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Towards Energy Efficient Multimedia Streaming to Mobile Devices

Mohammad Ashraful Hoque

Aalto University

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Towards Energy Efficient Multimedia Streaming to Mobile Devices

Mohammad Ashraful Hoque

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Abstract

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Abstract

The rapid development in mobile and telecommunication industries together pushed up the popularity of multimedia streaming applications among the smartphone users. The streaming applications in smartphones heavily depend on wireless networking activities as a substantial amount of data is transmitted from a server to the streaming clients. Because of the very high energy requirement of wireless network interfaces, multimedia streaming applications are considered as the most energy hungry applications. Therefore, improving battery life time of the smartphones is essential while experiencing multimedia streaming.

In this thesis, we investigate the energy consumption of modern mobile devices while experiencing multimedia from different video services and propose two energy efficient streaming techniques to reduce energy consumption of the smartphones when receiving multimedia content via Wi-Fi, 3G or LTE. The first technique is a server-side technique. It considers the available free buffer space at the client, burst size and TCP flow control while sending content to the client in periodic bursts. The second technique is a client-side technique that considers the probability of a user's abandonment during a video streaming session. In addition to the energy savings, we also study the performance of cellular networks in presence of our first proposed streaming technique.

Keywords Burst, Energy, HSPA, LTE, Multimedia, Power, PSM, PSM-A, Wi-Fi, Traffic Shaping, Wireless.

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Preface

This dissertation represents a culmination of work and learning, which has taken place during last three years from 2010 to 2013 in the Data Communication Software Lab, Aalto University School of Science. Even though I started my doctoral studies at the end of 2010, the foundation of this was established during my Masters thesis work which proceeded with the Nokia Research Center. In that work, we investigated the basic traffic shaping mechanism to save energy of mobile devices in TCP-based wireless multimedia streaming. The outcome of that work motivated me to do further research work in energy efficient wireless multimedia streaming to mobile devices.

This dissertation is article based and every published article was co-authored. My primary task has been to define problems and find ways to solve the problems. To that extent, I did literature study, traffic and power measurement of smartphones for multimedia streaming services, analyzed the measurement results, and developed energy efficient streaming services. I also assisted the co-authors in modeling the power consumption of smartphones.

Certainly, other generous peoples and institutions supported to finish my dissertation. I would like to pay gratitude to my supervisor Prof. Ylä-Jääski for believing in me and paving the way to explore my own research interests. He was always there to support me in every possible ways towards the completion of this thesis.

Thanks to my instructors, Dr. Matti Siekkinen and Prof. Jukka K. Nurminen, for guiding toward quality research and finally the successful dissertation. It would have been very difficult without their strong support and guidance. I was fortunate to have them with me. They always stood by me to listen and advice, which helped to overcome numerous challenges. I am grateful to them for sharing their experience and expertise in the work. I love working with them and we will continue.

I was involved in a collaborative work with Nokia Solutions and Networks (formerly Nokia Siemens Networks); in particular with Mika Aalto. Collaboration with NSN has been very successful and resulted in two articles for this thesis. I would like to thank Mika for active participation and hopefully such collaboration will continue.

I also would like to thank Prof. Dr. Ernst Biersack and Dr. Frank H.P. Fitzek for pre-examining my thesis. Their comments were encouraging, which helped me to improve the quality of my thesis. Thanks to Prof. Sasu Tarkoma for reviewing my thesis earlier and giving me feedback.

I extend my gratitude to the department secretaries and system administrators for creating excellent working environment. I would like to mention here about Soili Adolfsson, Kristiina Hallaselkä and Fatima Ksiksou for their support during my work.

Thanks to former colleagues; Dr. Yu Xiao, Dr. Miika Komu, Dr. Andrey Lukyanenko, Sumanta Saha, Vilen Loga, Anisul Hoq. The todo list from Yu Xiao and Miika Komu guided me to go through the dissertation process.

I appreciate the financial support from the Future Internet Graduate School and Academy of Finland. I would like to thank FIGS decision board and Katri Sarkio for their support during my work.

Thanks to my friends in Otanimei, Espoo. Without them, life would have been much more difficult. I would like to thank my uncle Kamal Uddin. Without his greatness, I would have not been in this position.

Finally and most importantly I am grateful to my family. My parents always wished to see me as a Doctor and I am happy that I have met their expectation. Particularly, I want to thank my beloved wife, Nusrat Naz, who endured all the boredom during my work. I am dedicating this thesis to her.

Helsinki, November 5, 2013,

Mohammad Ashraful Hoque

Contents

List of Abbreviations

AB-PSM	Adaptive Buffer Power Save Mechanism
AP	Access Point
CPC	Continuous Packet Connectivity
DASH	Dynamic Adaptive Streaming over HTTP
DMS	Dynamic Modulation Scaling
DRX	Discontinuous Reception
DTX	Discontinuous Transmission
DVS	Dynamic Voltage Scaling
DVFS	Dynamic Voltage and Frequency Scaling
EDCA	Enhanced Distributed Channel Access
FD	Fast Dormancy
FGS	Fine Grained Streaming
FSK	Frequency Shift Keying
GPS	Global Positioning System
HSPA	High Speed Packet Access
HSL	HTTP Live Streaming
HTTP	Hyper Text Transfer Protocol
LTE	Long Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency-Division Multiplexing
PASP	Power Aware Streaming Proxy
PSM	Power Saving Mode
PSM-A	Adaptive Power Saving Mode
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RRC	Radio Resource Control
RTCP	Real Time Control Protocol
RTP	Real Time Protocol
RT_PS	Real Time Power Saving Protocol
RTT	Round Trip Time
SISO	Single Input Single Output
STPM	Self Tuning Power Management
SVC	Scaleable Video Coding
TCP	Transmission Control Protocol

UDP	User Datagram Protocol
UAPSD	Unscheduled Automatic Power Save Delivery
WCDMA	Wideband Code Division Multiple Access
WNI	Wireless Network Interface
ZWA	Zero Window Advertisement
ZWP	Zero Window Probe

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Mohammad Ashraful Hoque, Matti Siekkinen and Jukka K. Nurminen. Energy Efficient Multimedia Streaming to Mobile Devices - A Survey. In *IEEE Communications Survey and Tutorials*, November 2012.

II Mohammad Ashraful Hoque, Matti Siekkinen, Jukka K. Nurminen and Mika Aalto. Dissecting Mobile Video Services: An Energy Consumption Perspective. In *14th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks*, WoWMoM 2013, Madrid, Spain, June 2013.

III Mohammad Ashraful Hoque, Matti Siekkinen, Jukka K. Nurminen. TCP Receive Buffer Aware Wireless Multimedia Streaming–An Energy Efficient Approach. In *23rd ACM Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV' 2013)*, Oslo, Norway, 6, February 2013.

IV Mohammad Ashraful Hoque, Matti Siekkinen, Jukka K. Nurminen. Using Crowd-Sourced Viewing Statistics to Save Energy in Wireless Video Streaming. In *19th Annual International Conference on Mobile Computing and Networking (MobiCom' 2013)*, Miami Florida, 29, September 2013.

V Matti Siekkinen, Mohammad Ashraful Hoque, Jukka K. Nurminen. Streaming over 3G and LTE: How to Save Smartphone Energy in Radio Access Network-Friendly Way. In *5th ACM Workshop on Mobile Video (MoVid 2013)*, Oslo, Norway, 6, February 2013.

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1. Introduction

Multimedia streaming has been popular since last decade with the rapid deployment of Internet connectivity to home users via cable modem and ADSL technologies. The proliferation of high-end mobile devices, such as smartphones, tablets and laptops, and wireless Internet access together have pushed the momentum further in recent days. By the end of 2013, the number of such mobile devices will exceed the total number of people on earth [1]. These mobile devices have Wi-Fi and mobile broadband access to get continuous access to the Internet. At present, a smartphone user enjoys average 2 Mbps mobile network speed. In addition, 750 thousand Wi-Fi access point had been installed around the globe and more than 750 million users are using those networks [2]. As a result, the Internet has witnessed the surge in the production and consumption of multimedia content of many areas such as education, news media and entertainment industries, and user generated content. For example, YouTube has one billion view from mobile users every day which is 25% of its global view[1]. The forecast says that the growth of multimedia streaming is increasing as mobile network connection speed is increasing and hence high bit rate videos are also more prevalent [1].

The multimedia content is delivered to the client using transport protocols, such as UDP and TCP, over IP. The research work during the last decade focused on UDP-based streaming protocols, such as RTP which even specifies the payload format for the content encoded with different compression algorithms [3]. However, such protocols do not have their own mechanism to deal with the timely delivery of content, packet loss or network conditions. Therefore, RTP requires the support of RTCP like protocols for loss recovery, dealing with jitter and network condition [4, 5, 6].

At the beginning, it was thought that TCP congestion control mechanism would hurt the user experience as it might incur delay because of TCP's retransmission and back-off nature. Though it had been the wisdom to use UDP for multimedia streaming, TCP has been the most prevalent form of streaming since more than last ten years. Commercial multimedia system providers such as Real Media, Windows Media support TCP-based streaming. Furthermore, studies throughout the last ten years have found a dominating portion of multimedia traffic in the Internet is of TCP-based [7, 8, 9]. The first reason behind the selection of TCP over UDP is that the TCP is a reliable protocol and thus requires no additional mechanism to recover from packet loss. The second reason is the NAT traversal.

1.1 Motivation

Along with high speed wireless Internet access, smartphones are equipped with a number of sensors, GPS, and high definition displays. Their processing capacity is also increasing. Apart from making phone calls, users can run simple to very complex applications. Nevertheless, these mobile devices have limited battery capacity. With the increase in computation capability and wireless Internet access, the battery capacity of mobile devices

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[1] Statistics - YouTube : http://www.youtube.com/yt/press/statistics.html

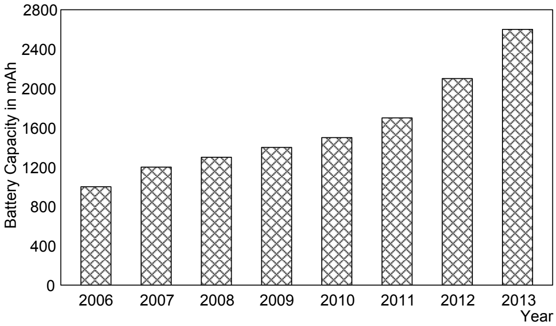

Figure 1.1. The battery capacity of smartphones in mAh.

is also increasing. Figure 1.1 shows that battery capacity has increased to double with the development in mobile industry during last seven years.

Using multimedia streaming applications over wireless networks, mobile devices consume power for encoding/decoding, wireless communication and presentation. The reason is that the compression algorithms are complex requiring high computing power for motion or object detection, compensation, and forward or reverse transformation. Therefore, many previous studies looked at the computational aspects of streaming and proposed dynamic voltage scaling (DVS) [10, 11], dynamic voltage and frequency scaling (DVFS) [12, 13], CPU register or cache optimization [14], traffic concealing at network interfaces [15], OS or application level optimization [16]. Display also has been optimized for low energy consumption while viewing multimedia content [17].

Data Rate	Wi-Fi	3G		LTE
(kbps)	54Mbps (W)	384kbps (W)	2Mbps (W)	>20Mbps (W)
Radio-128	1.07	1.10	1.10	1.62
Radio-192	1.07	1.17	1.15	1.65

Table 1.1. Power Consumption of wireless network interfaces in Nokia E-71 and HTC Velocity LTE phone when using streaming applications over Wi-Fi, 3G and LTE. Wi-Fi and 3G measurements are of Nokia E-71.

Although decoding and presenting consume significant amount of total energy, a wireless interface (Wi-Fi/3G/LTE) can deplete battery at an equal or even at a higher rate when receiving multimedia content [18, 19]. There are two reasons. First, wireless radios are high power consuming in nature. Second, multimedia streaming requires a continuous flow of traffic from server to the client which keeps the interface always active. However, the wireless network interfaces (WNIs) have their own power management mechanisms and all of them work in a similar fashion. If no packets are transmitted or received for a specific amount of time, the interfaces switch from active to more passive mode, which means that at least some parts of the radio circuitry are not powered on. During such an inactivity period, an interface spends a residual time in active state after each transmission or reception that leads to some energy spent doing nothing useful. We refer to this energy as *tail energy* [20].

Nevertheless, these power management techniques do not reduce energy consumption when a client is using multimedia streaming applications as the interval between the packets is so small that the mobile devices cannot enforce power saving mechanisms. Table 1.1 illustrates the power consumption of different WNIs during streaming sessions. First we measured total energy consumption during those streaming sessions which comprises the playback and the wireless interface power consumption. We isolated the playback power which is approximately 250-300mW (not shown in Table). Then we computed the WNI power consumption by subtracting the playback power from the total power. The results presented in Table 1.1 highlight the fact that the energy spent for downloading only is in most cases a very significant part of the total energy. Hence, though the capacity has increased, the average battery lifetime always lies in the range of 2-3 hours while running multimedia streaming applications in smartphones via Wi-Fi, 3G and LTE. Therefore, improving battery lifetime by reducing wireless communication energy consumption is the main focus of this research.

1.2 Problem and Scope

About a decade ago, the mobile phone only had GPRS/EDGE access, which did not have the sufficient capacity to provide sufficient bandwidth for multimedia streaming. The mobile devices, such as laptop, had only Wi-Fi access. Therefore, a lot of research focused on reducing Wi-Fi communication energy for UDP-based streaming. The common strategies which delivered energy savings are shaping traffic into periodic bursts, drive down the Wi-Fi interface into sleep state in between two consecutive bursts, and scheduling those bursts among multiple clients. These solutions work remarkably well for UDP-based multimedia streaming to mobile devices via Wi-Fi. However, existing commercial multimedia service use TCP as the transport protocol to deliver content to the client. Therefore, using existing energy efficient techniques can produce different results when content is transported over TCP instead of UDP to the client.

In this dissertation we ask the very basic question. *How can the maximum energy savings be achieved when receiving TCP-based multimedia content via Wi-Fi, 3G and LTE without compromising user experience and what is the impact on wireless networks?*

The magnitude of this question is very broad. Therefore, we limit our scope and focus of this research on the following aspects of multimedia for energy efficient streaming to mobile devices; *a)* streaming techniques used by the streaming services to deliver content to the clients, *b)* the buffer size at the streaming client, *c)* the user behavior and the wireless interface being used for streaming, and *d)* the impact on radio network signaling.

a) Along with the TCP congestion control, a number of other factors can distort user experience in consuming multimedia content, such as initial playback delay, users with different types of Internet access, bandwidth fluctuation, etc. TCP provides satisfactory performance when the end-to-end bandwidth of a user's connectivity is twice the encoding rate of the stream [21]. Modern streaming services, such as YouTube, Vimeo, Dailymotion, ShoutCast, also apply a number of techniques to deliver multimedia to the streaming clients; (1) Bit Rate Streaming, (2) Throttling, (3) Fast Caching, (4) Buffer Adaptive Streaming, and (5) Rate Adaptive Streaming. There are studies that analyze the merits of these streaming techniques from the server [9], network [22, 23] and fixed users [24, 25] perspective. These techniques also define how the wireless interfaces at the mobile device would be utilized.

b) Multimedia players maintain a fixed size playback buffer. The size of this buffer depends on implementation of the player. At the very beginning of a streaming session, the player receives content at a very high rate. If the playback buffer is of few hundred kilobytes, then the playback buffer and TCP receiver buffer both may become full immediately. Since the player decodes the content at the encoding rate, TCP flow control and this player behavior together control the receiving of the rest of the content from the streaming server.

c) Given that the streaming client has sufficient memory, the most energy efficient approach is to download the whole content at once at the beginning of a streaming session. If the content is not interesting, a user may abandon even after watching a very small fraction of the total duration. The actual amount of content download may vary depending on the duration of the video. Plissonneau and Biersack [26] have found that downloading of the longer videos are either aborted early or downloaded completely, whereas the downloading of short videos are aborted at any time. It is also found that on-demand videos are watched for less than 20% of their duration in general [25]. Therefore, downloading the whole content at the very beginning of a streaming session may lead to data and energy waste. The consequence can be severe for a user when streaming is carried over cellular network and the user has quota based subscription, which is becoming common nowadays. Furthermore, different WNIs have different tail energy characteristics. Therefore, downloading content in periodic chunks or bursts can provide a balance between data and energy waste. However, more precision can be achieved by considering WNI tail energy and users' interruption probability.

d) Traffic shaping can save energy of a mobile device as the WNI used for streaming can switch to low power consuming states between two consecutive bursts. These state transitions require the exchange of signaling messages between the mobile device and the network, specifically when using 3G and LTE interfaces for streaming. This signaling is important because the network performance heavily depends on the amount of signaling messages the network can handle. Globally many operators already have suffered service quality degradation and even network outage because of signaling storms created by the smartphones [27]. The number of signaling messages to be exchanged depends on the wireless network configuration and the standard implemented in mobile devices.

There are a number of areas in multimedia streaming to improve energy efficiency. However, we note that this thesis does not cover the following aspects of multimedia streaming.

- Energy efficient multimedia streaming from mobile devices is not focus of this research. However, the streaming mechanism we propose can be applied to reduce energy consumption when a mobile device streams multimedia to other devices.

- We do not reduce computation or display energy consumption when decoding and presenting multimedia content. However, we study the energy consumption of smartphones when using different types of players to decode the content of different quality, formats or container.

- Our proposed energy reduction solutions do not consider rate adaptive streaming, such as DASH. In DASH [28], a client receives content in fixed size periodic bursts where an individual burst contains the content of a fixed quality or encoding rate. The quality can be different in a separate burst depending on the bandwidth experienced by the client. However, we model the energy consumption of an individual burst taking into account the WNI, bandwidth of the client and the bit rate of the content. As a result, our solutions also can be applied for energy-aware rate adaptive streaming.

- Our solutions are only aware of the behavior of power management protocols that work

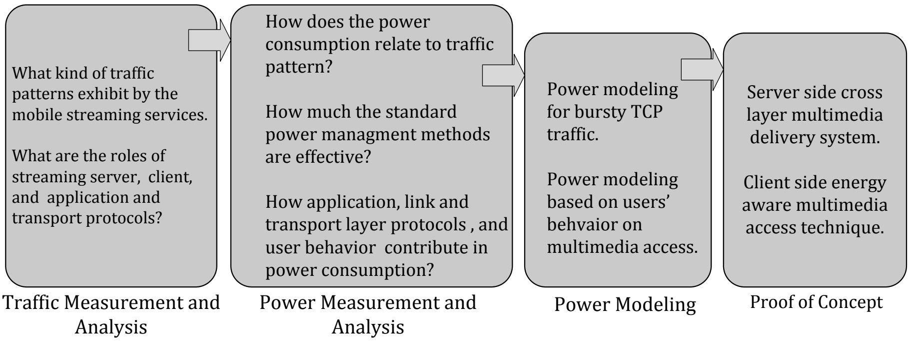

Figure 1.2. The research methodology used in this thesis.

the at MAC layer and the TCP flow control mechanism and thus we do not modify any existing protocol nor we introduce a new one. However, in case of 3G and LTE, we change network configuration parameters to study the effect of network configuration on the energy consumption of smartphones and impact on radio network signaling. Therefore, our contribution is also effective for network operators while configuring their networks and mobile vendors or researchers when designing energy aware wireless network access.

1.3 Methodology

The methodology followed in this thesis is heavily inclined towards measurement, analysis, modeling, and the proof of concept through simulation and implementation. The methods are presented in Figure 1.2. Publication II includes traffic, power measurement and analysis of various streaming services to smartphones. These methodologies together pave the way for identifying different streaming techniques and their effect on the energy consumption of smartphones. We used Wireshark[2] and tcpdump[3] to capture traffic. Wireshark and tcptrace[4] were sufficient to analyze individual traces. Such analysis uncovers the role of different vantage points (e.g. client, network operator and the server), transport protocol and the streaming application behind the streaming techniques.

In order to measure power consumption, we used the Monsoon Power Monitor[5]. We used the same device and Matlab to analyze the power traces. Power measurement and analysis tells us what kinds of power management techniques are implemented in smartphones of various mobile platforms and how much they are effective with the identified streaming techniques. In Publication III, we identify the effect of TCP receive buffer on the energy consumption through traffic and power measurements of burst shaped streaming. Then we model the energy consumption of bursty TCP traffic and simulate the relation between available buffer space at the client, burst size and power consumption. After that we implement an energy efficient multimedia delivery system. We apply similar methodologies in our Publication IV as well. We apply statistical analysis to calculate users' interruption probability while watching a video. Our Publication V includes both traffic and power measurements and analysis. It is necessary to mention here that unlike [29, 30] our power consumption models are for transport and application layers.

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[2] http://www.wireshark.org

[3] http://www.tcpdump.org

[4] http://www.tcptrace.org

[5] http://www.msoon.com

1.4 Contributions

The contributions of this thesis are based on traffic and power measurements, modeling, simulation, and prototype implementation. We observe traffic patterns of modern multimedia services in smartphones. Then we model the energy consumption considering TCP flow control and users viewing statistics of a video. We claim our contributions in identifying the multimedia delivery techniques and their energy efficiency, how TCP properties and user behavior can be synthesized to save energy of smartphones for wireless multimedia streaming. We do not try to optimize the effect of multimedia traffic on the fixed network, such as bufferbloat [31, 32]. Our contributions are listed briefly in the following sections.

1.4.1 Mobile Video Streaming Strategies

One of the main contributions of this thesis is the study of the solutions proposed in the literature and the multimedia delivery techniques used by modern video services to send content to the smartphones of various mobile platforms. Publication I covers the literature study. Publication II presents the measurement and analysis work with the video streaming services. In Publication II, we identify a number of streaming techniques. The importance of such study is imperative to understand the facts which work behind choosing a particular technique, the role of key players, such as server, mobile broadband operators and the client, on the delivery methods, and consequence on the energy consumption of mobile devices. The identified techniques do not provide optimal energy savings. There are a few reasons for this; *(i)* Buffer adaptive techniques are not aware about the effect of TCP flow control or server controlled low throughput traffic on the energy consumption of smartphones, *(ii)* The streaming techniques do not adapt to the access technology used, and user behavior and preferences on the engagement in watching [33].

1.4.2 TCP Receive Buffer Aware Streaming

We study the relationship between power consumption and TCP-based multimedia traffic shaping in Publication III. Specifically, we develop novel power consumption models for regular bursty traffic over TCP. From those models we derive a heuristic for energy optimal burst size for a given client. Then, we develop a cross layer streaming system called EStreamer which implements the heuristic. The heuristic makes EStreamer agnostic to different cellular network and Wi-Fi interfaces used for multimedia streaming.

1.4.3 Considering Users' Interruption Probability and Tail Energy of WNI

We identify the sources of energy inefficiency with the downloading strategies used by the mobile video streaming services. The downloading of content is formulated as a problem where a user can interrupt the watching. During a video streaming session, a user may abandon even after watching a very small fraction of the total duration of the content which leads to data waste and energy waste for downloading the content. Therefore, prefetching content in periodic bursts provides a balance between data and energy waste. However, energy waste also depends on the wireless interface being used for streaming as different WNIs have different energy consumption and tail energy characteristics. Hence, considering users' interruption probability can reduce energy waste by pre-fetching the right amount of content. We propose a download scheduling algorithm based on crowd-sourced users viewing statistics and tail energy characteristics of WNIs in Publication IV.

1.4.4 Impact on Radio Network Signaling

Publication V systematically studies the energy saving potential of traffic shaping to different kinds of devices, both, audio and video streaming services, and both, 3G (HSPA) and LTE networks with different configurations. From the results, we infer the standards implemented in smartphones. We primarily study the role of different standards and cellular network configurations on the energy consumption of smartphones, and the consequences on the cellular networks for signaling load.

1.5 Author's Contributions

The author had the following role and contributions:

- Publication I (19 p.): The author was the principal contributor in classifying the existing research in energy efficient multimedia streaming. He also did also the necessary traffic and power measurements, and analysis.
- Publication II (11 p.): The author was the team leader of this project. He proposed the original idea of studying mobile video services, did all the traffic, power measurement. Most of the measurement results were also analyzed by the author.
- Publication III (6 p.): The key idea of EStreamer was proposed by the author. He assisted the co-authors (Dr. Matti Siekkinen and Professor Jukka K. Nurminen) in the modeling tail energy consumption of burst shaped TCP traffic. He designed and developed the prototype of EStreamer and did all the measurements presented in the work.
- Publication IV (12 p.): The author had the original idea. He proposed to use audience retention information to schedule video download and to exploit Fast Start to accelerate the downloading. The author designed and developed the prototype for Android platform and did all the necessary measurements.
- Publication V (6 p.): The author designed and implemented the traffic shaping proxy. He did all the necessary traffic and power measurements.

1.6 Structure of the Thesis

This thesis is structured as follows. In the following chapter we go through the existing research in energy aware multimedia streaming to mobile devices. Then in chapter 3, we present the streaming techniques which are present with the modern mobile streaming services and address the issues which we consider as our research problems. In the same chapter, we present how our research addresses those issues. We draw conclusions in Chapter 4.

2. Background

This thesis is about energy efficient multimedia streaming. In this chapter, we briefly outline the related work that we covered in Publication I. In addition, recent work on rate adaptive streaming is also discussed. We leave out work on energy aware decoding and presentation. We begin with energy optimization work for the physical layer. Next we discuss standard and non-standard power management solutions for link layer. After that we outline cross layer and application layer approaches.

2.1 Physical Layer

Energy-aware optimization of physical layer would benefit all kind of applications. In physical layer, energy consumption is related with the capacity of the carrier channel and the transmission distance. Therefore, instead of utilizing the maximum capacity during a streaming session, solutions mostly considered to tune the modulation level to limit the transmission rate according to the actual bit rate of the content dynamically. This is also known as Dynamic Modulation Scaling (DMS). DMS is applied such that the lower the bit rate, the lower is the modulation level and the lower is energy consumption [34, 35]. In this case, the energy per bit is reduced by increasing the transmission time.

Changing only the modulation level may not always provide the smallest energy consumption because energy consumption also depends on the transmission distance [36]. As a result, it may also require changing the modulation scheme as well. For instance, if the transmission distance is more than a threshold, reducing modulation level does not reduce energy consumption using Quadrature Amplitude Modulation (QAM), rather energy consumption increases. In such a scenario Frequency Shift Keying (FSK) is more energy efficient [36]. However, changing modulation scheme or modulation level dynamically is impractical. The negotiation between the transmitter and the receiver is mandatory and hence there is protocol overhead. Furthermore, the implementation of a such scheme requires careful reconfiguration at the receiver in order to operate with proper modulation scheme or level [35].

2.2 Link Layer

The power management of wireless network interfaces works at link layer and the vast majority of solutions proposed changing the behavior of power or resource management protocols to improve the energy efficiency. We classify them as standard and non-standard solutions and discuss them separately for Wi-Fi and cellular network interfaces.

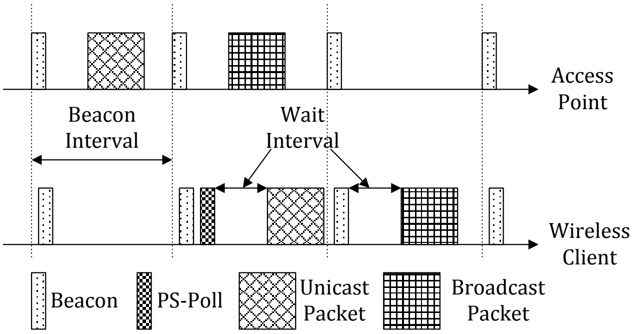


Figure 2.1. IEEE 802.11 PSM for multiple clients where a client is waiting for a unicast and a broadcast packet.

2.2.1 Wi-Fi Access (IEEE 802.11 Standards)

IEEE 802.11 interfaces come with default power saving mechanism called power saving mode (PSM) [37]. Using PSM a mobile device periodically wakes up to check whether it has any data to transmit/receive. Otherwise, the interface remains in sleep state. During this sleeping period, the access point (AP) buffers the incoming data for the client. When the client wakes up, it retrieves the buffered data by sending PS-Poll frame to the AP. Fig. 2.1 shows the basic power saving mechanism. PSM helps to reduce energy consumption only when the distribution of multimedia traffic is regular [19]. However, modern smartphones use a modified version of PSM called PSM Adaptive (PSM-A). PSM-A forces the interface to be in active mode for a few hundred milliseconds after transmitting or receiving packets [38]. Only iPhone 4 uses an aggressive PSM timeout value of around 30 ms and many others use ≈200 ms. However, still PSM is more energy efficient than PSM-A [38].

Channel contention is another source of energy waste for smartphones when multiple devices compete for the same wireless channel. The 802.11e amendment [39] called Enhanced Distributed Channel Access (EDCA) gives channel access priority to multimedia traffic over bulk transfers. EDCA comes with another power saving mechanism named Unscheduled Automatic Power Save Delivery (UAPSD) which is suitable when traffic exchange is duplex such as VoIP [40].

2.2.2 Beyond IEEE 802.11 standards

Modified PSM

A siginificant number of researches has considered changing the default behvaior of PSM. They try to utilize every possible idle period in between data packets to put the Wi-Fi interface in sleep state without incurring excessive delay [41, 42, 43, 44]. μPM tries to take the advantage of tiny duration between the retransmission of a frame [45]. Although, these solutions are applicable with multimedia streaming applications, such small idle periods are difficult to find because of the large volume of data exchange.

A recent work has proposed to wake up the Wi-Fi interface according to a TCP persist timer like schedule instead of waking periodically to save energy [46]. The authors have estimated significant energy savings compared with PSM for constant bit rate traffic. These solutions propose to change a single mobile device. Therefore, they do not reduce channel contention. In addition, they can be used only for local deployments, but not for commercial use.

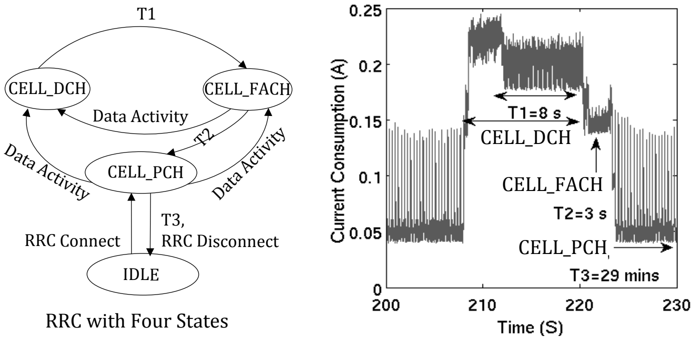


Figure 2.2. 3G RRC state machine with different states, state transitions with three inactivity timers and power consumption at different states. The value of the inactivity timers are vendor recommended.

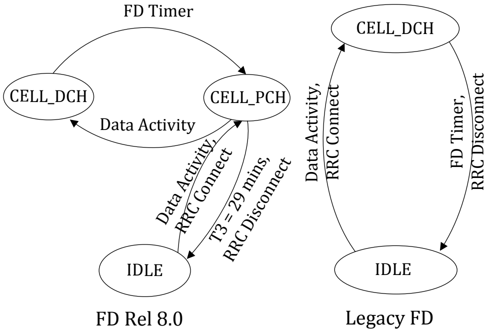


Figure 2.3. State transitions using different versions of FD

Toward contention-free Wi-Fi scheduling

It is very difficult to avoid energy waste due to channel contention and interference when Wi-Fi access points are getting densely deployed. Numerous solutions propose to reserve a time slice for each individual connected client [47, 48, 49]. A client wakes up only at its scheduled time and thus avoids contention with other competing clients. These novel solutions are very generic and thus suitable to reduce energy consumption for any kind of traffic and thus multimedia streaming. However, these TDMA-like mechanisms require changing 802.11 PSM and subsequently require modifying both client device and the AP which makes them difficult to deploy in practice.

NAPman [50] schedules channel access among multiple virtual APs. Each AP has its own beaconing schedule. The beacon for each virtual AP is staggered in time so that all clients do not request simultaneously to the AP. However, a client must associate twice with the AP. SleepWell [51], on the other hand, schedules access when multiple physical AP sharing the same channel by monitoring the activity patterns of nearby APs. This solution does not help, when other APs are operating on different but overlapping channels.

2.2.3 Cellular Network Access (3GPP Standards)

When using a cellular network interface (3G or LTE), the power management and state transitions of a smartphone are managed through the corresponding Radio Resource Control protocol (RRC).

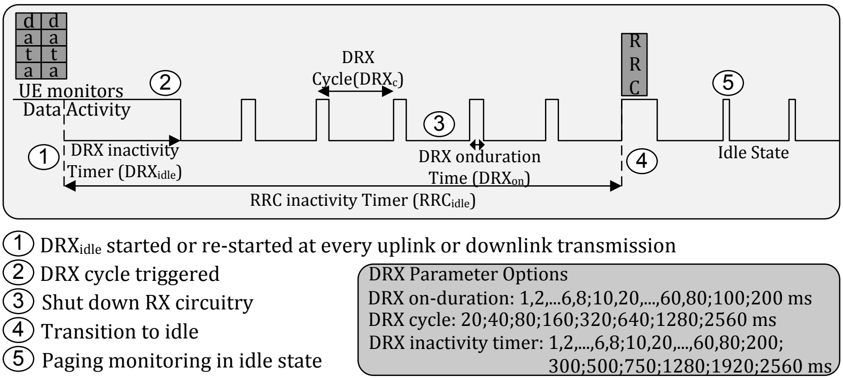


Figure 2.4. LTE DRX Cycles and timers.

HSPA/3G
In case of 3G, the RRC has four states [52]. Figure 2.2 shows the 3G RRC inactivity timers, state transitions and current consumption of a mobile device in each state. In CELL_DCH state, a mobile device occupies a dedicated data channel that provides the maximum throughout and lowest latency. CELL_FACH channel corresponds to a channel which is shared among all the mobile devices and provides less data capacity. And the CELL_PCH state enables to page a mobile device. IDLE refers to the disconnected state from RRC. Although the standard does not specify any fixed value of the inactivity timers, operators use values in the range of several seconds. During these inactivity periods, there is no data exchange and thus the energy spent is known as tail energy [53, 54]. If CELL_PCH is enabled in the network, then the mobile device is disconnected from the RRC after a very long time through CELL_PCH→IDLE transition. Otherwise, CELL_FACH→IDLE transition takes place when T2 expires. However, modern smartphones try to avoid long tail energy using a modified standard called Fast Dormancy (FD) with an inactivity timer of 3-5 seconds [55]. FD enables a mobile device directly to switch from CELL_DCH to CELL_PCH or IDLE state depending on the standard implemented in the smartphone and whether network supports CELL_PCH or not. Figure 2.3 illustrates that FD Rel 8.0 forces the transition via CELL_PCH. On the other hand, the legacy FD changes state directly from CELL_DCH to IDLE.

However, the transitions between the states require the exchange of signaling messages between a smartphone and the network. The amount of messaging is more when the device disconnects from the RRC [56]. Therefore, a network that does not support CELL_PCH or a mobile device with legacy FD implemented both contribute in additional signaling in the network as they both require RRC reconnection upon data activity.

LTE
Compared with 3G, LTE RRC protocol consists of only two states: RRC_CONNECTED and RRC_IDLE [57]. There is also an RRC inactivity timer which controls the transition from connected to the idle state. However, there is discontinuous transmission and reception (DTX/DRX) in LTE which enables a mobile device to be in low power state even when connected with RRC. DRX in connected state is also called cDRX. Figure 2.4 illustrates this mechanism. If there is data inactivity for DRX_{idle} time, the device begins a DRX cycle (DRX_c) and wakes up for DRX_{on} time to check data activity. The device changes from RRC_CONNECTED to RRC_IDLE state when the RRC inactivity timer, RRC_{idle}, expires and the device enters in the paging monitoring mode in the IDLE state. Since there are

only two states, the amount of signaling is less. In addition, enabling DRX does not produce additional signaling in the network (Publication V).

2.2.4 Network Parameter Configuration in Cellular Networks

In cellular networks, only the operator has control on the network or RRC parameters. The majority of the studies emphasize the fact that RRC protocols are not aware of the kinds of traffic. They propose aggressive timer settings or changing the inactivity timers dynamically based on traffic patterns [58, 59]. Static and shorter timer setting were proposed in [60] based on the inter arrival time between packets. Similar aggressive configuration was also suggested in [61].

Inclusion of FD in modern smartphones has enabled researchers to study the effect of the FD timer on the energy consumption as a mobile device can request the network to initiate the CELL_DCH→CELL_PCH or CELL_DCH→IDLE state transition. Qian et al. [62] advocated triggering FD based on the information provided by different applications. Recently, Deng and Balakrishnan [63] proposed to initiate FD dynamically with variable timer values instead of a fixed timeout value.

Unlike 3G, LTE has more parameters to configure when DRX is enabled, such as DRX cycle length and the DRX inactivity timer. Simulation studies found that LTE can be very energy efficient with DRX/DTX enabled [64, 65]. This is confirmed by a measurement study with a commercial LTE network in [66]. However, the energy savings depend on the traffic pattern of different applications and parameter configuration according to the pattern [67, 68]. For example, short DRX cycles can be suitable for VoIP traffic as the packets are spaced by 50-100 ms. In case of multimedia streaming; power saving of up to 50% is possible, when compared with other possible configurations, such as DRX inactivity timer with higher values [69].

The vast majority of work suggests or achieves energy savings by changing the network configurations. In this thesis, we show that standard power saving mechanisms and the proposed mechanisms for cellular network do not provide energy savings for multimedia streaming unless an upper layer mechanism such as traffic shaping is applied. The reason is that the spacing between packets are so small that even DRX like mechanism cannot take the advantage of small periodic cycles.

2.3 Cross Layer Approaches

Numerous energy efficient mechanisms work strictly above the link layer. They apply multimedia traffic shaping or scheduling. Certainly, a significant number of researches proposes to alternate the states of the wireless network interface at the client along with multimedia traffic management at the server, proxy or at the client. In this section, we briefly discuss the solutions according to the end points at which the solutions can be deployed. We begin with client-centric approaches.

2.3.1 Client-Centric

Most of the client centric solutions apply buffer adaptive mechanisms to generate idle periods and traffic prediction mechanisms to identify idle periods between packets. Then they rely on standard power saving mechanisms or implement their own mechanisms to drive the WNI into sleep state during those idle periods to save energy. We will also see how client-based solutions apply other techniques to schedule incoming traffic from the server.

Playback Buffer Management
Multimedia services always fill a large fraction of the player's playback buffer at the very beginning of a streaming session to tolerate bandwidth fluctuations. A number of solutions use this playback buffer information to save energy. A very early solution proposed to switch off the Wi-Fi interface when the playback buffer is full and to switch on the interface when the buffer drains to a low level. During the off period, the AP would buffer the incoming data for the client [70]. The fuzzy adaptive approach also applies similar mechanism [71]. Self-Tuning Power Management (STPM) [72] also uses buffer information to save energy when streaming via Wi-Fi. STPM differs from the earlier two in a way that the system activates PSM when the playback buffer is full. The AP buffers the incoming traffic during this short period. When the buffer drains out, STPM puts the interface into continuous active mode. In Chapter 3, we show that modern video players still apply such effective technique to save wireless communication energy.

Traffic Prediction
Another popular method is to predict the arrival time of the incoming traffic. This method has been widely utilized to model the energy consumption of wireless network interfaces [30] and to manipulate the WNI to save energy. Researchers identified that the traffic pattern of Windows Media, QuickTime and RealNetwork multimedia formats [73]. Window Media traffic tends to be regular and predictable. Whereas Real and QuickTime Media traffic are not periodic and impossible to predict. Based on these findings, a history-based prediction policy was introduced to estimate the sleep interval and operate on the Wi-Fi interface accordingly [73]. Later on, a linear prediction-based method was proposed to estimate the sleep interval more precisely in order to reduce energy consumption and packet loss [74].

Exploiting TCP Flow Control
There are also solutions which try to exploit transport protocol property to generate bursty traffic out of continuous data transmission. Yan *et al.* [75] showed that if the TCP receiving window is choked down and choked up periodically at the streaming client then incoming traffic from the server becomes bursty. This mechanism artificially invokes TCP flow control. Although there is exchange of zero window advertisement/probe (ZWA/ZWP) messages, Wi-Fi interface can be forced to sleep to avoid this small traffic and thus to save energy [38]. However, such mechanism cannot be used when streaming via 3G/LTE as the control is to the network operator and forcing these interfaces to the sleep state would bar the smartphone from basic phone functioning.

Scheduling Traffic among Multiple Wireless Interfaces
Today smartphones have a number of high speed wireless interfaces, such as Wi-Fi, 3G/LTE or Bluetooth. Nowadays, even Bluetooth speed is increased to 3 Mbps. As a result, there is a trend in research community to utilize these interfaces according to their power consumption and maximum data transfer capacity order. CoolSpots [76] schedules low bit rate multimedia traffic via Bluetooth and higher bit rate traffic via Wi-Fi. However, only one interface can be used at a time. Cool-Tether provides energy-efficient communication by creating Wi-Fi hotspot in presence of multiple mobile devices and provides Internet connectivity via a 3G enabled smartphone [77]. Similar mechanism also can be used for energy efficient content distribution [78, 79].

2.3.2 Proxy or AP Assisted Solutions

A fair number of research work applied their techniques in proxy servers, in a Wi-Fi AP or in the cellular network. These mechanisms estimate playback buffer status at the client and apply traffic shaping or scheduling at the middle box.

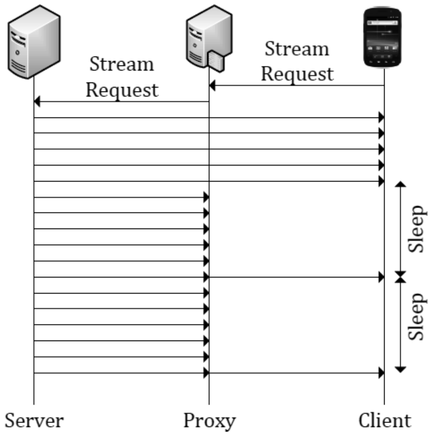


Figure 2.5. Proxy-based traffic shaping of multimedia content.

Traffic Shaping

In a proxy-based solution, a streaming client sends the stream request to the proxy. Then the proxy forwards the request to the server and receives incoming multimedia content from the server. Proxy accumulates the incoming data for a while and sends to the client as a single burst. In this way the client gets the opportunity to put the WNI into low power consuming state between two successive bursts and hence can save energy [80]. Fig. 2.5 shows how a proxy-based traffic shaping mechanism works.

Shenoy and Radkov [81] applied transcoding on both constant and variable bit rate traffic in a proxy and then used traffic shaping technique on the transcoded media at the proxy along with the history based prediction at the client to reduce Wi-Fi energy consumption. They also introduced a protocol to convey information to the client when to wake up to receive the next burst. A standalone energy saving protocol also exists in literature, RT_PS [82], which is the extension of their previous research [83, 84]. This protocol employs buffer adaptive mechanism described in Section 2.3.1 and generates ON-OFF traffic pattern. The exception is that a client explicitly tells the proxy about the possible buffer starvation when the OFF period is about to end.

Scheduling Bursty Traffic

only traffic shaping is not sufficient when multiple streaming clients are being served by the same access point using a single channel. In this scenario, a mobile client can starve for the playback buffer while the AP serves the other clients. In this case, a streaming client pays high energy cost by waiting at the idle state to receive data from the AP. Therefore, some kind of scheduling at the streaming server, proxy or in an AP is essential.

A system architecture for energy efficient streaming is presented in [19]. The system has three proxy modules; a server-side proxy, a proxy in the AP and a client-side proxy. The server-side proxy shapes the traffic into bursts, the AP proxy schedules those bursts among multiple clients. These two modules also send information to the client-side proxy to inform when to wake up to receive the burst. Another realistic scenario with TCP web traffic and UDP-based multimedia was considered in [85] and scheduling was done in a local transparent proxy. In a separate proxy based solution, Zhang and Chanson [86] applied two heuristics based scheduling, which prioritize a client either with low RTT or a client with small residual battery capacity.

2.3.3 Server-Assisted Solutions

In a server-assisted solution, a server may shape traffic into periodic bursts by adding an additional buffer such as AB-PSM [87]. Server sent data accumulates into this secondary buffer. During this period, a streaming client can keep its WNI into sleep state. When the secondary buffer is filled, the data is sent to the client in a single burst. Later on, AB-PSM was upgraded to a system wide solution in which the server would also select the bit rate, the client would adjust brightness and volume level according to the present battery level [88]. There are some other methods where a client specifically tells the server to send bursty traffic or a server tells the client to switch on/off the wireless interface [89].

In a different system, the server pre-processes multimedia content to generate some annotations based on the relative size of the packets and the request timestamps. Then the server embeds these annotations into MPEG stream and sends to the client. The Wi-Fi AP, on the way, discovers these annotations and sends bursty multimedia traffic to the client [90].

2.4 Application layer Mechanisms

The energy efficient techniques we discussed in previous sections do not modify the actual multimedia content. On the other hand, the application layer mechanisms apply content adaptation to increase battery life. The principle purpose of content adaptation is to serve mobile devices with different computation or display properties. The amount of traffic is also reduced as the quality degrades. Recently, there is a new issue, with the quota based subscribers in cellular network, of adjusting video quality to the quota [91]. However, these methods are equally effective in reducing WNI and decoding energy consumption by trading quality with battery life.

2.4.1 Scalable Video Coding

Scalable Video Coding (SVC) enables to encode a single multimedia stream by structuring the compressed data of bit streams coming from different transmission channels into layers [92]. The base layer contains the content of lower quality. The additional layers improves the quality further and called enhancement layers. Therefore, a control algorithm is required to select the number of layers according to the energy condition. For instance, SVC was integrated with an MPEG-4 streaming system (FGS [93]) in which a mobile device sends it decoding capability to the server and server decides the number of layers accordingly [94]. The system also uses DFS at the mobile client when the energy level drops below a certain threshold. Power-Aware Streaming Proxy (PASP) also applies similar mechanism and intelligently drops small objects which are too small for a mobile device to display [95].

Because of the layered architecture, SVC can be also used in a way such that each client have the basic layer and the enhancements layers are distributed among multiple users. Later on, sharing these layers during playback can reduce Wi-Fi communication energy of mobile devices significantly [96, 97].

2.4.2 Content Selection

Content selection is another form of adaptive streaming to deal with device and network diversity. Therefore, switching to a lower quality stream at the server provides energy savings at the client [19]. Other than bandwidth or display size, selecting multimedia content based on the mobile devices battery level can also improve battery life significantly [98, 99]. However, multiple copies of the same stream are required, which is very resource consuming.

2.4.3 HTTP Rate Adaptive Streaming

The content adaptation techniques discussed so far were proposed during the last decade. At that time, HTTP had the interface only for constant bit rate streaming and Wi-Fi had been the only wireless interface suitable for multimedia streaming. Nowadays, there are a number of rate adaptive multimedia frame works, such as Apple's HTTP Live Streaming [100], Microsoft's smooth streaming, and Adobe's adaptive streaming [101]. Other than these, a number of video streaming services employ their own rate adaptive algorithms, such as Netflix. Recently, SVC is also included under HTTP [102, 103].

Most of these new rate adaptive mechanisms use chunk mode streaming where a client estimates the available bandwidth and requests a chunk of fixed size to the server based on the bandwidth. Such mechanisms available to date deal with the challenges like multiple streaming clients at the bottleneck switch or AP [104] and TCP flow control [105]. These networking conditions may lead the client player toward false bandwidth estimation. The effect of wrong bandwidth estimation is quality fluctuation, unfairness to other competing users [106] and frequent fluctuation hurts user experience [107]. Therefore, the focus of the most recent studies is dealing with such quality fluctuation by optimizing at different end points; i.e. client [108, 91] and server [109].

Since the majority of the methods downloads content in periodic chunks, there is potential to reduce energy consumption of mobile devices when streaming via wireless networks. The larger the chunk size, the lower is the energy consumption. In Publication II, we describe the energy consumption with HLS. In this thesis, we show how energy consumption can be reduced further by utilizing global viewing statistics of a video. There is also use of local viewing statistics [110]. In addition, location based bandwidth profiling also can be used to optimize energy consumption further for HTTP rate adaptive streaming [111, 112].

2.4.4 Media Transcoding

Transcoding on the fly is another way to deal with network bandwidth and device heterogeneity for multimedia streaming. The server contains only one copy of the stream and new content is generated at the server, proxy or at the AP based on a client's request and served [81]. It is shown that energy consumption reduces significantly at the client [113]. The above mentioned solutions consider a streaming service between a mobile client and a fixed host or server. It is also possible that a mobile device acts as a server and another mobile device acts a client. A dynamic transcoding framework was proposed for a mobile device (i.e. the server) which selects the transcoding parameters for the streaming mobile client [114]. However, transcoding requires heavy computation and thus this method is energy hungry. Therefore, transcoding might be acceptable in mobile devices like laptops but not in smartphones or tablets.

2.5 Summary and Limitations

The solutions covered in this chapter work at different layers of the Internet protocol stack and at different end points of end-to-end client and server communication path. Therefore, these two factors together define the scope of deployment of these solutions.

- There are some solutions from which every kind of applications can gain energy benefits, e.g. physical and link layer solutions in general. The most of the physical or link layer mechanisms are access technology dependent, such as Wi-Fi.
- A number of solutions target only multimedia streaming applications. The upper layer solutions, such as traffic shaping, can be applicable with a number of wireless network technologies. However, there are also a fair number of cross layer mechanisms which directly operate on the wireless network interface and thus have limited applicability when the streaming is carried over a different wireless network.
- Concerning the deployment of the energy efficient mechanisms, physical and link layer solutions are applicable at the streaming client. These mechanisms require changes at the client and also at the Wi-Fi access point or in the cellular network configuration. Therefore, the usage of these mechanisms can be restricted only for the local deployments.
- The upper layer mechanisms, such as history based traffic and user behavior prediction, are easily deployable in mobile devices. Therefore, a pure client-centric solution is the most straightforward from the mobile device vendors' or software developers' perspective. In contrast, traffic shaping and scheduling are suitable to apply at the server or in a proxy.

In short, a majority of the work apply traffic shaping on UDP-based streaming traffic to save Wi-Fi communication energy. However, in literature we could not find such study which investigates the energy efficiency of the streaming techniques used by the commercial video services. Study on the energy efficiency of TCP-based multimedia traffic shaping is also absent. Although there is traffic prediction based mechanisms, the mechanisms which consider users video viewing abandonment probability and tail energy properties of WNIs do not exist either. There is also lack of studies which consider the impact of energy efficient streaming techniques on the network performance.

3. Towards Energy Efficient Multimedia Streaming to Mobile Devices

In the previous chapter, we outlined the solutions proposed during the last decade for energy-efficient multimedia delivery to mobile devices. They work at different layers of the Internet protocol stack, and at different vantage points between client-server communication path. Most of the solutions are wireless access technology dependent and they are for UDP-based multimedia streaming. On the other hand, TCP is the most prevalent form of streaming nowadays. In this chapter, we highlight our contributions in TCP-based energy efficient multimedia streaming. First, we briefly mention streaming techniques and their energy efficiency that exist in practice with modern multimedia services, which we identified in Publication II. Considering their limitations in providing energy benefits to mobile devices we introduce energy efficient solutions, which we proposed in Publication III and Publication IV for two end points; server and client respectively. Finally, we discuss the impact on radio network signaling (Publication V).

3.1 Mobile Multimedia Services

In Publication II, we identify that mobile video services, such as YouTube, Vimeo and Dailymotion, apply five streaming techniques to the smartphones of five different mobile platforms (see Figure 3.1). There is no systematic way of choosing a technique during a streaming session. In most of the devices, the techniques can vary based on service, quality of the video, the player type (i.e. Flash, HTML5 or the native App). HTTP rate adaptive streaming was observed only in iPhone. However, one concrete observation is that the choice of a wireless interface does not influence the selection of a technique.

There are two techniques applied by the streaming servers; Fast Caching and Throttling. Both of them guarantee smooth playback. The throttle rate can vary based on the service and the player type. For instance, Dailymotion, and Vimeo throttle bit rate 1.25 times the encoding rate to the Flash and native players in Android devices. Whereas YouTube throttles 1.25 times the encoding rate to the Flash based player and twice of the encoding rate to the native applications in Android and iOS devices. Although YouTube takes the throttling rate as a parameter in the URL for Flash player, it does not work with other values than 1.25 as we have tried.

In general throttling takes place over a single TCP connection. Since the player has to maintain a large growing buffer, the YouTube player in the iPhone closes the existing connection whenever the playback buffer is full. After a while some space is freed, the player sends another HTTP request over a new TCP connection. However, there can be significant data waste if the player does not send HTTP request with the byte range which starts exactly from the beginning of a key frame. Such data waste can be mitigated by buffer adaptive streaming. A recent work proposed to reduce the throttling factor so that the playback buffer is never filled completely during a streaming session [115].

The remaining strategies identified in Publication II are exclusively applied by the streaming clients. Figure 3.2 illustrates how a particular strategy is chosen. Bit rate streaming

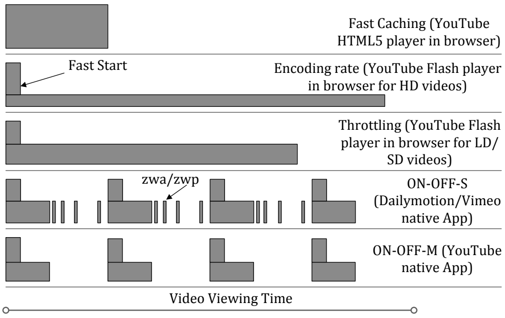


Figure 3.1. Typical mobile video streaming strategies with different mobile video services.

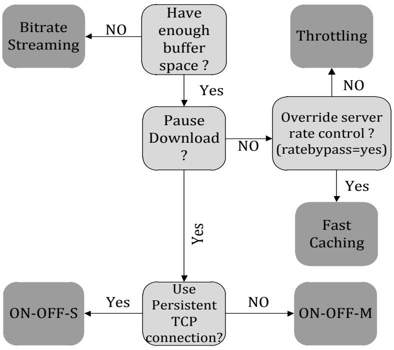


Figure 3.2. Choice of a streaming technique.

takes place when the player has a very small buffer and the consumption rate is very small compared to the sending rate of the server (i.e. Fast Caching or Throttling). Therefore, when the playback buffer becomes full, the remaining content begins to accumulate into the TCP receive buffer. This activates TCP flow control and the transmission from the server is paused. Since the player decodes at the encoding rate, the same amount of buffer space is freed per second and thus from the TCP receive buffer. In this way the interplay between the player behavior and TCP receive buffer together mandates the sending rate of the server.

In contrast, ON-OFF techniques actually are the results of smart implementation of buffer adaptive mechanism by the players. The players maintain a lower and an upper level threshold of the playback buffer. Some players employ ON-OFF patterns either using a persistent TCP connection (ON-OFF-S) or using multiple TCP connections (ON-OFF-M). In the first case, the player does not read from the TCP socket during an OFF period and thus activates TCP flow control like the bit rate streaming discussed above. The only difference is that the socket reading events are scheduled according to the buffer thresholds. In the latter scenario, the player closes a TCP connection when an ON period ends and thus during an OFF period there is no traffic exchange at all. Li et al. [110] proposed GreenTube which also downloads a video content using multiple TCP connections. However, all the players in android devices apply these client-controlled methods on the server sent throttled traffic.

The discussed streaming techniques do not change the quality of the video upon bandwidth fluctuations; rather they rely on large buffer to maintain user experience on playback quality, not the video quality. On the other hand, HTTP rate adaptive streaming emphasizes video quality. Among all the services, only the Vimeo uses rate adaptive mechanism in iPhone. It downloads video chunks of a specific quality after every ten seconds. Meanwhile, the player measures the throughput continuously and requests the chunks of a higher quality if the bandwidth permits. This is similar to the ON-OFF mechanisms as the content is downloaded in periodic chunks.

However, in low bandwidth situation, all the streaming techniques diminish and converge to bit rate streaming. The reason is that a streaming client can receive content at a higher rate than the encoding rate only when there is sufficient bandwidth. Therefore, the players which apply the buffer adaptive mechanisms find that buffer status never touches the upper threshold in a low bandwidth condition. The main observation is that throttling and ON-OFF techniques persist in the traffic pattern as long as the available bandwidth is higher than the encoding rate. The rate adaptive mechanisms work differently as they select the video chunks of lower quality according the bandwidth.

3.2 Streaming Services and Power Consumption

In Publication II, we also emphasize the energy consumption of smartphones while streaming video from the specified video services. We consider the energy consumption aspects of wireless communication, video quality, container and the player type. Since, it is impossible to separate the contribution of individual elements in total energy consumption of a smartphone, as for example any WNI, we first identify playback current consumption which is mainly spent for decoding and presentation. Then we isolate the contribution of wireless interface from the total current consumption trace.

3.2.1 Device Variation

In chapter 2, we discussed how DMS can be utilized to dynamically adapt the modulation with the data rate and thus power consumption. Through measurements with Android and Symbian devices we have found that an Android device consumes lower energy compared to a Symbian phone when receiving the same stream via Wi-Fi. For example, streaming a 128 kbps audio to Nokia E-71 consumes 990 mW, whereas Nexus S consumes 390 mW. The difference is more than 50%. From the Android devices' debug log we have identified that these devices use DVFS mechanism to adapt the voltage and operating frequency of the CPU while receiving content via Wi-Fi at a constant rate. Using DVFS, the length of the inactivity timer is about 2 seconds. In case of PSM-A, all the smartphones use an inactivity timer of 200 ms, except iPhone as mentioned earlier in Chapter 2.

3.2.2 Impact of Video Quality, Player and Container

In general, the playback power consumption of mobile devices increases as the quality or bit rate of the content increases. The increase is not significant when streaming different quality contents of the same container. Among different players, the native video players consume the least energy and the HTML5 player consumes the maximum energy. The reason can be that the native application can use system resources for decoding more efficiently than the web-based players or can apply DVFS-like mechanisms. Most importantly, HTML5 is an emerging technology and still requires going through further optimization to be used in multimedia streaming. Energy consumption may also depend on the video container. This is more likely to be related with the codec. The mp4 container is used with the content encoded with H.264 codec. However, 3gpp provides the better energy efficiency. In this case, the codec is mpeg4. VP-8 and FLV are the codecs for webm and x-flv containers respectively. These two are the most expensive container formats from the energy consumption perspective.

3.2.3 Impact of Streaming Techniques

The discovered streaming techniques also define how the wireless interface at the streaming client would be utilized and thus the energy consumption. Since all the techniques are not available in a single platform, it is difficult to compare the energy efficiency of the techniques we identified. Furthermore, current consumption can be different because the hardware characteristics and firmware implementation of these interfaces can vary among multiple devices. However, Publication II provides an approximate comparison.

When content is downloaded using bit rate streaming, it is expected that wireless interface would be always busy till the end of a streaming session. Therefore, average current consumption is very high. We have found that current consumption varies among the devices when streaming via Wi-Fi. Figure 3.3 shows that Galaxy S3 consumes only 30 mA

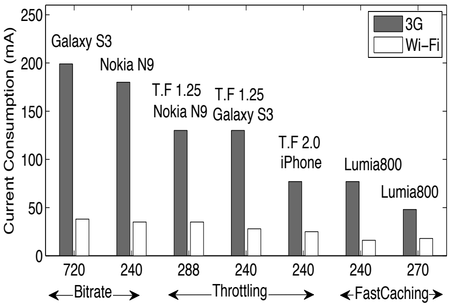


Figure 3.3. Avg. streaming current consumption when bit rate streaming, throttling and fast caching is used.

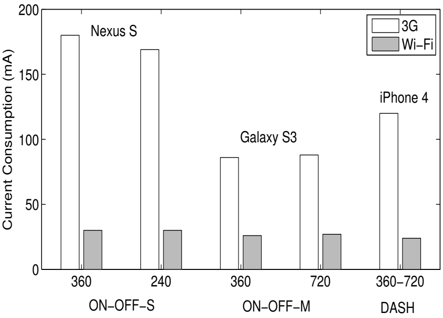


Figure 3.4. Avg. streaming current consumption using ON-OFF-S, ON-OFF-M and DASH.

when streaming a 2 Mbps high definition video via Wi-Fi. This is considerably very small with respect to the usage of the interface, whereas Nokia N9 consumes almost same current for streaming the lowest quality of the same video. The reason is that Galaxy S3 uses DVFS when receiving traffic via W-Fi.

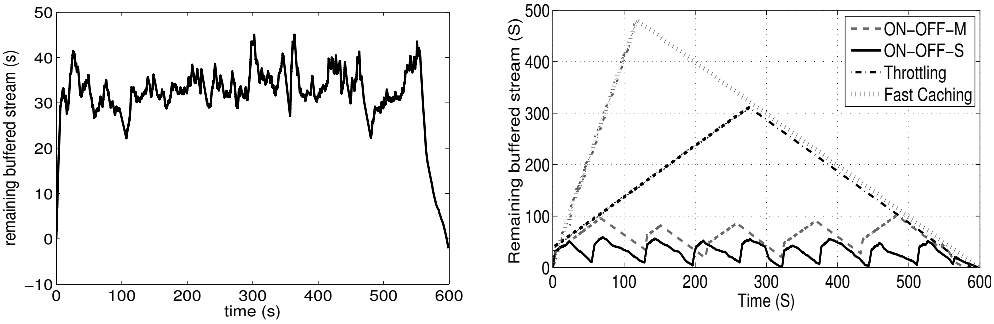
On the contrary, throttling reduces the total downloading time and thus smartphones' energy consumption compared when bit rate streaming is used. The downloading time also depends on the throttling factor. ON-OFF-S mechanism reduces Wi-Fi energy consumption further. However, this technique does not reduce energy consumption when streaming via 3G (see Figure 3.4). This is because of the TCP flow control messages, i.e. ZWA/ZWP. The adaptive mechanism using multiple TCP connections solves this flow control problem and thus provides significant energy savings when streaming via 3G. In this case, energy consumption is similar to the throttling as this technique is actually applied over throttling. Therefore, content is received at the throttled rate. Therefore, actual downloading period or WNI usage time remains same.

HLS is similar to ON-OFF-M and consumes less energy when streaming via Wi-Fi. However, one important difference is that a client requests a chunk after every 10 seconds. This interval is long enough expiring only T1 timer in 3G network. As a result, the total current consumption is higher than ON-OFF-M but less than ON-OFF-S or bit rate streaming. Finally, a streaming client spends very little energy when the content is downloaded using fast caching as the wireless interface remains inactive during the rest of the playback period.

3.2.4 Limitations

Figure 3.5 shows the playback buffer status during the streaming sessions using different streaming techniques. Using bit rate or encoding rate streaming, a player always keeps 30-40 s equivalent content in the playback buffer so that the player can tolerate short term bandwidth fluctuation. Fast Caching and throttling choke down long term fluctuation. Buffer adaptive mechanisms reduce excessive data generated by Fast Caching or throttling. Therefore, these streaming techniques are also effective in wireless multimedia streaming as much as streaming to a host in the fixed network.

From the energy consumption perspective, clearly Fast Caching and Throttling are the most energy efficient techniques when a user watches the complete video. At this point, it is natural to ask, is there any penalty if a user abandons the video before completing the session? At least two issues can be named from a user's perspective; data and energy



(a) Playback buffer (in second) using bit rate streaming (b) Playback buffer (in second) using other streaming techniques

Figure 3.5. Playback buffer status of the streaming clients during multimedia streaming sessions using different techniques.

waste because of unnecessary download. Although, ON-OFF mechanisms provide a good balance between data waste and energy savings, there are few limitations of the identified techniques. First, the ON-OFF technique, which uses the persistent TCP connection, is not aware of the TCP flow control. Second, ON-OFF-M suffers from the low bit rate traffic. Third, DASH-like mechanisms alleviate the problem of low bit rate traffic by downloading a chunk using the maximum bandwidth but the interval between two consecutive downloads are not long enough to save energy when streaming via cellular network. Finally, two common limitations of the discovered techniques are that they do not consider the power consumption characteristics of different WNIs and they are unaware of the users' interruption probability during a streaming session.

3.3 TCP Receive Buffer aware Multimedia Streaming

In Publication II, we showed that the energy consumption of a WNI depends on how the content is received by the streaming clients. If the content is sent at some fixed constant rate then the interface is always active during a streaming session. Therefore, receiving content in periodic bursts has been attractive since last decade as the interface is active only to receive bursts and can be in sleep or low power state during the idle period between two consecutive bursts (see Figure 3.6). However, such burst transmission requires higher bandwidth than the encoding rate. In addition, such burstiness does not always guarantee energy savings. Although high bit rate bursty traffic can reduce energy consumption, TCP flow control shows that even the exchange of few bytes during an OFF period can have severe impact on the energy consumption.

Publication III presents the power consumption models for TCP-based burst shaped multimedia traffic. These models demonstrate the relationship between the available buffer space at the client, burst size and power consumption. The relation is such that power consumption decreases as long as the client buffer can accommodate an entire burst of data. Alternatively, power consumption begins to increase sharply depending on the tail energy characteristic of a wireless interface. This stems from the fact that the client can hold only the sum of available space at the player buffer and TCP receive buffer equivalent content. The remaining content of a burst is received at the encoding rate.

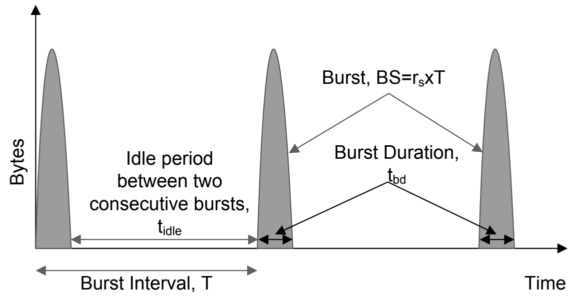
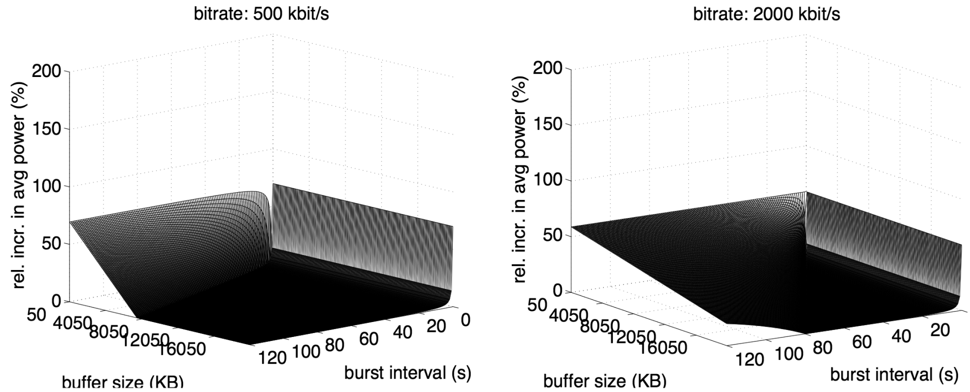
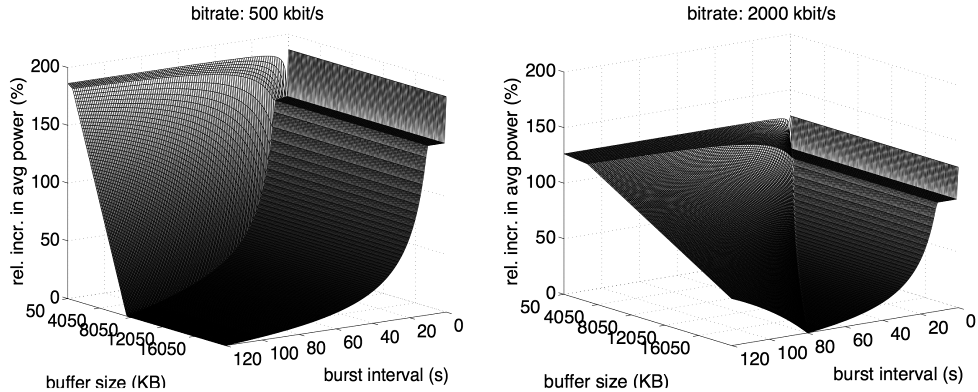


Figure 3.6. Definition of burst, burst duration, burst interval and the idle period.



(a) 500kbps stream over Wi-Fi.

(b) 2Mbps stream over Wi-Fi.



(c) 500kbps stream over LTE.

(d) 2Mbps stream over LTE.

Figure 3.7. Average power consumption with different burst intervals and amount of buffer space.

Figure 3.7 illustrates the relationships when streaming low and high bit rate video via Wi-Fi and LTE. One observation is that power consumption decreases sharply with Wi-Fi than LTE as the burst interval increases. This reflects the ramification of large tail energy of LTE without DRX. The next perception is that energy savings potential is higher for low encoding rate streams than the high bit rate streams. This emerges from the fact that when encoding rate is low there is more bandwidth to exploit. The most important finding

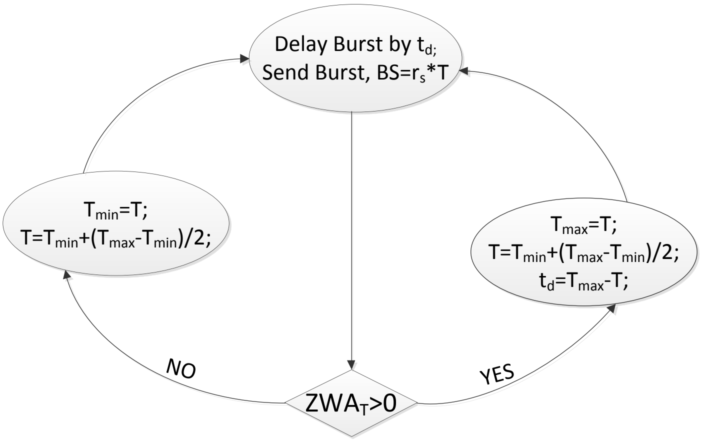


Figure 3.8. EStreamer's traffic shaping mechanism.

is that while the burst interval of few tens of seconds yields significant energy savings, if the corresponding burst size is larger than the available buffer space, power consumption increases. The reason is that the remaining content is received at the encoding rate of the content. This aspect affects significantly when streaming via LTE as the power consumption does not scale with the bit rate and tail energy consumption is also high. This explanation also applies for 3G as the interface also suffers from very long tail energy.

From those models we show that if the burst size exceeds TCP receive buffer size then power consumption increases. Therefore, there is a optimal burst size or burst interval for which the energy consumption would be the minimum. Based on this, we implement an energy efficient multimedia delivery system called EStreamer. It can be integrated with a streaming server or with a proxy server. It is a cross layer mechanism. At the network layer it checks the IP packets for TCP receive window advertisements from the streaming clients. At application layer EStreamer decides the burst interval, T, based on the buffer status of the client.

A simple method to find the optimal burst interval is to begin with a small value of T and then gradually increase the burst interval to find T_{opt}. However, relying on this approach it may take very long time for EStreamer to find T_{opt}. EStreamer applies binary search to speed up the finding of the optimal burst interval. The flow chart in Figure 3.8 demonstrates the detection of T_{opt}. Initially, EStreamer selects $T = T_{max}/2$ seconds. If the player can accommodate the corresponding burst, then EStreamer increases T. Otherwise, client sends zero window advertisements and EStreamer decreases the burst interval. In this way, EStreamer can reduce energy consumption of smartphones by 35-60% depending on the encoding rate of the content and the WNI being used for streaming.

3.4 Tail Energy and Users' Interruption Probability

Among the discussed streaming strategies, only EStreamer is aware of TCP behavior and tail energy consumption of the wireless network interfaces. However, none of the streaming strategies try to optimize energy waste for unnecessary content download. In Publication IV, we show there are two conflicting sources of energy waste. First, aggressive prefetching may result in data and energy waste if the user abandons watching the video. Second, ON-OFF mechanisms reduces the downloading unnecessary content but consequence is energy waste because of the tail energy.

The key question here is that how to predict when a user will abandon watching a video. One way to solve this problem is by maintaining history of users video viewing habit in their smartphones [110] such that a user is less patient and watches only first few seconds of the video or a moderate user watches on an average 50% of the video. However, these are not sufficient to catch the actual behavior of a user. This is because, the actual behavior mostly depends on the content i.e. how interesting the video clip is. For instance, it is likely that a user will watch the complete music video clip of her favorite artist. Besides, users video clip selection also can be motivated by the service providers' recommendation system [116]. The other facts which may influence users' local viewing history are video quality, initial buffering, and the number of buffering events [33]. Hence, a number of facts influence such statistics and therefore it is difficult to model user behavior.

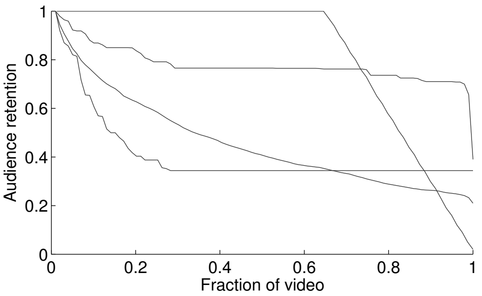


Figure 3.9. Audience retention information of multiple videos from YouTube.

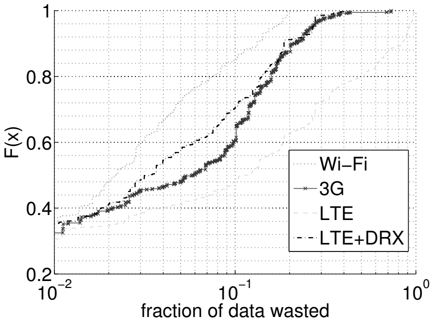


Figure 3.10. The smaller the tail energy, the less unnecessary content is downloaded when using eSchedule.

Publication IV proposes to use crowd-sourced video viewing statistics collected by the streaming services. Instead of using individual users' viewing history, the underlying idea is to use per video specific statistics on how the video has been watched so far by a number of users. Such statistics give useful insights about how a new user will watch the video. An example of such statistics is YouTube's audience retention graph for every video. Figure 3.9 shows some example graphs for four video clips. At present, YouTube collects this information when the user plays video using browser player and the player periodically sends playback information to some Google statistics server (Publication V). Each graph shows the engagement of the audiences from the beginning or any arbitrary point to another point for a specific video. These curves spotlight that some videos have majority of the audiences engaged till the end of the video, some others loose the audiences at the very beginning.

In Publication IV, we use audience retention information to reduce energy consumption of smartphones. To that extent we propose a download scheduler, called eSchedule, which takes this audience retention information as an input parameter. The other important parameters are the TCP throughput, encoding rate of the stream, wireless interface being used for streaming and parameterized power model for that interface. First, it calculates the interruption probability of the user from the audience retention information. Then the scheduler computes energy optimal chunks of variable size in seconds. Along with audience retention, tail energy property of WNI has great influence on chunk size. If the video streaming is carried over 3G and the audience retention suggests that there is a strong probability of viewing the large fraction of the video, then the eSchedule computes a large chunk size. The reason is that 3G suffers from large tail energy because of the long inactivity timers. On the other hand, tail energy for Wi-Fi is negligible. Therefore, when using Wi-Fi and the audience retention suggests poor probability of viewing then the scheduler selects smaller chunk size and thus reduces the probability of both data and energy waste. We evaluate the performance of eSchedule via simulation. Figure 3.10 shows the relation between data waste and tail energy.

We also implemented a prototype of eSchedule and a downloader as an Android application, called StreamThrottler. We evaluated the performance of the application through real traffic and power measurements. The maximum energy saving can be close to 80%. The downloader bypasses the server controlled sending rate by exploiting Fast Start. At this moment, the audience retention information is available to the video owner. Due to privacy concerns we suggest that the video service providers can integrate eSchedule with their players which will receive audience retention information from the servers via some secure API.

3.5 Impact of Traffic Shaping and Cellular Network Configurations on Radio Network Signaling

In Publication V, we study the energy savings at the streaming mobile devices with different cellular network configuration in presence of the EStreamer (Publication III). At the same time, the effect of different parameter settings on the radio network signaling is also emphasized. The necessity of this study arises from the fact that modern mobile devices are equipped with 3G/LTE interfaces and the state transitions of these interfaces require radio network signaling between the smartphone and the network. The amount of signaling message exchange is important for the network as in an extreme case the network can face resource outage because of the signaling load.

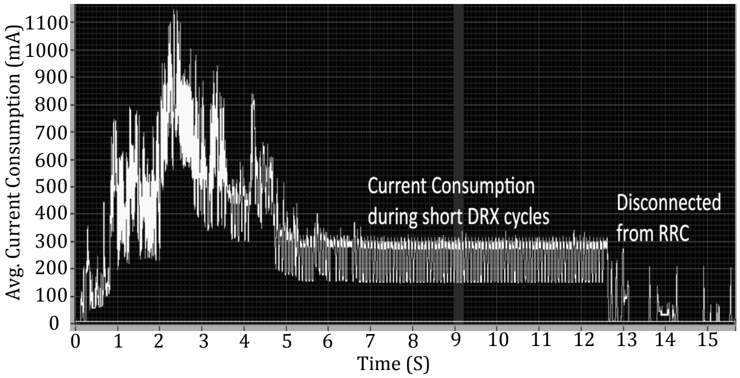


Figure 3.11. Current consumption of Lumia 920 with a DRX cycle of 80 ms.

The energy saving strategies presented so far in this thesis reduce energy consumption by allowing the wireless interfaces to transition to low power consuming states between two consecutive data burst transmission/receptions. The interface can switch to low power states only when the inactivity timers expire. Therefore, the lower the inactivity timer, the faster is the transition and the larger is the energy savings. If a smartphone supports Fast Dormancy, then the device can request the network for transitioning to the CELL_PCH or IDLE state. In case of LTE, power consumption decreases if DRX is enabled. The power consumption decreases further if the RRC inactivity timer is increased. The reason is that transition from RRC_CONNECTED→ RRC_IDLE requires a non-negligible amount of power and when RRC inactivity timer is small the number of such transitions are higher.

The energy savings gained in smartphones comes at a price of signaling messages. In case of RAN signaling, our findings in Publication V can be summarized as follows. The signaling load in the network increases if the network does not support CELL_PCH state. A similar situation can arise if the network supports CELL_PCH state but the mobile device has the legacy Fast Dormancy implemented as explained in 2.2.3. The reason is that in both scenarios the mobile device goes through CELL_DCH→IDLE transition. As result, the device is disconnected from the RRC and requires a lot of signaling again when is reconnected to RRC. Small inactivity timer also can increase signaling but the magnitude is far less than the described two scenarios.

For LTE, the introduction of DRX does not produce additional signaling in the network. In addition, a mobile device can select a suitable DRX profile, such as DRX cycle length [57]. Therefore, DRX parameters can be configured dynamically based on the service requirements. In this case, it is also important that a smartphone or network should select the DRX profile which is actually supported by the mobile device. Otherwise, the battery can be drained very quickly at the smartphone. One such example is presented in Figure 3.11. We can see that even though DRX is enabled power consumption is stable at 200 mA without any data transmission. However, such dynamic profile switching can add additional signaling in the network.

3.6 Future Directions

In this thesis, we propose and apply energy efficient streaming techniques for constant bit rate streaming. In this section, we discuss the potential future work in multimedia delivery or energy efficient multimedia delivery based on the results of this thesis.

We have shown how small playback buffer at the client and TCP flow control together control the delivery of multimedia content at a client. The client receives content at the encoding rate. Although using a DASH-like mechanism a client receives content from the server in fixed size chunks, again TCP flow control can be triggered if the client cannot accommodate a chunk at once. The consequence is low bandwidth estimation by the player and thus frequent quality variation and negative impact on user experience. From the energy consumption perspective, the client will suffer from high energy consumption as the remaining content will be received at the encoding rate after filling the TCP receive buffer. Therefore, there are two research problems; (i) defining an optimal buffer size for the client to avoid TCP flow control and (ii) optimizing energy consumption due to TCP flow control when using DASH-like techniques.

As discussed in section 3.4 that eSchedule accepts throughput and encoding rate of the stream along with other parameters. Therefore, eSchedule also can be integrated with DASH like players for energy efficient HTTP rate adaptive streaming. In addition, some other parameters also can be considered such signal strength to select the appropriate bit rate instead of solely depending on the throughput measurement. In addition, network activity events by other applications also can be leveraged to amortize the tail energy further. However, standalone audience retention only expresses the global viewing statistics of a particular video. It does not expose the viewing characteristics of an individual user. GreenTube uses average viewing history of an individual user to amortize tail energy. Nevertheless, the engagement of an individual watching videos depends on some quality variables, such as initial buffering, number of buffering event, buffering ratio, and average bit rate. The engagement may depend also on the user's preference on the content type. Therefore, a naive mechanism can suffer from false estimation when average viewing is only 20% of the content but the user watches the complete video as for example. Only using global viewing statistics also can provide similar result in a scenario where the audience retention shows strong viewing probability but the user abandons the video as she does not like the content. Therefore, combining these local and global statistics can provide more accuracy in determining an optimal chunk size and subsequently reduce data and energy waste.

Modern mobile devices are equipped with one or two very high resolution cameras. It is getting very common to use these cameras for video conferencing and streaming live events. However, such applications require both encoding of the stream and then transmitting content to other devices, which are very energy consuming tasks. It would be interesting to see what kind of energy-aware mechanisms are supported by these devices.

4. Conclusions

Energy consumption of mobile devices during multimedia streaming is an important issue because of the power consumption nature of wireless network interfaces. Many reseacrh have been considering physical layer, power management at MAC sublayer, traffic shaping and scheduling at upper layers to reduce energy consumption. However, still there are research problems to address as the new challenges are emerging with the rapid development in mobile computing and wireless networking.

In this thesis, we have studied the traffic patterns of modern mobile multimedia services to smartphones, the wireless power management strategies available to date in these mobile devices and the consequence of these on the energy consumption. From the traffic pattern, we have identified the streaming techniques. Our power measurement results have shown that power consumption of wireless interfaces depends on these traffic patterns. Therefore, some of the identified techniques are more energy efficient than the others. However, they are not aware about the power consumption characteristics of wireless network interfaces. They do not consider users abandonment probability during a streaming session either.

Furthermore, traffic shaping also can be effectively used to reduce energy consumption for TCP-based streaming. To that extent, we investigated the effect of TCP's behavior on multimedia delivery and on the energy consumption of the receiving mobile device. We have shown that energy consumption decreases as long as the receiving client can accommodate an entire burst at once into the player buffer and TCP receive buffer together. Alternatively, power consumption increases when the burst exceeds TCP receive buffer at the client. We have introduced a cross layer multimedia delivery system called EStreamer which can be integrated at the streaming server or somewhere in the Internet as a proxy server.

In addition, we have also demonstrated that energy waste can be reduced significantly if it is possible to estimate how much of the content a user might watch. We have proposed one scheduling algorithm that judicially selects the size of a chunk based on the tail energy property and audience retention information. Although our algorithm does not try to reduce data waste, we demonstrate that data waste depends on the tail energy consumption. The lower the tail energy, the smaller is the chunk size and the less is the data waste.

We have demonstrated that both approaches can be applied to achieve significant energy savings without compromising user experience using Wi-Fi, 3G and LTE. Our contribution also lies in studying the impact of different network configurations on the energy consumption of smartphones and radio network signaling. Finally, we have also suggested how our contribution is useful for further research in energy efficient multimedia streaming.

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