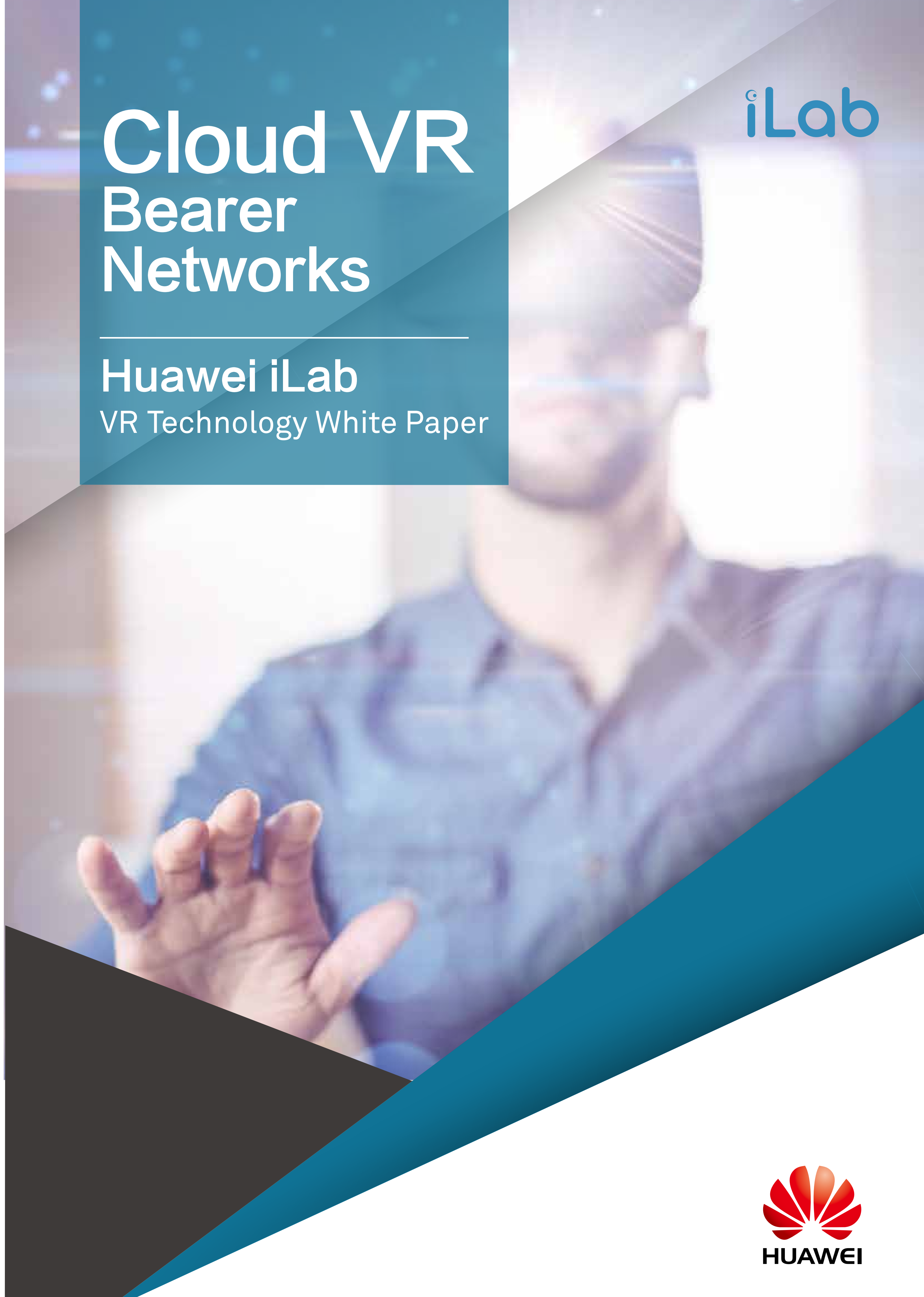

Cloud VR Bearer Networks

Huawei iLab

VR Technology White Paper

iLab

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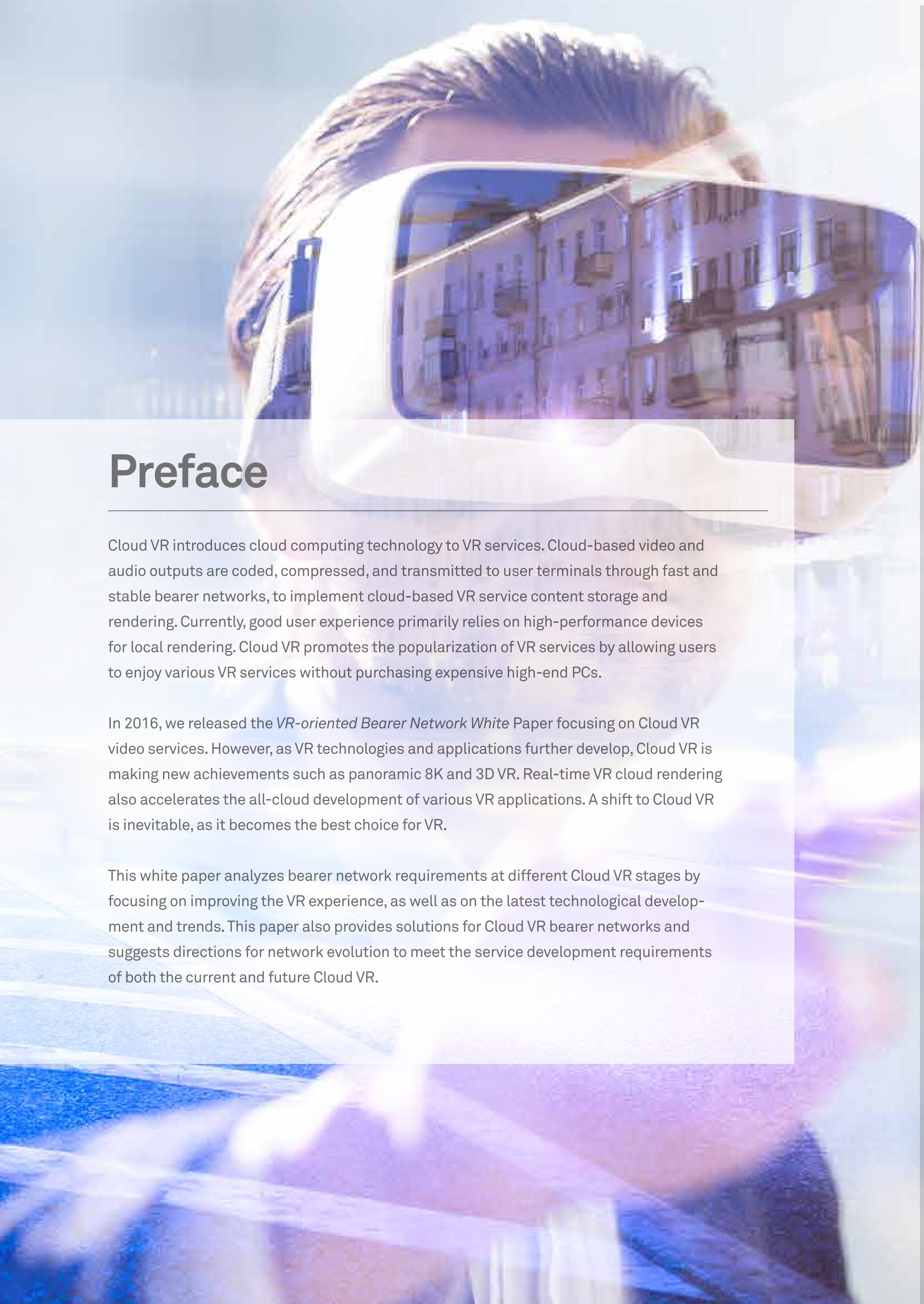

Preface

Cloud VR introduces cloud computing technology to VR services. Cloud-based video and audio outputs are coded, compressed, and transmitted to user terminals through fast and stable bearer networks, to implement cloud-based VR service content storage and rendering. Currently, good user experience primarily relies on high-performance devices for local rendering. Cloud VR promotes the popularization of VR services by allowing users to enjoy various VR services without purchasing expensive high-end PCs.

In 2016, we released the *VR-oriented Bearer Network White* Paper focusing on Cloud VR video services. However, as VR technologies and applications further develop, Cloud VR is making new achievements such as panoramic 8K and 3D VR. Real-time VR cloud rendering also accelerates the all-cloud development of various VR applications. A shift to Cloud VR is inevitable, as it becomes the best choice for VR.

This white paper analyzes bearer network requirements at different Cloud VR stages by focusing on improving the VR experience, as well as on the latest technological development and trends. This paper also provides solutions for Cloud VR bearer networks and suggests directions for network evolution to meet the service development requirements of both the current and future Cloud VR.

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1. Cloud VR: The Best Choice and an Inevitable Trend

1.1 VR Service Overview

Virtual reality (VR) is recognized as the platform for next-generation Internet and computing. VR is a computer-generated virtual environment (VE). This environment may be a replication of the real world or a representation of an imaginary world. In this virtual environment, people can interact with 3D spatial information in real time.

VR services have transformed the man-machine interaction mode, shifting the operation interface from two-dimensional to three-dimensional. We classify VR services into weak-interaction VR and strong-interaction VR based on the angle of interactive experience between users and the VE.

Weak-Interaction VR

Weak-interaction VR implies that users do not trigger actual interactions, such as touching, with entities in the VE, and can choose the viewing point and location. In weak-interaction VR, the user experience is passive, and contents are pre-determined. VR video services, such as VR videos and VR live broadcast, are typical weak-interaction VR services. These have the following features:

- **Passive experience**

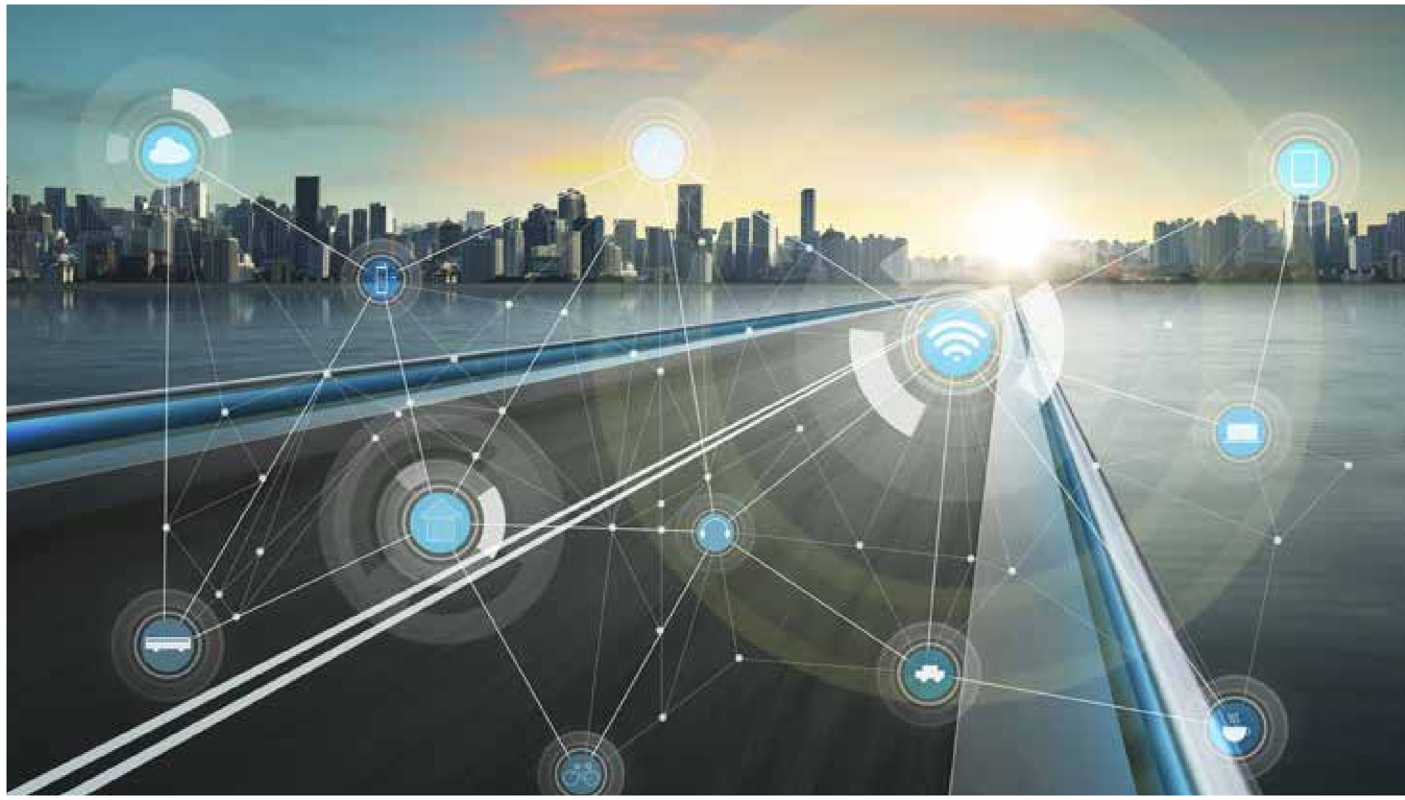
  Content is pre-determined. Users passively experience content in the VE.

- **Limited freedom**

  Although users can choose the viewpoint in the VE, only nearby scenes can be viewed. The degree of freedom is limited compared with location tracking and positioning.

- **Limited interactivity**

  Users do not have actual interaction or have limited interactivity with entities in the VE, for example, when users turn their heads to change the viewing angle.



Strong-Interaction VR

As the technology for interactivity develops, the interaction modes and effects of VR will gradually evolve towards natural interactivity. Technologies such as hand gesture recognition, eye movement tracking, touch feedback, and brain-computer interface will transform weak-interaction VR to strong-interaction VR, greatly improving user interaction and immersion.

Strong-interaction VR means that users can interact with the VE through interactive devices and respond in real time through objects in the VE, allowing users to feel changes in the VE. In strong-interaction VR, image generation in the virtual space depends on input from the user, in contrast to the pre-planned content of weak-interaction VR. VR games, VR home fitness, and VR social media are all strong-interaction VR services. These have the following experience features:

- Strong interaction

Users can use interactive devices to interact with the VE, themselves, and other users.

- Real time

Entities in the VE respond to interactions in real time, allowing users to experience changes in the VE.

- Immersion

Users experience immersion in another world through interactive devices.

- Multi-terminal and network-based

Group users share the same VE through networks, achieving a group VE interactive experience.

As of late 2017, VR products on the market primarily include mobile phone–based, PC-based, and all-in-one VR. Among these products, the limited rendering and computing capabilities of mobile phone–based VR and all-in-one VR restrict their use to weak-interaction VR services, such as VR videos. PC-based VR, however, benefits from the powerful rendering and computing capabilities of high-end PCs and hosts and is therefore used in strong-interaction VR services, such as VR games and VR fitness, providing good user experience with balance.

1.2 Rapid Evolution from VR to Cloud VR

The key features of Cloud VR are cloud-based contents and rendering. Powerful cloud capabilities can improve the VR user experience and reduce the cost of terminals, promoting the evolution of VR to Cloud VR, as well as the fast popularization of VR services.

Evolution from Weak-Interaction VR to Cloud VR

VR video services and other weak-interaction VR services require users to download VR videos before watching. Users, however, prefer to stream VR videos online. In recent years, global OTT video streaming platforms have provided a large number of VR videos online, and this number is growing rapidly. In addition, VR live broadcast of events such as VR live concerts and live sports events is also gaining popularity as a new business model.

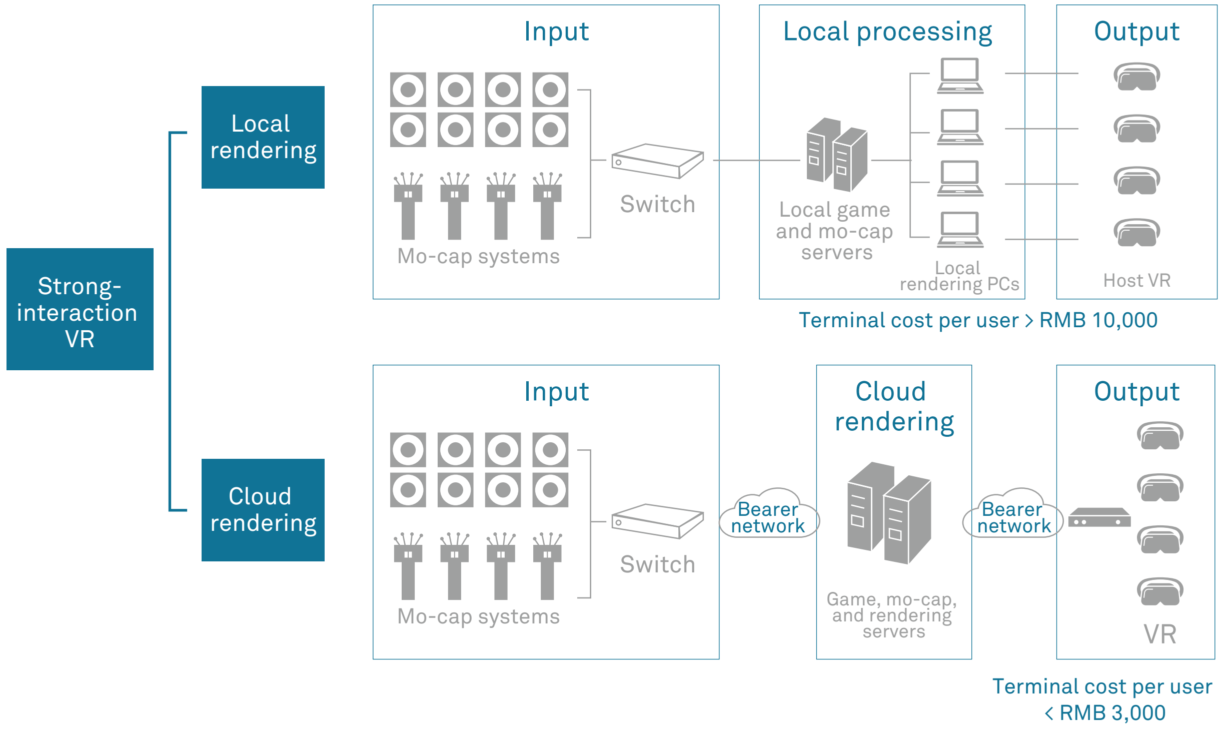
Cloud Rendering Supports Rapid Evolution from Strong-Interaction VR to Cloud VR

Most strong-interaction VR games are local applications. Despite the mode of gaming, whether online gaming or single-player or multi-player local gaming, local rendering is used in all cases. This requires that the terminals have strong computing and rendering capabilities to provide a good gaming experience. Mobile phone–based VR and all-in-one VR have limited rendering and computing capabilities and therefore can only support simple games. Only high-end PCs or hosts can render excellent visual effects and provide good interactive VR experiences.

However, high-end PCs or hosts are expensive, hampering the popularization of VR services. In this case, maturing real-time cloud rendering technology can put complicated rendering and computing processing on the cloud and deliver the outputs to users through high-speed low-latency networks, greatly lowering requirements for terminal performance, reducing VR terminal costs, and improving VR popularization.

Figure 1-1 takes VR multi-player gaming as an example. Cloud rendering makes high-end PCs unnecessary and requires that terminals have only basic capabilities such as network connectivity, video and audio decoding, and image display. A common all-in-one VR, phone-based VR, or STB+common VR headset can provide good user experience and greatly lower the user consumption threshold.

Figure 1-1 Cloud rendering greatly reduces terminal costs



On September 15, 2017, the Cloud VR platform of Dalian Tiantu Cable TV Network was put into operation, implementing cloud rendering. Dalian Tiantu Cable TV Network takes advantage of the powerful computing capability of the cloud platform and provides users with various VR services through fast and stable broadcast and television networks. Users can access and enjoy services through STBs. VR applications are all rendered on cloud servers and streamed to the VR headsets of users. The Cloud VR platform will accelerate the transformation from local VR to Cloud VR, making VR services more accessible for households.

For strong-interaction VR, cloud rendering marks the emergence of Cloud VR. Although strong-interaction services of Cloud VR place high bandwidth and latency requirements on the network, the current network can meet these requirements. There are still many technologies to develop, and there is a long way to go to achieve the ultimate experience. Chapter 3 "Network Requirements at Different Cloud VR Stages" will explain the stages of development and evolution of Cloud VR in terms of experience improvement.

Four Driving Forces of Cloud VR Development

The four main advantages and driving forces of Cloud VR development are as follows:

- Reduction in VR costs for users

Huawei iLab's research, and recommendations by Oculus Rift, HTC Vive, Valve, and Steam VR, show that the minimum configuration requirements for a guaranteed basic VR experience include GPUs equivalent to GeForce GTX 970/AMD 290 or better, CPUs equivalent to Intel i5-4590 or better, and RAM of at least 8 GB. The total cost of a PC-based VR headset and a matching high-end PC exceeds RMB 10,000, which is a large amount for a working-class family.

In contrast, Cloud VR requires terminal devices to have only basic functions such as video decoding, end rendering, image display, and receiving and uploading of control and interaction signals. For example, VR STB decoding can be used with end-terminal rendering processing. Together with a PC-based VR headset, the total cost of terminals reaches around RMB 3,000.

- Protection for VR content copyrights

Most VR contents are viewed off-line, making them difficult to manage. Content copyrights of VR content providers cannot be protected. However, with Cloud VR, content management becomes easy, and copyrights can be protected. Precise management and provisioning can be implemented on the cloud.

- Improvement in user experience

Cloud VR can improve logical computing and image processing capabilities. The distributed computing capabilities of many-core servers, GPU clusters, and the cloud are brought into full play. The latest GPU rendering and AI analysis technologies are used to make up for the inadequacy of VR terminals and to improve user experience.

- Acceleration of VR commercial popularization

Currently, the high per-user cost, lack of contents, difficulty of popularization result in poor ecosystem. After VR moves to the cloud, user costs are greatly reduced, popularizing VR in more households and enriching people's VR experience. As a result, the high-quality VR content and VR commercial scenarios will continue to develop.

1.3 Typical Applications of Cloud VR

According to the prediction in the 2016 VR/AR industry report of Goldman Sachs, three out of nine major VR application domains that will be popularized by 2025 are VR games, VR videos, and VR live broadcast. This section will introduce a few typical Cloud VR applications.

Cloud VR Games

Cloud VR gaming is the most typical strong-interaction application. This introduces cloud computing technology to VR game platforms. The cloud server performs complex computing and image rendering of games, and compresses them into video and audio streams for transmission over high-speed broadband networks to players' headsets. By transferring the computing and rendering capabilities that VR games require to cloud servers, players no longer need to purchase high-end PCs to obtain a good gaming experience.

Figure 1-2 Service architecture diagram of Cloud VR games

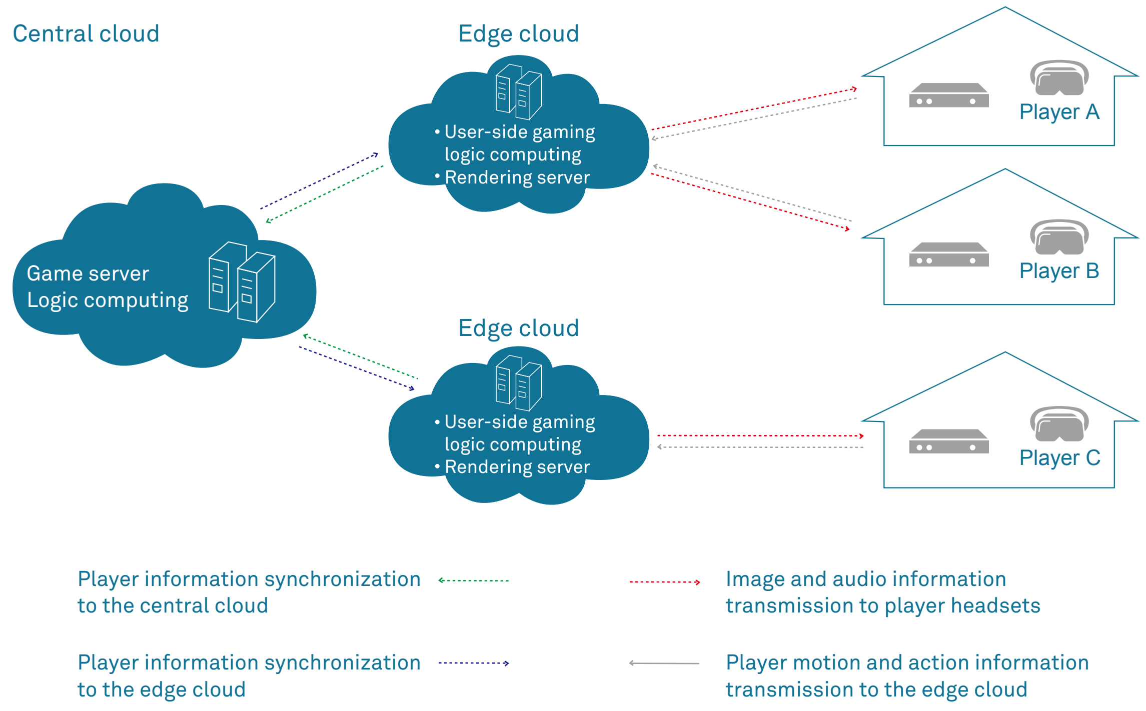
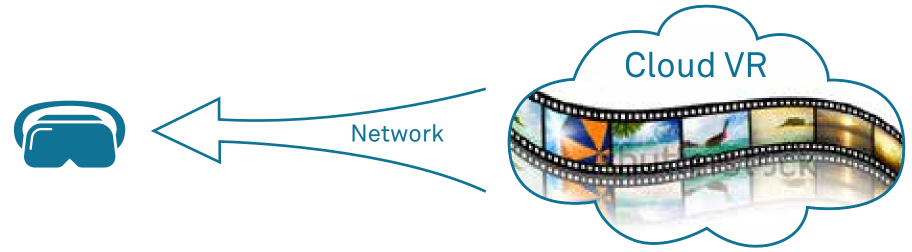


Figure 1-2 shows the service architecture of Cloud VR games, which is constructed on both the central and edge clouds. Some of the functions of the rendering and game engines are deployed on the edge cloud, implementing user-side gaming logic computing and image rendering. The edge cloud is closer to users, meaning lower latency and a more satisfactory real-time interaction experience. Game servers, however, are deployed on the central cloud, implementing other functions of the game engine and user status synchronization.

Cloud VR Videos

Cloud VR videos refer to VR video on demand (VoD). The key is cloud-based video contents, which are streamed from the cloud to local terminals over networks.

Figure 1-3 Cloud VR video playing diagram



Cloud VR videos provide a brand-new watching experience. They are the first type of VR application that most users become familiar with. Currently, Cloud VR videos are supported on most OTT video streaming platforms around the world. For example, YouTube, Youku, and iQIYI all have a dedicated VR video section that focuses on the creation of a content ecosystem.

VR Live Broadcast

VR live broadcast is the result of the convergence of traditional video streaming and VR technologies. This is implemented by panoramic shooting, real-time splicing, code streaming, and CDN distribution. In contrast to traditional live broadcast, VR live broadcast is panoramic, 3D, and interactive. It gives viewers an unprecedented immersion experience. VR live broadcast, as a new form of live event or concert broadcast, has gradually penetrated our life. For example, the VR live broadcast of the concert of Faye Wong, a famous female singer in China, had an audience of over 20 million. Industry-leading operators, such as British Telecom, SKT, and AT&T, have started commercial VR live broadcast of the English Premier League. In addition, VR live broadcast technologies were also used for the 2017 Chinese Spring Festival Gala, *Sing! China*, and other events. Through VR live broadcast, audiences can get close to their idols across thousands of miles, and experience the atmosphere as if they were present at the venue.

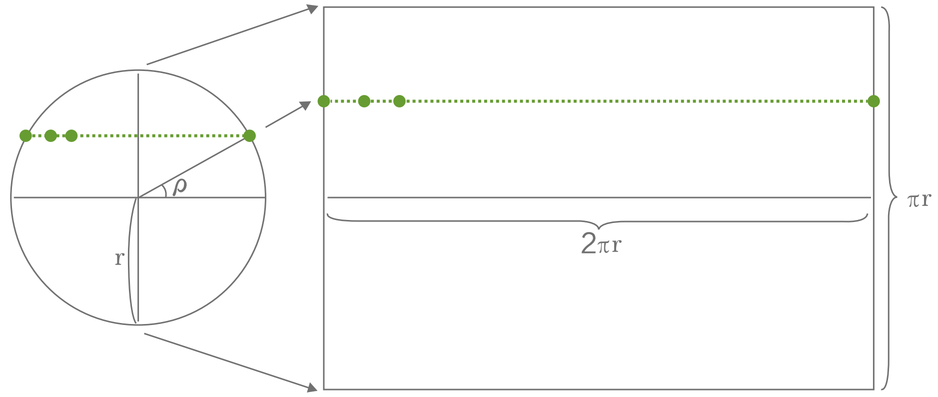
In addition to the few typical Cloud VR applications listed above, there are also VR fitness, VR social networking, and others. Cloud VR applications have penetrated people's life and will definitely promote the prosperity of the VR industry.

2. Key Technologies of Cloud VR

2.1 Full-View and FOV

The view of users in the VE can be considered as a spatial sphere. The horizontal field of view (FOV) is 360° and vertical FOV is 180°. When a user uses a terminal, the visual information that a single eye picks up is only part of the entire spherical data, with the area depending on the FOV provided by the terminal.

Figure 2-1 Spatial sphere unfolding diagram



For example, if the FOV is 90°, information per eye accounts for 1/8 of the entire spherical data (90/180 x 90/360). If the FOV is 120°, the ratio becomes 2/9.

2.2 Experience of Image Quality and Interaction

Experience issues in VR include issues with the perception experience and physiological experience. To accelerate VR popularization, the industry urgently needs to resolve physiological experience issues. Currently, physiological experience has the following four major issues that the industry is working on:

- Visual information quality

It is generally accepted that an overly low image quality can fatigue the eyes and cause dizziness. The key effort of the industry in recent years should be on improvement of content quality, particularly the improvement of resolution and image quality.

- Motion-to-photons (MTP) latency

Industry opinion is that the MTP latency cannot exceed 20 ms, otherwise it will cause dizziness. The currently leading VR terminal vendors, such as Oculus and HTC Vive, have managed to shorten the MTP latency to 20 ms through end-to-end software and hardware performance improvement, starting from sensor tracing elements, display technology and GPU.

- Motion-sensing conflict

If motion feedback output is missing, the physical motion of the user does not match the virtual information captured by the eyes, causing dizziness. To resolve this issue, VR terminals must fully explore the value of VR new media to provide a multi-sensory experience, including visual, audio, touching, and motion feedback.

- Vergence-accommodation conflict

This conflict is also known as focusing conflict. It exists in display terminals that utilize the dual-eye parallax principle. Because no depth data is provided by the light emitted from the screen, the focus of the eyes is on the screen. As a result, the focus adjustment of the eyes mismatches the visual depth, causing dizziness. To resolve this issue, a new technology is needed to record and restore the intensity and angle of the light emitted from a spot in the 3D space by using the record of the light field and the projection technology. This technology will mature further through future development.

This section describes three issues that have undergone major breakthroughs in the industry in recent years: visual information quality, MTP latency, and motion-sensing conflict.

Image Quality Experience

Due to differences between the full view and FOV in VR, the traditional description of OTT video resolution corresponds to that of the full-view resolution of VR 360 videos. The single-eye resolution (FOV resolution) determines the image quality experience of VR 360 videos, which can be converted into pixels per degree (PPD), the number of pixels visible per one degree in the FOV area. The higher the PPD value, the higher the pixel density in the FOV, and the better the image quality experience. The PPD value for a normal-sighted user is about 60. If the PPD is higher than 60, most people will not be able to identify individual pixels.

An online 4K VR video on YouTube, for example, has a resolution value of 960 x 960 in a 90° FOV per eye, which corresponds to only 10 PPD. The single-eye resolution is far lower than the 60 PPD required by normal-sighted retinas. The actual image quality experience is much poorer than watching SD videos on traditional TVs, which have a resolution value of 22 PPD.

Immersive VR terminals have the FOV higher than that of traditional TVs. To achieve the same level of image quality experience, the same PPD value requires VR terminals to have much higher single-eye resolution and full-view resolution. The full-view 4K resolution is far behind the desired video quality, making it essential to improve the resolution value to 8K or higher. A 90° FOV, for example, has a single-eye resolution value of 1920 x 1920 (PPD = 22) when the full-view resolution reaches 8K. When the full-view resolution is upgraded to 12K, the single-eye resolution will become 2880 x 2880 with the PPD value increasing to only 32. In the rest of this white paper, an evolutionary roadmap for the VR experience will be demonstrated.

Interactive Experience

For MTP latency, industry opinion is that latency over 20 ms will cause dizziness. This means that when the viewing angle is changed, either by the user turning their head or another way, the overall latency across the terminal, network, and cloud should ensure that the change of the motion and the change of the image in the FOV are consistent. The refresh latency of the FOV image cannot exceed 20 ms, and missing all or part of the image information in the FOV is not permissible. Similarly, for motion-sensing conflicts, the convergence capability of visual, audio, feeling, and motion feedback also requires that the display latency caused by motion be less than 20 ms to avoid dizziness.

2.3 Projection and Coding Technologies

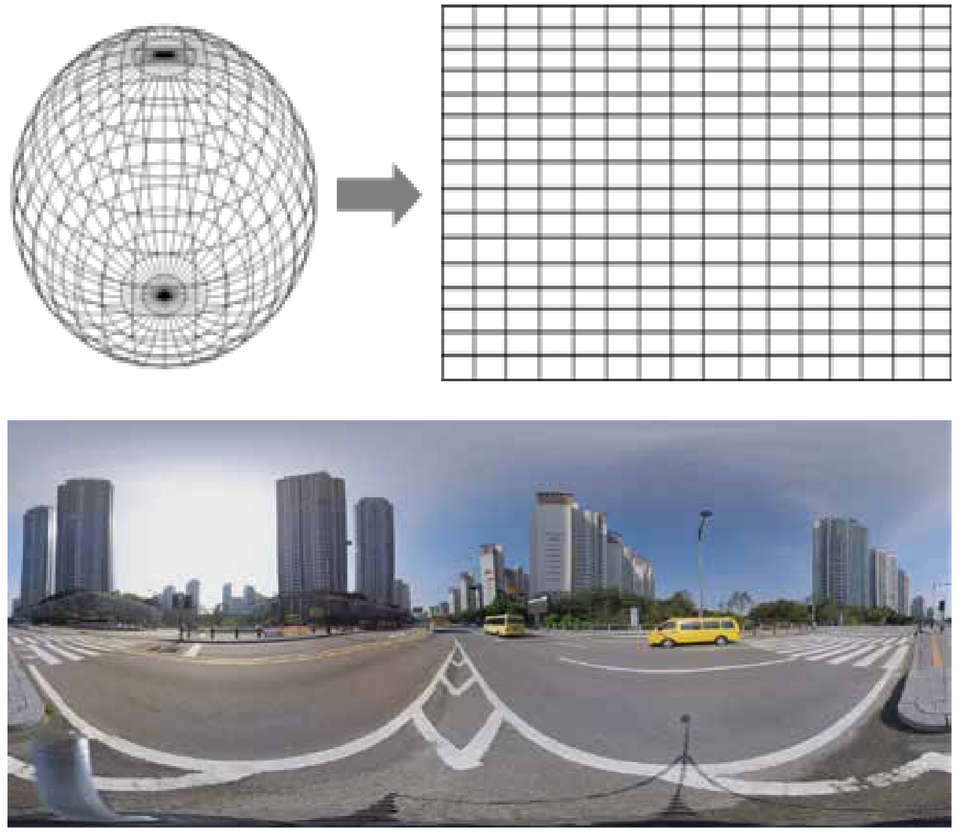
The projection and coding technologies determine the media information volume contained in the VR image media files, and the form in which they are produced and organized. These technologies are essential, to quantize the network requirements of meeting certain user experience.

Projection Technology

To convert the spatial sphere information viewed by users in VR images into 2D media formats, a new projection technology that has not been used in traditional videos is needed.

Currently, equirectangular projection (ERP) is the mainstream VR image format, but images are subject to distortion and the efficiency of compression reaches a bottleneck. This projection method uses the classical meridian and parallel map concept and unfolds the sphere into a planar rectangular. The meridians and parallels of the ERP intersect at 90° with the largest area distortion and without angle distortion. The angles remain unchanged mainly due to the distortion of the area. When the sphere is unfolded, the equator area has low distortion and the polar areas have the highest distortion. Polar areas are increased to keep the angles unchanged and therefore redundant ineffective pixels are introduced, causing low compression efficiency for video coding. YouTube, Samsung Gear, Youku, and iQIYI all use this projection format to produce VR media files.

Figure 2-2 ERP diagram



Platonic solid projection (PSP) is a new focus of the industry due to its low distortion and high compression efficiency. It uses another type of concept of classical map projection. The sphere is divided into multiple spherical trapezoids based on isometric meridians and parallels and then projected onto a polyhedron. This polyhedron can be a tetrahedron, cube, pyramid, or dodecahedron. Each trapezoid is projected individually, making the distortion extremely low. Samsung submitted a proposal on the PSP projection format on the MPEG meeting in May 2016. Table 2-1 describes the polyhedral projection diagrams.

Table 2-1 Polyhedral projection diagrams

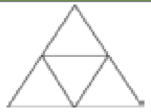
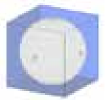
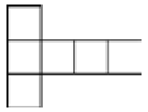
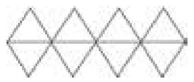
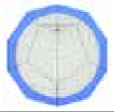
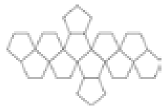
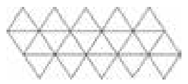
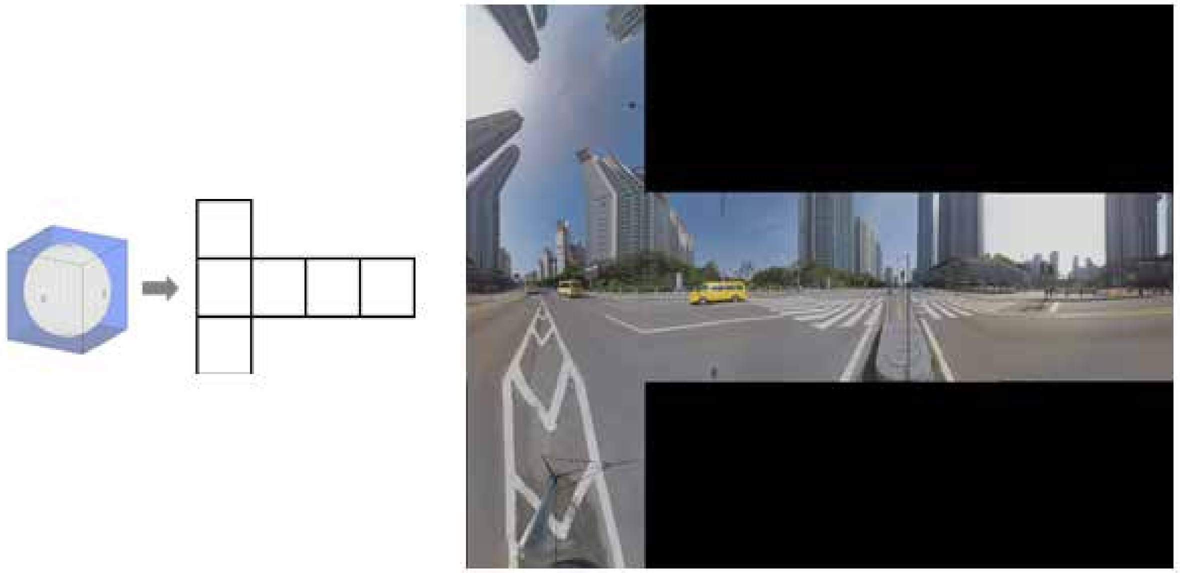
Projections	3D Model	2D Projection	Vertexes	Area Ratio	
				vs. Sphere	vs. ERP
Tetrahedron (4 faces)			4	3.31x	2.11x
Cube (6 faces)			8	1.91x	1.22x
Octahedron (8 faces)			6	1.65x	1.05x
Dodecahedron (12 faces)			20	1.32x	0.84x
Icosahedron (20 faces)			12	1.21x	0.77x

Figure 2-3 Cube (6 faces)



Coding Technology

VR images can be compressed using common video coding technologies. Currently, the most applied video coding technologies include H.264, HEVC, and VP9. According to industry test results, the compression efficiency of HEVC and VP9, with the same image quality guaranteed, is about 30% higher than that of the latest version of H.264. Recent research by MPEG and other standards organizations shows that H.266, the next generation of HEVC, outperforms HEVC in compression efficiency by 30%.

For VR images with 3D effects, two images with binocular parallax are synthesized to establish 3D effects. Regarding the media format, two images corresponding to the left and right eyes are coded to the same frame. The format of the two images can be left and right or up and down. Regarding the volume of uncompressed information, the volume of 3D VR images is double that of 2D images. Content viewed by the left and right eyes in 3D is highly interrelated. To obtain the same image quality, the compression efficiency must be further improved. According to industry test results, with the same coding technology, the compression efficiency of 3D VR images is 25% higher than that of 2D VR images.

2.4 Transmission Technology Roadmap

The online transmission of VR images uses two main technological schemes: full-view transmission and FOV transmission. Strong-interaction VR involves only the FOV (non-full-view) transmission scheme, whereas weak-interaction VR involves both transmission schemes.

Full-View Transmission Scheme

The full-view transmission scheme transmits 360° images to terminals. When users turn their heads, the image switching processing is done locally. With the same single-eye resolution, VR images have much larger bit rates than common 2D videos, normally by five- to tenfold, due to their frame rate, bit depth, and 360° features. For example, the ultimate panoramic VR video with single-eye 8K resolution requires 5G bandwidths, presenting a great challenge to the network and a huge burden to the costs.

In the full-view transmission scheme, a frame of data received by the terminal contains the information of the full view of the spatial sphere. Interaction signals generated when users change their viewing angles are processed on local terminals, which decode corresponding FOV information from the locally loaded frames and restore the data to the player. Users can then view the visual information from a normal viewing angle. Therefore, the 20 ms latency requirement of the interaction experience depends on terminals and does not involve network latency and cloud latency. This scheme has a high bandwidth requirement but a low latency requirement, and is a "bandwidth to latency" transmission scheme. This transmission scheme can use existing mainstream video transmission technologies, such as MPEG.DASH, HLS, and HPD. A function that restores and projects FOV information from full-view frames is added to terminal players.

FOV Transmission Scheme

Regarding the full-view transmission scheme, users can view only part of the entire spatial sphere with the rest of the area merely taking up network bandwidth, greatly wasting network resources. To resolve this issue, the industry proposes the FOV transmission scheme which transmits differentiated VR images based on the FOV.

The FOV transmission scheme focuses on the high-quality image transmission of the current FOV area. Specific technologies that implement FOV transmission are not yet standardized. The following two methods are dedicated to weak-interaction VR.

- Pyramid-shaped projection transmission scheme (Facebook)

Figure 2-4 Pyramid-shaped projection transmission scheme

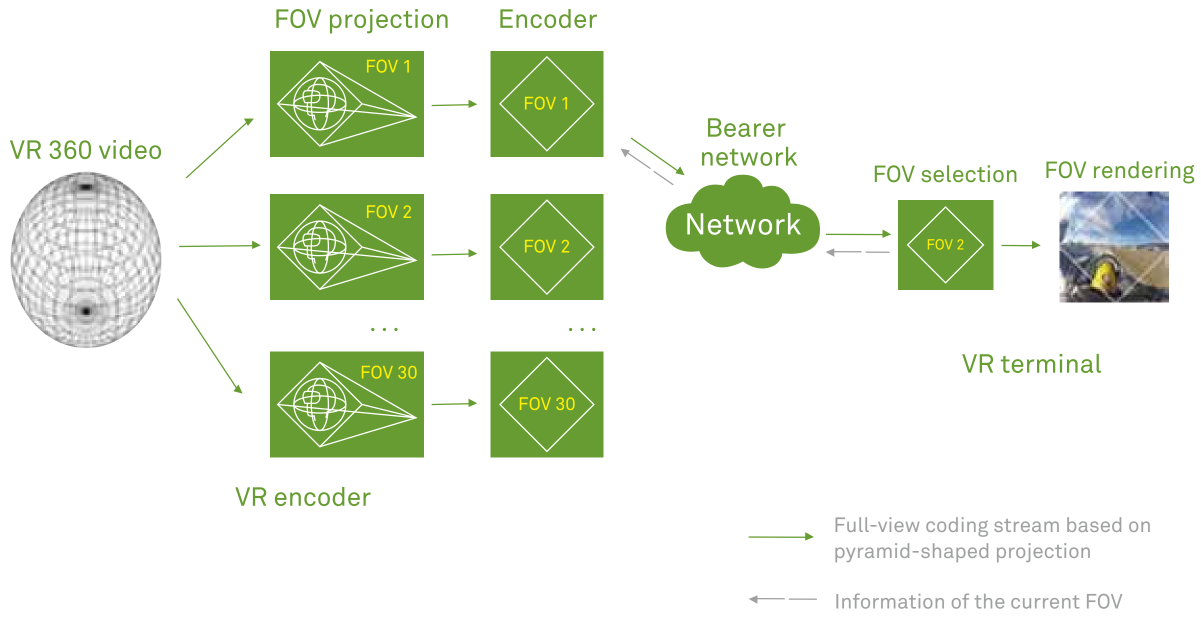


Figure 2-4 demonstrates the pyramid-shaped projection transmission scheme. At the content preparation side, a full-view coding stream with uneven quality for each FOV is prepared. High-quality coding is used in the FOV area, and low-quality coding is used outside the FOV area. Terminals request corresponding FOV files from the server based on the user's current viewing pose. When the user turns their head and the viewing angle changes, the terminal requests the new corresponding FOV file from the server.

In the FOV transmission scheme released by Facebook, the spatial sphere is divided into 30 FOVs. Each FOV file is only 20% of the size of the original file and the transmission rate is also 20% of the original rate, greatly reducing the bandwidth requirement of watching VR videos and improving the utilization rate of bandwidth. On the other hand, the total size of all the FOV files is six times that of the original file, occupying a relatively large storage space. However, bandwidth resources are more valuable than storage space.

- Tile Wise transmission scheme (Huawei)

Figure 2-5 Tile Wise transmission scheme

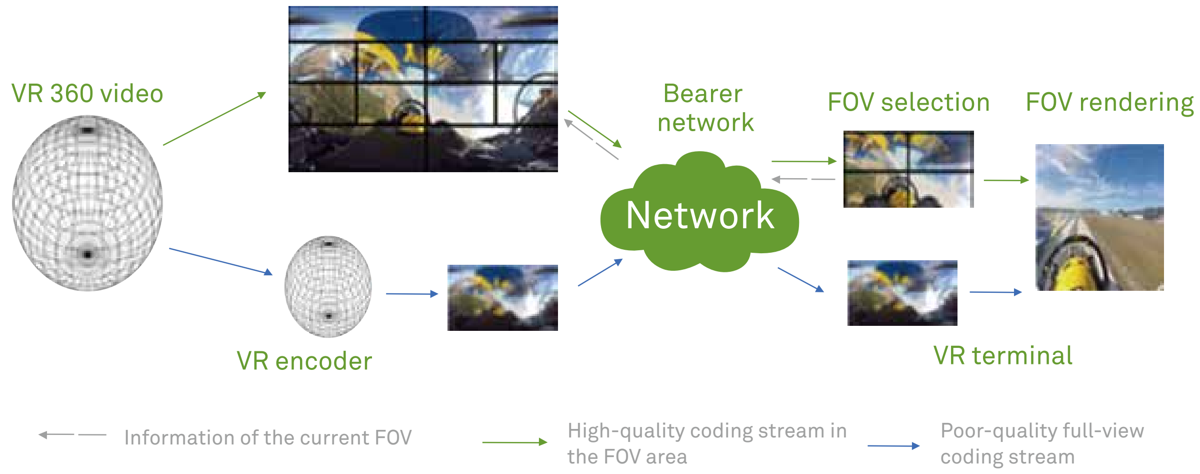


Figure 2-5 demonstrates Huawei's Tile Wise transmission scheme, which combines poor-quality full-view transmission and high-quality FOV transmission. On the content preparation side, preparation of each FOV is no longer needed. VR images are divided into multiple tiles with each tile corresponding to an individual decoding stream. A poor-quality full-view VR coding stream is also prepared. Terminals obtain the poor-quality full-view coding stream and a high-quality coding stream (of a tile) by selection.

Table 2-2 compares the network requirements of the full-view, pyramid-shaped, and Tile Wise transmission schemes.

Table 2-2 Network requirements for the three transmission schemes

Requirement	Full-View	Pyramid-shaped	Tile Wise
Bandwidth	High	Medium-low	Medium
Latency	Low	High	Medium
Satisfaction level	· The current network architecture can be inherited. · Pressure of bandwidth expansion is high.	Network optimization is needed for latency assurance.	The current network architecture can be inherited.

In contrast to weak-interaction VR services, strong-interaction VR services involve only the transmission of the FOV area with high-quality coding streams. Areas outside the FOV are not involved. Therefore, strong-interaction VR services require a higher frame rate and a lower end-to-end latency.

2.5 Rendering Technology

Rendering is a process of using perspective principles to project a 3D virtual space entity onto a plane to form binocular vision. It focuses on pre-rendering low overhead and latency, and post-rendering high image quality. This technology aims to provide a smooth, clear, and real-time VR visual experience. In particular, strong-interaction VR services require real-time rendering due to factors such as MTP latency and motion-sensing conflict.

Inadequate rendering capabilities cannot meet users' high experience requirements. Therefore, reducing computation overheads and rendering latency is becoming a key topic in the development of rendering technologies. Development of rendering technology mainly involves the following aspects:

» Improvement of rendering technology. For example, multi-resolution coloring and multi-view rendering reduce GPU and CPU workload, and asynchronous time warp (ATW) is implemented on the terminal side to reduce the rendering latency.

» Integration and innovation of rendering processing, cloud computing, light field, and artificial intelligence. Typically, the computing technology and rendering processing are introduced to the cloud rendering technology, and complex computing is transferred to the cloud, directly resolving experience issues caused by inadequate local hardware.

Cloud Rendering Technology

To bring a more vivid immersive experience to users, effects such as 12K/24K resolution and real-time lighting need to be implemented. However, existing GPU hardware cannot meet these requirements. Therefore, the use of cloud rendering technology to move rendering to the cloud is proposed. Terminals transmit various types of sensor data, such as 6DoF orientation and position information, and interaction control information in real time. The cloud computing cluster then completes image rendering and sends the result to the terminals.

Cloud rendering technology deploys most computing on the cloud, so that consumers can obtain high-quality 3D rendering effects on lightweight VR terminals. Terminals are no longer restricted by high hardware performance requirements, and consumers can obtain hierarchical immersive experience (high, medium, or low) based on fees. Meanwhile, real-time rendering must be ensured by end-to-end low latency.

ATW Rendering Technology

In VR rendering, the complexity of content varies. Therefore, the rendering of complex content possibly cannot be completed within the refreshing period of one frame. As a result, no new content is generated after screen refreshing, and users will perceive that as a freeze. To resolve this issue, ATW rendering technology has been proposed in the industry.

This technology determines the head pose in the frame by means of pose prediction, computes the pose difference based on the pose upon generation of the previous frame image, changes the position of the previous frame image based on the pose difference, and generates an intermediate image in a new frame, resolving freezing issues caused by the lack of the current frame.

ATW rendering technology can ensure the smooth visual experience of users in most cases. Theoretically, ATW can continuously generate new images based on one frame of image. However, errors between the generated images and the actual rendered images will accumulate due to the continuous distortion. As a result, the image quality will deteriorate.

Multi-resolution Coloring Technology

Due to VR distortion, the four edges of an image are compressed during rendering and cannot be displayed after the re-sampling of a large number of pixels rendered from application contents. In fact, the rendering overhead of these pixels can be reduced. GPU vendors in the industry propose multi-resolution coloring technology to reduce rendering overhead.

In this technology, an image is divided into grids. The central area retains the original resolution, and the resolution of the four edges and corners is compressed by 1/2 and 1/4 (this can be changed as required). During the rendering of application content, the image is drawn by the GPU at once.

Multi-view Rendering Technology

In contrast to common application rendering, the VR rendering of each frame needs to simultaneously render the images for both the left and right eyes. In each frame, one rendering task is submitted separately for the images on the left and right eyes. Therefore, CPU/GPU resources occupied by VR rendering are twice as many as those occupied by common application rendering. To resolve this issue, multi-view rendering technology has been proposed by the industry, so that the images for the left and right eyes are simultaneously rendered after only one task is submitted.

Most information of the images for the left and right eyes is the same, and the images differ only slightly in parallax. Therefore, in the multi-view rendering technology, the CPU needs to submit only one rendering task and parallax information to the GPU, and then the GPU can render the images for the left and right eyes, greatly reducing CPU resource occupancy and improving the frame rate.

Light Field Rendering Technology

The existing VR imaging method is basically the 2D imaging method with binocular parallax. The focus points and convergence point of the eyes do not remain at the same position for a long time. The former is located on the screen plane, and the latter is located on the virtual plane generated by the binocular parallax. As a result, vergence-accommodation conflict occurs, causing dizziness and other physiological discomfort and the loss of immersion.

Restoring the content that can be seen by eyes in the real world may restore the perfect immersion. By changing the focal length, eyes collect the light reflected on surfaces of objects at different distances, in different positions, and in different directions. The complete set of all this is the light field. A vendor in the industry has developed a light field camera that collects light field information. Light field rendering technology restores the collected light field information to meet the higher immersion experience requirements of users. Collection, storage, and transmission of light field information still face many basic issues such as enormous data volumes, and the light field rendering technology is still in an early stage. However, it may become a key rendering technology in the future as users have higher requirements for VR experience.

3. Network Requirements at Different Cloud VR Stages

3.1 Four Stages of Cloud VR

The development of Cloud VR revolves around experience, especially improvement in profile, interactive, and immersive experience. The compatibility between transmission technologies and network technologies determines the level of immersive experience that can be delivered by Cloud VR. We believe that the Cloud VR experience may evolve through the following stages:

- Early stage
- Entry-level experience stage
- Advanced experience stage
- Ultimate experience stage.

In this section, we have made some predictions about the terminal, content, experience, network, and commercial application for each stage.

Early stage

The early stage of Cloud VR is also called pre-VR, and barely reaches the entry level in terms of experience. We believe that this stage should be marked by the fairly high-level hardware and software that were generally available as of 2016. A typical terminal is HTC VIVE with a 2K resolution, and the typical content provider is YouTube, which provides 4K VR video, almost equivalent to 240p PPD on a traditional TV screen in profile.

For weak-interaction VR services, the full-view transmission scheme is used at this stage. To ensure a good user experience, strong-interaction VR services need higher frame rates than weak-interaction VR services. In addition, strong-interaction VR services use only the FOV transmission mode, and require that the terminals support ATW rendering technology to obtain smooth experience.

Entry-level experience stage

Cloud VR at the entry-level stage is called entry-level VR. The generally available hardware and software will be improved to a higher level. The terminal screen resolution has improved to 4K and the full-view resolution to 8K. As a result, the profile that users receive approaches the 480p-equivalent PPD effect on traditional TV screens.

For weak-interaction VR services, full view remains the preferred transmission scheme to ensure a good watching and interaction experience for customers. However, with the emergence of full-view 8K 3D video and bandwidths beyond 100M, the FOV scheme will be increasingly used. In the case of strong-interaction VR services, resolution is further improved, and so is the demand for bandwidth.

Advanced experience stage

Cloud VR at the advanced experience stage is called Advanced VR. At this stage, the screen resolution, chip performance, ergonomics of terminals, and the quality of content are significantly improved. The profile received by users is approaching 720p PPD on a traditional TV screen. At this phase, Cloud VR places significantly higher requirements on bandwidth and latency to ensure good experience of services.

For weak-interaction VR services, the full-view transmission scheme will pose higher requirements on network bandwidth. Therefore, the FOV scheme becomes popularly accepted to lower the requirements on bandwidth. In the case of strong-interaction VR services, lower network latency is required to improve the interaction experience of users.

Ultimate experience stage

Cloud VR at the ultimate experience stage is called Ultimate VR. At this stage, the development of terminals and the content can provide users with the best experience. The resolution and frame rate are significantly improved, and the per-eye image reaches retina level, approaching to 4K-equivalent PPD on a traditional TV screen. In addition, technologies, such as H.266 hardware video encoding standard and light field rendering, will be widely used.

For weak-interaction VR services, the requirements of full view transmission on network bandwidth are too high. Therefore, FOV transmission will be widely used. In the case of strong-interaction VR services, resolution is further improved, and the demand for bandwidth is increased.

3.2 Network Requirements of Cloud VR

Network requirements vary along with interaction modes. Networks must meet the requirements of VR services to ensure a good interaction experience. Weak-interaction VR places high requirements on bandwidth, while strong-interaction VR places high requirements on both bandwidth and latency.

Table 3-1 lists the requirements on bandwidth, latency, and packet loss for weak-interaction and strong-interaction VR services at each stage.

Table 3-1 Network requirements at different Cloud VR stages

Standard		Pre-VR	Entry-Level VR	Advanced VR	Ultimate VR
Continuous experience duration		Less than 20 minutes	Less than 20 minutes	20 to 60 minutes	Over 60 minutes
Estimated time for commercial use		Now	Now–2 years	3–5 years	6–10 years
Video resolution		Full-view 4K 2D video (full frame resolution 3840 x 1920)	Full-view 8K 2D/3D video (full frame resolution 7680 x 3840)	Full-view 12K 3D video (full frame resolution 11520 x 5760)	Full-view 24K 3D video (full frame resolution 23040 x 11520)
Single-eye resolution		1080*1200 [with view angle of 100°]	1920*1920 [with view angle of 110°]	3840*3840 [with view angle of 120°]	7680*7680 [with view angle of 120°]
Color depth (bit)		8	8	10	12
Encoding standard		H.264	H.265	H.265	H.266
Frame rate (weak-interaction VR/strong-interaction VR) (Note 1)		30/90	30/90	60/120	120/200
Weak-interaction VR services	Typical bit rate (Note 2)	16 Mbps	Full-view: 50 Mbps (2D) 80 Mbps (3D) FOV: 26 Mbps (2D) 42 Mbps (3D)	Full-view: 420 Mbps FOV: 220 Mbps	Full-view: 2.94 Gbps FOV: 1.56 Gbps
	Typical bandwidth requirement (Note 3)	25 Mbps	Full-view: 75 Mbps (2D) 120 Mbps (3D) FOV: 40 Mbps (2D) 63 Mbps (3D)	Full-view: 630 Mbps FOV: 340 Mbps	Full-view: 4.40 Gbps FOV: 2.34 Gbps
	Typical round trip time (RTT)	30 ms	30 ms (2D) 20 ms (3D)	20 ms	10 ms
	Typical packet loss (Note 4)	2.40E-4	2.40E-5	1.00E-6	1.00E-6
Strong-interaction VR services	Typical bit rate	18 Mbps	40 Mbps (2D) 60 Mbps (3D)	390 Mbps	680 Mbps
	Typical bandwidth requirement (Note 5)	50 Mbps	120 Mbps (2D) 200 Mbps (3D)	1.40 Gbps	3.36 Gbps
	Typical RTT	10 ms	10 ms	5 ms	5 ms
	Typical packet loss (Note 4)	1.00E-6	1.00E-6	1.00E-6	1.00E-6

NOTE

- Note 1: Strong-interaction VR services, such as Cloud VR games, require a high frame rate to ensure a good interaction experience.
- Note 2: For weak-interaction VR services, the full-view transmission scheme is used at the Pre-VR stage.
- Note 3: The typical network bandwidth is calculated as 1.5 times the bit rate.
- Note 4: For weak-interaction services, packet loss is calculated based on the latency to be achieved, bandwidth, and TCP throughput. In the case of ultimate VR, TCP no longer meets the transmission requirements, and a better or new transmission protocol must be used. Strong-interaction services have low tolerance for packet loss.
- Note 5: The typical bandwidth for strong-interaction VR services must meet the maximum transmission speed of I frames and P frames. In addition, strong-interaction VR services also place high requirements on latency and frame rate, which also means requirements on bandwidth.

4. Cloud VR-oriented Bearer Network

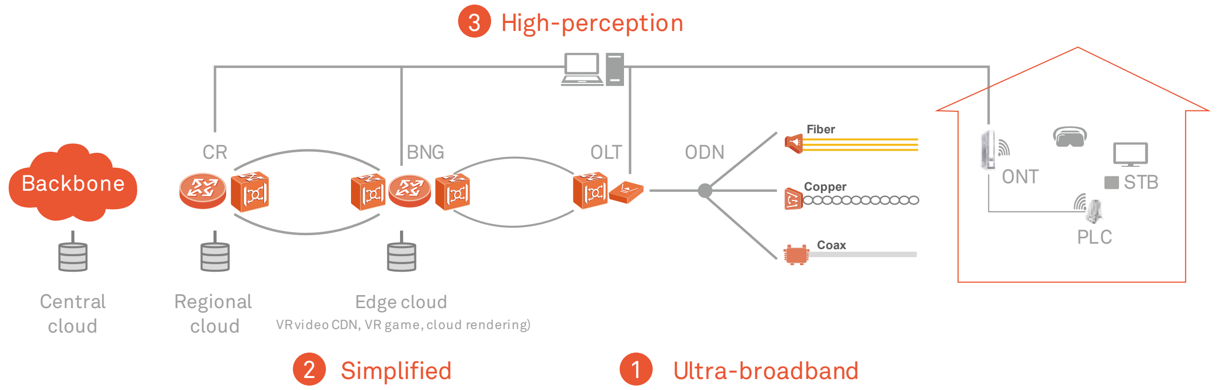
4.1 Early and Entry-level VR on the 4K Network

Pre-VR (full-view 4K) places similar requirements on the bearer network as 4K, with the bandwidth requirement of 20 Mbps to 50 Mbps. Pre-VR can be quickly provisioned on a 4K-ready bearer network. Entry-level VR (full-view 8K) places similar requirements on the bearer network as 8K, with the bandwidth requirement of 50 Mbps to 200 Mbps. On a 4K-ready bearer network, entry-level VR can be provisioned with simple network upgrade using the existing technologies and products. This chapter describes suggestions for deploying the bearer network for pre-VR and how to upgrade the network to support the rapid provisioning of entry-level VR.

4.1.1 VR Bearer Network Architecture

Similar to 4K videos, VR videos have high-bandwidth and high-perception traffic. Therefore, the network architecture must be ultra-broadband, high-perception, and simplified. Figure 4-1 shows the target network architecture for early and entry-level VR.

Figure 4-1 Network architecture for early and entry-level VR



Ultra-broadband Access

The current home broadband package of 100 Mbps bandwidth has been popularized. This access bandwidth can basically meet the 20 Mbps to 50 Mbps bandwidth requirements for pre-VR (full-view 4K). VR HMDs cannot be viewed by multiple people on the same screen as in TV viewing. If multiple people in the same home are watching a VR video at the same time, the bandwidth requirement increases exponentially. If different people in a household use different VR HMDs to view VR videos, the bandwidth package must be upgraded to be greater than 200 Mbps. The bandwidth requirement for entry-level VR (full-view 8K) is 50 Mbps to 200 Mbps. This means that the bandwidth must be greater than 200 Mbps for the video viewing of a single person. If multiple users view entry-level VR at the same time, the bandwidth must be greater than 500 Mbps.

Simplified Network

With the exponential increase of video services, the multi-level aggregation and high-convergence network architecture built for traditional services, such as voice, web, and OTT video services. is facing great challenges. To reduce the probability of video congestion and bearer costs, a streamlined IP network layer has becomes more popular.

High-Perception Network

VR is a type of high-perception experience service and is sensitive to packet loss and delay. Network performance issues that may cause intermittent erratic display or frame freezing are hard to locate using traditional methods such as viewing alarm information. A new O&M methodology or system is needed to rapidly optimize networks and to avoid user complaints and churn.

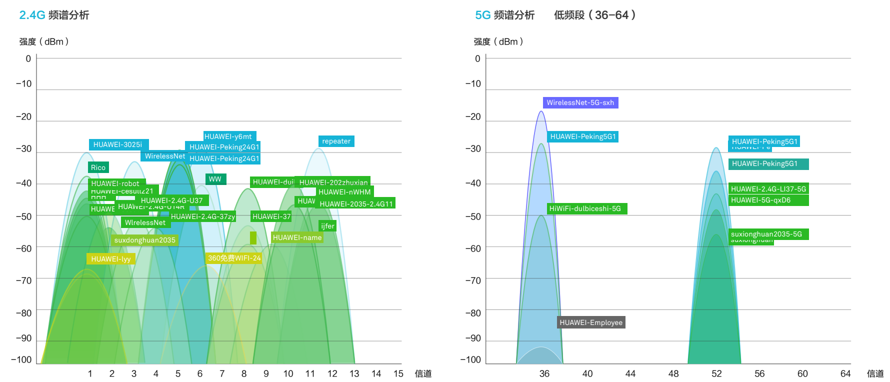
4.1.2 Home Network Design

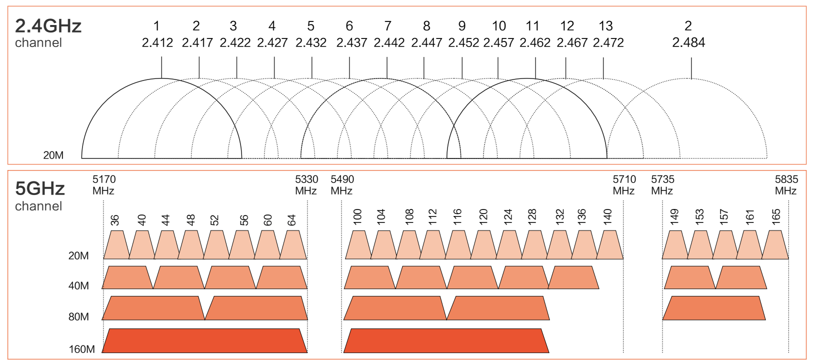
As VR HMDs are worn on users' heads, the Wi-Fi connection mode is generally used to ensure VR mobility. This requires seamless Wi-Fi coverage in the areas where VR is used. Currently, most of the Wi-Fi devices used by home users are purchased and networked by the users themselves. Diverse Wi-Fi device specifications are prone to poor Wi-Fi performance and user experience. In addition, there is no efficient method for locating and resolving Wi-Fi performance issues. As a result, user complaints cannot be addressed in a timely manner.

Key Challenges for VR Service Bearing on Home Wi-Fi Networks

- Signal interference

The transmission medium of Wi-Fi is shared air interfaces. Wi-Fi defines backoff performed on the CSMA/CA at the MAC layer. When multiple APs use the same frequency band, performance greatly deteriorates. When the 2.4 GHz frequency band uses the 20 MHz frequency bandwidth, there are only 3 non-overlapping channels and it is difficult to find a channel that does not interfere with the others. When the 40 MHz frequency bandwidth is used, there is only one non-overlapping channel. Therefore, 2.4 GHz cannot use the 40 MHz frequency bandwidth. Although there are many 5 GHz channels, channel conflicts between neighboring APs still exist due to incorrect configurations.





- Signal attenuation

The Wi-Fi transmission rate is closely related to the signal strength. A closer distance to the Wi-Fi gateway brings stronger signal strength and a higher connection rate. The signal strength of long-distance transmission or where there is isolating wall is weak. Wi-Fi signals cannot penetrate the metal, but the door of the information box where the home gateway is placed is mostly a drilling metal plate. This causes severe attenuation of Wi-Fi signals. Table 4-1 describes the Wi-Fi signal attenuation caused by home obstacles.

Table 4-1 The Wi-Fi signal attenuation caused by home obstacles

No.	Obstacle	Attenuation	No.	Obstacle	Attenuation
1	Bearing wall	20 to 40 dB	2	Concrete wall	10 to18 dB
3	Floor	30 dB	4	Hollow brick wall	4 to 6 dB
5	Plasterboard wall	3 to 5 dB	6	Glass door and window	2 to 4 dB
7	Wooden door	3 to 5 dB	8	Reflective glass door and window	12 to 15 dB
9	Wooden furniture	2 to 10 dB	10	Wood partition wall	5 to 8 dB
11	Metal object	Total reflection	12	Water	Full absorption

- Mutual influence of services

A home Wi-Fi AP is typically connected to different terminals. In addition to VR, Internet surfing, download, and other non-VR video services exist on the network. All these services preempt resources and influence each other.

Suggestions for the VR-oriented Wi-Fi Home Network Solution

- VR services carried based on the 802.11ac standard over the fifth generation of Wi-Fi.

802.11ac works on the 5 GHz frequency band with more channels and less interference. The maximum physical rate of a single antenna (single spatial stream) can reach 433 Mbps. The actual rate can reach over 100 Mbps, which meets the bandwidth requirement for early and entry-level VR. The 802.11ac standard on 5 GHz frequency band adopts a lot of optimization technologies to improve the bandwidth and working efficiency. Such technologies include the following:

» Larger channel bandwidth binding. Compared with 802.11n that supports a maximum of 40 MHz frequency bandwidth, 802.11ac supports 80 MHz frequency bandwidth, with the transmission rate at the physical layer doubled. In addition, 802.11ac supports an optional 160 MHz channel bandwidth.

» Higher density modulation mode. 802.11ac still adopts OFDM modulation, but the order is increased from 64 QAM in 802.11n to 256 QAM. This makes the number of data bits of the subcarrier increased from 6 to 8, with the rate increased by around 33%.

» More MIMO spatial stream. The multiple-input multiple-output (MIMO) of 802.11n supports a maximum of four spatial flows. The number of spatial flows supported by 802.11ac goes up to 8, a 100% increase.

» Support for MU-MIMO. 802.11n only supports single-user MIMO (SU-MIMO), requiring the AP and terminals to be equipped with multiple antennas to send and receive data among multiple spatial flows. For the reasons of cost and size, most terminals do not have multiple antennas, and therefore do not support SU-MIMO. 802.11ac supports multi-user MIMO (MU-MIMO). MU-MIMO is not limited to the number of antennas on terminals and enables multiple terminals that have a single antenna to use different spatial flows, allowing spatial multiplexing among multiple users. This reduces the waiting time for Wi-Fi channel shared among terminals and greatly improves the Wi-Fi performance in multi-terminal scenarios.

» Support for beamforming. 802.11ac adopts the beamforming technique. Beamforming implements phase weighting by using the correlation of the output signals from multiple antennas so that the signals are superposed and enhanced in the direction of Wi-Fi terminals, achieving signal gains.

NOTE

802.11n supports both the 2.4 GHz and 5 GHz frequency bands. Due to high interference, the 2.4 GHz frequency band cannot guarantee bandwidth and therefore cannot meet the bandwidth requirements for VR. 802.11n supports the 5 GHz frequency band at the maximum physical rate of 600 Mbps. However, 802.11n requires devices to be equipped with multiple antennas (4 x 4MIMO). 802.11ac supports the maximum physical rate of 433 Mbps with a single antenna and therefore has advantages over 802.11n in both cost and bandwidth. 802.11n will not become the mainstream or preferred Wi-Fi technology for VR services.

- Smart channel management.

Wi-Fi has multiple 5 GHz frequency band channels. The relationship of channels and power between neighbor APs needs to be well handled to achieve the optimal video experience. Manually configuring the channels and power for each AP creates a repetitive workload. If the environment is changed, the configured AP channels and power may fail to meet requirements. The Wi-Fi devices that support smart channel management are recommended so that the devices can work over the optimal channels and power.

» The purpose of smart power management is to ensure the widest coverage with the minimum interference. Strong coverage areas and weak coverage areas are defined based on the room layout and service demands. The strong coverage area must cover the terminal service points of main services provided by the AP. If a neighbor AP is in an invalid area, coverage insufficiency may occur. Allow more neighbor APs to be located in the weak coverage area to ensure coverage overlapping to a certain extent. Do not allow neighbor APs to enter the strong coverage area. Otherwise, there may be difficulty in allocating non-conflicting channels. The AP transmit power can be adjusted to increase/decrease the coverage area to achieve the preceding principles.

» For example, when a new distributed AP joins, the transmit power of the gateway and AP is decreased to prevent meaningless external interference. When a distributed AP becomes faulty, the transmit power of the gateway and AP is increased to improve coverage. The more data traffic there is, the larger the transmit power and the greater the external interference. Therefore, given that the performance requirements are met, the transmit power can be reduced when the traffic volume and the bit error rate are low. When the traffic volume or bit error rate is increased, control the power packet by packet by increasing the transmit power of the gateway or AP. The gateway and AP check the signal strength of each terminal in real time. If the signal strength of a terminal is greater than the target value (close distance to the AP), data packets are sent to the terminal to automatically reduce the actual transmit power. If the signal strength of a terminal is lower than the target value (long distance from the AP), the transmit power is increased during packet sending.

- VR-preferred Wi-Fi scheduling

The distributed coordination function (DCF) specified in IEEE 802.11 is based on the CSMA/CA principle, allowing all terminals to obtain channels with equal opportunities. IEEE 802.11e added the QoS feature for the 802.11 protocol-based WLAN system and defined the Wi-Fi multimedia (WMM) standard.

» WMM defines VO (Voice), VI (Video), BE (Best effort), and BK (Background) priority queues to ensure that high-priority packets are sent and use wireless channels in priority.

» WMM defines the enhanced distributed channel access (EDCA) mechanism so that high-priority packets are sent in priority and have higher bandwidth. EDCA parameters include the following:

- Arbitration Inter-Frame Spacing Number (AIFSN). In the 802.11 protocol, DIFS is a fixed value. WMM allows configuration of different DIFS values for different ACs. The larger the DIFS value, the longer the waiting time for the user. A shorter waiting time brings more opportunities to obtain channels.
- Exponent form of minimum contention window (ECWmin) and exponent form of maximum contention window (ECWmax) determine the average backoff time. The larger the ECWmin and ECWmax values, the longer the average backoff time.
- Transmission opportunity (TXOP). This parameter indicates the maximum time for occupying a channel after a successful competition. A larger TXOP value indicates the longer duration for a user to occupy a channel.

» The air interfaces of VR video services can be used in priority by configuring a higher priority, smaller AIFSN, ECWmin, and ECWmax, and a larger TXOP on the video head-end. For carrier-operated video services, enter a correct priority into the IP header during head-end video packet encapsulation to ensure that packets can be mapped to the VO or VI queue. For non-carrier-operated OTT services, use ACL rules to remark packet priorities to ensure that VR services can be mapped to the VO and VI queue.

- Distributed Wi-Fi coverage

The distributed Wi-Fi network solution is recommended for home networks to resolve signal attenuation and achieve seamless Wi-Fi coverage. The deployment and design principles for the distributed Wi-Fi coverage of home networks are as follows:

» Gateway deployment location. Determine the ONT deployment location based on the position of the broadband access line. If fibers are extended to the living room, placing the smart ONT in the living room is recommended. If fibers extend to the information box instead of the living room, the ONT can only be placed in the information box. Network cables can be used to extend fibers to the upstream gateway of LAN in the living room.

» Whether to use distributed APs. Determine whether to use distributed APs and the specific number of APs according to the house size and the number of rooms. Using the Ethernet link as the backhaul link between the distributed AP and gateway is preferred. The priority goes to the G.hn power line and then 5 GHz relay. Do not use 2.4 GHz Wi-Fi as a relay.

NOTE

As for the current power line transmission standards Homeplug AV2 and G.hn, MIMO allows the physical transmission rate to reach over 1 Gbps, which can meet the bandwidth requirements for early and entry-level VR. Because power line signals are prone to interference by other electric equipment, instability situations, such as signal fluctuation, may occur during peak hours. Selecting G.hn-based power AP with better interference immunity is recommended. G.hn uses the FFT-OFDM modulation (OFDM based on the fast Fourier transformation) and QC-LDPC FEC-based PHY to ensure excellent interference immunity. The efficient 4096QAM modulation mode is used to ensure high-speed network traffic.

» Deployment position of distributed APs. Determine the position of distributed APs based on the room structure, indoor obstacles, and electric equipment interference. Place the distributed AP in the middle of the coverage area with a wide view. A higher position ensures better coverage. Take into consideration any blocking of Wi-Fi signals by the bearing wall, floor, and reflective glass. Place the distributed AP far away from microwave ovens, wireless mouse devices, and cordless telephones. The common service points are the focus for coverage. Determine in advance whether the signal strength is enough for common surfing service points, such as the sofa in the living room, study, writing desk, and bed in the main bedroom. If the signal strength is not powerful enough, adjust the gateway or AP position or add a distributed AP.

Summary of VR Service Requirements on Home Wi-Fi Networks

» Use the 802.11ac standard over the fifth generation of Wi-Fi to carry VR services.

» Guarantee the Wi-Fi performance by choosing non-overlapping channels and ensuring no obstruction between VR devices and APs.

» Guarantee VR services by optimizing the VR service priority and the WMM parameters of Wi-Fi.

» Use the distributed Wi-Fi solution to improve seamless signal coverage of the home network.

4.1.3 Access Network Design

The access network is the closest to terminals and functions to aggregate terminals. There are three main access technologies: FTTH access, FTTB/C access, and coaxial access.

Suggestions on FTTH Planning

The mainstream FTTH modes are GPON and EPON. This section describes the suggestions on bandwidth requirements for VR services at various stages.

Planning of Split Ratio and OLT Uplink Bandwidth

Table 4-2 Suggestions on the split ratio of FTTH

PON	Capacity	Split Ratio	Short- and Mid-Term	Long-Term
			50 to 100M	200 to 1,000M
EPON	1G	1:32	Basically fulfilled	Not fulfilled
		1:64	Not fulfilled	Not fulfilled
GPON	2.5G	1:32	Fulfilled	Not fulfilled
		1:64	Basically fulfilled	Not fulfilled

NOTE
These calculations take 50% convergence into consideration (corresponding to the actual provisioning rate and user online rate of the PON interface).

Table 4-3 OLT uplink bandwidth planning

User Bandwidth	Number of Concurrent Users	Convergence Ratio	Upstream Bandwidth
100M	500	1:4	12.5G
100M	1000	1:4	25G
100M	2000	1:4	50G
100M	7168	1:6	120G
100M	8000	1:6	133G

- EPON access network design

Given that the downstream bandwidth of a single interface is 1G and the convergence ratio is 50%, the split ratio of 1:32 can meet the bandwidth package of 50 to 100 Mbps in the short- and mid-terms. As the actual bearer efficiency of EPON lines is less than 1G and there is large traffic burst of gigabit users, using EPON to develop gigabit users is not recommended. Assume that the OLT has 16 service slots, configuring 14 service boards is recommended, with two boards reserved for upstream interface expansion. A total of 7168 (14 x 16 x 32 = 7168) EPON users are supported. According to the long-term planning of carrying 7168 users, the uplink must support 120G. It is recommended to deploy 2 x 10G uplink for 500 users at the preliminary stage and monitor the upstream traffic to determine whether to perform expansion.

- GPON access network design

For GPON-based FTTH, the 2.5 Gbps downstream bandwidth of a single interface is used for calculation. The 1:64 split ratio is recommended, which can meet the bandwidth requirements (50 to 100 Mbps) for short- and mid-term user development but not the bandwidth requirements (200 to 1000 Mbps) for long-term user development. Assume that the GPON OLT has 16 slots, you are advised to configure a service board with 14 slots, with two service slots reserved for upstream interface board expansion. A maximum of 14336 (14 x 16 x 64 = 14336) GPON users are provided. However, due to network device security requirements in many countries and regions, the remote disaster recovery design is required if the number of users exceeds the upper limit. For example, if there are over 10,000 users, deploying these users on two devices in different positions is recommended. Traditionally, the voice service has mandatory requirements for disaster recovery design. It is recommended to deploy less than 8000 users in a single OLT chassis. According to the long-term planning of carrying 8000 users, the OLT uplink must support 133G. It is recommended to deploy 2 x 10G in the upstream direction for 500 users and monitor the upstream traffic to determine whether to perform expansion.

- Suggestions for OLT architecture

For FTTH evolution, the selection of the device architecture is as important as the planning of the bandwidth, capacity, and split ratio. In the traditional centralized OLT architecture, data is forwarded through the switching chip. In the big video era, the switching chip has become the bottleneck of the system performance. OLT evolution towards the distributed architecture is recommended, as follows:

» On the distributed OLT, each service board has its own forwarding engine that can independently complete routing table lookup and packet forwarding, which greatly improves the system switching capacity and performance and supports non-blocking forwarding of 160G bandwidth packets on 10G PON boards.

» The distributed boards with large cache are used to anticipate the high-burst traffic brought by video services and gigabit users.

To cope with the popularization of VR services and ever-increasing user package acceleration, EPON and GPON need to evolve to 10G. During the evolution, keep the ODN unchanged and do not deploy the 1:128 split ratio. This is because the 1:128 split ratio has high requirements for ODN quality and requires huge engineering workload in ODN split acceleration. Once a rogue ONT exists on the PON line, the 1:128 split ratio has great impact on the user scale. In view of compatibility, you are advised to evolve EPON to 10G EPON and evolve GPON to 10G GPON.

- EPON evolving to 10G EPON

The upstream wavelengths of EPON and 10G EPON overlap and can share the same ODN through time division multiplexing. The downstream wavelengths of EPON and 10G EPON do not overlap and they receive the corresponding wavelengths based on the wavelength scope. Therefore, the ODN remains unchanged during EPON evolution to 10G EPON, and the 10G EPON board needs to be added so that EPON users can be smoothly migrated to 10G EPON and the OTN of the EPON can be reused. Replace the ONT of the EPON with that of the 10G EPON as required.

There are two types of 10G EPONs: symmetric and asymmetric. The asymmetric 10 EPON provides 1.25G for the uplink and 10G for the downlink. The symmetric 10G EPON provides 10G for the uplink and 10G for the downlink. Because the upstream rates vary between EPON and 10G EPON, the upstream bandwidth planning is complex when EPON and 10G EPON users co-exist. This is shown in Figure 4-2 and Figure 4-3.

Figure 4-2 EPON/10G EPON wavelength range

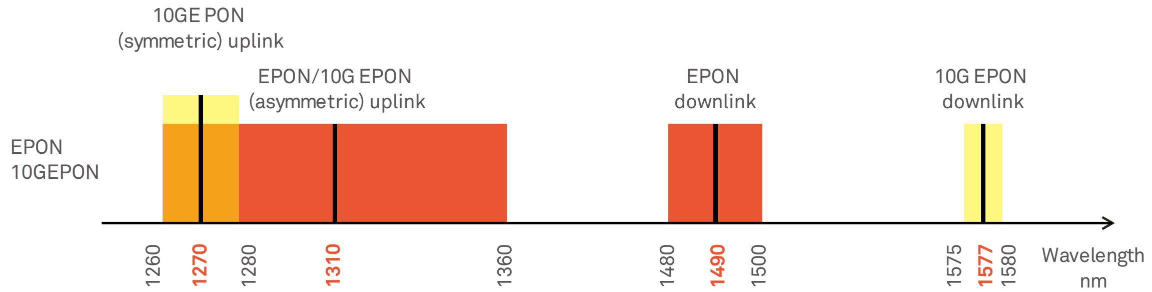
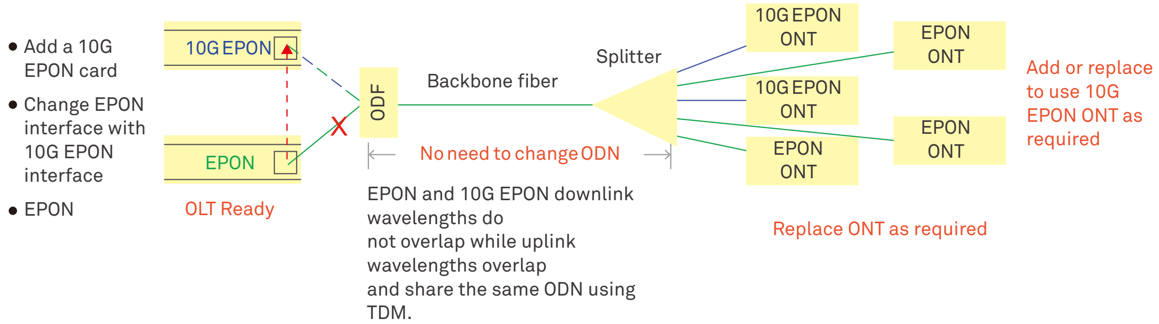


Figure 4-3 Deployment suggestions on EPON evolving to 10G EPON



- GPON evolution to 10G GPON

The upstream wavelengths of GPON and 10G GPON overlap and can share the same ODN through time division multiplexing (TDM). The downstream wavelengths of GPON and 10G GPON do not overlap and they receive the corresponding wavelengths based on the wavelength scope. GPON and 10G GPON are independent of each other and therefore are easy to plan and manage. In case of GPON evolution to 10G GPON, the WDM1r multiplexer is needed. The ONT of the GPON can still be used and can be replaced with the ONT of 10G GPON as required. Because the deployment of the WDM1r multiplexer introduces extra attenuation, it is recommended to reserve 2 to 3 dBm optical budget for newly deployed GPON. If the optical budget is insufficient, upgrade the optical module for the deployed PON interfaces on the live network. 10G PON is divided into asymmetric 10GPON (XG-GPON) and symmetric 10G PON (XGS-GPON). The asymmetric 10G PON provides 2.5G uplink and 10G downlink. The symmetric 10G PON provides 10G uplink and 10G downlink. This is shown in Figures 4-4 and 4-5.

Figure 4-4 GPON/10G GPON wavelength range

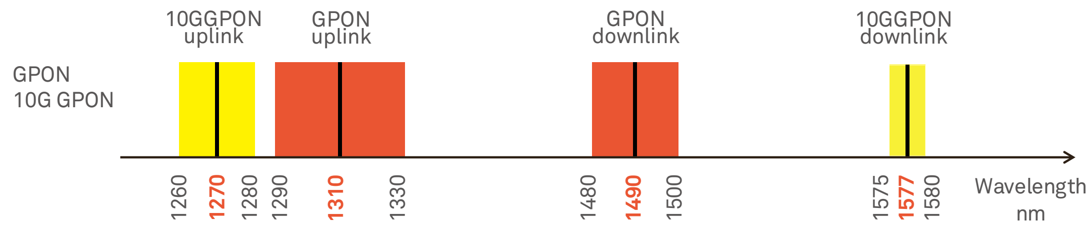
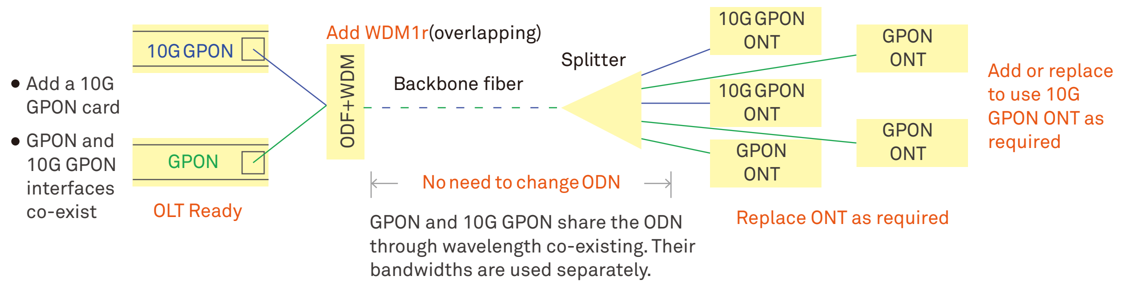


Figure 4-5 GPON evolving to 10G GPON



Summary of VR Service Requirements for the FTTH Access Network

- EPON

The split ratio does not exceed 1:32. Developing gigabit users is not recommended. Configure 2 x 10GE for the uplink at the preliminary stage and perform expansion as required.

- GPON

The split ratio can be set to 1:64. Developing a few gigabit users is recommended. Configure 2 x 10GE for the uplink at the preliminary stage and perform expansion as required.

- 10GPON

The split ratio can be set to 1: 64 to meet the user access requirement of 200 to 1000 Mbps.

- OLT

It is recommended to use the distributed OLT with the service boards featuring high-capacity, non-blocking, and large cache.

Suggestions on Copper Access Design

The indicators that may affect VR services include the bandwidth, packet loss rate, and delay. These indicators are closely related to the copper distance, copper technology, and noise interference.

» The typical network KPIs for various copper access technologies are as follows:

- ADSL2+ provides up to 24 Mbps access bandwidth. Due to the limitations of line length and noise interference, the actual bandwidth is generally less than 10 Mbps, which cannot meet the bandwidth requirement of 4K and VR services.
- VDSL2 supports 100 Mbps download bandwidth. The vectoring technology uses far-end crosstalk (FEXT) cancellation to improve the line rate. The 0.5 mm copper wire in an access distance of 300 m can provide up to 120 Mbps access bandwidth. Over typical access distances of 500 m, it can still provide access bandwidths of 100 Mbps.
- SuperVector extends the working frequency band from 17 MHz to 35 MHz. With vectoring FEXT cancellation used, SuperVector can provide 300 Mbps for a distance of 300 m and 100 Mbps for a distance of 700 m. SuperVector is recommended for distances of 300 to 700 m.
- G.fast brings copper wires into the gigabit era. G.fast provides 400 Mbps for a distance of 300 m. G.fast is recommended for distances of 0 to 300 m.

Table 4-4 Typical network KPIs for copper access

Copper Access Technology	Bandwidth (DS)	RTT (ms)	PLR
VDSL2	50M @ < 1000 m	10 to 20	10-4 to 10-5
Vectoring	50M to 120M @ < 800 m	10 to 20	10-4 to 10-5
Super Vector	100M to 300M @ 300 to 500 m	10 to 20	10-4 to 10-5
G.fast	1.2M to 200MG @ 100 to 500 m	2 to 6	10-4 to 10-5

» Deployment suggestions on ultra-broadband copper access are as follows:

- The delay on copper wires is mainly introduced by interleaving. The higher the degree of interleave depth, the stronger the anti-interference capability of a line, the lower the packet loss rate, and the larger the delay. The longer the line, the greater the interference introduced by lines. Moving the site downstream to upgrade the traditional ADSL2+/VDSL2 to Vectoring/SuperVector/G.fast is recommended to increase the access bandwidth. Shorten the copper cable distance to reduce the noise during transmission, thereby decreasing the degree of interleave and RTT. At the same time, enable link retransmission to improve the tolerance of packet loss.
- Typical delays for ultra-broadband copper line deployment are as follows: RTT of 10 ms to 20 ms for VDSL2/Vectoring; RTT of 10 ms to 20 ms for SuperVector, delay of 2 ms to 6 ms for G.fast. In the lab environment, the packet loss rate can reach 10-5 to 10-7. Under the live-network condition, the E2E packet loss rate ranges from 10-3 to 10-5. Enabling line retransmission is recommended to reduce the packet loss rate.
- Move the FTTC/B sites downstream to rapidly implement 100+ Mbps bandwidth access. Move the sites downstream so that broadband services in the CO equipment room can be moved downwards to the street cabinet or corridor. Use fiber uplink to the metro network to greatly reduce the CO equipment room space and OPEX. Reuse copper access resources and shorten the copper distance. Use Vectoring and G.fast technologies to provide high-speed data access.
- Because the copper wire performance is affected by factors such as distance and crosstalk, install the line diagnosis system on the copper network. Perform line performance evaluation before service provisioning to determine the rate of service provisioning and then package to be used.

Summary of VR Service Requirements for the Copper Access Network

» Install the copper line diagnosis system. Perform line performance evaluation before service provisioning to determine the rate of service provisioning and the package to be used.

» Use the Vectoring, SuperVector, and G.fast technologies, with the copper wire distance meeting at least 50 Mbps bandwidth.

» Enable line retransmission and reduce the interleave depth to reduce the delay to 8 ms to 12 ms.

» When the copper bandwidth is insufficient, move FTTC/FTTB sites downstream.

Suggestions on Coaxial Access Design

In traditional broadcast modes, regardless of whether users are viewing a video, all the programs are broadcast to the user, which uses a lot of spectrum resources. This mode is crucial when SD or a few HD channels are used. However, the broadcast mode renders the existing spectrum resources insufficient when it comes to high-bit-rate videos like 4K and VR. As IP-based video services gradually take a dominant position, the traditional TV service in broadcast mode is in face of huge challenges, and IP-based new services like air shift are not supported. Therefore, building a high-bandwidth converged IP network has become an inevitable trend. The reference for coaxial access design in this climate is as follows:

» Distributed D-CCAP design based on DOCSIS 3.0. DOCSIS 3.0 provides up to 32 channels and 1.6 Gbps downstream bandwidth. Give the 50 Mbps bandwidth for each program and the 50% deployment rate, connecting each distributed D-CCAP to up to 66 users is recommended. So far, most of the cable carriers use DOCSIS 3.0 to implement the Internet service. The TV programs are still transmitted in broadcast mode. As a large number of DOCSIS 3.0 spectrum resources are still reserved for broadcast videos, provisioning many 4K/VR videos on the DOCSIS 3.0 network is not recommended. This move can be considered only when a few programs are available.

» Distributed D-CCAP design based on DOCSIS 3.1. DOCSIS 3.1 currently provides a downstream bandwidth of 4 Gbps. When future spectrum resources are released, an upstream bandwidth of 10 Gbps can be supported, which is suitable for IPTV and 4K videos. Give the 50 Mbps bandwidth for each program and the 50% deployment rate, each D-CCAP can be connected to 164 to 410 users. This is also suitable for the number of users currently connected to remote optical modes.

The application of G.fast to coaxial cables is under discussion. Therefore, all spectrum resources will be used for bandwidth expansion in the future, regardless of copper wires or coaxial cables. The traditional broadcast videos will be phased out and replaced with IP-based multicast and VOD services.

Summary of VR Service Requirements for the Coaxial Access Network

» Do not deploy a large number of 4K or VR services on the DOCSIS3.0 network.

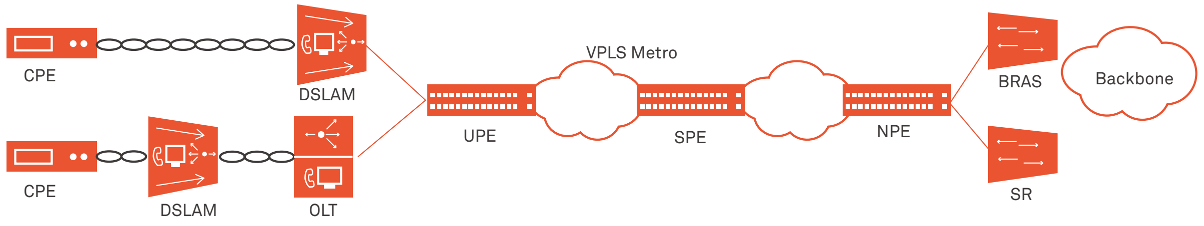
» Implement distributed D-CCAP design based on DOCSIS 3.1. Allow each D-CCAP to be connected to 164 to 410 4K or VR users.

4.1.4 Metro Network Design

Low-Convergence, Flattened Network Design for the VR Bearer Network

As of late 2017, many networks have not yet evolved to the 4K-ready network architecture, and the FTTx + VPLS + BRAS network architecture is still commonly used. This network architecture began to be used in the PC era and is characterized by low bandwidth, high convergence, and low perception. This network architecture, shown in Figure 4-6, is suitable for low-bandwidth and low-concurrency services such as web browsing and voice services and cannot undertake the bearing of 4K video and VR services.

Figure 4-6 The FTTx + VPLS + BRAS network architecture



First, the traditional multi-level aggregation network hinders the fast flow of high-speed video streams. Each level of the aggregation network is equivalent to a traffic light. Delay or packet loss may occur during queuing in the event of network congestion. When the high-convergence multi-level aggregation network carries video services, video traffic needs to pass through multiple traffic lights, which increases the probability of packet loss and large delays.

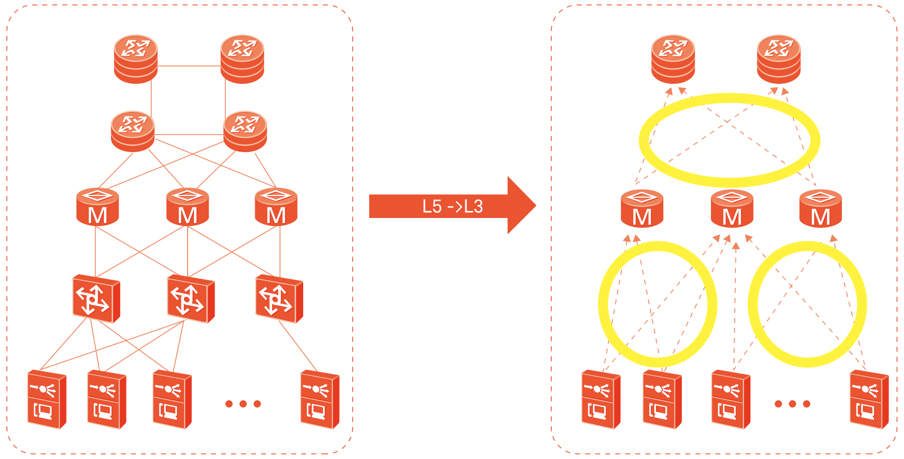
Additionally, the high concurrency and low convergence characteristics of video services cause each expansion to involve multiple aggregation nodes, which increases network costs. Taking the 10GE ring with five nodes as an example, if 5G traffic (non-convergence space) is added to the video traffic at a site, a 10GE interface must be expanded for each node in the ring.

Second, the traditional way of deploying BRASs at a high position prohibits the CDN from moving downstream to the metro network. The BRAS is the first hop of the home gateway, and video traffic reaches the CDN over the BRAS. This deployment causes video traffic to reach the CDN over a long path, which increases network costs. Also, the cloud rendering of VR games has high requirements for network delay. To ensure service experience, the cloud rendering server must be deployed on the network edge closest to the user. Deploying BRASs at a high position hinders the cloud rendering server from being deployed at the network edge.

The target VR bearer network should adopt low-convergence and flattened network design. The main technical measures are as follows:

» Reduce the network convergence layers from 5 to 3 to decrease the congestion probability and expansion cost.

Figure 4-7 Reduction of network and convergence layers



» Move the BNG to the edge to support the free deployment of CDN and cloud computing. The position of CDN deployment determines the traffic direction, delay, and packet loss of video streams, which affects the construction costs of video services. After the BNG is moved downstream, the CDN server can be moved downstream also. Sparing bandwidth by storage is a common move in the industry. When the CDN is moved downstream, the CDN costs will increase due to the reduction of the device usage of the streaming server, new storage server construction, and server mapping. At the same time, the numbers of forwarding hops and network devices are reduced, which lowers the network expansion costs. Therefore, in actual deployment, the optimal cost can be achieved only with CDN and network deployment taken into account. VR cloud gaming presents high requirements for delay, requiring the cloud rendering server to be close to users. The cloud computing is moved downstream along with the BNG, which supports the development of the cloud gaming service. In addition, BNG to edge reduces VPLS segmentation and simplifies O&M, which brings additional OPEX.

» OTN to CO. The traditional multi-level aggregation network does not require much fiber deployment. As the IP network becomes delayed, IP ring-to-tree reconstruction brings excessive demands for fibers. The fiber deployment and connection adjustment period is long, and cannot support the demand of rapid bandwidth provisioning for 4K/VR video services. The OTN to CO deployment can quickly resolve excessive fiber requirements. With WDM multiplexing used on the OTN, a pair of fibers can transmit up to 80 wavelength channels, providing ultra-large single-fiber bandwidth, optimal distance, no traffic convergence, and fast bandwidth on demand (BOD).

Evaluation on Metro Network Device Capabilities

With the development of 4K and VR services and the ever-increasing user base, the metro network traffic will increase by 10-fold, 100-fold, or even 1000-fold. Table 4-5 provides an assessment of the traffic model of a streamlined metro network.

Table 4-5 Traffic model evaluation

Device Model	OLT	BNG	CR
Upstream and downstream convergence ratio	1:2	1:2	1:2
User scale on the device	4000 users connected to each OLT	20 OLTs connected to each BNG	10 BNGs connected to each CR

Table 4-6 VR Development Stages

VR Development Stage		Pre-VR (4K VR)	Entry-level VR (8K VR)
User bandwidth requirement (Mbps)		100	200
Penetration rate		15%	15%
Concurrency rate		10%	10%
Bandwidth requirement	OLT downlink (Gbps)	6	12
	OLT uplink (Gbps)	3	6
	BNG downlink (Gbps)	60	120
	BNG uplink (Gbps)	30	60
	CR downlink (Gbps)	150	300
	CR uplink (Gbps)	75	150
	OLT (Gbps)	9	18
	BNG (Gbps)	90	180
	CR (Gbps)	225	450

NOTE

OLT downlink bandwidth = User bandwidth x Number of users on each OLT x Penetration rate x Concurrency rate

OLT uplink bandwidth requirement = OLT downlink traffic x Convergence ratio

BNG downlink bandwidth requirement = Number of OLTs connected to the BNG x OLT uplink bandwidth

BNG uplink bandwidth requirement = BNG downstream traffic x Convergence ratio

CR downlink bandwidth requirement = Number of BNGs connected to the CR x BNG uplink bandwidth

CR uplink bandwidth requirement = CR downlink traffic x Convergence ratio

Device bandwidth requirement = Upstream link bandwidth requirement + downstream link bandwidth requirement

Summary of Metro Network Design

- Streamlined network design

By moving the BNG to the metro edge or core, the metro network is reduced from multiple layers to only one layer, which simplifies network planning, service provisioning, and service management and reduces the number of network devices.

- Rapid service provisioning and simplified O&M

With BNG moving downstream, the routing design and VLAN design are simplified, and the complex VPLS design is not needed, which accelerates service deployment.

- Moving the BNG downstream to support the moving of CDN/cloud computing downstream

With CDN deployment and network construction costs taken into account, this move delivers the minimum CAPEX and supports the development of cloud gaming.

- OTN to CO

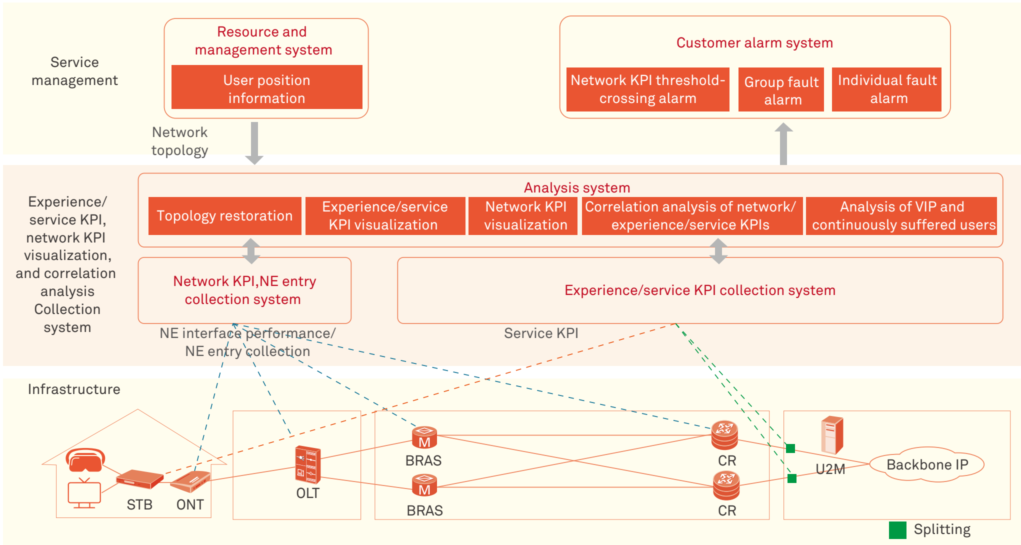
This provides the basic interconnection channels with ultra-large single-fiber bandwidth, optimal distance, no traffic convergence, and fast BOD.

4.1.5 VR Bearer Experience Guarantee

VR is a type of high-perception service, and therefore user experience guarantee is of vital importance. A lot of users choose to unsubscribe from services or to de-register from networks when they have poor experience, instead of submitting complaints to carriers. Carriers need an active experience guarantee to prevent subscriber churn.

To implement cost-effective precise fault demarcation and locating, the video experience of each user needs to be perceived and mapped to the network for analysis. Figure 4-8 shows the elements of ensuring VR video experience.

Figure 4-8 he elements of ensuring VR video experience



The elements in Figure 4-8 are as follows:

» Infrastructure layer

Allows network device to be managed and provides device KPIs.

» Information collection system

Collects KPIs of numerous netwaork devices and user services. Video service KPI detection can be performed using probes or directly on terminals. An objective forecast algorithm (such as U-vMOS) is used to evaluate users' video experience. The KPIs of network devices are obtained by collecting interface data.

NOTE

In contrast with common video viewing, VR viewing has more dimensions of perception. The current service KPI detection can reflect the VR images but not users' head movement interaction experience. For details about the evolution of VR QoE evaluation, see section 4.2.4.

» Analysis system

Supports real-time quality reports and network KPI ranking, service KPI and network KPI correlation, and analysis on VIP and continuously suffered users. The performance indicators of network devices can be separately scanned to discover performance issues. This, however, cannot determine whether the video quality is affected. The performance indicators must be associated with network KPIs to discover the specific network devices or KPIs that affect the video quality.

» Customer system

The experience guarantee system is interconnected with the customer resource management system to obtain the subscriber's home area and provide the video service quality summary of the area. The system can also be interconnected with the customer alarm system to deliver work orders about the discovered faults to the O&M department.

4.1.6 VR Broadcasting Bearer Optimization

Due to shooting limitations, VR is more suitable for broadcasting scenarios. In recent years, online broadcasting has become an important service in the Internet industry and is still developing at high speed. Currently, more and more sports events, concerts, and reality shows support VR broadcasting. The playback time of the broadcasting service is closely related to the time when a hotspot event occurs. Traffic bursts have an obvious tidal effect. Currently, OTT broadcasting services are typically carried in TCP unicast mode. The load of the video server and the consumption of network traffic increase along with the number of users viewing. If OTT vendors construct the CDN server based on the views at peak hours, the cost is huge and the resource usage is low due to the tidal effect of traffic. If the CDN server is not constructed based on the views at peak hours and the video bit rate is reduced to relieve the bandwidth pressure, user churn exists due to deteriorating user experience. The VR broadcasting service addresses the tidal effect issue by reducing the bit rate. This causes poor user experience. The VR broadcasting service still needs to be improved.

MOD Solution Overview

For broadcasting services, in order to maximize business benefits, OTT vendors are concerned about how to control costs without affecting experience. Carriers are concerned about how to implement low-cost bandwidth operations for OTT streaming and participate in the business value chain of OTT streaming. In this climate, the multicast on demand (MOD) solution is introduced based on the pain points of OTT vendors and carriers. The MOD solution uses multicast to carry OTT streaming services by opening carriers' multicast capabilities to OTT vendors. After the unicast bearer mode is changed to the multicast bearer mode, the network traffic and CDN server load do not increase with the number of users viewing OTT streaming. Regardless of the actual number of users, the CDN server load and network traffic always correspond to one unicast user. This solution resolves the traffic burst issue caused by the tidal effect of the OTT streaming services, while avoiding the experience deterioration issue caused by too many viewing users. In addition, carriers can implement prioritized guarantee for multicast traffic to improve the viewing experience of users.

The MOD solution is easy to deploy and requires few `network reconstruction. It only requires the video server to perform unicast-to-multicast modification on OTT streaming on the ONT on the home network. For the intermediate network, the multicast capability needs to be enabled and traffic can be controlled based on the multicast validity. For unicast-to-multicast on the video server, carriers can provide the transcoding server, or OTT is used to distribute traffic to the multicast root node of carriers over VPN tunnels. Because most smartphones do not support multicast, the third-party routing device purchased by users does not support multicast. In this case, the ONT is used to change multicast back to unicast. In addition, the solution requires OTT vendors to perform simple reconstruction on the streaming to support joining and leaving of multicast. The way of reconstruction can be integrating the existing SDK or based on the interface document.

The MOD solution has the following advantages:

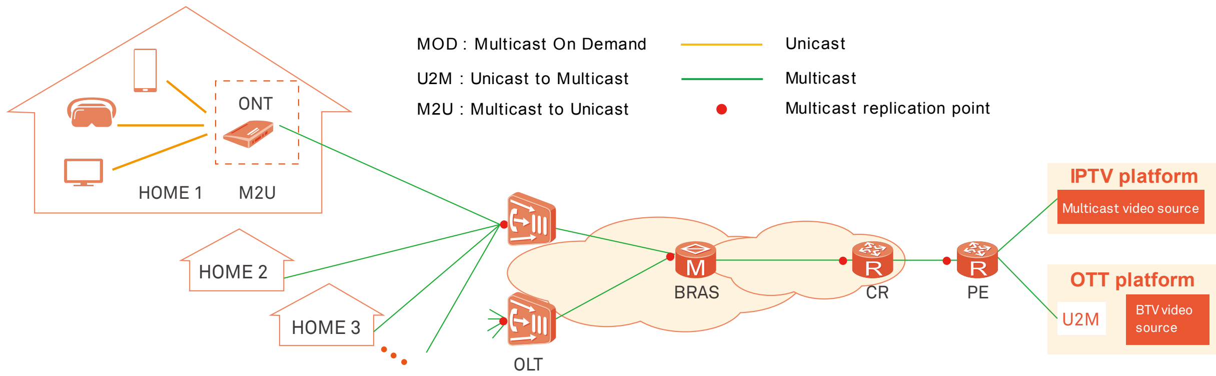
» It greatly reduces the video server load and the traffic cost of the OTT streaming platforms. The Internet traffic, backbone network traffic, and metro network traffic are reduced. In traditional ways, millions of copies of traffic are consumed when millions of users are watching live programs. In multicast mode, only one copy of traffic is used.

» Carriers' inter-network settlement costs are saved, making the carrier network healthier. This solution avoids the tidal effect and prevents traffic bursts during peak hours. In unicast mode, network imbalance often occurs due to CDN, and the investment in maintaining the carrier network is huge. The MOD solution reduces backbone and metro network traffic, making the network more smooth and healthy.

» This solution adds new profitability methods for carriers. Currently, most of the revenues of the streaming field are obtained by CDN vendors. The MOD solution provides the cost-effective streaming optimization, which reduces the CDN costs for streaming enterprises while obtaining gains for carriers.

» The MOD solution combines the advantages of IPTV streaming and OTT streaming. It can be used for OTT streaming to reduce the CDN and bandwidth costs and improve user experience. It can also be used for IPTV streaming so that terminals (such as smartphones and tablets) that do not support multicast can view streaming.

Figure 4-9 MOD solution



4.2 Network Evolution for Advanced VR and Ultimate VR

With the improvement of the screen resolution and chip performance of VR HMDs as well as of VR content quality, VR videos are gradually evolving towards the advanced level (full-view 12K) and ultimate level (full-view 24K). At the advanced VR stage, the improving VR image experience brings higher requirements for network bandwidth (200 Mbps to 1 Gbps), requiring more than 1 Gbps access bandwidth. The ultimate VR brings the single-eye image to the retina level. For the full-view transmission that has high bandwidth requirements (2 Gbps to 5 Gbps), the FOV transmission solution is required to reduce the bandwidth requirements. In the full-view transmission solution, the 20 ms delay of VR interaction experience does not involve network delay and cloud + device delay. In the FOV solution, the network delay is included in the 20 ms delay of VR interaction experience. This means that the FOV transmission solution has high requirements for delay. Therefore, the future network must evolve towards higher bandwidth and lower delay in response to the advanced VR and ultimate VR.

Traditional bearer network construction seldom takes into account service experience requirements. Generally, network planning or expansion is performed upon threshold-crossing of bandwidth usage. VR has high requirements for bandwidth and is delay sensitive. To meet the requirements for VR, the bearer network construction and evolution must follow the following principles:

» Service experience can be guaranteed based on each service interaction, such as the head movements that switch angles.

» Network capabilities are based on the delay requirement for each interaction. For example, angle switching in the VR immersive experience requires the delay within 10 milliseconds.

» The network bandwidth of the bearer network must be planned based on service delay requirements. For example, the bearer network must meet the high-traffic transmission of VR within 10 milliseconds.

4.2.1 Bearer Technology Evolution for Higher and Broader Bandwidth

High-bandwidth Wi-Fi Technology

To meet the Gbps bandwidth requirements for future VR services, the home Wi-Fi network must support 802.11ax, the next-generation Wi-Fi standard. The 802.11ax standard achieves up to 10 Gbps air interface rate and has more powerful anti-interference capability to guarantee performance indicators, such as the packet loss rate, delay, and bandwidth stability. The following performance indicators will be needed:

- More powerful anti-interference

802.11ax introduces the orthogonal frequency division multiple access (OFDMA) technology that is used in 4G LTE cell base stations, allowing users to use only a subset in subcarrier within a specified period, thereby improving the bandwidth utilization of the same channel. With the use of a new spatial multiplexing technology, the 802.11ax standard can efficiently identify air interface conflicts and perform backoff. The 802.11ax standard combines a lot of methods such as dynamic idle channel evaluation and dynamic power control to improve the identification of interference signals and noise reduction performance.

- Higher transmission rates

802.11ax introduces 1024 QAM. Compared with 802.11ac that provides up to 256 QAM, 802.11ax improves the maximum physical rate of each 80M frequency bandwidth spatial stream from 433 Mbps to 600.4 Mbps. The theoretical maximum physical rate (160M frequency bandwidth, 8 spatial streams) is increased from 6.9 Gbps to around 9.6 Gbps, an increase of approximately 40%.

- Longer transmission range

802.11ax provides four times of subcarriers, 1/4 of subcarrier interval, and four times of symbol time compared with 802.11ac. This is beneficial to channel evaluation and balance. Especially in anti-multipath fading, and outdoor scenarios, 802.11ax provides better robustness and performance and thereby covers a larger range.

- More powerful concurrency

802.11ac defines only downstream MU-MIMO, and a single node independently transmits data in the upstream direction. 802.11ax supports upstream MU-MIMO. With the upstream/downstream MU-MIMO and OFDMA technologies, 802.11ax supports concurrent transmission for multiple users using multi-spatial-flow and multi-subcarrier, increasing the air interface efficiency, reducing application delay and user backoff against conflicts. This provides a better transmission efficiency for multi-user scenarios.

Currently, IEEE 802.11 is considering the 60 GHz-based next-generation Wi-Fi standard 802.11ay. The 802.11ay standard uses technologies such as channel bonding and MU-MIMO to provide 20 to 40 Gbps bandwidth, aiming to achieve uncompressed video frame data transmission. The 802.11ay technology can be used for wireless VR HMDs. It uses wireless transmission technologies to perform seamless video transmission to address user experience issues caused by the connections between the HMD and host.

Ultra-Broadband Access Technology

- FTTH access technology evolution

The PON standard is continuously developing with both single-wavelength acceleration and multi-wavelength stacking used. The single-wavelength 25G has become a hotspot for standards and technology research. The single-wavelength 25G PON uses fixed wavelengths, which are easy to implement. In addition, the industry chain of single-wavelength 25G PON components is mature. These components share the industry chain with the data center and Ethernet, thereby reducing the optical component costs and improving reliability. IEEE 802.3 has started to speculate the 25G/100G PON standard, and ITU-T also has set out the technology research on the next-generation PON requirements for the 10G+ rate. In addition, both device vendors and optical module vendors are actively following the related technology research and standard formulation.

- Copper access technology evolution

The DSL technology that is being deployed is G.fast. By extending to the 106 MHz or 212 MHz spectrum, G.fast uses technologies such as STDD-OFDM and E-Vectoring to provide 1 to 2 Gbps upstream or downstream rate bandwidth for P2P, with a delay of around 2 ms. ITU-T has launched the standard research on the next-generation G.mgfast at 5 to 10 Gbps in Q4. The next-generation G.mgfast aims to provide a higher bandwidth and lower delay, with the bandwidth increased by 5-fold to 10-fold. Carriers are actively responding to the standard formulation.

- Coaxial access technology evolution

The cable technology that is being deployed is DOCSIS 3.1. DOCSIS 3.1 provides the downstream bandwidth of 10 Gbps, upstream bandwidth of 1.5 Gbps, and maximum delay of 10 ms based on the 1.2 GHz spectrum. DOCSIS 3.1 supports over 128 channels of 4K and 8K video services. The future cable technology uses spreading or full-duplex FDX to dig out the coaxial bandwidth potential, providing up to 25 Gbps bandwidth and reducing the delay to below 2 ms.

Large-Capacity Metro Network Device

The popularization of video services creates high requirements for processing metro network devices, and metro network devices must be upgraded to a higher capacity. Table 4-7 and Table 4-8 describe the traffic model evaluation for the advanced VR and ultimate VR.

Table 4-7 Traffic model evaluation

Device Model	OLT	BNG	CR
Upstream and downstream convergence ratio	1:2	1:2	1:2
User scale on the device	4000 users connected to each OLT	20 OLTs connected to each BNG	10 BNGs connected to each CR

Table 4-8 VR development stage

VR Development Stage		Advanced VR (12K VR)	Ultimate VR (24K VR)
User bandwidth requirement (Mbps)		1000	5000
Penetration rate		30%	50%
Concurrency rate		20%	40%
Bandwidth requirement	OLT downlink (Gbps)	240	3000
	OLT uplink (Gbps)	120	1500
	BNG downlink (Gbps)	2400	30000
	BNG uplink (Gbps)	1200	15000
	CR downlink (Gbps)	12000	150000
	CR uplink (Gbps)	6000	75000
	OLT (Gbps)	360	4500
	BNG (Gbps)	3600	45000
	CR (Gbps)	7020	225000

NOTE

BNG: At the advanced VR stage, the required BNG processing capability is 3.6T. At the ultimate VR stage, the required BNG processing capability is 45T. To avoid packet loss during network congestion, the link usage is typically below 70%, and the BNG processing capabilities of these two stages are 5T and 64T, respectively.

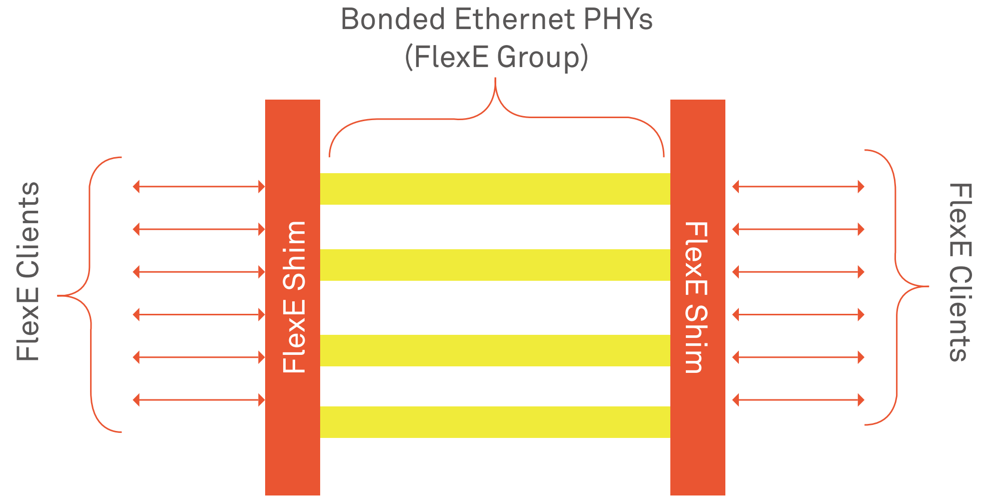
CR: At the advanced VR stage, the required CR processing capability is 7T. At the ultimate VR stage, the required CR processing capability is 225T. Given the link usage of 70%, two CR processing capabilities of these two stages need to reach 10T and 321T, respectively. The CR capacity shown in the preceding table is calculated based on the situation where 10 BNGs are connected to each CR. On the live network, however, there are only two CRs connected to the backbone network for backup and load sharing. In a city with 5 million population under this network model, the CR capacity needs to reach the P bit level at the ultimate VR stage.

4.2.2 Bearer Technology Evolution for Lower Delay

The bandwidth of an IP network is shared by multiple services, and it is difficult to guarantee delay-sensitive services. FlexE is an interface technology used to implement service isolation and network slicing on the bearer network. FlexE is oriented for delay-sensitive services, such as 5G and VR. FlexE supports physical isolation and bundling of large-granularity bandwidth services, allowing service isolation on the same interface and decoupling of the MAC-layer rate and physical-layer rate. FlexE allows network design and expansion in more flexible ways, helping to deliver stable E2E low-delay networks.

In March 2016, the Optical Networking Forum (OIF) officially released the first-generation Flex-ETH standard based on the 100 Gbps rate. Flex-ETH is defined as in the middle of the Ethernet L2 layer and L1 layer to achieve on-demand configuration of the user-side interface rate with services between different interfaces isolated. The current configuration granularity is 5 Gbps. FlexE is oriented for delay-sensitive services, such as 5G and VR. FlexE supports physical isolation and bundling of large-granularity bandwidth services, allowing service isolation on the same interface and decoupling of the MAC-layer rate and physical-layer rate. FlexE allows network design and expansion in more flexible ways, helping to deliver stable E2E low-delay networks.

Figure 4-10 Overall Flex-ETH architecture



Flex-ETH has similar forwarding behavior as OTN, which delivers the bandwidth bundling of physical interfaces or more fine-grained division. The bandwidth of each interface is divided according to the fixed timeslot. Client packets are distributed between interfaces at the adaptation layer Shim. Flex-ETH allows service isolation on the same interface and decoupling of the MAC-layer rate and physical-layer rate, achieving network design and expansion in more flexible ways. The orchestration between Flex-ETH and service provisioning is performed based on the SDN architecture.

4.2.3 Smart and Flexible Cloud+Network Network

VR places higher requirements on bandwidth and delay. If VR content providers provide only the content, carriers provide only common pipes, and data can be forwarded along with other Internet data. If congestion occurs on any nodes, E2E service quality cannot be guaranteed. To solve this problem, the network needs to address the characteristics and transmission requirements of the carried services and provide guarantee for the services as required. The network does not get aware of services. The service owner or user applies for network transmission resources. Due to service diversity and volatile features, perceiving all service characteristics cause network complexity and close coupling with services, which adversely affects service and network development. In response, the pipe provider, that is, the carrier can provide differentiated, customized services to meet the on-demand, dynamic, open, and E2E requirements, described as follows:

- On-demand

Traffic or service objects can be identified based on network requirements (such as the bandwidth, delay, packet loss rate, and jitter), source/destination IP address, 5-tuple, or other service characteristics. However, with the ever-increasing services to be carried, network resources need to be dynamically expanded based on service requirements. When service requirements are not as strict as previously, capacity reduction can be performed for network resources.

- Dynamic

As services have different network requirements and the periods are uncertain, the QoS for network devices is not statically configured in advance. Instead, the QoS is calculated in an E2E manner at the second level upon a session. Resources are allocated and scheduled along network nodes and instantly released when a service is stopped, which improves the resource usage.

- Open

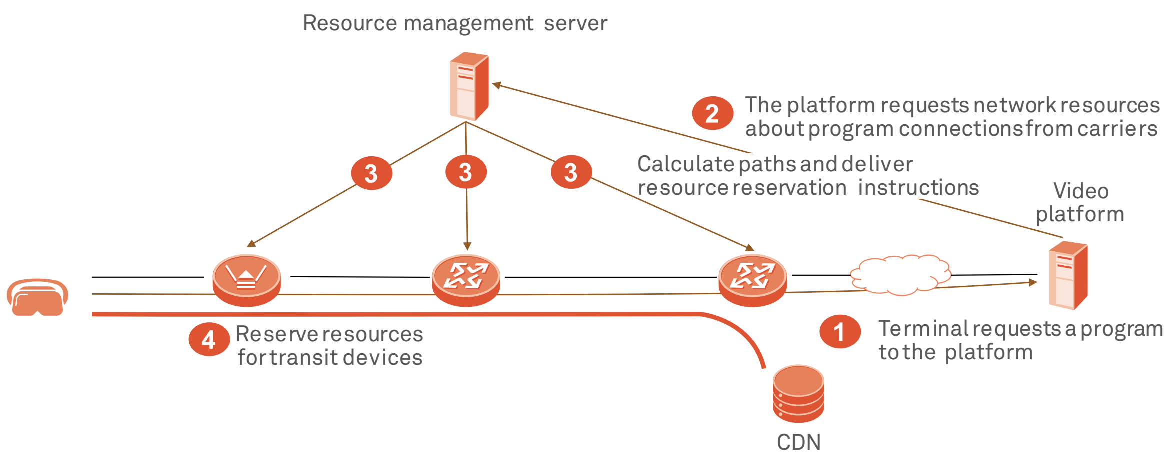
Carriers provide user-friendly, clearly defined, and well-developed interfaces, which can be customized by OTT vendors for guarantee network quality, including service application, adjustment, releasing, accounting, reconciliation, and settlement.

- E2E

Service data flows pass each network node in serial mode. The congestion on any node on the path may affect the entire service. Therefore, E2E management and calculation are required to ensure service quality for each node. A centralized management unit is required to obtain the device status (bandwidth, delay, and jitter) of each network device in real time. When a service request exists, the management unit can calculate the appropriate path based on the device status and delivers resource reservation restrictions to each device, thereby achieving path readiness.

When users use the VR service, the service platform that provides the VR service is the first to obtain this information. The service platform needs to send a request to the network controller and sends the user information to the controller. The controller checks whether users' service requirements are met based on the user information, VR service information (source IP address of the user, IP address of the service platform, and bandwidth and delay requirements) and dynamically requests for E2E hard pipe resources based on the usage of link and forwarding resources. Figure 4-11 depicts a smart and flexible network based on VR.

Figure 4-11 Smart and flexible network based on VR



4.2.4 Technology Evolution for VR Service Experience Guarantee

In contrast with common 4K video viewing, VR is more complex all the way from the creation of video content to the video viewing process. Various types of faults may occur, and it is hard to demarcate video experience deterioration issues. Currently, there is a lack of effective ways to rapidly demarcate and locate experience issues. Therefore, to implement E2E network O&M with fast fault awareness and locating, probes must be deployed at the cloud, pipe, and device sides to monitor service quality in real time. In addition, a well-designed user experience evaluation system will help vendors to optimize their products and help service providers improve the service experience quality, which facilitates the industry chain development. At present, a hierarchical, multi-perception VR QoE evaluation solution is proposed in the industry to implement modeling based on the real user experience to measure the media quality in network transmission.

Currently, the VR User Experience Quality Evaluation System program has been approved at ITU-T SG12. This program will produce recommendations about the VR service quality and provides suggestions on QoE factors, QoE/QoS requirements, testing methodology, and the objective quality evaluation model. This program plans to be developed in five phases, as follows:

- Identification of the VR service and pipe technology.
- Identification of the key quality factors that may affect VR QoE.
- Definition of the methods for measuring the quality of VR QoE.
- Determination of the objective and subjective evaluation methodologies for VR quality.
- Production of suggestions for requirements guaranteeing good VR QoE.