VR is on the Edge: How to Deliver 360° Videos in Mobile Networks

Conference Paper · August 2017

DOI: 10.1145/3097895.3097901

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ABSTRACT

VR/AR is rapidly progressing towards enterprise and end customers with the promise of bringing immersive experience to numerous applications. Soon it will target smartphones from the cloud and 360° video delivery will need unprecedented requirements for ultra-low latency and ultra-high throughput to mobile networks. Latest developments in NFV and Mobile Edge Computing reveal already the potential to enable VR streaming in cellular networks and to pave the way towards 5G and next stages in VR technology.

In this paper we present a Field Of View (FOV) rendering solution at the edge of a mobile network, designed to optimize the bandwidth and latency required by VR 360° video streaming.

Preliminary test results show the immediate benefits in bandwidth saving this approach can provide and generate new directions for VR/AR network research.

CCS CONCEPTS

• **Networks → Mobile networks**; *Logical / virtual topologies*; *Cloud computing*; • **Human-centered computing → Virtual reality**;

KEYWORDS

360° video delivery, Field of view, Mobile network, Edge computing

ACM Reference format:
Simone Mangiante, Guenter Klas, Amit Navon, Zhuang GuanHua, Ju Ran, and Marco Dias Silva. 2017. VR is on the Edge: How to Deliver 360° Videos in Mobile Networks. In *Proceedings of VR/AR Network '17, Los Angeles, CA, USA, August 25, 2017,* 6 pages.
https://doi.org/10.1145/3097895.3097901

VR/AR Network '17, August 25, 2017, Los Angeles, CA, USA

ACM ISBN ISBN 978-1-4503-5055-6/17/08…$15.00
https://doi.org/10.1145/3097895.3097901

1 INTRODUCTION

In recent years, virtual and augmented reality (VR/AR) applications delivered over wireless networks have attracted interest from academia and industry. They have been often identified as killer use cases of the 5G ecosystem and been showcased at industrial and standardization events [14].

For enterprise users and vertical markets such as manufacturing and design, health care, transportation, and retail, VR/AR is expected to raise productivity, allowing workers to visually interact with data (e.g. remote maintenance). For consumers, VR/AR will provide immersive experiences and personalized content. Content providers are already developing solutions to enrich knowledge by combining video and augmented information for training and education, sports, tourism, remote diagnostics and surgery. Additionally, gaming on VR/AR will put players into interactive scenes and social networks will encourage users to share those experiences.

However, a real immersive VR experience is yet to come due to several technical challenges [3], one of them being its delivery through a mobile network. Today, virtual reality services are mainly consumed statically by nature, using powerful, customized, heavy head mounted displays (HMDs) like Oculus[1] and HTC Vive[2]. We envision that the current localized VR/AR applications will move to the cloud and be delivered to smartphones, as their operating systems and apps will include VR capabilities[3].

360° multi-perspective immersive videos have a key role in enabling VR/AR applications. VR traffic quadrupled in 2015, from 4.2 PB per month in 2014 to 17.9 PB per month in 2015. Globally, VR traffic will increase 61-fold between 2015 and 2020 [7]. In 2016 we observed an increased spread of 360° videos: more than 8000 new videos on YouTube were watched more than 250,000 times daily; more than 1000 new videos were created for the Oculus platform; worldwide popular events such as NBA games and the US Open golf tournament were streamed live using 360° video technology.

The development of VR 360° videos focuses on user immersive experience and evolves from single view to 3D/multi-view and from no interaction to full interaction, which will bring the network tremendous challenges in allowing ultra-high throughput and ultra-low latency. Furthermore, additional challenges for VR are posed

[1]https://www.oculus.com/
[2]https://www.vive.com
[3]Google Daydream, https://vr.google.com/daydream/

by end devices that must be lightweight but at the same time have high processing power to handle VR video processing.

After presenting VR network requirements in Section 2, we show in Section 3 how current developments in mobile network can be exploited and propose a new solution in Section 4. We analyze results from our preliminary tests in Section 5 before concluding with planned further work in Section 6.

2 NETWORK REQUIREMENTS

Latency is the most important quality parameter of VR/AR applications. VR/AR is latency sensitive because human perception requires accurate and smooth movements in vision. Large amounts of latency can lead to a detached VR experience and can contribute to a motion sickness sensation. VR/AR developers and industries agree that application round-trip latency should be less than 20 ms [5] in order for the Motion-To-Photon latency (MTP) [11] to become imperceptible. Other researches indicate that 15 ms should be the required MTP threshold, and even 7 ms would be ideal [4]. Current local VR/AR systems use customized and tuned technologies in their HMDs to meet the 20 ms threshold. In network-based/cloud VR/AR applications, the actual latency budget for the transport network can be derived by estimating the latency of all the components involved in the process, as we did in Table 2, and happens to be extremely low. When streaming video, caching can help reducing latency, but interactive VR/AR user actions are less predictable than static content.

The network bandwidth for VR/AR is the throughput required to stream the related 360° video to a user and it is another critical parameter for the quality of VR/AR application. The resolution of a VR immersive video viewed using a HMD positioned few centimeters from the user's eyes needs to approximate the amount of detail the human retina can perceive. Thus 8K quality and above is necessary for VR, as a 4K VR 360° video only has 10 pixels per degree, equivalent to a 240p on a TV screen. We believe that the VR 360° video experience may evolve through the stages listed in Table 1, requiring a network throughput of 400 Mbps and above, more than 100 times higher than the current throughput supporting HD video services.

2.1 Bandwidth, Compute and Latency Tradeoff

Display technology requires very high refresh rate to provide immersive experiences. Switching views in VR is similar to switching channels in IPTV, whose latency is about 700 ms using FCC (fast channel change). Taking into account the MTP latency threshold of 20 ms and considering that a smooth VR playback typically requires throughput to be 1.5 times the average video bitrate, we deduce the network burst with fast-flush performance should be more than 50 times better than current IPTV.

Current VR 360° video services are in early-stage and delivered using a wasteful and still limited technology [8], since the full 360° video is transmitted over the network and the user device has to process it according to mouse or head movements in order to switch to a new field of view. Figure 1 shows the complete process of generating and consuming such a video:

(1) Multi camera array is used to capture video

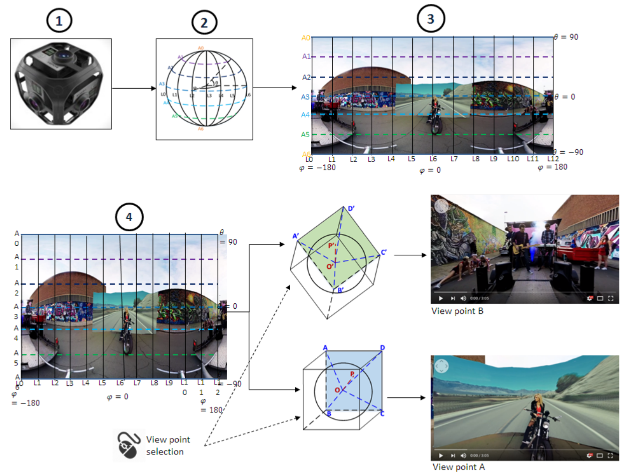

Figure 1: VR 360° video producing and viewing

(2) Images are then projected on a sphere and stitched together to obtain a spherical video
(3) The spherical video is unfolded to 2D plane using the equirectangular projection
(4) Viewer can see any view in every direction: given a specific view point (θ_0, ϕ_0), the 2D plane image is projected into a sphere and then rendered on the display.

Massive compute power is required by the end user device to process and render the complex equirectangular video quickly enough to ensure minimal MTP latency. Therefore, a bandwidth/compute/latency tradeoff should be considered as a new media network model (Figure 2), improved from the traditional store and forward model, for delivery optimization and adaptive services for different users. Table 1 summarizes our vision regarding bandwidth and latency requirements for network VR/AR applications, related to different VR experience stages [10]. The network bandwidth requirement is estimated based on 1.5 times the bit rate. The latency value is determined by MTP latency requirement and VR development stage forecast.

3 MOBILE NETWORK ENVIRONMENT

A telecommunication operator's 4G/LTE network is generally composed of a backhaul divided into hierarchical levels of aggregation that we call POC (Point Of Concentration). From a base station

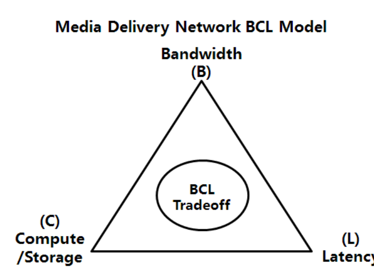

Figure 2: BCL model

[4] http://blogs.valvesoftware.com/abrash/latency-the-sine-qua-non-of-ar-and-vr/

Table 1: VR network requirements (bandwidth and latency)

VR resolution		Equivalent TV res.	Bandwidth	Latency
Early stage VR (current)	1K*1K@visual field 2D_30fps_8bit_4K	240P	25 Mbps	40 ms
Entry level VR	2K*2K@visual field 2D_30fps_8bit_8K	SD	100 Mbps	30 ms
Advanced VR	4K*4K@visual field 2D_60fps_10bit_12K	HD	400 Mbps	20 ms
Extreme VR	8K*8K@visual field 3D_120fps_12bit_24K	4K	1 Gbps (smooth play) 2.35 Gbps (interactive)	10 ms

(eNodeB) to the telecom operator's core network (Evolved Packet Core or EPC in 3GPP terminology [1]), traditionally hosting LTE control and user plane components (e.g. S-GW, P-GW as defined by 3GPP), traffic typically hits 3 POCs along the 3GPP S1 interface:

- POC3. the aggregation point closest to the devices. Instances deployed in a large national network: around few thousands, aggregating multiple (order of magnitude of 10) base stations;
- POC2: an intermediate aggregation point. Instances deployed in a large national network: from several hundreds to a few thousands;
- POC1: the aggregation point closest to the EPC components. Instances deployed in a large national network: up to very few hundreds.

In this typical topology, the average network roundtrip latency is distributed as shown in Figure 3.

3.1 Network Function Virtualization (NFV)

In the last years, the rising paradigms of Software Defined Networks (SDN) and Network Function Virtualization (NFV) are transforming telecom operators' networks, making them more flexible and responsive. NFV leverages IT technologies (e.g. virtualization, standard servers, open software) to virtualize network functions in order to create better managed services and dynamically chain them. Virtualization and convergence of fixed and mobile transport generated other initiatives like Cloud-RAN [6] and CORD [5], aiming to achieve the freedom to move and scale network functions throughout the whole network. Developments towards 5G [2] added more features and use cases, promising that 5G networks will be able to support communications for some special scenarios not currently supported by 4G networks. 5G will play an instrumental role in enabling low latency and high throughput networks for a smooth VR/AR experience.

The current process of "cloudification" of telecom operator networks led to the introduction of MEC (Mobile Edge Computing, to be expanded to Multi-access Edge Computing) [4, 12].

3.2 Mobile Edge Computing (MEC)

MEC provides distributed cloud-computing capabilities at the edge of the mobile network, within the Radio Access Network (RAN) and in close proximity to customers. The aim is to reduce network congestion and response time, achieve highly efficient network operation, and offer a better user experience. Leveraging IT technologies and APIs, MEC also allows mobile operators to open their network to authorized application developers and content providers, providing direct access to real-time information from the underlying radio transport (e.g. an API to the Radio Network Information Service which provides real-time details about the device's radio access bearer). Moving workloads to the edge is then the argument for enabling highly responsive services, supported by smaller and slimmer devices, with improved user QoE (Quality of Experience) in 4G networks immediately, without waiting for 5G enhancements. Thanks to NFV elasticity and the increasing availability of compute, storage, and network resources at many locations within an operator network, MEC platforms can be deployed in principle in any location: at base stations, co-hosted with LTE small cells [13], at any POC aggregation hub (e.g. next to a router, provided that sufficient resources are available), at Cloud-RAN sites, and in the main datacenters.

Any deployment strategies will depend on a number of factors, such as level of new CAPEX costs involved, opportunities for sharing of infrastructure between MEC software platform and other network functions (e.g. distributed 3GPP functions), and use case requirements. MEC platforms, as stated by ETSI MEC ISG, have to leverage management and orchestration functionality from existing NFV environments as much as possible to achieve easy deployment and integration in the mobile network [9]. Therefore, MEC has already the potential to enable high quality 360° video delivery and obtain other significant benefits like saving backhaul bandwidth. We envision that 360° video delivery components (e.g. streaming engine, transcoding, caching) hosted in a MEC platform at a location providing the right latency, combined with forthcoming display and

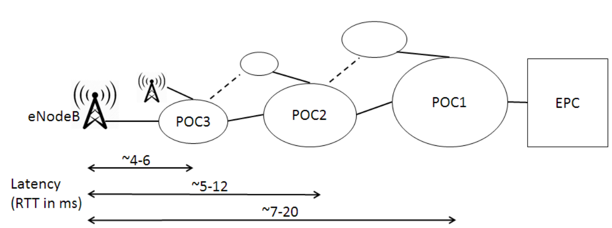

Figure 3: Example of a mobile network topology

[5] Central Office Re-architected as a Datacenter, http://opencord.org/

computing technologies, will achieve a total latency comparable to current local VR scenarios, as shown in Table 2.

4 PROPOSED SOLUTION

4.1 Edge FOV Rendering

In order to address the challenges presented in Section 2, we propose an edge processing technology that will be able to perform Field Of View (FOV) rendering of 360° VR videos [15], optimize the required bandwidth and reduce the processing power requirements on end devices, also improving their battery utilization. Ultra-low network latency must be guaranteed in order to achieve effective real-time FOV rendering as the experience becomes interactive and upstream control indications are sent from end devices to the network.

Optionally, motion prediction can be performed at the edge in order to anticipate the FOV requested by the user. This component can loosen the VR latency requirement where the network cannot support it. We believe that the transmission delay can be relaxed to a few hundred milliseconds at a low cost of bandwidth.

The overall flow is specified in Figure 4:

(1) A 360° video service (e.g. generating content from a public cloud and/or from cameras at an event venue) produces a 360° video stream at the video hub, which is delivered to a μCloud. μCloud is what we call an either virtualized or physical deployment, designed to tackle specific heavy and real-time calculation like video transcoding, co-hosted within a MEC platform or directly attached to it through a fast network.
(2) The μCloud processes the 360° video and performs optional motion prediction, FOV extraction, and transcoding and optimization for mobile devices. The computed FOV is then streamed to the end user.
(3) FOV control indications, representing the angle the user is currently looking at, are sent upstream from the user to the μCloud, which in turns computes and streams the requested FOV.

Optionally, a low-resolution full view stream can be delivered to end users' devices together with FOV. The low-resolution stream acts as a fallback option to ensure a minimal user experience in bad network situations with little extra cost. Should the FOV data fail to be delivered in time, the user device loads and displays the low-resolution stream. When the network recovers, the user device may switch back to the FOV input stream.

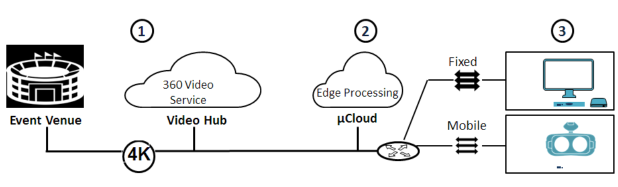

Figure 4: Edge FOV rendering flow

Table 2: Latency of VR components in different approaches (RTT in ms)

Component	Local VR	Current online VR	Future online VR with MEC
Sensor	1	1	1
Transport	2 (USB and HDMI)	40 (network to cloud)	5 (network to MEC location)
Computing	3 − 5	100+	7
Display	10 (refresh)	15 (decode and refresh)	5 (decode and dynamic refresh)
Total	18	150+	18

4.2 Effective Resolution Vs. Delivered Resolution

When the spherical video is unfolded to a 2D plane using the equirectangular projection, 4K 360° source video quality means that a user actually enjoys a much lower effective resolution (~1K) at any selected FOV. Typically, the FOV is 90° wide horizontally and approximately 60° wide vertically. The ratio between the FOV and the source video is 1:3 on the vertical axis and 1:4 on the horizontal axis, accounting to 1:12 ratio in the total area. Translating this into pixels, in order to provide a 4K video at the user device equipped with a 16:9 display, the source equirectangular projection video delivered over the network will have to be at a 16K resolution.

One of the main advantages of edge FOV rendering technology for VR is actually to enable a 4K effective resolution quality that cannot be achieved today with traditional streaming mechanism in a mobile network. Besides improving latency to end users and saving bandwidth by reducing the amount of data to be transmitted, applying FOV rendering technologies to a MEC node/platform offloads the computation power from the end device to the edge of the network and enables thin clients to support high quality VR experience.

5 PRELIMINARY EVALUATION

To assess the role and value of edge computing to reduce traffic sent over an operator's radio access network for VR 360° live and on-demand video streaming, we deployed a 4G LTE test lab environment whose logical network topology is depicted in Figure 5.

The user device (laptop or mobile) is connected to a 4G/LTE small cell. A MEC platform/node is deployed transparently between the small cell and the EPC and it can be enabled by configuration to intercept and process/redirect the traffic. The μCloud FOV enhancement is connected to both the MEC node and the EPC to enable two different scenarios (long-dashed and dotted path in Figure 5): FOV rendering hosted at the edge of the network and FOV rendering hosted in the core of the network. We can simulate different network segments' conditions (e.g. MEC location, EPC location, the public internet) using impairment nodes. The central cloud is connected to an Eyesir 360° 4K source camera [6] and hosts a media streaming server. The solid path represents the scenario where the full 360° video is delivered to the end user.

[6]http://www.perfant.com/en/product.html

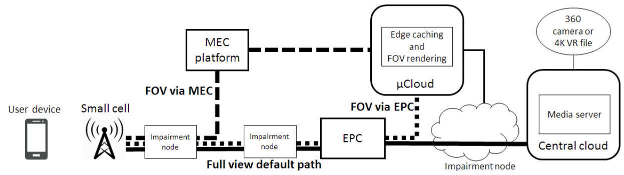

Figure 5: Logical network topology of the test environment

Table 3 lists the main metrics characterizing the lab setup for the preliminary tests. The values represent the currently available baseline using the equipment in our controlled lab environment. They reproduce a realistic scenario where the μCloud is deployed either in POC1 or POC2 and they may be further tuned as explained in Section 6.

We sequentially tested two delivery options, targeting two users through the long-dashed (User #1) and solid (User #2) path in Figure 5. The traffic flow is as follows:

(1) A live stream from the source camera or a 4K VR file (on-demand) is published to the Central Cloud.
(2) The stream destined to User #1 is routed via the μCloud. The same stream is delivered directly to User #2.
(3) For User #1 FOV rendering is applied on the μCloud and the selected FOV is sent to the user in 4K. For User #2 the full 360° video is delivered.

In this first stage of evaluation, end-to-end live streams have been successfully transmitted in our lab environment, and have been tested with and without MEC. A static FOV cropping and rendering (without real-time FOV control indicators from the user) is applied in the μCloud without any special hardware acceleration, then the FOV is transmitted via the mobile network and played by Potplayer [7] in a PC client. The resulting actual delay between frame output at source and playback at the user device (including total network latency and other delays) is 859 ms, which illustrates that we could achieve sub-second delay, while real network environments settle at several seconds at present.

The resolution of the original full view at the source is 3840x1920 pixels. The μCloud computes a predefined FOV resolution of 1280x1024 pixels, representing a horizontal view angle of 120° and a vertical view angle of 96°. This cropped portion safely approximates what a user typically sees (stated in Section 4.2) and it is an accurate FOV to be delivered to the client device. Such computed area watched by the end user occupies 17.8% of the original full view, which means the bandwidth saving could theoretically reach 82.2%.

[7] http://potplayer.daum.net/

Table 3: Test lab setup metrics

Metric	Value
Available bandwidth between central cloud and μCloud	1 Gbps
Available bandwidth between μCloud and user	22 Mbps
Network latency (RTT) between central cloud and user	30 ms
Network latency (RTT) between μCloud and user	13 ms

Table 4: Collected metrics from preliminary tests

Metric	No μCloud (User #2)	μCloud & FOV (User #1)
Frames per second (FPS) during play	18	29
Throughput between source camera and μCloud	N.A.	30 Mbps
Throughput observed at the user device	22 Mbps	5.85 Mbps
Traffic savings in core and radio access	80.5%	

The bandwidth saving observed in our tests could reach 80.5%. The first subset of collected data is shown in Table 4.

In order to get a smooth playback, the typical throughput is recommended to be 1.5 times the average video bitrate. In our experiment, the available bandwidth at the air interface (the bottleneck within the access network) is 22 Mbps, not even matching the average bitrate of the full 4K video stream. That causes frame loss and results in lower FPS for User #2, while User #1 needs less throughput for the FOV reduced resolution and experiences higher FPS. FOV processing and rendering at a MEC location reduces the mobile traffic in different segments of an operator network: the radio access, because a FOV stream consumes a considerably (more than 80%) less amount of bandwidth; the backhaul and core, because the full stream flows once from the central cloud to the μCloud (where it can be cached for on-demand usage) and it is not replicated as many times as users requesting it. Given the first promising results, we believe that leveraging MEC infrastructure in VR video delivery leads to significant benefits for different stakeholders: mobile network operators, who own the enabling infrastructure to provide new VR services and save bandwidth in the backhaul/core; VR broadcasters and video content providers, who can reach a massive amount of mobile users; and end users, who can experience good quality VR services from early stage.

6 CONCLUSION AND FUTURE WORK

In this paper we presented a FOV rendering application at the edge of a mobile network enabling improved VR 360° live video delivery to mobile devices. Considering our decomposition of future online VR latency requirements in Table 1, many development opportunities exist in each network VR processing stage. More research and validation over different types of access networks, with different user equipment and multiple device connectivity, will be conducted. We plan to exploit our modular and configurable test lab to get more data by testing more scenarios. Leveraging various equipment and impairment behaviors, we can simulate realistic traffic conditions varying throughout the day (e.g. heavy congestion and higher latency at peak times). As an example, we will compare MEC platform deployments at various locations providing different resources and different values of latency to the end users, in order to find the sweet spot in the bandwidth/compute/latency model introduced in Section 2 and to identify the business impact.

User mobility was not in the scope of this work, but it will be investigated in the future. It will become a requirement as supported devices get lighter and more portable, and more complex mobility-aware applications arise. Users can switch to a base station served by the same MEC node or by a different MEC node: both scenarios will be considered in order to develop the best mechanisms to cope with mobility.

Hardware and software components of the μCloud will be target of future research, with the aim of understanding the tradeoff between bespoke hardware features designed to enhance video applications (e.g. GPU and custom processors) and smarter software counterparts executable on commercial off-the-shelf machines. This work will be assessing also the efficiency of FOV rendering at the edge considering the broad variety of equipment available at different locations within mobile networks.

More research will be done on VR value-added services (e.g. content delivery network optimized for VR/AR) in edge clouds inside or close to the access network, testing a pre-commercial solution articulating the benefits for different stakeholders for live and on-demand scenarios.

ACKNOWLEDGMENTS

We thank Rame Canolli, Nick Edwards from Vodafone Innovation Lab, Han Lei, Li Feng, Li Jin, Zhu JiRong, Dr. Itsik Dvir, Amiram Allouch and Guy Almog from Network Architecture Technology Lab of Huawei Technologies, for all the valuable guidance and support in every stage of the proposal and the evaluation deployment.

REFERENCES

[1] 3GPP. 2016. *3GPP Evolved Universal Terrestrial Radio Access (EUTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN) - Overall Description, Stage 2.* TS 36.300 Release 13. 3GPP.

[2] Jeffrey G Andrews, Stefano Buzzi, Wan Choi, Stephen V Hanly, Angel Lozano, Anthony CK Soong, and Jianzhong Charlie Zhang. 2014. What will 5G be? *IEEE Journal on selected areas in communications* 32, 6 (2014), 1065–1082.

[3] Ejder Baştuğ, Mehdi Bennis, Muriel Médard, and Mérouane Debbah. 2016. Towards Interconnected Virtual Reality: Opportunities, Challenges and Enablers. *arXiv preprint arXiv:1611.05356* (2016).

[4] Michael Till Beck, Martin Werner, Sebastian Feld, and S Schimper. 2014. Mobile edge computing: A taxonomy. In *Proc. of the Sixth International Conference on Advances in Future Internet*. Citeseer.

[5] John Carmack. 2013. Latency Mitigation Strategies. (2013). Retrieved 2017-05-26 from https://www.twentymilliseconds.com/post/latency-mitigation-strategies/

[6] Aleksandra Checko, Henrik L Christiansen, Ying Yan, Lara Scolari, Georgios Kardaras, Michael S Berger, and Lars Dittmann. 2015. Cloud RAN for mobile networks - A technology overview. *IEEE Communications surveys & tutorials* 17, 1 (2015), 405–426.

[7] Cisco. 2016. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015-2020. (2016). Retrieved 2017-05-26 from http://www.cisco.com/c/en/us/solutions/service-provider/visual-networking-index-vni/index.html

[8] Mohammad Hosseini and Viswanathan Swaminathan. 2016. Adaptive 360 VR Video Streaming: Divide and Conquer! *arXiv preprint arXiv:1609.08729* (2016).

[9] Yun Chao Hu, Milan Patel, Dario Sabella, Nurit Sprecher, and Valerie Young. 2015. Mobile edge computing - A key technology towards 5G. *ETSI White Paper* 11 (2015).

[10] Huawei. 2016. Whitepaper on the VR-Oriented Bearer Network Requirement. (2016). Retrieved 2017-05-26 from http://www-file.huawei.com/~/media/CORPORATE/PDF/white%20paper/whitepaper-on-the-vr-oriented-bearer-network-requirement-en.pdf

[11] Katerina Mania, Bernard D Adelstein, Stephen R Ellis, and Michael I Hill. 2004. Perceptual sensitivity to head tracking latency in virtual environments with varying degrees of scene complexity. In *Proceedings of the 1st Symposium on Applied perception in graphics and visualization*. ACM, 39–47.

[12] Yuyi Mao, Changsheng You, Jun Zhang, Kaibin Huang, and Khaled B Letaief. 2017. Mobile Edge Computing: Survey and Research Outlook. *arXiv preprint arXiv:1701.01090* (2017).

[13] Takehiro Nakamura, Satoshi Nagata, Anass Benjebbour, Yoshihisa Kishiyama, Tang Hai, Shen Xiaodong, Yang Ning, and Li Nan. 2013. Trends in small cell enhancements in LTE advanced. *IEEE Communications Magazine* 51, 2 (2013), 98–105.

[14] Jason Orlosky, Kiyoshi Kiyokawa, and Haruo Takemura. 2017. Virtual and Augmented Reality on the 5G Highway. *Journal of Information Processing* 25 (2017), 133–141.

[15] Feng Qian, Lusheng Ji, Bo Han, and Vijay Gopalakrishnan. 2016. Optimizing 360 video delivery over cellular networks. In *Proceedings of the 5th Workshop on All Things Cellular: Operations, Applications and Challenges*. ACM, 1–6.