Received: 15 April 2018 | Revised: 29 June 2018 | Accepted: 23 July 2018
DOI: 10.1002/ett.3506

SPECIAL ISSUE ARTICLE

WILEY

360-degree video offloading using millimeter-wave communication for cyberphysical system

Hyun-Wook Kim[1] | Tuan Thanh Le[2] | Eun-Seok Ryu[2]

[1]Contents Convergence Research Center, Korea Electronics Technology Institute, Seongnam, Korea

[2]Department of Computer Engineering, Gachon University, Seongnam, Korea

Correspondence
Eun-Seok Ryu, Department of Computer Engineering, Gachon University, Seongnam 461-701, Korea.
Email: esryu@gachon.ac.kr

Funding information
Korea Electric Power Corporation, Grant/Award Number: R17XA05-68; GRRC program of Gyeonggi province

Abstract

This paper describes an adaptive scheme of 360-degree video streaming over millimeter-wave (mmWave) communication for cyberphysical system. It consists of two parts, ie, (1) 360-degree video streaming and offloading over mmWave 802.11ad 60 GHz wireless link and (2) 360-degree video decoding, postprocessing, and display by using scalable high-efficiency video coding. The mmWave communication is high-speed wireless technology to increase the capacity of video transmission. However, current studies on video streaming over mmWave focus on long distance, and mobile devices process many tasks such as video decoding, postprocessing, and display by themselves. Therefore, the performance of mobile device seriously degrades in the case of high-resolution video streaming, such as 4K. Furthermore, the synchronization of real-time video streaming at high speed is an important issue to ensure the quality of service (QoS), especially when the mobile device is moving. Thus, this paper focuses on real-time video streaming over mmWave with optimized QoS for high-resolution video. Furthermore, this study implemented an offloading mechanism to handle the offloading tasks between a powerful GPU-based PC and a mobile device. The experimental results show that the proposed method provides high-performance 360-degree video streaming in QoS-sensitive video streaming applications.

1 | INTRODUCTION

Currently, video streaming is the most popular service of multimedia systems. The transmission of compressed video over 2.4 GHz or 5 GHz wireless networks may not be suitable for certain delay-sensitive applications such as wireless virtual reality (VR) or video game interaction at high resolution. Specifically, it is extremely difficult to ensure the quality of service of high-resolution video streaming in real-time models. Because 4K video streaming applications require much greater wireless network capacity than previous HD services, it is difficult to maintain performance for 360 video streaming. Only a few approaches have been proposed to handle video streaming over millimeter-wave (mmWave) communication to provide high capacity.

Because of the development of large spectrum resources for multimedia services, mmWave communication has become a promising candidate to become the core technology for high-bandwidth multimedia systems. Recently, the mmWave 60-GHz band has attracted interest because it can provide up to 7 GHz of contiguous bandwidth. Therefore, it has excellent potential to satisfy the rapidly growing of demand for wireless network capacity.

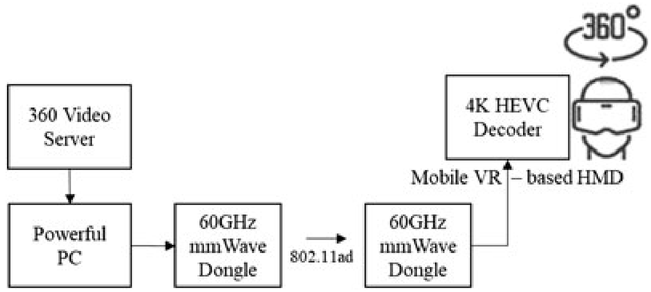


FIGURE 1 Conceptual architecture of the proposed system. HEVC, high-efficiency video coding; HMD, head-mounted device; mmWave, millimeter wave; VR, virtual reality

As shown in Figure 1, the new video coding technology was standardized, and the provided commercial version is called high-efficiency video coding (HEVC). High-efficiency video coding can provide as much as twice the bandwidth compared with H.264 advanced video coding technology. In other words, HEVC can double the bandwidth capacity for video transmission at the same data rate. Figure 1 also shows that the prosed system consists of a 360-degree video server and client, a mobile VR-based head-mounted device (HMD). Here, mobile VR supports both software and hardware 4K HEVC decoders. Now, in a joint effort between VR video and 360-degree video streaming, our purpose is to make 360 and VR video content look even more realistic in a higher bandwidth system. Additionally, the proposed scheme aims to implement a flexible system with the equirectangular projection. The most familiar representation is one where latitudes and longitudes are used to form a square grid. This is known as equirectangular projection. Equirectangular projection has the advantages of being both rectangular and straightforward to visualize. It is also relatively easy to manipulate using existing video editing tools. However, when used for video transmission, it has serious problems. First, the poles get many pixels, and the equator gets relatively few. This is challenging because spherical videos usually have their important content distributed around the equatorial region, which is the viewer's horizon. It also has high distortion, which makes existing video compression technology work harder.

Currently, research on video streaming over mmWave communication largely focuses on outdoor coverage. Support for scalable HEVC (SHVC) video encoding/decoding has not been properly addressed. Additionally, mobile VR handles all video decoding and processing locally, but the video processing performance is not sufficient for 4K or 8K 360 video streaming. Therefore, this paper presents an adaptive approach to handle 360 video streaming for mobile VR using mmWave wireless communication. We also design a real system based on the proposed approach and present an implementation of our offloading scheme to share video-coding tasks between mobile VR device and powerful PC. The objective of this paper is to present the details of our methodology and results from our mmWave system. The results of experimental tests conducted using many test cases demonstrate that significant indoor coverage is possible when using 802.11ad mmWave communication with existing wireless networks, such as 802.11ac wireless networks.

The remaining parts of this paper are organized as follows. Section 2 describes related approaches that were considered and experimentally tested by demonstration. Section 3 addresses challenging issues in real-time video streaming with high-resolution video streaming and presents proposed scheme. Section 4 shows the implemented demonstration and evaluation results. Finally, Section 5 presents conclusions about the proposed scheme and future work.

2 | RELATED WORK

2.1 | Millimeter-wave communication for indoor environments

Enhancing wireless services is one of the key driving forces behind fifth-generation communication technology, which is fueled by an insatiable demand for faster and better user experiences. Wireless networks face soaring demands for wireless data as consumers increasingly utilize mobile devices to share and consume HD multi-media traffic. Additionally, as the capabilities of mobile devices continue to grow with advancements such as high-resolution cameras, 4K and 8K video capability, and virtual and augmented reality, there is an ever increasing demand for faster and more reliable connectivity.

The use of high-frequency spectrum bands above 24 GHz, loosely known as mmWave, is emerging as a key fifth-generation technology. The use of these bands is highly compelling because the large bandwidths (100 MHz) available at these high frequencies enable extremely high data rates and significant increases in capacity. Historically, mmWave bands were not sufficiently robust for mobile applications because of increased propagation loss and susceptibility to blockage (eg, hand, head, and body). However, advanced antenna techniques are quickly fixing these issues.

Our first target is to verify the performance effect of the real environment for deploying mmWave communication in an indoor environment. Although the state-of-the-art literature has not addressed this issue directly, there are various other well-researched papers, such as other works,[1-4] that provide more details with relevant conclusions. Moreover, these studies also encouraged us to increase our effort in deploying the real indoor mmWave network. Additionally, the idea proposed in the work of Wang and de Veciana[5] provides an investigation of the effect of object blockage on the performance of mmWave links. On the other hand, these studies also show that it is necessary for network designer to decide what their intended end users are. In the work of Wu et al,[1] 60-GHz mmWave channel measurements and modeling were carried out for indoor office environments. Furthermore, it provided a 60-GHz channel model and its parameterization for office environments on the basis of the specified model, temporal, and spatial clustering properties. The performance of mmWave communication strongly depends on the system model and network design. In the work of Mohamed et al,[2] a beam-forming mechanism was proposed, which enables a mmWave access point (AP) to estimate the best beam to communicate with another host. Moreover, the sector sweep issue also addressed the access point to cover the best beam selection. There are useful details to handle the point-to-point mmWave connection between two hosts.

In the mmWave indoor scenario, characterized by much smaller distances between hosts, the main factor limiting deployment options are blockages by physical objects such as human bodies. Human body blockage was shown to cause severe signal blockage that reduces the spectral efficiency gains obtained from operation over larger bandwidths available in mmWave communication, as shown in the work of Lu et al.[6] Furthermore, as shown in the work of Gapeyenko et al,[7] which studied the peer-to-peer indoor mmWave communications scenario, under the assumption of a random direction of the interferer's main lobe, directional beams are required to maintain Gb/s links in crowded indoor areas.

Despite these detailed insights on the impact of affected elements, still little is known about the operation of 802.11ad mmWave devices. Thus, in this study, a test bed scenario was processed in a large indoor environment with a short distance between server and client.

2.2 | Real-time video streaming with SHVC

Currently, HEVC (also known as H.265 or MPEG-H part2) is an emerging technology in the area of video coding. Thus, many video service platforms and video applications are upgrading themselves to support HEVC. The first version of HEVC achieved a roughly 50% bitrate reduction over its predecessor H.264 advanced video coding at a comparable subjective quality.[8] The second version of HEVC[9] includes scalability HEVC (SHVC) extensions, multiview extensions (multiview HEVC), and format range extensions. The analyzed details of HEVC and SHVC can be reviewed in the works of Sullivan et al.[10,11] The extension SHVC coding provides a selection of different output decoded video resolution levels within one input encoded video bitstream. In a best effort to enhance video transmission to mobile devices, other works[12-14] provided some adaptive methods. From these studies, this work also considered related aspects that affect video streaming to mobile devices.

Scalable HVC provides a mechanism for coding video in multiple layers, where each layer represents a different quality representation of the same video scene. The base layer (BL) is the lowest quality representation. One or more enhancement layers (ELs) may be coded by referencing lower layers to provide improved video quality. Decoding a subset of layers of a scalable coded video bitstream results in video with a lower but still acceptable quality that would result if the full bitstream were decoded. This allows a more graceful degradation compared with nonscalable video bitstreams, where a reduction in bitrate typically causes more severe drops in video quality, often rapidly becoming of unacceptable quality for viewing. Compared with nonscalable video coding, scalable video coding typically costs more bits to achieve the same video quality.

In addition, Figure 2 shows the block of structure of a single SHVC encoder; from this SHVC architecture, we can see that it handles many resolutions input videos and provides one output-encoded bitstream. This means that the client can receive selective resolution decoded videos to display. Therefore, to enhance the capability of video streaming, instead of using single HEVC, the proposed system uses video coding with SHVC, as shown in Figure 3.

3 | 360-DEGREE VIDEO STREAMING OVER MMWAVE

In the past few years, 360-degree video has become a key technology. This technology is often placed in the VR category, but there are certain differences. This misclassification often occurs because of the ability to watch 360-degree video

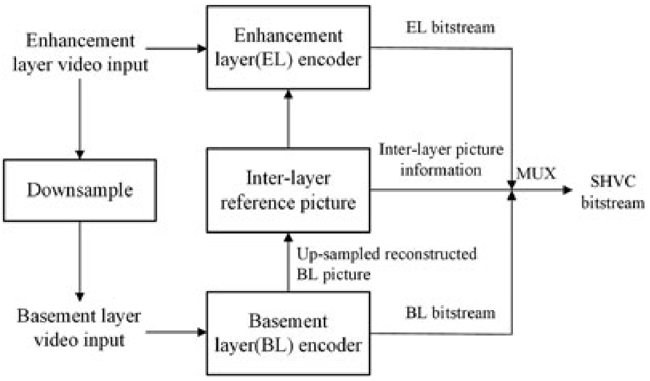


FIGURE 2 Scalable high-efficiency video coding (SHVC) encoder architecture. MUX, multiplexer

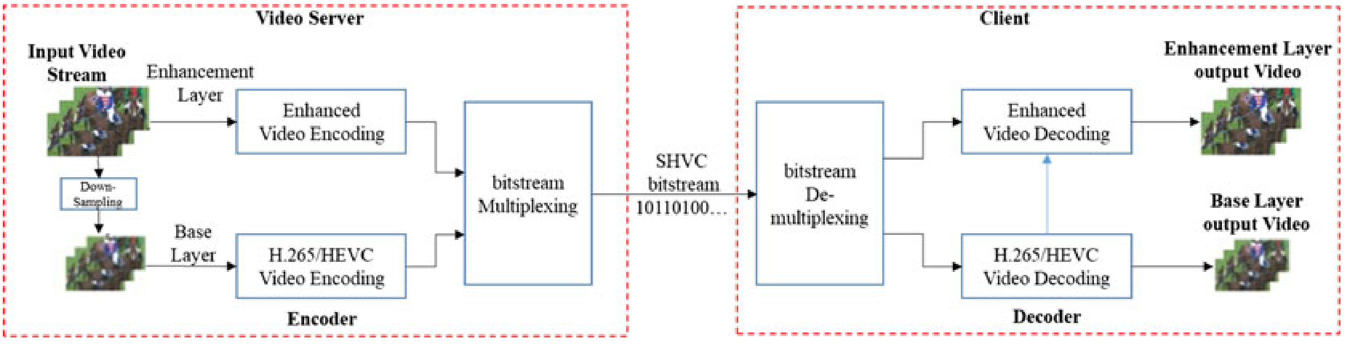


FIGURE 3 Video streaming processes using scalable high-efficiency video coding (SHVC). HEVC, high-efficiency video coding

content in a VR headset. In fact, 360-degree video can be viewed in many ways. You may watch one on your mobile phone as you scroll through your Facebook news feed by using your finger to move around in the 360-degree perspective. You may also view YouTube videos and use your mouse to manipulate the 360-degree viewport. Finally, you may actually wear a VR HMD to feel fully immersed in a video.

In this section, we discuss the details of the addressed issues and proposed scheme. The proposed scheme is used to effectively ensure the performance of real-time video streaming with SHVC video bitstream. Additionally, this part shows the challenges and limitations of real-time video streaming with high-resolution video. The last part in this section describes the implementation of proposed scheme; a real-system was implemented with 802.11ad Dongle mmWave devices.[15]

3.1 | The proposed scheme

The main ideas behind the proposed scheme are the following.

- To solve the 4K 360-degree video streaming issue, instead of other wireless 802.11 protocols, the mmWave 802.11ad 60 GHz link was applied to support high bandwidth. Additionally, an adaptive synchronization mechanism was implemented to cover real-time issues in high-speed video transmission.
- To avoid the overflow issue or poor performance issue of high-resolution video processing on mobile devices, the proposed scheme also incorporates an offloading mechanism to offload some tasks from the mobile device to a powerful PC. The proposed system with the offloading mechanism, as shown in Figure 4, would help decrease the mobile device processing time while ensuring high performance in playing 4K decoded video. The SHVC bitstream from the video server must separate into a BL bitstream and EL bitstream to enhance the performance of the offloading task.

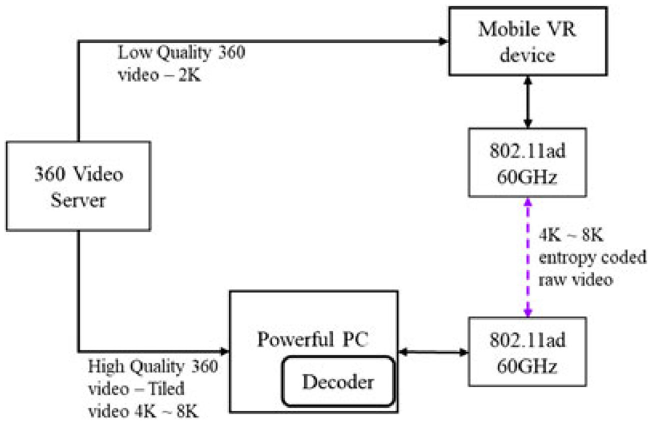


FIGURE 4 Proposed system for PC offloading. VR, virtual reality

- To enhance the performance of the overall proposed system in indoor environments, mmWave communication is initially set up as line of sight (LOS); the demonstration used an effective parameter set. Additionally, some optimized techniques were applied to the proposed system, such as effective buffer queue and memory management.

From these main ideas of the proposed scheme, an implementation was needed to demonstrate the operation of the proposed system in a real-world environment. As shown in Figure 4, the proposed system can handle video processing for both low-quality (LQ) video and high-quality (HQ) video.

3.2 | The implementation

To handle the video streaming in the real-time model, we designed the proposed system as a technical concept of the proposed scheme. In the proposed system, the streaming server and powerful PC could be regrouped in one machine. This approach was considered the best choice for our implementation.

1. *The reformatted data structure for mmWave wireless communication*: The packet structure on the application layer is illustrated in Figure 5. The packet of video streaming application was designed with an “app index” and “pkt index” to prevent packet loss and cover the synchronization issue by using a synchronization mechanism. The “pkt length” was optimized following the resolution of video streaming to ensure the performance of video transmission at high speed. The payload contains video data for both cases, encoded video bitstream, and raw decoded video. Moreover, the last four bytes are “offset” bytes for synchronization. In addition, the offset part also includes “reserved” bytes for future works to enhance the performance of mmWave communication. The new packet format is necessary for two reasons.

- The PC and mobile VR device send data packets to mmWave device firmware via USB connections. We cannot directly access the firmware of commercial mmWave devices to improve their internal protocols, and the mmWave device only supports user datagram protocol (UDP) connections.
- We send control packets from hosts to mmWave devices only to configure the parameters of the mmWave device firmware.

2. *PC offloading mechanism*: Generally, mobile VR receives full SHVC bitstream (include both BL bitstream and EL bitstream) from a video server after that it processes locally video tasks such as video decoding, postprocessing, and rendering tasks. Most of the mobile phones require many resources for performing good performances tasks properly in

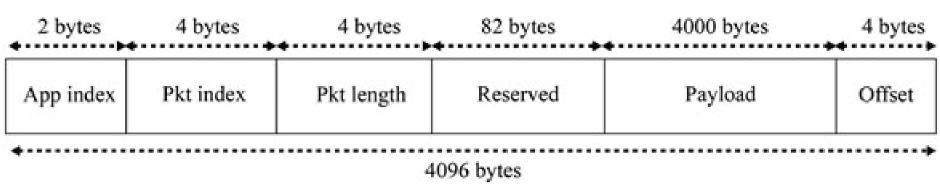


FIGURE 5 Packet structure of the video streaming application

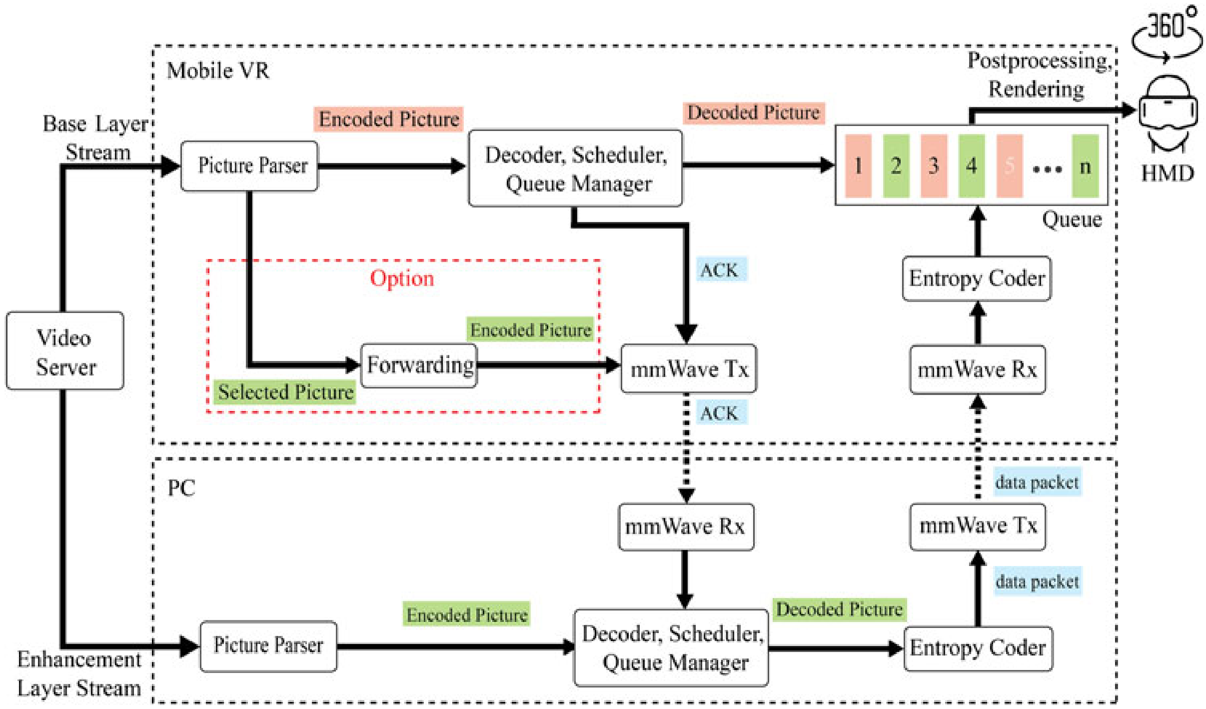


FIGURE 6 PC offloading mechanism. ACK, acknowledgment; HMD, head-mounted device; mmWave, millimeter wave; VR, virtual reality

mobile VR. For this purpose, our main objective is computing offloading the video decoding and postprocessing tasks from mobile VR to PC, so that mobile VR device only processes rendering task and display output video on HMD. However, the offloading mechanism requires more bandwidth rather than normal WiFi network offer. We implemented the first version of a wireless network using an 802.11ac, that can provide low speed approximately around 80 Mbps. Therefore, we considered mmWave 802.11ad 60 Ghz to solve high bandwidth requirement. Additionally, we have also proposed a separation of bitstream on video server to improve the proposed system. As shown in Figure 6, the proposed scheme provides an offloading mechanism to share tasks between mobile VR device and powerful PC. Finally, another option has introduced to load encoded pictures from picture parser of mobile VR to PC. This option allows mobile VR device can send EL bitstream to PC via the mmWave link. This is the effective case; PC cannot get EL bitstream directly from the video server. The process of the offloading mechanism for bitstreams are as follows.

- *Encoded bitstream division from an input encoded video bitstream:* For encoded bitstreams, the video server separates an input encoded video bitstream into two new bitstreams. Then, the bitstream with LQ video is transmitted to the mobile VR device via existing wireless network, and the other is sent to the powerful PC (as HQ video) via mmWave link.
- *Bitstream BL handling:* The BL of the bitstream is handled by the mobile device, including decoding, postprocessing, and display. These tasks create low load and the remaining resources on the mobile device can be spent on other tasks.
- *Bitstream EL processing:* The EL of the bitstream (including the referenced BL) are decoded by a powerful PC, and the raw output video is sent to mobile VR device through an mmWave link. These tasks incur a high load because they process a large amount of data, such as 4K or 8K video data. Using this method, a powerful PC can perform the task of EL decoding for a mobile VR, meaning the mobile device is free to perform other tasks. This work by the powerful PC is referred to as offloading. Therefore, offloading can help mobile VR devices to improve the probability of playing HQ 4K or 8K video with a smaller load.

3. *Synchronization mechanism*: Proposed scheme also consists of a synchronization mechanism to handle the issue of real-time transmission between PC and mobile VR, as shown in Figure 7; the mechanism is as follows: (1) Each data packet contains one identification number for indexing. (2) The PC sequentially sends packets to the mobile VR device via the mmWave link. (3) The index is then used again to build an acknowledgment (ACK) packet on the mobile VR. It then sends the ACK back to the PC. (4) After confirmation of the ACK is completed on the PC, it sends the next packet to the receiver. If the confirmation fails, the PC resends the current packet until it succeeds.

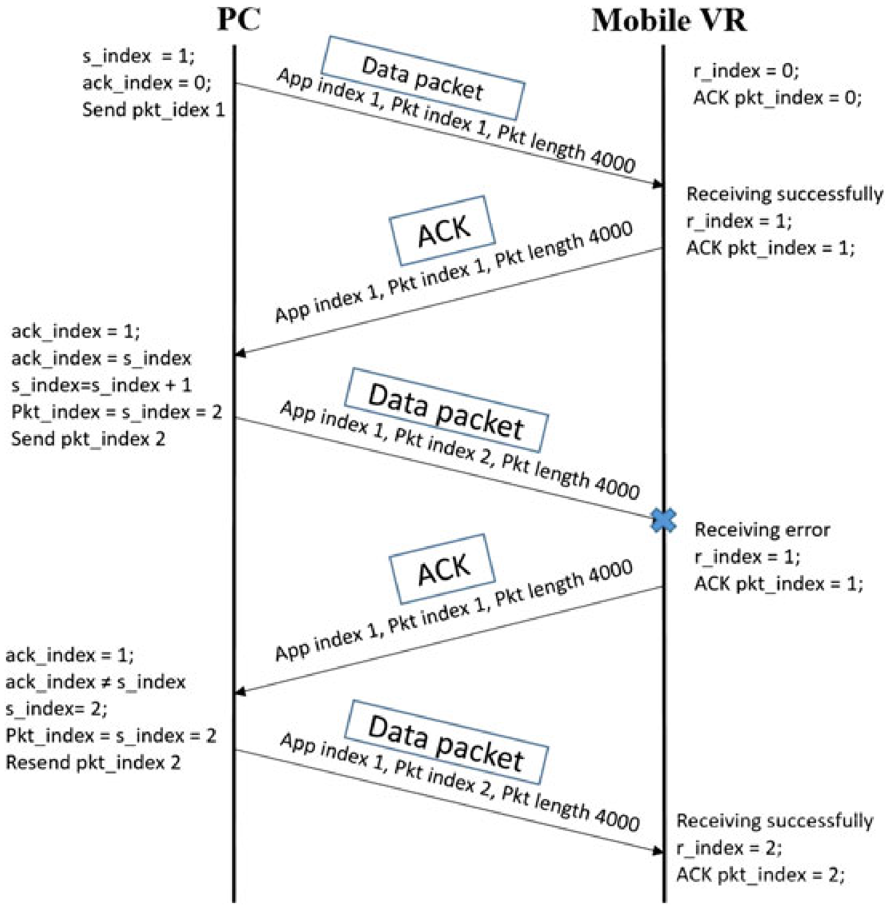


FIGURE 7 Synchronization mechanism using acknowledgment (ACK) over millimeter wave. VR, virtual reality

---

PC Offloading and Synchronization Mechanism

Input: SHVC bitstream
- N: {n} encoded picture in bitstream
Initial:
- Picture parser (PP), decoded picture buffer (DPB), data buffer (DB), synchronizer with timer 0, max buffer size (MAXB), SHVC decoder.
Main loop: ***while i < (Max of N) do***
1. Process input stream N using PP to get encoded picture ni to check BL or ELs.
2. BL encoded picture ni is written to DB
3. EL encoded picture ni is processed by SHVC decoder, then written to DPB
4. Apply proposed data packet structure to picture n_i using the scheduler. The raw data of picture ni becomes a payload of new data packet
  5. ***while (j * 4000 bytes) < size of (picture ni) do***
  Send the new data packet j to mobile VR device
  Wait for ACK from mobile VR, check 'pkt index' and decide between re-transmission of packet j or moving to the next packet (j + 1)
 end
6. Open display picture from DPB and open decoded picture ni on the client side
7. if (sizeof(DPB) > MAXB || sizeof(DB) > MAXB)
    Release data n0 to ni in DPB and DB
 end
end
Output: Decoded video

In 802.11ad, 60-GHz device[15] has some disadvantages in synchronization mechanism; the device only operates while using peer-to-peer mode, and additionally, it supports only UDP. This means that the mmWave devices can be active while connected one pair. Additionally, the information of layers on protocol stack is insufficient and not discussed in detail. Therefore, it is hard for us to access more features of the mmWave device to enhance UDP or implement transmission control protocol on the protocol stack.

4 | PERFORMANCE EVALUATION

For 360 video streaming, we first attempted to implement PC offloading over an 802.11ac wireless network. However, the link speed was only approximately 70 to 80 Mbps for data transmission. Therefore, our goal evolved to include improving network communication speed. In recent years, various papers have commented regarding the capacity of mmWave communication. Therefore, we began our project with the capability of mmWave products on the commercial market.

Compared with mmWave systems in simulations, our system may significantly enhance real performance when transmitting video content. To verify the proposed approach, we implemented a testbed as summarized in Figure 8 and

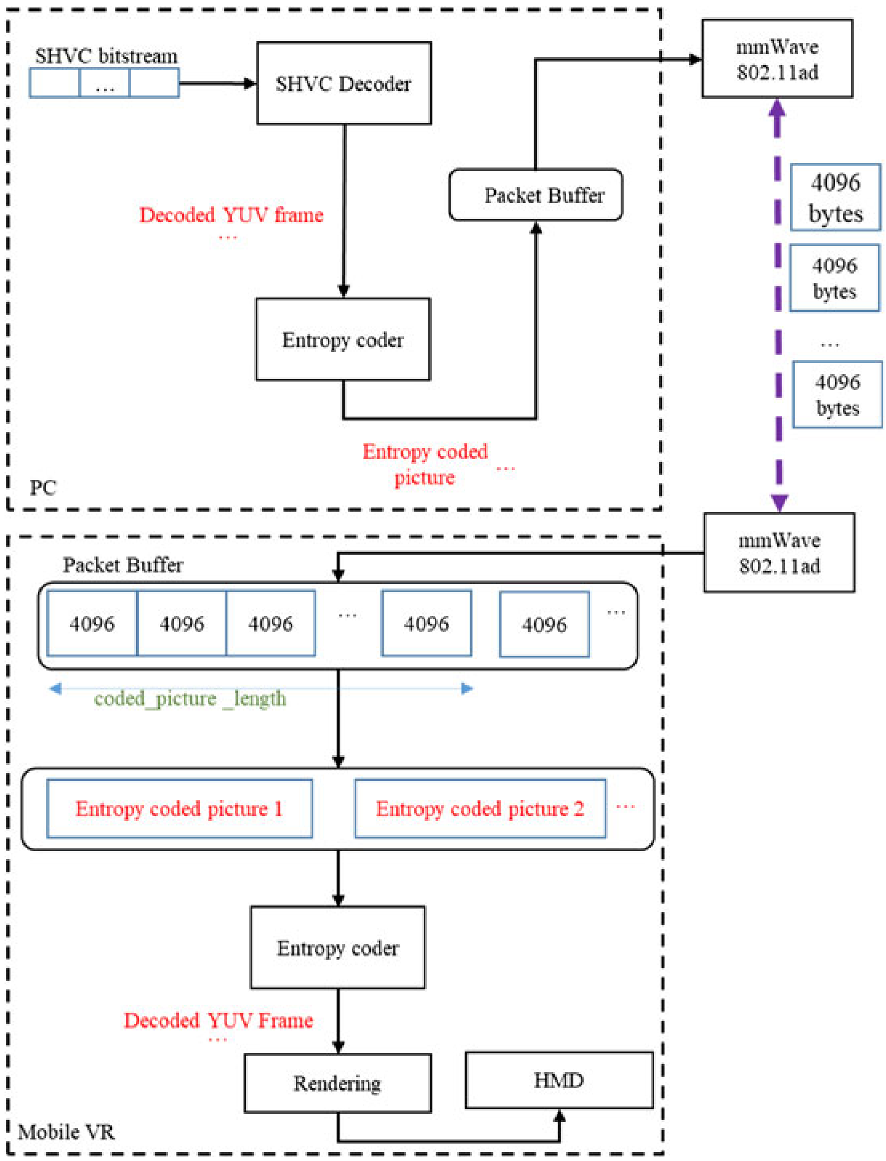


FIGURE 8 Test bed scenario for millimeter-wave (mmWave) communications. HMD, head-mounted device; SHVC, scalable high-efficiency video coding; VR, virtual reality

demonstrated in the 360-degree video streaming.[16] We set up a PC with a 2.8 GHz Intel quadcore 7700HQ CPU, 16 GB of memory, and mmWave Dongle devices. We used an Android Samsung Galaxy S7 phone with Samsung Gear VR for our mobile VR device. Instead of using a specified video server, we set up a powerful PC and fully functional streaming server. This means the powerful PC may receive encoded SHVC bitstream from the other sources. We also set up two Dongle MLWGU3V2-D[15] device to set up an mmWave link.

First, the video server extracts a BL bitstream from the original SHVC bitstream and forwards it to the mobile VR device via 802.11ad mmWave or 802.11ac wireless networks. This means the mobile VR device only handles BL processing. The performance of BL decoding on the mobile VR device is extremely optimized. Therefore, the implementation of the designed system focused on the second issue, meaning the original SHVC bitstream is decoded by the powerful PC, which is also responsible for postprocessing and display of ELs. Then, the raw output EL video (YUV format 4:2:0) is also sent to the mobile VR device via the mmWave link for display. At any given moment, the mobile VR device displays only LQ (BL) video or HQ (EL) video.

Many experimental tests with 802.11ad mmWave devices were performed to detect issues in the proposed approach. These tests helped to optimize our implementation for 360 video streaming over mmWave communication. Furthermore, a body blockage test confirmed that the throughput of the mmWave link decreases when human stands between the transmitter and receiver, but the link will be recovered immediately after the human moves out of the mmWave LOS area. Additionally, the scenario parameters were fixed to maintain stable operation of the proposed system. Table 1 provides the parameter set of the scenario, and Table 2 shows the details of DrivingInCity bitstream from joint collaborative team on video coding.[17]

As shown in Figure 9, the throughput of mmWave communication varied from 500 Mbps to 930 Mbps according to the distance between PC and mobile VR device. The tests revealed that at distances over 10 m, the throughput decreased to near zero. Through this test case, the selected distance for the demonstration of the proposed scheme is 2 m. We chose the 2 m value for these reasons, ie, (1) the mobile device can move around the powerful PC by many paths, (2) this distance results in the most substantial throughput, and (3) it seems to be a good distance between the human HMD and powerful PC's screen for playing video. We conducted many experiments for this case, and we find out that 0 to 3 meters is the most suitable distance for high throughput. Moreover, the mmWave link with range of 2 meters provides permanently

TABLE 1 Parameter set

Parameters	Value
mmWave MCS Level	1 to 7 (physical rate 1.9 Gbps)
mmWave Sector	Sector 0 to 15
mmWave Antenna	Radiation: type: endfire; polarization: linear
mmWave Frequency Channel	59.40 to 61.56 GHz
Distance (server-client)	1 to 3 m
Video Time	10 to 30 seconds
SHVC bitstream (ERP config)	PeopleonStreet(3840 × 2048_1920 × 1080); traffic(3840 × 2048 _1920 × 1080); DrivingInCity (3840 × 1920_1920 × 1080)

Abbreviations: ERP, enterprise resource planning; MCS, modulation and coding scheme; mmWave, millimeter wave; SHVC, scalable high-efficiency video coding.

TABLE 2 Joint collaborative team on video coding DrivingInCity 360 video bitstream

Parameters	Value
InputFile	DrivingInCity_3840x1920_30fps_8bit_420_erp.yuv
InputBitDepth	8 bits
InputChroFormat	420
FrameRate	30 fps
FrameSkip	0
Width	3840
Height	1920
Frames	300
Level	5.2

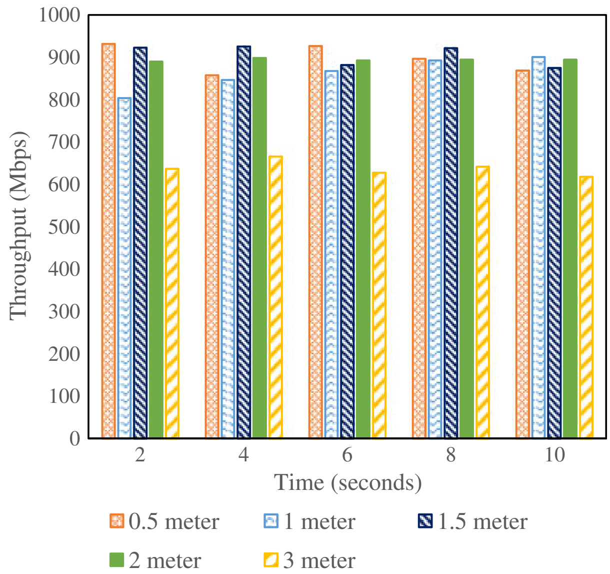


FIGURE 9 Data rate of millimeter-wave connection affected by distance

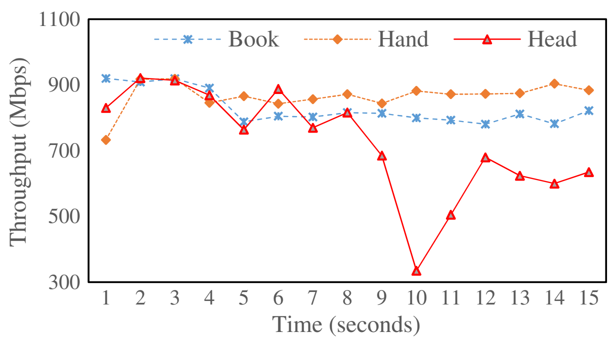


FIGURE 10 Data rate of millimeter-wave connection affected by obstacles

throughput of approximately 900 Mbps. In addition, with the range of 3 to 10 meters the mmWave link throughput drop exponentially.

Figure 10 presents the throughput based on different obstacles between the PC and mobile VR device. This result demonstrates that, if an obstacle stays in a fixed location, the throughput will decrease to near zero. Therefore, in our test, all obstacles pass through the mmWave area. At 10 seconds, the human head moves through the LOS area and the throughput quickly approaches zero. Therefore, recovery from human head blockage will be an interesting direction for future research on mmWave systems. We also determined that the packet loss of the UDP mmWave link varied from 10% to 20%. This indicates that there is a need to invest further effort to address both bandwidth and packet loss through superior synchronization mechanisms.

Here, experimental results showed the performance of the proposed scheme for SHVC video bitstream, compared with that before applying the proposed scheme. The demonstration of the proposed scheme was produced in a real-world environment, and we have not seen any previous research for video transmission or demonstration like ours. As shown in Figure 11, the result showed that the throughput of mmWave communications was near 300 Mbps, for both 2K resolution (Traffic bitstream) and 4K resolution (PeopleonStreet bitstream) videos. Furthermore, the packet loss issue was remedied by using ACK messages, resulting in a packet loss ratio of nearly 0%. Figure 12 presents the packet loss ratios before applying the synchronization mechanism. By using the mmWave ACK exchanging, all lost packets were retransmitted over the 802.11ad connection. This means the mobile device always received all the data without any packet loss. The number of retransmitted packets for 2K and 4K are 4.7% and 9.8%, respectively.

To investigate the system's support for movement, we also performed experiments with movement of the mobile VR device around the PC and measured the throughput according to the angle between the location of the PC and the mobile VR device. As shown in Figures 13A and 14, in most cases, the mmWave link provides a UDP connection with high

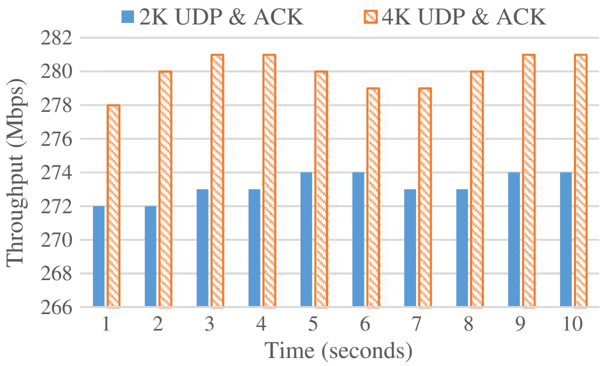


FIGURE 11 End-to-end throughput of real-time video streaming. ACK, acknowledgment; UDP, user datagram protocol

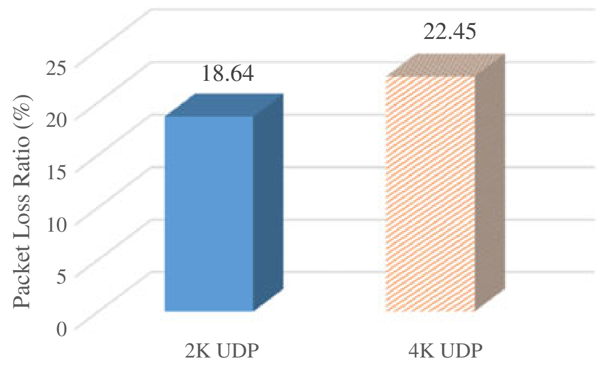


FIGURE 12 Packet loss comparison. UDP, user datagram protocol

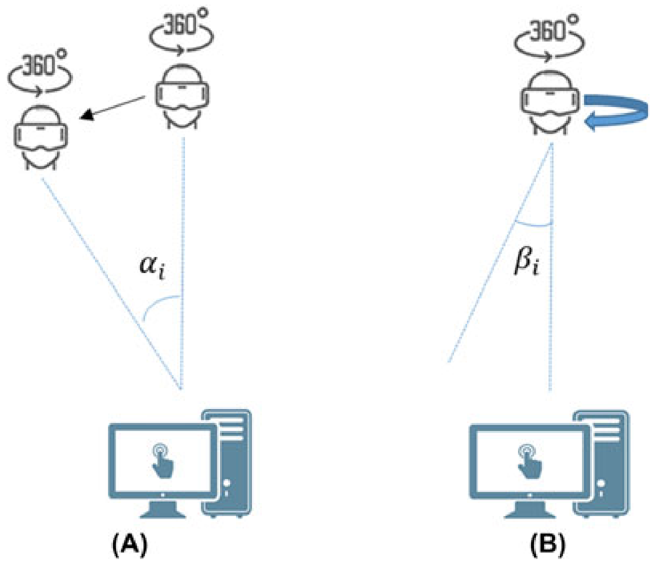


FIGURE 13 Experiments where (A) the mobile virtual reality (VR) device moves around the PC and (B) the mobile VR device changes viewing direction

performance and stability. However, when α_i was between 25° and 35°, the throughput of the connection decreased. At 30°, the value was zero. Additionally, test results are presented in Figures 13B and 15, where we kept the position of the mobile VR device constant and changed the viewing direction of the human head from LOS (0°) to 90° (by β_i) offset. From these results, we confirmed that 75° is the angle threshold for maintaining the mmWave connection in any sector. Between direct LOS and a 70° offset, mmWave communication can operate stably and provides a high-speed connection.

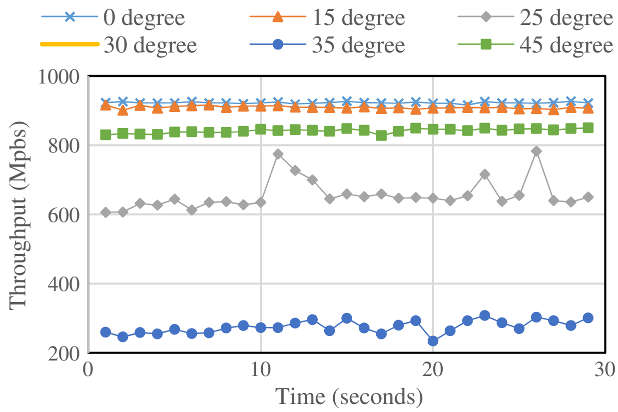


FIGURE 14 End-to-end throughput in the case the mobile virtual reality device moving around the PC

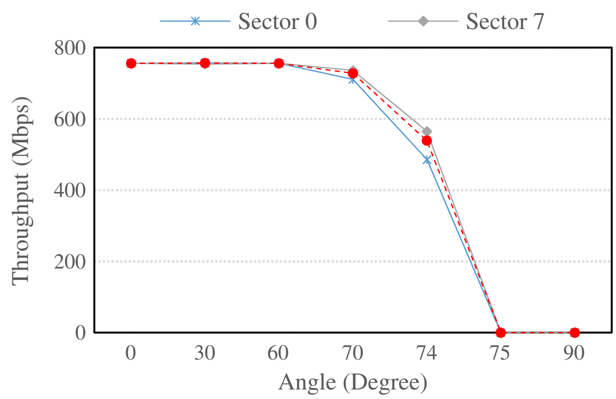
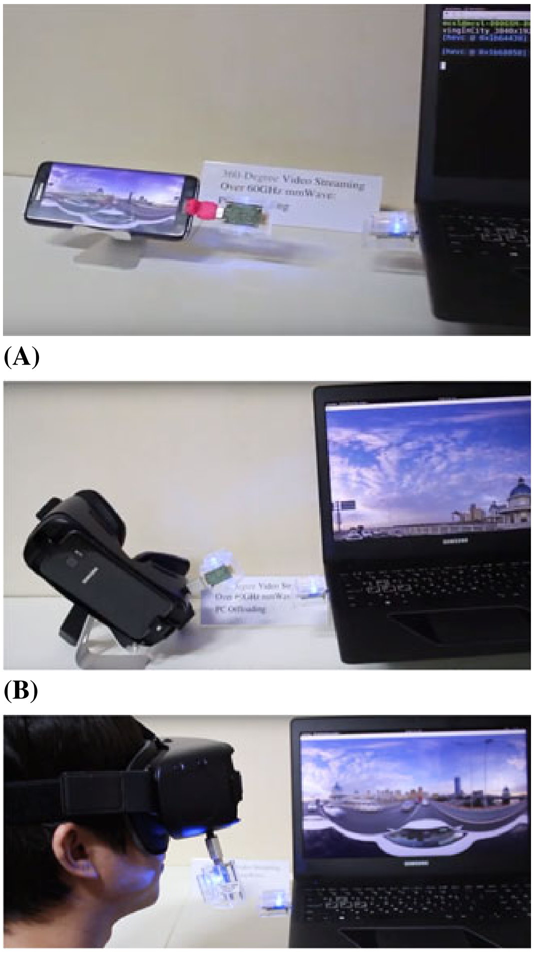


FIGURE 15 End-to-end throughput in the case the mobile virtual reality device just changing only viewing direction

The quality of 4K resolution video on the server side (powerful PC) and client (mobile device) was determined, as shown in Figure 16. For video streaming, we used raw video transmission over the mmWave link. For 4K video, the results shown in Figure 16 confirmed that the display quality is quite good for 4K resolution video on the mobile VR. The delay time is accepted quality of service sensitive. Moreover, in the case of long time 4K video, the latency time was small. This latency reflected the greatly increasing number of ACK packets.

The SSIM and PSNR values were compared between JCT-VC original YUV file and output YUV video on mobile VR device as illustrated in Table 3 and Table 4. FFmpeg tool[18] used to evaluate the SSIM and PSNR comparisons. Mostly, PNSR performs insufficiently as compared with other quality metrics while estimating the quality of images and particularly videos as perceived by humans. If PNSR values are higher than 38 dB it means that the quality of 360 videos on mobile VR device is tremendous.

Finally, we tested some optimized techniques in mobile programming to reduce the usage of mobile phone's resources such as memory allocation, multithreads processing, and queueing buffer to store temporary pictures. By implementing these techniques on the mobile phone, it will reduce the power consumption. The performance comparison between proposed system and streaming system using the 802.11ac wireless network is shown in Table 5. In the 802.11ac wireless network streaming system, the mobile phone receives the full SHVC bitstream from the video server and processes SHVC bitstream locally. We used same 4K video bitstream for tile partitioning Traffic_3840x2048_QP37_300 frames in testing both systems. The video decoder openHEVC software[19] was used to perform video decoding task. The experimental results show that our proposed scheme has enhance the overall performance of video streaming system. Especially, the proposed system helps speed up in video decoding task up to 67.4%. During the implementing of our demonstration, we found out that Dongle 802.11ad devices are underdeveloped and some features are not much advantageous as we expected. However, these results encouraged us to do more advanced research to reduce the limitations of video streaming over mmWave.



(A) (B) (C)

FIGURE 16 Demonstration of (A) DrivingInCity 360 video streaming over millimeter-wave (mmWave) communication, (B) 360 video streaming on mobile virtual reality–head-mounted device, and (C) A man watching 360 video streaming

TABLE 3 Structure similarity comparison

1920x1080	Y:0.960732 U:0.975590 V:0.973241 All:0.965293 (14.595809)
3840x1920	Y:0.965397 U:0.983823 V:0.98098 All:0.971066 (15.385930)

TABLE 4 PSNR comparison

1920x1080	y:38.00 u:44.63 v:44.16 average:39.25 min:38.07 max:41.89
3840x1920	y:40.69 u:46.77 v:46.01 average:41.86 min:40.79 max:44.78

TABLE 5 Comparison between proposed system and streaming system over 802.11ac wireless network–4K video stream

	Proposed system	Streaming system over an 802.11 ac wireless network
Average Throughput	281 Mbps	78 Mbps
Video decoding Task: time and FPS	18.60 seconds 16 FPS	57.14 seconds 5.25 FPS
PSNR Comparison	41.86 dB	39.94 dB

Abbreviations: FPS, frames per second; PSNR, peak signal-to-noise ratio.

5 | CONCLUSION

This paper has explained the performance evaluations of the deployment of 360-degree video streaming for VR service with mmWave communication. The proposed method shows that mmWave communication can enhance the performance of real-time video streaming in indoor environments. Furthermore, the proposed scheme also proved that mmWave can ensure high-resolution video transmission in a real-time model by applying its optimal mechanisms. First, the offloading mechanism provides the enhancement for loading of mobile devices. Second, synchronization mechanism answers the question of how the proposed scheme can handle the video streaming in real time.

Further work is needed to improve the performance for 4K raw video transmission by enhancement of synchronization. In addition, the offloading also need to be updated to play higher resolution video, such as 8K and 12K with SHVC coding. Furthermore, the experimental results can be used to implement future versions of video streaming systems using mmWave devices. Regarding the synchronization mechanism, additional handshake policies can be designed to stream videos more efficiently.

ACKNOWLEDGEMENTS

This research was supported by the Korea Electric Power Corporation (R17XA05-68). It was also supported by the GRRC program of Gyeonggi province (GRRC-Gachon2017[B01], Analysis of behavior based on senior life log). Two authors, Hyun-Wook Kim and Tuan Thanh Le, hold first authorship and have equal contribution. Eun-Seok Ryu is the corresponding author.

ORCID

Eun-Seok Ryu http://orcid.org/0000-0003-4894-6105

REFERENCES

1. Wu X, Wang C-X, Sun J, Huang J, et al. 60-GHz Millimeter-wave channel measurements and modeling for indoor office environments. *IEEE Trans Antennas Propag*. 2017;65(4):1912-1924.
2. Mohamed EM, Sakaguchi K, Sampei S. Millimeter wave beamforming based on WiFi fingerprinting in indoor environment. Paper presented at: 2015 IEEE International Conference on Communication Workshop (ICC Workshops); 2015; London, UK.
3. Liu P, Di Renzo M, Springer A. Line-of-sight spatial modulation for indoor mmWave communication at 60 GHz. *IEEE Trans Wirel Commun*. 2016;15(11):7373-7389.
4. Maccartney GR, Rappaport TS, Sun S. Indoor office wideband millimeter-wave propagation measurements and channel models at 28 and 73 GHz for ultra-dense 5G wireless networks. *IEEE Access*. 2015;3:2388-2424.
5. Wang Y, de Veciana G. Dense indoor mmWave wearable networks: managing interference and scalable MAC. Paper presented at: 2016 14th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt); 2016; Tempe, AZ.
6. Lu JS, Steinbach D, Cabrol P, Pietraski P. Modeling human blockers in millimeter wave radio links. *ZTE Commun*. 2012;10(4):23-28.
7. Gapeyenko M, Samuylov P, Gerasimenko M, et al. Analysis of human-body blockage in urban millimeter-wave cellular communications. Paper presented at: 2016 IEEE International Conference on Communications (ICC); 2016; Kuala Lumpur, Malaysia.
8. Tan TK, Mrak M, Baroncini V, Ramzan N. Report on HEVC compression performance verification testing. Paper presented at: 17th Meeting Joint Collaborative Team on Video Coding (JCT-VC) of ITU-T SG 16 WP 3 and ISO/IEC JTC 1/SC 29/WG 11; 2014; Valencia, Spain.
9. Boyce J, Chen J, Chen Y, et al, Draft high efficiency video coding (HEVC) version 2, combined format range extensions (RExt), scalability (SHVC), and multi-view (MV-HEVC) extensions, Paper presented at: 18th Meeting Joint Collaborative Team on Video Coding (JCT-VC) of ITU-T SG 16 WP 3 and ISO/IEC JTC 1/SC 29/WG 11; 2014; Sapporo, Japan.
10. Sullivan GJ, Ohm J-R, Han W-J, Wiegand T. Overview of the high efficiency video coding (HEVC) standard. *IEEE Trans Circuits Syst Video Technol*. 2012;22(12):1649-1668.
11. Sullivan GJ, Boyce JM, Chen Y, Ohm J-R, Segall CA, Vetro A. Standardized extensions of high efficiency video coding (HEVC). *IEEE J Sel Top Signal Process*. 2013;7(6):1001-1016.
12. Ryu E-S, Kim J. Error concealment mode signaling for robust mobile video transmission. *AEU-Int J Electron Commun*. 2015;69(7):1070-1073.
13. Ryu E-S, Yoo C. An approach to interactive media system for mobile devices. Paper presented at: 12th Annual ACM International Conference on Multimedia (MM '04); 2004; New York, NY.
14. Kim J, Ryu E-S. Quality analysis of massive high-definition video streaming in two-tiered embedded camera-sensing systems. *Int J Distributed Sens Netw*. 2014;10(3):634191.
15. Wigig Dongle product. https://www.seeedstudio.com/WiGig-USB3.0-Dongle--p-2827.ht

16. 360-Degree video streaming over mmWave Demo. https://youtu.be/7L8wGU50CZ8
17. JCT-VC - Joint Collaborative Team on Video Coding. [Online]. https://www.itu.int/en/ITU-T/studygroups/2013-2016/16/Pages/video/jctvc.aspx
18. FFmpeg tool. [Online]. https://www.ffmpeg.org/
19. Open HEVC Decoder. http://openhevc.github.io/openHEVC

How to cite this article: Kim H-W, Le TT, Ryu E-S. 360-degree video offloading using millimeter-wave communication for cyberphysical system. *Trans Emerging Tel Tech*. 2018;e3506. https://doi.org/10.1002/ett.3506