Ronny Hans, Ulrich Lampe, Daniel Burgstahler, Martin Hellwig, Ralf Steinmetz:
Where Did My Battery Go? Quantifying the Energy Consumption of Cloud Gaming. In: Proceedings of the 3rd International Conference on Mobile Services (MS 2014), p. 63-67, Institute of Electrical and Electronics Engineers (IEEE), June 2014.

Where Did My Battery Go? Quantifying the Energy Consumption of Cloud Gaming

Ronny Hans, Ulrich Lampe, Daniel Burgstahler, Martin Hellwig, and Ralf Steinmetz
Multimedia Communications Lab (KOM)
Technische Universität Darmstadt
Rundeturmstr. 10, 64283 Darmstadt, Germany
Email: {firstName.lastName}@KOM.tu-darmstadt.de

***Abstract*—With the growing maturity of the cloud computing paradigm, clouds are increasingly used for the delivery of complex multimedia services, rather than just simple infrastructure offers. A popular example of such services is cloud gaming, where video games are executed in the cloud and delivered to a (mobile) client via the Internet. While cloud gaming shifts the computationally complex and energetically expensive task of rendering the game content from the client to a server, it also requires the constant, energy-demanding use of wireless interfaces. In this work, we examine this trade-off based on a custom-designed mobile cloud gaming system called MCGS.KOM. Our experiments, which involve different mobile phones, varying game complexities, and various streaming quality levels, indicate that cloud gaming may facilitate substantial energy saving between 12% and 38% on the mobile device if WLAN is used as network connection type.**

***Keywords*—cloud computing, cloud gaming, mobile gaming, smartphone, energy, experiment, comparison**

I. Introduction

While the historic roots of cloud computing can be traced back to the time-sharing models that were prevalent among mainframe computers in the 1960s [1], its modern-day incarnation has arguably resulted from the decision of major IT firms – most notably Amazon – to sell their surplus data center capacities to third parties. Today, the corresponding Infrastructure as a Service (IaaS) market has gained in maturity and hence, the focus of practitioners and researchers is increasingly shifting toward more sophisticated multimedia services. Popular examples of such services include *cloud gaming* and *Desktop as a Service*. These multimedia services are usually provisioned using IaaS capacities, thus exploiting the scalability and flexibility of infrastructure clouds, and delivered to the end users using the Internet.

In the work at hand, we focus on a specific type of such services: *mobile cloud gaming*. It is situated at the intersection of three major trends, namely cloud-based service delivery, spread of mobile devices, and growing interest in digital entertainment. Hence, mobile cloud gaming provides a current, tangible example of cloud-based multimedia services. Nevertheless, the results of our research should also be applicable for related service types. The essential idea of (mobile) cloud gaming is that video games are centrally executed on high-end servers in a cloud data center and delivered to (mobile) clients as a video stream via the Internet, with the clients serving as simplistic input and playback devices [2]. From a customer perspective, one main advantage of cloud gaming is the ability to access games at any place and time, independent of any specific device upon which they are installed [3]. Furthermore, hardware expenditures are substantially reduced, because a simplistic thin client is usually sufficient for access [4]. In addition, games do not have to be purchased for a fixed (and commonly quite notable) amount of money, but can be leased on a pay-per-use basis. From the provider perspective, one main benefit is the prevention of copyright infringements [5]. In addition, distribution costs may be substantially reduced, because the need for the delivery of physical media is alleviated. Furthermore, the development process may be greatly simplified if games are exclusively developed for the cloud, rather than multiple different platforms.

However, as it has been explained in our past work [6], cloud-based multimedia services – and specifically, mobile cloud gaming – also pose new challenges. First, since cloud games use wireless and cellular networks as delivery medium, *latency* may impair the subjective user experience. Second, given that large amounts of data are transferred in cloud gaming, cost appears as a challenge, specifically in cellular networks that are usually characterized by limited data plans. Third, cloud-based service delivery may reduce battery drain by shifting computational load to the cloud, but also requires constant data transfer, hence resulting in potential *energy* challenges. In our previous research, we have provided initial results on above aspects, based on preliminary measurements and a brief analytical assessment [6]. The work at hand substantially extend these past efforts, with a focus on the third aforementioned challenge, i. e., energy consumption. We provide detailed results on this specific issue, based on high-frequency sampling of power consumption during local and stream-based game play on different mobile devices.

The remainder of this paper is structured as follows: In Section II, we describe our experimental approach. Results and are discussion are given in Section III. Section IV provides an overview of related work. A summary and a brief outlook on future work are given in Section V.

II. Experimental Approach

For the quantification of energy consumption in cloud gaming, we conceived an experiment that involved empirical measurements for two use cases, namely local and cloud-based multimedia service consumption, on different cellular phones and under consideration of different games and network connection types.

In general, energy remains a scarce resource on most mobile devices: As Perrucci et al. point out, the improvements in battery capacity on mobile devices have been very limited in recent years, with capacities only doubling once per decade [7]. Furthermore, these minor improvements are often mitigated by general design trends, such as the use of larger screens, more potent Central Processing Units (CPUs) and Graphic Processing Units (GPUs), or an increasing number of sensors. Further considering the natural weight and volume constraints of a mobile device, increases in energy supply through the pure enlargement of the battery are very difficult to achieve. Accordingly, a 2009 research report by Strategic Analytics raised the notion of a "cellphone energy gap", with an annual reduction of 4.8% in the average time interval between charge cycles [8]. Based on these arguments, it can easily be reasoned that the user acceptance of cloud-based multimedia services heavily depends on a moderate utilization of energy resources.

As mentioned above, our aim was to empirically measure and compare the energy consumption of mobile devices in two use cases, namely local and cloud-based multimedia service consumption. Once again, we focused on the specific scenario of cloud gaming; however, our approach should also provide a suitable indication for other types of multimedia services, for which the following arguments and assumptions hold.

Games commonly impose high load on the CPU and GPU of the mobile device for executing the game logic and rendering the game images. In contrast, cloud-based games tend to pose lower demands on these two components, since video streams can usually be decoded very efficiently in hardware. However, the radio modules are intensively used for the transfer of the audio/video stream, and such wireless data transfer has been empirically shown to be energetically expensive in the past [7].

To the best of our knowledge, there exists no commercial mobile cloud gaming provider to date. Hence, in our previous publication [6], we selected video streaming as a comparable application scenario for the experiments. In contrast, as a basis for the work at hand, we implemented our own mobile cloud gaming system, called *MCGS.KOM*. This approach should provide an even more accurate representation of commercial cloud gaming systems and also provides a fully controlled experimental environment.

MCGS.KOM comprises two components, namely a server and client application. The server component has been implemented in Microsoft Visual C++ 2010. The server waits for initial connection by the client on a designated port. Upon receiving a request, the server initiates the desired game, which is then executed in a separate thread. The server component uses VideoLAN media player[1] to capture the screen content of the game, convert it into a desired audio/video codec, and subsequently stream it to the initiating client. The client is essentially a player, which plays back the audio/video stream that is received from the server (downstream), and sends game control commands back to the server (upstream). The client has been implemented in Java 7 and exploits the built-in Android media player component for playback.

In order to obtain identical game content for both the cloud-based and local execution, we implemented our own game for both the server and client platform. The game content

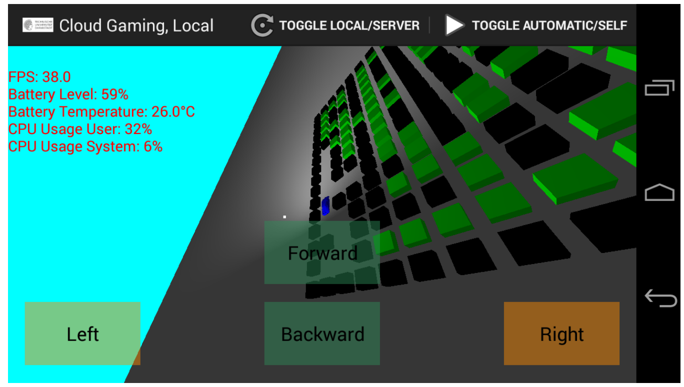

Figure 1. Screenshot of the dummy game that was used in the energy measurements.

consists of a character moving through a three-dimensional labyrinth (cf. Figure 1), with the ability to script the movement for identical behavior across all platforms and configurations. The game implementation uses OpenGL 2.0 and OpenGL ES 2.0 on the server and client platform, which is wrapped by a minimalistic C++ and Java program respectively. In order to simulate different game types with varying CPU and GPU load, the game allows to specify a complexity level. Concerning the GPU, higher complexity results in a higher number of graphical elements. Concerning the CPU, we use a function that recursively computes pi and vary the number of parallel threads as well as the temporal spacing between function calls.

Our experiment involved two contemporary cellular phones, namely a *Samsung Galaxy S* and a *Samsung Galaxy S3*, both operating under Android 4.1.2. In the case of cloud-based gaming, we used *WLAN* for connecting to the streaming server. The WLAN connection was encrypted using Wi-Fi Protected Access 2 (WPA2) with a preshared key, which is a common security measure in private application scenarios.

We did intentionally *not* regard cellular networks as connection type in our experiments for three reasons: First, we were not able to secure a private cellular access point. Given that public cellular access points are shared between multiple users and that phones may potentially switch access points throughout the measurements, such setup would provide an insufficient degree of control and hence, leading to potentially flawed results. Second, our past research has shown that cellular networks are characterized by high latencies [9], rendering such connection type less suitable for cloud gaming than a WLAN connection. Third, another previous publication of ours has pointed to prevalent data volume caps and high data transfer cost in cellular networks [6], which also limits the practical suitability of such networks for cloud gaming.

For the streaming-based scenario, a high- and low-quality stream were tested. Since the game features no audio content, the stream exclusively consisted of video content. The high-quality stream exhibits a resolution of 1,280 x 720 pixels, at a frame rate of 30 fps and a bitrate of 3,000 Kbit/s. The low-quality stream features a resolution of 640 x 360 pixels at 20 fps, using a bitrate of 1,000 Kbit/s. Both streams were encoded using the popular H.264 codec [10] and transmitted to the mobile clients via the *Real-Time Streaming Protocol* (RTSP). RTSP was selected since it is specifically tailored to

[1]http://www.videolan.org/vlc/

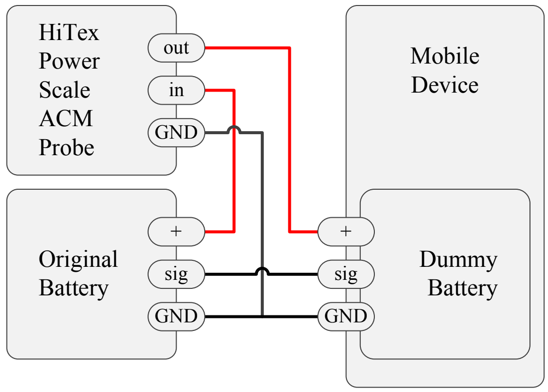

Figure 2. Circuit layout of the setup that was used for the energy consumption measurements.

real-time streaming scenarios and hence very well matches the application scenario of cloud gaming. Depending on the service type, other protocols – such as Hypertext Transfer Protocol (HTTP) – may also be applicable.

All measurements were made using the *HiTex PowerScale*[2], a high-accuracy energy profiling tool for the continuous measurement of the power consumption, i. e., voltage and current, of a device. For the experiment, we designed and built special measurement stations for each mobile device. The circuit layout of the setup is provided in Figure 2. The original battery of the respective mobile device is used as power source, with the current flowing through the Active Current Measurement (ACM) probe of the PowerScale system and subsequently to a dummy battery that is inserted into the mobile device. In addition, the signal pin(s) of the original battery is/are bypassed directly to the dummy battery and hence, to the mobile device. For each measurement, we used a sampling rate of 10 kHz over a time period of 300 seconds (i. e., five minutes) for each experimental configuration and subsequently parsed the binary result files using a self-developed Java tool and MathWorks Matlab[3].

Please note that in contrast to software-based solutions – such as *PowerTutor* [11] or *eprof* [12] – our measurement approach is *not* based on energy consumption models, but on the physical power consumption of the mobile device. In addition, our measurement procedure does not impose additional system load or consume additional energy during the measurement process. Thus, our hardware-based approach should provide a more accurate quantification of the energy requirements than a software-based solution.

From a formal standpoint, energy consumption is the dependent variable in our experiment. The independent variables are the *device*, the *game complexity*, the *connection type*, and the *video quality*. We followed a *full factorial* design in principal [13], hence testing each possible combination of values; however, the connection type is not relevant for local gaming and hence dismissed. Each experimental run was repeated five times to account for potential inaccuracies and outliers; the following results represent the mean value of these five measurements.

[2]http://www.hitex.com/index.php?id=powerscale
[3]http://www.mathworks.com/products/matlab/

III. Experimental Results and Discussion

The results of our experiment concerning energy consumption are listed in Table I and further visualized in Figure 3. Please note that we provide the observed mean electric power in Watts during the predefined measurement intervals in the illustration. The mean energy consumption in Joules, which is also listed in the table, can be deduced by simply multiplying the given power figures by the length of the intervals, i. e., 300 seconds.

Starting with the most interesting aspect, namely the difference in energy consumption between local and cloud-based gaming, our results clearly indicate that cloud-based service delivery can have substantial benefits. Depending on the game complexity and video resolution, energy savings between 12% and 20% could be observed for the older Samsung Galaxy S device. Interestingly, the figures are highest for medium game complexity, where the Galaxy S also exhibited the highest power consumption in local gaming.

Because this deviation comes unexpectedly, we conducted an additional series of verification measurements on the Galaxy S. Both the power traces and the observed battery temperatures indicate that the Galaxy S reduces its CPU and/or GPU clock speed after a brief time period if the game is locally executed with high complexity. This downclocking likely leads to reduced power draw, ultimately resulting in the observed reduction in energy consumption compared to a game execution with medium complexity.

For the newer Galaxy S3, we found very consistent results, with increases in game complexity resulting in higher energy demands for the local execution. Depending on the specific setup, energy savings for a streaming scenario were in the range between 34% and 38%, hence notably exceeding the figures observed for the Galaxy S. A possible explanation consists in the more potent hardware, i. e., CPU and GPU, of the Galaxy S3, which results in higher power consumption under computational load compared to the Galaxy S. In contrast, the energy consumption for the WLAN-based data transfer and stream decoding appears very similar across both devices, hence widening the gap between cloud-based and local delivery.

It is also worthwhile to note that the high resolution 720p video stream lead to smaller energy demands than the low resolution 360p stream in some experimental setups. This result is counter-intuitive at first, since the 720p stream requires more data transfer and hence, more energy for the WLAN module. However, a possible explanation is that the 360p video stream requires additional scaling – given the high screen resolution of both devices –, thus imposing additional load on CPU and/or GPU. Given the relatively small sample size, the statistical significance of these differences cannot be reliably judged; thus, this aspect should be further examined in future experiments.

In summary, the results of our second experiment confirm the findings of our previous work [6]: Cloud-based multimedia service provision may provide energy savings compared to a local execution on modern cellular phones if WLAN is used as network connection. Also, our results indicate that newer devices with more potent hardware may profit even more from the cloud-based delivery of services, since the use of more potent hardware results in relatively higher energy consumption for the local execution of multimedia-oriented apps.

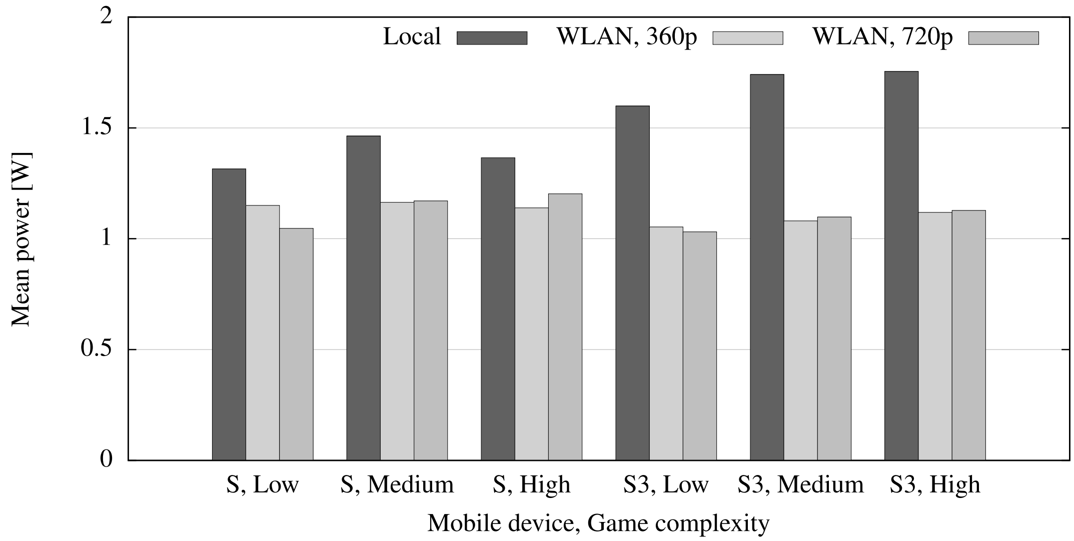

Figure 3. Observed mean power during 300 s of video game consumption, by mobile device and game complexity (sample size $n = 5$).

Table I. OBSERVED MEAN POWER AND MEAN ENERGY CONSUMPTION DURING/FOR 300 S OF VIDEO GAME CONSUMPTION (SAMPLE SIZE $n = 5$).

Device	Game complex.	Conn. type	Video quality	Power [W]	Energy cons. [J]
Galaxy S	Low	WLAN	360p	1.150	345.1
Galaxy S	Low	WLAN	720p	1.047	314.0
Galaxy S	Medium	Local	n/a	1.463	439.0
Galaxy S	Medium	WLAN	360p	1.165	349.4
Galaxy S	Medium	WLAN	720p	1.171	351.2
Galaxy S	High	Local	n/a	1.366	409.7
Galaxy S	High	WLAN	360p	1.140	341.9
Galaxy S	High	WLAN	720p	1.203	360.8
Galaxy S3	Low	Local	n/a	1.599	479.7
Galaxy S3	Low	WLAN	360p	1.053	315.9
Galaxy S3	Low	WLAN	720p	1.031	309.3
Galaxy S3	Medium	Local	n/a	1.741	522.2
Galaxy S3	Medium	WLAN	360p	1.080	324.1
Galaxy S3	Medium	WLAN	720p	1.098	329.4
Galaxy S3	High	Local	n/a	1.755	526.4
Galaxy S3	High	WLAN	360p	1.119	335.8
Galaxy S3	High	WLAN	720p	1.128	338.3

IV. RELATED WORK

To the best of our knowledge, the issue of energy consumption in cloud gaming has received very little from the research community so far. However, there exists some related research in similar areas that is relevant to the work at hand. A selected set of these previous research efforts is discussed in the following.

To start with, offloading, i. e., the concept of conserving energy or improving performance on mobile devices by means of moving computational tasks to the cloud, has been a vivid field of research in recent years [14]. For example, Kumar and Lu [15] have presented an analytical model that permits to estimate potential energy savings due to offloading, dependent on the computational complexity of a task, the data size, and the available bandwidth.

In terms of practical applications, Cuervo et al. [16] have proposed *MAUI*, a framework that automatically identifies and offloads certain functions of a mobile application. In their evaluation, the authors find benefits for offloading with respect to energy when WLAN is used, whereas performance benefits are demonstrated in both WLAN and third-generation cellular networks. Similar benefits in terms of energy consumption and performance have also been demonstrated by Kosta et al. as part of their *ThinkAir* framework [17]. In contrast to our work, both approaches focus on the offloading of selected computational tasks within an application, rather than the complete application as such.

An open-source cloud gaming system, called *GamingAnywhere*, has been proposed by Huang et al. [18]. While the authors evaluate the performance of their system with respect to QoS and QoE properties, they do not provide an assessment of energy demands. In contrast, our work permits a detailed comparison of energy consumption in local and cloud-based mobile gaming, based on two identical implementations of a game.

Empirical measurements concerning the energy demands of different components in a smartphone, such as CPU, GPU, screen, and wireless interfaces have been provided by Perrucci et al. [7]. The authors created a collection of Python scripts on a Nokia N95 smartphone to run an automated series of measurements; energy demands were subsequently quantified using the phone-based *Nokia Energy Profiler* and further validated through an external measurement device. While the work of Perrucci et al. is of interest for the analytical determination of energy demands of specific applications, it is not specifically tailored to the scenario of cloud gaming and would likely provide less accurate results than our approach, which is based on a configurable cloud gaming system and external high-frequency sampling.

Furthermore, in a past publication of ours, we investigated the influence of compression and parsing on the energy consumption of mobile Web service usage [19]. Although our research aim to optimize the energy-efficiency in mobile Web-based applications, this approach is neither tailored for could gaming where the content is delivered as an audio/video stream.

Lastly, as indicated before, the foundation for this paper has been laid in our previous work [6], which provided an initial assessment of the challenges for cloud-based multimedia services. Specifically, that work featured a brief analysis of energy demands for local and cloud-based gaming, using video streaming as a proxy application for cloud gaming. In contrast to the work at hand, which relies on high-frequency sampling using an external measurement system, our previous research was based on the battery level as reported by the smartphone. This approach provides a substantially less accurate quantification of energy demands.

V. Summary and Outlook

With the growing maturity of cloud computing, focus is increasingly shifting from simple infrastructure offers to more advanced multimedia services. However, specifically with mobile clients acting as consumer, these services pose novel challenges regarding non-functional aspects such as latency, cost, and energy consumption. In the work at hand, we empirically examined the latter aspect, based on the exemplary use case of mobile cloud gaming, with a focus on the consumer side.

For that purpose, we implemented a mobile cloud gaming system, called MCGS.KOM, as well as a prototypical gaming app for local execution on a phone. We conducted comparative experiments of both local and cloud-based gaming within a WLAN setting, using a Galaxy S and Galaxy S3 smartphone, under consideration of different game complexity and streaming quality levels. Our results indicate that cloud-gaming may facilitate energy savings between 12% and 38% on the mobile device compared to local gaming, with the gap substantially increasing for the more recent Galaxy S3 smartphone.

In summary, our results indicate that cloud gaming can be an appealing application for mobile phone users with respect to energy consumption, or rather, energy conservation. It potentially permits to consume computationally complex video games while at the same time maintaining prolonged battery lifetime. However, it should also be pointed out that neither the energy consumption nor the financial cost on the provider side were considered in our experiments, and that these two factors may easily outweigh the energetic benefits that were observed in our study.

A future direction of our work consists in the systematic extension of the experiments, e. g., through the inclusion of additional mobile devices and network types – most notable cellular networks – in the energy measurements. We additionally plan to analyze other application scenarios of cloud-based multimedia services, such as Desktop as a Service.

Acknowledgments

The authors would like to thank Nils Richerzhagen for his support in the conduction of the measurements.

This work has been sponsored in part by the E-Finance Lab e. V., Frankfurt a. M., Germany (www.efinancelab.de), by the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 318201, and by the German Research Foundation (DFG) in the Collaborative Research Center (SFB) 1053 – MAKI.

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All online references in this paper were last accessed and validated in February 2014.