Energy Efficient Multimedia Streaming to Mobile Devices – A Survey

Mohammad Ashraful Hoque, Matti Siekkinen, Jukka K. Nurminen

***Abstract*—Energy conservation in battery powered mobile devices that perform wireless multimedia streaming has been a significant research problem since last decade. This is because these mobile devices consume a lot of power while receiving, decoding and ultimately, presenting the multimedia content. What makes things worse is the fact that battery technologies have not evolved enough to keep up with the rapid advancement of mobile devices. This survey examines solutions that have been proposed during the last few years, to improve the energy efficiency of wireless multimedia streaming in mobile hand-held devices. We categorize the research work according to different layers of the Internet protocol stack they utilize. Then, we again regroup these studies based on different traffic scheduling and multimedia content adaptation mechanisms. The traffic scheduling category contains those solutions that optimize the wireless receiving energy without changing the actual multimedia content. The second category on the other hand, specifically modifies the content, in order to reduce the energy consumed by the wireless receiver and to decode and view the content. We compare them and provide evidence of the fact that some of these tactics already exist in modern smaprtphones and provide energy savings with real measurements. In addition, we discuss some relevant literature on the complementary problem of energy-aware *multimedia delivery from* mobile devices and contrast with our target approaches for *multimedia transmission to* mobile devices.**

***Index Terms*—Channel Modulation, Energy Efficiency, Mobile, Multimedia, Power Consumption, Proxy, Source Coding, Streaming, Survey, Wireless.**

I. Introduction

MULTIMEDIA streaming is nowadays a very important application as a result of the immense success of YouTube, ShoutCast and Netflix for instance. In fact, together with Web browsing, these multimedia applications have attracted the greatest amount of research interest in energy optimization. The reason is that in the process of streaming over wireless networks, mobile devices spend potentially a lot of power for decoding multimedia content, wireless communication, and presenting the content via speaker or display.

In modern smartphones, having the display on and decoding the multimedia content can together consume a large part of the energy. The energy required to decode audio or video depends on the computational complexity of the codec and/or compression algorithms used for encoding. Lin *et al*. [68] discovered that H.263+ [40] is the least energy hungry, and MPEG-4 [60] and Windows Media are the most energy hungry codecs or compression techniques. However, many research efforts improve battery life time of mobile devices by introducing different techniques while decoding, such as dynamic voltage scaling [97], CPU register or cache optimization [25], traffic concealing at the network interface [106], OS or application level optimization [78]. Display optimization for multimedia streaming to mobile devices also had been studied in [52].

Although display and decoding are often responsible for a large part of energy consumption, wireless interfaces can equally deplete the same amount of energy while running audio or video streaming applications in mobile devices. This communication energy spent by mobile devices while receiving multimedia content is the main focus of this survey. It has been measured that Wi-Fi interface can use roughly three times of the energy required to decode audio or video content [51], [35], whereas 3G interface requires around five times of the audio decoding energy [51]. The reason for such high energy consumption is the continuous flow of traffic which forces these wireless radios to be powered up most of the time during streaming. Although these wireless radios operate at the physical layer (PL), their power consumption highly depends on the wireless interface usage or management at the upper layers of the Internet protocol stack, such as at link layer (LL), network (NL), transport (TL) and application layer (AL). Therefore, these upper layers should be included in the optimization of energy consumption.

During the last ten years, a wide range of solutions had been proposed in the literatures to optimize energy consumption of the multimedia streaming clients. They suggested operation at different layers of the Internet protocol stack at different end points in client-server communication and in this survey we consider such solutions. We look at solutions that are applicable to commercial consumer mobile devices and, therefore, we limit the networking technologies to Wi-Fi, 3G and LTE. Furthermore, we study solutions only for Internet-based streaming and we exclude wireless personal area networks using short range technologies.

We classify the research according to the Internet protocol layers and present in Table I. Physical layer mechanisms play with different modulation schemes. Link layer solutions manage wireless interface at the mobile devices and apply energy-aware traffic scheduling for multiple wireless clients. We further classify link layer solutions into standard and non-standard techniques. Cross layer solutions propose combined protocols that operate on several layers or at least use information from other layers while optimizing the behavior of a protocol of another layer. We categorize them according

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M. A. Hoque, M. Siekkinen and J. K. Nurminen are with the Data Communication Software Research Group from the Dept. of Computer Science and Engineering, Aalto University School of Science (e-mail: firstname.lastname@aalto.fi).

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TABLE I
CLASSIFICATION OF THE RESEARCH WORK BASED ON THE INTERNET PROTOCOL LAYERS FOR OPTIMIZING WIRELESS RECEPTION ENERGY CONSUMPTION OF MOBILE DEVICES FOR MULTIMEDIA STREAMING.

Internet Protocol Layers	**Research Solutions**
• *Physical Layer* (PL)	[92], [93], [41]
• *Link Layer* (LL)	[10], [109], [9], [11], [80], [63], [79], [23], [85], [69], [117], [98], [50], [112], [90], [73], [27], [84], [83], [12], [110], [32], [61], [57]
• *Cross Layer*	• AL & LL: [51], [14], [20], [28], [13], [39], [96], [77], [34], [35], [84] • AL, NL & LL: [15] • TL & LL: [108], [81], [91], [37], [24], [21], [22] • NL & LL: [114], [100], [81], [45], [115]
• *Application Layer* (AL)	[26], [38], [89], [62], [17], [18], [82], [56], [74]

to the vantage point at which they operate (client, server, or proxy). Application layer techniques use scalable video coding (SVC), transcoding and content selection to reduce energy consumption of the mobile client and we look at work related to these three techniques. These solutions differ from the others in that they modify the actual multimedia content to reduce energy consumption.

We also study a few off-the-shelf smartphones with popular streaming services. We try to find evidence of practical usage of the optimization techniques presented in the literature. From a set of power consumption measurements and traffic traces, we identify some energy-aware streaming techniques and discuss them according to the above classification.

Though our focus is multimedia traffic reception at the mobile client, we also briefly discuss some solutions, such as power-aware source and channel coding. They try to optimize transmission energy consumption while transmitting multimedia from a mobile device. We feel that it is necessary to put both energy-aware multimedia reception and delivery techniques together in order to provide an overview of how the solutions for these two opposite activities differ. However, these research studies are excluded from the above classifications. We discuss them in a separate section.

The structure of this survey is as follows. Section II reviews a number of related surveys and layouts the importance of our survey. Section III discusses the methods we used to compare different approaches throughout the paper and our own measurement setup. After that we discuss physical and link layer solutions in section IV and V respectively. Cross layer solutions are presented in section VI. Then we describe application layer or content adaptation techniques in section VII. In section VIII, we present some energy-aware multimedia delivery techniques from mobile devices. Finally we point out the potential lessons can be learned from this survey and future research directions in section IX.

II. SCOPE AND RELATED SURVEYS

First of all, we focus solely on the energy efficiency of mobile devices and intentionally leave out all work that focuses on the energy efficiency of network infrastructure, such as cellular network base stations, or data centers. We refer the readers to some projects, such as EARTH and Green Touch [31], OPERA-Net [6], Mobile VCE Green Radio [4], and other recent surveys and articles that cover such work [47], [48], [107], [29].

Several other reviews touch on the same topic as our survey. These reviews/surveys fall into two categories. In the first are those that focus on cellular or Wi-Fi communication using hand-held devices, such as, laptops, tablets, smartphones, or PDAs. The other category embraces studies that focus on wireless sensor networks (WSN) and wireless personal area networks (WPAN), such as those presented in [76] and [36]. Our survey solely focuses on the first category and we exclude any work related to WSN and WPAN.

In a very recent article [104], Vallina-Rodriguez and Crowcroft looked at smartphone energy management techniques from the following perspectives: *(1)* energy-aware operating systems, *(2)* efficient resource management, *(3)* the impact of users' interaction patterns with mobile devices and applications, *(4)* wireless interfaces and sensors management, and *(5)* benefits of integrating mobile devices with cloud computing services. While they did touch on the wireless communication aspect, it was not the main focus of the article as opposed to our survey. In addition, while we focus specifically on multimedia streaming, they did not focus on any specific applications.

In a somewhat old but still relevant survey, Jones *et al*. [53] emphasized on the energy conservation of mobile terminals and classified solutions according to different layers of the Internet protocol stack. For instance, they [53] discussed standard 802.11 PSM for MAC sub-layer of the link layer, energy efficient routing protocol at the network layer and energy efficient TCP at the transport layer. Energy-aware video processing mechanisms at the application layer during low battery conditions were also briefly covered. Jones *et al*. presented a few solutions focusing on two kinds of video processing methods: *(1)* reducing video bit rate while encoding and *(2)* discarding specific bits at the wireless network interface. A similar survey, but on a smaller scale, was carried out by Sanctis *et al*. [42]. Miao *et al*. also reviewed these studies for Internet protocol layers [75]. They concentrated on cross layer optimizations using physical and link layers. Along with upper layer mechanisms, we mention some of the advanced physical layer techniques, such as Dynamic Modulation Scaling (DMS) and multi-antenna communication, multiple-in-multiple-out (MIMO), but for a comprehensive coverage of these topics, we refer the reader to the surveys presented in [75] and [43].

Energy efficient MAC protocols of the link layer were surveyed by Ray and Turuk [87]. Other than the standard 802.11 PSM, they also covered protocols such as energy efficient MAC for mobile ad-hoc network, energy conserving MAC, MAC using multiple wireless interface [102].

We found two surveys that are most relevant to mobile multimedia streaming [49], [116]. Of these two,[49] is already ten years old. It emphasized on MAC layer solutions and energy-efficient error control techniques. Extensive power-aware mobile multimedia was surveyed by Zhang *et al*. [116].

The authors specially focused on power adaptive technologies for video coding and transmission. In contrast, we specifically focus on the energy efficient solutions in the wireless communication, for both audio and video multimedia streaming toward mobile devices.

In [33], the authors provided an overview of network-aware applications for mobile multimedia delivery. However, they excluded energy-aware multimedia delivery techniques. Software strategies that are applicable to portable computer energy management were surveyed in [70]. The study covers all components of a portable device including wireless interfaces. Kennedy *et al.* [55] also addressed energy consumption of different components of a mobile device during multimedia streaming. In case of networking interface, the authors mostly focused on link layer solutions. They also considered some cross layer multimedia delivery mechanisms. Therefore, part of their study overlaps with our interest. While most studies analyze multimedia streaming in the regular client-server architecture, a survey on the research on quality of service for peer-to-peer media distribution was presented in [113]. However, that survey does not discuss energy consumption required for multimedia streaming.

The above discussion demonstrates the fact that only a small number of surveys are available on the topic of energy conservation for mobile multimedia streaming with cellular or Wi-Fi connectivity. However, little attention is given so far on the energy consumption of the wireless interfaces. Traffic shaping, scheduling and other power adaptive solutions for wireless multimedia streaming are also omitted from these existing surveys. For this reason, we consider the numerous solutions for energy efficient multimedia traffic reception at mobile devices in our survey.

III. Methodology

In this survey we group energy-aware multimedia transmission mechanisms according to the Internet protocol layers. We mainly analyze their potential to save energy but also study their applicability in terms of, e.g., effectiveness with specific access network type and transport protocol. We also discuss the solutions from the practical deployment point of view.

As we shall discuss energy savings by applying different approaches, total energy usages at different layers is calculated using some models. The model for physical layer is described in section IV. For link and upper layers, the model is defined as total energy consumption (E_t) over a period of time t. During t an wireless interface can be in different power consuming states (P_{si}). In section V, we discuss different states of Wi-Fi and cellular network interfaces and energy consumption at those states. The general model either for Wi-Fi or cellular network interface can be expressed as

$$E_t = P \cdot t = P_{s1} \cdot t_{s1} + P_{s2} \cdot t_{s2} + ... + P_{sn} \cdot t_{sn}.$$

The solutions which work above physical layer follow this model directly or indirectly. A fair number of approaches measure only the power consumption of the wireless interface when it is in different states, then directly fit into the model to estimate the energy consumption. For example, Anastasi *et al.* [24] used such measurement results from [63], then estimated energy consumption using the model. Others measure the total power consumed by a mobile device during a streaming session when the wireless interface is in different states, which includes the power draw caused by the application (e.g. media decoding). Hoque *et al.* [51] followed such approach to quantify the energy consumption of Nokia E-71 while using their traffic shaping proxy. Consequently, comparing the relative energy savings of the mechanisms can be sometimes misleading.

Furthermore, numerous link and cross layer techniques estimate energy savings by comparing their solution with standard energy saving mechanisms. Other techniques estimate energy savings by comparing their optimization outcome with the condition when no optimization at all is present. In order to provide a common ground for comparison, we apply the latter approach. We obtain the power draw for the cases without any kind of optimizations from the literature and from our own measurements where necessary and possible. We then compute the relative energy savings when applying, e.g., standard or nonstandard power saving mechanisms for physical and link layers or traffic and content manipulation techniques at upper layers. We mention other challenges in section IX.

While reviewing academic research we also looked what technologies are currently deployed by the leading video streaming services and mobile platforms and devices. We performed measurement tests for ShoutCast [3], YouTube [8], Dailymotion [1] and Vimeo [7] streaming services to five different smartphones and measured energy consumptions of mobile devices using Monsoon Power Monitor [5] during streaming sessions. We used the following combination of streaming services and mobile phones; *(I)* ShoutCast audio streaming to Nokia E-71, Samsung Nexus S and Galaxy S3. *(II)* YouTube video streaming to iphone 4, Nexus S and Galaxy S3. *(III)* Dailymotion video streaming to Nexus S. *(IV)* Vimeo video streaming to Nexus S and iPhone 4. We also used Lumia 800 to measure energy consumption at different states of the 3G RRC protocol.

In case of Wi-Fi, we used a D-Link DIR-300 and a Netgear N600 APs supporting 802.11 b/g(54 Mbps) and Quadrature Amplitude Modulation (QAM). For 3G access, we used a 6 Mbps subscription. During the playback of audio streaming application, we used the lowest volume level and turned off the display. In case of video streaming applications, volume was also kept in lowest level but the display was on.

IV. Physical Layer Mechanisms

Using a multimedia streaming application, a mobile device can possibly receive content from server at a certain rate. The mobile device spends energy to power up the wireless radio to receive the content. If the stream rate is 1 Mbps and the wireless network is Wi-Fi, then obviously it impractical to spend energy for the maximum 54 Mbps capacity while using a small fraction of it.

In physical layer, energy consumption (E_{bit}) is related with the capacity of the carrier channel and the transmission distance. Using Quadrature Amplitude Modulation (QAM) modulation with level b, the bulk transfer capacity of the

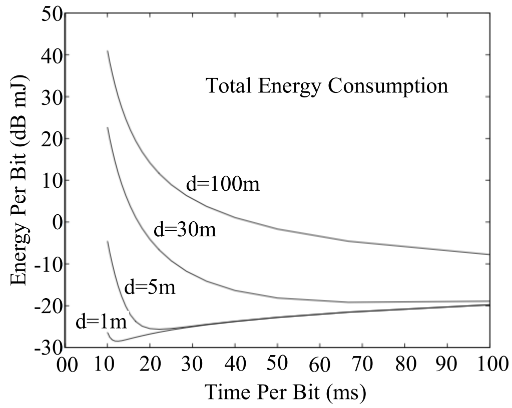

Fig. 1. The energy required in order to transmit a single bit, E_{bit}, decreases as more time is spent to send a single bit, i.e. T_{bit} increases [41].

channel, $R_b = L \cdot b$ bps, where L is the carrier bandwidth. The time required to transmit a bit (T_{bit}) over a radio channel is the inverse of the bulk transfer capacity of the channel (R_b); $T_{bit} = \frac{1}{R_b} = \frac{1}{L \cdot b}$ second.

$$E_{bit} = E_S + E_E = [P_S + P_E] \cdot T_{bit} = [C_S \cdot (2^b - 1) + C_E] \cdot \frac{1}{b}$$

The relation between E_{bit} and b was demonstrated by Schurges *et al.* [92], and can be expressed using the above equation. The energy required for the transmission of a bit is the sum of the energy spent by the power amplifier (E_S) and the electronics circuits (E_E) for that single bit. Here, C_S depends on the channel quality or transmission distance (d). From the model we can find that E_S is an exponential function of b, because of 2^b. It means that even if the modulation level is decreased by one, E_{bit} will be reduced significantly. The more detail about the model can be found in [92] and [41].

Four example plots are illustrated for different d in Fig. 1 using the model described above. In this case, the channel bandwidth is 10 KHz and the maximum data transfer capacity is 200 kbps. Hence, the maximum value of b is 20. The X-axis represents T_{bit} and Y-axis represents E_{bit} in terms of dB relative to millijoule, $\log_{10} \frac{E_{bit}}{0.001}$dB mJ. It is shown that E_{bit} decreases exponentially as time per bit T_{bit} increases (i.e. b decreases). Based on this information, Schurges *et al.* [92] proposed Dynamic Modulation Scaling (DMS) which dynamically adapts b of QAM on-the-fly and thus controls the energy consumption [92]. Later, Schurges *et al.* [93] explored a radio power management system based on DMS and applied for multimedia streaming application.

However, applying DMS based only on the streaming rate may not provide the minimal energy savings. Because, E_{bit} also depends on the transmission distance, d. Cui *et al.* [41] looked for an optimal modulation level at which energy consumption would be minimum for a particular d. We can see in Fig. 1 that energy consumption does not decrease monotonically when capacity of the channel decreases or time per bit (T_{bit}) increases for smaller distances (i.e. d=1, d=5), because E_{bit} is dominated by the electronics circuit energy consumption when d is very small. Hence, there exits an optimal modulation level (b_{opt}) for which E_{bit} is minimum.

TABLE II
POWER CONSUMPTION OF SMARTPHONES FOR DIFFERENT BIT RATE AUDIO STREAMS AND DOWNLOADING A 200 MB FILE VIA WI-FI.

Bit Rate	Nokia E-71	Nexus S	Samsung Galaxy S3
128 kbps	990 mW	350 mW	419 mW
192 kbps	1004 mW	390 mW	440 mW
256 kbps	1007 mW	390 mW	452 mW
File Download	1092 mW	998 mW	1012 mW

From the plot for 5 meters distance presented in Fig. 1, We can find that minimum E_{bit} is achieved when $T_{bit} \approx 20$ms. In this case, b_{opt} ≈9 and results in 75% energy savings as compared with the non-optimal case when b=20 [41]. As a result, the channel capacity is reduced from 200 kbps to 90 kbps. This is sufficient for some low bit rate streaming applications even with 10 kHz channel bandwidth.

Cui *et al.* [41] also demonstrated that if d becomes higher than a threshold value then it is not possible to reduce energy consumption by optimizing the transmission time further. In Fig 1, the threshold distance is 30 m and we can see that E_{bit} remains almost constant even when T_{bit} increases beyond 60 ms. If the transmission distance increases further, the mobile device might be unable to supply the required energy to the wireless radio, even with the lowest modulation level b=2. In such a case, the authors suggested Frequency Shift Keying (FSK) which is less bandwidth-efficient than QAM. However, using FSK b_{opt}=2 and the channel capacity reduces to 20 kbps.

From the above discussion we can say that though FSK consume less energy for longer distances, FSK may not provide sufficient bandwidth required for multimedia streaming. On the contrary, QAM can guarantee energy savings for multimedia streaming applications as it can provide reasonable bandwidth for multimedia applications within reasonable transmission distance with low energy cost. Nevertheless, changing modulation at any instance of discrete time is impractical, the reason being it requires negotiation between both sender and receiver, and creates protocol overhead. Therefore, the implementation requires careful reconfiguration of the receiver in order to operate on the proper modulation level [93].

This kind of optimization at the physical layer might be implemented with modern mobile phones. We investigated the power consumption of three smartphones while streaming different bit rate audio from some ShoutCast Internet Radio servers via Wi-Fi (refer: Table II). The smartphones were about 5 meters apart from the the Wi-Fi access point during measurements, i.e. d=5 m. From Table II, we can find that Nexus S consumes approximately 65% and Galaxy S3 consumes about 50% less power than Nokia E-71. However, all three devices consume almost same amount of power while downloading a file from the Internet. Therefore, we suspect that these devices might apply DMS when server sends traffic at the encoding rate of the multimedia content.

Multi-antenna techniques, such as MIMO, are also emerging in both Wi-Fi (802.11n/ac/ad) and cellular network standards (LTE-Advanced). For example, Halperin *et al.* measured 802.11n power consumption in [46] and showed that MIMO is not always more energy efficient than single-in-single-out (SISO) and, furthermore, characterized some of the situations

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TABLE III
ENERGY SAVINGS WHILE USING STANDARDIZED AND NON-STANDARDIZED LINK LAYER TECHNIQUES FOR WIRELESS MULTIMEDIA STREAMING TO MOBILE DEVICES.

Link Layer Approaches	Wireless Network	Energy Savings
(Tan *et al*. [100]) PSM	Wi-Fi	82%
(Tan *et al*. [100]) PSM-A	Wi-Fi	2%
Bontu *et al*. [32]	LTE	50%
μPM [69]	Wi-Fi	30%

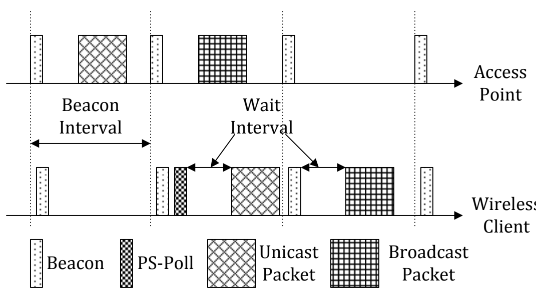

Fig. 2. IEEE 802.11 PSM for multiple clients.

where such a relationship holds and where not. More detailed survey can be found in [43].

V. Link Layer Solutions

There is a large number of solutions proposed to change the link layer protocols in order to improve the energy efficiency. Different solutions for both Wi-Fi and cellular networks can be divided into mechanisms that are and those that are not included in the standards. We go through both classes of solutions separately.

A. Wi-Fi Access (IEEE 802.11 Standards)

The IEEE 802.11 standard includes a Power Saving Mechanism (PSM) [10]. It is a cooperative mechanism between an wireless station (STA) and an access point (AP). STA tells AP its intention to go to sleep, during which the AP buffers any packets destined for the sleeping STA. Fig. 2 shows that AP periodically (usually after every 100 ms) broadcasts a traffic indication map message (TIM), also known as beacon. STA also wakes up periodically to receive a TIM. TIM informs STA if the AP has frames buffered for it; after which STA can request the buffered data by sending a PS-Poll frame. Otherwise, STA will go back to sleep until the next TIM. An Wi-Fi interface can be in four different states and the order of energy consumption is transmit>receive>idle>sleep.

Standard PSM saves energy only when the distribution of traffic is regular [35], whereas the distribution of multimedia traffic can be both regular and irregular depending on the streaming services. Besides that buffering at the access point may lead the TCP sender to estimate higher RTT and therefore may hinder the throughput of TCP based streaming applications. Subsequently, commercial Wi-Fi enabled mobile devices usually implement adaptive PSM (PSM-A), which keeps the wireless interface to be active for an extra period of time immediately after the transmission or reception of traffic [100]. We estimated that modern smartphones, such as Nokia E-71, Nexus S, Galaxy S3, Lumia 800 use an extra period that is approximately 200 ms long. Only iPhone 4 uses an aggressive value of around 30 ms. Tan *et. al* [100] showed that PSM is more energy efficient than PSM-A for multimedia streaming by using both PSM and PSM-A for the same video (refer: Table III). The obvious reason being, the STA rarely manages to sleep using PSM-A while receiving multimedia traffic. The measurement results presented in Table IV also illustrates the same fact that power consumption with PSM-A approaches to CAM as data rate of the stream increases.

TABLE IV
POWER CONSUMPTION OF NOKIA E-71 FOR STREAMING DIFFERENT BIT RATE AUDIO VIA WI-FI.

Bit Rate	PSM-A	CAM
64 kbps	530 mW	1006 mW
128 kbps	990 mW	1007 mW
192 kbps	1004 mW	1007 mW
256 kbps	1007 mW	1008 mW

Another limitation of legacy PSM is that when several multimedia streaming clients share the same access point, a client might have to wait longer period of time for data, while consuming unnecessary energy. The reason is that the AP might be serving a client for a long time, while keeping others waiting. This phenomenon is known as channel contention. Fig. 2 shows that the wireless client sends PS-Poll frame to the AP after receiving the beacon. But the wireless client spends some time in waiting to receive the actual data frames, as the AP might be serving some other clients during this waiting interval.

In order to reduce channel contention, the 802.11e amendment, now part of the IEEE 802.11-2007 standard, adds a new scheduling mechanism called Enhanced Distributed Channel Access (EDCA) [109]. EDCA gives channel access priority to multimedia traffic over bulk transfers, which will improve the energy efficiency, while receiving streaming traffic. Because, any possible waiting time due to channel contention is reduced. The 802.11e amendment also includes a modified power saving mechanism called Unscheduled Automatic Power Save Delivery (UAPSD). Using UAPSD, an AP delivers the buffered data to an STA upon receiving an upstream packet from the STA. Therefore, UAPSD is most useful with synchronous duplex traffic such as VoIP. Nevertheless, these mechanisms have the potential to offer significant power savings to the clients. However, the benefits depend on the exact usage scenario, such as the number and type of concurrent clients as shown in [80].

B. Beyond IEEE 802.11 standards

1) Modified PSM: Many research papers have been published on Wi-Fi access, modifying the standard PSM behavior in some way. Many of them leveraged the idle time more efficiently for sleeping than PSM does, while at the same time avoided the introduction of excessive delay. Some examples that utilized non-static beacons and prediction of idle times are presented in [23], [79], [63], [85]. These solutions focused on Web access scenarios, where such long and non-periodic idle intervals occur and are not as such suitable for using with streaming applications.

In a recent work, Song *et al*. [98] proposed an algorithm to avoid energy consumption to receive periodic beacons and thus increases the sleeping period of the Wi-Fi interface. Their mechanism works in three phases. *(1)* In presence of traffic, sleeping period is equivalent to one beacon interval. *(2)* After one beacon interval if there is no traffic to send or receive the beacon interval is doubled. *(3)* When the sleeping period reaches to a threshold value, it is increased linearly by one. Again when there is traffic, the algorithm reverts back to the first phase. Through simulation the authors estimated about 42% energy savings for constant bit rate traffic as compared with the standard PSM.

As opposed to the above mentioned proposals, Liu and Zhong [69] observed that the small overhead of modern hardware has made it feasible to execute very short time scale management of the Wi-Fi interface. As a result, the authors presented micro power management (μPM) to help the network interface to sleep, even when only short (<200ms) idle intervals are present. μPM does this by relying on Wi-Fi's link layer retransmission mechanism for frames missed during a short nap and by predicting frame intervals in order to bound the frame delay. Experimental results with their prototype implementation demonstrate roughly 30% power savings for video and audio streaming with a very low frame loss rate.

The referred solutions require only to change an wireless station. In combination with traffic shaping and scheduling mechanisms they can help to save energy while streaming. However, the common limitation is that they consider single wireless station. Therefore, they are prone to consume energy for channel contention. Besides, it is nontrivial to apply dynamic beacon interval or sleeping period for multiple STAs without proper coordination with the AP. We shall see in the next section how different approaches, such as NAPman [90], attack this problem. Moreover, as these solutions modify the link layer protocols, they can be used for local deployments, but may not be usable with all commercial devices.

2) Toward contention-free Wi-Fi scheduling: Wi-Fi is becoming more and more commonly and densely deployed in office and home environments. As a result, interference and channel access contention are becoming potential causes of extra energy consumption in those Wi-Fi networks. Clients need to spend more time awake, while waiting for their packets queued behind packets destined to other clients. Novel solutions, such as [117], [50], [112], slice the beacon interval into a number of time slots and assign a PSM client one such time slice. The client wakes up on it's scheduled time. They are designed to avoid energy waste due to contention and as such, are complementary to the other link layer optimization mechanisms for Wi-Fi. These mechanisms are also suitable for any kind of traffic, including multimedia streaming.

Among these, a rate-based scheduling (RBS) mechanism took specifically multimedia traffic into account [117]. The idea is that a mobile client should buffer data as much as possible, without affecting the QoS of other flows. In this case, QoS is the fair share of the link, which is provided by applying *start-time first fair queuing* (SFQ) [44] to each flow. RBS has two components: a scheduler and a client-side proxy. The scheduler is employed at the AP to schedule channel access among multiple flows. It suspends serving a flow when the client has enough data buffered to fulfill its QoS requirement. As a result, the client's Wi-Fi interface wakes up only when the buffered data runs out. The proxy at the client coordinates with the scheduler and manages the operating states of Wi-Fi based on the buffered data. For multiple H.263 streaming clients, Kholaif *et al*. [57] proposed an extension to the 802.11e MAC protocol.

NAPman [90] introduced a slightly modified scheduling mechanism at the AP, for fair but more energy efficient operation when multiple clients simultaneously use the AP. In addition, NAPman used virtual APs, each one having its own beacon. The beacons are then staggered in time so that all clients with buffered packets at the AP do not request them simultaneously. SleepWell[73], on the other hand, considered the scenario where multiple APs are within each others vicinity, operating on the same channel and interfering with each others transmissions. SleepWell-enabled APs modify their timestamps in order to control clients' sleep and wake-up schedules, by monitoring the activity patterns of nearby APs.

Though TDMA-like mechanisms, [117], [50], [112], guarantee contention free scheduling, they require to change 802.11 PSM. Consequently, it necessary to modify both STAs and APs. Besides, they do not consider CAM and PSM-A clients, which makes them further impractical to deploy. On other hand, NAPman supports PSM, PSM-A and CAM clients. But what makes it inefficient is that every client must associate with the AP twice. Association with the AP is a both time and energy consuming task. Besides, the number of PSM or PSM-A STAs can be supported by an AP is limited by the number of virtual APs. We have checked that a Netgear N600 AP can support maximum six virtual APs running OpenWrt [2]. Compared with NAPman, SleepWell schedules data transfer when no transmissions from other APs is expected. However, this solution does not help, when other APs are operating on different but overlapping channels.

C. Cellular Network Access (3GPP Standards)

In this section, we discuss the power saving mechanisms for different cellular network standards, such as 3G and LTE.

In case of WCDMA cellular network, the usage of radio resources and power consumption is controlled by the Radio Resource Control (RRC) protocol [9]. This protocol has three different states and these states correspond to three different logical transport channels. Fig. 3 illustrates the RRC state machine and the inactivity timers which control the usage of the logical channels. If the occupied channel is idle in CELL_DCH state for $T1$s, then the channel is released and the state is changed to CELL_FACH. Again, the state would be switched from CELL_FACH to the CELL_PCH and CELL_PCH to IDLE, if the corresponding timers expire due the channel inactivity. However, some operators may not enable CELL_PCH in their network and in that case, the state would be switched from CELL_FACH to IDLE.

Operating in different states draws different amount of power. A measured power consumption trace of Lumia 800 is presented in Fig. 4. The figure shows that the most energy consuming state is the dedicated channel (CELL_DCH) (200 mA) and the corresponding timer value is 8 seconds. Operating

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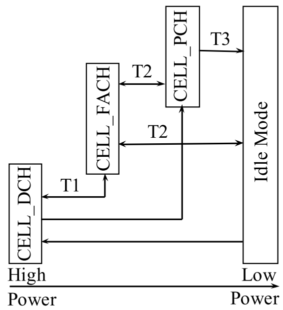

Fig. 3. 3G RRC state machine with CELL_DCH, CELL_FACH, CELL_PCH states and the corresponding inactivity timers.

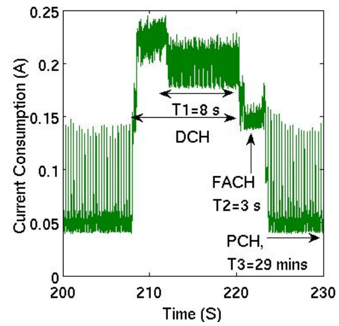

Fig. 4. Current consumption at different states and state transitions with the inactivity timer values in Lumia 800.

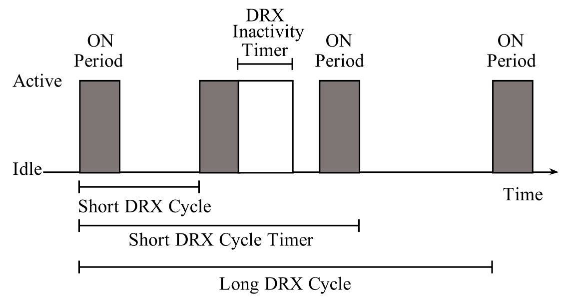

Fig. 5. LTE DRX Cycles and timers.

in CELL_FACH state consumes about 150 mA and the value of T2 is 3 seconds. However, these timer values are operator controlled and they usually have long values, in the order of at least several seconds. This means that while streaming over the 3G access, the network interface is constantly in CELL_DCH state and energy consumption is high. The extra energy consumption due to long inactivity timer values is sometimes referred to as tail energy [27], [84].

Fast Dormancy [12] was developed to reduce the unwanted effect of the inactivity timers. The basic idea is that a client is able to signal to the network when transmissions are completed. The network could then immediately set the client RRC state to CELL_PCH (see Fig. 3), for instance and thus avoid the tail energy. However, in order to reduce the energy consumption of streaming traffic, in between receiving packets, the interface should alternate between CELL_DCH and lower power states. Fast Dormancy may not be a sufficiently fine grained enough mechanism to achieve this.

The upcoming next generation cellular network standard LTE utilizes discontinuous reception/transmission (DRX/DTX) mechanisms to exhibit finer grained control over the interface. The LTE RRC [11] defines two states that a mobile device (UE in this context) can be in: RRC_IDLE and RRC_CONNECTED. DRX/DTX can be enabled in both states. DRX/DTX operate in a cyclical manner and use short and long cycles. Operating modes corresponding to these two cycles are also called light and deep sleep respectively.

The block diagram in Fig. 5 shows the operation of the DRX cycles over time. At the beginning of each DRX cycle, an ON-period follows, in which the UE turns its receiver on, to receive packets from the eNB (i.e., base station) and to monitor whether there are any pending downlink transmissions. If there are or if the UE wants to transmit upstream, the UE starts the DRX inactivity timer to keep it in an active state until the timer expires. Otherwise, the UE enters the idle state after ON-period and starts a counter that counts the number of consecutive short DRX cycles. When this counter reaches a threshold value, UE starts to use long cycles. The behavior of a long cycle is similar to that of a short one, except that the idle time after the ON-period is many times longer. When data transmission occurs during a long cycle, UE reverts back to short cycles. If there is nothing to be transmitted or received for a longer period of time, the network transitions from UE to RRC_IDLE state.

This kind of cyclical mechanism could be very suitable for streaming traffic, which is regularly periodic in nature. However, the parameters should be configured to match the application behavior, such as, using a very short value of the inactivity timer for streaming traffic. Otherwise, the timer risks of keeping the UE constantly awake in between receiving packets. To date, few papers have been published on the topic, as the very first commercial LTE networks have only recently been deployed. Nevertheless, a few papers describing analytical or simulation studies of the energy consumption of DRX/DTX do exist [110], [32], [61]. Of these studies, the one presented in [32] analyzes video streaming as one of the applications. Their results suggest that power saving of up to 50% is possible, when compared with other possible configurations, such as DRX inactivity timer with higher value.

A mechanism similar to the above described connected mode DRX in LTE is Continuous Packet Connectivity (CPC) for 3G (HSPA) which is specified in 3GPP TR 25.903. CPC has potential to greatly improve the energy efficiency of 3G devices for any type of traffic as soon as it gets widespread adopted.

D. Beyond 3GPP standards

Usable non-standardized optimization mechanisms for cellular networks do not exist; as they cannot be deployed in practice. For this reason, fairly little research has focused on application-level energy issues for 3G access.

There had been some research works that have measured the effect of different inactivity timers on energy consumption and proposed dynamic settings of the timeout values for these timers [27], [84]. For instance, Qian *et al.* explored RRC

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TABLE V
CLASSIFICATION OF THE TRAFFIC SCHEDULING AND SHAPING RESEARCH WORK BASED ON THE OPTIMIZATION END POINTS.

Traffic Scheduling	Research Solutions
• *Pure client-centric*	[20], [28], [26], [34], [?], [114], [100], [81], [95], [91], [37]
• *Proxy-assisted*	[96], [35], [62], [51], [45], [115], [23], [22], [24]
• *Server-client centric*	[13], [39], [14], [15], [84]

state machine settings in terms of inactivity timers using real network traces from different operators [84], [83]. They found that current RRC state machine uses static inactivity timers for all kinds of traffic. This is a limitation of the state machine and therefore, exist imbalances in radio resource allocation and usage, power consumption and performance. In order to deal with these, they proposed RRC state machine aware traffic shaping for multimedia streaming (see Section VI-C). Their study also suggests dynamic settings of the inactivity timers based on observed traffic pattern. However, such mechanisms would require substantial changes to the network equipment.

VI. CROSS LAYER APPROACHES

Optimizing energy consumption for multimedia streaming is not only limited to physical and link layer techniques. Researchers have found numerous ways to save energy consumed by receiving network traffic. These techniques work on the application, transport and network layer. They do not reduce the amount of traffic, but instead, focus on shaping, i.e. forming bursts out of constant or variable bit rate traffic, and scheduling it in such a way that the existing link layer power saving mechanisms can be used most beneficially. At the same time, QoS or other user imposed constraints may need to be considered. The reason for such dependency on lower layer protocols is that standalone traffic manipulation techniques at upper layers might not be adequate to provide significant energy savings. We shall see in section VI-A5 that an application layer technique does not deliver significant result for cellular network as the application is not aware about the effect of the mechanism on transport protocol TCP and further consequence on the energy consumption of the cellular network interface.

The solutions are going to be presented here do not operate strictly above link-layer. Indeed, quite a few combine shaping and scheduling with link layer techniques. Therefore, we term these works as cross layer techniques. We classify them according to the vantage point(s) (i.e. client, proxy, or server) at which the solutions can be deployed (refer: Table V).

A. Pure Client-Centric Solutions

Client-centric solutions have the advantage to be able to know and even control how the power hungry components use different resources at the mobile devices. However, as we will see, pure client-based solutions need to use clever tricks in order to influence the shape or schedule of incoming traffic from the multimedia servers.

1) Multimedia Player's Buffer Management: In multimedia streaming, it is crucial to provide uninterrupted playback to the user. To do this in presence of jitter, playback buffer is used in client players. Usually, servers send content to the client at a high rate initially (first few seconds) in order to fill the client's buffer.

Self Tuning Power Management (STPM) [20] exploits the buffer information to alternate the Wi-Fi interface between continuous active (CAM) and the power saving mode (PSM) as follows. When the interface is in PSM, AP buffers data destined for the client. The authors showed that STPM uses less energy than CAM but consumes more energy than standard PSM.

Bertozzi *et al.* [28] also introduced a playback buffer aware mechanism, which switches off the Wi-Fi interface until the playback buffer is reduced to a threshold level and then turns it on again. During the disconnection period, AP buffers the incoming stream for the mobile device and thus creates bursty traffic. The authors identified that energy consumption can be minimized if the playback buffer size is 120kB and the Wi-Fi interface is switched on only when the buffer reaches 48kB. However, turning on the Wi-Fi interface is a high energy consuming process, because it requires powering up the chip and in turn reassociating with the AP. Another adaptive multimedia streaming technique was implemented by Bagchi [26], in which a client player would pull streaming traffic from the streaming server via the Wi-Fi interface according to the client player buffer status.

2) Traffic Prediction: In [34], Chandra explored the network traffic pattern of different multimedia streaming formats, such as, Windows, Real and QuickTime Media, at the mobile devices. They showed that Window Media traffic tends to be regular and predictable. Real and QuickTime Media traffic, on the other hand, is irregular and thus impossible to predict. Based on these findings, they developed a history-based prediction policy to operate on the Wi-Fi interface. The next sleep interval is predicted by using the average of n earlier idle times ($idle_i$).

$$sleep_{n+1} = \frac{\sum_{i=0}^{n} idle_i}{n} - bias$$

A constant negative *bias* is added to the equation to avoid an excessively aggressive prediction, which would result in packet loss. Chandra applied this policy to all these media formats and observed that Window Media stream immensely benefited, as the power consumption fell from 160 to 40 Jules, with only 2% packet loss. Contrastingly, energy consumption for the other two formats were reduced, but at an expense of 30% packet loss. This led the authors to develop a linear prediction-based time series technique [108]. They demonstrated that linear prediction-based approach estimated sleep interval more precisely at the client than the history-based technique and offered more energy savings.

3) Tricks with TCP: Yan *et al.* [114] introduced a client-side approach to generate bursty traffic for TCP based applications and thus to save energy. The basic idea is to modify the mobile client's TCP receive window size to zero periodically at the network layer. Once the window size is set to zero, the server-side TCP cannot send packets to the client.

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TABLE VI
SOME CLIENT-BASED POWER SAVING TECHNIQUES FOR MULTIMEDIA STREAMING AND THEIR ENERGY SAVINGS.

Client-centric Approaches	Wireless Networks	Transport Protocol	Energy Savings
STPM [20]	Wi-Fi	UDP	25%
PSM-Throttling [100]	Wi-Fi	TCP	70%
Bertozzi *et al*. [28]	Wi-Fi	UDP	70%
Bagchi [26]	Wi-Fi	UDP	31-97%
Chandra [34]	Wi-Fi	UDP	70%
CoolSpots [81]	Wi-Fi& Bluetooth	TCP	40%
Chen *et al*. [37]	3G,Wi-Fi& Bluetooth	TCP	27%

Nevertheless, the TCP at the streaming server still receives data from the application until the congestion window is full. Therefore, when the client's receive window size is restored; the TCP at the server sends all the data in the congestion window, that results in a traffic burst.

In [100], the authors applied this connection choking and unchoking mechanism to TCP-based streaming services, such as, Real Media, Windows Media and YouTube. They choke and unchoke a TCP stream connection from the client after each at 200 ms intervals. As a result, a burst of packets is sent from the server. As soon as the client receives the first packet of the burst, it chokes the connection again. The Wi-Fi interface is driven down to the sleep state in between a choking and an unchoking period.

4) Exploiting Multiple Wireless Interfaces: Modern smartphones are equipped with multiple wireless networking interfaces, such as Bluetooth, Wi-Fi, and 3G. A consequence of this is a new trend towards effectively utilizing these interfaces jointly with the aim to reduce energy consumption. *CoolSpots* [81] is one of the pioneers of this new trend. If the available bandwidth in the Bluetooth network is greater than the stream encoding rate, then the stream will be served via Bluetooth, otherwise the Wi-Fi interface is used. However, when one interface is in use, the other interface is switched off.

Cool-Tether provides energy-efficient communication by harnessing Internet connectivity of multiple mobile devices [95]. It creates an Wi-Fi hotspot on-the-fly and uses 3G interface in order to provide Internet connectivity [27], [84]. It saves 38-71% energy by collecting web traffic. However, this architecture is not suitable for multimedia streaming, as collecting traffic incurs delay.

Saha *et al*. implemented a prototype of similar cooperative communication system and analyzed total energy consumption of mobile devices [91]. In this prototype, a group of users downloaded different chunks of a *mp3* file via a 3G interface. Later, all these users in the group they shared their chunks via Wi-Fi or Bluetooth network. Interestingly, total power consumption decreased, because the 3G interface is used for a shorter time compared to the complete download of that file over 3G. Chen *et al*. [37] used a similar technique to reduce energy consumption for multimedia streaming in mobile hotspots.

5) Comparison and Practical Measurement: The solutions discussed earlier shape traffic into periodic bursts and use low power consuming interfaces to save energy. We compare their energy savings of using them in Table VI. STPM consumes more energy compared to other mechanisms because the Wi-Fi interface alternates between CAM and PSM and also receives beacons from the AP. Therefore, this method is very similar to PSM-A. PSM-Throttling offers more energy savings as the method applies its own Wi-Fi interface management and it does not wake up to receive periodic beacons. Two other buffer adaptive approaches [28], [26] and the history based prediction mechanism [34], can also provide significant energy savings as the Wi-Fi interface wakes up only to receive data from the AP. According to Table VI, energy consumption can be reduced 27-40%, by intelligent traffic scheduling among multiple wireless interfaces of a mobile client.

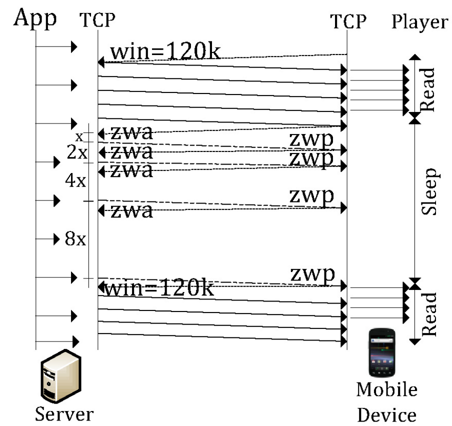


Fig. 6. Traffic shaping in Android phones by the video players and interaction with TCP.

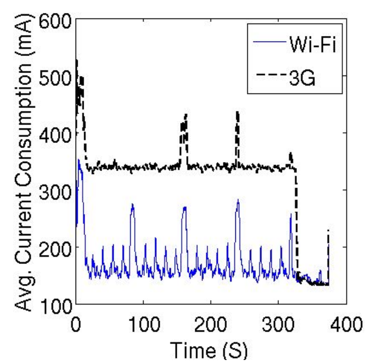


Fig. 7. Nexus S current consumption while streaming via Wi-Fi and 3G.

Generally speaking, most of the client-based traffic shaping mechanisms are not supported by modern smartphones or mobile devices because they require changes to the transport and link layer protocols. Besides, UDP-based methods may not be suitable for TCP based streaming applications. For example, switching off the Wi-Fi interface in between a YouTube streaming session would interrupt the playback as the corresponding TCP connection would be closed immediately. Besides, TCP has a strict requirement on packet delay. Therefore, burst generation at the network layer may delay packets too much which triggers TCP timeouts that make TCP sender to falsely conclude the presence of congestion and react accordingly.

TABLE VII
ENERGY SAVINGS IN NEXUS S FOR STREAMING VIA WI-FI AND 3G.

Video Players	Bit Rate(kbps)	Energy Savings(Wi-Fi)	Energy Savings(3G)
YouTube	583	43%	5%
Dailymoiton	452	45%	5%
Vimeo	400	48%	4%

We found YouTube, Dailymotion and Vimeo players in Nexus S manage their playback buffer so that the media traffic is shaped into periodic bursts. From the captured traffic pattern, we derive the underlying burst generation mechanism as shown in Fig. 6. The application stops reading data from TCP buffer when the playback buffer has enough data to play. The player reads again when the playback buffer is almost drained out. In between, the application continues only playback and we refer this as sleeping period (see Fig. 6).

Even though player stops reading at the application layer, from the traffic traces we found lower layer protocol message exchange never stops during the sleeping periods. When the player stops reading, the TCP buffer at the mobile client gets full and the client sends zero window advertisements (zwa) to the server. In response, server TCP pauses the transmission of data packets, starts the an exponential back-off persist timer (x) and sends zero window probe (zwp) to the client TCP according to the timer. Nevertheless, the server-side application keeps sending data to the server-side TCP. Again when the player reads TCP buffer, client TCP updates window size to a higher value and the server also begins sending data packets again. The current consumption for such bursty traffic via Wi-Fi interface is visible as spikes in Fig. 7. Nexus S uses PSM-A and we estimated 43-48% energy savings (refer: Table VII). On the contrary, current consumption for streaming 3G remains almost constant. We looked into traffic traces and found that the maximum time interval between packets is five seconds which is less than the inactivity timer $T1$'s value. Therefore, the mobile device does not get any chance to switch to lower power consuming CELL_FACH state. These Android video players optimize only the energy consumption of Wi-Fi interface. They are not aware about the effect of such application layer traffic shaping on TCP and in turn the consequence of TCP behavior on cellular network interface energy consumption. Nevertheless, LTE-based mobile phones would gain significant energy savings from this kind of traffic shaping with short DRX inactivity timer.

Though Wi-Fi-based tethering is already available with modern smartphones, such as Nexus S, Galaxy S3, iPhone 4, we could not find such solutions yet which could take advantage of the differing power characteristics of different link and physical layer technologies for multimedia streaming applications. Nevertheless, including some traffic shaping mechanism with these mechanism could improve energy savings further.

B. Proxy-Assisted Solutions

In proxy-based solutions, a proxy server estimates the playback buffer status or receives buffer information from the player, applies traffic shaping and scheduling mechanism accordingly. The client devices manipulate their wireless interface based on the feedback provided by the proxy. The

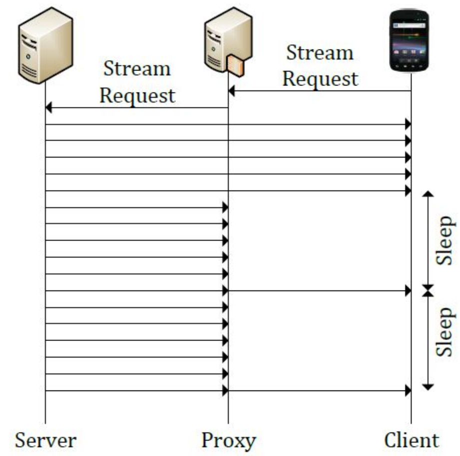


Fig. 8. Proxy-based traffic shaping of multimedia content.

proxy can be placed somewhere in the Internet, in the cellular operator's network or integrated with the Wi-Fi AP.

1) Traffic Shaping: Fig. 8 shows an example of proxy-based traffic shaping mechanism. A mobile device sends stream request to a proxy. The proxy forwards multimedia content to the client as bursts so that the mobile device can switch it's wireless interface into low power consuming states in between two consecutive bursts.

According to [62], it is possible to save power by sending packets in bursts from a proxy. Shenoy and Radkov [96] introduced two proxy-based traffic shaping techniques for the transcoded media. *(1)* Proxy converts a variable bit rate MPEG stream to a constant bit rate stream and sends it at a periodic interval to a client and the client uses history-based traffic prediction mechanism to power on and off its Wi-Fi interface. *(2)* Proxy forwards variable bit rate stream at a periodic interval and sends one control packet to indicate the next arrival time of the future packets. A mobile device uses this information to switch on the interface on time. We discuss the transcoding mechanism, in detail, in section VII-B.

An Energy-aware audio streaming protocol, called Real Time Power Saving protocol (RT_PS), was proposed by Anastasi *et al*. [24]. It is an extension of their previous research [21], [22]. It works on Real Time Streaming Protocol(RTSP)/ Real Time Protocol(RTP) stream on the top of UDP. This protocol is implemented as two separate modules: a proxy and a client. The proxy module is placed at an AP and the client module resides at a mobile host. Both of them work together based on an ON/OFF scheme. In an ON period, the proxy streams an audio stream at the peak rate to the mobile client and it ceases when bandwidth falls below a certain threshold. During an OFF period, a mobile device switches the Wi-Fi interface to sleep state. If the playback buffer falls below a dynamic level, the client warns the proxy about the possible playback starvation and the OFF period ends.

Hoque *et al*. [51] studied the energy consumption of a TCP-based audio streaming application in Nokia E-71 using a traffic shaping proxy. Their approach relied on the default power saving mechanisms available in the mobile phone. However, the authors identified two interesting behaviors of TCP-based streaming applications, both of which contribute to energy

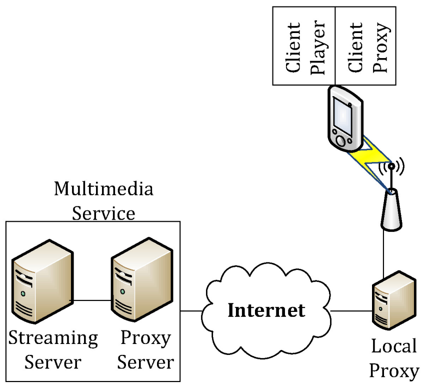


Fig. 9. Application specific streaming system architecture.

consumption. First, if the burst size is larger than the client TCP receive buffer size, the original burst is split into multiple bursts and energy consumption increases. Second, if the proxy moves further away (i.e. if RTT increases), the mobile device consumes more energy. The reason being, the actual burst splits into multiple bursts which are separated by RTT.

2) Scheduling Bursty Traffic: Although, it is possible to save power by applying a traffic shaping mechanism along with PSM (802.11 standard), serving multiple streaming clients at the Wi-Fi AP is a great challenge when using a single channel. The mobile client can starve while waiting and paying high energy cost at the idle state to receive data from the access point. We already reviewed a number of link layer solutions in section IV which reduce energy consumption due to channel contention. In this regard, we review some upper layer approaches which apply traffic shaping to generate bursty traffic and schedule such bursts together at some proxy server among multiple clients.

Chandra and Vahdat identified these limiting factors of the standard PSM and proposed an application specific system architecture for energy efficient scheduling and shaping of UDP-based streaming traffic [35]. The system architecture for scheduling multiple streaming clients is presented in Fig. 9, which consists of three separate proxy modules. The server-side and the local proxy shape traffic into bursts without any modification to the actual stream and transmit them at client-specific intervals. This allows multiple clients to access the same access point AP for streaming without waiting for each other. These two proxy modules send information about the next burst to the client-side proxy in order to control the Wi-Fi interface.

The system architecture provided by Chandra and Vahdat deal with multiple streaming clients. Whereas, Gundlach *et al*. [45] considered a real Internet access scenario and developed a transparent proxy to schedule both TCP web traffic and UDP-based bursty streaming traffic to the clients. The proxy sends the new schedule in a burst after all the clients have received the data of the previous schedule. They tried 56kbps, 256kbps and 512kbps rate video streams for multiple streaming clients simultaneously and achieved 53-77% energy savings for these different bit rate streams. In the presence of TCP cross traffic, the authors also achieved similar energy savings.

TABLE VIII
ENERGY SAVINGS FOR DIFFERENT PROXY-BASED TRAFFIC SHAPING AND SCHEDULING MECHANISMS.

Proxy-based Techniques	Wireless Network	Transport Protocol	Energy Savings
Shenoy and Radkov [96]	Wi-Fi	UDP	65-80%
Anastasi *et al*. [24]	Wi-Fi	UDP	70%
Hoque *et al*. [51]	Wi-Fi, 3G	TCP	70%,4%
Chandra and Vhadat [35]	Wi-Fi	UDP	83%
Gundlach *et al*. [45]	Wi-Fi	UDP	77%
Zhang and Chanson [115]	Wi-Fi	UDP	80%

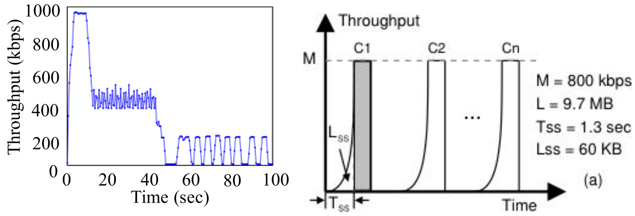
Zhang and Chanson [115] proposed two proxy-based scheduling algorithms for multiple streaming clients. In the first case, the proxy is unaware of the client's power characteristics and schedules a client with the lowest burst reception time with the highest priority. The second alternative was based on a heuristic approach that considers the client's idle power consumption and residual battery capacity.

3) Comparison and Practical Measurement: The energy savings offered by different approaches are shown in Table VIII. It is also shown that most of the research work focused on UDP-based multimedia streaming via Wi-Fi. They use their own link layer mechanism to switch Wi-Fi interface into sleep mode. Only the methods proposed by Hoque *et al*. [51], Zhang and Chanson [115] relied on the standard power saving mechanisms.

The state-of-the-art approaches, listed in Table VIII, apply unique different techniques and provide significant power savings. But, most of them are either inefficient or require dedicated infrastructure to apply in real streaming scenarios. For example, Shenoy and Radkov used a client side module which switched interface based on either traffic pattern or on a control packet [96]. If that control packet is lost, then Wi-Fi interface would be always in the active state. Similarly, the power saving protocol, RT_PS [24], is RTSP dependent and different media services have their own RTSP implementation. Therefore, deployment would require separate implementation of RT_PS for each of those services. The system architecture by Chandra and Vahdat requires both a server-side and local proxy: one generates bursts while the other schedules burst at the Wi-Fi AP for multiple clients [35]. The transparent proxy [45] cannot be deployed beyond local Wi-Fi network, as it collects client address using ARP spoofing.

The scheduling algorithms proposed by Zhang and Chanson [115] have different kind of limitations. The shortcoming of their first algorithm is that the client with the lowest reception time is served without any waiting time, whereas the client with the maximum reception time experiences the longest waiting time and therefore consumes more power. The second algorithm prioritizes a mobile device with the lowest battery capacity.

The traffic shaping mechanism proposed by Hoque *et al*. [51] is robust from the deployment point of view. It can be deployed anywhere in the Internet and users can save energy simply by configuring HTTP proxy settings in their smartphones. It does not matter which wireless interface is being used for streaming. In case of 3G, the measured savings were not significant, because of the inactivity timers and the



(a) YouTube Traffic Pattern (b) YouTube *chunk-mode* traffic pattern

Fig. 10. YouTube and proposed Chunk-based YouTube Streaming Patterns respectively [84]. In Fig. 10(b), M is the maximum throughput, L is the total transfer size, T_{SS} and L_{SS} are the duration of TCP slow start and the amount of data to be transferred during this slow start.

target device uses smaller TCP receive buffer for the 3G interface (refer: Table VIII).

We did not find any streaming services or applications which use such energy-aware traffic shaping proxy. We checked cellular network settings in smartphones and could not trace the existence of any proxy in the operator's network as well.

C. Server-Assisted Solutions

In client-server streaming services, a server sends multimedia content to a client. In this section, we describe research works that suggest either changing only the behavior of the server or both (i.e. client and streaming server) in order to increase battery life of mobile devices.

In [13], Acquaviva *et al.* extended the client-centric solution [28], to a server-assisted solution. They proposed two techniques to control the playback buffer and thus power consumption. In the first approach, a client informs its server when to send and not to send data based on the buffer status and switches the Wi-Fi interface on/off accordingly. In the second approach, server sends data in bursts, so that the client can play for a fixed period of time and tells the client to turn off the Wi-Fi interface.

Radu *et al.* [39] proposed a client-side technique which is different from other historical or statistical prediction based mechanisms, such as those described earlier. The media is preprocessed at the server to generate some annotations based on the relative size of the packets and the request timestamps. These annotations are embedded into MPEG stream and sent to the client. On the way, annotations are used by an Wi-Fi AP to shape traffic into bursts before forwarding it to the client.

Adams and Muntean [14] proposed a server-side traffic shaping mechanism called Adaptive-Buffer Power Save Mechanism (AB-PSM), which introduces an additional buffer at the server. This buffer hides stream packets from the client for a while and allows a mobile device to spend more time in the sleep state. The authors estimated a possible 50% reduction in energy consumption through AB-PSM. Subsequently, the authors incorporated this mechanism into a system-wide approach [15], in which they also considered the power consumption while decoding and playing stream at the mobile device. Energy saving in the decoding stage was achieved by sending the lowest bit rate stream. In the playing stage, power consumption was minimized by adapting screen brightness and volume at various levels.

TABLE IX
SERVER-ASSISTED SOLUTIONS AND THEIR ACHIEVED ENERGY SAVINGS.

Server-Assisted Approaches	Wireless Network	Transport Protocol	Energy Savings
Acquaviva *et al.* [13]	Wi-Fi	UDP	75%
Radu *et al.* in [39]	Wi-Fi	UDP	60-70%
Adams and Muntean [14]	Wi-Fi	UDP	50%
Qian *et al.* [84]	3G	TCP	80%

TABLE X
TRAFFIC BURSTINESS OF YOUTUBE FOR NEXUS S AND IPHONE, AND CORRESPONDING ENERGY SAVINGS FOR WI-FI AND 3G COMMUNICATION.

Device	Spatial Resolution	Rate (kbps)	Burst Interval	Energy Savings(WiFi)	Energy Savings(3G)
Nexus S	320x240	374	1200ms	30%	26%
Nexus S	640x360	917	600ms	28%	25%
Nexus S	848x480	1257	300ms	28%	26%
iPhone 4	640x360	535	500ms	53%	50%
iPhone 4	1280x720	2511	300ms	50%	48%

There are some proposals for energy efficient traffic manipulation in the cellular network access. In [27], Balasubramanian *et al.* proposed an algorithm called, TailEnder to pre-fetch and collect the traffic of delay tolerant applications (e.g. email, RSS feeds and web browsing) to reduce energy consumption. This kind of traffic scheduling is not suitable for streaming(see Fig. 10(a)). Qian *et al.* [84] proposed chunk-mode streaming technique and modeled traffic pattern, which is illustrated in Fig. 10(b). The total transfer is divided among multiple chunks and each chunk transfer utilizes the maximum available bandwidth. Compared with the traditional YouTube streaming technique, the authors estimated that *chunk-mode* could provide energy savings up to 80%.

1) Comparison and Practical Measurement: The server-assisted mechanisms listed in Table IX can guarantee significant energy savings. Most of these work are for UDP-based streams and reduce energy usage of the Wi-Fi interface; except for Qian *et al.* [84] who proposed traffic shaping of TCP-based multimedia content over 3G. Some of these proposals are protocol or infrastructure dependent, like the other client-based or proxy-assisted mechanisms. For example, Acquaviva *et al.* switched on and off the Wi-Fi interface during the burst interval and we already discussed that this method cannot be applied for TCP-based streaming applications. The annotation mechanism [39], AB-PSM [14] and chunk-mode [84] techniques depend on standard power saving mechanisms. Among these, annotation is infrastructure dependent, as it requires an Wi-Fi AP to look into the multimedia content to find those annotations and then shape traffic into bursts.

In Internet, there are some streaming services which send videos to mobile devices using chunk-mode or equivalent techniques. Chandra [34] observed that Real Media service streams at higher rate than the encoding rate. Therefore video is downloaded at the client in less time than Windows Media or QuickTime, and consequently, Real Media videos consume less power than other two services. Recently, Rao *et al.* showed that YouTube also uses this technique and streams 1.25 times of the encoding rate [86]. Besides this, server sends content as bursts of 64KB [19]. This burstiness is seen only with

TABLE XI
CLASSIFICATION OF THE RESEARCH WORK BASED ON DIFFERENT CONTENT ADAPTATION TECHNIQUES.

Content Adaptation Techniques	Research Solutions
• *Scalable Video Coding*	[38], [89], [17], [18]
• *Transcoding*	[96], [77], [82]
• *Content Selection*	[34], [35], [77], [56], [74]

Android phones when the browser is used to watch videos and with iPhone 4 using the native YouTube application. Every 64KB data is sent at a fixed periodic interval and this interval decreases as the spatial resolution of the video increases (refer: Table X). This periodic interval allows a smartphone to switch Wi-Fi interface into sleep state. Adams and Muntean [14] also proposed similar method to save energy. For Nexus S, we measured 25-28% reduction both in Wi-Fi and 3G energy consumption. In case of iPhone 4 the savings were about 50%, as it receives content at twice the encoding rate.

We also noticed a combination of one form of annotation and chunk-mode mechanism for YouTube streaming to the mobile browser in Galaxy S3. YouTube server embeds key-frame positions in the video header as annotations and the player in Galaxy S3 uses this information to request chunks after every 10 seconds interval. Apple's HTTP adaptive streaming also works in a similar fashion. In this case, Vimeo server informs client about the chunk or segment duration and at which bandwidth condition the player should request a particular segment. In both scenarios, the segments are downloaded at the maximum speed and we measured about 55% and 10% energy savings while streaming via Wi-Fi and 3G respectively.

VII. APPLICATION LAYER MECHANISMS

The most important application layer methods use different content adaptation mechanisms to prolong battery life of the multimedia streaming clients (refer: Table XI). These methods have emerged because of the need to serve heterogeneous devices with the same original content. They are especially useful when delivering multimedia content to resource-constrained mobile devices. While the original requirement was to fit content to devices with for example different displays, these techniques are applicable also for adjusting energy consumption of multimedia content reception and presentation. The key difference to the solutions presented in earlier sections is that these mechanisms modify the actual content. In this way, content adaptation provides a means to trade streaming quality for energy savings.

A. Scalable Video Coding

Scalable Video Coding (SVC) [94] is also known as layered video coding. It provides the capability to code a single video stream by using the bit rate of multiple transmission channels by structuring the compressed data of video bit streams into layers. The base layer corresponds to the lowest bit rate stream having the minimum quality, frame rate and spatial resolution. The enhancement layers increase the quality of the stream by increasing the frame rate and spatial resolution. The number of layers to be transmitted to a streaming client at any time is determined by a flow control algorithm based on the feedback received from the client. Therefore, this technique has potential to reduce network traffic and computational complexity at the mobile devices, which in turn reduce power consumption.

Choi *et al.* [38] included SVC for an MPEG-4 FGS streaming system [65], in which a mobile client can control its decoding capability according to the energy management policy. The mobile device sends its instantaneous decoding capability as a feedback message to the server and based on this information, the server determines the amount of data for a given frame to be sent to the mobile client. For instance, when the battery charge level of a mobile reduces to a predefined threshold, the power manager scales down the CPU frequency of the mobile client in order to extend the battery life. The authors measured a 20% reduction in Wi-Fi energy consumption using this approach.

A power aware streaming proxy (PASP) was designed by Rosu *et al.* [89] which uses scalable video coding to reduce the energy consumption of a mobile client. In this case, proxy relies on MPEG-4 stream structure and RTP payload format for MPEG stream to identify different video objects in the stream [58]. Afterwards, it forwards only the appropriate video layer to the client-based on the client rendering capacity and battery status. In between, the proxy may selectively drop less important object planes or drop objects which are too small for a mobile device to display. However, the proxy does not drop the RTP packets containing the media stream configuration information. Though PASP was designed for Wi-Fi network, authors planned to investigate other wireless technologies such as CDMA2000. However, we were unable not find any such follow-up work.

Albiero *et al.* exploited the cooperation among multiple users in [17] and [18] to reduce the energy consumption of different wireless interfaces for SVC schemes, where the number of participants was equal to the number of enhancement layers. The researchers showed that power consumption decreased by more than 50%, as the number of enhancement layers or participants increased.

B. Media Transcoding

Transcoding is another way to deal with network bandwidth and device heterogeneity for multimedia streaming. In this approach, only one bit stream of high quality is stored at the server. In order to meet the user device or network requirements, transcoding is performed at the server, at the access point, gateway or at some proxy server, which results in a new bit stream.

Shenoy and Radkov [96] introduced a streaming system which transcodes variable bit rate multimedia content in a proxy and then shape the resulting new bit rate media traffic into bursts at the proxy. The steps involved in transcoding are the followings. A mobile device sends a stream request to the proxy server via Wi-Fi and specifies its available energy for decoding, for network reception and the maximum spatial resolution of the display. Then, the proxy finds a combination of the spatial and chroma resolution which matches the client requirements. When the best match is found some external

TABLE XII
SOME CONTENT ADAPTIVE TECHNIQUES FOR WIRELESS MULTIMEDIA STREAMING AND THEIR ENERGY SAVINGS.

Adaptation Approaches	Wireless Networks	Transport Protocol	Energy Savings
Kennedy *et al*. [56]	Wi-Fi	UDP	16%
McMullin *et al*. [74]	Wi-Fi	UDP	16%
Choi *et al*. [38]	Wi-Fi	UDP	20%
Mohapatra *et al*. [77]	Wi-Fi	UDP	75%
Albiero *et al*. [17], [18]	WiFi,Bluetooth,GPRS	UDP	50-70%

transcoder, for example [30], can be invoked. One limitation of this approach is that the algorithm determines the transcoding parameters for each one-second interval. Thus the probability remains that the transcoding may not be uniform for the complete stream. Two enhancements were proposed to combat this.

(1) For a cached or stored video stream, the proxy quickly transcodes the stream for every one-second interval, then selects the lowest spatial resolution among all the intervals and re-transcodes the entire video stream based on the smallest spatial resolution.

(2) For a stream fetched in real time, the transcoding parameters are selected for the very first one-second interval. Then, proxy applies those parameters to the rest of the stream.

In a similar work by Mohapatra *et al*. [77], a proxy finds three standard intermediate spatial resolution formats for MPEG frames and also identifies eight dynamic transcoding parameters based on the frame and data rates. These parameters are applied at the proxy. The authors demonstrated that transcoding enabled a 57.5% energy saving at the mobile device for multimedia presentation, as the computational complexity was reduced.

The above mentioned solutions consider a streaming service between a mobile client and a fixed host or server. Poellabauer and Schwan [82] proposed a dynamic transcoding framework for global energy savings for multimedia streaming over Wi-Fi, where a mobile host acts as a server and another mobile device acts as a client. The framework dynamically provides a way to select an appropriate transcoder, parameters and the host (either client or server). However, dynamic transcoding introduces an additional computation cost for mobile devices and, therefore, provides energy savings only when data reduction is sufficient.

C. Content Selection

Similar to other content adaptation approaches discussed in the previous sections, content selection also deals with device, network bandwidth and CPU heterogeneity. It also reduces traffic for and power consumption of mobile devices. However, multiple copies of the same stream are required, which is very resource consuming.

Nevertheless, this particular technique can provide a simple but efficient power adaptive multimedia streaming framework over wireless networks. For example, Chandra and Vahdat [35] measured the energy consumption of different multimedia formats and stored the same video of different spatial resolutions at the server. They showed that switching to a lower fidelity stream at the server provides potential energy savings at mobile clients.

Mohapatra *et al*. [77] transcoded a video stream with different parameters and generated multiple copies of the same video in a proxy or server. Then, they profiled the average power consumption of mobile clients for these transcoded streams and later used these profiled values for stream selection rather than transcoding. Two other approaches select multimedia content based on the mobile devices battery level [56], [74]. The energy savings using these two approaches are shown in Table XII.

D. Comparison and Practical Measurement

We compare the content adaptation mechanisms in Table XII. All of the mechanisms reduce quality of the content and therefore offer energy savings both for multimedia presentation and for the Wi-Fi interface. It is shown that basic content adaptation methods ([56], [74], [38]) could save approximately 20% Wi-Fi energy simply by lowering the data rate. In a recent measurement study, Trestian *et al*. [101] also demonstrated that Wi-Fi communication energy decreases as the encoding rate of the video decreases while streaming to Android phones. From Table XII we can also find that applying some other traffic manipulation techniques, such as traffic shaping at the proxy [77] or using other low power consuming interfaces [17], can improve energy saving further to 70%. However, one common drawback of on-the-fly transcoding is that client players can suffer from longer initial playback delay. The delay can be even longer when transcoding is done twice, as for example Shenoy and Radkov did [96]. In this case, SVC and content selection can play positive role.

Nowadays, popular streaming services, such as YouTube, Dailymotion and Vimeo, provide video services using content selection for almost any kind of mobile devices, in which videos are transcoded beforehand for different spatial resolutions. The initial playback delay is shorter compared to transcoding. These video services support from lowest to very high quality videos. In a laptop or desktop PC, a user can select a video of the desired quality. However in a smartphone, the native applications support only two quality videos. The application automatically requests a better quality video when streaming via Wi-Fi and requests lower quality when cellular interface is used. If the higher quality video is being streamed via 3G, the YouTube player in Android phones notifies about the possible delay of using 3G interface. Therefore, data transfer capacity of wireless networks is the main reason behind such interface selection strategy, even though streaming via Wi-Fi would consume less energy than via 3G [51].

However, these video services do not support energy-aware or bandwidth-aware stream switching on-the-fly, rather they require user input to switch between high and lower quality streams and thus interrupt the playback. Though, SVC could have been an appropriate choice for bandwidth and energy-aware multimedia streaming, in recent years a new content adaptation method emerged which is called dynamic adaptive streaming over HTTP (DASH) [99]. In this case, a video service provider divides a video file into a number of segments. This segmentation is applied on the files of every video quality. The duration of each segment is same. For instance, in Apple's HTTP Live streaming the duration of each segment is 10 seconds. We found that Vimeo player in iPhone 4 uses Apple's rate adaptive method and downloads segment after every 10 seconds which is equivalent to the segment duration (see Section VI-C). Some other services that use rate adaptive streaming are Netflix and Adobe Dynamic Streaming [16].

VIII. Energy-Aware Multimedia Delivery From Mobile Devices

The solutions we discussed so far deal with the energy consumption of mobile devices while receiving multimedia content from the streaming servers. Here, we consider opposite scenario where a mobile device transmits audio/video. In such a scenario, a mobile device can benefit from the physical and link layer mechanisms, discussed in sections IV and V, while transmitting multimedia content. Although applying some traffic shaping mechanism would save transmission energy, we could not find such work in literature. Like Zhang *et al.* [116] we also discovered that a lot of work consider energy-aware content adaptation. In such a system, a mobile device encodes audio/video based on the wireless channel status or selects the transmission power based on the encoding rate while transmitting. However, these content adaptation methods are different from those discussed in section VI. Hence, we discuss them separately in this section.

In a joint source and channel coding system, the controller at the mobile device uses multimedia source coding or compression parameters based on the channel status information at the link layer, such as the probability of the packet loss or delay per packet. The transmitter gives each packet equal priority and adapts the transmission power in order to maintain a fixed rate of packet loss. Although this technique deals with channel fading, multi-path and shadowing effects by adapting power, the problem is that the transmitted multimedia content may result in poor quality if any important packet is lost, such as the packet containing the multimedia configuration parameters. Kim and Kim proposed an optimum power management scheme for CDMA systems, which controls transmission power of the wireless interface according to the importance of a packet [59].

However, in a low battery situation it is also impractical for a mobile device to use very high transmission power to improve the reliability of the transmission, i.e. the quality of the multimedia stream. Katsaggelos *et al.* [54], and Li *et al.* [67] showed that a proper selection of the encoding rate of the video, transmission power, modulation and channel coding together could be combined into a technique to provide energy savings for a mobile device or network while transmitting video. In a recent work, Ukhanova *et al.* [103] proposed a system which selects the encoding rate of the video stream and 3GPP RRC state machine parameters based on how much energy a UE wants to spend to transmit the video.

In their earlier work [71], Lu *et al.* found that energy per bit increases as channel quality degrades or transmission distance increases. To that extent, they suggested to adapt the bit rate at the source coder depending on the channel quality. In their later work [72], the authors considered compression complexity along with bit rate at the source coder and transmission power to improve energy savings further.

The techniques we discussed above are cross layer mechanisms, because the controller at the mobile devices either selects the encoding rate at the application layer based on the link layer state or adapts the transmission power at the physical layer based on the encoding rate. Other solutions in this cross layer category are object-based video coding [105] and transmitting key-frames over wireless networks [67]. Wu *et al.* [111] optimized adaptive modulation coding parameters at the physical layer, forward error correction at the link layer and source coding parameters at the application layer in order to improve the video quality constructed from the received video key-frames. Rodriguez [88] also discussed cross layer adaptive modulation with error coding at the link layer (e.g. forward error correction) for multimedia streaming.

Li *et al.* [66] applied DMS at the physical layer based on client's link layer buffer status to reduce transmission energy consumption (see Section IV). They also optimized idle and active time of the wireless interface at the link layer of the transmitting device to reduce energy consumption further.

IX. Lessons Learned and Future Directions

The first important lesson is that comparison of the effectiveness of proposed solutions in terms of energy savings is difficult for several reasons. The results depend on hardware characteristics and most studies have used different devices in evaluating the energy savings. To make matters worse, it is almost impossible to measure power draw of individual components, such as communication energy, of an off-the-shelf device. Instead, only total energy consumption can be measured, which increases the amount of differing hardware components that impact the results. The proposed techniques range from very recent ones to those proposed and evaluated over ten years ago and during this time hardware components have obviously changed significantly. In addition, there are no established practices that would specify the particular workload and other test case configurations to be used in the evaluation of a particular solution. For instance, not all the techniques that we reviewed used similar encoding rates or resolutions not to mention the same video content which undermines direct comparison of relative energy savings.

Ease of deployment and scope are among the key factors that differentiate the presented solutions. By scope we mean that some of the techniques can save energy with all kinds of applications, while others target only streaming applications. Typically, the lower the layer of the solution, the larger its scope. However, PHY/MAC layer solutions are tied to that particular technology, such as 802.11, whereas higher layer solutions, such as traffic shaping, can be useful with a range of lower layer technologies. Concerning deployment, we learned that solutions can be deployed at different vantage points. PHY/MAC layer mechanisms must be deployed at the client and usually also at the AP, while mechanisms that function on network layer or above can operate at the client, server, middlebox, or a combination of these. Deploying a purely client-based solution is most straightforward from a mobile device manufacturer or software developer point of view. In contrast, deploying a solution requiring server support is easy from the content service provider's perspective. Proxy-based solutions are a compromise between client and server-side techniques, which are especially applicable for mobile network operators that wish to provide more energy efficient service to their clients.

Given the large number of different kind of mechanisms which operate on different layers and at different vantage points, it is reasonable to ask which of them can be applied simultaneously and whether some of them conflict so that energy consumption increases as a result of competing solutions. Certain mechanisms are ineffective unless applied in combination with a particular lower or higher layer technology. An example is shaping streaming traffic into bursts which is effective almost on any time scale when using Wi-Fi access but does not necessarily help at all when using 3G access due to long inactivity timer values[51]. This is why cross layer solutions are dominant.

There are two notably different approaches in 802.11 based networks to reduce the energy consumption of the mobile device. One is to "race-to-sleep" meaning that transfer is completed with as high throughput as possible, and the other one is to use rate adaptation. In the case of streaming, the former approach leverages traffic shaping and PSM while the latter case relies only on new mechanisms for 802.11 PHY/MAC layers. It is unclear which approach is better, the jury is still out and new solutions are constantly emerging[64].

We list below a few topics that we have identified from this survey as being worthwhile to explore by future research:

- Energy efficiency of mobile multimedia over cellular network access has gained little attention to date. One reason is that the RRC protocol is controlled by the network operator. Although there are the upcoming Fast Dormancy and LTE's DRX/DTX mechanisms to optimize power consumption, measurement studies on real deployments are absent. Furthermore, solutions that take into account both, Wi-Fi and cellular network energy consumption characteristics would be welcome.
- Scheduling packet transmission happens on all the protocol layers from MAC to application layer. A combination of these scheduling decisions determines the eventual energy consumption characteristics. It can be a problem when energy efficient scheduling is being applied simultaneously on different layers and even at different vantage points. Thus, it is worthwhile to ask which layers and entities should take part in such scheduling and in which form of cooperation in order to reach energy optimal behavior.
- Variability in the instantaneous available bandwidth has lead to the development of rate adaptive streaming techniques. In this case, SVC at the server-side and DMS at the client-side together could provide significant energy savings. However, a new rate adaptive mechanism is developed over HTTP called DASH [99]. It is currently unclear which are the energy consumption characteristics of using these techniques. Therefore, both SVC and DASH can be explored further for bandwidth and energy-aware adaptive streaming so that the protocols would leverage the variability also in the energy efficiency of mobile device connectivity.
- Modern smartphones are equipped with multiple wireless network interfaces and in the future also alternative low power radio technologies, such as 802.15.4 and Bluetooth Low Energy, will be embedded. These technologies will provide a way to deliver low rate multimedia streams to the mobile handheld devices in a more energy efficient manner. Further research is needed before we can use these technologies in an energy optimal manner with streaming services.

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Mohammad Ashraful Hoque received his Bachelor degree from Shahjalal University of Science and Technology, Bangladesh in 2004. In 2010, he received his M.Sc. degree in Mobile Computing from Aalto University School of Science, Finland. He is currently working as a Ph.D. student at Aalto University School of Science. His research interests include power management for various wireless networks, transport protocols, medium access protocols and multimedia streaming over wireless networks.

Matti Siekkinen Senior Research Scientist Matti Siekkinen obtained M.Sc. in computer science from Helsinki University of Technology and in Networks and Distributed Systems from University of Nice Sophia-Antipolis in 2003, and Ph.D from University of Nice Sophia-Antipolis / Eurecom in 2006. His research interests include energy efficiency in ICT, network measurements, and Internet protocols.

Jukka K. Nurminen Jukka K. Nurminen started as professor of computer science at Aalto University at the beginning of 2011. He has a strong industry background with almost 25 years experience of software research at Nokia Research Center. His current research themes are related to services and applications in distributed systems with an emphasis on mobile solutions. Peer-to-peer technologies and energy-efficiency research are of particular interest. He received his M.Sc degree in 1986 and Ph.D. degree in 2003 from Helsinki University of Technology.