IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received April 15, 2019, accepted May 10, 2019, date of publication May 16, 2019, date of current version June 3, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2917291

Fog Computing as an Enabler for Immersive Media: Service Scenarios and Research Opportunities

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This work was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education under Grant 2018R1A6A3A03010650, in part by the European Union's H2020 Research and Innovation Program under Grant H2020-MSCA-ITN-2016-SECRET 722424, and in part by the German Federal Ministry of Education and Research (BMBF) as part of the project "Fast Robotics" under Grant 03ZZ0528E.

ABSTRACT Immersive media services, such as augmented reality and virtual reality (AR/VR),[a] 360-degree video, and free-viewpoint video (FVV), are popular today. They require massive data storage, ultrahigh computing power, and ultralow latency. It is hard to fulfill these requirements simultaneously in a conventional communication system using a cloud/centralized radio access network (C-RAN). Specifically, due to centralized processing in such a system, the end-to-end latency, as well as the burden on the fronthaul network, are expected to be high. Fog computing-based radio access networks (F-RAN), in contrast, have been widely considered as an enabler for immersive media. Our contribution in this paper is threefold: First, we propose various service scenarios reflecting the characteristics of immersive media. Second, we identify the technologies that are required to support the proposed service scenarios under F-RAN and discuss how they can support the proposed scenarios efficiently. Third, we discuss possible research opportunities.

[a] A list of acronyms can be found in the Appendix.

INDEX TERMS Fog computing, radio access networks, immersive media, free-viewpoint video, 360-degree video, virtual reality, augmented reality.

I. INTRODUCTION

Immersive media refer to the multimedia that provide users with an illusive environment entirely surrounding them such that they feel part of it. The last few years have witnessed a huge spread and commercialization of immersive media services, such as free-viewpoint video (FVV), 360-degree video, and augmented and virtual reality (AR/VR), in different fields ranging from entertainment to communications, education, and medicine [1], [2]. This spread generally can be attributed to the rapid advancement of networking technologies and the growth of smart devices market.

The interest in immersive media, e.g., creating high-performance computer graphics for games and other interactive applications, has been around for a long time. However, the prior attempts did not get close enough to reality, mainly because they were not able to fulfill a number of strict requirements. Specifically, the ideal end-to-end (E2E) latency for a seamless VR experience is less than 10 ms, including video rendering and refreshing the video on the head-mounted display (HMD) [3]. Also, according to [4], a high-quality 360-degree video requires at least 12K resolution (i.e., 11520 × 6480) and a high frame rate of 100 frames per second (fps). These requirements are hard to achieve, especially at the same time. This describes, for instance, why the head motion with old AR/VR technologies cannot be reflected in live streaming on the HMD on time, which causes motion sickness and, subsequently, discomforts such as headaches, eye strain, and nausea [5]. Furthermore, it is difficult for user equipments (UEs) to store and process huge amounts of data in real time.

Fog computing, which was firstly introduced by Cisco [6], is widely considered as a key enabler for immersive media services [3], [7], [8]. With this technology, a large amount

The associate editor coordinating the review of this manuscript and approving it for publication was James Gross.

of data can be stored and processed close to the point where it is generated. Specifically, storage and computation tasks are offloaded from the core network and centralized cloud servers to the so-called *fog nodes* or *edge nodes*. Examples of fog nodes include cellular base stations, set-top boxes, and UEs [9]. This way, high-performance immersive media services can be processed at nearby nodes, and thus the latency problem is solved.

In this paper, we first provide specific immersive media service scenarios under F-RAN, taking into consideration the characteristics of FVV, 360-degree video, and AR/VR spaces. For each service scenario, we describe the scenario itself as well as how its tasks can be offloaded to fog nodes. A variety of schemes and techniques are discussed to make the proposed service scenarios more feasible and realistic. We also discuss several research challenges and opportunities to solidify the proposed service scenarios. To the best of our knowledge, this paper is the first to provide such discussions.

In summary, we make the following three contributions:

1) *Perspectives*: We investigate how immersive media services will be offloaded to F-RAN. In particular, we propose F-RAN scenarios for notable immersive media services, and discuss the feasibility of each scenario.
2) *Survey*: We review the technologies that enable the proposed scenarios.
3) *Research opportunities and challenges*: We discuss several related research opportunities and challenges.

The remainder of this paper is organized as follows: In Section II, we give an overview of RAN architectures and describe the characteristics of notable immersive media services. Then, we propose service scenarios for immersive media services served in F-RAN, and discuss the feasibility of each scenario in Section III. Next, we highlight and discuss related research opportunities in Section IV. Finally, we conclude the paper in Section V.

II. BACKGROUND

A. C-RAN VS. F-RAN

C-RAN is one of the most widely used mobile network architectures. It was firstly proposed in [10] and later detailed by China Mobile [11]. The most important feature of C-RAN is the separation between the distribution unit (DU) and the radio unit (RU) to support enhanced capacity and coverage, and also to manage the network resources in an adaptive way [12]–[14]. As illustrated in Fig. 1(a), the baseband unit (BBU) and the remote radio head (RRH) are connected by a fronthaul interface (e.g., a common public radio interface (CPRI) [15]). The BBU typically manages the tasks that come from application servers and dynamically delivers the results to the RRH, which is responsible for radio frequency (RF) operations. However, C-RAN could impose a severe burden on the BBU pool as well as on the fronthaul network, especially in the upcoming 5G era where a large number of services and massive device connectivity are expected.

The F-RAN architecture has been recently proposed in [16] to overcome the aforementioned drawbacks of C-RAN. As shown in Fig. 1, the main difference between C-RAN and F-RAN is the location where the tasks, requested by the UEs, are controlled and processed. In C-RAN (Fig. 1(a)), the user request is passed from the RRH to the application server. In contrast, in the case of F-RAN (Fig. 1(b)), the request can be handled at the fog access points (F-APs) close to the user, without passing it through the fronthaul network. Consequently, the users receive their desired services from F-RAN much faster, with less power consumption. In general, the management and control are handled by the global control node (GCN), also known as high power node (HPN) [16]. F-RAN can become more advantageous by applying two advanced modes: (i) cooperative mode and (ii) device-to-device (D2D) mode. The cooperative mode enables the F-APs to cooperatively process the requests, whereas the D2D mode enables the UEs to directly communicate with each other. However, these two modes require effective and efficient resource allocation to avoid interference [17]–[19].

The features of F-RAN can be summarized as follows:

- *Ultra-low latency:* Since the F-APs are close to the UEs, low-latency services are possible.
- *Proximity:* The requests can be processed and computed through the F-APs as well as the UEs themselves, without going through a centralized BBU pool.
- *User location awareness:* Since the F-APs can be aware of the locations of the UEs by the GCN, F-RAN can provide location-based services.
- *Network status awareness:* F-RAN can also provide differentiated services by utilizing the state of network connections. For example, seamless video streaming can be provided by changing the video quality according to the network conditions.

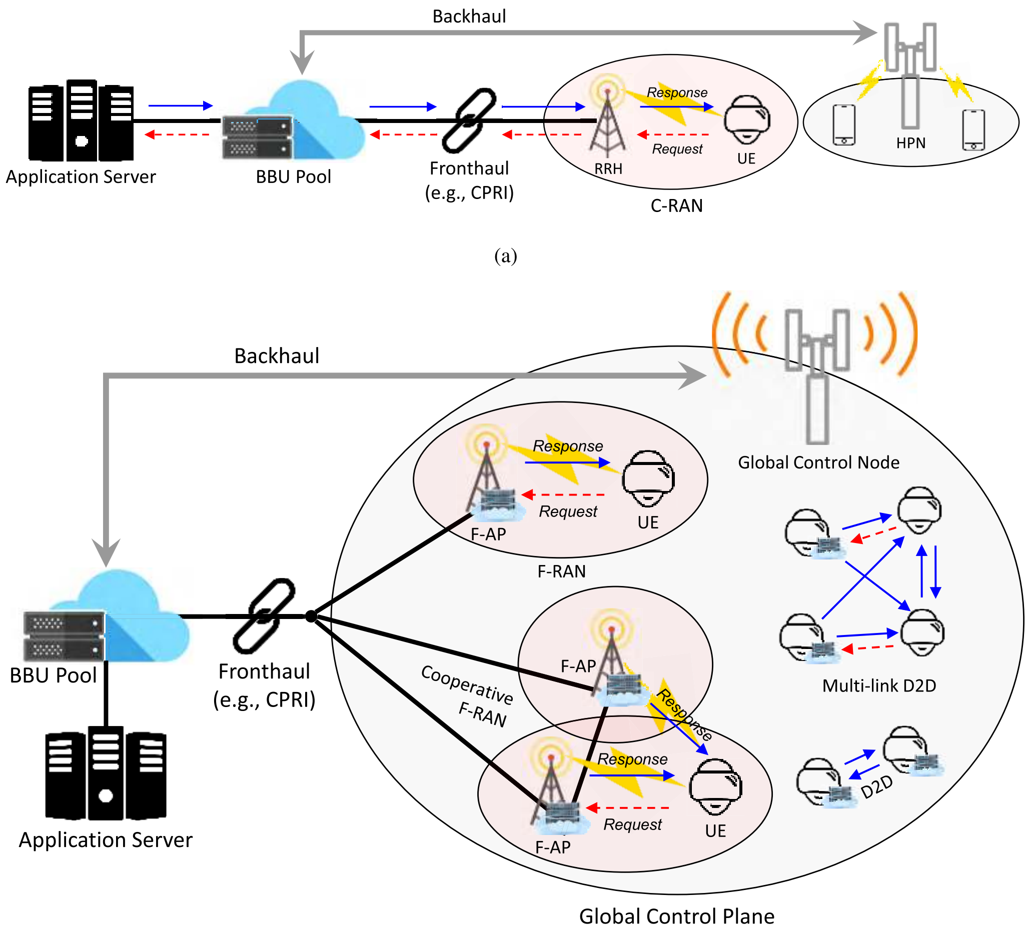
B. CHARACTERISTICS OF IMMERSIVE MEDIA

According to [20], immersive media services can be categorized into four types: (i) free navigation, (ii) interactive all-reality, (iii) light-field communications, and (iv) light-field editing. Currently, free navigation and interactive all-reality services can be easily experienced, even though they are not fully commercialized yet. On the other hand, capturing and editing light-field videos are not achievable yet, because they require complicated hardware and setup. Although the release of modern equipment like Lytro Immerge [21] has made the process easier, the resolution of the captured light-field videos is still low [22]. Therefore, we focus only on free navigation and interactive all-reality services.

In the following, we give an overview of three notable immersive media services: (i) FVV, (ii) 360-degree video, and (iii) AR/VR spaces. The first two belong to *free navigation*, while the third belongs to *interactive all-reality*.

1) FREE-VIEWPOINT VIDEO

FVV enables the users to freely navigate their viewpoints. Free-viewpoint TV (FTV) is a notable FVV application [23],



(a)

(b)

FIGURE 1. Radio access network (RAN) architectures. (a) Cloud/centrfalized radio access network (C-RAN). (b) Fog-based radio access network (F-RAN).

and it is considered as the next-generation broadcasting system [24]. FVV is typically synthesized by depth-image-based rendering (DIBR), but not captured by many cameras, due to transmission bandwidth and cost constraints. For example, as shown in Fig. 2, assume that seven viewpoint videos are required to provide a free-viewpoint. If DIBR is used, seven viewpoints can be synthesized through some videos and the corresponding depth information, without transmitting all the seven videos. In addition, even if the depth map cannot be captured at the transmitter side, it can be estimated with the captured 2D videos [25]. The compression efficiency of DIBR can be significantly improved by using multi-view video coding (MVC). Specifically, MVC achieves more than 50% bit rate saving, in comparison with the conventional simulcast [26].

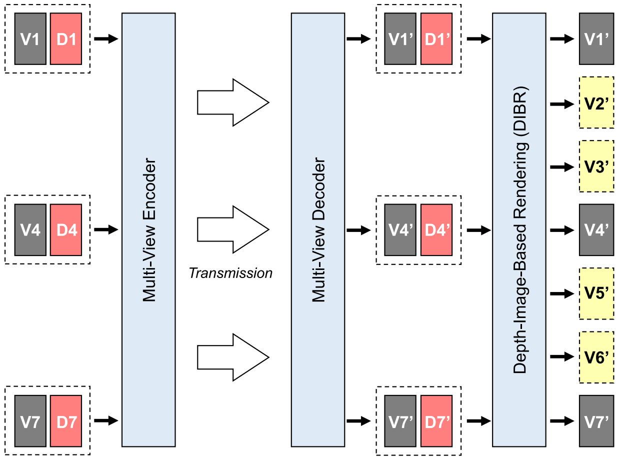


FIGURE 2. The principle of DIBR in FTV systems.

2) 360-DEGREE VIDEO

Over the last few years, 360-degree video devices such as HMDs and 360-degree cameras, have become more popular. However, there is still a room to improve these devices in terms of bandwidth, latency, and resolution. The 360-degree video technology is based on two main techniques: (i) projection and (ii) tiling. Projection enables a spherical 360-degree video to be projected to a two-dimensional plane. This is an indispensable part for video encoding and decoding.

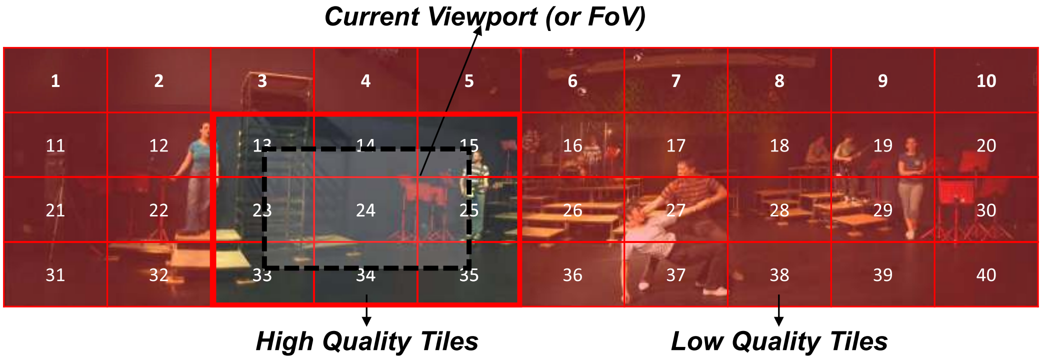


FIGURE 3. An example of tile-based adaptive streaming.

Equirectangular projection (ERP) [27] is a straightforward method, which provides the lowest number of discontinuities. However, it requires many pixels and imposes high data rates. Various projection methods have been proposed recently to address these problems by trying to reduce the number of pixels without deteriorating the user's quality of experience (QoE). Notable examples include cubemap projection (CMP) [28], pyramid projection (PMP) [29], icosahedral projection (ISP) [30], segmented sphere projection (SSP) [31], and rotated sphere projection (RSP) [32].

Tiling, as shown in Fig. 3, divides each video frame into small rectangular regions. Each of the resulting regions can be independently encoded, transmitted, and decoded [33]. This way, the user's current viewport can be encoded in high quality, while the rest of the view is encoded in low quality. Furthermore, the quality of the tiles can be adjusted adaptively in accordance with the network conditions. This technique is generally called adaptive bitrate streaming (ABS) [34]–[37], and it can save the bandwidth by up to 72% [35].

3) AR/VR SPACES

AR augments the objects in a real world by perceptual information, while VR uses computer technology to create an interactive experience simulating reality. According to [22], providing six degree-of-freedom (6-DoF) by using the multimedia captured in the real world (not by computer graphics) is the main focus of current VR researches. Realizing life-like VR spaces without human discomfort requires at least 2.7 Tbps[1] [38].

Structure-from-motion (SfM) is a traditional technique that makes AR/VR spaces possible by reconstructing 3D motions and scenes from unstructured images and videos [40], [41]. The complexity of SfM is high, because it requires a separate matrix for each camera view. This problem can be solved by applying a technique called redundant view mining [42], which is able to reduce the processing time by about 36%. More recently, machine learning techniques have been used in the VR field, for instance, to support sophisticated view synthesis [43], [44] and super-resolution AR/VR [45], [46]. However, the evaluations in these studies were based on a limited number of video frames, which means that a breakthrough to process a huge amount of videos with a high data rate (e.g., 2.7 Tbps) is still required.

III. F-RAN AS AN ENABLER FOR IMMERSIVE MEDIA

In this section, we provide perspectives on how F-RAN can support three notable immersive media services: (i) FTV, (ii) 360-degree video, and (iii) AR/VR spaces.

A. FTV SERVICE IN F-RAN

Fig. 4 shows an architecture for FTV, including three cases classified according to the location where different components are processed. In *Case 1*, the F-APs are responsible for all processing tasks, such as video correction, depth estimation, view synthesis (i.e., DIBR), video encoding, storage, and transmission, which leads to a huge burden on the F-APs. This problem can be solved by increasing the computing power and storage capacity of the F-APs. While this case is ideal in terms of latency, it is infeasible due to its high deployment costs.

In *Case 2*, the captured views are only encoded and stored in the F-APs. If the requested viewpoint is not the captured one (i.e., not stored in the F-APs), the UEs have to estimate the corresponding depths and synthesize the viewpoint. In this case, the UEs can display the requested viewpoint with a low latency if only the desired view is captured in advance. That is, this case is impractical because it is hard to perform the required processing on the UEs in real time, especially if the users frequently change their viewpoints. Otherwise, the prices of the UEs would be not affordable.

In *Case 3*, the depth estimation and view synthesis are separately handled by the F-APs and the UEs, respectively. This way, the burden of the rendering part, which imposes huge data processing, is distributed between the F-APs and the UEs. Specifically, the F-APs estimate and store all of the corresponding depths from the captured (original) videos and transmit them to the UEs. The UEs, in turn, synthesize the desired viewpoints. This case may result in high latency if

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[1] We consider 162° × 135° fields of view (FoV), 60 pixels per degree, 96 bits per pixel, 1800 fps refresh rate, and display stream compression [39].

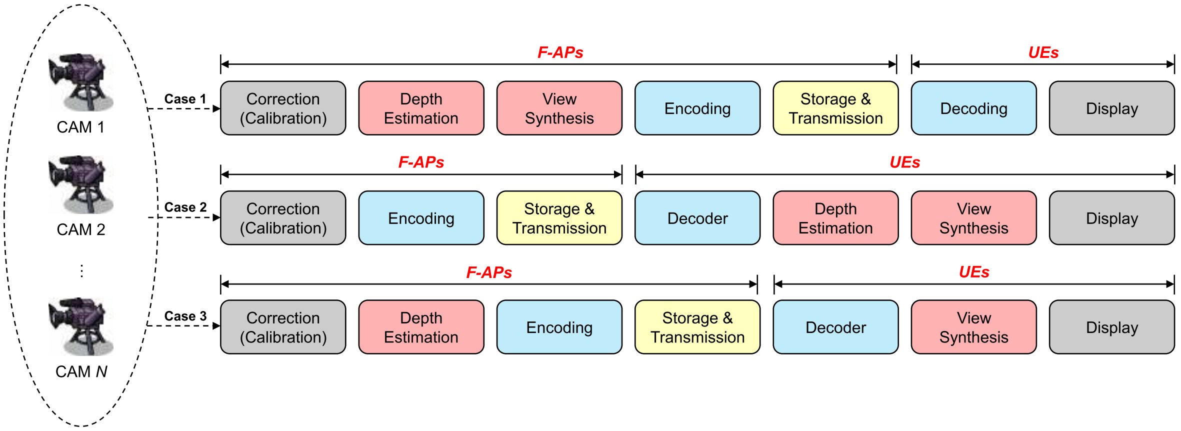

FIGURE 4. FTV architecture and its three cases in F-RAN.

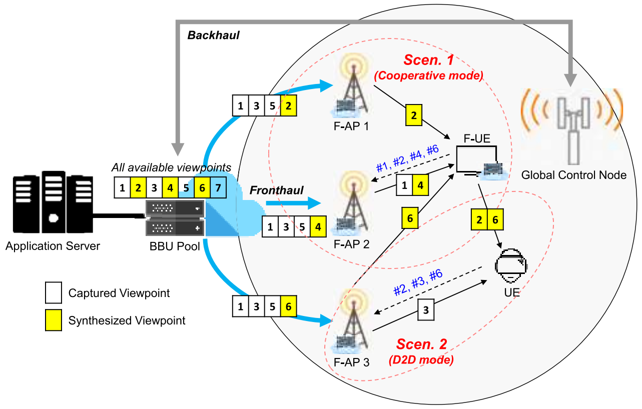

FIGURE 5. FTV scenarios in F-RAN.

the UEs have low computing power, such as smart phones, or the UEs would be expensive.

We propose a service scenario for FTV under F-RAN to address the problems mentioned in Sec. II-B.1 (i.e., huge data processing with low latency). Fig. 5 shows the proposed scenario, which enables a low latency service, with a low cost, even if the UEs are regular mobile devices. In this scenario, to reduce the CPU capacity and storage capacity requirements of individual F-APs, the CPU capacities and the storage capacities of all the F-APs are combined, and used together (i.e., cooperatively) to, respectively, store and process the available viewpoints, which are created in advance. The BBU pool is responsible for rendering the videos, because it has higher computing power and storage capacity than the F-APs and UEs. The captured viewpoints are forwarded from the application server to the F-APs through the BBU pool, to store (or cache) them, regardless of the user request. In this time, the BBU pool synthesizes the middle virtual viewpoints and distributes them on the F-APs without overlapping.

As part of this scenario, we propose an orchestration framework for FTV services. The framework consists of the following four components:

- *Request handler (RH)* is a dispatcher, responsible for handling the requests received from the UEs.
- *View seeker (VS)* manages information about which F-AP owns a certain viewpoint in the coverage.
- *Placement manager (PM)* is responsible for placement decisions, such as full channel state information (CSI) based on the signal-to-interference-plus-noise ratio (SINR) and IP address.
- *Scheduler (SC)* determines the selected candidates for the RH to establish connections.

The scenario also includes an orchestration protocol. Fig. 6 provides an example of this protocol for *"Scen. 1: Cooperative F-RAN"*, which is illustrated in Fig. 5. The protocol works in the following order:

1) UE 1 requests the desired viewpoint videos from a nearby F-AP (i.e., F-AP 2).
2) F-AP 2 checks whether the requested video is available or not, and notifies the result to the GCN.
3) The RH dispatches the request to the VS.
4) The VS knows which F-AP has the requested viewpoint video, and thus the candidates' information are pushed to the PM and the SC.
5) The SC requests full CSI about the target F-APs (as a GET request) from the PM.
6) The PM sends the requested CSI (as a GET response) back to the SC.
7) Based on the full CSI, the SC determines which mode is suitable both for transmission as well as for allocating the resources. Then, the selected mode is shared with the other components. For instance, the mode can be determined based on the channel capacity considering links interferences [47], cache size, or the intensity of coverage probability [48], [49].
8) The RH sends a connection establishment request, along with the requested channels and viewpoint videos, to the target F-APs.
9) Finally, the radio bearer is created and the requested viewpoints are transmitted cooperatively. The cooperative transmission can be achieved with network

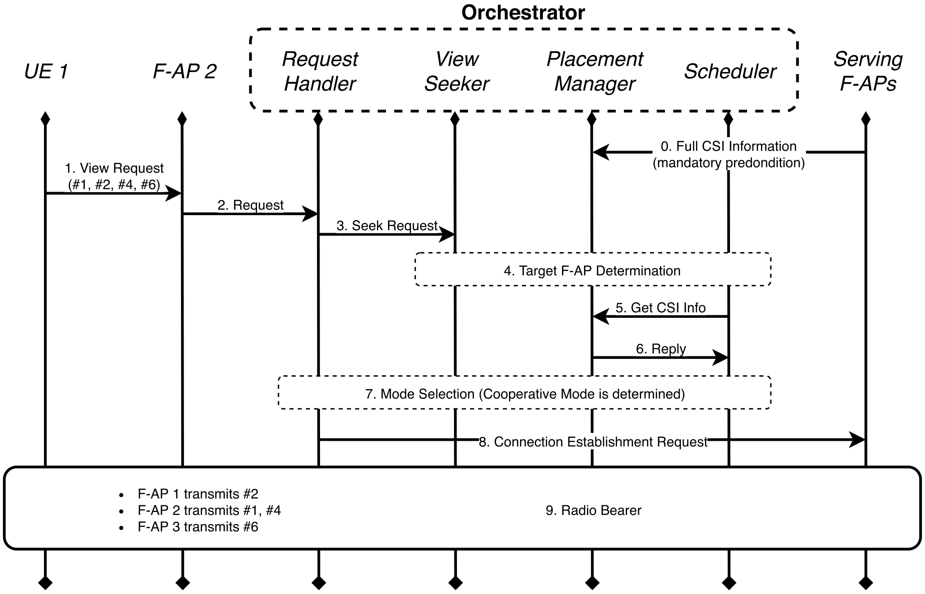

FIGURE 6. The proposed orchestration protocol for FTV services.

coding (NC)[2] [50], [51], or with coordinated multipoint (CoMP) transmission and reception[3] [54].

B. 360-DEGREE VIDEO SERVICE IN F-RAN

Although HMDs and 360-degree cameras are being actively released since 2015, they are still not popular. This can be attributed to one or more of the followings reasons:

- *High prices:* In order to provide a sense of immersion with high quality, at least a full-view sphere resolution of 12K to 24K, FoV resolution of 4K, viewing angle of 120 degrees, frame rate of 60 to 120 fps, and refresh rate of 90 Hz need to be satisfied [4]. In addition, the frame rate and refresh rate should be synchronized (i.e., a multiple of each other). Otherwise, the time intervals between individual frames would be sometimes larger and, therefore, the effective frame rate would be lower. Currently, it is hard to fulfill these requirements at an affordable price.
- *Uncomfortable moving:* Most high-performance HMDs perform high-quality graphics processing (e.g., FoV rendering) on PCs, which limits the movement. Although there are standalone HMDs, they still have limited computing power, resolution, and battery life.
- *Improper video delivery method:* High-quality 360-degree videos should be delivered to HMDs in streaming (not downloading) way. When streaming a 360-degree video to a large number of users, it is necessary to minimize the traffic generated in the communication network.

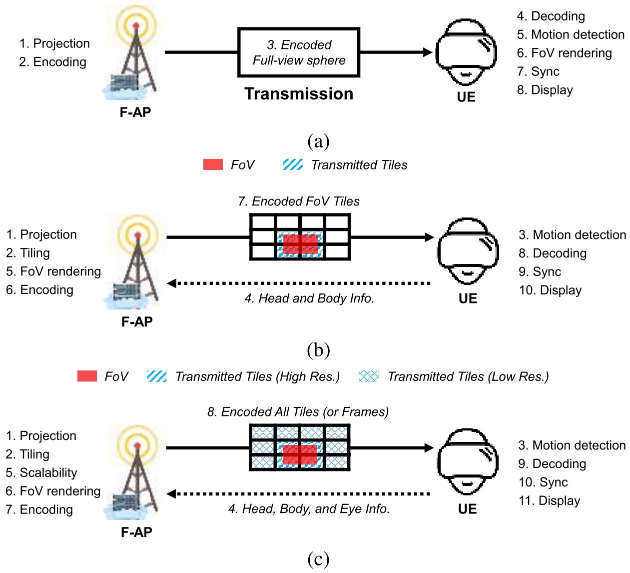

FIGURE 7. Immersive 360-degree video streaming in F-RAN. (a) Case 1: Full-view streaming. (b) Case 2: FoV-based streaming. (c) Case 3: Adaptive bitrate streaming.

Offloading computation tasks to F-APs brings several advantages. Specifically, it minimizes the need for high-performance PCs, thus relaxes the cost problem. Moreover, since the F-APs are close to the UEs, video streaming with low latency can be also achieved.

Offloading 360-degree videos can be classified into three cases (see Fig. 7). In *Case 1*, as illustrated in Fig. 1(a), the F-AP streams the projected and encoded full-view 360-degree video to the UE. Since the F-AP streams a full view, any view request becomes unnecessary, and the UE only performs motion detection and FoV rendering on its own. Even though this case can reduce the latency, it requires a

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[2] NC can also improve the performance of distributed storage considered in our scenario, in terms of maintenance bandwidth [52], [53].

[3] Specifically, the joint transmission (JT) scenario can be realized via multiple-input and multiple-output (MIMO) schemes such as multi-link D2D [55], [56].

high computing power, which may translate into a high cost and a high battery consumption.

Fig. 7(b) depicts *Case 2* in which the F-AP streams only the tiled videos corresponding to the current FoV. That is, the F-AP performs FoV rendering by using the information sensed from the UE like head rotation. As a consequence, the required bandwidth and computing power of the UEs are significantly reduced in this case. According to [57], the FoV streaming reduces the bandwidth by more than half, compared with full-view streaming (*Case 1*). However, in order to guarantee motion-to-photon (MTP) latency within 10 ms, the round-trip time (RTT) has to guarantee an ultra-low latency (e.g., 1 ms [58]). Therefore, the RTT is likely to increase in the case of high mobility, because the UE has to request new tiled videos, and also the F-AP has to stream the new tiled videos.

Case 3 also considers FoV-based streaming, as shown in Fig. 7(c). However, the remaining tiled videos corresponding non-FoV are also streamed with low quality. Adaptive streaming techniques and feasible scenarios are already proposed in F-RAN [59], [60]. However, these studies have not consider tiled-based adaptive streaming. According to [61], [62], viewport prediction (VP) is the main challenge for implementing tile-based adaptive streaming. He *et al.* [61] proposed to split the 360-degree video not only spatially into tiles, but also temporally into layers for QoE optimization, which requires a special encoder. Qian *et al.* [62] solved this problem by producing smaller tiles. This problem can be also addressed by using scalable multi-view video coding (SMVC) [63]–[65]. In particular, SMVC can encode entire tiles (with low quality) and the FoV tiles (with high quality) using the same encoder. This way, the user can experience the media seamlessly even if the quality is low.

In addition to the above discussed cases, NVIDIA recently proposed a novel method [66], named foveated rendering, to reduce the bandwidth. The idea is to attach an eye-tracker, such as Tobii Gaming, to the HMDs to find out the region that the user is gazing at in FoV and send the information (eye-gaze signal) to the F-AP. The gazed and the surrounding regions are rendered with high quality and low quality, respectively, in the F-AP. According to [67], foveated rendering can save the bandwidth by up to 83%, compared with the conventional full-view 360-degree video streaming. However, since only the intra-coded picture can be used for random access when the user switches to a new quality of each tile, the response will take longer as the group of pictures (GoP) becomes larger. Otherwise, the intra-coded picture can be added more in the middle, which would require a higher bitrate. In summary, this is the most notable case than others. However, it requires very powerful VP algorithm that can improve accuracy even at frequent viewport changes.

C. AR/VR SPACES IN F-RAN

Fig. 8 shows a conceptual VR world that can be realized via F-RAN, consisting of three layers: (i) real world layer, (ii) virtual world layer, and (iii) social media layer. The real world layer denotes the world where we live, whereas the virtual world layer symbolizes the world virtually generated by the resources available in social media. The social media is exploited as an intermediary because they are already popular and also have enormous resources.

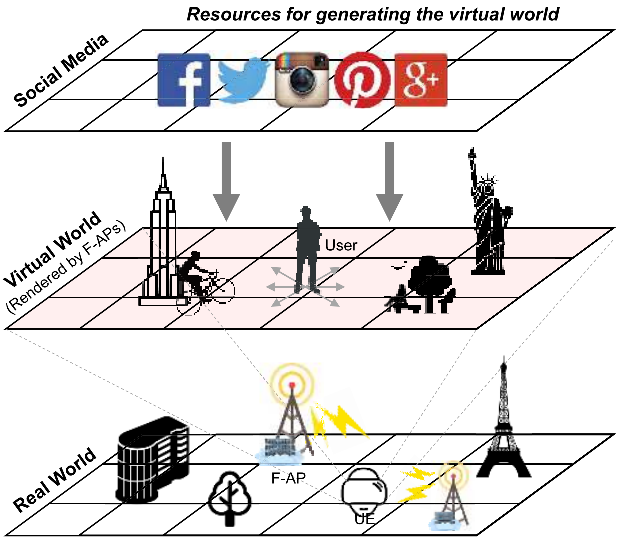


FIGURE 8. The concept of virtual world based on social media resources.

For life-like VR spaces [38], the virtual world should be made from reality-based multimedia rather than from computer graphics. Furthermore, the users should be able to move freely within the generated space. The amount of data that needs to be processed is expected to be enormous (refer to Section II-B.3). It is efficient to create the virtual world space in several adjacent F-APs in a distributed, cooperative manner. This way, adjacent F-APs generate the virtual (or augmented) space, corresponding to their locations (e.g., based on grids), as shown in Fig. 8.

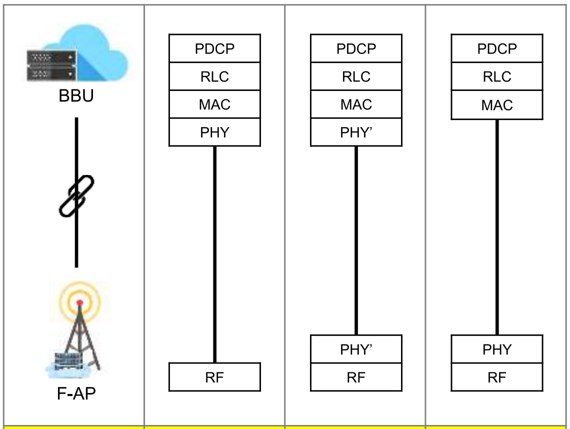
The key challenge for the virtual space is to classify the multimedia based on proper standards. For example, to generate a virtual city of New York using the multimedia stored in social media servers, all the multimedia captured near the statue of Liberty should be grouped together. It would be hard to reconstruct an appropriate VR space by DIBR or SfM, if there are multimedia from a different location (e.g., Empire State Building). Therefore, it is desirable to make each F-AP creates a unique VR space when the user exists in the corresponding real location. In addition to the location, the direction (i.e., angle), weather, and time can be also considered for the classification [22].

IV. RESEARCH OPPORTUNITIES AND CHALLENGES

In this section, we discuss related research opportunities and challenges, not covered in the previous sections.

A. CPRI FUNCTIONAL SPLIT

As discussed in Subsection II-A, the BBU and the RRH are connected via a fronthaul interface like CPRI. Through the



\	CPRI	PHY	MAC-PHY
Data Rate	2,500 Mbps	1,075 Mbps	152 Mbps
Latency	<0.25ms	0.25-2ms	2ms

FIGURE 9. CPRI's functional split options.

CPRI, user data, management data, and synchronization data can be exchanged with low latency. User data are transmitted in the form of baseband in-phase and quadrature (I/Q) bitstreams. The RRH receives these data, converts them to analogue form, amplifies and then radiates them through an antenna. However, the required data rate of the I/Q bitstreams (2,500 Mbps) is 16 times larger than that of the MAC's protocol data unit (152 Mbps) [104].

One solution for the aforementioned problem is the so-called *functional split*, in which the functions can be dynamically allocated between the BBU and the RRH. While there are eight functional split options [105], we focus only on three low-latency options (see Fig. 9): (i) the conventional CPRI, (ii) PHY split, and (iii) MAC-PHY split. In the MAC-PHY split, the MAC layer and the upper layers are located in the BBU, while the PHY and the RF layers are located in the F-AP. This option can reduce the data rate considerably. However, the latency would be increased because the F-AP has to handle everything in the PHY layer.

A more specific split within the PHY layer can be a compromise between the conventional CPRI and the MAC-PHY split. In particular, there are different blocks in the PHY layer, as shown in Fig. 10. Depending on the requirements of the desired service, different PHY functions can be dynamically allocated to the BBU and to the F-AP, without overlap. In spite of these advancements, designing CPRI's functional split methods suitable for data-intensive and latency-sensitive services is still an open research problem.

B. NETWORK SOFTWARIZATION

In order to support immersive media services, the design of the networks requires more programmability (or softwarization). This is enabled today by three technologies: (i) software-defined networking (SDN), (ii) network function virtualization (NFV), and (iii) network slicing. In the following, we give an overview of these technologies, highlight their potential roles to realize immersive media services, and discuss some of their open research issues.

1) SDN

Existing network devices expose a tight coupling between the data plane (i.e., the switching fabric) and the control plane (i.e., configuration management). This coupling does not only cause inflexibility, but also introduces high costs in terms of capital expenditure as well as operational expenditure. This coupling also hinders the speed of innovation. SDN addresses these issues by separating the data plane from the control plane, which allows to simplify and centralize the network management.

The idea of exploiting SDN to realize immersive media services was briefly mentioned in [68]. In particular, the authors pointed out that AR/VR spaces could benefit from SDN in order to meet the desired QoS requirements. In [69], the authors proposed cooperation between SDN and edge computing to fulfill different requirements. Kaur *et al.* [70] proposed flow management in edge-cloud interplay using SDN to avoid network congestion.

However, considering the huge amount of data generated by immersive media services, using SDN to support these services in a timely manner is still an open challenge. In addition, since AR/VR spaces can contain very sensitive information, constructing private virtual spaces, SDN might open the door for several types of denial-of-service (DoS) attacks.

2) NFV

Considering the high deployment cost and the scalability issue of proprietary networking devices, NFV allows the network functions to be deployed as virtualized software entities running on commodity hardware. Conventional researches on NFV service placement mainly focused on the cloud computing environment [71]–[73]. NFV researches in the fog computing environment is gaining an increasing interest (e.g., see [74]–[76] and the references therein). Specifically, the fog-based NFV service placement can be greatly advantageous to immersive media services. For instance, Zhao *et al.* [75] proposed to combine service function chain (SFC) requests so that multiple users can share the same services. Such sharing can assist immersive media services because it enables to improve resource utilization and also to handle frequent mobility.

Fig. 11 shows a potential mapping between SFC and FTV services, in which SFC consists of seven network functions (NFs) (refer to Fig. 4). The SFC can be distributed to different locations in accordance with various requirements such as hardware capacity, bandwidth, and distance. For instance, a SFC (red solid line) is rendered as follows: First, the correction and depth estimation functions are placed in the application server since they require huge hardware capacities (e.g., CPU, memory, and storage), and then the output is shared between the UEs. Next, the view synthesis, encoding, and storage/transmission functions are placed in the F-APs. This is because such functions are only well-suited for a specific

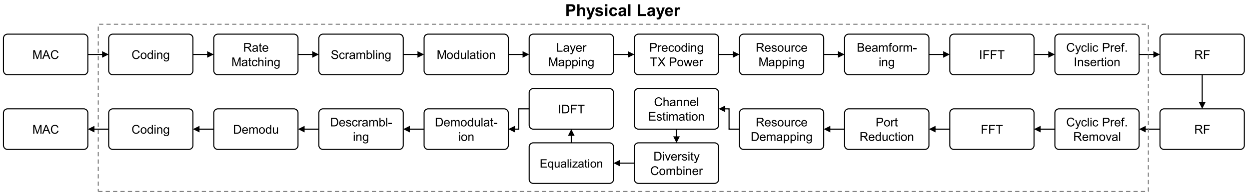


FIGURE 10. Block diagram for the physical layer.

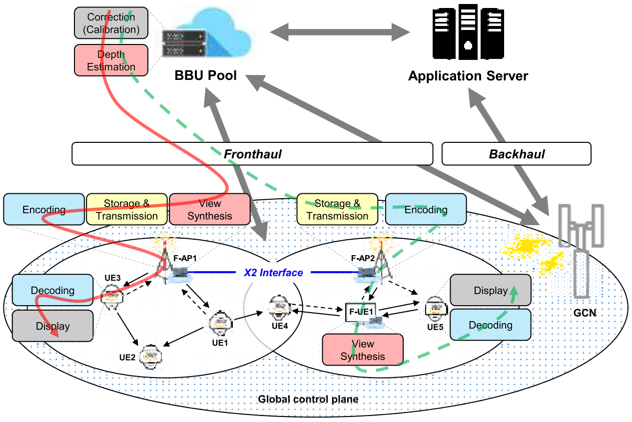


FIGURE 11. An example of mapping between SFC and FTV services.

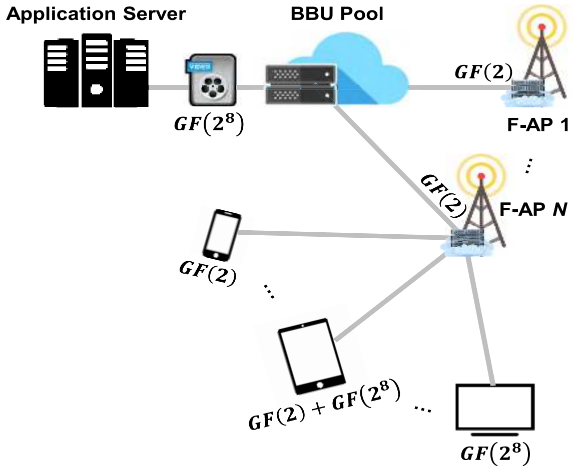


FIGURE 12. The principle of fulcrum network coding.

area and the capabilities of the NFs. The other NFs (i.e., decoding and display) are located on the user side since they can be processed in the UEs. In addition, it is worth noting that another SFC (green dashed line) offloads the view synthesis function to F-UE1. This not only reduces the burden on F-AP2, but also lowers the latency owing to the short communication between F-AP2 and UE5. In summary, the above scenarios are deployable with the support of SFC and its flexibility.

Since immersive media services are not only very diverse, but also sensitive to latency and requires high bandwidth and computations, the function placement should be treated as a multi-objective optimization problem. To the best of our knowledge, such an optimization has not been extensively researched yet.

3) NETWORK SLICING

Due to the fact that diverse immersive media services can be offered by different service providers, it is a challenge to guarantee the QoS requirements of all the services sharing the same infrastructure. This issue can be addressed with network slicing [77], in which a subset of the underlying physical network (i.e., a network slice) is dedicated such that a set of requirements (e.g., latency, throughput, and reliability) are guaranteed [78]. Therefore, network slicing is widely considered as one of the key enablers for 5G networks and immersive media.

Network slicing is still a hot research topic in the telecommunication and networking communities. Advanced researches are still expected on its standardization, realization, and implementation (exploiting SDN and NFV) [79], [80].

C. NETWORK CODING

Network coding (NC) stands out as one of the key solutions to tackle the massive increase of network traffic [81], [82], mostly resulting from immersive media [83]. Specifically, it has been shown that random linear network coding (RLNC) [84] and fulcrum network coding (FNC) [85] can significantly increase the network throughput and reliability, and thus can support immersive media.

RLNC is applicable to a sequence of packets within a data flow [86], and also can leverage the flexibility provided by SDN and NFV [87]. A considerable amount of researches has been conducted in the last years on using RLNC for video streaming applications [88]–[91]. However, it adds redundancy packets, which causes extra complexity and latency.

FNC is another NC protocol, able to solve the trade-off between the throughput and the latency [85], [92], [93], and thus can help to fulfill the requirements of immersive media services. Furthermore, FNC performs better than RLNC when the UEs have different computing capabilities. For example, the three UEs in Fig. 12, which have different (high, intermediate, and low) computing capabilities, can operate in different (high, intermediate, and low) Galois fields. FNC, unlike RLNC, also enables to combine different field sizes and allows the (heterogeneous) UEs to choose the size of the Galois field depending on their computing capabilities.

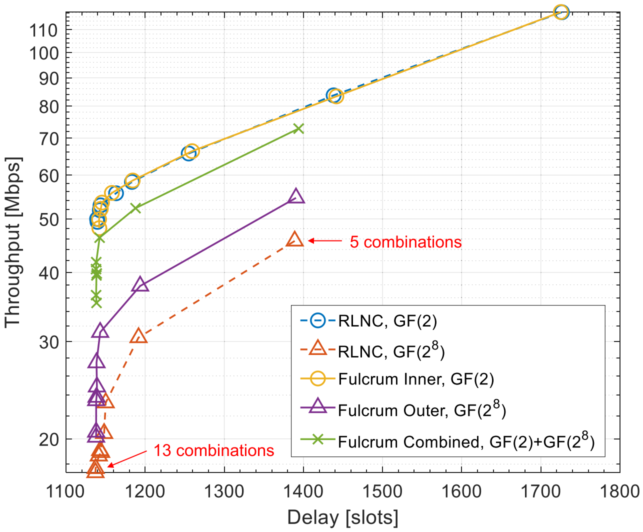


FIGURE 13. **The trade-off between throughput and delay. Each point indicates the average number of linear combinations from 5 to 13 (from the right).**

Fig. 13 shows the trade-off between the throughput and latency in terms of number of transmissions (1024 coded packets with 10% erasure). Specifically, both FNC inner (i.e., $GF(2)$) and RLNC with $GF(2)$ achieve the highest throughput, but with high delay. On the other hand, FNC outer (i.e., $GF(2^8)$) and RLNC $GF(2^8)$ achieve low throughput, with low delay. However, FNC-combined (i.e., $GF(2) + GF(2^8)$) has the potential to meet the two requirements (i.e., high throughput and low latency). As such, the FNC enables adaptive decoding according to the computing capabilities of UEs.

However, the challenge is the interplay between cooperative relaying and NC for content distribution. The cooperative relaying on its own has been introduced to improve the performance of wireless networks [94]. It has been also shown that combining it with NC can improve the network performance in massive content distribution scenarios [95]. However, such a combination of real scenarios has not been deeply investigated yet. Furthermore, NC, when used in F-RAN, would drain the batteries of the UEs, which is resolved yet.

D. DISTRIBUTED CODED CACHING

In-network caching is a technique with which popular contents are cached inside the network, close to the users, in order to alleviate the network traffic and also to reduce the latency. For example, in F-RAN, popular contents can be cached at the F-APs. There are already proposals to leverage network caching for immersive media services, particularly for AR/VR spaces [96], [97].

Distributed coded caching is an advanced caching technique, in which the cached contents are first coded (e.g., using RLNC), and then distributed over several caching nodes (e.g., F-APs) [98]. This technique can be exploited to support immersive media services further, after solving some important problems. Notable open problems include tuning the flexibility and the degree of freedom of distributed coded caching to optimize for the scale of a large number of caching nodes and their (potentially dynamic) workloads, optimization of content placement inside the network, as well as several sectury and privacy issues [99].

E. D2D COMMUNICATIONS

In the case of F-RAN, D2D communications are expected to reduce the latency as well as the burden on the fronthaul network [16], [48], [100]. However, there are open issues need to be addressed. For instance, social properties can affect the performance and resource allocation, because UEs belonging to different communities may not cooperate with each others. Further research on social-aware F-RANs is required to enhance the network performance. In addition, as shown in Fig. 1(b), when immersive media are exchanged between the UEs and the F-APs, advanced resource allocation, interference cancellation, and wireless transmission mechanisms are required. Even though several studies have been conducted in these directions [101]–[103], further research is necessary, especially from perspectives of practical deployments, to examine whether it is feasible to obtain high reliability and low latency.

V. CONCLUSIONS

We considered F-RAN as an enabler for immersive media services. In particular, we focused on three notable immersive media services: FVV, 360-degree video, and AR/VR spaces. For each service, we proposed specific scenarios and use cases to provide various perspectives under F-RAN. We also addressed research opportunities and challenges to solidify the proposed scenarios. In conclusion, integrating immersive media into F-RAN will significantly advance future media services and will also bring new business models.

ACKNOWLEDGMENT

The authors alone are responsible for the content of the paper.

APPENDIX: LIST OF ACRONYMS

6-DoF	Six degree-of-freedom
ABS	Adaptive bitrate streaming
AR	Augmented reality
BBU	Baseband unit
CMP	Cubemap projection
CoMP	Coordinated multipoint
CPRI	Common public radio interface
C-RAN	Cloud/centralized radio access network
CSI	Channel state information
D2D	Device-to-device
DIBR	Depth-image-based rendering
DoS	Denial-of-service
DPDK	Data plane development kit
DU	Distribution unit
E2E	End-to-end
ERP	Equirectangular projection
F-AP	Fog access point

FNC	Fulcrum network coding
FoV	Field of view
fps	Frame per second
F-RAN	Fog computing-based radio access network
FTV	Free-viewpoint TV
FVV	Free-viewpoint video
GCN	Global control node
GoP	Group of pictures
HMD	Head-mounted display
HPN	High power node
IoT	Internet of things
ISP	Icosahedral projection
JT	Joint transmission
MIMO	Multiple-input multiple-output
MTP	Motion-to-photon
MVC	Multi-view video coding
NC	Network coding
NF	Network function
NFV	Network function virtualization
PM	Placement manager
PMP	Pyramid projection
QoE	Quality of experience
QoS	Quality of service
RF	Radio frequency
RH	Request handler
RLNC	Random linear network coding
RRH	Remote radio head
RSP	Rotated sphere projection
RTT	Round-trip time
RU	Radio unit
SC	Scheduler
SDN	Software-defined networking
SFC	Service function chain
SfM	Structure-from-motion
SINR	Signal-to-interference-plus-noise ratio
SMVC	Scalable multi-view video coding
SSP	Segmented sphere projection
UE	User equipment
URLLC	Ultra-reliable low latency communication
VPP	Vector packet processing
VP	Viewport prediction
VR	Virtual reality
VS	View seeker

REFERENCES

[1] W. R. Sherman and A. B. Craig, *Understanding Virtual Reality: Interface, Application, and Design*. San Mateo, CA, USA: Morgan Kaufmann, Nov. 2018.

[2] "Augmented and virtual reality: The first wave of 5G killer apps," ABI Res. Qualcomm, San Diego, CA, USA, White Paper, Feb. 2017.

[3] M. S. Elbamby, C. Perfecto, M. Bennis, and K. Doppler, "Toward low-latency and ultra-reliable virtual reality," *IEEE Netw.*, vol. 32, no. 2, pp. 78–84, Mar./Apr. 2018.

[4] X. Corbillon, G. Simon, A. Devlic, and J. Chakareski, "Viewport-adaptive navigable 360-degree video delivery," in *Proc. IEEE Int. Conf. Commun.*, Paris, France, May 2017, pp. 1–7.

[5] R. T. Azuma, "A survey of augmented reality," *Presence*, vol. 6, no. 4, pp. 355–385, Aug. 1997..

[6] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, "Fog computing and its role in the Internet of Things," in *Proc. MCC Workshop Mobile Cloud Comput.*, Helsinki, Finland, Aug. 2012, pp. 13–16.

[7] Y. C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young, "Mobile edge computing: A key technology towards 5G," ESTI, Sophia Antipolis, France, ESTI White Paper 11, Sep. 2015.

[8] E. Bastug, M. Bennis, M. Medard, and M. Debbah, "Toward interconnected virtual reality: Opportunities, challenges, and enablers," *IEEE Commun. Mag.*, vol. 55, no. 6, pp. 110–117, Jun. 2017.

[9] P. J. Escamilla-Ambrosio, A. Rodríguez-Mota, E. Aguirre-Anaya, R. Acosta-Bermejo, and M. Salinas-Rosales, "Distributing computing in the Internet of Things: Cloud, fog and edge computing overview," in *Proc. Results Numer. Evol. Optim. Workshop (NEO)*, Tlalnepantla, Mexico. Cham, Switzerland: Springer, 2018, pp. 87–115. doi: 10.1007/978-3-319-64063-1_4.

[10] Y. Lin, L. Shao, Z. Zhu, Q. Wang, and R. K. Sabhikhi, "Wireless network cloud: Architecture and system requirements," *IBM J. Res. Develop.*, vol. 54, no. 1, pp. 4:1–4:12, Jan./Feb. 2010.

[11] K. Chen and R. Duan, "C-RAN: The road towards green RAN," China Mobile Res. Inst., Beijing, China, White Paper, Version 2.5, Oct. 2011.

[12] A. Checko *et al.*, "Cloud RAN for mobile networks—A technology overview," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 405–426, 1st Quart., 2014.

[13] J. Wu, Z. Zhang, Y. Hong, and Y. Wen, "Cloud radio access network (C-RAN): A primer," *IEEE Netw.*, vol. 29, no. 1, pp. 35–41, Jan./Feb. 2015.

[14] M. Peng, C. Wang, V. Lau, and H. V. Poor, "Fronthaul-constrained cloud radio access networks: Insights and challenges," *IEEE Wireless Commun.*, vol. 22, no. 2, pp. 152–160, Apr. 2015.

[15] A. de la Oliva, J. A. Hernandez, D. Larrabeiti, and A. Azcorra, "An overview of the CPRI specification and its application to C-RAN-based LTE scenarios," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 152–159, Feb. 2016.

[16] M. Peng, S. Yan, K. Zhang, and C. Wang, "Fog-computing-based radio access networks: Issues and challenges," *IEEE Netw.*, vol. 30, no. 4, pp. 46–53, Jul./Aug. 2016.

[17] M. Peng and K. Zhang, "Recent advances in fog radio access networks: Performance analysis and radio resource allocation," *IEEE Access*, vol. 4, pp. 5003–5009, Aug. 2016.

[18] Y.-Y. Shih, W.-H. Chung, A.-C. Pang, T.-C. Chiu, and H.-Y.Wei, "Enabling low-latency applications in fog-radio access networks," *IEEE Netw.*, vol. 31, no. 1, pp. 52–58, Jan./Feb. 2016.

[19] H. Zhang, Y. Qiu, X. Chu, K. Long, and V. C. M. Leung, "Fog radio access networks: Mobility management, interference mitigation, and resource optimization," *IEEE Wireless Commun.*, vol. 24, no. 6, pp. 120–127, Dec. 2017.

[20] *Technical Report of the Joint Ad Hoc Group for Digital Representations of Light/Sound Fields for Immersive Media Applications*, Standard ISO/IEC JTC1/SC29/WG1(JPEG) and WG11(MPEG), N72033 and N16352, Jun. 2016.

[21] T. Milliron, C. Szczupak, and O. Green, "Hallelujah: The world's first lytro VR experience," in *Proc. ACM SIGGRAPH VR Village*, Los Angeles, CA, USA, Aug. 2017, Art. no. 7.

[22] D. You, B.-S. Seo, E. Jeong, and D. H. Kim, "Internet of Things (IoT) for seamless virtual reality space: Challenges and perspectives," *IEEE Access*, vol. 6, pp. 40439–40449, Apr. 2018.

[23] T. Fujii and M. Tanimoto, "Free-viewpoint TV system based on ray-space representation," *Proc. SPIE*, vol. 4864, pp. 175–190, Nov. 2002.

[24] Samsung. (Jun. 2018). *KDDI and Samsung Successfully Complete Live Real-Time Free-Viewpoint Video Stream Test on 5G*. [Online]. Available: https://news.samsung.com/global/kddi-and-samsung-successfully-complete-live-real-time-free-viewpoint-video-stream-test-on-5g

[25] M. Tanimoto, T. Fujii, and K. Suzuki, "Reference software of depth estimation and view synthesis for FTV/3DV," Standard ISO/IEC JTC1/SC29/WG11, M15836, Oct. 2008.

[26] K. Müller *et al.*, "3D high-efficiency video coding for multi-view video and depth data," *IEEE Trans. Image Process.*, vol. 22, no. 9, pp. 3366–3378, Sep. 2013.

[27] A. Smolic and D. McCutchen, "3DAV exploration of video-based rendering technology in MPEG," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 14, no. 3, pp. 348–356, Mar. 2004.

[28] E. Kuzyakov and D. Pio. (Oct. 2015). *Under the Hood: Building 360 Video*. [Online]. Available: https://code.facebook.com/posts/1638767863078802/under-the-hood-building-360-video/

[29] E. Kuzyakov and D. Pio. (Jan. 2016). *Next-Generation Video Encoding Techniques for 360 Video and VR*. [Online]. Available: https://code.fb.com/virtual-reality/next-generation-video-encoding-techniques-for-360-video-and-vr/

[30] C. Pujara *et al.*, *AhG8: Efficient Frame Packing Method for Icosahedral Projection (ISP)*, document JVET-G0156, Torino, May 2017.

[31] Y.-H. Lee *et al.*, *EE4: ERP/EAP-Based Segmented Sphere Projection (SSP) With Different Padding Sizes*, document JVET-G0097, Torino, May 2017.

[32] A. Abbas and D. Newman, "A novel projection for omni-directional video," *Proc. SPIE*, vol. 10396, Sep. 2017, Art. no. 103960V.

[33] K. Misra, A. Segall, M. Horowitz, S. Xu, A. Fuldseth, and M. Zhou, "An overview of tiles in HEVC," *IEEE J. Sel. Topics Signal Process.*, vol. 7, no. 6, pp. 969–977, Dec. 2013.

[34] J. Le Feuvre and C. Concolato, "Tiled-based adaptive streaming using MPEG-DASH," in *Proc. Int. Conf. Multimedia Syst.*, Klagenfurt, Austria, May 2016, Art. no. 41.

[35] M. Hosseini and V. Swaminathan, "Adaptive 360 VR video streaming: Divide and conquer," in *Proc. IEEE Int. Symp. Multimedia*, San Jose, CA, USA, Dec. 2016, pp. 107–110.

[36] M. Graf, C. Timmerer, and C. Mueller, "Towards bandwidth efficient adaptive streaming of omnidirectional video over http: Design, implementation, and evaluation," in *Proc. ACM Multimedia Syst. Conf.*, Taipei, Taiwan, Jun. 2017, pp. 261–271.

[37] D. You, E. Jeong, and D. H. Kim, "MPEG-DASH MPD for tile-based hybrid stereoscopic 360-degree video streaming," in *Proc. Int. Conf. Ubiquitous Future Netw.*, Prague, Czech Republic, Jul. 2018, pp. 682–684.

[38] E. Cuervo, K. Chintalapudi, and M. Kotaru, "Creating the perfect illusion: What will it take to create life-like virtual reality headsets?" in *Proc. Int. Workshop Mobile Comput. Syst. Appl.*, Tempe, AZ, USA, Feb. 2018, pp. 7–12.

[39] F. G. Walls and A. S. MacInnis, "VESA display stream compression for television and cinema applications," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 6, no. 4, pp. 460–470, Dec. 2016.

[40] N. Snavely, S. M. Seitz, and R. Szeliski, "Photo tourism: Exploring photo collections in 3D," *ACM Trans. Graph.*, vol. 25, no. 3, pp. 835–846, Jul. 2006.

[41] S. Agarwal, N. Snavely, I. Simon, S. M. Seitz, and R. Szeliski, "Building rome in a day," in *Proc. IEEE Int. Conf. Comput. Vis.*, Kyoto, Japan, Sep./Oct. 2009, pp. 72–79.

[42] J. L. Schönberger and J.-M. Frahm, "Structure-from-motion revisited," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, Las Vegas, NV, USA, Jun. 2016, pp. 4104–4113.

[43] R. Huang, S. Zhang, T. Li, and R. He, "Beyond face rotation: Global and local perception GAN for photorealistic and identity preserving frontal view synthesis," in *Proc. IEEE Int. Conf. Comput. Vis.*, Venice, Italy, Oct. 2017, pp. 2439–2448.

[44] T.-C. Wang *et al.* (Aug. 2018). "Video-to-video synthesis." [Online]. Available: https://arxiv.org/abs/1808.06601

[45] J. Bruna, P. Sprechmann, and Y. LeCun, "Super-resolution with deep convolutional sufficient statistics," in *Proc. Int. Conf. Learn. Represent.*, San Juan, Puerto Rico, May 2016, pp. 1–17.

[46] C. Ledig *et al.*, "Photo-realistic single image super-resolution using a generative adversarial network," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, Honolulu, HI, USA, Jul. 2017, pp. 4681–4690.

[47] K. Doppler, C.-H. Yu, C. B. Ribeiro, and P. Janis, "Mode selection for device-to-device communication underlaying an LTE-advanced network," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2010, pp. 1–6.

[48] S. Yan, M. Peng, and W. Wang, "User access mode selection in fog computing based radio access networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 1–6. https://arxiv.org/abs/

[49] S. Yan, M. Peng, M. A. Abana, and W. Wang, "An evolutionary game for user access mode selection in fog radio access networks," *IEEE Access*, vol. 5, pp. 2200–2210, Jan. 2017.

[50] P. Pahlevani *et al.*, "Novel concepts for device-to-device communication using network coding," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 32–39, Apr. 2014.

[51] E. Magli, M. Wang, P. Frossard, and A. Markopoulou, "Network coding meets multimedia: A review," *IEEE Trans. Multimedia*, vol. 15, no. 5, pp. 1195–1212, Aug. 2013.

[52] A. G. Dimakis, P. B. Godfrey, Y. Wu, M. J. Wainwright, and K. Ramchandran, "Network coding for distributed storage systems," *IEEE Trans. Inf. Theory*, vol. 56, no. 9, pp. 4539–4551, Sep. 2010.

[53] A. G. Dimakis, K. Ramchandran, Y. Wu, and C. Suh, "A survey on network codes for distributed storage," *Proc. IEEE*, vol. 99, no. 3, pp. 476–489, Mar. 2011.

[54] D. Lee *et al.*, "Coordinated multipoint transmission and reception in LTE-advanced: Deployment scenarios and operational challenges," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 148–155, Feb. 2012.

[55] D. You and D. H. Kim, "Multi-device-to-multi-device communication in cellular network for efficient contents distribution," in *Proc. IEEE Int. Conf. Consum. Electron. (ICCE)*, Las Vegas, NV, USA, Jan. 2014, pp. 244–247.

[56] D. You and D. H. Kim, "Hybrid STBC–SM suitable for multi-link device-to-device communication in cellular networks," *Wireless Pers. Commun.*, vol. 96, no. 1, pp. 1507–1518, Sep. 2017.

[57] S. Mangjante, G. Klas, A. Navon, Z. GuanHua, J. Ran, and M. D. Silva, "VR is on the edge: How to deliver 360° videos in mobile networks," in *Proc. Workshop Virtual Reality Augmented Reality Netw.*, Los Angeles, CA, USA, Aug. 2017, pp. 30–35.

[58] Z. Xiang, F. Gabriel, E. Urbano, G. T. Nguyen, M. Reisslein, and F. H. P. Fitzek, "Reducing latency in virtual machines: Enabling tactile Internet for human-machine co-working," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 5, pp. 1098–1116, May 019.

[59] T. X. Tran, P. Pandey, A. Hajisami, and D. Pompili, "Collaborative multi-bitrate video caching and processing in mobile-edge computing networks," in *Proc. Annu. Conf. Wireless On-demand Netw. Syst. Services (WONS)*, Jackson, WY, USA, Feb. 2017, pp. 165–172.

[60] T. X. Tran, A. Hajisami, P. Pandey, and D. Pompili, "Collaborative mobile edge computing in 5G networks: New paradigms, scenarios, and challenges," *IEEE Commun. Mag.*, vol. 55, no. 4, pp. 54–61, Apr. 2017.

[61] J. He, M. A. Qureshi, L. Qiu, J. Li, F. Li, and L. Han, "Rubiks: Practical 360-degree streaming for smartphones," in *Proc. Annu. Int. Conf. Mobile Syst., Appl., Services*, Munich, Germany, Jun. 2018, pp. 482–494.

[62] F. Qian, B. Han, Q. Xiao, and V. Gopalakrishnan, "Flare: Practical viewport-adaptive 360-Degree video streaming for mobile devices," in *Proc. Annu. Int. Conf. Mobile Comput. Netw.*, New Delhi, India, Nov. 2018, pp. 99–114.

[63] N. Ozbek and A. M. Tekalp, "Scalable multi-view video coding for interactive 3DTV," in *Proc. IEEE Int. Conf. Multimedia Expo*, Toronto, ON, Canada, Jul. 2006, pp. 213–216.

[64] E. Kurutepe, M. R. Civanlar, and A. M. Tekalp, "Client-driven selective streaming of multiview video for interactive 3DTV," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 17, no. 11, pp. 1558–1565, Nov. 2007.

[65] D. You and D. H. Kim, "Hierarchical modulation for client-driven selective streaming of multi-view video over AWGN channels," *Signal Process., Image Commun.*, vol. 47, pp. 152–159, Sep. 2016.

[66] A. Patney *et al.*, "Towards foveated rendering for gaze-tracked virtual reality," *ACM Trans. Graph.*, vol. 35, no. 6, Nov. 2016, Art. no. 179.

[67] P. Lungaro, R. Sjöberg, A. J. F. Valero, A. Mittal, and K. Tollmar, "Gaze-aware streaming solutions for the next generation of mobile VR experiences," *IEEE Trans. Vis. Comput. Graphics*, vol. 24, no. 4, pp. 1535–1544, Apr. 2018.

[68] C. Westphal, "Challenges in networking to support augmented reality and virtual reality," in *Proc. Int. Conf. Comput., Netw. Commun.*, Silicon Valley, CA, USA, Jan. 2017, pp. 1–5.

[69] X. Li, D. Li, J. Wan, C. Liu, and M. Imran, "Adaptive transmission optimization in SDN-based industrial Internet of Things with edge computing," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1351–1360, Jun. 2018.

[70] K. Kaur, S. Garg, G. S. Aujla, N. Kumar, J. J. P. C. Rodrigues, and M. Guizani,, "Edge computing in the industrial internet of Things environment: Software-defined-networks-based edge-cloud interplay," *IEEE Commun. Mag.*, vol. 56, no. 2, pp. 44–51, Feb. 2018.

[71] S. D'Oro, L. Galluccio, S. Palazzo, and G. Schembra, "Exploiting congestion games to achieve distributed service chaining in NFV networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 2, pp. 407–420, Feb. 2017.

[72] A. Gupta, B. Jaumard, M. Tornatore, and B. Mukherjee, "A scalable approach for service chain mapping with multiple SC instances in a wide-area network," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 3, pp. 529–541, Mar. 2018.

[73] D. Li, P. Hong, K. Xue, and J. Pei, "Virtual network function placement considering resource optimization and sfc requests in cloud datacenter," *IEEE Trans. Parallel Distrib. Syst.*, vol. 29, no. 7, pp. 1664–1677, Jul. 2018.

[74] D. Li, P. Hong, K. Xue, and J. Pei, "Virtual network function placement and resource optimization in NFV and edge computing enabled networks," *Comput. Netw.*, vol. 152, pp. 12–24, Apr. 2019.

[75] D. Zhao, D. Liao, G. Sun, and S. Xu, "Towards resource-efficient service function chain deployment in cloud-fog computing," *IEEE Access*, vol. 6, pp. 66754–66766, Oct. 2018.

[76] B. Yang, W. K. Chai, G. Pavlou, and K. V. Katsaros, "Seamless support of low latency mobile applications with NFV-enabled mobile edge-cloud," in *Proc. IEEE Int. Conf. Cloud Netw.*, Pisa, Italy, Oct. 2016, pp. 136–141.

[77] I. Afolabi, T. Taleb, K. Samdanis, A. Ksentini, and H. Flinck, "Network slicing and softwarization: A survey on principles, enabling technologies, and solutions," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2429–2453, 3rd Quart., 2018.

[78] H. Wu, G. T. Nguyen, A. K. Chorppath, and F. H. Fitzek, "Network slicing for conditional monitoring in the industrial Internet of Things," in *Proc. IEEE Softw. Newslett.*, Jan. 2018, pp. 1–2.

[79] Q. Wang *et al.*, "SliceNet: End-to-end cognitive network slicing and slice management framework in virtualised multi-domain, multi-tenant 5G networks," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Valencia, Spain, Jun. 2018, pp. 1–5.

[80] A. Ksentini and N. Nikaein, "Toward enforcing network slicing on RAN: Flexibility and resources abstraction," *IEEE Commun. Mag.*, vol. 55, no. 6, pp. 102–108, Jun. 2017.

[81] T. Ho and D. Lun, *Network Coding: An Introduction*. Cambridge, U.K.: Cambridge Univ. Press, 2008.

[82] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204–1216, Jul. 2000.

[83] *Visual Networking Index (VNI) Global Fixed and Mobile Internet Traffic Forecasts*, Cisco, San Jose, CA, USA, Dec. 2018.

[84] T. Ho, M. Medard, J. Shi, M. Effros, and D. R. Karger, "On randomized network coding," in *Proc. Annu. Allerton Conf. Commun., Control, Comput.*, Monticello, IL, USA, Oct. 2003, pp. 1–10.

[85] D. E. Lucani *et al.*, "Fulcrum: Flexible network coding for heterogeneous devices," *IEEE Access*, vol. 6, pp. 77890–77910, Nov. 2018.

[86] M. Medard, F. H. P. Fitzek, M.-J. Montpetit, and C. Rosenberg, "Network coding mythbusting: Why it is not about butterflies anymore," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 177–183, Jul. 2014.

[87] F. Gabriel, G. T. Nguyen, R.-S. Schmoll, J. A. Cabrera, M. Muehleisen, and F. H. P. Fitzek, "Practical deployment of network coding for real-time applications in 5G networks" in *Proc. IEEE Annu. Consum. Commun. Netw. Conf.*, Las Vegas, NV, USA, Jan. 2018, pp. 1–2.

[88] L. Keller, A. Le, B. Cici, H. Seferoglu, C. Fragouli, and A. Markopoulou, "MicroCast: Cooperative video streaming on smartphones," in *Proc. Int. Conf. Mobile Syst., Appl., Services.* , Lake District, U.K.: Low Wood Bay, Jun. 2012, pp. 57–70.

[89] T. D. Assefa, K. Kralevska, and Y. Jiang, "Performance analysis of LTE networks with random linear network coding," in *Proc. Int. Conv. Inf. Commun. Technol., Electron. Microelectron.*, Opatija, Croatia, May/Jun. 2016, pp. 601–606.

[90] L. Aymen, B. Ye, and T. M. T. Nguyen, "Offloading performance evaluation for network coding-based cooperative mobile video streaming," in *Proc. Int. Conf. Netw. Future*, Buzios, Brazil, Nov. 2016, pp. 1–5.

[91] S. Pandi, R. T. Arranz, G. T. Nguyen, and F. H. P. Fitzek, "Massive video multicasting in cellular networks using network coded cooperative communication," in *Proc. IEEE Annu. Consum. Commun. Netw. Conf.*, Las Vegas, NV, USA, Jan. 2018, pp. 1–2.

[92] V. Nguyen *et al.*, "Adaptive decoding for fulcrum codes," in *Proc. IEEE Annu. Inf. Technol., Electron. Mobile Commun. Conf.*, Victoria, BC, Canada, Nov. 2018, pp. 133–139.

[93] V. Nguyen, G. T. Nguyen, F. Gabriel, D. E. Lucani, and F. H. P. Fitzek, "Integrating sparsity into Fulcrum codes: Investigating throughput, complexity and overhead," in *Proc. IEEE Int. Conf. Commun. Workshops*, Kansas City, MO, USA, May 2018, pp. 1–6.

[94] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[95] M. Di Renzo, M. Iezzi, and F. Graziosi, "On diversity order and coding gain of multisource multirelay cooperative wireless networks with binary network coding," *IEEE Trans. Veh. Technol.*, vol. 62, no. 3, pp. 1138–1157, Mar. 2013.

[96] J. Chakareski, "VR/AR immersive communication: Caching, edge computing, and transmission trade-offss," in *Proc. Workshop Virtual Reality Augmented Reality*, Los Angeles, CA, USA, Aug. 2017, pp. 36–41.

[97] J. J. Garcia-Luna-Aceves *et al*, "Network support for AR/VR and immersive video application: A survey," in *Proc. Int. Joint Conf. e-Bus. Telecommun.*, Jul. 2018, pp. 1–11.

[98] J. A. Cabrera, R.-S. Schmoll, G. T. Nguyen, S. Pandi, and F. H. P. Fitzek, "Softwarization and network coding in the mobile edge cloud for the tactile Internet," *Proc. IEEE*, vol. 107, no. 2, pp. 350–363, Feb. 2018.

[99] Z. Piao, M. Peng, Y. Liu and M. Daneshmand, "Recent advances of edge cache in radio access networks for Internet of Things: Techniques, performances, and challenges," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 1010–1028, Feb. 2019. doi: 10.1109/JIOT.2018.2866709.

[100] X. Chen and J. Zhang, "When D2D meets cloud: Hybrid mobile task offloadings in fog computing," in *Proc. IEEE Int. Conf. Commun.*, Paris, France, May 2017, pp. 1–6.

[101] H. Bagheri and M. Katz, "A resource allocation mechanism for enhancing spectral efficiency and throughput of multi-link D2D communications," in *Proc. IEEE Int. Symp. Pers., Indoor, Mobile Radio Commun.*, Washington, DC, USA, Sep. 2014, pp. 1391–1396.

[102] K. Manolakis and W. Xu, "Time synchronization for multi-link D2D/V2X communication," in *Proc. Veh. Technol. Conf.-Fall*, Montreal, QC, Canada, Sep. 2016, pp. 1–6.

[103] H.-C. Huang, J. Zhang, Z.-F. Zhang, and Z.-Y. Xiong, "Interference-limited device-to-device multi-user cooperation scheme for optimization of edge networking," *J. Comput. Sci. Technol.*, vol. 31, no. 6, pp. 1096–1109, Nov. 2016.

[104] P. Crane, "Towards 5G—An operators perspective: Evolution or revolution?" in *Proc. Int. Conf. Wireless Mobile Comput., Netw. Commun.*, Abu Dhabi, UAE, Oct. 2015, pp. 1–36.

[105] "Common public radio interface: eCPRI interface specification," Common Public Radio Interface, eCPRI Specification Version 1.2, Interface Specification, Jun. 2018. [Online]. Available: http://www.cpri.info/downloads/eCPRI_v_1_2_2018_06_25.pdf

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