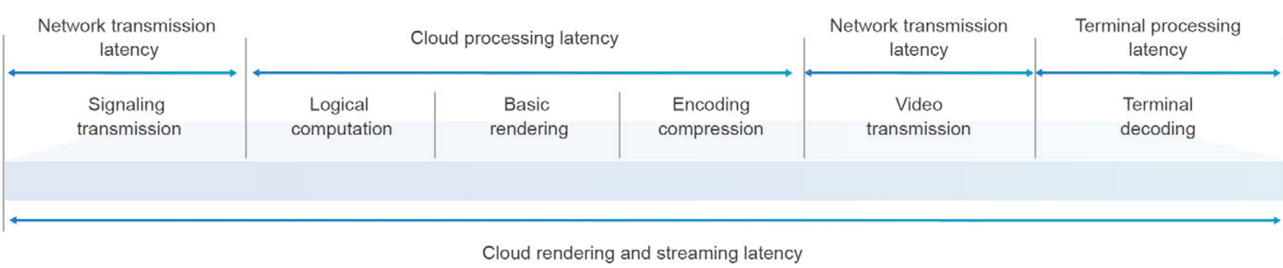


Figure 1-7 Composition of cloud rendering and streaming latency

02 Study on the Relationship Between Black Edges and User Experience

Huawei iLab has long been conducting research on Cloud VR user experience. According to early systematic research, the main factors affecting experience for strong-interaction services are image blurring and frame freezing, hysteresis of operation response and motion perception, and black edges. Among these factors, black edges are most sensitive to increases in latency, and easily affect user experience.

To explore the relationship between user experience and network latency, this chapter will study and quantify the relationship between the black edge size and user experience.

2.1 How to Quantify the Impact of Black Edges on User Experience

To quantify the impact of black edges on user experience, subjective experience must be represented using objective indicator data. The following figure shows the research roadmap designed by referring to human-factors engineering research methods in the industry.

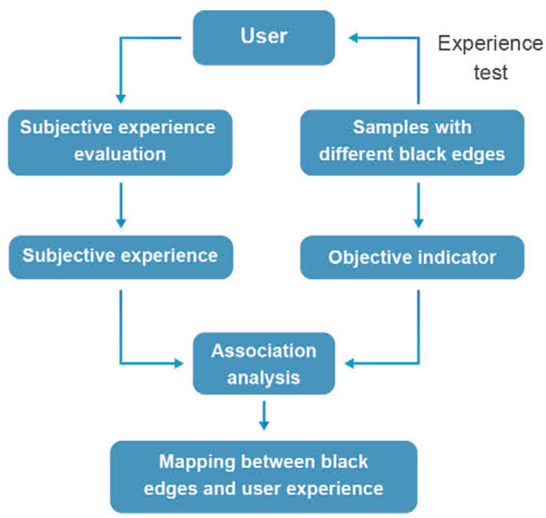


Figure 2-1 Roadmap of the research on the relationship between black edges and user experience

2.1.1 Constructing Experience Samples for Quantifying Black Edges Based on the Characteristics of Real Service Content

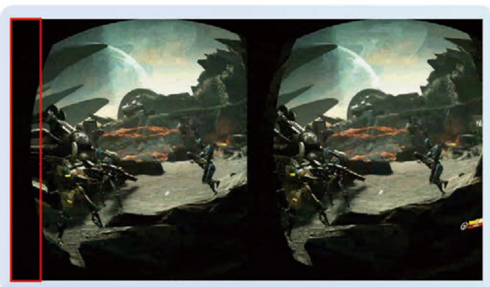
As discussed, the size of black edges is related to the head angular velocity. Therefore, we selected content with typical head motion experience requirements based on the characteristics of real service content before constructing a sample for quantifying black edges.

Strong-interaction Cloud VR services involve various types of content. From the perspective of head motion experience requirements, the following two types are typical:

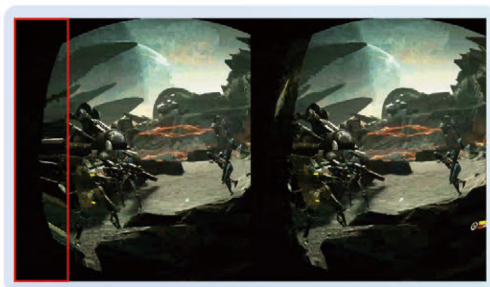
- Slow head motion: Mainly involves moving forward and backward or standing still. Movements are subtle and slow. A typical example is virtual skiing games.
- Fast head motion: Mainly involves frequent head motion or looking around. Quick and broad movements are required. A typical example is shooting games.

For the test, we selected a shooting game that is popular among Cloud VR users and involves many intense scenarios requiring quick head movements. We constructed screen recording content with different black edge ratios to use as experience samples in different black edge scenarios.

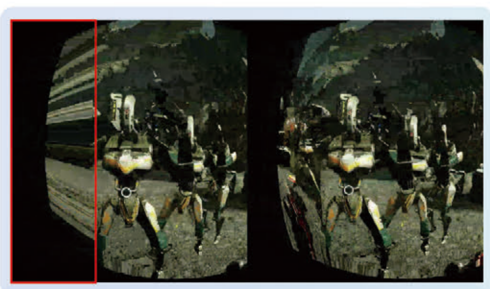
Example of black edges in gaming images



Black edge ratio of 10%



Black edge ratio of 20%



Black edge ratio of 30%

Screenshots of black edges were taken while screen recording content was played. The total width of the single-eye images and the width of the black edges were measured horizontally at the vertical center line of the images. The black edge ratio was defined as the black edge width divided by the total width of the single-eye images.

Source: VR game *BlackShield*

2.1.2 Test Engineers' Evaluation of Experience Using Black Edge Samples

In our analysis test, five test engineers evaluated the black edge samples subjectively.

2.1.3 Associating Quantified Black Edges and User Experience

Associations were drawn between the subjective experience evaluation results of test engineers and the black edge ratio in test samples, and provides the mapping between the black edge ratio and service experience.

2.2 Mapping Between Black Edges and User Experience

The human-factors engineering test and analysis showed that:

- Optimal service experience requires zero black edge.
- For good user experience, the black edge ratio must be less than or equal to 15%.

Experience Evaluation	Black Edge Ratio
Excellent	0%
Good	Black edge ratio ≤ 15%
Relatively poor	Black edge ratio > 15%

Note:

- Service experience evaluation results were obtained through subjective tests of test engineers and as such are strongly subjective.
- When different content is involved, black edges may be perceived differently by users.
- Cloud VR services are still in the early stage of development, and user experience still needs to be improved. In addition, different experience factors restrict each other and jointly affect user experience. The service experience evaluation results in the test are relative. As service experience improves, user expectations for experience will gradually increase and become increasingly strict. The values of black edges and experience evaluation in the above table will change accordingly.

03 Study on the Relationship Between Black Edges and Network Latency

3.1 Test Environment

3.1.1 Test Networking

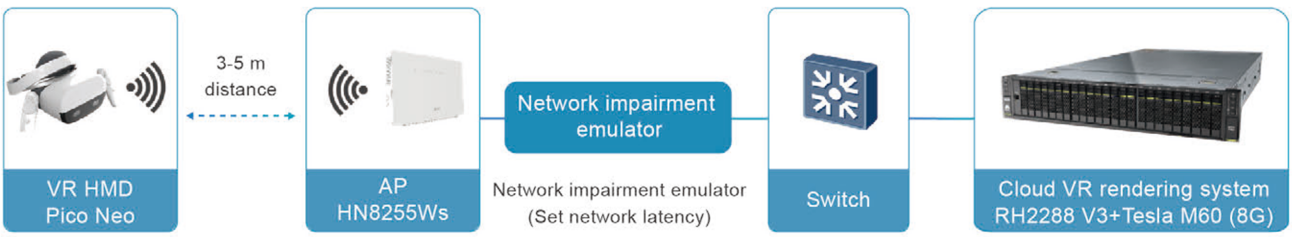


Figure 3-1 Test networking

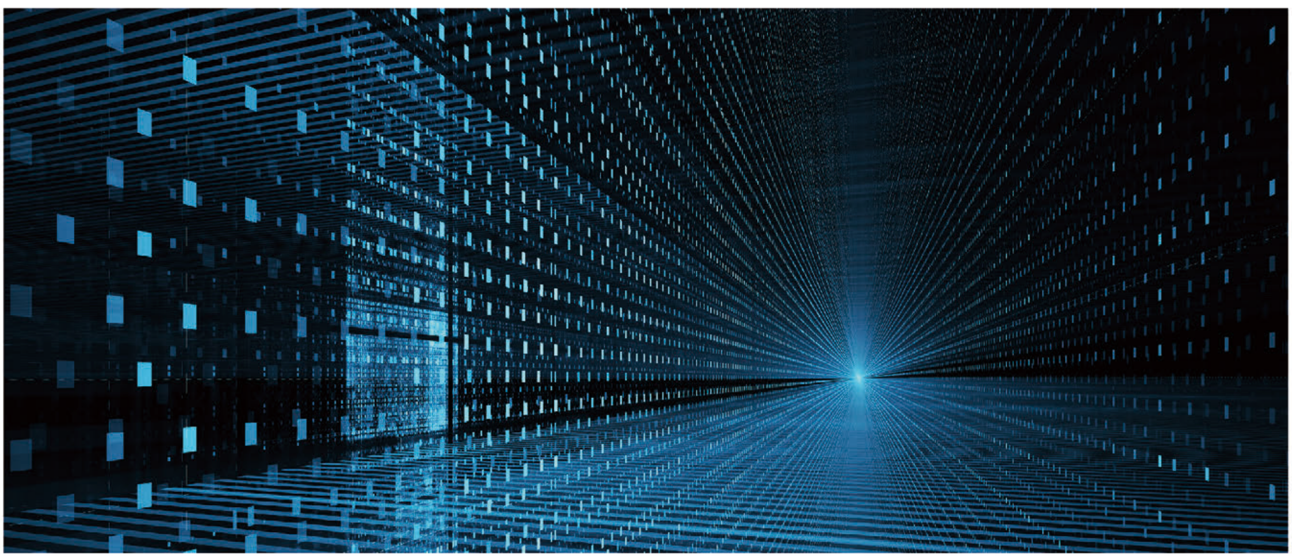
Role	Device Model
Cloud VR cloud rendering system	RH2288 V3 server and M60 graphics card
AP	HN8255Ws
VR HMD	Pico Neo (6DoF)

3.1.2 Cloud Rendering System Parameters

Parameter	Setting
Game	Black Shield
Resolution	2880*1600
Frame Rate	50 FPS
Encoding Mode	H.264
Bit Rate (Encoding Mode)	40 Mbit/s (CBR)
Transmission Protocol	TCP

3.1.3 Wi-Fi Environment Parameters

Parameter	Setting
Frequency Band	5 GHz
Channel (Frequency Bandwidth)	36-50 (80 MHz)
CU (Unloaded)	Less than 4% (as little interference as possible)



3.2 Test and Analysis Methods

1. Head motions were analyzed in testing games with typical head motion experience requirements.

- Method for testing head angular velocity: A mobile phone installed with a gyroscope data statistics app was bound to the VR HMD. The test engineers put on the HMD to use the strong-interaction service (gaming). The gyroscope data statistics app recorded head angular velocity.
- According to test data analysis, when test engineers experienced strong-interaction services with typical motion experience requirements, their heads moved at an angle of 100–120 degrees, and the head angular velocity was 160–220 degrees/second.

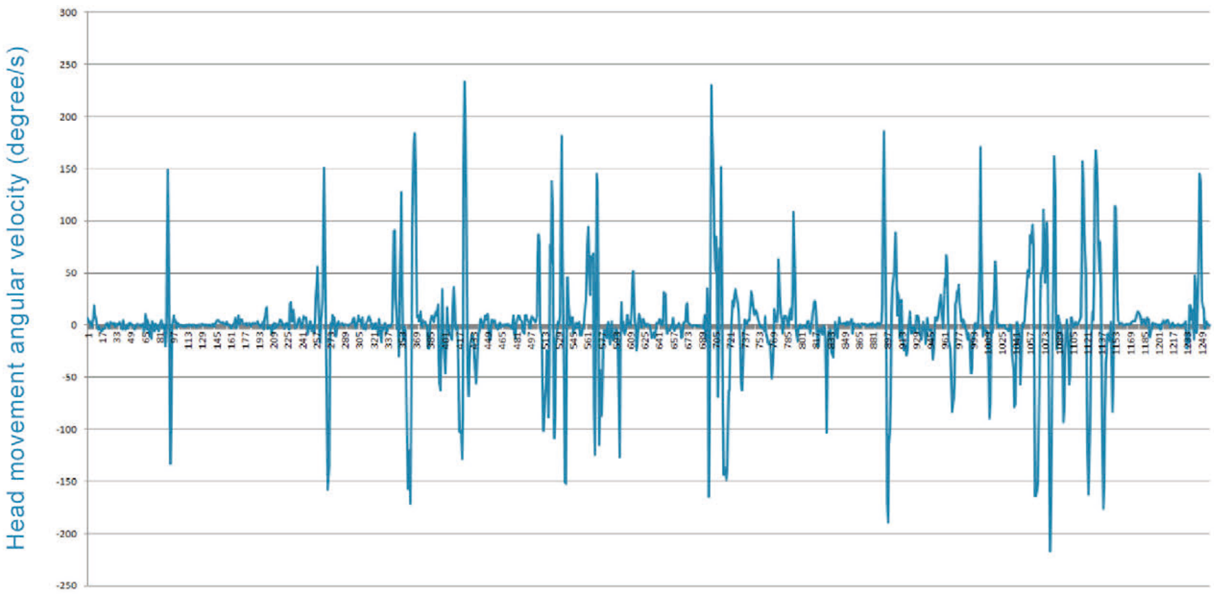


Figure 3-2 Real-time monitoring data of head angular velocity during use of strong-interaction services

2. The following data was tested and recorded under different network latency conditions:

- Setting different network latency values using a network impairment emulator
- Using the VR HMD to record the observed images during game play

3. Test results were analyzed.

- The image with the maximum black edge in each motion test was identified and the black edge ratio was calculated. Then the relationship between black edges and network latency was determined.
- Based on the mapping between black edges and user experience, network latency requirements for ensuring good user experience were determined.

3.3 Test Result: Good User Experience Requires Network Latency of 20 ms or Less

To ensure good experience of games that have typical head motion experience requirements, the black edge ratio must be less than 15% and the network latency must be less than 20 ms.

According to the test results, the black edge ratio does not increase linearly as network latency increases. This is mainly caused by the used transmission protocol. As network latency increases, the impact on instructions and video transmission latency is intensified.

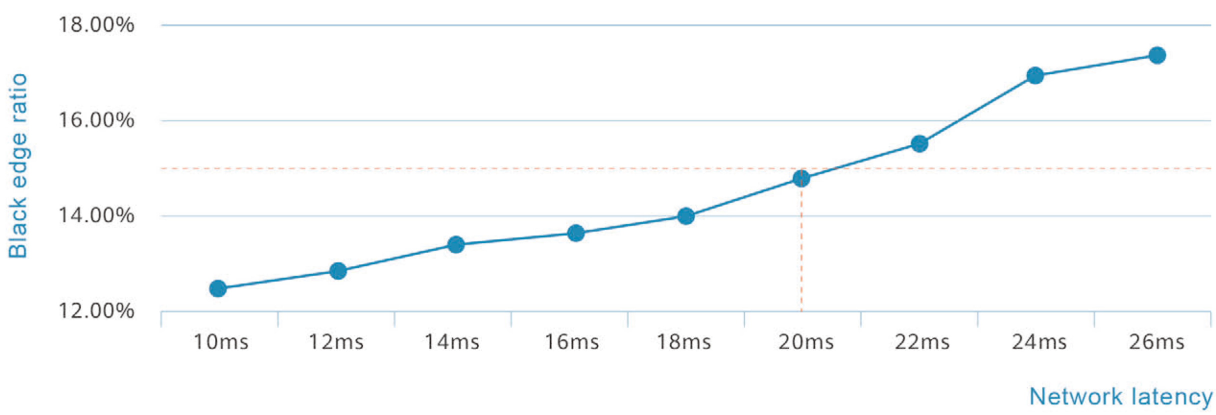


Figure 3-3 Mapping between the black edge ratio and network latency

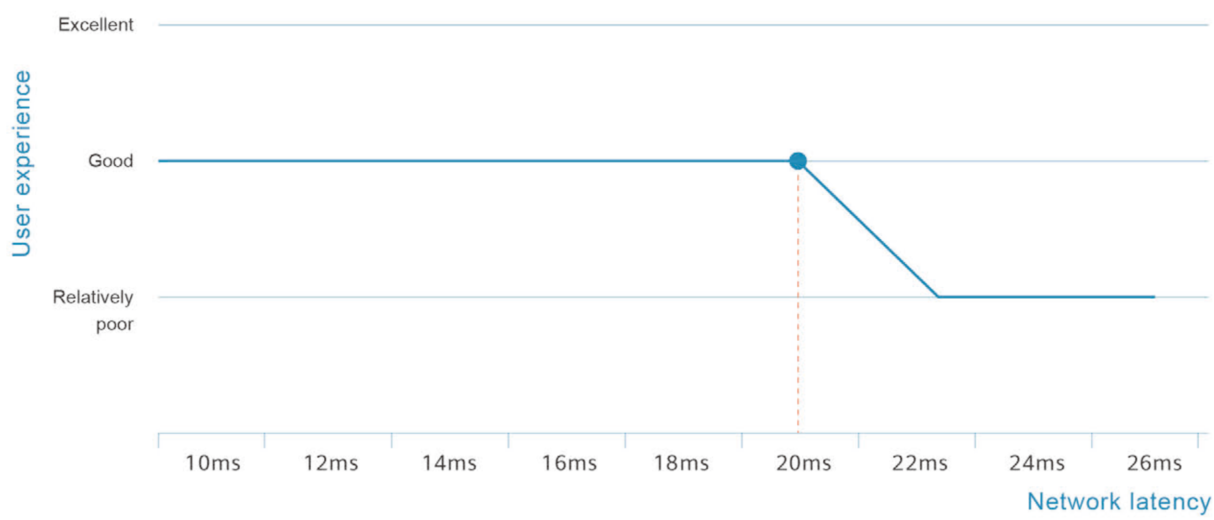


Figure 3-4 Mapping between user experience and network latency

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