IP-Based Cooperative Services Using ATSC 3.0 Broadcast and Broadband

Jae-young Lee, *Senior Member, IEEE*, Sung-Ik Park, *Senior Member, IEEE*,
Hyun-Jeong Yim, *Member, IEEE*, Bo-Mi Lim, *Member, IEEE*, Sunhyoung Kwon, *Member, IEEE*,
Sungjun Ahn, *Member, IEEE*, and Namho Hur, *Member, IEEE*

***Abstract*—This paper presents Internet protocol (IP)-based convergence of broadcast and broadband networks using Advanced Television Systems Committee (ATSC) 3.0–the next generation terrestrial broadcasting standard. In the broadcast network, the combination of Layered Division Multiplexing (LDM) and Scalable High Efficiency Video Codec (SHVC) is used, enabling efficient use of spectrum when mobile and fixed services are intended in a single radio frequency (RF) channel. The proposed use case of IP-based convergence is that a service is largely consumed through the high power high tower (HPHT) based broadcast network, and then alternative streams are requested via unicast for areas where broadcast signals are not receivable. The implementation details of broadcast and broadband convergence include MPEG Media Transport (MMT)/Real-time Objective delivery over Unidirectional Transport (ROUTE) description for broadcast useand Dynamic Adaptive Streaming over HTTP (DASH) for broadband use. To achieve seamless convergence between broadcast and broadband, transmission and reception systems based on ATSC 3.0 are hardware-developed and their implementation details are described. The proposed IP-based convergence use case of ATSC 3.0 broadcast and broadband is verified in a real-field environment using a public cellular network.**

***Index Terms*—ATSC 3.0, convergence, broadcast, broadband, LDM, and SHVC.**

I. Introduction

THE ADVANCED Television Systems Committee (ATSC) has developed the new next generation terrestrial broadcasting standard set of standards – ATSC 3.0. This new standard suite, which includes over 20 standard documents with different layers of system architecture, incorporates many state-of-the-art features over existing digital broadcasting standards: flexibility for broadcasters' operation, robust physical layer performance for mobile, handheldor indoor services, spectral efficiency when multiple services are configured in a single radio frequency (RF) channel, and all Internet protocol (IP) based transmission to cope with enhanced services [1].

In the ATSC 3.0 physical layer standard, the bit-interleaved coded modulation (BICM) consisting of low density parity check (LDPC) codesranging from 2/15 to 13/15 rates, bit interleavers, and non-uniform constellations (NUC) up to 4096QAM offers not only robustness and efficiency approaching to near-Shannon limits, but also provides flexibility for various use cases from mobile to fixed services [2]–[5]. Given the orthogonal frequency division multiplexing (OFDM) as a waveform scheme, flexible options of multiplexing technologies are supported including Time Division Multiplexing (TDM), Frequency Division Multiplexing (FDM), Layered Division Multiplexing (LDM), and even combinations of these multiplexing technologies [6]–[8]. LDM is known as a state-of-the-art technology adopted in ATSC 3.0 as it can provide superior performance advantage when different services (e.g., mobile and fixed) are superposed together with different power levels [9], [10]. In the ATSC 3.0 video standard, Scalable High Efficiency Video Coding (SHVC: Scalable HEVC) that is based on the scalability feature of HEVC is adopted as it can provide bit rate saving compared to HEVC simulcast. It is also known that when multiple services (e.g., mobile and fixed) are intended in a single RF channel, the combination of LDM and SHVC provides far better spectrum efficiency [11], [12], [13].

The all IP transmission of ATSC 3.0 offers distinct features over traditional broadcasting as it enables convergence or cooperation with IP based broadband networks. Leveraging uplink transmission as a return channel, a broadcaster can provide interactive or personalized services that will bring more attraction from audiences. Also, a broadcasting service could cooperate with available broadband networks such as mobile networks or Wi-Fi, so that further enhanced features of broadcasting services will be possible including quality improvement, service area extension, and rich media services [14], [15], [16].

This paper presents IP-based convergence of broadcast and broadband using ATSC 3.0. The proposed convergence use case is that the high power high tower (HPHT) broadcast is used for primary consumption of a service, and then broadband networks such as mobile network or Wi-Fi can be used to deliver alternative streams whenever broadcast signals are not

---

Manuscript received December 1, 2019; revised February 20, 2020; accepted February 26, 2020. Date of publication April 15, 2020; date of current version June 5, 2020. This work was supported by the Institute for Information & Communications Technology Promotion (IITP) grant funded by the Korea Government (MSIT) under Grant 2017-0-00081 (Development of Transmission Technology for Ultra High Quality UHD). Parts of this paper have been published in the Proceedings of the IEEE BMSB 2019, Jeju, South Korea. *(Corresponding author: Jae-Young Lee.)*

The authors are with the Media and Broadcasting Research Group, Electronics and Telecommunications Research Institute, Daejeon 34129, South Korea (e-mail: jaeyl@etri.re.kr; psi76@etri.re.kr; hjyim@etri.re.kr; blim_vrossi46@etri.re.kr; shkwon@etri.re.kr; sjahn@etri.re.kr; namho@etri.re.kr).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TBC.2020.2983301

receivable, e.g., shadowing areas in mobile reception or deep indoor reception. For the ATSC 3.0 broadcast, the combination of LDM of the physical layer and SHVC of the presentation layer is used to deliver spectral-efficient mobile and fixed broadcast services together in a single RF channel [11]. Implementation details for broadband convergence include MPEG Media Transport (MMT)/Real-time Objective delivery over Unidirectional Transport (ROUTE) for broadcast use and Dynamic Adaptive Streaming over HTTP (DASH) for broadband use. Hardware equipment including SHVC encoder platform, broadband server, transmission and reception ends enabling both broadcast and broadband deliveries is developed and used for the verification in real-field environments.

The remaining of this paper is organized as follows: In Section II, a theoretical aspect of LDM and SHVC technologies in the ATSC 3.0 standard and the advantage of the combined technology are described. The details of IP-based convergence based on the ATSC 3.0 standard is followed in Section III. Implementation details to achieve seamless convergence of ATSC 3.0 broadcast and broadband networks is described in Section IV. Real-field verification in mobile environments using ATSC 3.0 broadcast and deployed 4G LTE networks is shown in Section V. The final conclusion of this paper is presented in Section VI.

II. ATSC 3.0 LDM AND SHVC FOR BROADCAST DELIVERY

In the physical layer protocol of ATSC 3.0 standard, LDM is a Physical Layer Pipe (PLP) multiplexing scheme in which multiple PLPs share the same time and frequency resources, but those PLPs are multiplexed with different power levels, called LDM injection level. LDM PLPs allocated with different injection levels are defined as *Core Layer* (CL) and *Enhanced Layer* (EL). Note that ATSC 3.0 allows up to two layers of LDM, but each layer is also allowed to allocate multiple PLPs based on TDM and/or FDM depending on broadcasters' intended services. That is, when more than two PLPs are intended using an LDM configuration, the ATSC 3.0 physical layer standard allows LDM combination with TDM (e.g., LTDM: Layered Time Division Multiplexing) or with FDM (e.g., LFDM: Layered Frequency Division Multiplexing) [17], [18]. Core Layer PLPs (Core PLPs) are assigned above Enhanced Layer PLPs (Enhanced PLPs) in a single RF channel, and therefore,a larger portion of total transmission power is allocated to the CL and less power is given to the EL. Note that the LDM combined signal should be normalized, so that the total power after the combination is maintained to be equal to a single layer configuration. In a general LDM service scenario, the CL delivers more robust PLP(s) that may be targeted for indoor/mobile services, whereas the EL delivers higher data rate PLP(s) such as 4K-Ultra High Definition (UHD) or multiple HD services.

SHVC is a video coding technology consisting of multiple layers, in which each layer of a video content is able to provide different video quality. For multiple layers of SHVC, the smallest subset of a video content is defined as *Base Layer* (BL) that represents the lowest quality among the layered content, and there can be several *Enhancement Layers* (ELs) representing larger subsets of the video content in order to provide better quality. In the receiver side, the BL of the video content can be decoded as an independent stream, whereas ELs of the video content should be decoded by referencing the BL. Note that in the video standard of ATSC 3.0 the video scalability is allowed up to two layers based on the Main 10 profile, that is, one BL and one EL from a video content [19]. When multiple services are intended using a single video content (e.g., low rate mobile and high rate fixed services), a fixed service by SHVC is achieved by adding the BL (a mobile service) to the EL. Therefore, compared to HEVC simulcast, which independently applies HEVC to the mobile and fixed services from a single video content, SHVC offers bit rate saving opportunity. That is, depending on bit rate choices for the BL and EL, SHVC can provide better spectral efficiency since the fixed service by SHVC (i.e., BL + EL) can have the same quality of video as the fixed service that is independently encoded by HEVC.

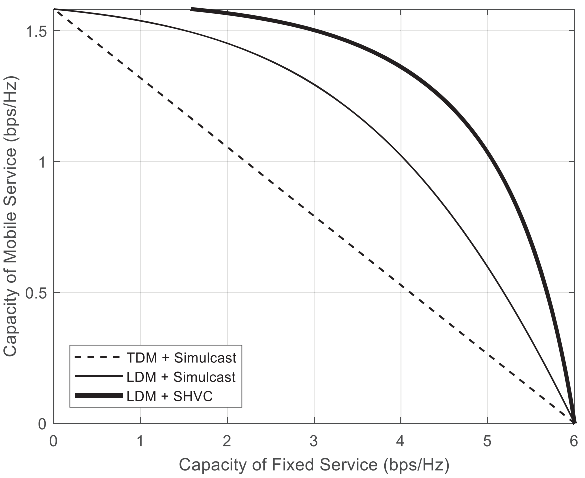


Fig. 1. Achievable capacities when mobile and fixed services are delivered in a single RF channel: TDM + Simulcast, LDM + Simulcast, and LDM + SHVC.

Figure 1 shows theoretical aspects of achievable capacities when mobile and fixed services allocated by separate PLPs are intended in a single RF channel. Theoretically it is known that LDM is power based capacity addition of two services, always providing better capacity than TDM or FDM that are based on simple linear addition of the two services, even though the amount of capacity gains can be varied depending on the targeted SNRs of mobile and fixed PLPs [11], [20]. As shown in the figure, capacity curves are developed representing the three cases: 1) TDM and HEVC simulcast combination; 2) LDM and HEVC simulcast combination; and 3) LDM and SHVC combination. In this example, both LDM and TDM configurations use a mobile PLP having the performance of 0 dB targeted (required) signal-to-noise ratio (SNR) and a fixed PLP with 15 dB targeted SNR. For the SHVC and simulcast comparison, it is assumed that the capacity of a fixed service becomes the bit rate addition of SHVC BL and EL. Note that in practice, depending on bit rate choices of BL and EL, the

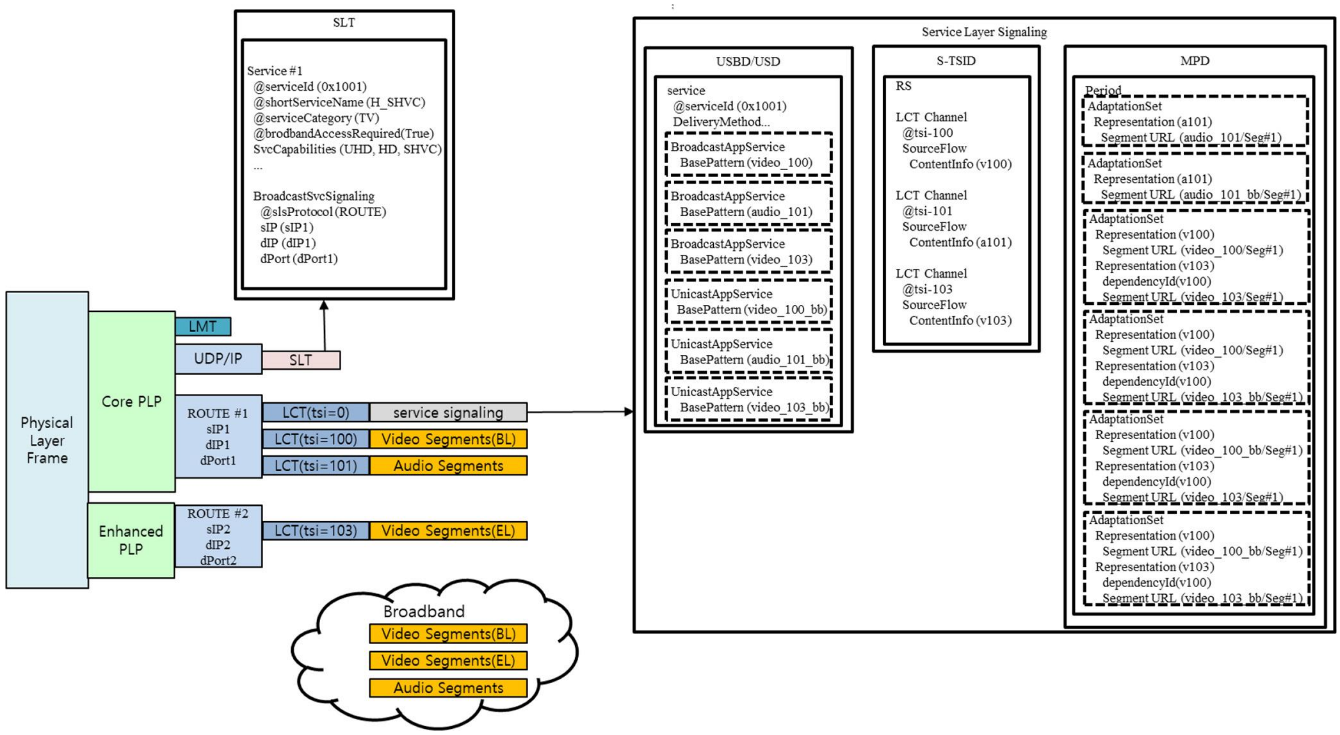


Fig. 2. (a) Equipment configuration for ATSC 3.0 broadcast and broadband transmission, (b) Receiver equipment inside the vehicle for ATSC 3.0 broadcast and broadband reception, and (c) Mobile test route for ATSC 3.0 broadcast and broadband cooperation.

bit rate addition of BL and EL can provide better quality of video compared to the fixed service of HEVC simulcast [11]. This implies that the achievable capacity of LDM and SHVC combination in practice can be even better than the theoretical curve shown in Figure 1.

III. IP-BASED CONVERGENCE OF ATSC 3.0 AND BROADBAND NETWORKS

In ATSC 3.0, the format of transmitted signals is IP-based in order to enhance the feasibility of convergence and cooperation with other IP based networks such as mobile networks. In the signaling, delivery, synchronization, and error protection standard of ATSC 3.0 allows two options for service delivery over a broadcast network – MMT and ROUTE. For service delivery over a broadband network, only DASH is allowed to use [21].

A. ROUTE and DASH Implementation

ROUTE is inherited from DASH for unidirectional transfer of DASH segments in order to be used as a broadcast mode, and therefore, the Media Presentation Description (MPD), which describes a representation of DASH delivery, is used to define broadcast delivery by ROUTE [14]. Figure 2 shows an entire set of low level signaling (LLS) description for the proposed broadcast and broadband convergence use case when ROUTE for broadcast and DASH for broadband are used. As shown in the MPD of Figure 2, the same representation ID is used for both broadcast and broadband deliveries in order to indicate the same content being delivered over the both networks. For example, the representation ID of *v100* is used for the SHVC BL content, and it has different Segment URLs such as *video_100/Seg#1* for the broadcast delivery and *video_100_bb/Seg#1* for the broadband delivery. Note that this approach is intended for a handoff situation, that is, when the SHVC BL content (*v100*) is lost from the broadcast, a receiveris able to request the same content (*v100*) through the broadband.

Since the proposed broadcast and broadband convergence use case is based on SHVC, the dependency between the BL and EL should be defined. In the MPD of Figure 2, for example, the representation ID of *v103* has dependency with *v100*, as denoted by *dependencyID(v100)*, and therefore, *v100* indicates the BL and *v103* indicates the EL. Note that in the MPD of Figure 2, four Adaptation Sets are defined related to SHVC services: 1) BL and EL over broadcast; 2) BL over broadcast and EL over broadband; 3) BL over broadband and EL over broadcast; and 4) BL and EL over broadband.

B. MMT and DASH Implementation

When MMT is used for a broadcast mode, the ATSC 3.0 standard allows to DASH over broadband, and therefore, signaling descriptions for MMT and DASH should be separately defined by the MMT Package (MP) table and the MPD, respectively. Figure 3 shows the details of LLS description when the proposed broadcast and broadband convergence use case is defined by MMT over broadcast and DASH over broadband. As shown in Figure 3, the relationship between MMT and DASH packages are explicitly defined in the User Service Bundle Description/User Service Description (USBD/USD)fields. That is, when a broadcast signal is lost

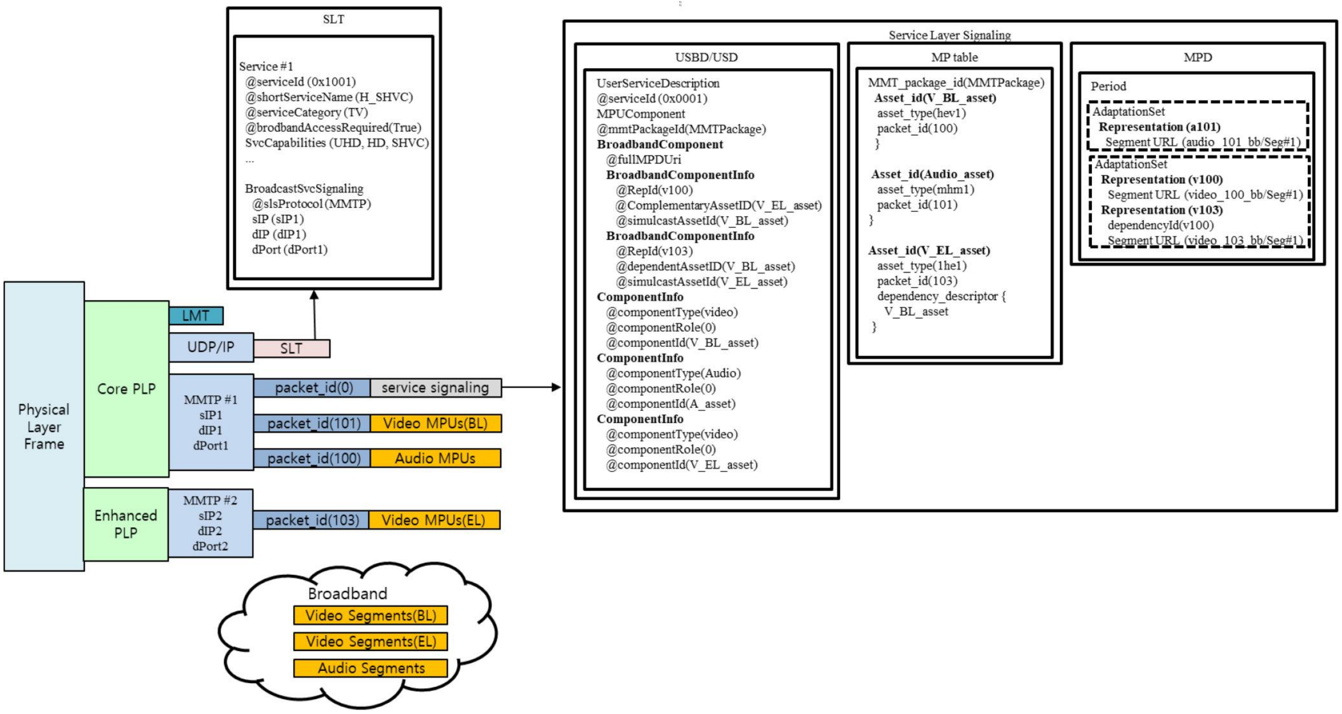


Fig. 3. (a) Equipment configuration for ATSC 3.0 broadcast and broadband transmission, (b) Receiver equipment inside the vehicle for ATSC 3.0 broadcast and broadband reception, and (c) Mobile test route for ATSC 3.0 broadcast and broadband cooperation.

and the same content is requested through broadband, the field *@simulcastAssetID()* in USBD/USD is used, and this denotes that the MMT package defined as *V_BL_asset* in the MP table and the DASH package defined as *v100* in the MPD are the same SHVC BL content, as in Figure 3. For the SHVC hybrid delivery, *@dependencyAssetID()* is explicitly defined in USBD/USD such that *V_BL_asset* of MMT is the BL content and *v103* of DASH is the EL content for a single service. In addition, *@ComplementaryAssetID* is explicitly defined in USBD/USD such that *v100* of DASH is the BL content and *V_EL_asset* of MMT is the EL content for a single service, and this is to denote the BL being delivered by a broadband and the EL delivered by a broadcast.

IV. IMPLEMENTATION FOR SEAMLESS CONVERGENCE OF BROADCAST AND BROADBAND

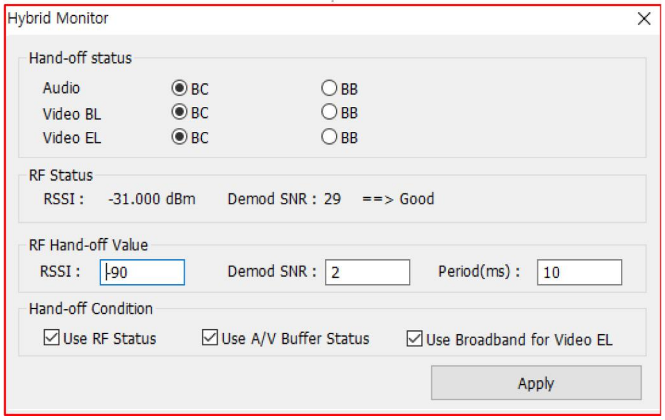
In the proposed use case of this paper, seamless convergence of broadcast and broadband networks means that an audio/video (A/V) service is seamlessly delivered when any switching between the two networks is executed. Such seamless experience by viewers can be achieved with additional implementation strategies in the transmission and reception ends within the scope of the ATSC 3.0 standard, and therefore, no further requirement of the ATSC 3.0 standard other than the signaling descriptions in Section III is needed.

A. Implementation of Transmission and Reception Ends for Seamless Switching

For a hybrid delivery using broadcast and broadband networks, fine synchronization between the broadcast and broadband signal paths is required. Also, a receiver that receives signals from broadcast and broadband needs to be time synchronized with a time server that requires broadband connectivity, such as the network time protocol (NTP).

In the case of ROUTE, the ROUTE delivery over broadcast contains the DASH segment being delivered over broadband. Therefore, when ROUTE is used over broadcast, from an A/V encoder or a packager which output IP packaging of contents, the same presentation time stamp (PTS) should be used for DASH segments over broadband and ROUTE streams over broadcast. A receiver that maintains time synchronization with an NTP server should be able to keep tracking PTSs of ROUTE and DASH streams, and also determine which stream to decode depending on signal availability from broadcast or broadband networks. For example, when a receiver cannot find a ROUTE segment with a PTS $t + 1$ over broadcast, it will be able to request and receive the DASH segment with PTS $t + 1$ over broadband. It should be also noted that a receiver needs to have enough memory to buffer DASH segments over broadband and keep tracking the same content of ROUTE segments over broadcast. Since broadband networks based on unicast may be time-variable due to traffic congestion, network latency or distance between a server and a receiver, appropriate receiver buffer size can be heuristically determined.

Another approach to achieve seamless convergence of broadcast and broadband contents is to use the PTS information in video frames. As the PTS information is also used in every video frame (e.g., 30 or 60 frames per second), a receiver that maintains time synchronization is able to track the PTS of video frames from both broadcast and broadband, and switch contents between these networks seamlessly. When



Hybrid Monitor

Hand-off status

Audio ● BC ○ BB

Video BL ● BC ○ BB

Video EL ● BC ○ BB

RF Status

RSSI : -31.000 dBm Demod SNR : 29 ==> Good

RF Hand-off Value

RSSI : -90 Demod SNR : 2 Period(ms) : 10

Hand-off Condition

☑ Use RF Status ☑ Use A/V Buffer Status ☑ Use Broadband for Video EL

Fig. 4. A monitoring and control software to monitor an RF signal status and determine the switching between broadcast and broadband networks.

MMT is used over broadcast, a media processing unit (MPU) of the MMT protocol may contain different contents than a DASH segment over broadband. Therefore, using the PTS information in video frames can be more feasible approach for seamless switching when MMT is used for broadcast and DASH is used for broadband.

B. Use of Physical Layer Parameters for Fast Seamless Switching

The buffering method for switching between broadcast and broadband as described in Section IV-A is one of the feasible approaches, but this normally requires a large size of receiver buffer in order totake into account variable delay of a broadband network and cause decoding latency. In order to achieve faster switching between broadcast and broadband networks, physical layer parameters such as received signal strength indicator (RSSI) and SNR can be monitored at the receiver and used to switch the network seamlessly.

Normally broadcast receivers are able to obtain the RSSI and SNR values in real-time, and also obtain the information of modulation and code rate (ModCod) of PLP(s) being transmitted through preamble decoding (i.e., L1-Basic and L1-Detail in ATSC 3.0). Since such ModCod information in the preamble is directly related with at which RSSI or SNR levels a receiver is able to work, the receiver can use pre-defined threshold values of RSSI and SNR, in order to determine when to switch to the broadband network and when to switch back to the broadcast network. Figure 4 shows a receiver control software that is developed to monitor the RF status of RSSI and SNR information and allows to input the threshold values for then etwork switching decision. Note that in real-field environments, even though the RSSI is high enough, there can be serious multipath which results in low SNR. Conversely, there can be a field environment such that fair enough SNR value is achieved, but the signal strength can be very low. To accommodate these real-field situations, the control software is designed to monitor the RSSI and SNR values together, and then the receiver performs the switching when either one of the values meets the threshold values. That is, if one of the RSSI and SNR values in RF status becomes equal to or lower than the threshold values (i.e., RSSI and SNR in handoff value in Figure 4), then the receiver requests to a broadband server to acquire the broadband signal. Conversely, when switching back to the broadcast network, both RSSI and SNR values should be higher than the threshold values.

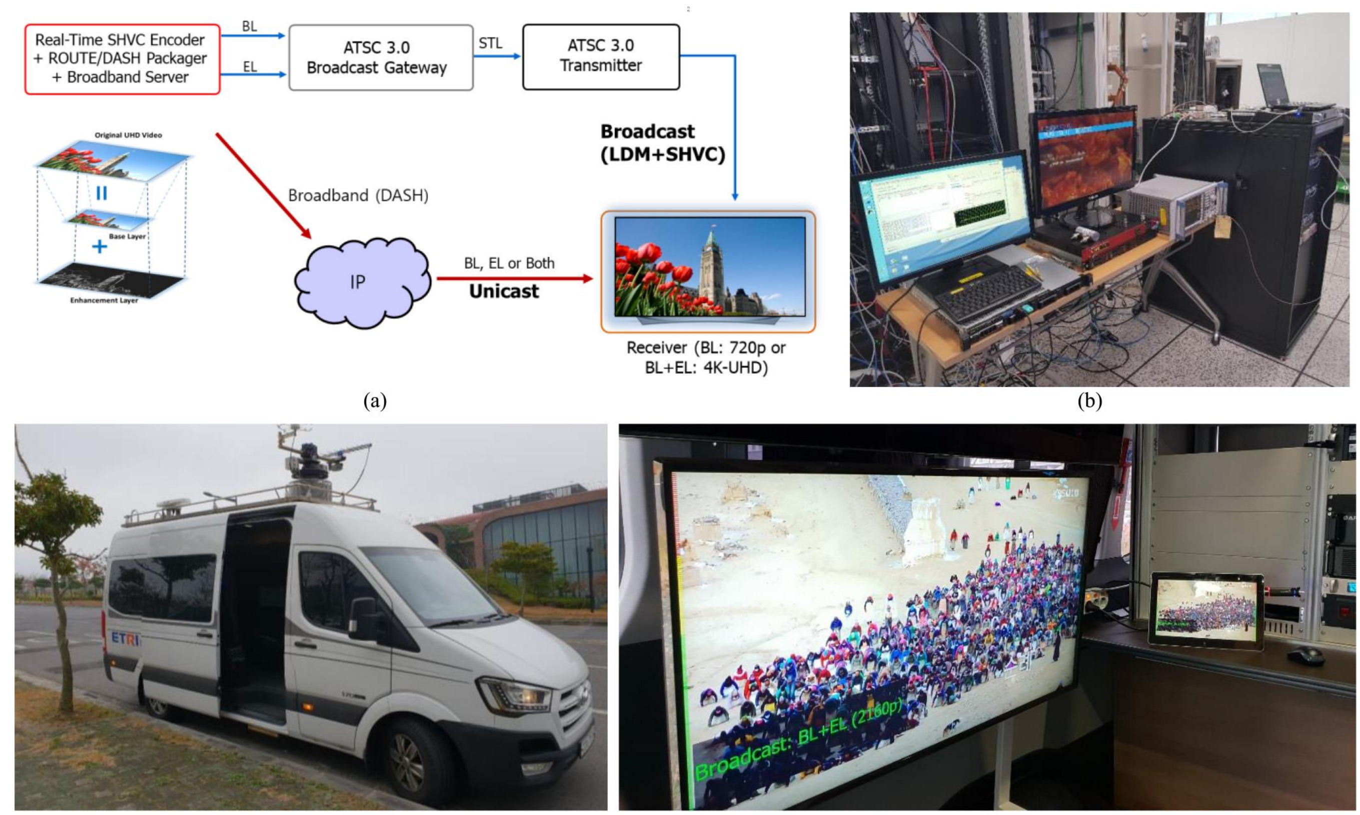
The proposed switching method using the physical layer parameters enables fast switching between the networks, as the receiver does not necessarily decode up to IP packets and buffer them to observe which packets are lost when performing the network switching. Furthermore, by setting-up the threshold values to be a little higher than the actual required SNR of the system, the receiver is able to switch the broadband right before the actual decoding errors in the physical layer, which is eventually helpful for seamless switching. Note that in practice the receiver is able to use both buffering method (as in Section IV-A) and physical layer parameters monitoring method together for better seamless experience for viewers.

V. FIELD VERIFICATION

A. Equipment Set-Up

The proposed use case of ATSC 3.0 broadcast and broadband convergence was hardware developed and verified in a real-field environment. The ATSC 3.0 test bed built in Jeju TechnoPark, Jeju, South Korea was used, and for broadband connectivity, public 4G LTE networks deployed in the Jeju city area were used [22]. Figure 5 shows the hardware equipment configuration for the field verification, studio/transmitter equipment in the facility, and receiver equipment inside a mobile testing vehicle. As studio equipment, a real-time SHVC encoder platform was developed, which integrates UDP/IP/ROUTE (or MMT) packaging for IP delivery over broadcast, and a broadband server with TCP/IP/DASH packaging for broadband delivery. Note that IP deliveries over broadcast and broadband were implemented conforming the ATSC 3.0 standard of signaling, delivery, synchronization and error correction (A/331) [21]. The developed SHVC encoder platform had a real-time A/V source input, and IP output to an ATSC 3.0 broadcast gateway. The ATSC 3.0 broadcast gateway then sends out the studio-to-transmitter (STL) output to two ATSC 3.0 transmitters. One transmitter was located at the Jeju TechnoPark facility, and the other transmitter was located at a downtown area of Jeju city, while they are constructing a single frequency network (SFN) using RF channel 50 [22], [23].

In the reception side, a 0 dB gain omni-directional antenna was used for mobile testing. The test vehicle was equipped with an ATSC 3.0 professional receiver decoding up to ATSC Link- layer Protocol (ALP) streams, and feeding UDP/IP/ROUTE (or MMT) streams as well as the physical layer information such as RSSI and SNR to a separate IP-layer decoder. The developed IP-layer decoder was also able to receive 4G LTE signals using a commercial dongle receiver. Hence, the IP-layer decoder was able to switch between the broadcast and broadband signals depending on the information of RSSI and SNR as well as decoder buffer monitoring, as described in Section IV.



(a) (b)

(c) (d)

Fig. 5. (a) Equipment configuration for the proposed ATSC 3.0 broadcast and broadband convergence use case; (b) Transmission equipment located at JejuTechnoPark; (c) Mobile test vehicle equipped with receiver equipment of the proposed convergence services; and (d) Receiver equipment inside the test vehicle.

TABLE I
PRESENTATION, TRANSPORT AND PHYSICAL LAYER PARAMETERS FOR THE FIELD VERIFICATION

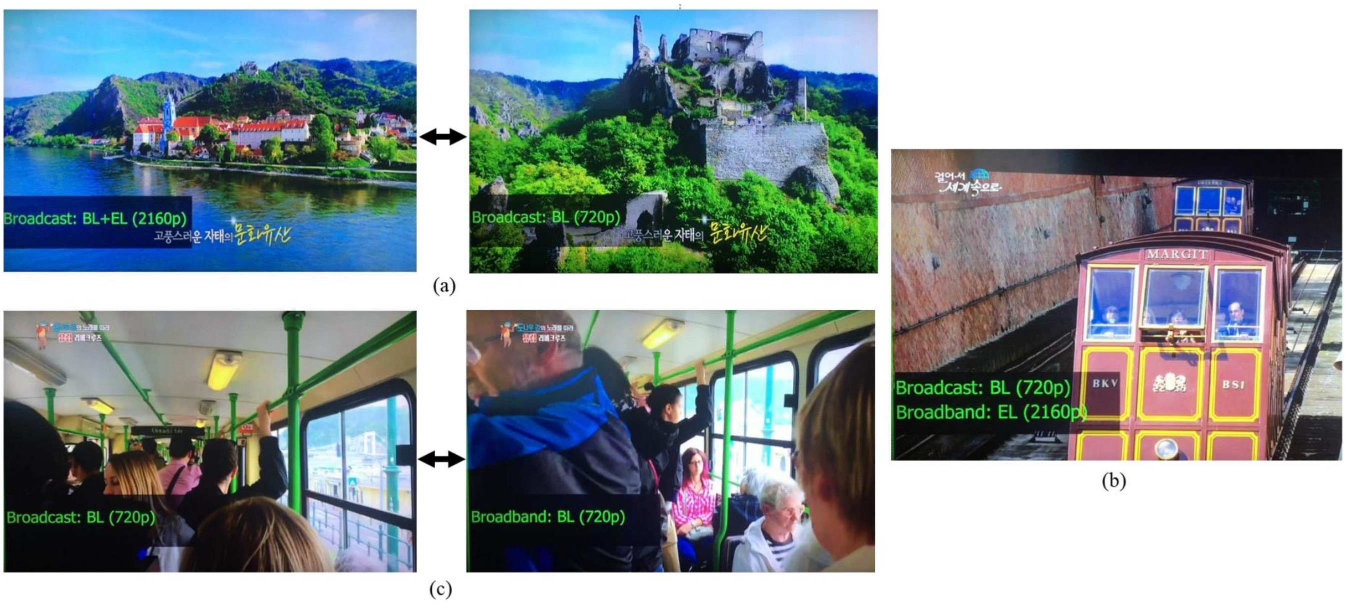
	Presentation and Transport Layer
Video	Codec: SHVC Base Layer: 720p (60 fps) Enhancement Layer: 2160p (60 fps)
Audio	MPEG-H
Transport Layer	Broadcast: ROUTE Broadband: DASH

		Physical Layer
Waveform Parameters		FFT Size: 16K Guard Interval: 768 Samples Pilot Pattern: SP8_2
Framing and Interleaving		Frame Length: ~ 250 ms (Symbol-aligned mode) Convolutional Time Interleaver (1024 depth)
PLP Parameters	LDM Core PLP	ModCod: QPSK & 5/15 Code Rate PLP Data Rate: 3.4 Mbps Required SNR (AWGN): -0.3 dB
	LDM Enhanced PLP	ModCod: 64QAM & 5/15 Code Rate PLP Data Rate: 10.1 Mbps Required SNR (AWGN): 14.9 dB
Bandwidth		6 MHz

Fig. 6. Mobile testing route depicting three different service scenarios depending on RF signal strength of the ATSC 3.0 broadcast tower.

B. Field Testing Configurations

Table I shows the details of presentation layer (video and audio), transport layer and physical layer configurations used for the field verification. As described in Table I, an A/V service was SHVC encoded to consist of BL of 720p HD stream and EL of 4K-UHD stream. In the transport layer, ROUTE and DASH packages were implemented for broadcast and broadband deliveries, respectively. In the physical layer, LDM was used such that a Core PLP carried SHVC BL having



(a)

(b)

(c)

Fig. 7. (a) Seamless switching between BL and BL + EL in the broadcast coverage ①; (b) Hybrid service of BL from broadcast and EL from broadband in the service area ②; and (c) Seamless switching between broadcast and broadband networks in the service area ③.

3.4 Mbps capacity, and an Enhanced PLP carried SHVC EL having 10.1 Mbps capacity. The theoretical performance in the Additive White Gaussian Noise (AWGN) channel of Core and Enhanced PLPs was -0.3 dB and 14.9 dB, respectively. Therefore, the configuration intended to have a 720p mobile HD service working around 0 dB SNR and a fixed 4K-UHD service working around 15 dB SNR together, while the data capacity of fixed 4K UHD service can be added with the mobile data capacity (i.e., Core PLP) due to the use of SHVC.

C. Testing Results and Observations

For field verification of the proposed ATSC 3.0 broadcast and broadband convergence service, a mobile testing was conducted as depicted in the testing route of Figure 6. As shown in the figure, the testing route was categorized into the following three different service scenarios depending on the signal strength mainly from the ATSC 3.0 broadcast transmitter #1 located at the JejuTechnoPark facility:

① Switching between the SHVC BL and EL depending on RF channel conditions within the broadcast coverage;
② Hybrid service that receives the SHVC BL from the broadcast network and SHVC EL from the 4G LTE network;
③ Switching between the broadcast and broadband networks to receive the SHVC BL signal depending on the broadcast signal availability.

The first service scenario was mostly observed within the service area ① of Figure 6, where fairly good broadcasting signal strength was received from the ATSC 3.0 transmitter tower #1. In the broadcast configuration using LDM, as the LDM Core PLP was targeted for a mobile service and the LDM Enhanced PLP was targeted for a fixed service, it was observed that the 4K-UHD content (SHVC BL + EL) was mostly viewed when the vehicle was stopped, whereas the 720p HD (SHVC BL) was viewed in the most of mobile conditions. The receiver was designed to maintain video frame synchronization between BL and BL+EL, so that seamless switching between 720p and 4K-UHD (BL and BL + EL) was shown depending on the broadcast signal strength (channel conditions) as depicted in Figure 7 (a).

The second service scenario was shown in the service area ② of Figure 7, where relatively lower signal strength from the broadcast tower #1 was measured. In this area, since the SHVC EL was not receivable from the tower due to lower signal strength, the receiver requested the SHVC EL via the public 4G LTE network, as depicted in Figure 7 (b). Since the same PTS of IP packets was used from broadcast and broadband, the receiver was able to receive the needed packets of SHVC EL from the broadband, in order to show a mobile 4K-UHD service using the hybrid network of broadcast and broadband.

The last service scenario was shown in the service area ③, where the signal strength from the broadcast was low enough such that RF signals were occasionally broken during the mobile measurements. Note that the black lines in the testing route of Figure 6 indicate errors in forward error correction (FEC) block of Core PLP occurred during the measurement. In the service area ③, the receiver used the buffering method described in Section IV-A and the method using the physical layer parameters described in Section IV-B together, in order to achieve seamless switching between the broadcast and broadband networks as depicted in Figure 7 (c). The receiver used one second of buffer to monitor which packets were missing from the broadcast, and then to request/receive the identical packets from the broadband. Note that the receiver buffer size was adjustable depending on the broadband network conditions such as end-to-end latency and delay jitter. The method using the physical layer parameters also helped seamless switching between broadcast and broadband, as the threshold values of RSSI and required SNR for Core PLP were set accordingly.

During the real-field testing using both broadcast and broadband networks, as the broadband delivery is based on unicast, that is one-to-one delivery, the successful reception of a service over broadband was highly dependent on the network conditions. It was noted that when the test was conducted during the time that large amount of network traffic was consumed, there was an occasional impact for SHVC EL delivery over the broadband. Since the SHVC BL was much smaller amount of data, the broadband delivery of SHVC BL was successful during the most of testing time. The proposed ATSC 3.0 convergence use case was that the ATSC 3.0 broadcast is being used for dominant consumption of a service, and the seamless switching to broadband can be used when needed (e.g., shadowing area, underground, or deep indoor where HPHT broadcast signals are not reachable). Therefore, in the proposed use case, the broadcast and broadband networks are intended to be complementary each other, in order to provide better quality of experience to viewers, comparing to a service being delivered through either broadcast only or broadband only.

VI. CONCLUSION

This paper presented IP-based cooperative services of broadcast and broadband networks using the ATSC 3.0 standard. The combination of LDM and SHVC was used to provide the most spectral-efficient broadcast configuration when mobile and fixed services are intended in a single RF channel. Then, the proposed convergence use case was that given the broadcast signal was used for dominant consumption of an A/V service, the broadband network could be complementarily used to provide alternative SHVC BL, EL, or BL + EL streams depending on the broadcast signal availability. The implementation details for broadcast and broadband convergence were compliant with the ATSC 3.0 standards, and included the IP-layer description of MMT/ROUTE over broadcast and DASH over broadband, as well as the implementation of transmission/reception ends to achieve seamless switching. The proposed convergence use case of ATSC 3.0 broadcast and broadband was verified in the real-field environment using the ATSC 3.0 broadcast and public 4GLTE network.

REFERENCES

[1] R. Chernock *et al.*, "ATSC 3.0 next generation digital TV standard—An overview and preview of the issue," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 154–158, Feb. 2016.

[2] L. Fay *et al.*, "ATSC 3.0 physical layer specification: An overview," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 159–171, Feb. 2016.

[3] L. Michael and D. Gómez-Barquero, "Bit interleaved coding and modulation for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1,pp. 181–188, Feb. 2016.

[4] K.-J. Kim *et al.*, "Low density parity check code for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 189–196, Feb. 2016.

[5] N. Loghin *et al.*, "Non-uniform constellations for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 197–203, Feb. 2016.

[6] M. Earnshaw *et al.*, "Physical layer framing for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 263–270, Feb. 2016.

[7] H. Jeong *et al.*, "Flexible and robust transmission for physical layer signaling of ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 204–215, Feb. 2016.

[8] P. Klenner *et al.*, "Physical layer time interleaving for the ATSC 3.0 system," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 253–262, Feb. 2016.

[9] S.-I. Park *et al.*, "Low complexity layered division multiplexing system for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 233–243, Feb.2016.

[10] J.-Y. Lee *et al.*, "Multiple service configurations based on layered division multiplexing," *IEEE Trans. Broadcast.*, vol. 63, no. 1, pp. 267–274, Mar. 2017.

[11] J.-Y. Lee *et al.*, "Efficient transmission of multiple broadcasting services using LDM and SHVC," *IEEE Trans. Broadcast.*, vol. 64, no. 2, pp. 177–187, Jun. 2018.

[12] L. Zhang *et al.*, "Using non-orthogonal multiplexing in 5G-MBMS to achieve broadband-broadcast convergence with high spectral efficiency," *IEEE Trans. Broadcast.*, vol. 66, no. 2, Jun. 2020.

[13] E. Iradier *et al.*, "Using NOMA for enabling broadcast/unicast convergence in 5G networks," *IEEE Trans. Broadcast.*, vol. 66, no. 2, Jun. 2020.

[14] G. K. Walker *et al.*, "ROUTE/DASH IP streaming-based system for delivery of broadcast, broadband, and hybrid services," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 328–337, Feb. 2016.

[15] K. Park, Y. Lim, and D. Y. Suh, "Delivery of ATSC 3.0 services with MPEG media transport standard considering redistribution in MPEG-2 TS format," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 338–351, Feb. 2016.

[16] M. Simon *et al.*, "Methods of coordinating ATSC 3.0 broadcast and 5G unicast services 3GPP release 16 and beyond," *IEEE Trans. Broadcast.*, vol. 66, no. 2, Jun. 2020.

[17] J.-Y. Lee *et al.*, "Layered division multiplexing for ATSC 3.0: Implementation and memory use aspects," *IEEE Trans. Broadcast.*, vol. 65, no. 3, pp. 496–503, Feb. 2019.

[18] *ATSC Recommended Practices: Guidelines for the Physical Layer Protocol*, ATSC, Washington, DC, USA, Document A/327:2018, Oct. 2018.

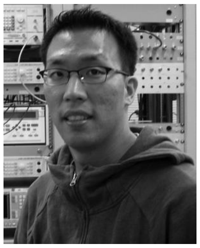
[19] *ATSC Standard: Video-HEVC*, ATSC, Washington, DC, USA, Document A/341:2019, Feb. 2019.

[20] D. Gómez-Barquero and O. Simeone, "LDM versus FDM/TDM for unequal error protection in terrestrial broadcasting systems: An information-theoretic view," *IEEE Trans. Broadcast.*, vol. 62, no. 4, pp. 571–579, Dec. 2015.

[21] *ATSC Standard: Signaling, Delivery, Synchronization, and Error Protection*, ATSC, Washington, DC, USA, Document A/331:2019, Jun. 2019.

[22] S.-I. Park *et al.*, "Performance analysis of all modulation and code combinations in ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 65, no. 2, pp. 197–210, Jun. 2019.

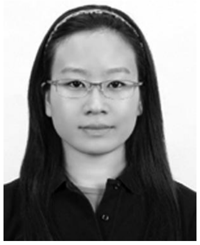
[23] J.-Y. Lee *et al.*, "ATSC 3.0 and LTE cooperation for LDM and SHVC based mobile broadcasting," in *Proc. IEEE BMSB*, Jun. 2019, pp. 1–2.



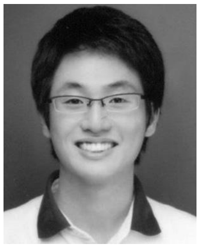
Jae-young Lee (Senior Member, IEEE) received the B.S. degree (Highest Hons.) in electrical and computer engineering from Rutgers University in 2001, the M.S. degree in electrical and computer engineering from the University of Wisconsin at Madison in 2003, and the Ph.D. degree in engineering science from Simon Fraser University in 2013. In 2003, he joined Electronics and Telecommunications Research Institute, where he is currently a Principal Research Associate with the Media & Broadcasting Research Group. He is the Chair of ATSC Specialist Group on Physical Layer (S32), which focuses on the physical layer of the next generation digital TV standard. His research interests are in the areas of digital signal processing for various applications, including digital broadcasting, telecommunications, and human–computer interaction systems.

Sung-Ik Park (Senior Member, IEEE) received the B.S.E.E. degree from Hanyang University, Seoul, South Korea, in 2000, and the M.S.E.E. degree from POSTECH, Pohang, South Korea, in 2002, and the Ph.D. degree from Chungnam National University, Daejeon, South Korea, in 2011. Since 2002, he has been with the Broadcasting System Research Group, Electronics and Telecommunications Research Institute (ETRI), where he is a Project Leader and a Principal Member of Research Staff. He has over 200 peer-reviewed journal and conference publications, and multiple best paper and contribution awards for his work on broadcasting technologies. His research interests are in the area of error correction codes and digital communications, in particular, signal processing for digital television. He currently serves as an Associate Editor for the IEEE TRANSACTIONS ON BROADCASTING and *ETRI Journal*, and a Distinguished Lecturer of IEEE Broadcasting Technology Society.

Hyun-Jeong Yim (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in multimedia and computer science from Sookmyung Women's University, Seoul, South Korea, in 2003, 2005, and 2010, respectively. In 2010, she joined Electronics and Telecommunications Research Institute, South Korea, where she is currently a Senior Research Member with Broadcasting System Research Department. Her research interests are in the area of digital broadcasting system, data broadcasting, multimedia scene representation, and Web 3D.



Bo-Mi Lim (Member, IEEE) received the B.S. degree from Ajou University, Suwon, South Korea, in 2008, and the M.S. degree from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, in 2010. Since 2010, she has been a Member of Research Staff with Broadcasting System Research Department, Electronics and Telecommunications Research Institute. Her research interests are in areas of wireless communication system design and digital broadcasting.



Sunhyoung Kwon (Member, IEEE) received the B.S. degree in electrical communications engineering from Information and Communications University, Daejeon, South Korea, in 2008, and the M.S. and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology, Daejeon, in 2010 and 2020, respectively. Since 2010, he has been with the Broadcasting System Research Group, Electronics and Telecommunications Research Institute, where he is currently a Senior Member of Research Staff. His research interests are in the area of digital broadcasting and communications.

Sungjun Ahn (Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, in 2015 and 2017, respectively. Since 2017, he has been with Media Research Division, Electronics and Telecommunications Research Institute, where he is currently a Research Engineer. His research interests include stochastic geometry analysis, signal processing, and optimization for wireless communications and digital broadcasting.

Namho Hur (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical and electronic engineering from the Pohang University of Science and Technology, Pohang, South Korea, in 1992, 1994, and 2000, respectively. He is currently with the Telecommunications and Media Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon, South Korea, where he is the Project Leader of 'Development of Transmission Technology for Ultra High Quality UHD.' He was the Chair of the Future of Broadcast Television Initiative Management Committee from April 2018 to April 2019. His research interests include realistic digital broadcasting systems.