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Simulation and measurement: Feasibility study of Tactile Internet applications for mmWave virtual reality

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Numerous wearable technology companies have recently developed several head-mounted display (HMD) products for virtual reality (VR) services. 5G wireless networks aim at providing high-quality 3D multimedia services such as VR, augmented reality, and mixed reality. In this study, we examine the application of millimeter-wave (mmWave) technology to realize low-latency wireless communication between an HMD and its content server. However, the propagation characteristics of mmWave present several challenges such as the deafness, blockage, and beam alignment problems, and interference among content servers. In this study, we focus on an environment that provides VR services in the mmWave band and introduce existing techniques for addressing such challenges. In addition, we employ a commercialized IEEE 802.11ad VR dongle to measure the actual data rate of an mmWave VR application and identify the degree to which the performance deteriorates when the above problems occur. Finally, we verify the feasibility of the proposed solutions through a simulation of several VR scenarios in the mmWave band.

KEYWORDS
beam alignment problem, blockage problem, deafness problem, mmWave band, virtual reality

1 | INTRODUCTION

Virtual reality (VR) employs wearable devices, often in combination with other devices, to generate realistic images, audio, and other sensations that simulate physical presence in an imaginary environment. VR technology can be applied to various industries for creating new services and changing our way of life [1]. It comprises *content* consumed by consumers, a *network* for transmitting and receiving traffic, and *device hardware* for displaying VR videos. VR applications are popularly used as a form of entertainment such as in gaming. Moreover, VR is being studied in the medical, industrial, military, and educational domains [2,3]. In addition, technology development for devices such as glasses, body suits, gloves, and head-mounted displays (HMDs) can be competitive. In particular, major information and communications technology companies such as Samsung (Gear VR), Facebook (Oculus Rift), Google, Sony, and Microsoft are developing new HMD products.* Such devices can be used for various applications such as gaming, surgery training, and sightseeing [4].

To develop VR content that ensures 360-degree viewing and user-interaction experience, a network with high bandwidth (approximately 1 GHz) and low latency (10 ms)

*N. Pino, *The best VR headset 2019: which headset offers the most immersion for your buck?*, techradar, last modified Aug. 5, 2019, https://www.techradar.com/news/the-best-vr-headset

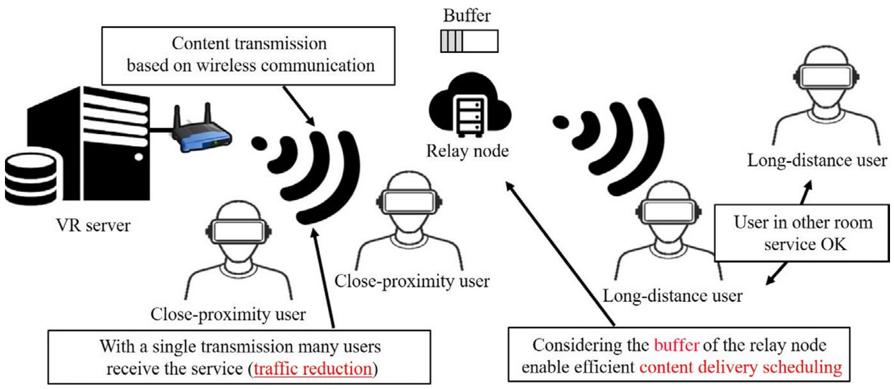

FIGURE 1 Advantages of a wireless VR system

is required [3]. In addition, high-quality VR systems must stream multiple Gbps of data from a content server to devices such as HMDs. Therefore, devices in existing VR systems are connected to content servers via wires such as high definition multimedia interface (HDMI) cables, which ensure a multi-Gbps data transfer rate. In practice, most commercialized HMD devices including the Oculus Rift and HTC Vive are connected via wires to a VR content server. However, wires associated with the device and content server can lead to the following problems:

- *Restriction of user movement*: User movement is restricted to the length of the wire. In addition, the user may become trapped because of an intricately entangled line.
- *Limitation of multiuser services*: If one content server transmits the same content to multiple users (eg, VR movie service), each user must be connected by separate wires.
- *Difficulty in expanding services*: New wired links (between server—server or server—devices) are required to expand services with additional content servers/user devices. Therefore, as the number of users or servers increases, the cost of expanding the service will also increase significantly.

One solution to the above problems is to configure wireless links between the VR device hardware and content server as presented in Figure 1. In practice, there has been an attempt to address the above drawbacks using a network adapter such as the HTC Vive wireless adapter.[†] Unfortunately, typical wireless systems such as Wi-Fi cannot support the required data transfer rates. Moreover, strict latency constraints on VR systems (approximately 10 ms) preclude the use of compression/decompression algorithms to accommodate lower data transfer rates [5]. Therefore, to replace an HDMI cable with a data transfer rate of 1.8 Gbps[‡] with a wireless link, we must employ a wide frequency band with a low-latency service. Similarly, Tactile Internet,[§] which ensures minimal delays associated with transmission, has been gaining considerable attention for VR systems [6].

A core technology of Tactile Internet services is the application of a millimeter-wave (mmWave) band. The term mmWave refers to high-frequency radio frequency signals of bandwidth 30 GHz (wavelength: 10 mm) to 300 GHz (wavelength: 1 mm). The mmWave frequency is divided into licensed frequency, which mainly uses the 28 GHz band (wavelength: 10 mm), and unlicensed frequency, which uses the band of frequencies 60 GHz (wavelength: 5 mm) and above. The licensed mmWave band is used by service providers in outdoor environments to establish high-capacity links such as wireless backhaul [7,8] or V2X links for autonomous driving [9]. On the other hand, the unlicensed mmWave band has been used in mobile edge computing in indoor environments [10]. For instance, the 60-GHz band frequency has been used as a link for cache-prefetching, AR/VR, and computing offloading between terminals and edge nodes.

In addition, a hybrid technique that uses 28 GHz as a backhaul and 60 GHz as access links is being considered. Several vendors are in the process of commercializing VR system products that use the unlicensed mmWave band,[‖] because VR applications operate in indoor environments with limited coverage. The 802.11ay standard operates in the mmWave band and can transmit over a bandwidth of up to 8.64 GHz (channel bonding), exhibiting a data transfer rate greater than 10 Gbps or 20 Gbps using a multiple-input multiple-output (MIMO) system, which has the advantages of better spatial reuse and longer transmission range. However, the use of mmWave links for VR applications has its own challenges. As such high-frequency signals require a clear line-of-sight (LOS) between the transmitter and the receiver, they do not perform well in the presence of obstacles or in the case of reflections. In other words, such links are effective when the receiver on the

[†]HTC Vive, "VIVE Wireless Adapter," accessed Aug. 15, https://www.vive.com/us/wireless-adapter/.

[‡]High-speed HDMI (Category 2) uses up to 1.8 Gbps of bandwidth.

[§]According to the International Telecommunication Union (ITU), Tactile Internet is defined as a service that combines ultra-low latency with extremely high availability, reliability, and security.

[‖]I. Khan, *Qualcomm's new 60 GHz Wi-Fi chips promise better VR*, Engadget, last modified 16 October 2018, https://www.engadget.com/2018/10/16/qualcomm-60ghz-chips/

headset faces the transmitter and has a clear LOS. If the user turns his/her head to look around or if other people in the environment obstruct the receiver's LOS to the transmitter, the signal will be lost. In fact, if the user places his/her hand in front of the headset, it will block the signal and result in an interruption of the data stream. This problem is further complicated by the fact that mmWave antennas are highly directional and typically generate narrower beams. Therefore, even a small obstacle such as a user's hand can block the signal. While temporary outages are common in wireless communication, VR data are non-elastic; they cannot tolerate any degradation in the signal-to-noise ratio (SNR) or data transfer rate.

One naive solution for overcoming such challenges involves deploying multiple mmWave transmitters in the room to ensure that a clear LOS always exists between the transmitter and the headset receiver. However, this defeats the purpose of a wireless design because it requires enormous cabling complexity, involving many HDMI cables being laid in the environment to connect each transmitter to the content server. Furthermore, the requirement of multiple full-fledged mmWave transceivers will significantly increase the cost of VR systems and limit their adoption in the consumer market.

In this article, we present a discussion on the feasibility of Tactile Internet applications for mmWave VR systems. We assume that each user wearing an HMD receives services from a content server through beamforming. Furthermore, we measure user satisfaction based on the desired quality of VR video and latency, including the data rate that can be achieved by considering the interference caused by other content servers and users in the mmWave VR application scenario. Finally, we present a discussion on the limitations associated with the upper layer such as the *deafness problem, blockage problem, and beam misalignment* when employing the mmWave VR system. We then present the appropriate solutions to these issues. In addition, we use a commercialized IEEE 802.11ad VR dongle to measure the actual data rate of an mmWave VR system and identify how the existing technique can improve performance via simulation.

First, we present the technical challenges of mmWave VR systems. Subsequently, we present a discussion on the relevant techniques for overcoming the above limitations, and we demonstrate examples of solutions to the problems. The performance of the mmWave VR system is evaluated based on case studies. Finally, we present the conclusions and suggest future directions of research.

2 | REQUIREMENTS FOR MMWAVE VR

This section includes a discussion on the requirements for implementing an mmWave VR environment. Particularly, owing to the capacity available using mmWave links, it is possible to send high-quality videos, which require higher data rates. In addition, we present a discussion on the frequency characteristics of the mmWave band.

2.1 | Requirements for high-quality VR services

For high-quality VR video streaming, a content server must transmit traffic with a data transfer rate of multi-Gbps. According to the 116th MPEG meeting, the following requirements must be satisfied to support high-quality VR video streaming [11].

- Pixels/degree of VR device30 (number of pixels per degree).
- Resolution: 11 520 × 6480 (four times the 4K vertical resolution).
- Frame rate: 90 fps (90 fps can prevent nausea through low delay).
- Environment-based or scene-based audio (360-degree surround sound and object-oriented audio).
- Maximum video and audio delay: 20 ms (time difference between user interaction and VR image and audio).

To satisfy the above requirements, 16K video data must be generated. Assuming a low-delay big-picture coding structure, a data rate of 1094 Mbps (approximately 1 Gbps) must be supported. Therefore, in the case in which several nodes that receive a VR service are deployed (eg, a VR military training application), the content server must support data transfer rates of approximately 1 Gbps times the number of nodes. Among existing wireless technologies, 802.11ad and 802.11ay use the mmWave band (60 GHz) and exhibit data transfer rates of 6.4 Gbps and 10 Gbps to 20 Gbps, respectively. This 60 GHz multi-Gbps wireless technology focuses on enabling wireless and real-time high-quality HD video transmission for wireless display applications. We conducted a feasibility study to verify if VR applications can be realized using 802.11ad technology.

2.2 | Frequency characteristics of mmWave

Even though mmWave wireless networks include several benefits based on the ultra-wide available bandwidth, the communication using mmWave wireless links is *highly directional* and *highly attenuated*, owing to their high carrier frequency in the 60 GHz IEEE 802.11ad LOS path loss model [12]:

$$L(d) = A + 20\log_{10} f + 10n\log_{10} d[\text{dB}], \tag{1}$$

where $A = 32.44$ dB is a specific value for a perfect isotropic antenna and d denotes distance in a kilometer scale. Furthermore, the path loss coefficient is set as $n = 2$, and f denotes the carrier frequency in gigahertz; therefore, $f = 60$. To provide services to VR devices located in other rooms, a technique for relaying messages by arranging relay nodes is required because of the high path loss in the mmWave band.

As beamforming is required, spatial reuse can be maximized and inter-node interference can be minimized. However, because of the propagation characteristics of mmWave, problems such as deafness,¶ blockage, interference, and misalignment from node mobility can occur. We present a discussion on these limitations in the context of the mmWave VR system in the following section.

3 | RESEARCH CHALLENGES FOR MMWAVE VR

In this section, we include the technical challenges faced by a mmWave VR system when providing high-quality VR video streaming.

3.1 | Deafness problem

As mentioned previously, the mmWave VR system is configured using a wireless connection between a content server and a VR device such as an HMD. A content server transmits video to a VR device through beamforming. Once a server manages a plurality of VR devices, they should send a content request frame to receive the service. However, if the server is communicating with the VR device in the other direction, it cannot receive the request message from the VR devices located at different locations. Consequently, the originator of the request message will send more messages, increasing the contention window. During this time, messages to the content server are blocked, that is, the *deafness problem* occurs (see Figure 2A).

The deafness duration increases significantly as the number of VR devices that receive content from the server [13] increases. To address such a problem, the VR device that requests for content must determine whether the server is currently in a deafness state (ie, whether it is providing content to another VR device). A fundamental solution to this problem involves identifying whether a node encounters deafness. In [13], a deafness-aware medium access control (DA-MAC) protocol that distinguishes deafness from collision by exploiting two channels (data and control) was proposed. According to the different responses to a content request frame based on the two channels, the DA-MAC sender can identify normal, deafness, and collision cases.

¶When a receiver is communicating in the other direction, it cannot hear the communication request of the neighboring nodes.

Applying their technology to the mmWave VR system, the VR user transmits a content request frame, which includes data and control channels, to the associated VR content server. Then, we can consider the following scenarios.

- *Normal case:* If the server is idle, it receives two content request frames from the data/control channels. Then, it sends a reply frame to both channels. If the server successfully receives request frames from both channels, it begins transmitting the data frame only on the data channel.
- *Deafness case:* If the content server provides services to another user, it receives only the request frame from the control channels. The VR user who transmitted the content request frame then receives only one reply frame from the control channel. Therefore, the node attempts to connect to another content server to provide VR services.
- *Collision case:* If the content server does not receive any data because two content request frames collide on either channel, the senders' (more than two VR users) retransmission timer will expire, and they will retransmit the content request frames on both channels after the back-off duration.

The VR user who transmits the content request frame can detect an actual network failure by distinguishing deafness from collision using the above technique. If the sender is aware that the receiver is in a deaf state, it begins communicating with another content server that can provide services to the user, thereby improving aggregate throughput.

3.2 | Blockage problem

In the mmWave VR system, the signal may be interrupted by a user experiencing the VR content or other obstacles in the room. As the VR device and content server in the mmWave link must employ a directional antenna to concentrate power and compensate for the high path loss, this problem becomes more severe [14,15]. The user experiencing the content may interfere with the establishment of a clear LOS between the device and the content server because of various obstacles such as the user's hand, head, and action, resulting in the attenuation of the received SNR (see Figure 2B).

In [16], the authors obtained the attenuated SNR values of 48%, 90%, and 110% caused by the user's hand, head, and action, respectively (in decibel scale). To address this problem, it is possible to consider increasing the number of content servers or to relay signals by arranging a relay node in a place where a clear LOS is possible between the content server and the relay node.

A principal solution to the blockage problem is transmitting content in the direction of the LOS path. Accordingly, the server's beam can be directed toward the wall so that the

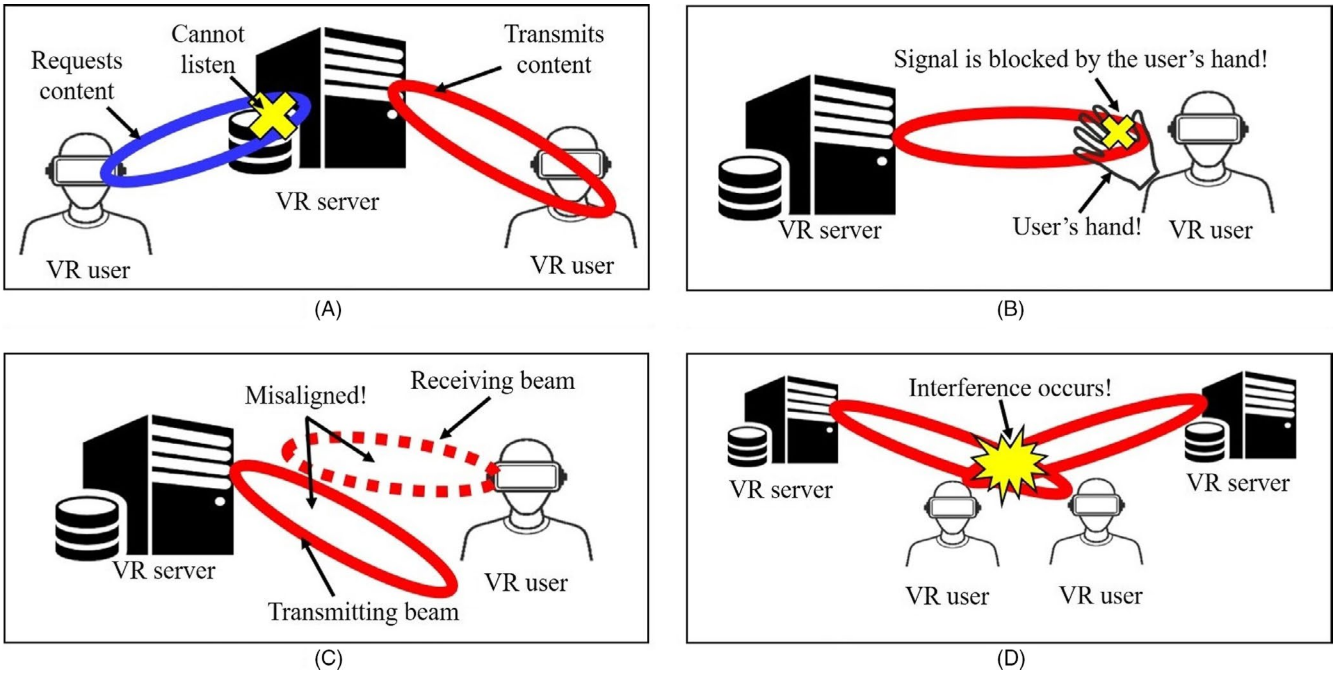

FIGURE 2 Technical challenges for mmWave VR systems: (A) Deafness problem, (B) blockage problem, (C) Beam misalignment, and (D) interference between VR servers

user can receive reflected signals. Unfortunately, the wall does not reflect the signal perfectly and scatters the signal, resulting in high signal attenuation.

In [16], the authors designed a programmable mmWave mirror for controlling the incidence and reflection angles. In their method, the SNR value between the content server and the HMD is monitored. When the SNR is lower than the threshold value, the signal is reflected by the mirror to maintain signal quality. However, their method has a limitation in that the reception/reflection angles of the mirrors are fixed; therefore, if the number of HMDs to be served is increased or the position of the HMD to be served is altered, a scalability problem arises because the mirrors must be re-installed.

Therefore, to address this problem efficiently, we require technology that can (a) monitor the location of the user, (b) search for the optimal reflection angle based on the user's behavior, and (c) relay the content (routing scheme).

3.3 | Beam misalignment

The movement of the VR headset creates a critical challenge for mmWave links. To compensate for the high path loss, mmWave radios use highly directional antennas to focus the signal power in a narrow beam. Such directional antennas can be implemented using phased arrays. As the wavelength is very small (in the order of a millimeter), tens or hundreds of such antennas can be packed into a small space, creating a pencil-beam antenna. The beam can be electronically steered in a few microseconds. However, the real challenge involves identifying the correct spatial direction that aligns the transmitter's beam with the receiver's beam. This is particularly difficult in VR applications because the headset is in a natural mobile state.

Numerous studies have demonstrated that even a minor head rotation of a few degrees can cause a major degradation in SNR [17]. Such a reduction in SNR creates outages in VR applications. This confirms the need for real-time beam tracking to realign the transmitter's and receiver's beams with the movement of the user's head (see Figure 2C).

To address the beam misalignment problem, it is necessary to arrange the transmission/reception beams by controlling the direction of the transmission beam in real time by capturing the location and orientation of the HMD. In fact, the HTC VR system uses a laser tracker and an inertial measurement unit to provide real-time tracking of the orientation and position of the HMD. However, this approach is not a fundamental solution because it requires additional laser tracker systems and is highly dependent on VR devices.

An alternative solution is to employ the ISM band used by Bluetooth or Wi-Fi as a control channel [18]. As the ISM band exhibits a lower frequency and smaller signal attenuation than the mmWave band, the signal can be transmitted over a long distance such that the direction and position information of the HMD can be transmitted in real time.** However, the ISM band has a low data rate and latency owing to its relatively low bandwidth, which limits the synchronization with the mmWave VR system.

**Most VR systems on the market support -/Bluetooth communication and the cost of implementation is very low [18].

3.4 | Interference between VR servers

In the mmWave band, the use of directional antennas can maximize spatial reuse, but interference between signals cannot be avoided when the number of receiving nodes increases. If a MIMO environment is assumed for the content server, it can simultaneously provide services to a large number of VR users. However, even if a MIMO environment is considered, the number of users that can simultaneously receive services is limited because of the limited computing power of a content server.

Therefore, if a large number of VR users are deployed in the topology—for example, a military training application—a large number of content servers must also be deployed. In this case, when there is no beam management technique, interference between signals generated from content servers cannot be avoided [19]. Interference between signals causes a deterioration in the quality of the received signal (ie, SNR) of the VR user, which makes it impossible to provide high-quality VR video (see Figure 2D). To address this problem, smart beam scheduling and load-balancing techniques between the VR user and the content server are required. In the mmWave environment, owing to the directivity of the signal, the inter-signal interference is smaller than that in the case of other technologies, and spatial reuse is maximized. However, interference can frequently occur in applications that deploy large nodes. To address this issue, it is best to position the content servers and VR users appropriately at locations where interference does not occur. However, if the node moves, the matched beam between the server and the node will be changed and interference occurs again. Therefore, the solution has limitations for application to VR systems with the mobility of nodes. Channel hopping, a technique conventionally used for interference management, can be an alternative solution. In this solution, the receiving node monitors the SNR. If the SNR falls below a predetermined threshold, the user can send a message to the content server to switch to another channel through the ISM control channel. The content server can select another candidate channel and switch to avoid interference.

4 | CASE STUDY FOR MMWAVE VR

4.1 | Experimental test

To measure how real data transfer rates can be achieved, we used an mmWave VR (IEEE 802.11ad-based) dongle (refer to Figure 3).[††] We connected the VR dongle to a laptop and measured the achievable data transfer rate using SpeedTest, an application that sends VR video (approximately 1 Gbps traffic generated) to a laptop computer equipped with a dongle. The detailed scenario topology is as follows:

- **Distance test:** measuring data rate by changing the LOS distance between transceivers from 0.5 m to 4 m.
- **Obstacle test**: installing obstacles such as book, hand, and head with a fixed distance of 1.5 m between transceivers.
- **Beam-align test**: measures data rate while changing the angle of the receiver with a fixed distance of 1.5 m between transceivers.
- **Interference test**: We arranged two sets of dongle devices across each other with a fixed distance of 1.5 m between transceivers.

In our experiment, we used a Peraso WiGig USB 3.0 dongle that supports a transmission power of 170 mW and a Phy rate of up to MCS7 (up to 1.9 Gbps) [20]. In addition, in all scenarios, all the dongles were lifted by a human and the experiment was measured along the distance.

As summarized in Table. 1, the achievable data transfer rate of the VR system on the market is approximately 900 Mbps, not 4.62 Gbps as provided by IEEE 802.11ad. Better performance can be achieved if the actual hardware and layer-to-layer transmission overhead can be overcome. In addition, the data transfer rate decreases as the distance increases because of high-signal attenuation in the mmWave band. Particularly after 3 m, the intensity of the signal suddenly drops and data rate drops by approximately 38% at a distance of 4 m. In an obstacle test, the achievable data rates fell by up to 23% when disturbed by a person's head. In addition, the achievable data rate is reduced according to the degree of misalignment between Tx and Rx, and the performance decreases by up to 70% when the beam is misaligned by 35 degrees. Finally, we measured the performance of interference with two sets of dongles. In this experiment, the closer the distance between the dongle sets, the lower was the achievable data rate. The performance is expected to decline sharply as more sets of dongles are deployed, owing to increased interference.

Therefore, such problems in the upper layer are yet to be addressed and must be solved using existing techniques that improve high-quality VR streaming capabilities.

4.2 | Simulation scenario

In this section, we measure the achievable data transfer rates and streaming quality based on the signal-to-interference-plus-noise ratio in an mmWave VR environment that exhibits interference from the surrounding beamforming. As simulation parameters, the transmission power of the content server is set to 19 dBm, the antenna gain to 24 dBi, and the carrier frequency to 60 GHz [21]. First, we measure the

[††] Although IEEE 802.11ay is the latest technology in the mmWave band, commercial products are yet to be released. Therefore, in this study, we used the IEEE 802.11ad dongle for convenience of the experiment.

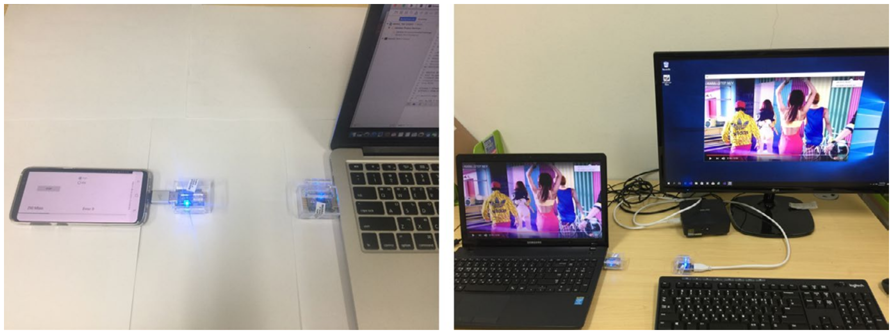

FIGURE 3 Experimental equipment for measuring the achievable data rate between the mmWave dongle and the content server

TABLE 1 Result of the experimental test (one dongle set (TX/ RX) for distance, obstacle, and beam alignment tests, and two sets of dongles were placed in the interference test. In a dongle set, the spacing between TX and RX is 1.5 m.)

Distance test	0.5 m	1 m	1.5 m	2 m	2.5 m	3 m	3.5 m	4 m
	928.5 Mbps	922.6 Mbps	893.7 Mbps	889.6 Mbps	883.4 Mbps	748.7 Mbps	670.5 Mbps	577.7 Mbps
Obstacle test	Obstacle: Book		Obstacle: Hand			Obstacle: Head		
	828.7 Mbps		875.6 Mbps			685.6 Mbps		
Beam align test	0 Degree		15 Degrees		25 Degrees		35 Degrees	
	922.6 Mbps		909.1 Mbps		657.4 Mbps		275.1 Mbps	
Interference test	1 m		2 m		3 m		4 m	
	693.3 Mbps		706.7 Mbps		763.7 Mbps		797.9 Mbps	

signal power received by a user from the content server and calculate the supported modulation coding scheme (MCS). Based on the MCS level, the achievable data transfer rate and the quality of streaming can be determined. As the current prototypes are all implemented based on a single-carrier mandatory MCS, we conducted our simulations based on this information, that is, the maximum is 4.62 Gbps with MCS12.

Figure 4 presents the VR-based military training scenario topology simulated in this study. In the simulation topology, it is assumed that a total of 24 users wear HMD devices and four content servers provide content to six soldiers through beam switching.[‡‡] In addition, it is assumed that the measurement area is 30 m × 30 m, the soldier's height is 180 cm, and each soldier can move within a private space of 3 m × 3 m.

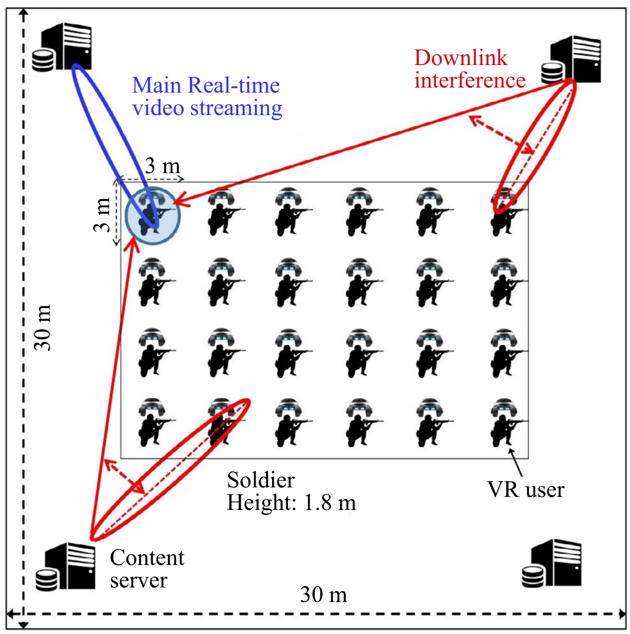

FIGURE 4 Reference VR scenario for military training with 60 GHz radio technologies (the presented size values are obtained from a dismounted soldier training system)

4.3 | Results and discussion: Achievable data rate

In this section, we present a discussion on the simulation results of the achievable data transfer rate, including the corresponding user satisfaction of video streaming while considering the interference phenomenon between content servers. In this simulation, each soldier randomly selects a content server. This helps determine the azimuth angle, elevation angle, and the direction of the antenna radiation pattern formed from the content server. In the simulation, the main video streaming link is assumed to be fixed. All other links between servers and devices are

‡‡P. Zamora, Virtual training puts the `real' in realistic environment, *United State Army (press release)*, Mar. 4, 2013.

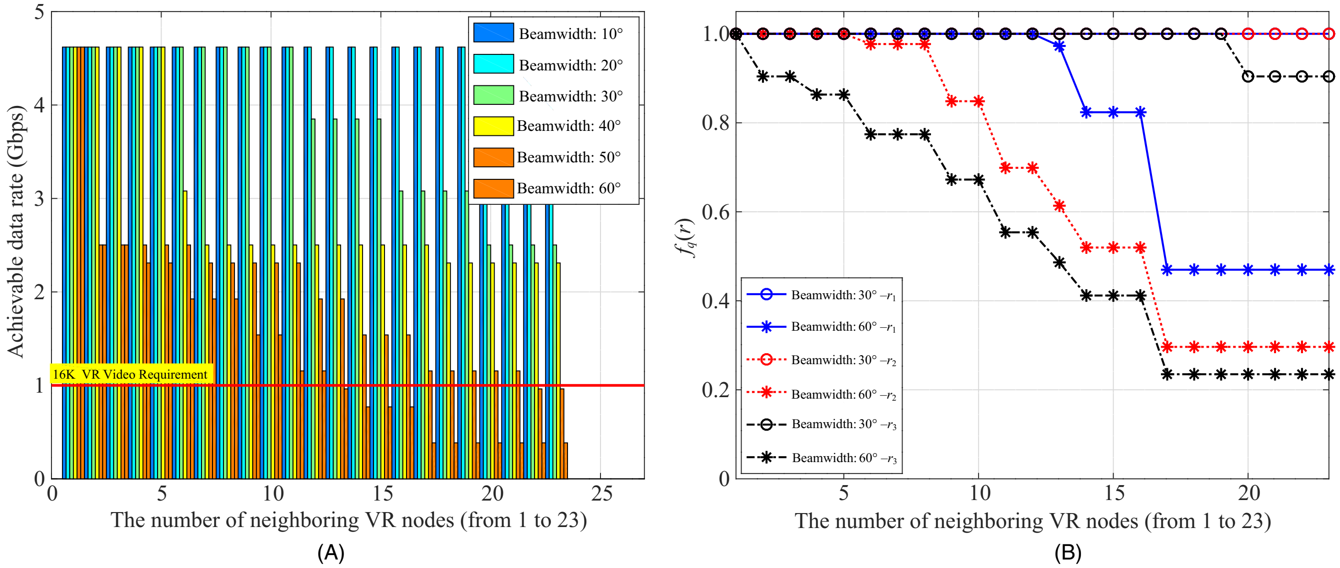

FIGURE 5 Achievable data transfer rate and quality of service (QoS) satisfaction of the main stream (one VR node and one content server); the number of neighboring nodes: 1 to 23; beamwidth 10 to 60 degrees for (A), 30 and 60 degrees for (B); r_{max} denotes the transfer rate requirement of the user data. (A) Achievable data rate (more than 1 Gbps is required to support high-quality VR streaming data). (B) Quality estimation $f_q(r)$ derived from achievable rate, $r_{max} = 1$ Gbps for r_1, $r_{max} = 2$ Gbps for r_2, and $r_{max} = 3$ Gbps for r_3

considered interference links. Assuming this environment, we change the number of neighboring VR nodes from 1 to 23 and the beamwidth from 10 degrees to 60 degrees while measuring the achievable data transfer rates and user satisfaction. If the attained achievable data transfer rate is less than the full-quality threshold, the quality degrades logarithmically and monotonously as presented in [22].

In Figure 5A, when the beamwidth is 10 or 20 degrees, the best MCS level is always provided even if the number of neighboring VR nodes is 23. If the MCS level is 12, the maximum achievable data transfer rate is 4.62 Gbps. Therefore, the main video streaming achieves the maximum quality $f_q(r) = 1$. However, when the beamwidth increases to 30 degrees or greater, the available MCS level decreases as the number of neighboring VR nodes increases. In fact, as the number of nodes increases, the interference of the main stream increases and the achievable data transfer rate is reduced because of interference from the signals reflected by the walls. Notably, the simulation determines the data transfer rate achievable on one channel, and IEEE 802.11ad uses four sub-channels; therefore, it was predicted that a larger number of VR nodes can be served if the problems associated with the upper layer are resolved.

As shown in Figure 5A, when the beam angle is 30 degrees or less, the QoS is fully satisfied for users receiving 16K VR video (approximately 1 Gbps) or higher video quality (approximately 2.3 Gbps), even if the number of neighboring nodes is 23. Once the beam angle is 60 degrees, the content server can provide the maximum video quality until the number of neighboring nodes is 12 for 16K VR video. However, thereafter, the video quality to be provided falls sharply for all VR videos.

Based on the extensive simulation, the impact of sources of interference on the performance degradation increases as (a) the beamwidth increases and (b) the number of interfering sources increases.

Figure 6A presents the data rate of VR systems based on IEEE 802.11ad and [13] compared with the theoretical maximum data rate shown in Figure 5. In this scenario, VR nodes and the content server suffer from interference and the deafness problem. As shown in the figure, the data rate of the main stream decreases as the number of neighboring VR nodes increases. In this scenario, as the number of content servers is smaller than the number of VR nodes when $N > 4$, content servers must provide service to more than two VR nodes. In other words, a content server that provides service to multiple nodes may face the deafness problem when a VR node sends a content request frame to the content server when communicating with another VR node. Therefore, in environments with VR nodes, interference and the deafness problem occur frequently. Therefore, the data transfer rate is low. In particular, we observed that the data transfer rate of IEEE 802.11ad-based technology, which does not address the deafness problem, sharply decreases as the number of nodes increases. However, a VR system based on [13], which addresses the deafness problem, demonstrated approximately a 40% performance improvement over the IEEE 802.11ad-based technology. In Figure 6B, when the number of VR users is 16 or more, the QoS is reduced for all users. Even if the users receiving 16K VR video ($r_{max} = 1$) are satisfied with the provided QoS, this scenario assumes that the VR node is stationary and located within the LOS distance. Therefore, in practical environments, the degradation of the quality factor can be more serious.

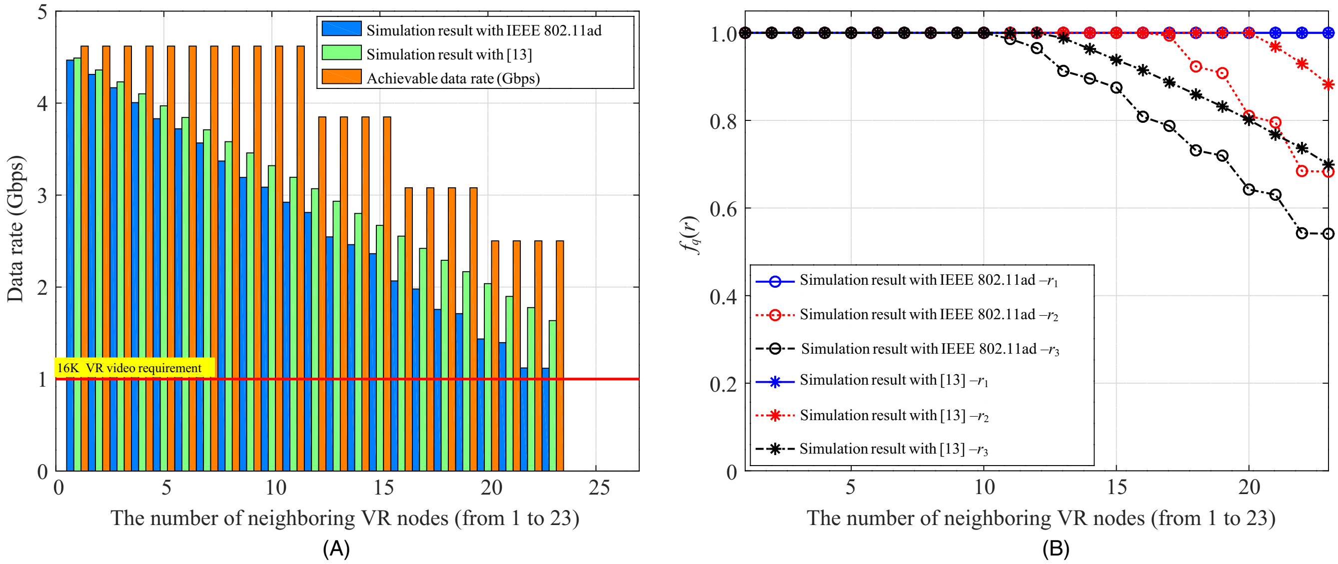

FIGURE 6 Simulation results for the data transfer rate and QoS satisfaction of the main stream in the deafness scenario; the number of neighboring nodes: 1 to 23; beamwidth is 30 degrees; r_{max} denotes the transfer rate requirement of the user data. (A) Simulation results for data rate (more than 1 Gbps is required to support high-quality VR streaming data). (B) Quality estimation $f_q(r)$ derived from achievable rate, $r_{max} = 1$ Gbps for r_1, $r_{max} = 2$ Gbps for r_2, and $r_{max} = 3$ Gbps for r_3

Figure 7A presents the data transfer rate of VR systems based on IEEE 802.11ad and [16] in a blockage scenario. In this scenario, we assume that the VR node moves along a limited area (3 m × 3 m per the VR node), which causes the blockage problem whereby the LOS is not formed for a certain period of time. Unlike the above results, when the number of VR nodes increased to 20 or more, it was confirmed that the VR node cannot receive the 16K video service (refer to Figure 7B). Inspired by the research in [16], we achieved an average performance improvement approximately 12% when installing mirrors to address the blockage problem (in this simulation, we deployed four mirrors in the given topology). Notably, as the number of nodes increased, the performance increased dramatically when the mirrors were installed. This is because the blockage problem frequently occurs when a large number of VR nodes are deployed within a limited topology size.

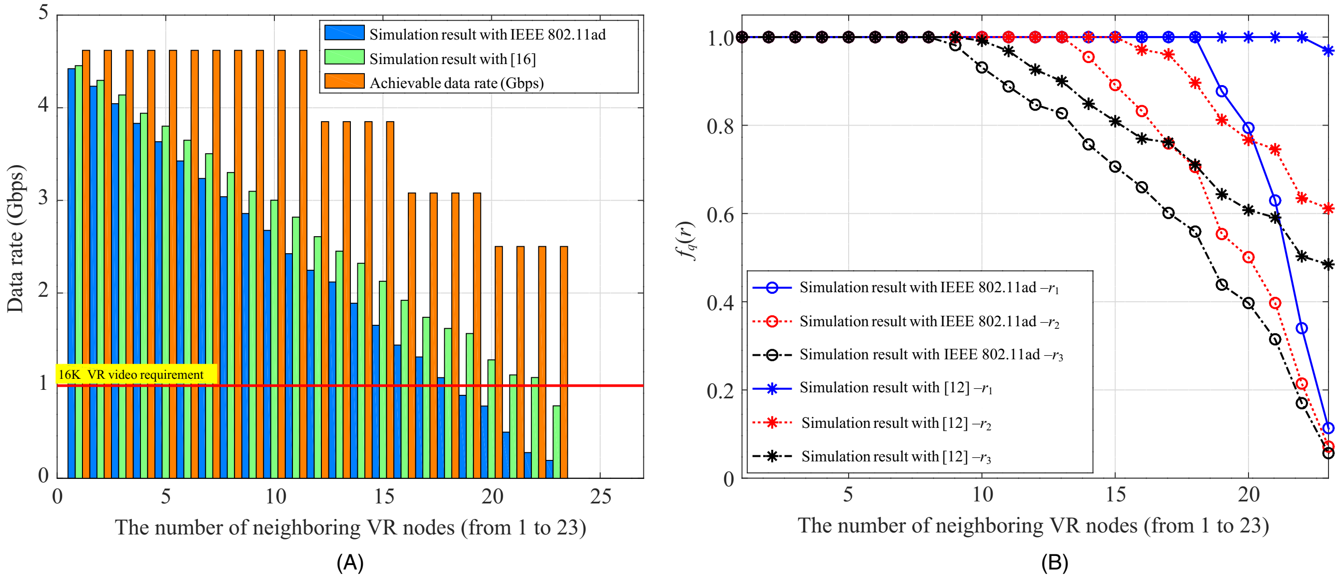

FIGURE 7 Simulation results for the data transfer rate and QoS satisfaction of the main stream in the blockage scenario; the number of neighboring nodes: 1 to 23; r_{max} denotes the transfer rate requirement of the user data. (A) Simulation results for data rate (more than 1 Gbps is required to support high-quality VR streaming data). (B) Quality estimation $f_q(r)$ derived from achievable rate, $r_{max} = 1$ Gbps for r_1, $r_{max} = 2$ Gbps for r_2, and $r_{max} = 3$ Gbps for r_3

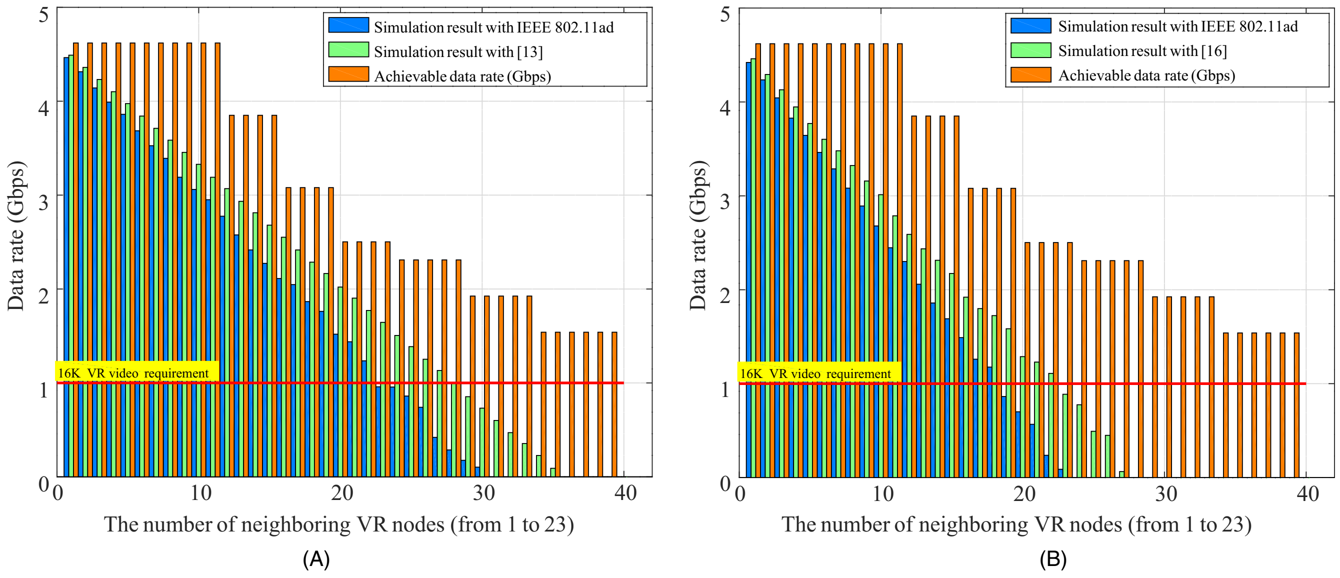

FIGURE 8 Simulation results for data transfer rate; the number of neighboring nodes: 1 to 40. (A) Simulation results of the data rate in a deafness scenario. (B) Simulation results of the data rate in a blockage scenario

In addition, we performed an experiment by increasing the number of users up to 40 in the same scenario topology for a large-scale simulation. Figure 8A,B shows the data transfer rate versus the number of neighboring VR nodes in the deafness and blockage scenarios, respectively. As shown in the figure, the data rate is below 1 Gbps when the number of users is more than 28 in the deafness scenario and more than 22 in the blockage scenario. Although, in theory, high-quality VR service is possible when a large number of nodes are deployed, the results of the experiment are below 1 Gbps. This problem is analyzed to be caused by interference between nodes owing to frequent beamforming as more VR nodes are serviced per content server.

4.4 | Results and Discussion: Latency

We measured the latency to evaluate the user's QoS. Figure 9 and Figure 10 illustrate the latency between the content server and the VR node in the deafness and blockage scenarios as described in the previous section, respectively. As shown in the figure, IEEE 802.11ad-based VR systems do not satisfy the minimum requirement of latency of 10 ms. This is because the IEEE 802.11ad-based VR system does not address the limitations associated with the upper layer, including deafness, blockage, and beam misalignment.

As shown in Figures 9 and 10, we determined that the performance degradation because of blockage is more critical than that because of deafness. This is because of the

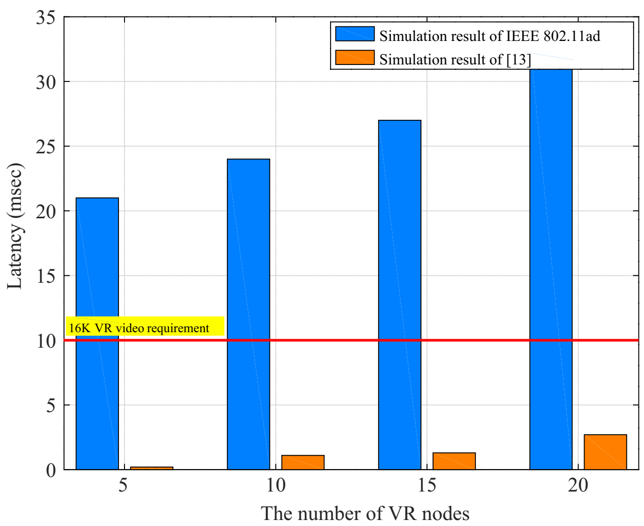

FIGURE 9 Latency vs the number of VR nodes in the deafness scenario

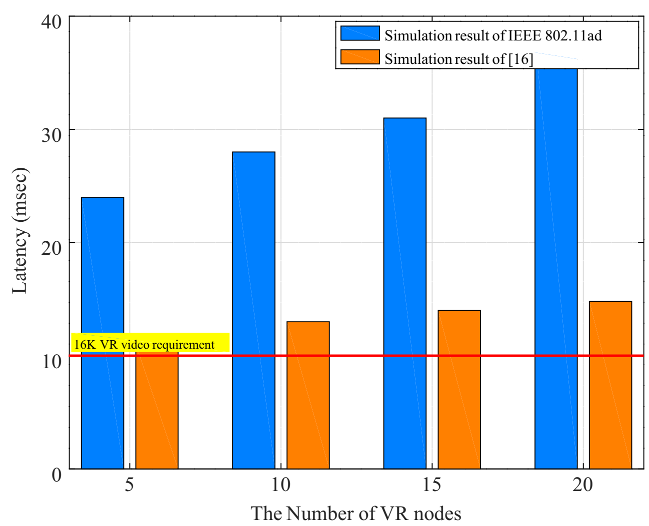

FIGURE 10 Latency vs the number of VR nodes in the blockage scenario (four mirrors are deployed for [16])

nature of VR applications, and communication disruptions arising out of blockage occur more frequently than the deafness problem. Fortunately, existing techniques (eg, [13]) that address the deafness problem appear to address the problem of latency increase because of deafness. However, as shown in Figure 10, techniques for addressing blockages [16] can be limiting in environments with a large number of nodes. Particularly, in an environment in which a large number of nodes are placed, the blocking phenomenon of the signal can be further intensified. Therefore, a relay technique capable of addressing the problem in this environment will be studied.

5 | CONCLUSION

To support user mobility and service scalability, existing VR systems connected via wires are expected to be replaced by wireless VR systems in the near future. In this article, we present a discussion on the feasibility of a wireless VR system using the mmWave band. mmWave VR systems exhibit very high data transfer rates. However, there are problems that must be addressed, including deafness, blockage, beam alignment, and interference. Based on our experiments, a commercialized mmWave VR system provides a data transfer rate of approximately 900 Mbps because of the overhead time between layers and the limited computing power of the hardware (eg, image processing time), and the achievable data transfer rate drops drastically when the above problems occur. We also simulated the VR scenario when the problem at the upper layer is resolved, that is, the maximum data transfer rate (4.62 Gbps/channel) provided by IEEE 802.11ad is available. Simulation results demonstrate that, when beamforming is performed using a thin beam, high-quality VR videos can be provided for each node even if the number of nodes increases. In addition, in the deafness and blockage scenarios, the performance is satisfactory when the existing techniques, for example 802.11ad or 802.11ay, are applied. However, the existing techniques still show limitations when a large number of nodes are deployed. In our future work, we will explore techniques to address blockage and deafness problems via building mmWave VR testbeds.

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