Cloud VR Network Solution White Paper (2018)

Huawei iLab·Ultimate Experience

Released by Huawei iLab

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Preface

Cloud VR is a new cloud computing technology for VR services. With fast and stable transport networks, VR content is stored and rendered in the cloud, and video and audio outputs are coded, compressed, and transmitted to user terminals. Local rendering requires expensive high-performance devices to provide acceptable user experience. With Cloud VR, users enjoy VR services without purchasing expensive hosts or high-end PCs, promoting VR service popularity.

In 2017, Huawei iLab released the Cloud VR Bearer Networks White Paper. In 2018, Huawei continues to focus on improving VR user experience. Using the latest technologies and commercial deployment experience of Cloud VR, Huawei further analyzes the transport network requirements in different phases of Cloud VR. Huawei's analysis culminates in the Cloud VR network solution and network evolution direction as references for operators to deploy Cloud VR services.

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01 Cloud VR Overview

1.1 Cloud VR Service Scenario Overview

VR is a virtual environment constructed by computers, wherein people can interact in real time using three-dimensional spacial information. The China Academy of Information and Communications Technology (CAICT), Huawei iLab, and Huawei C&SI Business Consulting Dept have identified Cloud VR scenarios and categorized them as B2C or B2B. The categorizations shown in Table 1-1 are based on research and industry insights from within and outside China.

Table 1-1 Cloud VR service scenario overview

Cloud VR B2C Application Scenario	Cloud VR B2B Application Scenario
Cloud VR IMAX	Cloud VR education
Cloud VR live broadcast	Cloud VR eSports arena
Cloud VR 360° video	Cloud VR marketing
Cloud VR gaming	Cloud VR healthcare
Cloud VR music	Cloud VR tourism
Cloud VR fitness	Cloud VR real estate
Cloud VR karaoke	Cloud VR engineering
Cloud social VR	
Cloud VR shopping	

According to an VR/AR industry report released by Goldman Sachs and the current business situation of operators, the following VR applications will gain popularity first: VR IMAX, VR 360° video, VR live broadcast, VR gaming, and VR education. Services in these application scenarios are further classified as having strong or weak interaction.

Weak-interaction VR services mainly comprise VR video services, including IMAX theater, 360° panoramic video, and VR live broadcast. Users can select the view and location, but users do not interact with (for example, touch) entities in the virtual environment. Strong-interaction VR services include VR games, VR home fitness, and VR social networking. In these scenarios, users can interact with virtual environments through interactive devices. The virtual space displayed needs to respond to interactions in real time.

1.2 Three Phases of Cloud VR Development

The development of Cloud VR centers on experience: continuous improvement in image quality, interaction, and immersive experience. The synergy between content production, transmission, and network technologies determine the level of Cloud VR experiences. Huawei divides the evolution of Cloud VR service experience into the following three phases: fair-experience, comfortable-experience, and ideal-experience phases.

Fair-experience Phase

In the fair-experience phase, most content is 4K, and the terminal screen resolution is 2K to 4K. The image quality viewed by users is equivalent to the Pixels Per Degree (PPD) effect of 240P/380P on a traditional TV.

For VR video services, the major solution is full-view transmission. To ensure user experience, the frame rate of strong-interaction VR services must be higher than that of common VR video services. In addition, full-view transmission does not apply to strong-interaction VR, which uses the Field of View (FOV) transmission mode, and the terminals need to support asynchronous rendering to provide smooth experience.

Comfortable-experience Phase

In the comfortable-experience phase, most content is 8K, the terminal screen resolution is 4K to 8K, and chip performance and ergonomics are improved. The image quality viewed by users is equivalent to 480P video on traditional TV.

In this phase, network bandwidth and latency must be significantly improved to ensure good user experience of Cloud VR services. For VR video services, full-view transmission will be the first choice to ensure good viewing and interaction experience. However, 360° 8K 3D video requires bandwidths of higher than 100 Mbit/s if full-view transmission is used. The FOV transmission solution lowers the bandwidth requirements, especially relevant for strong-interaction VR services, which require higher resolution and bandwidth.

Ideal-experience Phase

In the ideal-experience phase, most content is 12K or 24K. The terminal screen resolution is 8K to 16K. The development of content and terminals, coupled with technologies such as H.266 video coding standard and light field rendering, provides optimal VR experience.

For VR video services, the full-view transmission solution poses high requirements on network bandwidth. In contrast, the FOV solution poses lower requirements and will be the mainstream solution. In the case of strong-interaction VR services, the resolution is significantly improved, further increasing the required bandwidth. In addition, the user interaction experience requires lower network latency.

1.3 Cloud VR Network Development Strategy

Each phase of Cloud VR development requires unique development strategies as follows:

1. Fair-experience phase: Home Wi-Fi networks are added, and 4K-ready bearer network expansion and upgrade are performed.

- Add high-performance 5 GHz APs on home Wi-Fi networks for Cloud VR services and properly plan the channels to avoid interference from the original Internet access service.
- Expand and upgrade the 4K-ready bearer networks, such as upgrading OLT PON, expanding the capacity of OLT uplinks, flattening metro networks, and implementing OTN to CO.

2. Comfortable-experience phase: Home Wi-Fi and bearer networks are upgraded to guarantee bandwidth and latency.

- The 802.ac 4 x 4 MIMO or 802.11ax technology needs to be used in home Wi-Fi networks.
- The capacity of bearer networks needs to be expanded: The FTTH access needs to be upgraded to 10G EPON/GPON, metro networks require hardware devices with larger capacity and better integration, control plane and user plane separation is needed for cloudified applications, and cloud rendering server needs to be moved closer to users.
- Networks whose bandwidth and latency can be guaranteed need to be built to sense the intents and quality level, identify faults, and optimize networks.

3. Ideal-experience phase: Networks are evolving towards higher bandwidth and lower latency.

- The 60G Wi-Fi technology might be used, and the fixed networks will evolve to 25G, 50G, and 100G PON technologies.
- Cloud rendering servers need to be moved downward to metro edge, and networks will evolve towards cloud-network synergy.

02 Network Requirements of Cloud VR

2.1 Key Factors Affecting Cloud VR Experience

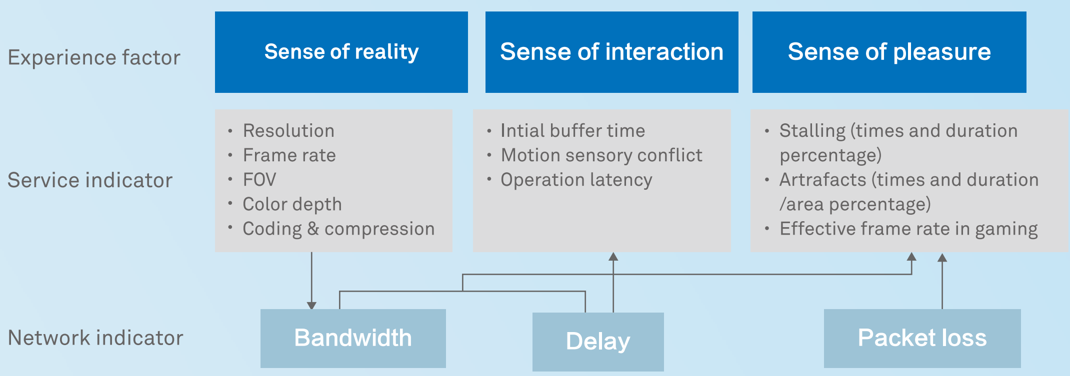
The three characteristics and advantages of VR are immersion, interaction, and imagination (3I).

- **Immersion:** 3D images are generated by a computer to create a virtual environment that feels like the physical world.
- **Interaction:** People can use sensor devices to interact with each other in the virtual environments generated and feel like they are in the real world.
- **Imagination:** The virtual environment inspires the imagination of users.

Accordingly, the experience evaluation factors of VR include sense of reality, interaction, and pleasure.

- **Sense of reality:** The sense of reality depends on resolution, color depth, frame rate, and encoding compression technologies. If the audio and video quality is too low, the environment does not feel real and users are unable to immerse themselves. The bandwidth of the Cloud VR transport network must meet the requirements of high-quality video transmission to ensure user experience.
- **Sense of interaction:** Cloud VR implements computing and rendering on the cloud. Any latency from remote processing compromises the sense of immersion and imagination. The dizziness caused by latency is the biggest problem facing Cloud VR. In addition, the latency in loading, switchover, and joystick operations compromises VR interaction.
- **Sense of pleasure:** The sense of pleasure depends on the smoothness of VR services. Frame freezing and artifacts compromise pleasurable experience. Therefore, network performance indicators, such as bandwidth, latency, and packet loss rate, must meet the requirements of Cloud VR.

Figure 2-1 Relationship between the key factors of Cloud VR experience and the network



2.2 Deterministic Low Latency Required by Cloud VR

For traditional 4K services, latency only slightly affects the channel switching time and loading duration. Therefore, the latency requirements for traditional 4K services are not demanding and can be lowered based on network conditions.

However, the latency must be deterministic for strong-interaction VR services, because images are remotely rendered in the cloud. Otherwise, the screen refresh quality and user interaction are compromised. According to the theoretical models and actual test results, the latency must be ⩽ 20 ms in the fair-experience phase, ⩽ 15 ms in the comfortable-experience phase, and ⩽ 8 ms in the ideal-experience phase, posing new challenges to networks.

2.2.1 Latency Requirements of VR Services

Network latency between 20 to 40 ms can meet the requirements of Cloud VR video services. Latency only affects the loading time. However, strong-interaction Cloud VR services pose the following latency requirements to ensure user interaction and pleasure:

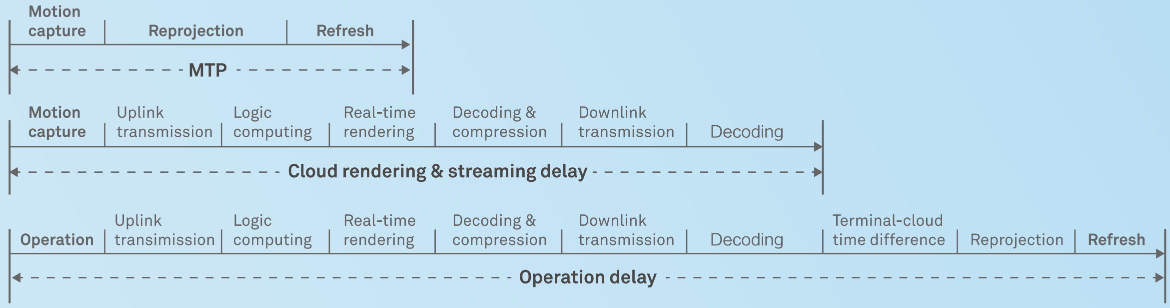
1. The MTP latency must be ⩽ 20 ms (the latency depends only on the processing speed of the terminal and has nothing to do with the network in the case of asynchronous rendering between the cloud and terminal).

2. The requirements on cloud rendering and streaming latency are as follows:

   - In the fair-experience phase, latency within 70 ms is acceptable. Black edges and quality deterioration are acceptable.
   - In the comfortable-experience phase, latency within 50 ms is acceptable. In this case, black edges are eliminated.
   - In the ideal-experience phase, latency within 30 ms is acceptable, image distortion is unnoticeable when users move.

3. The acceptable operations latency is ⩽ 100 ms. The operation latency includes cloud rendering and streaming latency, latency caused by the secondary rendering on terminals, and latency caused by asynchronous time warping and screen refreshing. The maximum latency caused by cloud rendering and streaming is 70 ms. Therefore, the minimum remaining latency is 30 ms, which is greater than the latency caused by asynchronous time warping and screen refreshing for MTP. Therefore, meeting cloud rendering and streaming requirements meets the operation latency requirement.

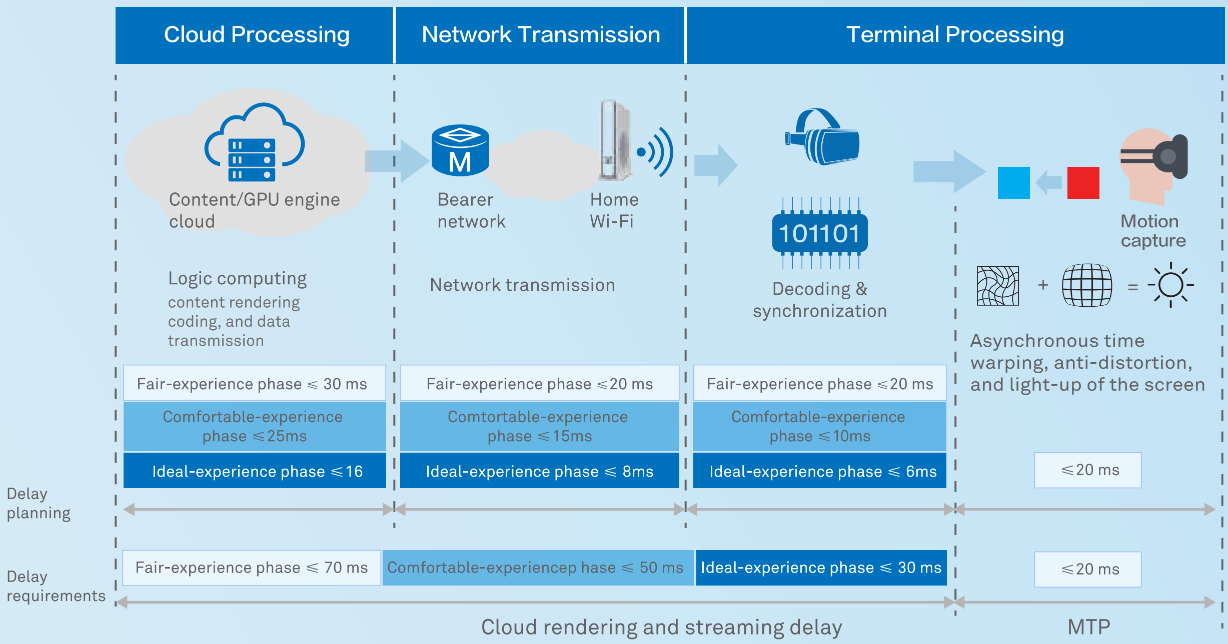
Figure 2-2 MTP, cloud rendering, and streaming latency in asynchronous rendering between the cloud and terminal



2.2.2 Network Latency Distribution in Cloud VR

Latency in cloud rendering and streaming derives from three factors: processing on the cloud, transmission on the network, and processing on the terminal.

Figure 2-3 Recommended E2E latency planning for strong-interaction VR services



The following table recommends network latency levels for home Wi-Fi, fixed access network, and metro network latency.

Phase	E2E Network RTT	Home Wi-Fi	Fixed Access Network	Metro Network
Fair–experience Phase	≤ 20 ms	≤ 10 ms	≤ 2 ms	≤ 8 ms
Comfortable–experience Phase	≤ 15 ms	≤ 7 ms	≤ 2 ms	≤ 6 ms
Ideal–experience Phase	≤ 8 ms	≤ 5 ms	≤ 2 ms	≤ 1 ms

If only weak-interaction VR video services are involved and the required latency in video playing or channel switching is no more than 1s, the network latency should be no more than 20 ms. If no latency requirement is imposed on the loading process during video playing or channel switching, the required network latency can be 30 to 40 ms.

2.3 Cloud VR Requires n x 4K Video Bandwidth

The immersive terminals of Cloud VR have a greater FOV than a traditional TV. To achieve the same definition as 4K video, the resolution, frame rate, and bitrate of Cloud VR must be higher than those of the 4K video services, posing higher bandwidth requirements on networks.

According to the actual tests and theoretical analysis, Cloud VR has the following bandwidth requirements:

Network KPI	4K Video	Fair-experience Phase of VR (4K Panorama)	Comfortable-experience Phase of VR (8 KB Panorama)	Ideal-experience Phase of VR (12K/24K Panorama)
Bandwidth per service	≥50 Mbit/s	≥80 Mbit/s	≥260Mbit/s	≥1 Gbit/s

2.3.1 Factors Affecting Cloud VR Bandwidth

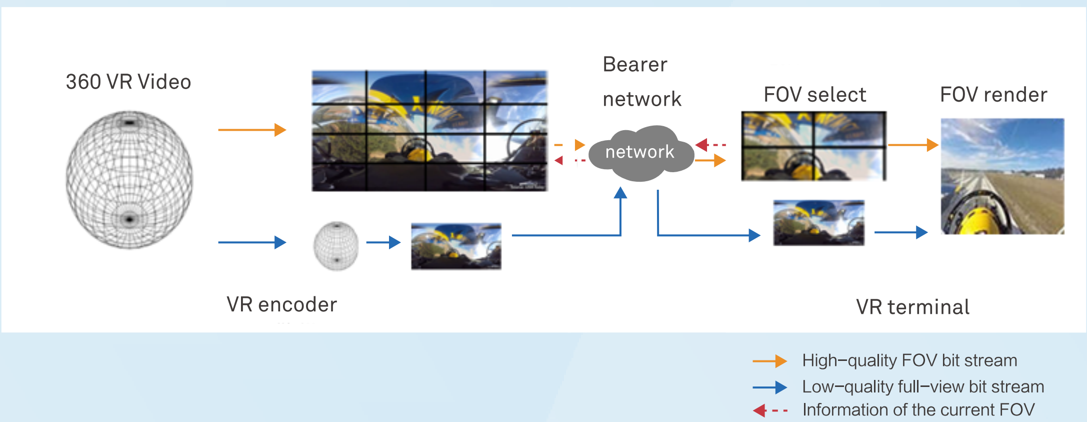
The factors that affect the bandwidth requirement of Cloud VR include resolution, frame rate, color depth, FOV, coding and compression, and transmission mode.

- **Resolution:** The FOV of immersive VR terminals is significantly higher than that of traditional TVs; therefore, to achieve the same level of image quality, the VR terminals must have much higher single-eye resolution and full-view resolution. Even full-view 4K resolution provides far from satisfactory video quality, and increasing the resolution to 8K or higher is essential. For example, if FOV is 90°, full-view resolution is 8K, and single-eye resolution is 1920 x 1920, the PPD is 22. The actual experience is equivalent to traditional SD video.
- **Frame rate:** If the frame rate is too low, images suffer poor quality or retention, dizzying the users. The frame rate should be at least 90 frames per second (FPS) to ensure good Cloud VR gaming experience. VR videos have lower requirements on frame rate, and a rate of 30 FPS can ensure good experience.
- **Color depth:** In the fair-experience phase of Cloud VR, the color depth requirement is not high if the image definition is not high. Generally, a color depth of 8 bits is sufficient. As the resolution increases, the color depth will increase to 10 to 12 bits.
- **FOV:** The view of users in a virtual environment can be considered as a spatial sphere. The horizontal FOV is 360° and vertical FOV is 180°. When a user uses a terminal, a single eye picks up only a small part of the entire spherical data, with the area depending on the FOV provided by the terminal. The horizontal and vertical FOVs of one eye are 160° and

150°, respectively, and the horizontal FOV of two eyes is about 200°. Currently, the FOV supported by VR terminals (such as TV sets or VR glasses) in the fair-experience phase of Cloud VR is about 90° to 110°, and the spherical data observed by a single eye through a VR terminal is less than 19% of the available data. As the industry develops, the FOV will increase to provide better experience.

- **Coding and compression technology:** H.264 encoding is used in the fair-experience phase of Cloud VR. However, 8K content requires an upgrade from H.264 to H.265, which improves the compression ratio by 30% for the same image quality. The latest research of MPEG and other standard organizations show that H.266, the next generation coding technology, can further improve the compression ratio by 30%, and is therefore recommended for 8K content in the ideal-experience phase.
- **Transmission mode:** There are two main technical directions for VR video transmission: Full-view transmission and FOV transmission. Full-view transmission involves sending 360° images to terminals. When users turn their heads and images they see are switched according to their FOV, and terminals perform just-in-time processing on images, such as bit stream parsing, video decoding, and image rendering. However, the transmission of portions of images that are not seen by users is a severe waste of network resources. In contrast, the FOV transmission solution focuses on the high-quality transmission of images within the current FOV. There are no unified FOV transmission technologies. The tile-wise transmission solution recommended by Huawei combines low-quality full-view transmission with high-quality visual area transmission. On the content preparation side, VR images are divided into multiple tiles, and each area corresponds to a multi-tile code stream that can be decoded independently. Simultaneously, a low-quality full-view VR code stream is prepared. The client obtains a low-quality full-view code stream and a high-quality code stream of the tile selected based on the FOV.

Figure 2-4 Tile-wise transmission solution



2.3.2 Bandwidth Requirements of Cloud VR

Bandwidth Requirements of Cloud VR Video Services

For VR video services, full-view transmission is used in the fair-experience phase. With industry development and increase of resolution, the FOV transmission solution can be used to minimize the required network bandwidth.

The bitrate in the full-view transmission solution is calculated as follows:

Average bitrate = (number of pixels of the image to be transmitted) x (number of bits per pixel) x (frame rate) / (compression ratio)

For 2D videos, the number of pixels of the image to be transmitted is the full-view resolution; for 3D videos, it is about twice that number. The number of bits per pixel after sampling is 12 when the color depth is 8 bits, 15 when the color depth is 10 bits, and 18 when the color depth is 12 bits.

To accommodate traffic bursts, the required network bandwidth should be 1.5 times the average bitrate:

Required network bandwidth = 1.5 x average bitrate

The tile-wise FOV transmission solution (low-quality full-view transmission and high-quality FOV transmission) requires only 53% of the bandwidth required for full-view transmission.

Based on the preceding calculations, the estimated bandwidths required by VR video services in the three phases of Cloud VR development are as follows:

Phase		Fair-experience Phase	Comfortable-experience phase	Ideal-experience Phase
Typical full-view resolution		4K (3840*1920)	8K (7680 x 3840)	12K (11,520 x 5760)/24K (23,040 x 11,520)
Typical terminal resolution		2K	4K	8K
FOV		90° to 110°	120°	120° to 140°
Color depth (bits)		8	8	10~12
Coding standard		H.264/ H.265	H.265	H.265/ H.266
Frame rate		30	30	60~120
Compression ratio (Note 1)		133	230	410 (12K), 1050 (24K)
VR video service	Typical bitrate	40 Mbit/s	Full-view: 90 Mbit/s FOV: 50 Mbit/s	Full-view: 290 Mbit/s (12K) 1090 Mbit/s (24K) FOV: 155 Mbit/s (12K) 580 Mbit/s (24K)
	Typical bandwidth requirement	60 Mbit/s	Full-view: 140 Mbit/s FOV: 75 Mbit/s	Full-view: 440 Mbit/s (12K) 1.6 Gbit/s (24K) FOV: 230 Mbit/s (12K) 870 Mbit/s (24K)

Note 1: The 4K compression ratio in the fair-experience phase is the typical value in the industry based on H.264. The compression ratio in subsequent phases is calculated based on industry experience and factors such as coding mode, frame rate, and resolution:

(1) The compression ratio of H.265 is about 30% higher than that of H.264.

(2) If the frame rate is doubled, the compression ratio needs to be increased by about 50%.

(3) If the resolution is doubled, the compression ratio needs to be increased by about 15%.

Bandwidth requirements for strong-interaction services

For strong-interaction VR services, real-time rendering is performed based on the current FOV. Therefore, FOV transmission is used. Strong-interaction service streams consist of I-frames and P-frames. An I-frame contains all the information about the image, and intraframe coding is used to restore the image. A P-frame is a forward predicted frame, and the image is restored algorithmically based on the previous I-frame or P-frame. Each Group of Pictures (GOP) contains one I-frame and N P-frames, where N = (GOP time) x (frame rate) – 1.

Strong-interaction services use asynchronous rendering and asynchronous time warping technologies. To minimize the user experience impact of black edges around the new FOV during asynchronous time warping, extra-perspective rendering and transmission are needed. An extra of 6° in each direction is recommended. The asynchronous rendering between the cloud and terminal adjusts the positions of objects based on depth of field or motion vector. This requires 15% more information about the depth of field and motion vector to be transmitted for each image frame.

The bitrate is calculated as follows:

Average bitrate = [(I-frame size x 1 + P-frame size x GOP time x frame rate) x (1+ redundancy error correction information)] / GOP time

Frame size = (number of pixels of the image to be transmitted) x (number of bits per pixel) x (additional depth of field information) / (compression ratio)

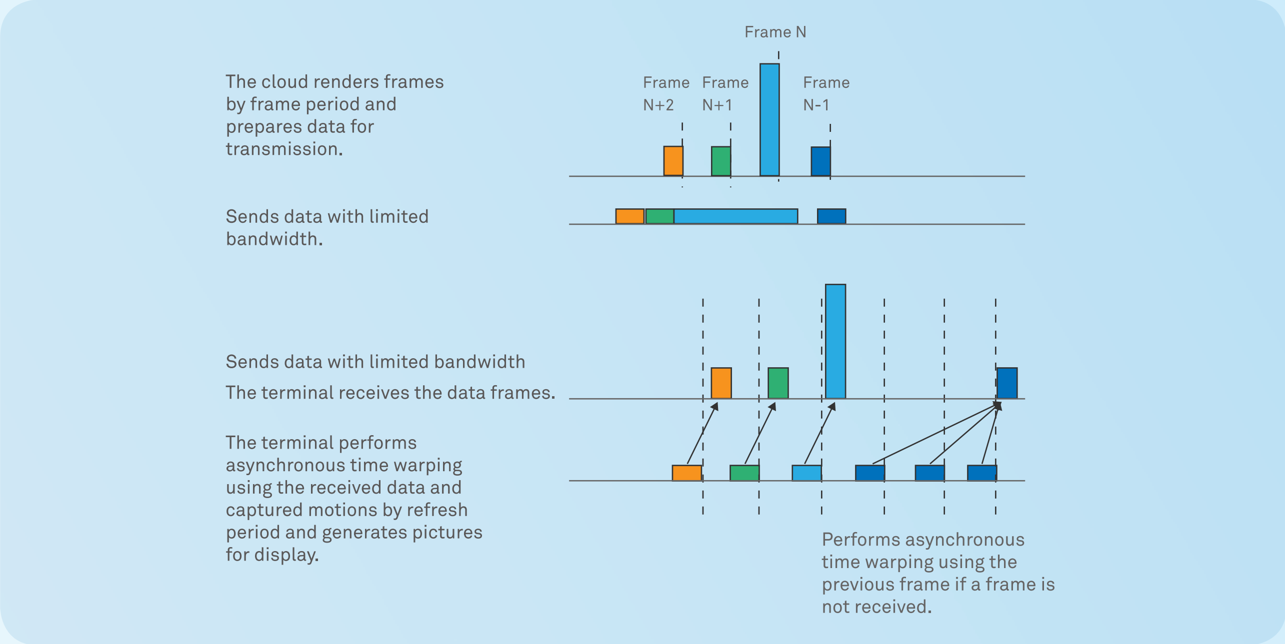
Number of pixels of the image to be transmitted = (Single-eye resolution) x

$$\left(1+\frac{\text{Rendering perspective in ATW}}{\text{FOV}}\right)^2 * \left(1+\text{FOV extra pictures}\right)^2$$

The estimated percentage of redundancy error correction information is 10%, the average GOP time is 2 seconds, and extra perspective degrees is 12 horizontally and vertically (6 degrees in the left, right, up, and down directions). The extra picture of the FOV is about 10%.

The cloud generates I-frames and P-frames concurrently in strong-interaction services. Therefore, the network bandwidth must meet the transmission requirements of both I-frames and P-frames. To ensure image quality and meet cloud rendering and streaming latency requirements, the frame transmission takes 10 to 15 ms in the fair-experience phase, 5 to 10 ms during the comfortable-experience phase, and 4 ms in the ideal-experience phase.

Frame data transmission time = (Frame size) / bandwidth. The bandwidth required by a P-frame is calculated using the following formula: P-frame required bandwidth = (P-frame size) / (frame transmission time), I-frames are large, and there is only one frame during each GOP time. Transmitting each I-frame in time would be too bandwidth-demanding. When a terminal cannot receive an I-frame in time, frame insertion can be used to generate a picture based on the previous frame (see the following figure). However, frame insertion impacts user experience. It is recommended that no more than two frames be inserted.



Therefore, an I-frame needs to be sent within three frame periods, and a P-frame needs to be sent within the time period reserved for the frame transmission. That is:

Bandwidth requirement = max[I-frame size / (3 x frame period), P-frame size / frame transmission time]

Based on the preceding calculations, the estimated per-user bandwidths required by strong-interaction services in the three phases of Cloud VR development are as follows:

Phase		Fair-experience Phase	Comfortable-experience phase	Ideal-experience Phase
Typical content resolution (Note 1)		2K (equivalent full-view resolution: 4K)	4K (equivalent full-view resolution: 8K)	8K/16K (equivalent full-view resolution: 12K/24K)
Typical terminal resolution		2K (1080 x 1200 x 2)	4K (1920 x 1920 x 2)	8K (3840 x 3840 x 2)/ 16K (7680 x 7680 x 2)
FOV		90° to 110°	120°	120° to 140°
Color depth (bit)		8	8	10~12
Coding standard		H.264/H.265	H.265	H.265/H.266
Compression ratio (I-frame /P-frame)(Note 2)		25/75	38/165	50/255 (8K) 83/585 (16K)
Frame rate (FPS)		50–90	90	120–200
Strong-interaction VR service	Typical bitrate	40 Mbit/s	90 Mbit/s	360 Mbit/s (8K) 440 Mbit/s (16K)
	Typical bandwidth requirement	80 Mbit/s	260 Mbit/s	1 Gbit/s (8K) 1.5 Gbit/s (16K)

Note 1: Strong-interaction services use real-time rendering, and no full-view images are involved. Therefore, the content resolution refers to the resolution of pictures to be rendered.

Note 2: The 4K compression ratio in the fair-experience phase is the typical value in the industry based on H.264. The compression ratio in subsequent phases is calculated based on industry experience and factors such as coding mode, frame rate, and resolution:

(1) The compression ratio of H.265 or H.266 is about 30% higher than that of H.264.

(2) If the frame rate is doubled, the compression ratio needs to be increased by about 50%.

(3) If the resolution is doubled, the compression ratio needs to be increased by about 15%.

2.4 Packet Loss Requirements of Cloud VR

Currently, video on demand (VoD) services use TCP transmission. Packet loss reduces TCP throughput and causes frame freezing. A typical formula for calculating the TCP throughput is as follows:

$$\text{Throughput} \leqslant \min\left(\text{Max}\,(\text{BW}), \frac{\text{WSS}}{\text{RTT}}, \frac{\text{MSS}}{\text{RTT}} \times \frac{1}{\sqrt{P}}\right)$$

The packet loss rate requirements of VoD services can be calculated as follows under given RTT and bandwidth:

Phase	Fair-experience Phase	Comfortable-experience phase	Ideal-experience Phase
RTT	20ms	20ms	20ms
Bandwidth	60M	140M	440M
Packet loss rate	⩽9e-5	⩽1.7e-5	⩽1.7e-6

UDP is recommended for strong-interaction and live video services. However, UDP is a connectionless protocol and therefore more prone to packet loss than is TCP, potentially causing problems such as erratic display and black screen. Based on the test data in 4K videos, when there is no RET retransmission, packet loss in 1E-5 slightly affects user experience, but in 1E-6, the impact cannot be perceived. Therefore, the recommended packet loss requirements are as follows:

Phase	Fair-experience Phase	Comfortable-experience phase	Ideal-experience Phase
Packet loss rate	⩽1e-5	⩽1e-5	⩽1e-6

2.5 Cloud VR Network Requirements

Based on the preceding analysis, Cloud VR videos have higher requirements on network bandwidth than traditional video services. Strong-interaction VR services impose even higher requirements on network bandwidth and latency.

Table 2-1 shows that Cloud VR services have different network requirements in three phases, including bandwidth, delay, and packet loss rate.

Table 2-1 Network KPI requirements in different phases of Cloud VR

Phase		Fair-experience Phase	Comfortable-experience phase	Ideal-experience Phase
Predicted commercial application time		2018	2019–2020	2023–2025
Typical video full-view resolution		4K	8K	12K to 24K
Typical strong-interaction content resolution (Note 1)		2K	4K	8K to 16K
Terminal resolution		2K to 4K	4K to 8K	8K to 16K
FOV		90° to 110°	120°	120° to 140°
Color depth (bit)		8	8	10~12
Coding standard		H.264/H.265	H.265	H.265/266
Frame rate (FPS)		30 (video services) 50–90 (strong-interaction services)	30 (video services) 90 (strong-interaction services)	60–120 (video services) 120–200 (strong-interaction services)
VR video service	Bitrate	≥40 Mbit/s	Full-view: ≥90 Mbit/s FOV: ≥ 50 Mbit/s	Full-view: ≥ 290 Mbit/s (12K) ≥ 1090 Mbit/s (24K) FOV: ≥ 155 Mbit/s (12K) ≥ 580 Mbit/s (24K)
	Bandwidth requirement (Note 2)	≥60 Mbit/s	Full-view: ≥ 140 Mbit/s FOV: ≥ 75 Mbit/s	Full-view: ≥ 440 Mbit/s (12K) ≥ 1.6 Gbit/s (24K) FOV: ≥ 230 Mbit/s (12K) ≥ 870 Mbit/s (24K)
	Recommended network RTT level (Note 3)	≤20ms	≤20ms	≤20ms
	Packet loss requirement	≤ 9e-5	≤1.7e-5	≤1.7e-6
Strong-interaction VR service	Bitrate	≥ 40 Mbit/s	≥ 90 Mbit/s	≥ 360 Mbit/s (8K) ≥ 440 Mbit/s (16K)
	Bandwidth requirement (Note 1)	≥ 80 Mbit/s	≥260Mbps	≥ 1 Gbit/s (8K) ≥ 1.5 Gbit/s (16K)
	Network RTT requirement	≤20ms	≤15ms	≤8ms
	Packet loss requirement	≤ 1e-5	≤ 1e-5	≤ 1e-6

Note 1: Strong-interaction services use real-time rendering, and no full-view images are involved. Therefore, the content resolution refers to the resolution of pictures to be rendered.

Note 2: The bandwidth requirement is calculated on the assumption that each user has only one VR terminal.

Note 3: If the required loading time is within 1s during playing or channel switching, the RTT must be within 20 ms. If the loading time requirement is not demanding, an RTT of 30 to 40 ms is acceptable.

03 Cloud VR Network Solution in the Fair-Experience Phase

This section describes the bearer network deployment solution of Cloud VR service in the fair-experience phase. Some solutions are not deployed on the live network. For details about the commercial deployment solution on the live network, see Cloud VR Solution Practice Report released by Huawei iLab.

3.1 Target Network Architecture

In the fair-experience phase of Cloud VR, the bandwidth of a single-channel VR service is 80 Mbit/s. After 4K IPTV and Internet access services are enabled, the user bandwidth is 80 Mbit/s (VR) + 50 Mbit/s (4K IPTV) + 100 Mbit/s (HSI) = 230 Mbit/s or higher. The VR screen mirroring service is downloaded through the 4K IPTV channel. The headend needs to compress the VR screen mirroring traffic to the level of 4K video bandwidth. If the headend cannot compress the traffic, the bandwidth changes to 80 Mbit/s (VR) + 80 Mbit/s (4K IPTV, including the screen mirroring traffic) + 100 Mbit/s (HSI) = 260 Mbit/s. Considering that most headends do not compress the screen mirroring service, the bandwidth of 260 Mbit/s is used for calculation.

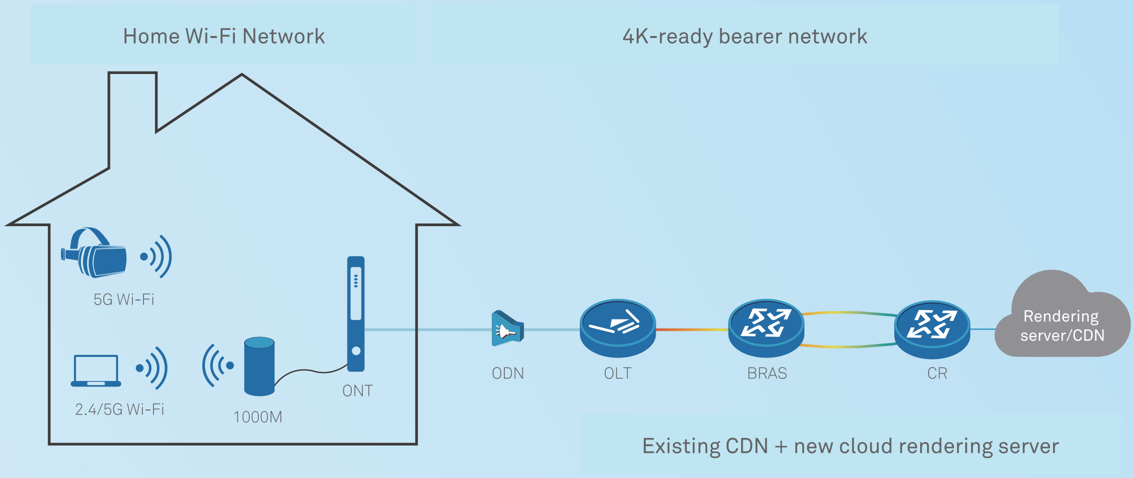
In the fair-experience phase, the network RTT must be 20 ms or shorter. Table 3-1 lists the network RTT in each segment:

Table 3-1 Cloud VR latency requirements in the fair-experience phase

E2E Network RTT	Home Wi-Fi	Fixed Access Network	Metro Network
≤20 ms	≤10ms	≤2ms	≤8ms

In the fair-experience phase, existing networks are reused to minimize Cloud VR deployment cost. Therefore, the Cloud VR network solution is Wi-Fi home network+4K-ready bearer network+existing CDN/new cloud rendering server, as shown in Figure 3-1.

Figure 3-1 VR target architecture



- **Wi-Fi home network:** Traditional 4K STBs can be connected through network cables. However, Cloud VR HMDs must use Wi-Fi access. Therefore, the key is deploying high-performance APs.
- **4K-ready bearer network:** The 4K-ready simplified bearer network architecture can be used to minimize Cloud VR deployment cost and improve deployment speed. To meet the bandwidth and latency requirements of Cloud VR, parts of 4K-ready bearer networks can be transformed as follows:

  - Upgrade GPON/EPON to 10G GPON/EPON.
  - Increase the capacity of uplink ports.
  - Improve the capacity of metro networks and provide one-hop connections to OTN.
- **Existing CDN/new cloud rendering server:** During the fair-experience phase, the existing CDN resources can be used for Cloud VR content distribution, and new cloud rendering servers can be used for Cloud VR gaming content distribution. The CDN/cloud rendering servers are usually deployed within the metro network.

This solution brings the following benefits:

- **Maximizes the reuse of live network resources:** The resources of the IP, optical, FTTH access, and CDN networks can be reused and upgraded to solve most problems.
- **Simplifies deployment:** The reuse of existing networks for Cloud VR eliminates the need for an additional VLAN, IP address, and authentication account configurations.
- **Create sales opportunities for new home products/services:** Opportunities to sell new home gateways and intelligent networking services are created for operators based on the high experience assurance requirements of Cloud VR.

3.2 Home Network Planning and Design

3.2.1 Challenges Faced by Cloud VR Home Network

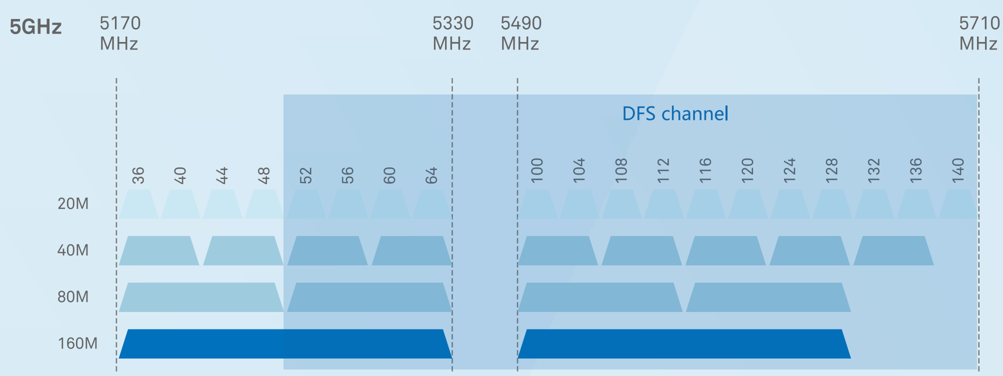
VR HMDs generally use Wi-Fi connections for mobility. When Wi-Fi is deployed on VR HMDs, there are three types of problems and challenges:

- There are few available 5 GHz Wi-Fi channels, making the planning difficult when Cloud VR is carried.
- The capabilities of existing Wi-Fi gateways are varied.
- Cloud VR and the existing home services must coexist without affecting each other.

◆ Few Available 5 GHz Wi-Fi Channels Makes Planning Difficult

2.4 GHz frequency band channels are few and overlap with each other. There are only three non-overlapping 20-MHz channels. The total frequency bandwidth is less than 80 MHz, which makes carrying the Cloud VR services difficult. The theoretical maximum rate of 5 GHz Wi-Fi is 3466 Mbit/s, which is suitable for carrying the Cloud VR service.

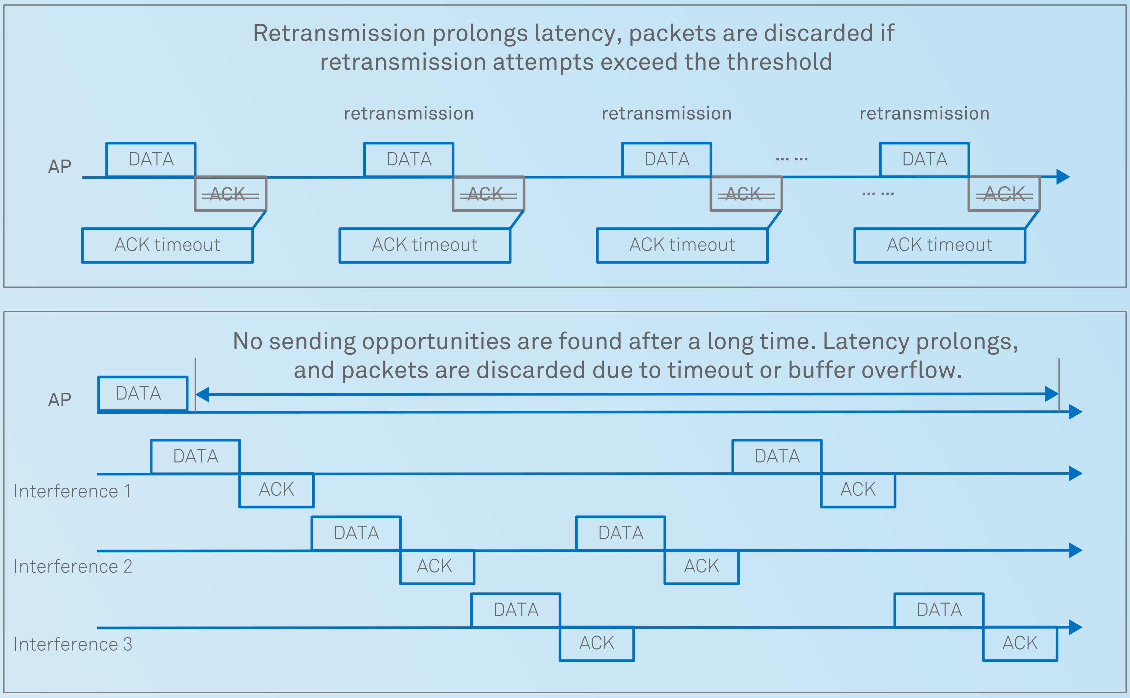
Figure 3-2 5G Wi-Fi spectrum planning in Europe



5G Wi-Fi spectrum distribution is shown in the preceding figure (Europe is used as an example): There are 19 20-MHz channels, 9 40-MHz channels, 4 80-MHz channels, or 2 160-MHz channels. Most of them are DFS channels. The number of non-DFS channels is small. Only one non-DFS 80-MHz channel is available. To reduce complexity, most of the existing consumer-level APs in the market do not support DFS channels. As a result, the 5G Wi-Fi in the home network is congested in non-DFS channels, causing serious interference.

Interference causes contention and conflicts over the air interface. Packets need to wait for a long time to be sent or need to be resent when a conflict occurs during transmission, which prolongs packet transmission latency. If the latency exceeds the device tolerance or the number of retransmission attempts exceeds the threshold, packet loss occurs. In addition, interference decreases Wi-Fi availability. If the bandwidth is lower than that required by Cloud VR, the packets in queues increase and packet loss occurs.

Figure 3-3 Latency and packet loss caused by interference



In conclusion, the planning and utilization of 5G Wi-Fi channels must be solved during Cloud VR deployment.

◆ The Capabilities of Existing Wi-Fi Gateways Are Varied

Currently, many devices support 5G Wi-Fi, but the price and performance of these devices vary greatly. According to the tests of several common 5G Wi-Fi products conducted by iLab, different product models adapt differently to interference. Table 3-2 lists the test results.

Table 3-2 Different types of devices support different levels of interference

Product Model	No Interference	Interference from Two Adjacent Channels	Interference from One Source on the Same Channel and One Source on an Adjacent Channel	Interference from Two Sources on the Same Channel
Model 1	PASS	FAIL	FAIL	FAIL
Model 2	PASS	PASS	FAIL	FAIL
Model 3	PASS	PASS	FAIL	FAIL
Model 4	PASS	PASS	PASS	FAIL
Model 5	PASS	PASS	PASS	PASS

According to the test results, it can be concluded that:

- All five models meet RTT latency requirements if there is no interference.
- Four of the models meet RTT latency requirements in the case of interference from two adjacent channels.
- Only two of the models meet RTT latency requirements in the case of interference from one source on the same channel and one source on an adjacent channel.
- Only one model meets RTT latency requirements in the case of interference from two sources on the same channel.

Therefore, it is important to select high-performance Wi-Fi products during Cloud VR deployment.

◆ Cloud VR and Existing Home Services Must Coexist Without Affecting Each Other

Cloud VR is a new service on the existing 4K-ready network. Therefore, it is necessary to consider its coexistence with existing 4K IPTV and HSI services to avoid interference.

In a 4K-ready transport network, wired access is recommended for IPTV and Wi-Fi for Internet access. Therefore, it must be ensured that Internet access and Cloud VR do not affect each other.

3.2.2 Cloud VR Home Network Planning Suggestions

To address the above challenges, the following aspects require attention during the deployment of Cloud VR home network:

- Select a proper Wi-Fi frequency bandwidth and channel to ensure sufficient bandwidth and minimize interference.
- Select high-performance Wi-Fi gateways.
- Select a proper networking mode to ensure that Cloud VR and existing home services coexist without affecting each other.

Recommendation: 80-MHz Frequency Bandwidth, 2 x 2 MIMO, and Operators Providing Channel Planning

The frequency bandwidth of 5 GHz Wi-Fi can be 20 MHz, 40 MHz, 80 MHz, or 160 MHz. Different frequency bandwidths support different rates.

Currently, most VR HMDs support 2 x 2 MIMO. Therefore, the following calculations are based on 2 x 2 MIMO. The following snapshot shows the maximum theoretical rate of different frequency bandwidths in different Modulation and Coding Scheme (MCS) modes in the 2 x 2 MIMO scenario.

Table 3-3 Wi-Fi rates

MCS index[a]	Spatial Streams	Modulation type	Coding rate	Data rate（in Mbit/s）[9][b]							
				20MHz channels		40MHz channels		80MHz channels		160MHz channels	
				800ns GI	400 ns GI	800 ns GI	400 ns GI	800ns GI	400 ns GI	800ns GI	400 ns GI
0	2	BPSK	1/2	13	14.4	27	30	58.5	65	117	130
1	2	QPSK	1/2	26	28.9	54	60	117	130	234	260
2	2	QPSK	3/4	39	43.3	81	90	175.5	195	351	390
3	2	16-QAM	1/2	52	57.8	108	120	234	260	468	520
4	2	16-QAM	3/4	78	86.7	162	180	351	390	702	780
5	2	64-QAM	2/3	104	115.6	216	240	468	520	936	1040
6	2	64-QAM	3/4	117	130.3	243	270	526.5	585	1053	1170
7	2	64-QAM	5/6	130	144.4	270	300	585	650	1170	1300
8	2	256-QAM	3/4	156	173.3	324	360	702	780	1404	1560
9	2	256-QAM	5/6	N/A	N/A	360	400	780	866.7	1560	1733.4

Because of the small number of 5G Wi-Fi channels, co-channel interference may be unavoidable after 5G Wi-Fi is deployed on a large scale. When a channel experiences interference from two sources on the same channel, the actual data rate is about MCS6 rate x 50% x (1-40%) when 50% duty cycle and 40% transmission loss are considered according to MCS6 mode. That is, the rate of 20-MHz frequency bandwidth is 39 Mbit/s, the rate of 40-MHz frequency bandwidth is 81 Mbit/s, the rate of 80-MHz frequency bandwidth is 175 Mbit/s, and the rate of 160-MHz frequency bandwidth is 350 Mbit/s. Since the 160-MHz frequency bandwidth is not supported by terminals, the 80-MHz frequency bandwidth is recommended for Cloud VR.

The 5G frequency band planning varies by country and the number of channels available for 5G Wi-Fi is different. For example, in Europe, only four 80-MHz channels can be deployed for 5G Wi-Fi. The channel selection process is complex, and users seldom have the Wi-Fi deployment capability. Therefore, it is recommended that operators provide door-to-door installation services to scan and identify Wi-Fi channels on site, and set proper Wi-Fi channels and gateway installation positions based on the scanning results.

Requirements of High-performance Wi-Fi Gateway: Strong Immunity to Interference, DFS Channels, and Gigabit Ports

Building a high-performance Wi-Fi gateway standard is recommended for product screening to prevent the low-performance Wi-Fi gateway from affecting Cloud VR service experience. According to the iLab test results, a high-performance Wi-Fi gateway has the following features:

- The air interface transmission latency is shorter than 10 ms and the transmission rate is higher than 80 Mbit/s when two to four channels are experiencing co-channel interference.
- Supports DFS channels and radar detection. For example, in Europe, only four channels of 5G Wi-Fi can be used for Cloud VR transmission, and three of the channels are DFS channels. Severe co-channel interference will be caused if all home Wi-Fi networks are deployed on the non-DFS channel. Therefore, the three DFS channels must also be used to prevent such interference. The Wi-Fi gateway running on a DFS channel must support the periodic DFS detection function to check whether a radar is working on the current channel. If a radar is detected, the channel must be switched to another channel.
- Provides two or more GE ports to support flexible networking modes and reduce line reconstruction requirements.

Recommendation: High-performance Independent AP for Cloud VR

Cloud VR is a new service on the existing 4K-ready network. Therefore, it is necessary to consider its coexistence with existing 4K IPTV and HSI services to avoid interference. Therefore, it must be ensured that Internet access and Cloud VR do not affect each other. To address these issues, three common networking methods are available. However, not all of them are recommended.

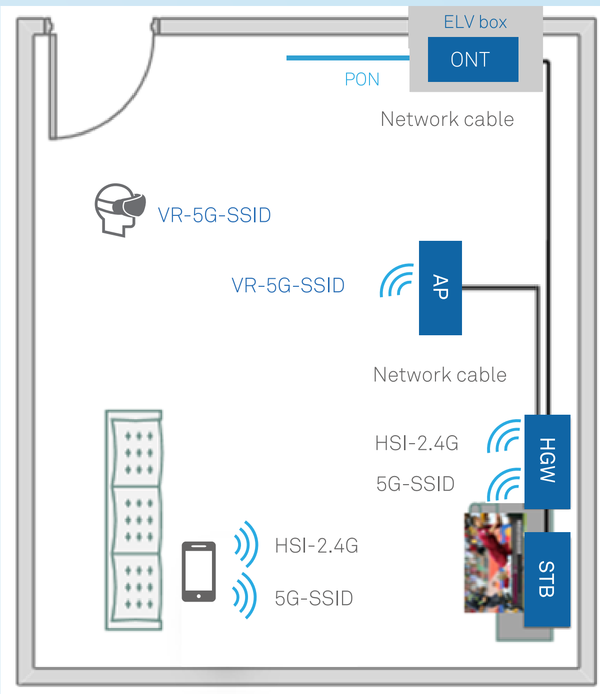
- **Solution 1: Use a dedicated high-performance AP for Cloud VR to ensure good experience. This method is recommended.**
- **Solution 2: Use existing ONT/HGW for Cloud VR. The ONT/HGW devices on the live networks support only one 5GHz band.** Cloud VR and Internet access services share the same band. The experience of VR servicesmight be affected. Moreover, the ONT/HGW devices do not support DFS channels.Therefore, this method is not recommended.
- **Solution 3: Replace the ONTs on live networks with tri-band Wi-Fi ONTs (2 x 5 GHz band + 1 x 2.4 GHz band).** A large number of ONTs are deployed in the extra-low-voltage boxes. The ONTs cannot provide access for Cloud VR even when they are replaced by tri-band ONTs. Moreover, no tri-band Wi-Fi ONT product is available in the market. Therefore, this method is not considered.

During deployment, the connection varies according to the ONT location:

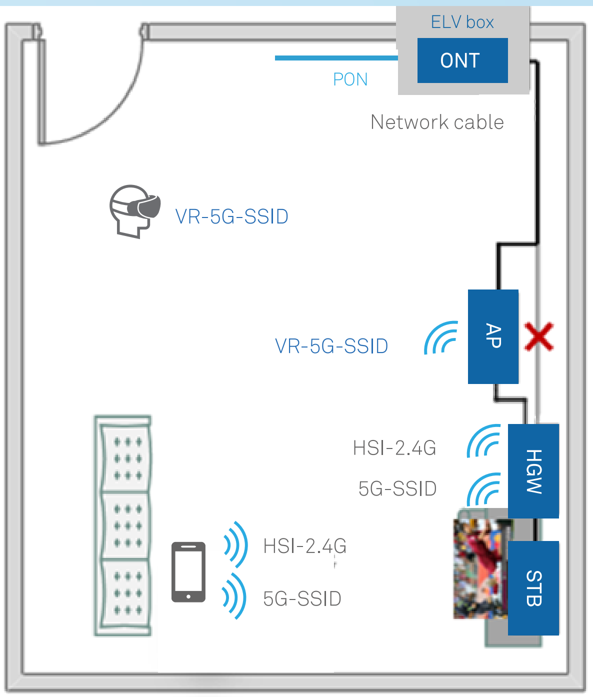
Scenario1: The AP can be connected in two ways when the ONT is deployed in the extra-low-voltage box.

When the ONT is deployed in the extra-low-voltage box, the ONT is often connected to the HGW in the living room through a network cable. The 5 GHz or 2.4 GHz Wi-Fi of the HGW is used for Internet access, and the Ethernet port of the HGW is used for IPTV. Cloud VR requires an extra AP, which can be connected in two modes:

Figure 3-4 Connection of the dedicated Cloud VR AP (ONT in ELV box)



Mode 1: AP is directly connected to the Ethernet port of HGW



Mode 2: AP is connected between the ONT and the HGW

- **Mode 1: Connect the AP to the HGW through a network cable. This method is easy and suitable for Gigabit HGW products.**

  This method does not require any change to the existing home networking. However, the Cloud VR traffic must be forwarded to the AP by the HGW. Therefore, the HGW must provide high bandwidth. Cloud VR requires 80 Mbit/s bandwidth during the fair-experience phase, and Gigabit and 100M HGWs can be used. In the comfortable-experience phase, Cloud VR requires 260 Mbit/s bandwidth. In this case, only Gigabit HGW can be used.

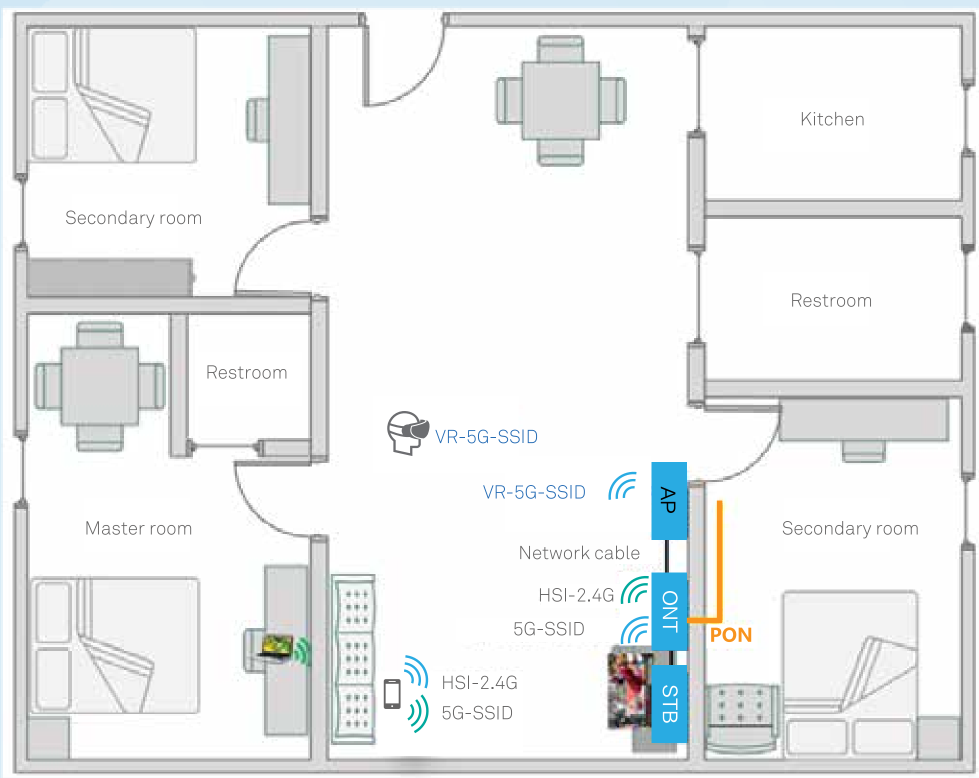
- **Mode 2: Place the AP between the ONT and HGW. This method is complex and suitable for 100M HGW products.**

  This method requires changes to the existing networking. The PPPoE dial-up function must be moved upward to the ONT, and the configurations are complex. However, the new AP only carries Cloud VR traffic, and the HGW does not carry Cloud VR traffic. Therefore, 100M HGW products can be used.

Scenario2: The ONT is deployed on the desktop in the living room, and the AP is directly connected to the ONT through a network cable.

When the ONT is deployed on the desktop in the living room, the 5 GHz or 2.4 GHz Wi-Fi of the ONT is used for Internet access, and the Ethernet port of the ONT is used for IPTV. Cloud VR requires an extra AP, which must be connected to the ONT through a network cable, as shown in Figure 3-5.

Figure 3-5 Connection of the dedicated Cloud VR AP (ONT on the desk in the living room)



3.3 Access Network Design: 10G GPON Products Are Mainly Used, and EPON/GPON Products Are Restricted

The acceptable latency on the access network is 2 ms or shorter for Cloud VR in the fair-experience phase. Therefore, neither copper nor cable solutions are suitable for Cloud VR. The only option is FTTH.

The major FTTH solutions are GPON and EPON, which can meet the latency requirements of Cloud VR in the fair-experience phase. Therefore, the focus is on bandwidth, as shown in Table 3-4.

Table 3-4 Bandwidth available to FTTH users

PON	Capacity	Split Ratio	Convergence Ratio	Available Bandwidth	Support for VR in the Fair-Experience Phase
EPON	1Gbit/s	1:64	50%	32 Mbit/s	Limited support
		1:32	50%	64 Mbit/s	Limited support
GPON	2.5Gbit/s	1:64	50%	78 Mbit/s	Limited support
		1:32	50%	156 Mbit/s	Limited support
10G EPON/G PON	10Gbit/s	1:64	50%	312 Mbit/s	Support
		1:32	50%	625 Mbit/s	Support

Note: Available bandwidth = Capacity/Split ratio/Convergence ratio

The bandwidth requirement of Cloud VR overlaying 4K IPTV and Internet access is 260 Mbit/s or higher. Therefore, no matter whether EPON or GPON is used, Cloud VR cannot be deployed on a large scale, and only a small number of users are supported.

To meet VR bandwidth requirements on a large scale, FTTH access modes must be upgraded to 10G EPON/10G GPON. Even if the split ratio is 1:64 and the convergence is 50%, the bandwidth available to each user reaches 312 Mbit/s, meeting the requirements of Cloud VR in the fair-experience phase.

The suggestions for upgrading from EPON and GPON to 10G EPON/10G GPON are as follows:

- **Evolution from EPON to 10G EPON:** EPON and 10G EPON have the same upstream wavelengths. They can share the same ODN in time division multiplexing (TDM) mode. The downstream wavelengths do not overlap, and the corresponding wavelengths are received based on the wavelength range. Therefore, there is no need to change the ODN during the evolution from EPON to 10G EPON, and only 10G EPON boards are needed for the smooth migration from EPON to 10G EPON. The original ONTs can be used or replaced with 10G EPON ONTs as required. Because the upstream rates vary between EPON and 10G EPON, the upstream bandwidth planning is complex when EPON and 10G EPON boards co-exist.

Figure 3-6 EPON/10G EPON wavelength range

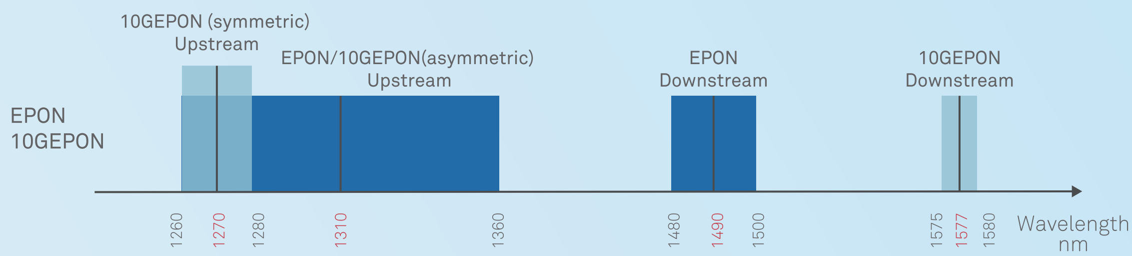
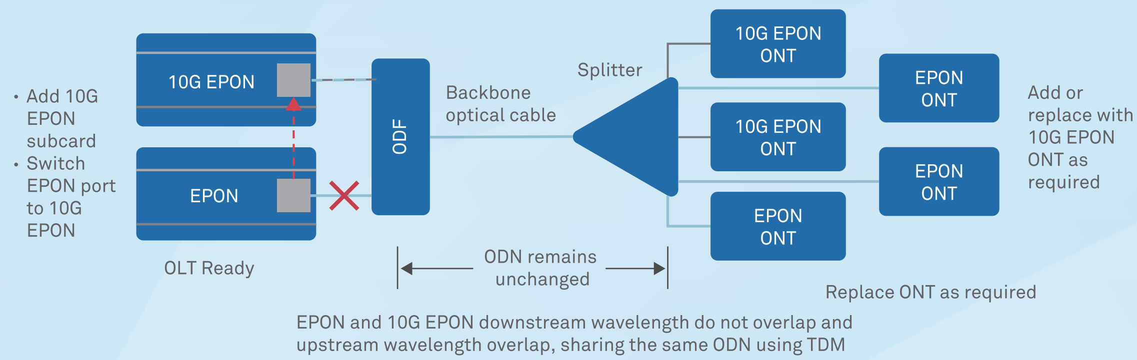
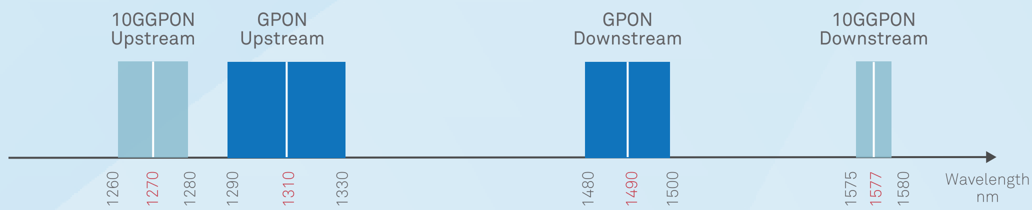


Figure 3-7 Deployment suggestions for EPON upgrade to 10G EPON



- **Evolution from GPON to 10G GPON:** As shown in Figure 3-8, the upstream wavelengths of GPON and 10G GPON do not overlap so the same ODN can be shared using wavelength division multiplexing (WDM). The downstream wavelengths do not overlap and the corresponding wavelengths can be received based on the wavelength range. Because GPON and 10G GPON are independent of each other, bandwidth can be planned independently.

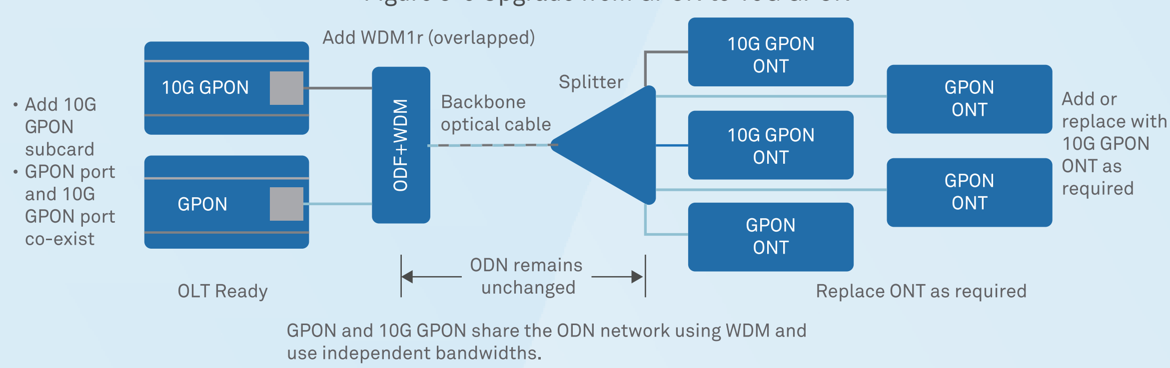
Figure 3-8 GPON/10G GPON wavelength range



There are two solutions for the evolution from GPON to 10G GPON.

- **External WDM1r multiplexer solution:** The multiplexer transmits the multiplexed wavelengths of the 10G GPON ports and GPON ports through the same backbone optical fiber. The original GPON ONTs can be used or replaced with the 10G GPON ONTs as required. The WDM1r multiplexer will introduce extra attenuation. For newly deployed GPON, it is recommended that 2-3 dBm optical budget be reserved. If the optical budget is insufficient, use optical modules of higher power and sensitivity.

Figure 3-9 Upgrade from GPON to 10G GPON

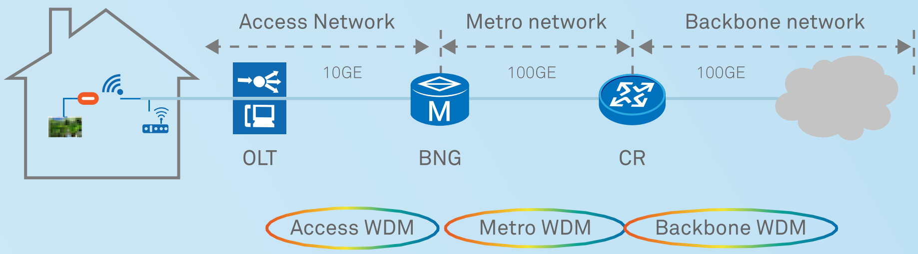


- **Combo board solution:** 10G GPON and GPON capabilities are integrated in the board. The optical module has a built-in multiplexer. The PON ports on the live network can be connected to the Combo unicast PON ports, and the original GPON ONTs can be used or replaced with 10G GPON ONTs as required.

3.4 Metro Network Design: Reusing 4K-ready Networks

In the fair-experience phase of Cloud VR, the 4K network architecture can be used, as shown in Figure 3-10.

Figure 3-10 Cloud VR metro network architecture in the fair-experience phase



Similar to the 4K metro network, Cloud VR metro network involves the following technical measures:

- **The network is flattened to reduce unnecessary convergence:** The OLT access device must be directly connected to the BNG of the metro network gateway, and the BNG must be directly connected to the CR device of the metro core network.
- **BNGs are moved closer to users:** This method avoids the complexity of VPLS and supports deployment of CDN/cloud rendering servers, reducing latency.
- **OTN to CO:** A large number of optical fibers are needed in the process of network flattening. The WDM devices are moved downward to the metro network edge/OLT site to provide interconnection infrastructure pipes featuring ultra-high bandwidth, low latency, and zero packet loss.
- **Network link utilization is monitored in real time:** If the link usage exceeds the threshold required for VR services, capacity expansion is needed to prevent packet loss caused by burst traffic.

In the fair-experience phase, the deployment scale of Cloud VR is small. Assume that the user penetration rate is about 30%, the concurrency rate is expected to be lower than that of IPTV. The concurrency rate varies with areas. Assume that the concurrent rate is 50% on OLTs, 20% at metro network edge, and 10% at metro network core. The metro network capacity required Cloud VR can be calculated as follows:

- **Required capacity on the uplink port of an OLT:** Number of users on the OLT (1500) x penetration rate of VR users (30%) x concurrency rate (50%) x bitrate in fair-experience phase of Cloud VR (40 Mbit/s) = 9 Gbit/s
- **Required capacity on the metro edge device:** Number of users on the metro edge device (20,000) x penetration rate of VR users (30%) x concurrency rate (20%) x bitrate in fair-experience phase of Cloud VR (40 Mbit/s) = 48 Gbit/s
- **Required capacity on the metro core device:** Number of users on the metro core device (1,000,000) x penetration rate of VR users (30%) x concurrency rate (10%) x bitrate in fair-experience phase of Cloud VR (40 Mbit/s) = 1.2 Tbit/s

It can be concluded that capacity expansion of the metro network will be required after Cloud VR is deployed in the fair-experience phase to avoid the congestion.

- It is recommended that the OLT upstream ports be upgraded to 2 x 10GE at least.
- Metro edge devices must be upgraded to 2 x 100GE at least and must be connected to the metro core network.
- It is recommended that metro core devices be upgraded to 400 Gbit/s per slot or Tbit/s cluster platforms.

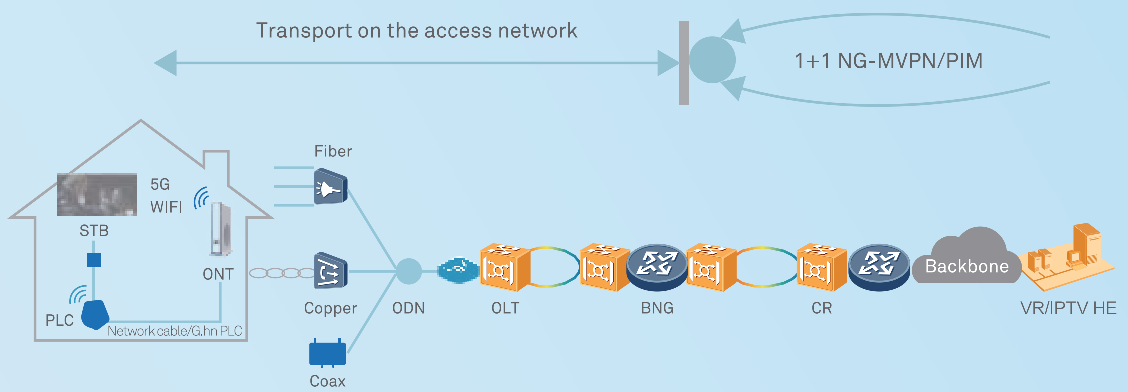
In addition to bandwidth, the latency of the metro network must be less than 8 ms (including the one on the CDN network). It is recommended that the overall forwarding latency of metro devices and the forwarding latency of the CDN network be less than 1 ms, with the remaining 6 ms reserved for the latency introduced by the fiber distance and queue cache. This requires that the CDN/cloud rendering server be deployed within the metro network.

3.5 Cloud VR Transport Design

3.5.1 4K Transport Solution

The Cloud VR transport network evolved from the 4K-ready video transport network. It is therefore necessary to provide some up-to-date information about the 4K IPTV transport solution.

Figure 3-11 4K IPTV transport solution



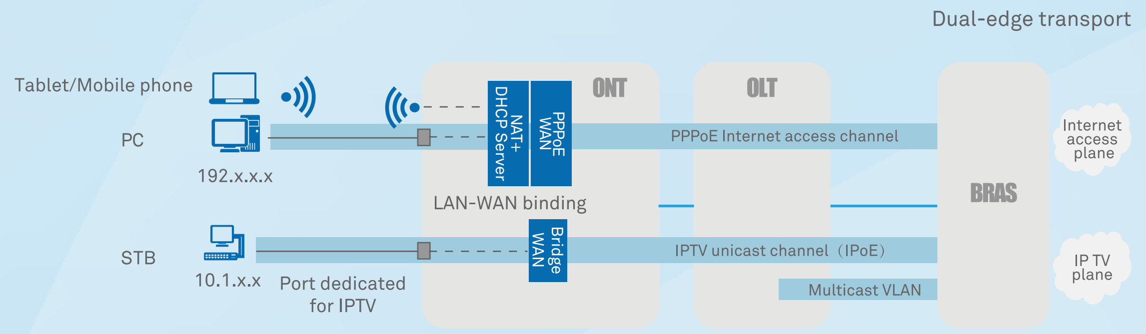
As shown in the figure, the 4K IPTV transport solution consists of two parts:

- IPTV transport on the metro network: Multicast mainly uses NG-MVPN and PIM+VPLS technologies. These technologies are mature and can be used for Cloud VR transport, and therefore are not described in this white paper.
- IPTV transport on the access network: Currently, the mainstream solution is to carry IPTV services based on dual channels. However, a few carriers use the single-channel transport solution. The Cloud VR transport mode varies depending on the dual-channel or single-channel transport solution.

3.5.2 Cloud VR Transport Solution in Dual-Channel Scenarios

In a dual-channel scenario, the STB is connected to the dedicated IPTV port of the ONT to perform independent dial-up using a dedicated IP address. This solution is inherited from the IPTV transport on the private network and is still the mainstream solution.

Figure 3-12 Dual-channel IPTV transport solution

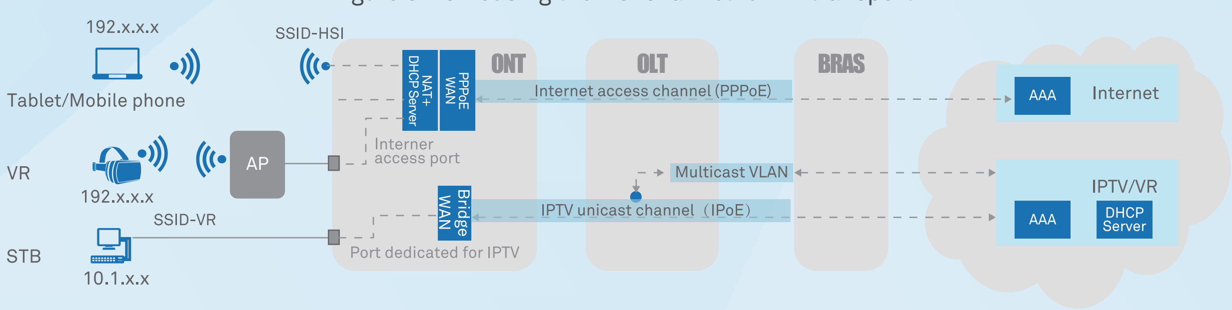


As VR services continue to emerge, three dual-channel transport solutions have become available.

Solution 1 (Recommended): Reusing the HSI Channel for VR Transport

As shown in Figure 3-13, like other Internet access terminals, the VR HMD obtains the IP address from the ONT and reuses the PPPoE Internet access channel for transport.

Figure 3-13 Reusing the HSI channel for VR transport

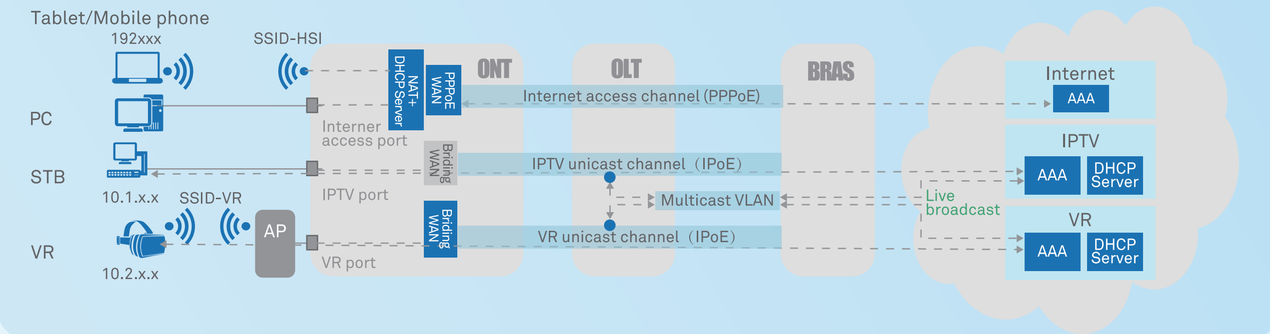


In this solution, the HMD can access the network without any special processing, making it the simplest deployment solution. VR multicast services are not provided by default, and live VR services are delivered in VOD mode. If, in the future, the number of users is large, multicast services can be separated and sent to the ONT independently, which does not affect the dial-up mode.

Solution 2: Using an Independent Channel for VR Transport

As shown in Figure 3-14, based on the 4K IPTV transport solution, this solution adds an IPoE logical channel to carry VR services. In this case, a port dedicated for the VR AP needs to be reserved on the ONT and is bound to the bridge WAN port of the independent IPoE channel.

Figure 3-14 Using an independent channel for VR transport

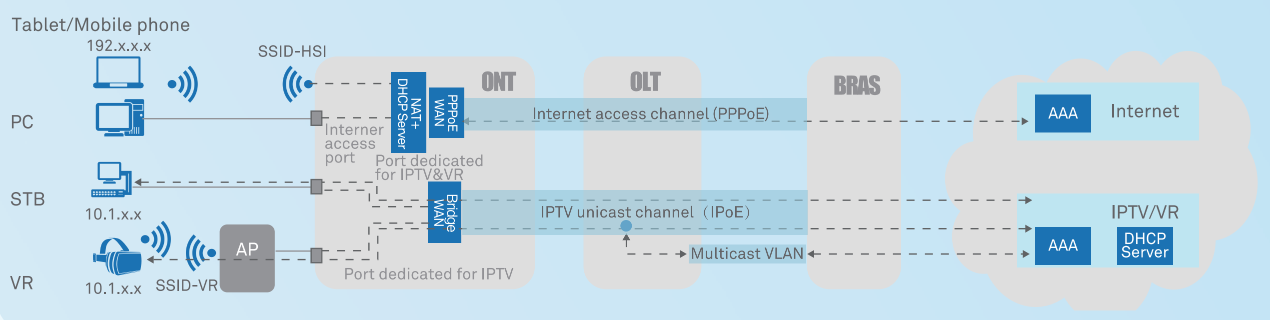


This solution involves planning the VLAN ID, IP address, and routing policy of the VR dedicated channel between the ONT and BRAS. The AAA server and DHCP server, which authenticate the VR unicast channel, are added. In addition, the OSS service provisioning system needs to be reconstructed, and doing so is complex.

Solution 3: Reusing the IPTV Channel for VR Transport

As shown in Figure 3-15, the VR service is carried over the IPTV channel. The ONT binds the dedicated port that is connected to the dedicated AP for Cloud VR to the existing IPTV channel. The VR HMD, like the STB, performs IPoE dial-up authentication through the IPTV channel.

Figure 3-15 Reusing the IPTV channel for VR transport



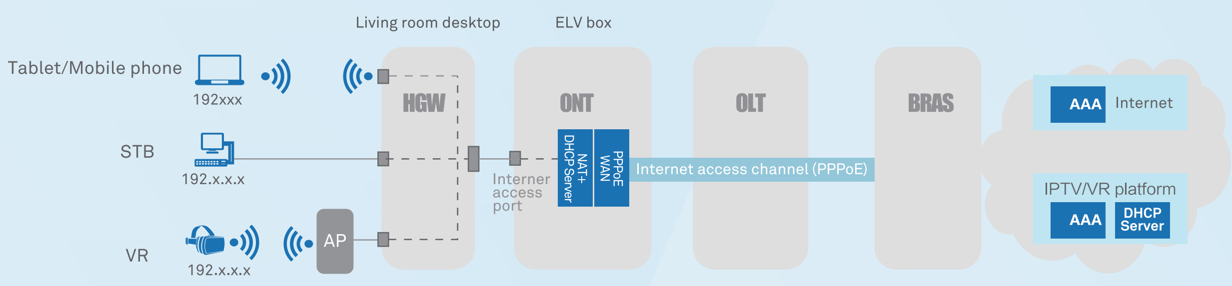
In this solution, when an operator provisions a service, a corresponding IPoE account needs to be added on the AAA server for the VR HMD. When the VR HMD goes online, it must support the DHCP Option 60/61 field for IPoE authentication. The reconstruction process is also complex. Therefore, this solution is not recommended.

3.5.3 Cloud VR Transport Solution in Single-Channel Scenarios

In the single-channel solution, ONTs are placed in extra-low-voltage boxes. The network cable between the living room and the extra-low-voltage box is used to connect to the HGW for Internet access. As a result, the STB does not have an independent network cable to connect to the dedicated IPTV port of the ONT, so it can only reuse the Internet channel.

After the Cloud VR HMD and corresponding AP are added, Cloud VR services can only be carried over single channels, as shown in Figure 3-16.

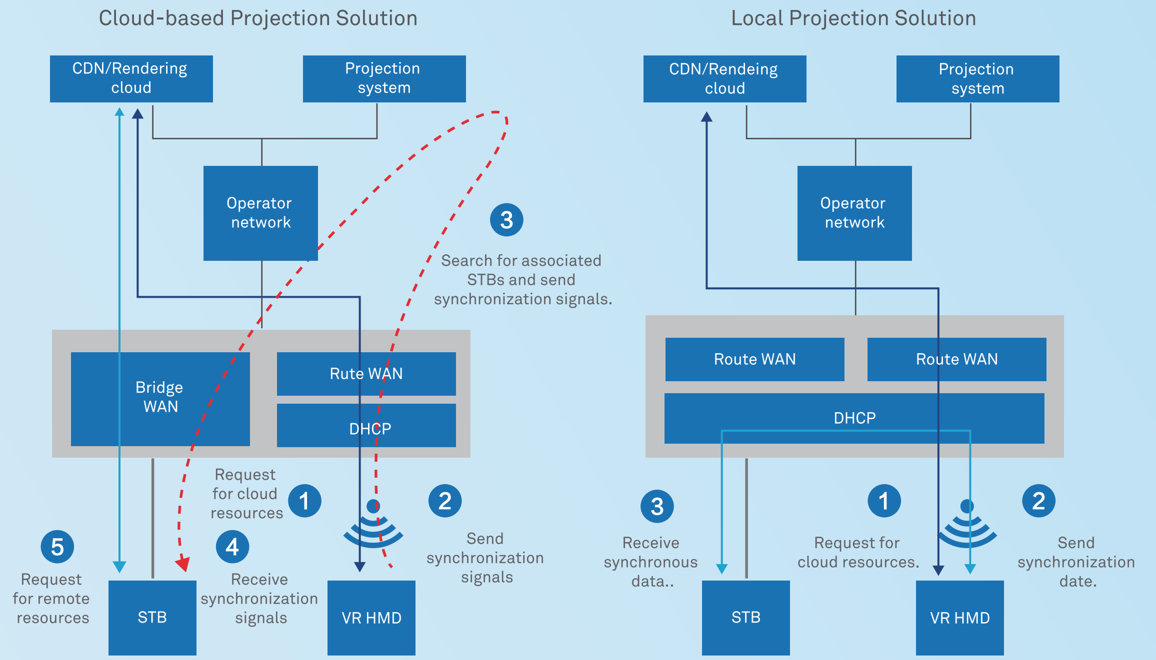
Figure 3-16 Cloud VR transport solution in single-channel scenarios



3.5.4 Suggestions for Screen Mirroring Traffic Transport

VR screen mirroring is the process of using a specific program to display the images that are viewed by a Cloud VR user on a terminal through the TV screen. During this process, users can share images in the virtual world with others, which is a rigid requirement for VR services. To implement Cloud VR screen mirroring, the HMD, STB, and headend need to exchange signaling and data. Currently, two types of Cloud VR screen mirroring solutions are provided: cloud-based (XMPP) and local (DLNA), as shown in Figure 3-17.

Figure 3-17 Comparison of the screen mirroring solutions



Cloud-based (XMPP) screen mirroring solution (recommended)

In this solution, the cloud-based system synchronizes traffic to the IPTV system, and the STB extracts screen mirroring traffic from the IPTV system. The traffic of the STB and that of the HMD is independent from each other. Therefore, the network bandwidth should be the total bandwidth needed for STB and HMD traffic.

This solution has been put into commercial use. It is relatively mature and reliable, and therefore is recommended.

Local (DLNA) screen mirroring solution (not recommended)

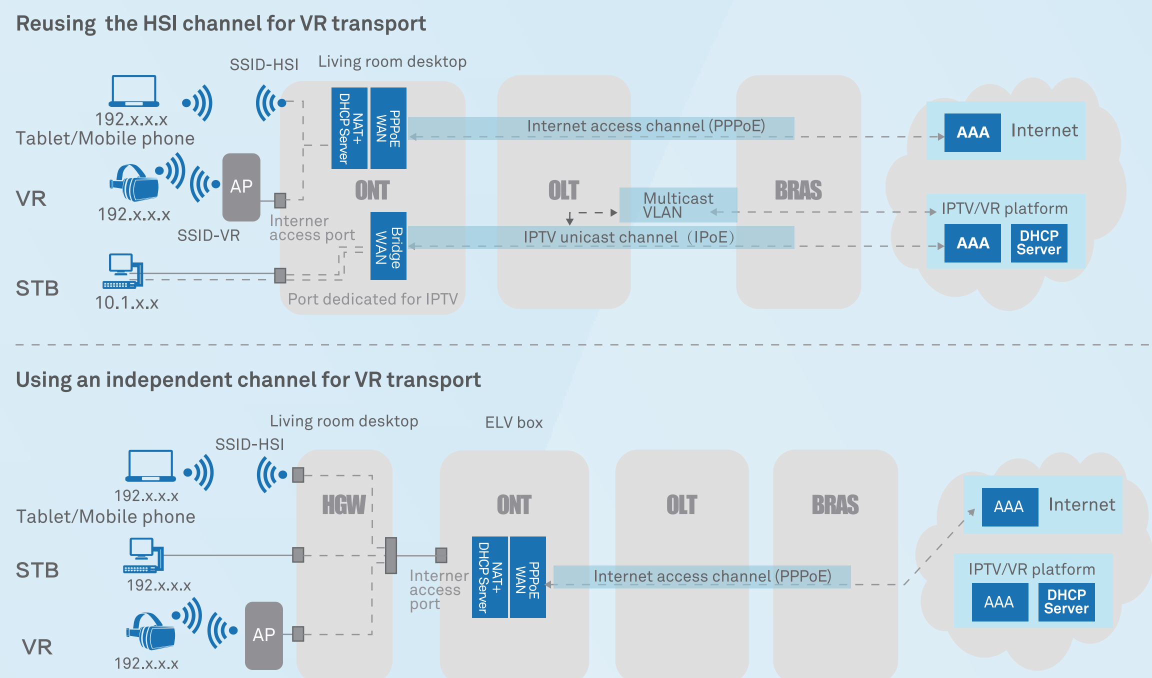
In this solution, DLNA is used to transmit screen mirroring traffic between the HMD and STB. Because the Wi-Fi AP and terminal need to forward two copies of traffic, the actual experience is poor and the terminal power consumption is high. In addition, this solution requires the HMD and STB on the same subnet (that is, Cloud VR reuses the IPTV channel), which is difficult to implement on the live network.

Therefore, this solution is not recommended.

3.5.5 Summary

- On the metro network, because Cloud VR reuses the Internet channel, it is recommended that the IP multicast/unicast technology be used for Cloud VR transport.
- On the access network, dual-channel and single-channel transport can be performed at the same time on the operator's network. It is recommended that Cloud VR reuse the Internet channel regardless of whether dual-channel or single-channel transport is being performed. In this way, the Cloud VR HMD can quickly access the network like a mobile phone, and no special network deployment or reconstruction is required.

Figure 3-18 Recommended VR deployment solutions



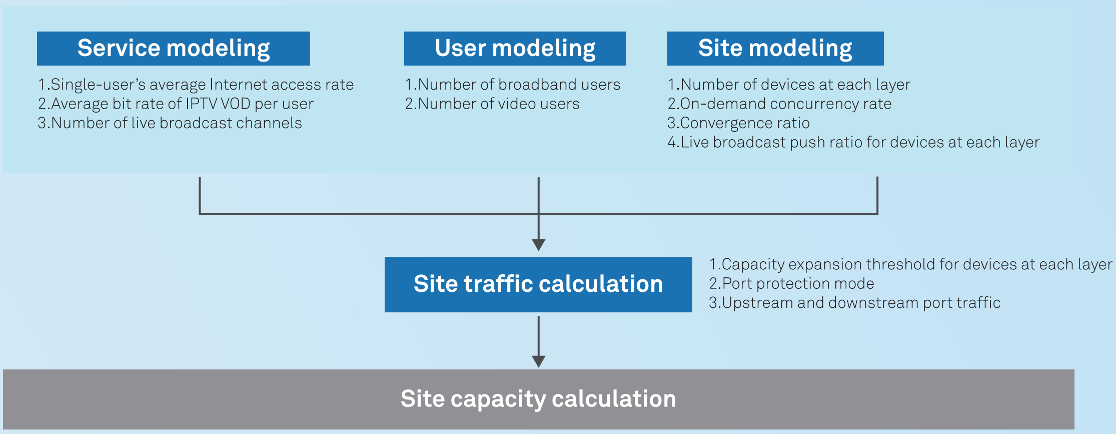
- The cloud-based screen mirroring solution has low requirements on the authentication, Wi-Fi, and CPU capabilities of the Cloud VR HMD. The actual effect of cloud-based screen mirroring is better than that of local screen mirroring. Therefore, cloud-based screen mirroring is recommended.

3.6 Bandwidth and QoS Deployment Design

3.6.1 Bandwidth Planning Method

During network capacity planning, operators need to model the service traffic rate, number of users, and site conditions. Based on the results of the modeling, operators can obtain a traffic forecast for the entire network and each site, and then add port protection and link capacity redundancy to obtain an accurate site capacity. Figure 3-19 shows the capacity planning process.

Figure 3-19 Capacity planning process for a VR network



- **Service modeling:** The objective of service modeling is to obtain data, including the average Internet access rate, average IPTV VOD bitrate, average bitrate of Cloud VR VOD (including gaming), IPTV live broadcast traffic, and Cloud VR live broadcast traffic. The calculation method is as follows:
  - Average Internet access rate ≈ Egress traffic from metro core devices (minus IPTV and VR traffic)/ Number of connected users.
  - Average IPTV VOD bitrate = ∑ IPTV VOD bitrate x VOD duration ratio. If the duration ratio of the 4K/HD bitrate is high, the average VOD bitrate is high. If the playback duration ratio of the SD bitrate is high, the average VOD bitrate is low.
  - Average bitrate of Cloud VR VOD (including gaming) = ∑ Cloud VR VOD bitrate x Usage duration ratio
  - Total live broadcast traffic = ∑ Channel bitrate x Number of channels. (Live broadcast channels include IPTV live broadcast channels and VR live broadcast channels.)

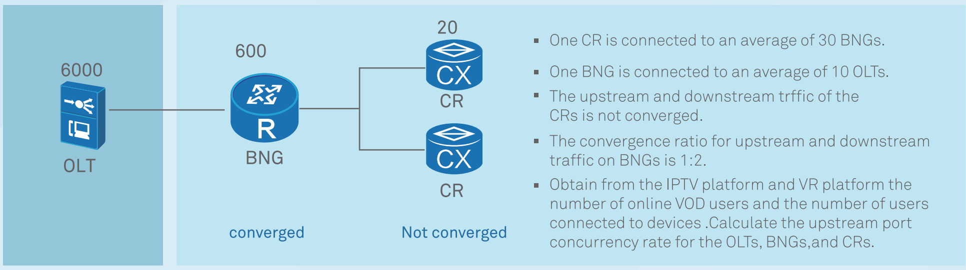
- **User modeling:** The objective of user modeling is to obtain the number of network-wide broadband users, the number of video users, and the subsequent growth target data. The data is usually determined by an operator's marketing department based on existing data and business development targets. Table 3-5 lists the results of user modeling.

Table 3-5 User modeling results

Year	2017	2018	2019	2020
Number of Broadband Users	10000000	11000000	12000000	12500000
IPTV Video Penetration Rate	50%	60%	80%	100%
Number of IPTV Video Users	5000000	6600000	9600000	12500000
Cloud VR Penetration Rate	-	1%	5%	10%
Number of Cloud VR Users	-	110000	550000	1100000

- **Site modeling:** The objective of site modeling is to define the site topology, the number of sites, site concurrency rate, and convergence ratio to prepare for future site capacity calculations. Figure 3-20 shows the information involved in site modeling.

Figure 3-20 Site modeling



After the service modeling, user modeling, and site modeling, a site's capacity requirements can be determined. The general calculation process is as follows:

- Internet access traffic at a site = Number of broadband users x Average Internet access rate per user
- IPTV VOD traffic at a site = Number of concurrent IPTV users x Average bitrate of VOD users
- Cloud VR VOD (including gaming) traffic at a site = Number of concurrent Cloud VR VOD users x Cloud VR average bitrate
- Live broadcast traffic at a site = Total live broadcast traffic (including live VR broadcasts) x Live channel push rate of a device
- Traffic volume at a site = Internet access traffic + IPTV VOD traffic + Cloud VR VOD (including gaming) traffic + Live broadcast traffic

You can further estimate a site's device port requirements based on the traffic volume at the site and the network topology.

3.6.2 QoS Deployment Suggestions

Since different services have different network requirements, and they need to be classified. To ensure QoS, services with different priorities enter queues with different port priorities.

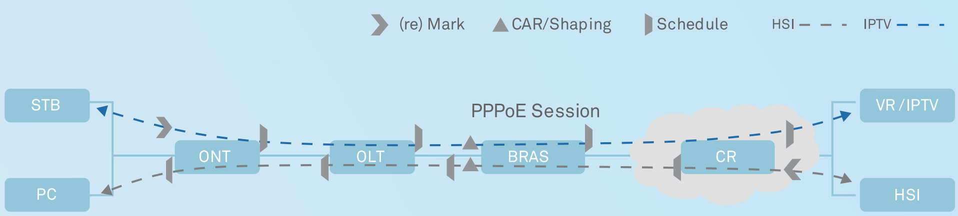
- IPTV/VR live broadcast: Sensitive to packet loss, which affects lots of users. It requires a high priority.
- VR gaming: Strong-interaction VR gaming, which is sensitive to latency. It requires a high priority.
- IPTV/VR VOD: Ensures self-operated VOD services preferentially in compliance with traffic planning.
- Internet OTT: Ensures basic bandwidth and best-effort forwarding.

Table 3-6 Suggestions for video service priority allocation

Services	802.1P	DSCP	EXP	Wi-Fi WMM
IPTV live broadcast, VR live broadcast, VR gaming	5	101110 (EF)	5	AC_VI
IPTV VOD, VR VOD	4	100010(AF4)	4	AC_VI
HSI	0	000000（BE）	0	AC_BE

After the priorities have been defined, the corresponding actions need to be performed on network nodes in order for QoS to take effect. QoS actions include remarking priority, CAR/shaping, and scheduling. At least one type of action needs to be deployed on network nodes. The typical deployment rules are as follows:

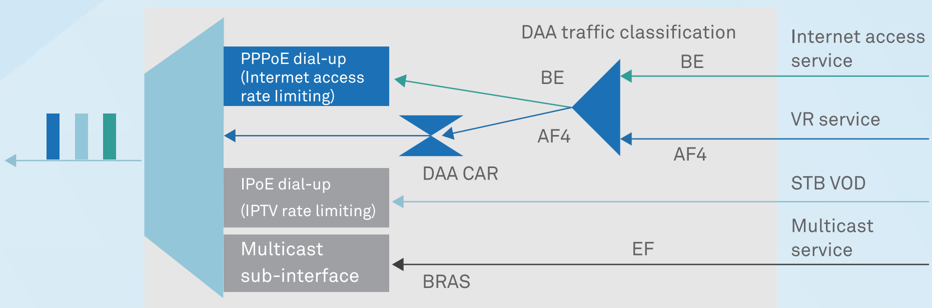
Figure 3-21 E2E QoS deployment suggestions



- **Remarking priority deployment:** Generally, the ONT identifies IPTV traffic based on different ports or DHCP packet characteristics in the upstream direction and remarks the traffic priority. In the downstream direction, the CR identifies the corresponding services based on the IPTV or VR address segment or port + VLAN ID and remarks the service priority.
- **CAR/shaping (rate limiting):** Generally, the CAR or shaping mode can be used by the BRAS to limit the rate of upstream and downstream packets based on the rate limit defined in the service package. No buffer is used for CAR rate limiting, and no scheduling process is involved. Therefore, no queuing latency is introduced. However, burst traffic is transmitted transparently downstream. CAR rate limiting is applicable to scenarios where the downstream device buffer is large. In the shaping mode, user traffic is shaped through queues. Burst traffic is suppressed to the 10 ms level, which has a small impact on the downstream. Traffic shaping also introduces a delay jitter. Shaping is applicable to scenarios where the downstream device buffer is small. With Cloud VR, you are advised to use the CAR mode because the shaping mode introduces a delay jitter.

In Cloud VR deployment, it is recommended that VR services reuse the Internet channel. To prevent VR services from being affected by Internet package rate limiting, you are advised to deploy DAA to separate VR services for independent rate limiting. As shown in Figure 3-22, multicast services are carried over independent sub-interfaces without undergoing rate limitation. The VoD service is limited by IPoE dial-up. The Internet access service and VR service are carried by the same PPPoE dial-up. DAA is deployed on the PPPoE Internet access channel to separate VR services and use DAA CAR to limit the rate, which prevents Internet access services from having an impact on VR services.

Figure 3-22 DAA deployment on the PPPoE Internet access channel



- **Scheduled deployment:** The core objective of scheduled deployment is to ensure VR and IPTV traffic preferentially and avoid the starvation of HSI services. Scheduling policies can slightly vary depending on network nodes.
  - **Metro devices:** Because there are many services, the metro network usually uses the SP+WFQ scheduling mode. The SP scheduling mode is generally used for services with high importance but low traffic, such as voice, management, and live broadcast services. The WFQ scheduling mode is used for video, enterprise, and HSI services. The WFQ queue weight is critical and needs to be set based on the traffic volume of each service. Assume that a site's multicast traffic is 0.7 Gbit/s, the VoD traffic is 2.5 Gbit/s, and two devices are bound through 2 x 10GE trunks. Then assume that the multicast traffic ratio is 3.5% and the VoD traffic ratio is 12.5%. Considering the uneven hash of port aggregation and some unexpected factors, it is recommended that the actual multicast queue weight be reset to 10% or higher and the VoD queue weight be 25% or higher.

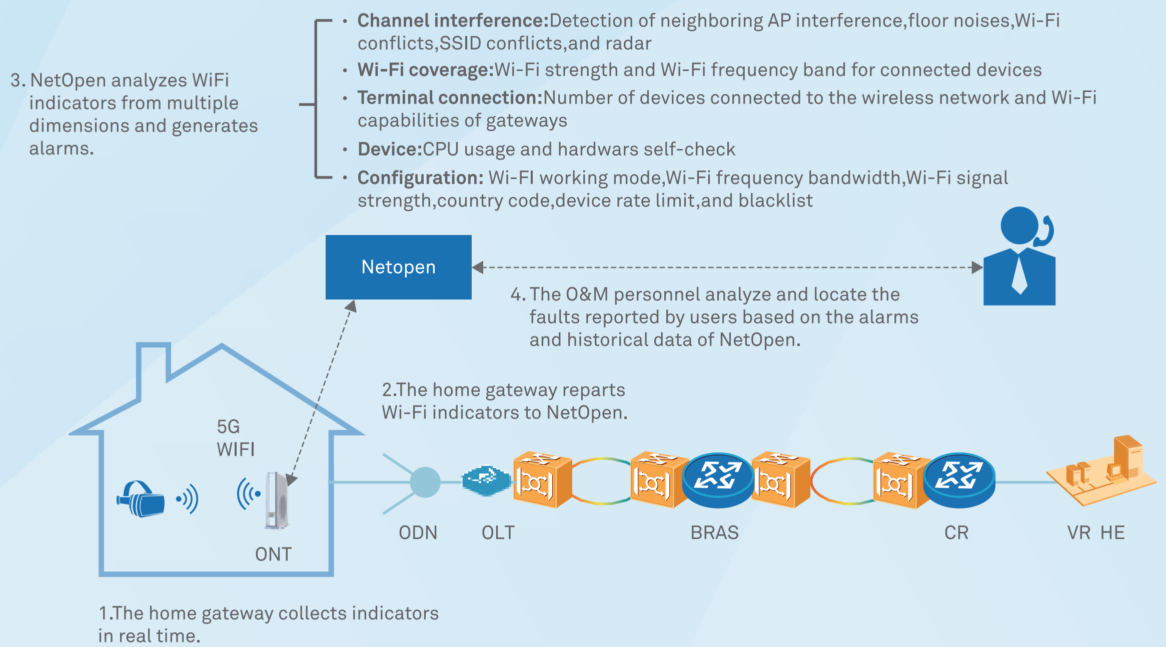
- **Access OLT:** If there are a number of services on the OLT, adopt SP+WFQ scheduling. If there are only broadband services on the OLT, the default SP scheduling mode can be used to avoid complex planning and deployment. The PON ports are planned by split ratio, and the reserved bandwidth is sufficient. Even if the SP scheduling mode is used, there is still an extremely low probability that Internet access traffic will be affected by video traffic and fail to be forwarded. The upstream video traffic on the OLT's upstream port is very small. Therefore, it is hard for Internet access traffic to be affected by the video traffic and not be forwarded.
- **Wi-Fi air interface:** If the video and common Internet access services share a Wi-Fi channel, it is recommended that the Wi-Fi Multimedia (WMM) mechanism be used to ensure that the video traffic is forwarded preferentially. This is done so by preferentially preempting the radio channel for the video service.

3.7 Cloud VR O&M Solution

The current Cloud VR O&M system has not been built. It is also difficult to perform CloudVR O&M. According to a classification of poor-QoE problems with 4K IPTV, more than 60% of problems occur on the home Wi-Fi side. Therefore, you are advised to temporarily analyze home Wi-Fi indicators using the Wi-Fi Sense solution to guarantee Cloud VR services on home networks.

The core component of the solution is NetOpen. This communicates with the ONT and Cloud VR-dedicated APs to obtain Wi-Fi indicators for comprehensive analysis. It also identifies problems in the home network and provides optimization measures. The implementation process is as follows:

Figure 3-23 Guaranteed-experience provided by the Wi-Fi Sense solution



1. After obtaining the IP address from the BRAS through the PPPoE Internet access channel, the home gateway registers with NetOpen using the domain name.

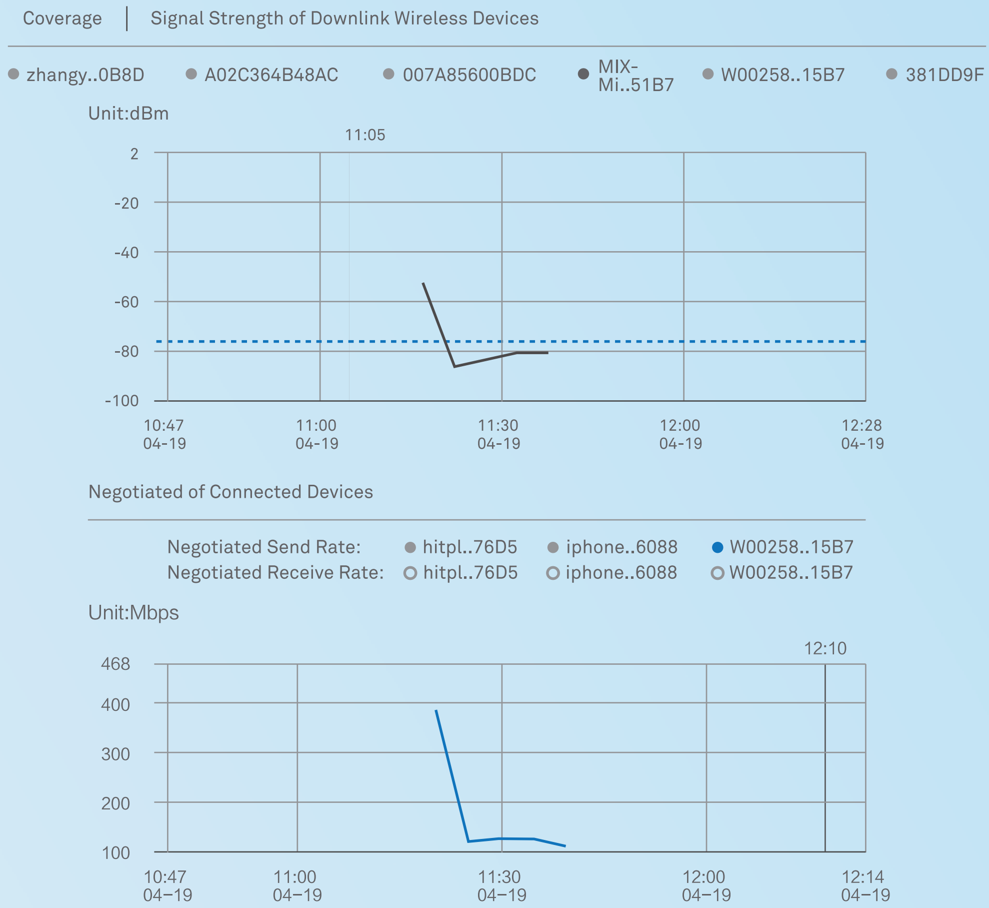
2. The home gateway integrates the indicator collection plug-in to collect home network indicators in multiple dimensions and report them to NetOpen in a timely manner. As shown in the preceding figure, the home gateway monitors key information such as Wi-Fi information, home network topology, connected device information, and signal strength and download rate of connected devices, and periodically reports the collected information to NetOpen.

3. After receiving the data reported by the home gateway, NetOpen generates alarm information for factors that may affect user experience based on analysis of channel interference, Wi-Fi coverage, terminal connections, devices, and configurations. It then generates historical data reports.

After receiving users' complaints about their VR experience, the operator can use NetOpen to determine terminal indicators such as the home network topology, Wi-Fi strength of the VR HMD, and negotiated rate, analyze whether the problem has been caused by the VR HMD, and then analyze channel interference, configuration, and device information to find out the cause of the poor VR experience.

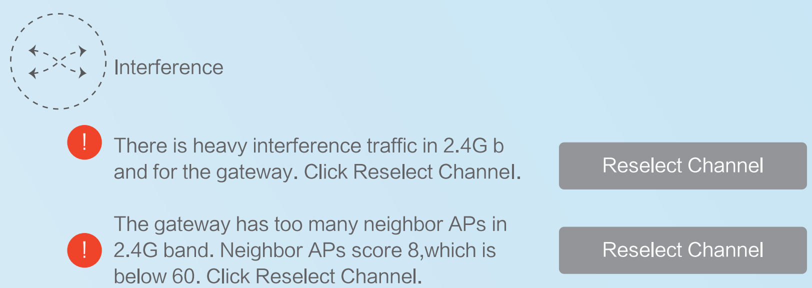
As shown in Figure 3-24, the historical curves of the signal strength and the negotiated rate of the Wi-Fi terminal show that the negotiated rate decreases due to weak Wi-Fi signal strength on the terminal. This results in a worse VR experience.

Figure 3-24 Weak Wi-Fi signal strength, resulting in poor VR quality



In addition to signal strength and the negotiated rate, co-channel interference is another possible reason for video quality deterioration. As shown in Figure 3-25, when severe interference is detected, NetOpen reports an alarm to notify about channel deterioration. You can manually reselect a Wi-Fi channel to optimize it.

Figure 3-25 Severe Wi-Fi channel interference, resulting in poor VR quality



04 Assumption of the Cloud VR Network in the Comfortable-Experience Phase

This chapter analyzes the theory of transport network deployment solution for Cloud VR services in the comfortable-experience phase. Currently, no commercial case is available.

4.1 Assumption of the Target Network Architecture

In the comfortable-experience phase of Cloud VR services, the bandwidth of a single VR service is 260 Mbit/s. After the 4K IPTV and Internet access services are provisioned, the recommended user bandwidth is as follows: 260 Mbit/s (VR) + 50 Mbit/s (4K IPTV) + 100 Mbit/s (HSI) = 400 Mbit/s. The VR projection service is downloaded through the 4K IPTV channel. The headend needs to compress the VR projection traffic to the bandwidth level of 4K videos. If the headend cannot compress the projection traffic, the bandwidth changes to the following: 260 Mbit/s (VR) + 260 Mbit/s (4K IPTV, including projection) + 100 Mbit/s (HSI) = 620 Mbit/s. In the future, most headends will be able to compress projection traffic, and the bandwidth will be unified to 400 Mbit/s.

In this phase, the network RTT is 15 ms. See Table 4-1 for details.

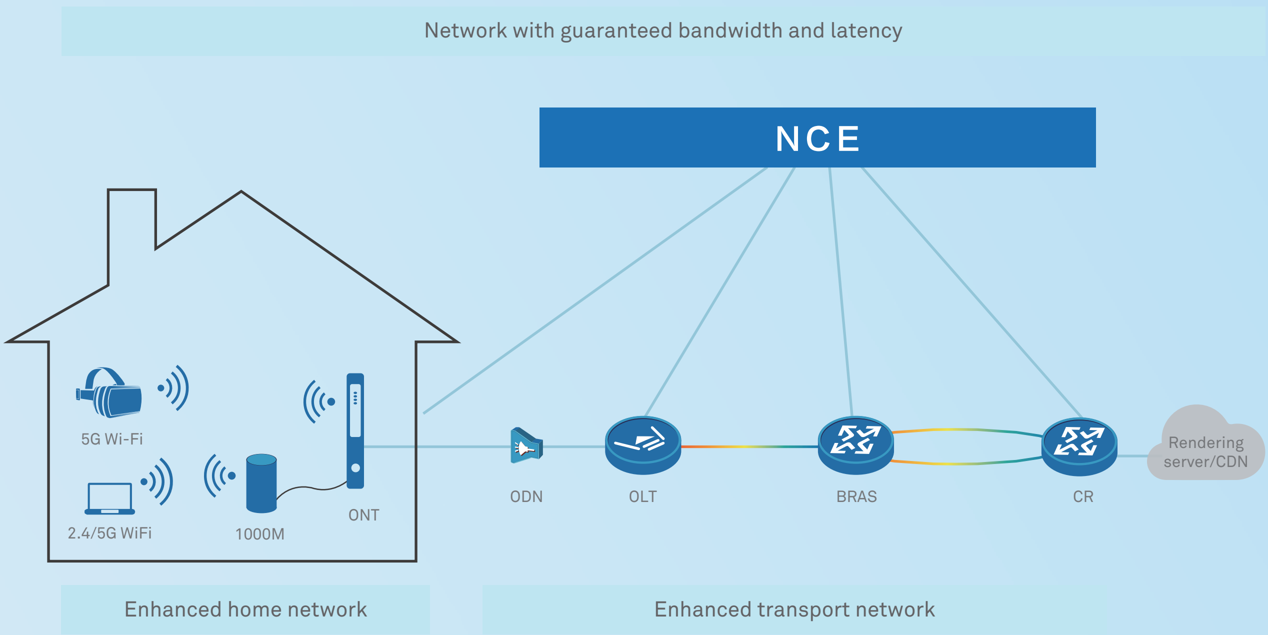
Table 4-1 RTT requirements in the comfortable-experience phase of Cloud VR services

E2E Network RTT	Home Wi-Fi RTT	Fixed Access RTT	Metro Transport RTT
≤15 ms	≤7 ms	≤2 ms	≤6 ms

Cloud VR has high requirements on bandwidth and latency in this phase, so the Wi-Fi access and transport network technologies need to be enhanced. A new network architecture also needs to be constructed to guarantee both the bandwidth and latency.

The core concept of the comfortable-experience Cloud VR solution is "Enhanced home network/ transport network + Bandwidth and latency guaranteed network". See Figure 4-1.

Figure 4-1 Target network architecture in the comfortable-experience phase of Cloud VR



- **Enhanced home network:** Like the fair-experience phase, independent APs are still recommended for the home network in this phase. However, the Wi-Fi capability needs to be upgraded so that the rate will reach 260 Mbit/s or higher and the latency will reach 7 ms or shorter.
- **Enhanced transport network:** The 10G GPON devices are deployed on the entire access network, and the capacity of the metro network is upgraded to N x 100 Gbit/s or Tbit/s, and the cloud rendering server is moved downwards.
- **Network with guaranteed latency and bandwidth:** The concept of guaranteeing latency and bandwidth is introduced to reconstruct the network.

4.2 Assumption of the Home Network Solution

The comfortable-experience phase inherits the networking mode from the fair-experience phase. Independent high-performance APs are used to carry Cloud VR services. However, the Wi-Fi rate must reach 260 Mbit/s or higher and the latency must reach 7 ms or shorter. Therefore, IEEE 802.11ac 4 x 4 MIMO or 802.11ax technology must be used.

4.2.1 IEEE 802.11ac 4 x 4 MIMO

In the fair-experience phase of Cloud VR, 5 GHz Wi-Fi uses a frequency bandwidth of 80 MHz, home 5G Wi-Fi has two weak interference sources, the VR HMD supports 2 x 2 MIMO, and the Wi-Fi rate uses the MCS6 rate. Considering a duty cycle of 50% and transmission loss of 40%, the rate of the 80 MHz frequency bandwidth is 175 Mbit/s.

In the comfortable-experience phase, APs and VR HMDs can support higher-rate spatial streams to increase bandwidth, as shown in Figure 4-2.

- If 3 x 3 MIMO is used, the connection rate is at the MCS5 level upon certain interference deterioration, and the actual rate is 234 Mbit/s (780 Mbit/s x Duty cycle of 50% x Efficiency of 60%). This brings risks to the transport of comfortable-experience VR.
- If 4 x 4 MIMO is used, the connection rate is at the MCS5 level upon certain interference deterioration, and the actual rate is 312 Mbit/s (1040 Mbit/s x Duty cycle of 50% x Efficiency of 60%). This meets the requirements of comfortable-experience VR.

Therefore, it is recommended that APs and VR HMDs be upgraded to support 4 x 4 MIMO to meet the requirements of comfortable-experience VR.

Table 4-2 Wi-Fi rates corresponding to IEEE 802.11ac 3 x 3 MIMO and 4 x 4 MIMO

MCS index[a]	Spatial Streams	Modulation type	Coding rate	Data rate (in Mbit/s) [9][b]							
				20MHz channels		40MHz channels		80MHz channels		160MHz channels	
				800ns GI	400 ns GI	800 ns GI	400 ns GI	800ns GI	400 ns GI	800ns GI	400 ns GI
5	3	64-QAM	2/3	156	173.3	324	360	702	780	1404	1560
6	3	64-QAM	3/4	175.5	195	364.5	405	N/A	N/A	1579.5	1755
7	3	64-QAM	5/6	195	216.7	405	450	877.5	975	1755	1950
8	3	256-QAM	3/4	234	260	486	540	1053	1170	2106	2340
9	3	256-QAM	5/6	260	288.9	540	600	1170	1300	2340	2600
5	4	64-QAM	2/3	208	231.2	432	480	936	1040	1872	2080
6	4	64-QAM	3/4	234	260	486	540	1053.2	1170	2106	2340
7	4	64-QAM	5/6	260	288.8	540	600	1170	1300	2340	2600
8	4	256-QAM	3/4	312	346.8	648	720	1404	1560	2808	3120
9	4	256-QAM	5/6	N/A	N/A	720	800	1560	1733.2	3120	3466.8

4.2.2 IEEE 802.11ax

Based on the 5G Wi-Fi standard IEEE 802.11ac, the following improvements have been made in the formation of IEEE 802.11ax:

- OFDMA is introduced to improve the efficiency of a single channel's bandwidth utilization.
- 1024-QAM is introduced to increase the physical rate by nearly 40%.
- The number of subcarriers is four times the number in IEEE 802.11ac, widening coverage.
- Uplink MU-MIMO is supported, increasing the air interface efficiency and providing better transmission efficiency for multi-user scenarios.

IEEE 802.11ax can achieve a maximum ideal air interface rate of 10 Gbit/s. After the bandwidth loss caused by overhead and signal attenuation is eliminated, the actual data rate can meet the requirements of comfortable-experience and ideal-experience VR. Currently, the IEEE 802.11ax standard is mature, but supports only a few products.

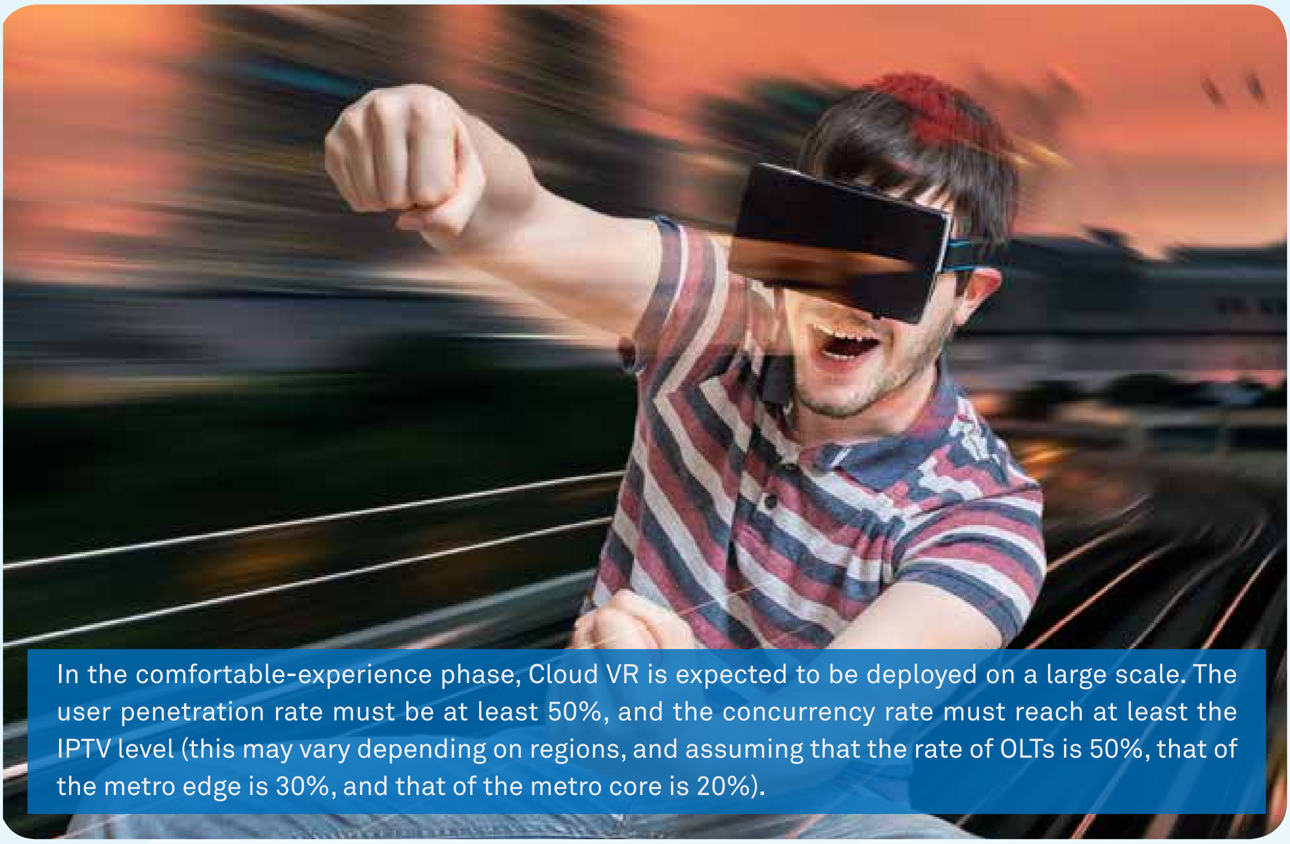
4.3 Technical Requirements on the Access Network

In the comfortable-experience phase, the total access bandwidth of Cloud VR, IPTV, and HSI services is 400 Mbit/s. As described in the previous chapter, EPON/GPON is not suitable for large-scale deployment of fair-experience Cloud VR services, not to mention comfortable-experience Cloud VR services. Therefore, only 10G EPON/GPON is recommended.

As described in the following table, 10G EPON/GPON cannot reach the 400 Mbit/s bandwidth if the split ratio is 1:64. Therefore, the actual number of installation users needs to be controlled. If the split ratio is 1:32, the bandwidth requirements for comfortable-experience VR can be satisfied.

PON	Capacity	Split Ratio	Convergence Ratio	Bandwidth Available to Users	Support for VR in the Comfort-Experience Phase
10G EPON/GPON	10Gbit/s	1:64	50%	312 Mbit/s	Limited support
		1:32	50%	625 Mbit/s	Support

4.4 Technical Requirements on the Metro Network



In the comfortable-experience phase, Cloud VR is expected to be deployed on a large scale. The user penetration rate must be at least 50%, and the concurrency rate must reach at least the IPTV level (this may vary depending on regions, and assuming that the rate of OLTs is 50%, that of the metro edge is 30%, and that of the metro core is 20%).

The new capacity requirements for Cloud VR on the metro network can then be calculated as follows:

- **Capacity required by OLT upstream ports:** Number of OLT users (assuming that it is 1500) x VR user penetration rate 50% x Concurrency rate of 50% x Bitrate of fair-experience VR (assuming that it is 90 Mbit/s) = 33.75 Gbit/s
- **Capacity required by metro edge devices:** Number of edge device users (assuming that it is 20,000) x VR user penetration rate of 50% x Concurrency rate of 30% x Comfortable-experience VR bitrate (assuming that it is 90 Mbit/s) = 270 Gbit/s
- **Capacity required by metro core devices:** Number of core device users (assuming that it is 1 million) x VR user penetration rate of 50% x Concurrency rate of 20% x Comfortable-experience VR bitrate (assuming that it is 90 Mbit/s) = 9 Tbit/s

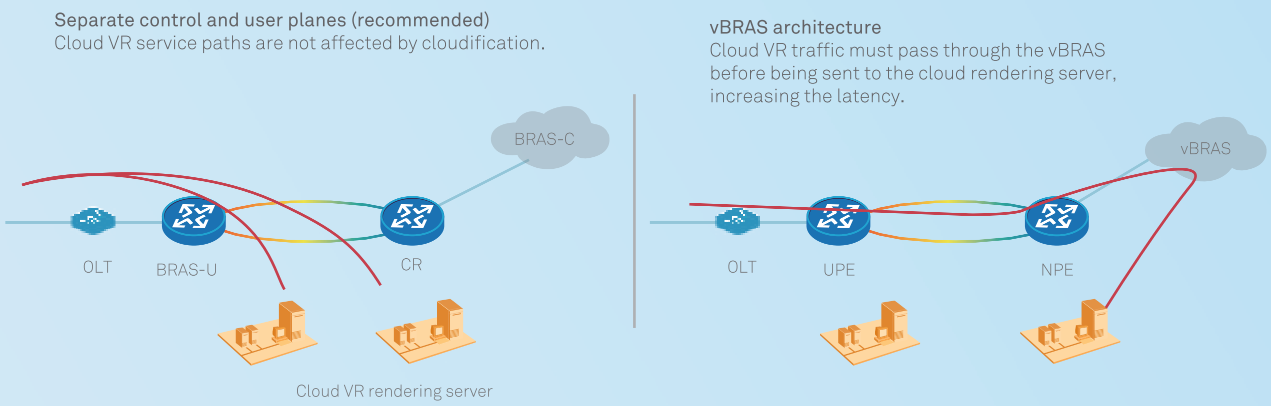
Therefore, after comfortable-experience Cloud VR is deployed on a large scale, the capacity requirements of the metro network are huge, meaning that boards/devices with higher rates and integration are required.

- It is recommended that the OLT upstream ports be upgraded to 4 x 10GE at least. If possible, upgrade them to 2 x 100GE.
- Metro edge devices must be upgraded to 4 x 100GE at least and must be connected to the metro core network.
- It is recommended that metro core devices be upgraded to the Tbit/s cluster platforms.

In addition to bandwidth, the latency of the metro network must be less than 6 ms (including the one on the CDN network). It is recommended that the overall forwarding latency of metro devices and the forwarding latency of the CDN network be less than 1 ms, with the remaining 4 ms reserved for the latency introduced by the fiber distance and queue cache. This requires that the CDN/cloud rendering server be deployed within the metro network.

In this phase, the cloud-based architecture of the metro network is gradually deployed. To reduce the forwarding latency, it is recommended that the cloud-based architecture adopt the CU separation mode (that is, the control plane is cloud-based and the forwarding plane continues to use physical devices). The fully software-based vBRAS mode is not recommended.

Figure 4-2 Cloud-based architecture of CU separation on the metro network

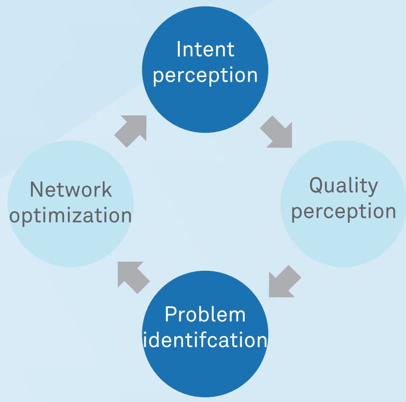


4.5 Assumption of the Guaranteed-Bandwidth and Latency Solution

Bandwidth can be guaranteed through a traditional Wi-Fi/PON upgrade and the expansion of the metro network capacity. Guaranteeing latency is a new topic. No mature architecture or commercial solution is currently available. The following only describes the theoretical requirements of the solution.

Theoretically, there are four requirements for the network with guaranteed bandwidth and latency, as shown in Figure 4-3.

Figure 4-3 Requirements for the network with guaranteed bandwidth and latency



- **Intent perception:** Because there are various services with different SLAs and levels of importance on the network, to guarantee the optimal Cloud VR experience, Cloud VR services and their SLAs need to be identified based on intent perception.
- **Quality perception:** The service quality of Cloud VR and the corresponding network quality both need to be measured and evaluated to form a database for subsequent problem identification and optimization.
- **Problem identification:** Based on the data collected in quality perception, big data and AI technologies can be used to classify and analyze problems to better find bottlenecks in the network.
- **Network optimization:** Automatic and manual optimization measures can be taken for network bottlenecks to ensure that the network is always in the optimal transport state for Cloud VR. For example, for Wi-Fi bottlenecks, an automatic channel calibration technology may be used to improve the transmission rate. If the network capacity is insufficient, it needs to be expanded manually.

In addition to these engineering methods, product capabilities can also be improved using several technical methods, thereby reducing the bandwidth consumption and latency requirements of Cloud VR. These methods include but are not limited to reducing Wi-Fi latency, reducing the bandwidth consumption of the projection proxy, and using FOV for live broadcasting.

05 Expectation of the Cloud VR Network in the Ideal-Experience Phase

Alongside improvements made to the screen resolution and chip performance of VR HMDs and the quality of VR content, VR videos are gradually evolving towards ideal-experience (full-view 12K and 24K). This will require bandwidth of 1 Gbit/s or higher and network RTT of less than or equal to 8 ms. Table 5-1 describes the requirements for each network.

Table 5-1 Latency requirements in the ideal-experience phase of Cloud VR

E2E Network RTT	Home Wi-Fi RTT	Fixed Access RTT	Metro Transport RTT
≤8 ms	≤5ms	≤2ms	≤1ms

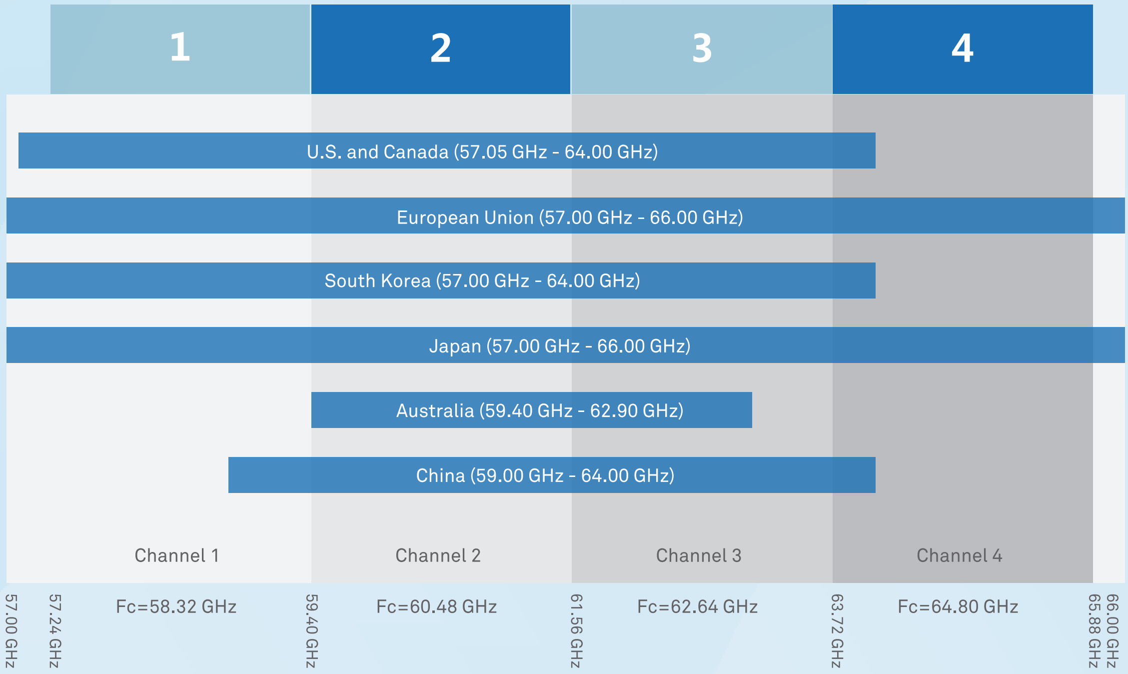
In the ideal-experience phase, networks need to evolve towards higher bandwidth and lower latency.

- **Home network Wi-Fi technology:** Supports the X x Gbit/s bandwidth rate. It is recommended that IEEE 802.11ax or 60 GHz Wi-Fi be used to further reduce interference and latency.
- **Access technology:** The access network needs to be upgraded to 25G/50G PON to provide Gbit/s access for each user.
- **Deterministic low-latency transport network:** The cloud rendering server is deployed on the edge of the metro network. In addition, network slicing and cloud-network synergy technologies are used to guarantee deterministic low latency.

5.1 Wi-Fi Technology Evolution: 60 GHz

Regardless of whether 2.4G or 5G Wi-Fi is used, it is difficult to ensure that channels carrying VR services are not affected by adjacent Wi-Fi signals, even if channel optimization is performed. VR experience still faces challenges. In densely populated areas, the 60 GHz frequency band has more spectrum resources than the 5 GHz frequency band. In Figure 5-2, the frequency bandwidth is 2.16 GHz, and the number of frequencies supported varies depending on the area. It is hard, however, for 60 GHz Wi-Fi to be affected by neighboring APs due to its poor wall penetration capability. Therefore, 60 GHz Wi-Fi is suitable for VR services with small mobility and heavy traffic.

Figure 5-1 International free 60 GHz spectrum ranges

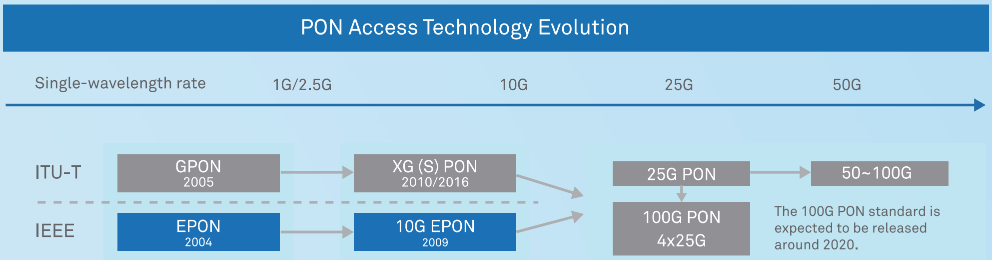


Based on the current IEEE 802.11ad technology, a wider channel can support a data transmission rate of up to 7 Gbit/s by using a low-power modulation scheme. Future IEEE 802.11ay is more advanced. It uses a more advanced 8-PSK debugging mode, supports a maximum of eight spatial streams, and extends the 2.16 GHz frequency bandwidth to 4.32 GHz, 6.48 GHz, and even 8.64 GHz frequency bandwidths. The theoretical maximum rate can reach 275 Gbit/s.

5.2 Access Technology Evolution: 25G to 50G and Even 100G PON

The next-generation PON technology involves 25G PON being implemented through single-wavelength acceleration, or 50G/100G PON being implemented by stacking multiple 25G wavelengths. Considering a convergence ratio of 50%, when the split ratio is 1:32 or 1:64, the 25G PON technology can provide 1 Gbit/s bandwidth for users, meeting the requirements for ideal-experience VR.

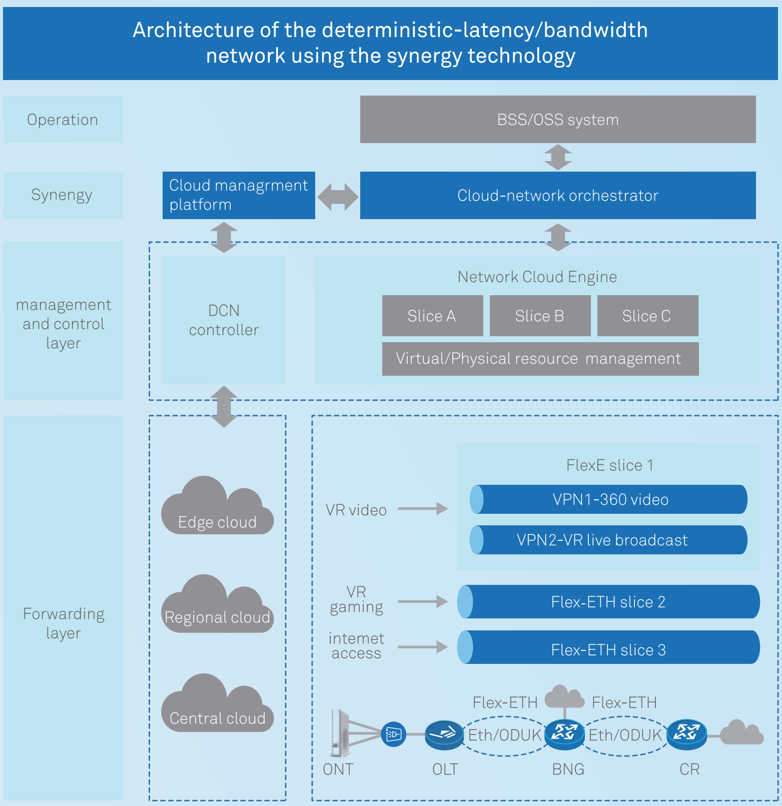
Figure 5-2 PON technology evolution



5.3 Cloud-Network Synergy Network with Deterministic Low Latency

The network with deterministic latency/bandwidth uses three technologies: edge rendering, network slicing, and cloud-network synergy.

Figure 5-3 Architecture of the deterministic-latency/bandwidth network with cloud-network synergy



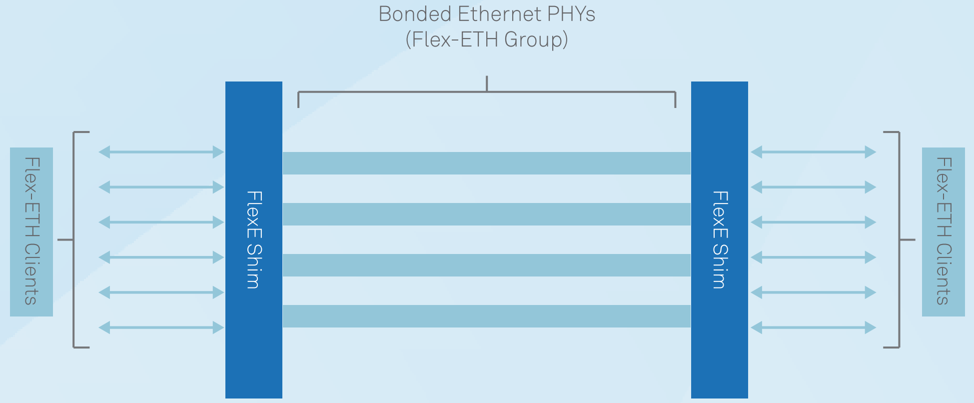
Edge Rendering

Edge rendering means that network edge devices have certain computing and storage capabilities and can implement real-time distribution of Cloud VR gaming/video services to reduce latency.

Network Slicing

The bandwidth of a traditional transport network is shared by multiple services. It is difficult to avoid service traffic conflicts and ensure the latency for latency-sensitive services. Flexible Ethernet (Flex-ETH) is an interface technology that enables isolated service transmission and network slicing on the transport network. In March 2016, the Optical Internetworking Forum (OIF) officially released the first-generation Flex-ETH standard that supports 100 Gbit/s. Flex-ETH is defined as the middle layer between Ethernet Layers 1 and 2. It implements on-demand configuration of user-side interface rates. Services on different interfaces are isolated from each other. Flex-ETH can meet the low latency requirements of Cloud VR services.

Figure 5-4 Overall architecture of Flex-ETH



Cloud-Network Synergy

Due to limited Flex-ETH network slices on network devices, it is difficult to allocate an independent Flex-ETH for each user in advance. To achieve optimal resource utilization, the cloud-network synergy technology is used to allocate physical pipes only when needed, achieving on-demand and dynamic resource allocation. The cloud-network synergy technology has the following characteristics:

- **On-demand:** Resources can be allocated based on specific Cloud VR service requirements on the network, such as bandwidth, latency, packet loss rate, and jitter. In addition, network resources can be expanded or reduced based on the volume of Cloud VR services on the network.
- **Dynamic:** Because the Cloud VR traffic is heavy, resources may be wasted if they are planned statically. The best way is to perform second-level E2E calculation when a Cloud VR service session is generated. Resources are dynamically allocated and scheduled on each device node that the service passes through, and resources can be released immediately when the service is terminated, thereby improving resource utilization.
- **E2E:** Cloud VR service data flows pass through each node in serial mode on the network. Congestion of any node on the entire path will affect the entire service. Therefore, to guarantee quality of Cloud VR services, E2E unified management and calculation are required, ensuring that each node provides quality guarantee for the service.
- **Open:** Cloud-network synergy is not only used for operators' self-operated services, but can also be used by OTTs to promote Cloud VR services. Cloud-network synergy should provide friendly, clear, and complete interfaces for OTTs to customize network quality for services such as Cloud VR.

A Acronyms and Abbreviations

Acronym andAbbreviation	Full Spelling
AP	Access point
BNG	Broadband network gateway
BRAS	Broadband remote access server
CDN	Content delivery network
CO	Central office
CR	Core router
CU	Control plane, User plane
DoF	Degrees of freedom
DFS	Dynamic Frequency Selection
FOV	Field of view
FTTB	Fiber to the building
FTTC	Fiber to the curb
FTTH	Fiber to the home
HGW	Home gateway
HLS	HTTP live streaming
HSI	High-speed Internet
KPI	Key performance indicator
MIMO	Multiple-input and multiple-output
MU-MIMO	Multi-user multiple-input and multiple-output
OFDM	Orthogonal frequency-division multiplexing
ONT	Optical network terminal
OLT	Optical line terminal
OTN	Optical transport network
OTT	Over the top
PON	Passive optical network
PPD	Pixels per degree
QAM	Quadrature amplitude modulation
RTT	Round-trip time
SD	Standard definition
STB	Set-top box
VR	Virtual reality
WMM	Wi-Fi Multimedia

HUAWEI TECHNOLOGIES CO., LTD.
Bantian, Longgang District
Shenzhen518129, P. R. China
Tel:+86-755-28780808

www.huawei.com