Characterizing and Optimizing Emerging Mobile Applications From the System Perspective

by

Xing Liu

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Computer Science and Engineering)
in The University of Minnesota, Twin Cities
2020

Doctoral Committee:

Professor Zhi-Li Zhang, Chair
Assistant Professor Feng Qian
Assistant Professor Evan Suma Rosenberg
Principal Inventive Scientist Dr. Bo Han, AT&T Labs – Research

To my family.

ACKNOWLEDGEMENTS

I would like to thank many people who helped me during this long journey of Ph.D. study...

TABLE OF CONTENTS

LIST OF FIGURES

Figure

LIST OF TABLES

Table

ABSTRACT

Characterizing and Optimizing Emerging Mobile Applications From the System
Perspective

by

Xing Liu

Chair: Zhi-Li Zhang

The past few years have witnessed exciting mobile technologies advances: high-speed LTE
access has become a norm, mobile devices are unprecedentedly powerful, VR/AR has even-
tually stepped out of the lab, wearable devices are waving computing into our daily lives,
etc. Although above remarkable achievements have boosted the emergence of various novel
mobile applications, there still remains three major challenges for researchers, developers
as well as the mass mobile users. First, emerging mobile applications are still relatively
new to the commercial market, and the research community lacks a thorough understand-
ing of their ecosystem. Second, emerging mobile applications pose stringent requirements
for computing and networking capability, leaving their quality of experience (QoE) suffers
in the presence of constrained mobile CPU/GPU and challenging network condition. Third,
emerging mobile applications are operating under tight battery budget, however they often
time incur non-trivial energy overhead. My dissertation is dedicated to address above chal-
lenges identified in three representative emerging mobile usage scenarios: *360° live video*,
Virtual Reality(VR), and *wearable applications*. The goal is to uncover their unique charac-
teristics by comprehensive measurements, propose optimizations towards their major inef-

ficiencies, and implement empirical system to improve the QoE. Specifically, we designed and implemented LIME (LIve video MEasurement platform), a generic and holistic system allowing researchers to conduct crowd-sourced measurements with 360° live video streaming. We utilized LIME to perform a first study of personalized 360° live video streaming on popular commercial platforms. LIME reveals significant network utilization inefficiencies across different streaming platforms that were previously ignored. Our findings suggested that bringing viewport-adaptive streaming into 360° live video could significantly improve viewer side QoE in the presence of challenging network conditions. Inspired by the 360° video measurement study, we further studied generic VR. We designed, implemented, and evaluated an untethered multi-user VR system, called Firefly, that supports more than 10 users to simultaneously enjoy high-quality VR content using a single commodity server, a single WiFi access point (AP), and commercial off-the-shelf (COTS) mobile devices. Firefly employed a series of innovations to adapt to the stringent networking and rendering requirements of supporting high quality VR on commodity smartphones. Our prototype of Firefly demonstrated, for the first time, the feasibility of supporting 15 mobile VR users at 60 FPS using COTS smartphones and a single AP/server. We also performed in-depth characterization of emerging wearable applications. In particular. We conducted an IRB-approved measurement study involving 27 Android smartwatch users. Using a 106-day dataset collected from our participants, we performed indepth characterization of three key aspects of smartwatch usage in the wild: usage patterns, energy consumption, and network traffic. Our findings revealed root causes for wearables' shortened battery life and we proposed optimizations to further improve the energy efficiency of smartwatches.

CHAPTER I

Introduction

Emerging mobile applications have experienced a bloom in the recent years particularly thanks to the growing diversity and capability of mobile gadgets, namely handheld, head mounted, and wearable devices. As reported by Statista [1], the total number of VR/AR users has doubled from 60 millions to 125 millions over the past 4 years, and will continue to show steady growth in the future. Also, wearable device usage is becoming more and more common and its user base is expanding at a remarkable pace. As documented [2], the amount of wearable device users has increased 124% compared with 4 years ago, with the total number reaching 57 millions as of 2019. Despite the popularity of emerging mobile devices and their applications, there remain three major challenges associated with developers and their mass users.

First, we lack a systematic understanding of the ecosystem of emerging mobile applications. Novel streaming service such as 360° live video allows users to enjoy real-time *panoramic* content from their smartphones, tablets, even web browsers. Although being increasingly popular, the service is still relatively new to the commercial market, and we are unfamiliar with its live characteristics such as bandwidth consumption, streaming quality, latency, stalls, *etc*. Also, the high data rate of panoramic content makes its QoE being more sensitive to challenging network condition. For example, in our user study we found that more than 65% of the 360° live viewing sessions produce a lower perceived image

quality than 480P. Therefore, QoE of 360° live video streaming needs to be improved, and a systematic characterization is the first step.

Second, emerging mobile applications such as untethered VR pose stringent requirements for computation and networking, whose capability are often limited in a mobile usage scenario. In particular, today's commodity mobile devices are far from being powerful enough to perform heavy-duty real-time rendering for high-quality VR. A naive solution is to build an real-time offloading model where rendering tasks are distributed to edge server, however previous studies [3, 4] indicate that this approach incurs overwhelming bandwidth usage by streaming the rendered content to mobile clients. Another key challenge is multi-user scalability, which calls for strategic decisions of splitting the client-server workload, as well as scalable approaches for rendering and distributing the content.

Third, emerging mobile applications, for example wearable apps, are operating under tight energy budget. Based on our findings, the battery capacity of a typical smartwatch is only 10% $\sim$ 25% compared to that of smartphones. The average standby time for popular off-the-shelf smartwatches is only around 40 hours, much lesser compared with traditional watches. Practicing good energy efficiency is especially important for smartwatches given its small battery capacity. In literature, very few efforts have been made on understanding the energy profile and usage behavior of smartwatch, not to mention optimizing its energy efficiency.

My thesis is dedicated to address above challenges for three representative emerging mobile applications which are *360° live video*, *untethered VR*, and *wearable applications*. The goal is to *uncover their unique characteristics, propose optimizations towards major inefficiencies, and implement empirical system to improve the QoE*. Here I elaborate the contributions of my dissertation in the following three sections.

1.1 *Measuring the State of the Art*: Understanding Commercial 360° Live Video Streaming Services

Personalized 360° live video streaming is an increasingly popular mobile service that allows a broadcaster to share panoramic videos in real time with worldwide viewers. Compared to video-on-demand (VOD) streaming, experimenting with live broadcast is harder due to its intrinsic live nature, the need for worldwide viewers, and a more complex data collection pipeline. In addition, 360° live video requires much higher bandwidth to provide the same perceived quality as regular video streaming. It has more stringent QoE requirements to prevent VR motion sickness, and it incurs higher workload across all entities: *broadcasters*, *streaming infrastructure*, and *viewers*.

We provided insights for todays commercial 360° live video streaming services. The overall goals are two-fold. First, due to a lack of measurement tools, we develop a measurement system called LIME (LIve video MEasurement platform), which allows researchers to conduct crowd-sourced measurements on commercial or experimental live streaming platforms. Second, we present, to the best of our knowledge, a first study of 360° personalized live video streaming on commercial platforms. We select YouTube and Facebook as the target platforms given their popularity.

To summarize, we made the following contributions. First, the LIME infrastructure itself is a generic, holistic, and crowd-sourced measurement system. LIME can be used in conjunction with the majority of todays commercial live video streaming platforms. Second, leveraging LIME, we collected data from 548 users in 35 countries who have watched more than 4,000 minutes of 360° live videos. We use this dataset to examine 360° live video streaming performance in the wild. Third, we quantified the impact of viewport adaptiveness on 360° live video streaming, and identified inefficiencies of commercial platforms that diminish the benefits of viewport adaptiveness.

3

1.2 *Improving the Quality of Experience*: Engineering High Quality Untethered Multi-user VR over Enterprise Wi-Fi

Virtual Reality has registered numerous applications. Despite the recent trend of "cutting the cord" and making VR untethered over wireless networks, providing immersive user experience on mobile devices still poses numerous challenges. The CPU/GPU power of a smartphone is at least one order of magnitude lower than its desktop counterpart [5], not to mention the energy/heat constraints; the heterogeneity of their computational capabilities should also to be taken into consideration; stringent network requirements (delay and data rates) of untethered VR can be hardly supported by state-of-the-art wireless networks; another key challenge is multi-user scalability, which makes above limitations even more urgent.

We designed, implemented, and evaluated an untethered multi-user VR system, called Firefly, that supports more than 10 users to simultaneously enjoy high-quality VR content using a single commodity server, a single WiFi access point (AP), and commercial off-the-shelf (COTS) mobile devices. Firefly employs a series of techniques including offline content preparation, viewport-adaptive streaming with motion prediction, adaptive content quality control among users, to name a few, to ensure good image quality, low motion-to-photon delay, high frame rate at 60 FPS, scalability with respect to the number of users, and fairness among users.

Firefly is to our knowledge the first system that can scale untethered multi-user mobile VR. We make multi-fold contributions: (1) the design of Firefly, (2) a study of real VR users motion, and (3) our prototype implementation that demonstrates the support of 15 VR users at 60 FPS using COTS smartphones and a single AP/server. With emerging wireless technologies (*e.g.*, 802.11ax and 5G), we believe that Firefly has the potential to scale up to even more users.

1.3 *Optimizing the Energy Efficiency*: Characterizing Wearable Usage In The Wild

Smartwatch has become one of the most popular wearable computers on the market. It brings convenience into our daily routine by enabling various interactions such as push notifications, health tracking, voice command, navigation, *etc*. Smartwatches are operating under limited energy budget. The battery capacity of a typical smartwatch is only 10% ∼ 25% compared to that of smartphones. Charging a watch usually requires special charging dock, making it difficult for users to charge the watches during the day. It is critical to ensure energy efficient practice for smartwatches since a shortened standby time will undermine user experience.

The very first step towards optimizing smartwatches' energy efficiency is to systematically understand their usage in the wild. To this end, we conducted an IRB-approved measurement study involving 27 Android smartwatch users. Using a 106-day dataset collected from our participants, we performed in-depth characterization of three key aspects of smartwatch usage in the wild: usage patterns, energy consumption, and network traffic.

Our contributions towards optimizing smartwatch energy efficiency can be summarized as follows. First, we developed a automated, lightweight, and self-contained measurement data collection system. The data collection infrastructure is compatible with any smartwatch that runs Android Wear OS. Second, We derived accurate and comprehensive power models for popular commodity Android Wear watches. Third, we performed systematic measurements of smartwatches usage patterns, energy consumption profiles, and network traffic characteristics using a 106-day dataset collected from 27 users. Based on our findings, we identified key aspects in the smartwatch ecosystems that can be further improved, and provided insights towards optimizing energy efficiency.

1.4   Thesis Organization

This dissertation is structured as follows...

CHAPTER II

Background

2.1 TBD

CHAPTER III

Conclusion and Future Work

3.1   Future Work

.

BIBLIOGRAPHY

BIBLIOGRAPHY

[1] "Number of virtual reality (VR) and augmented reality (AR) users in the United States," `https://www.statista.com/statistics/1017008/united-states-vr-ar-users/`.

[2] "Number of wearable device users in the United States," `https://www.statista.com/statistics/543070/number-of-wearable-users-in-the-us/`.

[3] Boos, K., Chu, D., and Cuervo, E., "Flashback: Immersive virtual reality on mobile devices via rendering memoization," *Proceedings of the 14th Annual International Conference on Mobile Systems, Applications, and Services*, ACM, 2016, pp. 291–304.

[4] Lai, Z., Hu, Y. C., Cui, Y., Sun, L., Dai, N., and Lee, H.-S., "Furion: Engineering high-quality immersive virtual reality on today's mobile devices," *IEEE Transactions on Mobile Computing*, 2019.

[5] Satyanarayanan, M., Gao, W., and Lucia, B., "The computing landscape of the 21st century," *Proceedings of the 20th International Workshop on Mobile Computing Systems and Applications*, ACM, 2019, pp. 45–50.

[6] "Amazon Mechanical Turk." `https://www.mturk.com`.

[7] "Open Broadcaster Software," `https://obsproject.com/`.

[8] "Insta360," `https://www.insta360.com/`.

[9] "Amazon Mechanical Turk," `https://www.mturk.com`.

[10] "Tesseract-OCR," `https://github.com/tesseract-ocr/tesseract`.

[11] Yin, X., Jindal, A., Sekar, V., and Sinopoli, B., "A Control-Theoretic Approach for Dynamic Adaptive Video Streaming over HTTP," *Proceedings of SIGCOMM 2015*, ACM, 2015, pp. 325–338.

[12] Huang, T.-Y., Johari, R., McKeown, N., Trunnell, M., and Watson, M., "A buffer-based approach to rate adaptation: Evidence from a large video streaming service," *ACM SIGCOMM Computer Communication Review*, Vol. 44, No. 4, 2015, pp. 187–198.

[13] Mao, H., Netravali, R., and Alizadeh, M., "Neural Adaptive Video Streaming with Pensieve," *Proceedings of SIGCOMM 2017*, ACM, 2017, pp. 197–210.

[14] Dimopoulos, G., Leontiadis, I., Barlet-Ros, P., Papagiannaki, K., and Steenkiste, P., "Identifying the root cause of video streaming issues on mobile devices," *Proceedings of the 11th ACM Conference on Emerging Networking Experiments and Technologies*, 2015.

[15] Duanmu, Z., Zeng, K., Ma, K., Rehman, A., and Wang, Z., "A Quality-of-Experience Index for Streaming Video," *IEEE Journal of Selected Topics in Signal Processing*, Vol. 11, No. 1, 2017, pp. 154–166.

[16] Moorthy, A. K., Choi, L. K., Bovik, A. C., and de Veciana, G., "Video Quality Assessment on Mobile Devices: Subjective, Behavioral and Objective Studies," *IEEE Journal of Selected Topics in Signal Processing*, Vol. 6, No. 6, 2012, pp. 652–671.

[17] Qi, Y. and Dai, M., "The Effect of Frame Freezing and Frame Skipping on Video Quality," *International Conference on Intelligent Information Hiding and Multimedia Signal Processing*, 2006.

[18] Siekkinen, M., Masala, E., and Kamarainen, T., "A First Look at Quality of Mobile Live Streaming Experience: the Case of Periscope," *IMC*, 2016.

[19] Wang, B., Zhang, X., Wang, G., Zheng, H., and Zhao, B. Y., "Anatomy of a Personalized Livestreaming System," *IMC*, 2016.

[20] "Samsung Gear VR," https://www.samsung.com/global/galaxy/gear-vr/.

[21] "Google Cardboard," https://vr.google.com/cardboard/.

[22] "Bluetooth VR controller," https://www.amazon.com/VR-Bluetooth-Controller-Kasonic-Smartphones/dp/B01E7Z72NQ/.

[23] "BYOD Popularity," https://www.forbes.com/sites/larryalton/2017/03/27/how-important-is-a-byod-policy-5-strategies-for-millennials/.

[24] "The very real health dangers of virtual reality," https://www.cnn.com/2017/12/13/health/virtual-reality-vr-dangers-safety/index.html.

[25] "Keeping the virtual world stable in VR," https://www.qualcomm.com/news/onq/2016/06/29/keeping-virtual-world-stable-vr.

[26] "How to Build a PC for Virtual Reality," https://www.logicalincrements.com/articles/vrguide.

[27] Jiang, J., Sekar, V., and Zhang, H., "Improving Fairness, Efficiency, and Stability in HTTP-Based Adaptive Video Streaming With Festive," *Proceedings of CoNEXT 2012*, ACM, 2012, pp. 97–108.

[28] Huang, T.-Y., Johari, R., McKeown, N., Trunnell, M., and Watson, M., "A Buffer-Based Approach to Rate Adaptation: Evidence from a Large Video Streaming Service," *Proceedings of SIGCOMM 2014*, ACM, 2014, pp. 187–198.

[29] "Equirectangular Projection," `http://mathworld.wolfram.com/EquirectangularProjection.html`.

[30] "Next-generation video encoding techniques for 360 video and VR," `https://code.fb.com/virtual-reality/next-generation-video-encoding-techniques-for-360-video-and-vr/`.

[31] "Google AR and VR: Bringing pixels front and center in VR video," `https://blog.google/products/google-ar-vr/bringing-pixels-front-and-center-vr-video/`.

[32] Yu, M., Lakshman, H., and Girod, B., "A framework to evaluate omnidirectional video coding schemes," *Proceedings of the Symposium on Mixed and Augmented Reality (ISMAR) 2015*, IEEE, 2015, pp. 31–36.

[33] Qian, F., Han, B., Xiao, Q., and Gopalakrishnan, V., "Flare: Practical viewport-adaptive 360-degree video streaming for mobile devices," *Proceedings of the 24th Annual International Conference on Mobile Computing and Networking*, ACM, 2018, pp. 99–114.

[34] He, J., Qureshi, M. A., Qiu, L., Li, J., Li, F., and Han, L., "Rubiks: Practical 360-degree streaming for smartphones," *Proceedings of the 16th Annual International Conference on Mobile Systems, Applications, and Services*, ACM, 2018, pp. 482–494.

[35] Fan, C.-L., Lee, J., Lo, W.-C., Huang, C.-Y., Chen, K.-T., and Hsu, C.-H., "Fixation Prediction for 360 Video Streaming in Head-Mounted Virtual Reality," *Proceedings of the Workshop on Network and Operating Systems Support for Digital Audio and Video*, ACM, 2017, pp. 67–72.

[36] Hou, X., Dey, S., Zhang, J., and Budagavi, M., "Predictive View Generation to Enable Mobile 360-degree and VR Experiences," *Proceedings of the Workshop on Virtual Reality and Augmented Reality Network*, ACM, 2018, pp. 20–26.

[37] Bao, Y., Wu, H., Zhang, T., Ramli, A. A., and Liu, X., "Shooting a moving target: Motion-prediction-based transmission for 360-degree videos," *2016 IEEE International Conference on Big Data (Big Data)*, IEEE, 2016, pp. 1161–1170.

[38] "Oculus Rift," `https://www.oculus.com/rift-s/`.

[39] "Office Unity Asset," `https://assetstore.unity.com/packages/3d /environments/urban/qa-office-and-security-room-114109`.

[40] "Museum Unity Asset," `https://assetstore.unity.com/packages/ 3d/environments/museum-vr-complete-edition-89652`.

[41] Zhang, L., Tiwana, B., Qian, Z., Wang, Z., Dick, R., Mao, Z. M., and Yang, L., "Accurate Online Power Estimation and Automatic Battery Behavior Based Power Model Generation for Smartphones," *CODES+ISSS*, 2010.

[42] Qian, F., Wang, Z., Gerber, A., Mao, Z. M., Sen, S., and Spatscheck, O., "Profiling Resource Usage for Mobile Applications: a Cross-layer Approach," *Mobisys*, 2011.

[43] Huang, J., Qian, F., Gerber, A., Mao, Z. M., Sen, S., and Spatscheck, O., "A Close Examination of Performance and Power Characteristics of 4G LTE Networks," *Mobisys*, 2012.

[44] Pathak, A., Hu, Y. C., Zhang, M., Bahl, P., and Wang, Y.-M., "Fine-grained power modeling for smartphones using system call tracing," *EuroSys*, 2011.

[45] Pathak, A., Hu, Y. C., and Zhang, M., "Where is the energy spent inside my app?: fine grained energy accounting on smartphones with Eprof," *EuroSys*, 2012.

[46] Nika, A., Zhu, Y., Ding, N., Jindal, A., Hu, Y. C., Zhou, X., Zhao, B. Y., and Zheng, H., "Energy and Performance of Smartphone Radio Bundling in Outdoor Environments," *WWW*, 2015.

[47] Chen, X., Jindal, A., Ding, N., Hu, Y. C., Gupta, M., and Vannithamby, R., "Smartphone Background Activities in the Wild: Origin, Energy Drain, and Optimization," *MobiCom*, 2015.

[48] "Monsoon Power Monitor," `https://www.msoon.com/LabEquipment/ PowerMonitor/`.

[49] Dong, M., Choi, Y.-S. K., and Zhong, L., "Power Modeling of Graphical User Interfaces on OLED Displays," *DAC*, 2009.

[50] Dong, M. and Zhong, L., "Chameleon: A Color-Adaptive Web Browser for Mobile OLED Displays," *MobiSys*, 2011.

[51] Miao, H. and Lin, F. X., "Tell Your Graphics Stack That the Display Is Circular," *HotMobile*, 2016.

[52] Liu, R. and Lin, F. X., "Understanding the Characteristics of Android Wear OS," *MobiSys*, 2016.

[53] Siekkinen, M., Masala, E., and Kämäräinen, T., "A first look at quality of mobile live streaming experience: the case of periscope," *arXiv preprint arXiv:1605.04270*, 2016.

[54] Wang, B., Zhang, X., Wang, G., Zheng, H., and Zhao, B. Y., "Anatomy of a personalized livestreaming system," *Proceedings of the 2016 Internet Measurement Conference*, ACM, 2016, pp. 485–498.

[55] Tang, J. C., Venolia, G., and Inkpen, K. M., "Meerkat and periscope: I stream, you stream, apps stream for live streams," *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, ACM, 2016, pp. 4770–4780.

[56] Pires, K. and Simon, G., "YouTube live and Twitch: a tour of user-generated live streaming systems," *Proceedings of the 6th ACM multimedia systems conference*, ACM, 2015, pp. 225–230.

[57] Zhang, C. and Liu, J., "On crowdsourced interactive live streaming: a twitch. tv-based measurement study," *Proceedings of the 25th ACM Workshop on Network and Operating Systems Support for Digital Audio and Video*, ACM, 2015, pp. 55–60.

[58] Deng, J., Tyson, G., Cuadrado, F., and Uhlig, S., "Internet scale user-generated live video streaming: The Twitch case," *International Conference on Passive and Active Network Measurement*, Springer, 2017, pp. 60–71.

[59] Hei, X., Liang, C., Liang, J., Liu, Y., and Ross, K. W., "A measurement study of a large-scale P2P IPTV system," *IEEE transactions on multimedia*, Vol. 9, No. 8, 2007, pp. 1672–1687.

[60] Kaytoue, M., Silva, A., Cerf, L., Meira Jr, W., and Raïssi, C., "Watch me playing, i am a professional: a first study on video game live streaming," *Proceedings of the 21st International Conference on World Wide Web*, ACM, 2012, pp. 1181–1188.

[61] Li, Y., Zhang, Y., and Yuan, R., "Measurement and analysis of a large scale commercial mobile internet TV system," *Proceedings of the 2011 ACM SIGCOMM conference on Internet measurement conference*, ACM, 2011, pp. 209–224.

[62] Silverston, T. and Fourmaux, O., "Measuring p2p iptv systems," *Proceedings of NOSSDAV*, Vol. 7, 2007, p. 2.

[63] Sripanidkulchai, K., Maggs, B., and Zhang, H., "An analysis of live streaming workloads on the internet," *Proceedings of the 4th ACM SIGCOMM conference on Internet measurement*, ACM, 2004, pp. 41–54.

[64] Kuzyakov, E. and Pio, D., "Next-generation video encoding techniques for 360 video and VR," 2016.

[65] Kuzyakov, E. and Pio, D., "Under the hood: Building 360 video," 2015.

[66] Lee, J., Kim, B., Kim, K., Kim, Y., and Noh, J., "Rich360: optimized spherical representation from structured panoramic camera arrays," *ACM Transactions on Graphics (TOG)*, Vol. 35, No. 4, 2016, pp. 63.

[67] Nasrabadi, A. T., Mahzari, A., Beshay, J. D., and Prakash, R., "Adaptive 360-degree video streaming using scalable video coding," *Proceedings of the 25th ACM international conference on Multimedia*, ACM, 2017, pp. 1689–1697.

[68] Zhou, C., Li, Z., and Liu, Y., "A measurement study of oculus 360 degree video streaming," *Proceedings of the 8th ACM on Multimedia Systems Conference*, ACM, 2017, pp. 27–37.

[69] Jiang, N., Swaminathan, V., and Wei, S., "Power evaluation of 360 vr video streaming on head mounted display devices," *Proceedings of the 27th Workshop on Network and Operating Systems Support for Digital Audio and Video*, ACM, 2017, pp. 55–60.

[70] Almquist, M., Almquist, V., Krishnamoorthi, V., Carlsson, N., and Eager, D., "The prefetch aggressiveness tradeoff in 360 video streaming," *Proceedings of the 9th ACM Multimedia Systems Conference*, ACM, 2018, pp. 258–269.

[71] Corbillon, X., Devlic, A., Simon, G., and Chakareski, J., "Optimal set of 360-degree videos for viewport-adaptive streaming," *Proceedings of the 25th ACM international conference on Multimedia*, ACM, 2017, pp. 943–951.

[72] Corbillon, X., Simon, G., Devlic, A., and Chakareski, J., "Viewport-adaptive navigable 360-degree video delivery," *2017 IEEE international conference on communications (ICC)*, IEEE, 2017, pp. 1–7.

[73] Graf, M., Timmerer, C., and Mueller, C., "Towards bandwidth efficient adaptive streaming of omnidirectional video over http: Design, implementation, and evaluation," *Proceedings of the 8th ACM on Multimedia Systems Conference*, ACM, 2017, pp. 261–271.

[74] Petrangeli, S., Swaminathan, V., Hosseini, M., and De Turck, F., "An http/2-based adaptive streaming framework for 360 virtual reality videos," *Proceedings of the 25th ACM international conference on Multimedia*, ACM, 2017, pp. 306–314.

[75] Qian, F., Ji, L., Han, B., and Gopalakrishnan, V., "Optimizing 360 video delivery over cellular networks," *Proceedings of the 5th Workshop on All Things Cellular: Operations, Applications and Challenges*, ACM, 2016, pp. 1–6.

[76] Xiao, M., Zhou, C., Liu, Y., and Chen, S., "Optile: Toward optimal tiling in 360-degree video streaming," *Proceedings of the 25th ACM international conference on Multimedia*, ACM, 2017, pp. 708–716.

[77] Xie, L., Xu, Z., Ban, Y., Zhang, X., and Guo, Z., "360probdash: Improving qoe of 360 video streaming using tile-based http adaptive streaming," *Proceedings of the 25th ACM international conference on Multimedia*, ACM, 2017, pp. 315–323.

[78] Xie, L., Zhang, X., and Guo, Z., "Cls: A cross-user learning based system for improving qoe in 360-degree video adaptive streaming," *2018 ACM Multimedia Conference on Multimedia Conference*, ACM, 2018, pp. 564–572.

[79] Sun, L., Duanmu, F., Liu, Y., Wang, Y., Ye, Y., Shi, H., and Dai, D., "Multi-path multi-tier 360-degree video streaming in 5G networks," *Proceedings of the 9th ACM Multimedia Systems Conference*, ACM, 2018, pp. 162–173.

[80] Xie, X. and Zhang, X., "Poi360: Panoramic mobile video telephony over lte cellular networks," *Proceedings of the 13th International Conference on emerging Networking EXperiments and Technologies*, ACM, 2017, pp. 336–349.

[81] Broeck, M. V. d., Kawsar, F., and Schöning, J., "It's all around you: Exploring 360 video viewing experiences on mobile devices," *Proceedings of the 25th ACM international conference on Multimedia*, ACM, 2017, pp. 762–768.

[82] Afzal, S., Chen, J., and Ramakrishnan, K., "Characterization of 360-degree videos," *Proceedings of the Workshop on Virtual Reality and Augmented Reality Network*, ACM, 2017, pp. 1–6.

[83] Liu, X., Xiao, Q., Gopalakrishnan, V., Han, B., Qian, F., and Varvello, M., "360 innovations for panoramic video streaming," *Proceedings of the 16th ACM Workshop on Hot Topics in Networks*, ACM, 2017, pp. 50–56.

[84] Abari, O., Bharadia, D., Duffield, A., and Katabi, D., "Cutting the cord in virtual reality," *Proceedings of the 15th ACM Workshop on Hot Topics in Networks*, ACM, 2016, pp. 162–168.

[85] Abari, O., Bharadia, D., Duffield, A., and Katabi, D., "Enabling high-quality untethered virtual reality," *14th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 17)*, 2017, pp. 531–544.

[86] Liu, L., Zhong, R., Zhang, W., Liu, Y., Zhang, J., Zhang, L., and Gruteser, M., "Cutting the cord: Designing a high-quality untethered vr system with low latency remote rendering," *Proceedings of the 16th Annual International Conference on Mobile Systems, Applications, and Services*, ACM, 2018, pp. 68–80.

[87] Tan, Z., Li, Y., Li, Q., Zhang, Z., Li, Z., and Lu, S., "Enabling Mobile VR in LTE Networks: How Close Are We?" *Proceedings of SIGMETRICS 2018*, ACM, 2018.

[88] Li, Y. and Gao, W., "MUVR: Supporting multi-user mobile virtual reality with resource constrained edge cloud," *2018 IEEE/ACM Symposium on Edge Computing (SEC)*, IEEE, 2018, pp. 1–16.

[89] Bao, Y., Zhang, T., Pande, A., Wu, H., and Liu, X., "Motion-prediction-based multicast for 360-degree video transmissions," *2017 14th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*, IEEE, 2017, pp. 1–9.

[90] Liu, X., Vlachou, C., Qian, F., and Kim, K.-H., "Supporting untethered multi-user VR over enterprise wi-fi," *Proceedings of the 29th ACM Workshop on Network and Operating Systems Support for Digital Audio and Video*, 2019, pp. 25–30.

[91] Qiu, H., Ahmad, F., Bai, F., Gruteser, M., and Govindan, R., "AVR: Augmented vehicular reality," *Proceedings of the 16th Annual International Conference on Mobile Systems, Applications, and Services*, ACM, 2018, pp. 81–95.

[92] Ran, X., Slocum, C., Gorlatova, M., and Chen, J., "ShareAR: Communication-Efficient Multi-User Mobile Augmented Reality," *Proceedings of the 18th ACM Workshop on Hot Topics in Networks*, 2019, pp. 109–116.

[93] Zhang, W., Han, B., Hui, P., Gopalakrishnan, V., Zavesky, E., and Qian, F., "CARS: collaborative augmented reality for socialization," *Proceedings of the 19th International Workshop on Mobile computing Systems & Applications*, ACM, 2018, pp. 25–30.

[94] Huang, J., Xu, Q., Tiwana, B., Mao, Z. M., Zhang, M., and Bahl, P., "Anatomizing Application Performance Differences on Smartphones," *Proc. ACM MobiSys*, 2010.

[95] Falaki, H., Mahajan, R., Kandula, S., Lymberopoulos, D., and Estrin, R. G. D., "Diversity in Smartphone Usage," *Mobisys*, 2010.

[96] Shepard, C., Rahmati, A., Tossell, C., Zhong, L., and Kortum, P., "LiveLab: Measuring Wireless Networks and Smartphone Users in the Field," *HotMetrics*, 2010.

[97] "PhoneLab: A Smartphone Platform Testbed," `https://phone-lab.org/`.

[98] Qian, F., Quah, K. S., Huang, J., Erman, J., Gerber, A., Mao, Z. M., Sen, S., and Spatscheck, O., "Web Caching on Smartphones: Ideal vs. Reality," *Mobisys*, 2012.

[99] Rosen, S., Nikravesh, A., Guo, Y., Mao, Z. M., Qian, F., and Sen, S., "Revisiting Network Energy Efficiency of Mobile Apps: Performance in the Wild," *Proc. ACM IMC*, 2015.

[100] Nikravesh, A., Yao, H., Xu, S., Choffnes, D., and Mao, Z. M., "Mobilyzer: An Open Platform for Controllable Mobile Network Measurements," *Mobisys*, 2015.

[101] Chen, X., Ding, N., Jindal, A., Hu, Y. C., Gupta, M., and Vannithamby, R., "Smartphone Energy Drain in the Wild: Analysis and Implications," *SIGMETRICS*, 2015.

[102] Gouveia, R., Karapanos, E., and Hassenzahl, M., "How Do We Engage With Activity Trackers? A Longitudinal Study of Habito," *UbiComp*, 2015.

[103] Lazar, A., Koehler, C., Tanenbaum, J., and Nguyen, D. H., "Why We Use and Abandon Smart Devices," *UbiComp*, 2015.

[104] Lyons, K., "What Can a Dumb Watch Teach a Smartwatch? Informing the Design of Smartwatches," *ISWC*, 2015.

[105] Min, C., Kang, S., Yoo, C., Cha, J., Choi, S., Oh, Y., and Song, J., "Exploring Current Practices for Battery Use and Management of Smartwatches," *ISWC*, 2015.

[106] Poyraz, E. and Memik, G., "Analyzing Power Consumption and Characterizing User Activities on Smartwatches: Summary," *IEEE International Symposium on Workload Characterization (IISWC)*, 2016.

[107] Liu, R., Jiang, L., Jiang, N., and Lin, F. X., "Anatomizing System Activities on Interactive Wearable Devices," *APSys*, 2015.

[108] LiKamWa, R., Wang, Z., Carroll, A., Lin, F. X., and Zhong, L., "Draining Our Glass: An Energy and Heat Characterization of Google Glass," *APSys*, 2014.

[109] Huang, J., Badam, A., Chandra, R., and Nightingale, E. B., "WearDrive: Fast and Energy-Efficient Storage for Wearables," *USENIX ATC*, 2015.

[110] Santagati, G. E. and Melodia, T., "U-Wear: Software-Defined Ultrasonic Networking for Wearable Devices," *MobiSys*, 2015.

[111] Ham, M., Dae, I., and Choi, C., "LPD: Low Power Display Mechanism for Mobile and Wearable Devices," *Usenix ATC*, 2015.

[112] Shen, S., Wang, H., and Choudhury, R. R., "I am a Smartwatch and I can Track my User's Arm," *MobiSys*, 2016.

[113] Nirjon, S., Gummeson, J., Gelb, D., and Kim, K.-H., "TypingRing: A Wearable Ring Platform for Text Input," *MobiSys*, 2015.

[114] Mayberry, A., Hu, P., Marlin, B., Salthouse, C., and Ganesan, D., "iShadow: Design of a Wearable, Real-Time Mobile Gaze Tracker," *MobiSys*, 2014.

[115] Chen, X., Grossman, T., Wigdor, D., and Fitzmaurice, G., "Duet: Exploring Joint Interactions on a Smart Phone and a Smart Watch," *ACM CHI*, 2014.

[116] Plaumann, K., Muller, M., and Rukzio, E., "CircularSelection: Optimizing List Selection for Smartwatches," *ISWC*, 2016.

[117] Wang, H., Lai, T. T., and Choudhury, R. R., "MoLe: Motion Leaks through Smartwatch Sensors," *MobiCom*, 2015.

[118] Liu, X., Zhou, Z., Diao, W., Li, Z., and Zhang, K., "When Good Becomes Evil: Keystroke Inference with Smartwatch," *CCS*, 2015.