Adaptive Energy Optimization in Multimedia-centric Wireless Devices: A Survey

Martin Kennedy, Adlen Ksentini, Yassine Hadjadj-Aoul, and Gabriel-Miro Muntean

***Abstract*—Over the last couple of years, there has been an exponential increase in the number of applications accessible from various mobile handsets, including Facebook, Twitter, YouTube, etc. In particular, rich media service distribution among smart-phones and other handheld devices is becoming increasingly popular among users. In fact, the next generation wireless technologies have put significant emphasis on supporting distribution of rich media content and video-on-demand services. However, energy consumption in the handheld wireless devices is a major bottleneck that hinders the growth of mobile device based rich media services. The biggest problem today in the mobile world is that the mobile devices are battery driven and the battery technologies are not matching the required energy demand. This paper outlines the major energy-consuming components in handheld devices like smart-phones, PDAs and other multimedia-centric wireless devices. Further, this paper surveys different research works on how the energy consumption could be optimized and provides detailed discussions on the latest energy saving techniques in the major components of the mobile devices. In addition, the paper surveys other systemic energy optimization techniques so that the overall battery life of the device is increased. Major global research projects and their research focus are then surveyed. Finally, a brief summary is provided along with some open research problems and different possible future research directions.**

***Index Terms*—CPU, decoding, display, energy-efficient, network interface, smart-phone, video streaming.**

I. INTRODUCTION

THERE is a great demand in society for simultaneous audio and video communication between different wireless devices in the latest heterogeneous wireless network environment (i.e., 3G, WiMAX, WLAN, WAN, MAN, etc.). Notably, there has been significant research on architecture design, handover mechanisms, chip design, application development, etc. that has enabled growth of telecommunication systems. In addition, the rapid increase in the number of applications and the equally supporting growth in the semi-conductor industry, have seen the size of the wireless device shrinking even as new applications have been continuously added to the device. At the same time, the battery consumption of these wireless devices (i.e. the overall energy utilization) has also been rapidly increasing. However, this severely contradicts the European Union (EU) energy-related goals. For example at the end of 2006, the EU pledged to cut its annual consumption of primary energy by 20% by 2020 [1]. However, as of today, the telecom industry creates a carbon footprint equal to running approximately 3 million three-bedroom family homes [2], or almost the whole of the global aviation industry – that is 61 billion kWh. With current projections, this consumption will double by 2014. The ITU (International Telecommunication Union) confirms that similar to aviation, ICT is responsible for 2.5% of greenhouse gas (GHG) emissions [3] and Gartner research identifies that around 10% of these emissions come from mobile phones [4].

Significantly, Gartner reports that by 2013, mobile phones and other browser-enabled wireless devices (like PDAs, netbooks, palmtops, etc.) will overtake PCs as the most common web access device worldwide [4]. The current development in the battery technology is insufficient to keep pace with this growth. An important factor that hinders rich media contents' streaming for long periods of time is the limited battery life of the wireless device. Paradoxically, energy utilization in the mobile devices has already been rising rapidly. Unlike the semiconductor industry whose growth has followed the Moore's Law of doubling the number of transistors in a chip every 18 months, the average annual gain in the battery has been improving by only 6% over the years. Panasonic, one of the global market leaders in battery production, revealed that even with their latest research on battery technology, their average annual increase in battery capacity is in the region of 11% [5]. This has had a serious impact on the practical use of the mobile device and is expected to play a major role in the design of next generation wireless devices. In particular, there are four broad classes of energy intensive applications in smart-phone/high-end wireless devices. These include data communication (e.g. Voice over Internet Protocol (VoIP)), image viewing/retrieval, graphic intensive games (including online games) and streaming of multimedia content (video with audio).

All four classes of applications mentioned above would result in energy consumption at different components of the device like CPU, screen, RAM, SD card, speaker, amplifier, GPU, RF front-end, etc. For instance:

i Data communication applications would consume extensive energy at the network interface.
ii Image retrieval/playout would result in significant energy consumption in the display screen and network interface.
iii Graphic intensive games would potentially result in significant energy consumption at the CPU and screen, with additional energy consumption at the network interface for online games. Notably, in the case of games, once the background video content gets loaded, the change in the foreground would be minimal, though rapidly changing.
iv Notably, real-time multimedia streaming would potentially

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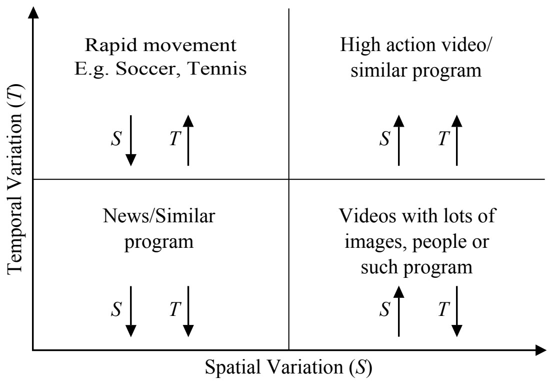

Fig. 1. Spatial and temporal complexity variation of a video content.

result in high-energy consumption across several device components including CPU (encoding/decoding), screen (video, images), audio (speakers, headphones), memory (RAM, SD card), Graphics Processing Unit (GPU) and network interface (transmission, reception, etc).

It can be seen that among different applications, multimedia streaming would potentially result in energy consumption across several components in the device, more than any other application. Hence, in terms of the energy consumed, applications like 'data communication', image retrieval' and 'online games' could be considered as a subset of energy consumed during multimedia streaming. Hence, multimedia-centric applications and streaming in wireless devices form the focus of this paper.

In case of rich media content, video encoding (i.e., MPEG-2, MPEG-4, H.264, etc.) plays a significant role in deciding the bandwidth and the energy used in video transmission. Importantly, the classification of the video content (in terms of spatial and temporal content complexity) plays a very prominent role in the amount of consumed energy. For example, Fig. 1 shows four different types of video content. In case of news or a similar program with negligible background fluctuations, there are very small changes in both spatial and temporal domains (third quadrant in Fig. 1). Therefore, only minor changes in encoding are needed to transmit the differential information between subsequent frames. Hence, the bandwidth required to transmit information about different frames would be minimal. On the other extreme, in case of high-action movie content with rapid changes in both foreground and background (first quadrant in Fig. 1), the amount of information differentiating the subsequent frames, and thereby the bandwidth required to transmit the same duration of video content at the same quality level, would be very high. Unfortunately, this results in battery life being strongly dependent on the content.

Notably, over recent years, the smart-phone segment, already with market of more than 10 billion euro, has been growing at a rate of more than 30-50%. In this context, it is forecasted that mobile data traffic will double every year in the coming few years, and multimedia streaming will account for almost 66 percent of the traffic by 2014 [6]. This results in higher power consumption in the devices, which in turn reduces the battery lifetime. Hence, there is a strong need to provide a fundamentally different solution for dynamically increasing the battery life. The first step in increasing the battery life is to have a good energy management system, which in turn requires a good understanding of where and how the energy is used in the device, how much of system energy is consumed by which parts of the device and under what circumstances.

The objective of this paper is to identify the major energy-consuming components in multimedia-centric high-end mobile devices, before exploring existing solutions and future directions to increase battery lifetime. The main contribution of this paper is to provide a comprehensive survey on the different components where the energy consumption could be reduced and present current research works in these areas. To begin with, Section II models the energy consumption across different components in a typical smart-phone device. Section III describes the state-of-the-art research on energy optimization in the major components of the mobile devices along with state-of-the-art research on solutions that consider/affect CPU, screen and network interface jointly while optimizing the energy consumption at the same time. Notably, Section IV surveys major global research projects on energy optimization techniques for wireless devices. Finally, Section V provides a brief summary and an outlook for future research.

II. MAJOR ENERGY CONSUMING COMPONENTS IN HIGH-END MOBILE DEVICES

Battery depletion in a wireless device depends on both the hardware and software of a device. The exact amount of energy consumed by each of these components in the device is dictated by the device characteristics and the nature of the applications running on the device. In order to get a comprehensive analysis of the energy consumption behavior in a high-end wireless device, a specific device, the HTC Nexus One, was considered and various tests were performed. This device was selected because of its wide range of functionality and because it runs Android, an open source operating system well-studied and highly popular [7]. This is critical to our studies as it allows for a deeper understanding of the power distribution between the device components. For this reason, few other mobile operating systems would have been suitable. It is worth mentioning here that power management studies in smart-phones have been done in [8, 9], but for different sets of devices: the *Openmoko Neo Freerunner* and the 1st Android HTC phone, the *HTC Dream*. However the HTC Nexus One is a newer device with more modern hardware components: an AMOLED screen, a 1 GHz ARMv7 CPU, a dedicated GPU and many sensors. As a result, even though this device is no longer state-of-the-art, the trends that can be derived from utilizing it for testing purposes are relevant to the state-of-the-art devices now on the market because of common hardware technologies. The test system composed of the Nexus One phone (running Android 2.1) and a multimedia (video and audio) streaming server in a wireless IEEE 802.11g network (Wireless Local Area Network (WLAN) or Wi-Fi). The phone was connected to an external measurement setup that monitored and logged its power consumption during the execution of various tests. These tests, specifically designed

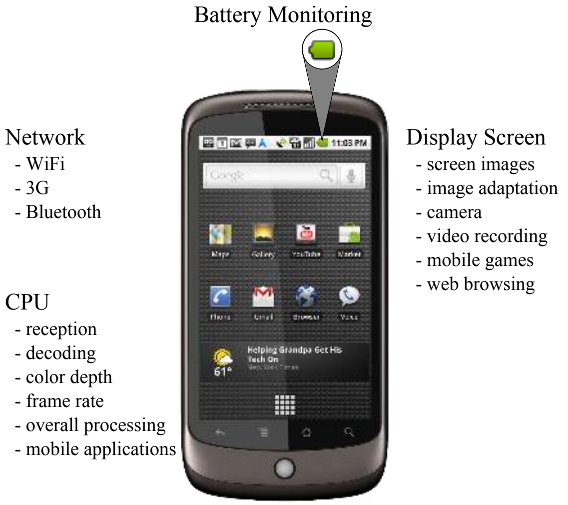

Fig. 2. Smart-phone and its different components.

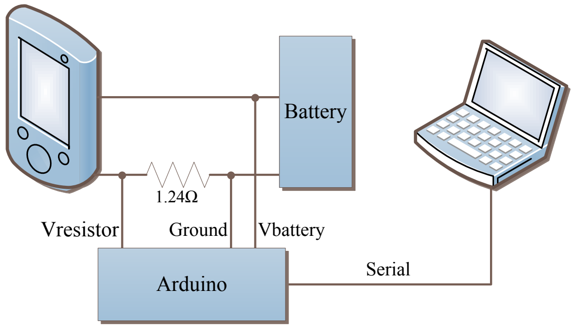

Fig. 3. Schematic of measurement set-up.

for the analysis of the energy consumption, included receiving and playing audio and video streams over the wireless network as well as applications to monitor the CPU usage and to automatically change device settings in order to put the phone into different states (e.g. changes in the screen brightness). The aim of these tests was not just to measure the overall system power, but also to measure the exact breakdown of power consumption by the device's main hardware components.

Fig. 2 illustrates the smart-phone and the potential major energy-consuming components in any handheld device. The power consumption was measured as shown in Fig. 3. A shunt resistor (1.24 Ω) was inserted between the phone and the battery, in order to calculate the power consumption by measuring the voltage drop across the resistor. All these measurements were sampled by an Arduino[1] micro-controller, which logged the instantaneous power-consumption of the device onto a computer. In order to break down the power consumption, experiments for each device component were performed by changing the parameters of one component, while leaving those of the other components constant [13]. The additional information was provided by Android's battery usage statistics, which gave a rough indication of the percentage of battery usage attributed to each of the major consumers

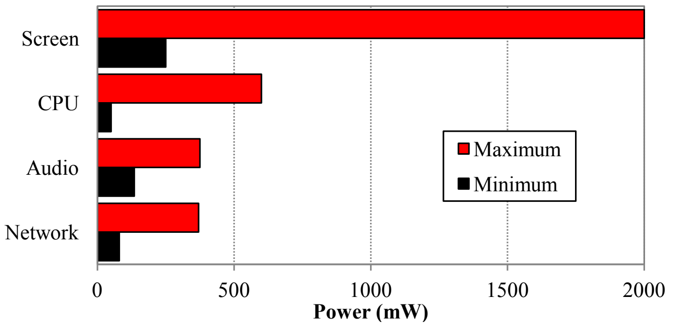

Fig. 4. Energy distribution of different components in the Nexus One mobile device.

[11]. A detailed explanation on the measurement set-up and how the tests were performed is provided in [9][12][13] though the paper [13] in itself focuses on proposing new energy-saving mechanisms in the smart-phone. Further, in order to ensure that the resistor did not have an effect on the overall power measurements, two different high-precision resistors (0.22 Ω ± 1% and 1.24 Ω ± 1%) were considered in our work and the tests were repeated. However, apart from the slightly higher voltage drop across the 1.24 Ω resistor, there was no noticeable change in the power consumed by the major components. Notably, it was observed that there were four major energy-consuming components - *screen*, *CPU*, *speaker* and *network interface*. The energy consumed in these four major components was measured as follows:

i The screen was tested by measuring different pairs of brightness levels and pixel colors.
ii The CPU was tested by running an application that gradually changes the CPU activity usage in steps from 0% up to 100%. The application does this by starting arbitrary background processes at dynamic intervals. Setting the interval between the background processes allows the CPU usage to be increased or decreased as desired. The power consumption of the device was measured for the different CPU usage levels and recorded for that specific CPU level.
iii The audio playout was tested by playing the same song at different volume levels, using the speakers and the earphones.
iv The effects of the network interface and the audio-visual quality in multimedia streaming were tested in a single experiment in which the same audio-visual content was played using different quality settings over a wireless network stream.

Fig. 4 shows an important result in terms of energy consumption in the Android Nexus One device. It shows the minimum and the maximum energy consumption values of the four major energy-consuming components. The energy consumed by the screen was calculated by measuring the power of the same process with the screen first enabled and then disabling it. Further, the power drawn by CPU was obtained by monitoring the CPU usage and subtracting the screen's power consumption. Once these values were obtained, the other components' energy consumption was acquired by calculating the power difference of the additional contribution that was

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[1] Arduino homepage [Online] http://www.arduino.cc

Component	Minimum	Maximum
CPU	usage at 0%	CPU usage at 100%
Screen	Brightness at 1%	Brightness at 100%, white pixel color
Audio	Audio playback muted	Audio playback at highest volume using speakers
Network	Connected to a Wi-Fi network, idle	Connected and receiving a high quality video stream

TABLE I
MINIMUM AND MAXIMUM POWER VALUES IN NEXUS ONE MOBILE DEVICE

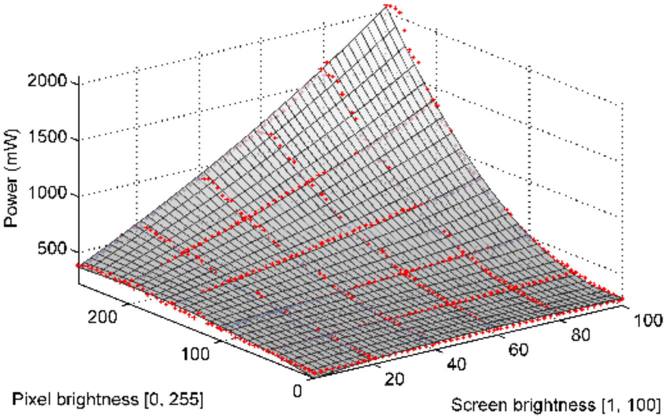

Fig. 5. Power measurements in the device screen.

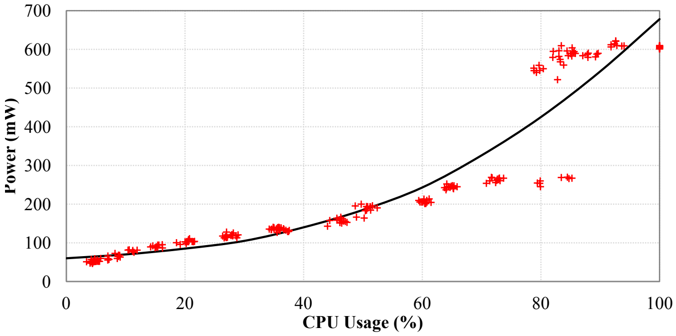

Fig. 6. Power consumption in CPU.

caused while another component was in use. It can be observed from Fig. 4 that in case of multimedia transmission, the *display screen* and the *CPU* consume the maximum amount of power followed by the wireless network interface. Further, the maximum power consumption in the display screen was *eight times* more than the minimum power consumption. This factor increased to *sixteen times* in case of CPU and was *five times* in case of wireless network interface. Hence, in order to support optimum quality and long lasting video transmission to the end-user while on the move, the energy in the display, processor and in the wireless interface would need to be considerably reduced. Hence, it is imperative to thoroughly investigate and propose an energy-optimal adaptive scheme for multimedia-centric wireless devices.

A. *Screen*

The screen's power consumption ranges from about 0.25 W to 2 W. For the tests, the red, green and blue pixel components were kept at identical levels. The energy consumption was found to depend on both the brightness level of the screen as well as the brightness of the pixels' colors. From the measurements shown in Fig. 5, it can be observed that the consumption increased approximately in a linear fashion with the screen's brightness and exponentially with the color brightness. If the screen brightness is less, then the power consumption does not increase significantly with the increase in the pixel brightness. However, if the screen brightness is high, then the power consumed increases exponentially with an increase in the pixel brightness. This is mainly because of the energy characteristics of the particular Organic Light-Emitting Diode (OLED) display. Further, the amount of power that could be saved even at the low-end of the screen brightness could be understood from Fig. 5. Even at the lowest possible brightness level, the screen could be made to consume 5% less power by simply changing the (RGB color) pixel intensity in the screen. This improvement could be further enhanced by changing the brightness level. Hence, in order to accurately estimate the power consumption and possible energy savings, it is essential to investigate the average pixel brightness especially with increasing brightness level.

B. *CPU*

The CPU's power consumption depends on its usage and ranges from about 50 mW to 650 mW. The results from two executions of the same test can be seen in Fig. 6. The two graphs are marked by a straight line and by a series of '+' symbols respectively. It can be observed that the power increased with the usage in a linear fashion but increased sharply at about 80% usage. This behavior was also noted in [8] and [9]. However, there has not been any comprehensive answer that could be derived for such a behavior. It still requires a significant amount of investigation to derive a definite answer for such a behavior. Notably, this manifests into the following: reducing the CPU usage from 70% and lower, yielded a relatively little power savings compared to a reduction that takes the usage from any value higher than 80% to any value lower than 70%. However, this assumed that the usage information provided by the Android API is always accurate. Nevertheless, the measurements gave an indication about the energy-saving potential of the CPU and put it into relation with the other components.

C. *Speaker*

During the modeling stage, it was observed that while playing back audio, the power consumption increased from a minimum of 85 mW at the lowest to 185 mW at the highest volume. Of these, around 80 mW were caused by an increase

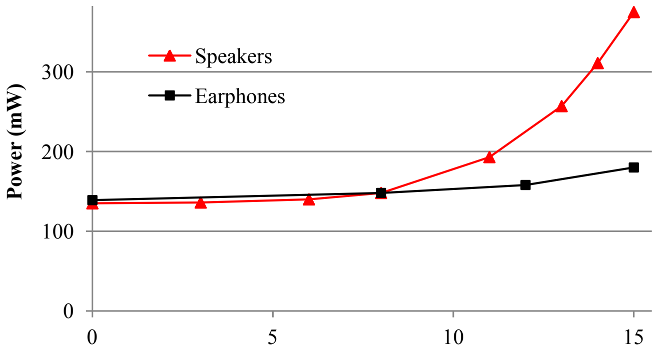

Fig. 7. Power consumption in audio playback.

in the CPU usage. The consumption increased with an increase in the volume (i.e., sound), but the difference in energy consumption when playing audio through ‘earphones’ was marginal while the consumption increased exponentially when using speakers; as can be observed in Fig. 7. This implied that the audio interface offers nearly almost no savings when earphones are used and reducing the volume in this case to save energy does not yield significant results. The main reason for the higher power increase in case of speaker is because there are two components in the audio subsystem: amplifier and codec. While the amplifier is a hardware component, the codec is a small piece of software responsible for multimedia decoding and playout, under the control of the CPU. An increase in the volume increases the energy consumption of both the CPU usage (due to increased codec activity) and the amplifier circuitry.

D. Network Interface

	Low Quality(LQ)	High Quality(HQ)
Codec	MPEG-4	MPEG-4
Video Bit-rate	128 kbps	1536 kbps
FPS	10 frames/second	23 frames/second
Dimensions	200 x 120 px	800 x 480 px
Audio Bit-rate	32 kbps	128 kbps

TABLE II
VIDEO ENCODINGS USED

In order to test the energy consumption in the network interface, a particular video clip was encoded using low and high quality settings as in Table 2. A continuous multimedia stream resulted in significant energy consumption across the network interface. As shown in Fig. 4, the network interface consumes around 400 mW of power during continuous streaming. Further, the average power consumed in the network interface was found to be around 350 mW while using 3G, around 300 mW during Wi-Fi and less than 100 mW while using Bluetooth. A separate study on the energy consumption analysis in the network interface in different traffic scenarios can be found in [11][14]. This shows the amount of energy that could be potentially saved in the network interface.

E. Total Device Energy Consumption

In order to deduce information about both the multimedia quality and the network effects on the energy consumption, two different scenarios were considered.

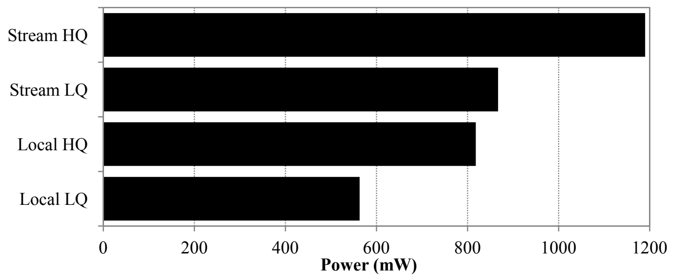

Fig. 8. Energy consumption comparison during video playback.

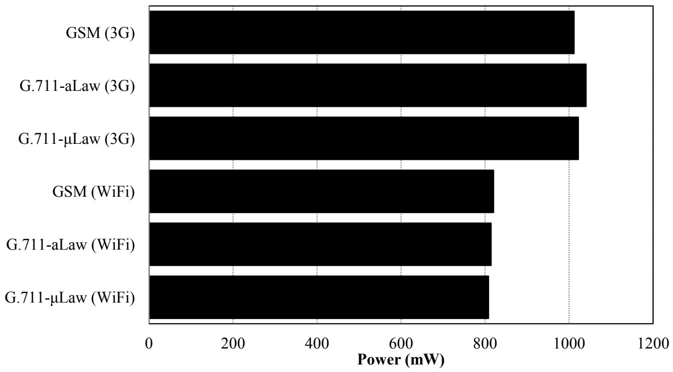

Fig. 9. Energy consumption comparison during VoIP.

Firstly, a particular video clip (based on the encoding scheme mentioned in Table II) was played both locally and streamed using Wi-Fi. Fig. 8 puts the measurements for each video clip into relation. The power difference between the low quality (LQ) and high quality (HQ) video was 255 mW for the local playback and 325 mW for the stream. The difference was greater in case of streaming, as the HQ stream not only increases the computational power but also the data rate of the received stream. The power difference between the local playback and the stream is 305 mW for LQ video and 372 mW for HQ video. Further, it was observed that the network interface accounted for about 370 mW while receiving HQ stream and offered savings up to 70 mW when the quality was reduced. Notably, a quality reduction lowered the computational power, which resulted in savings up to 255 mW.

Secondly, the power consumption of the device was measured for a VoIP call using the 3CXPhone application [15]. This call was repeated for three different audio codecs (GSM, G.711 a-Law and G.711 μ-Law) over Wi-Fi and 3G networks. As can be seen in Fig. 9, the 3G cellular interface consumed on average 210 mW more than the IEEE 802.11 wireless interface for VoIP calls. Additionally, for VoIP calls over 3G, the GSM codec is the most power-efficient of the three codecs while for Wi-Fi, the G.711 μ-Law codec performs most efficiently. This behavior difference is due to the contrasting energy-per-bit characteristics of Wi-Fi and cellular networks. Notably, it illustrates that considerable power could be saved in VoIP applications based on the choice of network and audio codec.

To summarize, the device screen (display), the CPU (processor) and the network interface were the three major energy-consuming components of the HTC Nexus One device. Further, though the tests performed in [9] did not consider intense multimedia centric applications, they had also found that Graphics and CPU were the two major energy-consuming components in the three devices that they had considered. Having obtained substantial observations of different Android-based smart-phones, the authors in this paper, did not consider testing any other smart-phone. Instead, the focus has been on surveying the different energy optimization mechanisms in different components. Keeping this in mind, the next section describes the different state-of-the-art research works carried out in the individual energy consuming components of the device. This approach would help in clearly understanding the different avenues for optimizing the energy consumption across the three major components.

III. STATE-OF-THE-ART RESEARCH IN MAJOR ENERGY-CONSUMING DEVICE COMPONENTS

This section surveys the different research works carried out over the years, in the three major energy-consuming components listed in Section II. Several research works have been carried in recent years to optimize the required power in a handheld wireless device while simultaneously providing all the requisite functionalities. In order to provide efficient rich media delivery for mobile phones, different individual power-saving schemes have been proposed for *screen*, *CPU* and *network interface*. These energy saving techniques are designed such that they do not cause severe degradation to the user quality-of-experience (QoE), i.e., the user perception of the quality-of-service (QoS). The different energy saving schemes in the individual components are as follows:

A. Screen

Over the years, different techniques have been proposed to adjust *display resolution*, contrast and screen brightness based on human factors in order to reduce display power consumption. Pedram *et al.* [16] first proposed a Concurrent Brightness and Contrast Scaling (CBCS) technique that aims at conserving power by reducing the backlight illumination of TFT-LCD screens, while retaining the image fidelity through preservation of the image contrast. Unlike liquid crystal display (LCD) panels that require high intensity backlight, OLED's display panels naturally consume low power and provide high image quality. Dong *et al.* performed significant research on manipulating the colors of pixels on OLED screens in order to conserve energy on mobile devices [17]. The first step was to create a model for an OLED device so that an optimal solution can be achieved. This involved devising a device independent mechanism for assessing pixel-by-pixel, the energy required in order to display each of the available colors on the OLED screen. This is quite a long and computationally intensive process to be performed in an iterative fashion. Hence, the authors created a shortened and simplified approximation algorithm. The new algorithm decreased the computational cost of the calculation by 1600 times while still achieving 90% accuracy. Dong *et al.* then investigated using color transformations. In [18], the current colors of the different Graphical User Interface (GUI) themes are assessed in terms of their energy efficiency. They are then altered to different colors, which maintain the overall contrasts of the different colors' on the page, while providing significant energy savings. Energy reductions of over 75% were achieved on the display while still showing a GUI to users with acceptable visual quality. In [19], the same authors succeeded in combining the work presented in their previous two papers in order to create a fully functional Android application. The application creates an energy-color model of the device's OLED screen and then uses it to perform color transformations to websites.

In terms of video streaming, the initial research works considered the video stream to comprise of a series of image frames and dynamically changed the backlight by applying backlight-scaling techniques to each image frame individually [20]. But, in reality, the backlight level may change notably across consecutive frames, which in turn would result in flickering effects. In order to solve this, the work in [21] determines the backlight level for an image by considering the preceding frame's pixel values and backlight level. However, the main disadvantage of this approach is that frequent switch in the backlight level introduces inter-frame brightness distortion [22]. In a recent yet landmark paper, Hsiu *et al.* have proposed an optimization mechanism for dynamic backlight scaling for mobile streaming applications [3]. Their dynamic programming algorithm minimizes the energy consumption of the backlight when displaying a video stream. In another work, Cheng *et al.* [24] discussed quality based backlight optimization for video playback on handheld devices while Pedram *et al.* recently proposed a technique based on dynamic voltage scaling (DVS) of the OLED panel [25]. The proposed method by Pedram *et al.* [25] saves power in the driver transistor and the internal resistance with an amplitude modulation driver, and in the internal resistance with a pulse width modulation driver, respectively. An overview on power management for a specific application-type, like mobile games, is provided in [26]. In terms of screen adaptation, Anand *et al.* proposed a non-linear tone mapping technique to dynamically increase the image brightness while playing games [27][28]. Though their focus was on adaptation while playing games, the same principle could be extended for video streaming as well. A significant insight that can be derived from these approaches is that the power consumption of OLED screens can be reduced adaptively, depending on many factors, e.g. gamma correction, screen brightness and chromaticity. An important point to be noted is that techniques like backlight optimization, dynamic voltage scaling, etc. could be done dynamically in real-time, based on the application and the nature of the content.

Existing adaptive solutions affect equally the whole viewing area of the multimedia frames in the content bitrate adjustment process. A noteworthy technique in optimizing energy consumption in a screen is to consider a region of interest (RoI). A RoI in video terminology is classified as an area of a video frame that attracts the most amount of attention from viewers. As an example, while watching a football match, the viewer may be most interested in looking at the area around the football (though this may not be the case for everybody).

Fig. 10. Different pre-defined region-of-interest blocks in a smart-phone.

There are certain regions in each frame of any video sequence on which the users focus more than the others. The authors in [29] found that when a high-resolution window is adapted at the point-of-gaze and the resolution in peripheral areas is degraded, the users had longer initial saccadic latencies in peripheral areas (the time taken to identify a visual target), than when a low resolution was uniformly displayed across the whole display window. Further, the authors in [30] found that if the degradation is increased in the peripheral areas, then in order to maintain the user's perceived quality of experience, the size of the adapted high-resolution window at the point of gaze also needs to be increased [31]. Using gray scale images, the five factors that were known to influence user-attention could be merged seamlessly. These include *contrast with region background, region size*, *shape*, *location and determination of foreground* and *background areas*. These factors were combined into an overall "Importance map" (IM), which was used to classify the importance of image regions. Based on the IMs, the authors demonstrated a technique for controlling adaptive quantization processes in an MPEG encoder [32].

In a recent work, Agrafiotis *et al.* [33] present a framework for model-based, context-dependent video coding, based on exploitation of characteristics of the human visual system. The system utilizes variable-quality coding, based on priority maps, which are created using mostly context-dependent rules. There has been considerable interest in RoI research, primarily based on the premise that where a user's gaze rests corresponds to the location of the symbol currently being processed in working memory. Consequently, the idea has been to allocate screen area dynamically, with more resources being earmarked for the portion corresponding to the RoI. The authors, in [34], propose a scalable RoI (SRoI) algorithm, which can support fine-grained scalability in region of interests with low computing complexity in order to achieve better objective and subjective video quality.

Fig. 10 shows an illustration of typical smart-phone with pre-defined block of RoI. In this scenario, the display region of the phone is divided into 20 pre-defined blocks, though in reality, this could be any number. Further, the RoI could consist of one or more blocks in the screen. Each block selected as the RoI could be decoded with a very high quality while decoding the other regions in the frame using a lower quality. These blocks within the frame could be then superimposed to form a single RoI based adaptive encoded frame. However, a major problem with using the RoI methods is that the bordering area between the RoI and the non-RoI needs to be handled carefully, without affecting the perceived quality. There are several methods for discovering the RoI in a video sequence, which include eye-tracking (with cameras), and video processing and analysis [32]. These could be broadly classified into two categories.

Passive setting of RoI: The passive method involves defining regions of interest and regions not of interest beforehand, and assigning Signal-to-Noise Ratio (SNR) elements according to the regions. This method is used for Closed Circuit TeleVision (CCTV), for example, where the user wants higher resolution for a certain region [35]. This method handles the pre-set RoI with high resolution in the encoding stage. **Active setting of RoI**: The active method does not set a pre-defined RoI, for it would change regularly based on the environment or contents. The RoI detection methods include using a Motion Vector (MV) to select the region with a large vector value as a RoI setting [35][36]. The vector value is derived from monitoring the number of differences of movement between consecutive video frames in the stage of movement prediction and is used to divide regions with Flexible Macroblock Ordering (FMO) [37]. Other methods include adjusting the quantization value in the encoding stage to improve resolution in just the regions of interest, and making it go through the high high (HH) filter in the wavelets conversion stage to improve resolution [38][39].

While a purely passive scheme would result in improper selection of RoI, an active and dynamic setting of RoI would not be very practical on a battery-powered device as it would consume too much energy for mobile devices. An alternative to this would be to find the RoI on the streaming server itself, which could then transmit RoI metadata alongside the video. Ji *et al.* have shown how RoI processing can be combined with quality scalability to maximize energy-savings and QoE [40]. Further, Ji *et al.* showed that up to a 15% energy reduction could be achieved with adaptive RoI processing with minimal degradation in video quality [41]. In case of smart-phones and handheld devices, the RoI could be assumed to be located near the center of each video frame. While this assumption could be tolerated to initially explore whether energy savings may be obtained from RoI-aware decoding, a more advanced system would be required for determining the RoI in a real application [41]. Additionally, the proposed algorithm for implementing the decoding adaptations does not make use of temporal scalability or spatial scalability. A deeper insight reveals that though RoI results in notable energy savings, one might need additional information like real-time metadata in order to determine the RoI before video transmission. Further, it needs to be verified whether the adaptation of the video stream on the server could be performed using RoI mechanisms to maximize the QoE-to-bit-rate ratio. This is a significant research challenge that would have to be addressed in the coming years.

B. CPU

In high-speed embedded systems, high-speed and high performing CPU's and GPU's are used to handle multimedia applications. The Intel Atom processor or Central Processing Unit (CPU) chip is one of Intel's smallest processors. It is most commonly used in computers with compact design, such as netbooks. The latest CPU is Medfield; an Atom system on a chip (SoC) built using Intel's 32 nm high-k metal gate process technology. Medfield has low power consumption, a small footprint and has been optimized for performance. It will enable the creation of tablets less than 9 mm thick that weigh less than 1.5 pounds and have batteries that will supposedly last all day [42]. Recently, ARM has developed the microprocessor, A7 that uses the company's most energy-efficient chip design to date. Alongside the forthcoming Cortex A15 in the power-saving architecture mode, the A7 will also feature in high-end smart-phones [43]. In ARM's system, the dynamic selection of generic cores would be invisible to the applications and middleware, and would be managed by ARM system IP. It would have two types of core in the same chip. Applications such as gaming and video playback would be performed on the more powerful A15 chip, while tasks that require less power, such as making a phone call would be assigned to the A7 to conserve power. The transfer of tasks between cores would be triggered by the same mechanism, which handles dynamic voltage and frequency scaling, now common in high end chips. In this context, it should be noted that the CPU frequency is directly proportional to the voltage and the amount of computations carried out. Hence, the energy savings related to CPU functionality during multimedia delivery could be broadly divided into two sections – *Dynamic hardware resources configuration (DHRC) with frequency/voltage scaling* and *data encoding/decoding*.

1) Dynamic hardware resources configuration (DHRC) with Frequency/Voltage scaling: Dynamic voltage scaling (DVS) is one of the most effective approaches in reducing the power consumption of embedded systems, wherein, the supply voltage can be reduced adaptively to the minimum value and still ensure proper operation. Shin *et al.* proposed a novel intra-task dynamic voltage scheduling (IntraDVS) framework for low energy real-time applications. IntraDVS fully exploits all workload-variation slack times, achieving a significant improvement in the energy consumption. Further, IntraDVS provides an automatic tool that converts DVS-unaware programs into DVS-aware ones, thereby resulting in the mechanism being very practical for use. However, while generally effective in reducing the energy consumption of multi-task real-time systems, the IntraDVS has several practical limitations. A detailed study on IntraDVS and its successor, InterDVS can be found in [44]. In [45], Yang and Song proposed an algorithm for dynamically scaling the voltage supply to a mobile device's CPU. The decoding time for each video frame is predicted and used to select a frequency level on the CPU that will successfully decode a certain ratio of frames in time for presentation on the screen. Yang *et al.* presented a different DVS scheme, the Low Overhead Optimal Schedule for Realistic CPUs (LO-OSRC) for mobile devices. Using LO-OSRC, the CPU frequency/voltage levels positively affect the energy saving of the optimal speed schedule in the stochastic DVS model - *the more the levels*, *the more the energy saving*. Further, the major benefit of LO-OSRC is that the scheme was actually tested on ARM v5 processors that were designed for smart-phones/PDAs. However, note that the energy saving has still not reached the derived lower bound [46] which leaves the platform open for developing further solutions.

In order to maximize energy savings, some papers in the literature proposed to combine the frequency scaling technique and the dynamic hardware resources configuration in order to take advantage of both approaches while considering their mutual impacts. In [47], the authors proposed a framework, named DEPS, "Dynamic Energy Performance Scaling," which combines the two technologies. The proposed solution discovers the optimal tradeoff, maximizing the energy savings and guaranteeing the deadline of the considered application. As the power dissipated by the CPU is directly related to the hardware resources involved for a particular application, some approaches consider turning off unnecessary hardware during operation [48]. For instance, one approach is to adapt the code based on the application need. In [49], the authors proposed a power aware cache partitioning technique that enables significant energy savings by exploiting the power-gating circuit, which allows shutting off some parts for power control. In [50], the authors proposed a novel instruction queue (IQ) resizing technique, which considers both energy consumption and performance. In fact, in contrast with the former approaches, the proposed dynamic resizing technique detects, at runtime, possible memory level parallelism while exploiting a prediction mechanism to accurately tune the IQ length.

2) Coding/Decoding: Over recent years, a notable contribution in the Flexible Macroblock Ordering (FMO) is that by offloading all the processing from device's CPU to purpose designed hardware (a GPU), the performance and energy efficiency increase dramatically. However, its main disadvantage is that it requires extra changes in the hardware set-up of the device. In terms of adaptive video transmission, the method proposed in [51] focuses on video delivery over UDP/IP networks, which deploys a network QoS mechanism and determines the significance brought by encoding related parameters.

Over the last decade, *scalable video coding* (SVC) has been proposed, as an extension of H.264/MPEG-4, in order to provide an efficient adaptive framework for wireless video streaming. It provides a network-friendly scalability at a bit stream level with a moderate increase in the decoder complexity, relative to single-layer H.264. Notably, it supports functionalities such as bit rate, format and power adaptation, graceful degradation in lossy environments and lossless rewriting of quality scalable bit streams. SVC details a mechanism for decoding the video stream dynamically at one of multiple quality levels and results in significant improvements in coding efficiency with an increased degree of supported scalability relative to the scalable profiles of prior video coding standards [52]. As shown in Fig. 11, using SVC, a scalable stream can provide dynamically different numbers of video layers (base

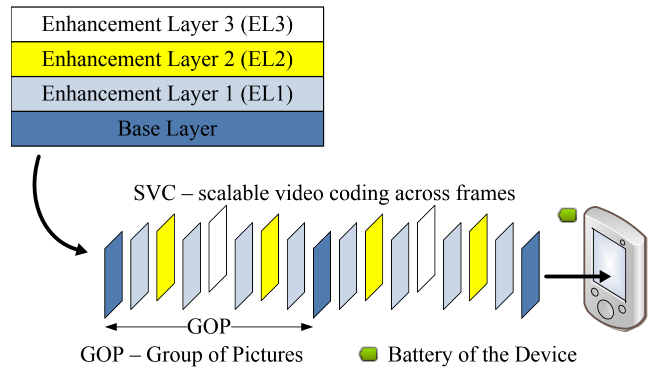

Fig. 11. An illustration of energy-based scalable video coding (SVC) across different wireless devices.

layer and the different enhancement layers) to heterogeneous clients, according to the client's processing capability and importantly, the remaining battery-life of the device. In [53], the authors proposed a novel algorithm for scaling the frame-rate of a video sequence during the video decoding process for reducing the decoding time and power consumption. The algorithm assesses the level of movement between the immediately preceding decoded video frames. If the level of movement between the previous frames is above a certain threshold, then the current frame is decoded as normal. However, if the level of movement is below the threshold, then the current frame can be discarded without decoding it and its reference frame is displayed again. Further, the dynamic scaling is achieved through any combination of three scaling mechanisms:

i **Temporal Scalability**: Changing the frame-rate of the received video stream by dropping whole frames. In MPEG videos, B-Frames can be dropped without affecting any of the previous or following frames in a Group of Pictures.
ii **Spatial Scalability**: Changing the resolution of the video.
iii **Quality Scalability**: Changing the quantization parameter for each macro-block in the video decoder. This has been proven to yield a 42% decrease in energy consumption during video decoding with a mere 13% quality degradation in the video [54].

In order to support the ongoing technological evolution of mobile phones, the development of system-on-chip (SoC) platforms is needed. Actually, hardware solutions for SVC have been deployed on general purpose CPU or DSP chips which support tremendous amount of computation and specific parallel processing. That is, once a high performance CPU chip was found, the remaining work dealt with the design of a software system for SVC. Over the years, many research projects on SVC software have been done. In [55], a fast mode decision algorithm for inter-frame SVC was proposed. In [56], the authors proposed a fast mode decision algorithm for spatial and SNR scalable video coding while [57] provides an architecture for transcoding from H.264 to SVC that supports SNR scalability. Even though high performance CPUs have been developed over the years, a single CPU inside a smart phone is not enough to efficiently cover video recording, SVC encoding, and video broadcasting at the same time. However, a mobile system cannot afford to have an extra high performance CPU due to the energy constraints in the device. In this regard, a chip model has been proposed in [58] that can be used as a co-processor chip or IP working together with CPU in the same way as a multiplication accelerator. This chip provides simplicity, scalability and area efficiency while achieving functions included in a typical SVC. However, this model does not support all functions and modes for SVC.

In an important observation, the current research efforts do not take into account color depth reduction which when reduced could potentially result in a reduction in the number of bits sent from CPU to the display. This is probably because the smart-phone industry is not ready to tradeoff video quality and the overall user experience at any cost. However, given the extremely short battery life of devices in the case of multimedia-based applications, this is an area worth investigating. Further, it should be noted that real-time adaptive and dynamic scaling, based on the instantaneous video content, is still not available. These are some of the open problems that need to be dealt with over the coming times.

C. *Speaker*

There has been considerable work on energy-efficient multimedia streaming, though there has been very little effort specifically on remote audio playout. This is because, as shown in Section II, the audio component consumes little power on its own. The major power consumed during remote playout is in the CPU (mainly due to the processing of codecs, which is a CPU activity and considered in Section III.B) and in the network interface (considered in Section III.D). Hence, there is not much state-of-the-art work on energy optimization in the audio playout component in itself and it is, therefore, not considered in depth in this paper.

D. *Network Interface*

As shown in Fig. 4, a large part of energy consumption in a wireless device is a direct consequence of the continuous use of the wireless network interfaces for communication/multimedia streaming. Further, as seen in Section II.D, both Wi-Fi and cellular interfaces consume more than 300 mW of power during multimedia streaming. Hence, most of the research efforts on *data transmission* and *reception* rely on designing power efficient protocols. The basic power saving method used for saving energy in wireless devices is to put the Wireless Network Interface Card (WNIC) into *sleep* mode when it is idle. However, saving energy for real-time traffic is more critical than for best-effort traffic, as the way to select the *sleep/awake* up periods is hard to define and has a direct impact on user QoS/QoE. Whatever the considered real-time application (VoIP or video streaming), there is a tradeoff between maximizing energy conservation and maintaining acceptable user QoS/QoE. VoIP communication is characterized by a constant traffic flow with a small packet size (typically around 20 ms of encoded voice) in both directions (uplink and downlink). Video streaming, on the other hand, is constituted by a remote server that sends traffic flow (downlink) with a variable bit rate (VBR) or Constant Bit Rate (CBR) to a client installed on the mobile device. Each application has

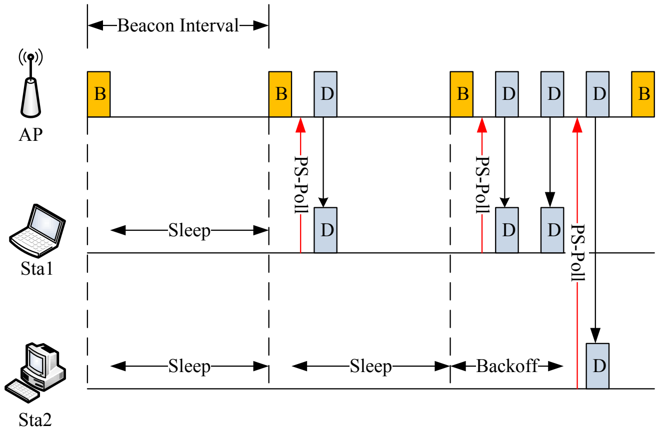

Fig. 12. IEEE 802.11 PSM mode.

its own requirement in term of QoS - VoIP and TCP-based video streaming are more sensitive to end-to-end delays (and delays variation, i.e. jitter) than to packet loss, while UDP-based video streaming is more sensitive to loss than end-to-end delays (and jitter) which are absorbed by the application buffer. Accordingly, it is hard to define a common efficient power saving mechanism for both applications, especially following the device-centric concept.

Given the exponential increase in the amount of data/video transmissions over the network interface, the energy consumed in the network interface is expected to increase continuously over the next 3-5 years. Hence, this sub-section provides an in-depth focus on the different works in this direction. This sub-section reviews power saving mechanisms proposed at the network communication level. It then analyzes existing mechanisms in today's most commonly used network interfaces in smart phones, namely WLAN and 3G/4G. Further, a special focus is provided to solutions dedicated to WLAN by illustrating a classification of these solutions regarding the targeted application, and particularly real-time applications. In addition, it presents solutions that are proposed for heterogeneous wireless and multi-hop wireless networks.

1) Power efficient communication for WLAN – IEEE 802.11: WLAN (IEEE 802.11) is one of the most widely deployed and used wireless technologies in mobile devices. The IEEE 802.11 standard outlines a built-in Power Save Mechanism (PSM) as shown in Fig. 12, whereby, a simple energy-saving technique is to put the WNIC of a device into *sleep* mode when not in use [59]. In PSM, the wireless station is allowed to transit to the lower power *sleep state* if it is not involved in sending or receiving packets. The Access Point (AP) has to be notified of the decision made by the wireless station in order to buffer packets destined for this station. Thus, the AP informs the associated stations periodically through the beacon frame and specially by enabling the Traffic Indication Map (TIM) field, if they have buffered packets destined for them. Fig. 12 depicts a use case describing the PSM with IEEE 802.11 terminals. During the power save mode, stations are in one of these two states, namely, the *awake state* and the *sleep state*. During the *awake state*, wireless stations are fully powered. In contrast, during the *sleep state*, wireless stations are not able to transmit or receive packets, which results in very low power consumption. When a station finds out that there are pending packets at the AP, it asks for these packets through Power Save (PS) polls. Thus, the station stays in the awake state until the buffered packets are received. Otherwise, it goes to the sleep state. Aiming at addressing QoS issues that appear when power save delivery (PSD) mode is used, the 802.11e group [60] included two others modes - UPSD (unscheduled power save delivery) and SPSD (scheduled power save delivery). In UPSD, stations decide on their own when to awake to request the frames buffered at the AP. This mode takes advantage of the fact that a station with data to transmit awakes from sleep period to send its packets, and hence can receive packets without having to wait for notification in the next beacon sent from AP. On the other hand, SPSD is a centralized mechanism where the AP determines a schedule for stations to awake and receive frames that are buffered at the AP. The recently introduced IEEE 802.11n standard [61] includes a couple of new power save features that reduce energy consumption, namely Spatial Multiplexing Power Save (SMPS) and Power Save Multi-Poll (PSMP). Battery life is becoming an important issue with 802.11n, since using multiple input multiple output (MIMO) antennas generally consumes more power. When taking advantage of MIMO, the WNIC has to manage the overall power consumption more effectively. SMPS improves the original 802.11 power save by allowing the 802.11 clients to inform the AP that they plan to sleep in order to conserve power. Within SMPS, 802.11n clients can maintain only one antenna (actually, one transmit/receive chain) turned on while sleeping, turning the other transmit/receive chains off to conserve more power. On the other hand, PSMP enhances the 802.11e unscheduled power save features. With unscheduled PSMP, sleeping clients can inform APs when they're ready to wake up and send traffic instead of waiting until the AP broadcasts a TIM frame. With scheduled PSMP, clients can inform the AP about a reservation through sending a Traffic Specification (T-Spec), thus avoiding the power otherwise wasted when contending with other clients using the same channel.

The main issue associated with these solutions is to compute exactly when the interface should go to the sleep mode and when it should wake up. In fact, depending on the sleep period, these protocols can increase the packet delays, which has a negative impact on the real-time applications and hence on user QoE. In case of VoIP, increasing the end-to-end delays has a dramatic impact on the user QoE as packets with end-to-end delays exceeding the packet late loss threshold (250 ms as defined by the ITU-T) are withdrawn at the receiver side. In case of TCP-based video streaming, these delays increase the connection round trip time (RTT) due to lagged data reception that degrades the throughput of the connection. Therefore, sleeping periods need to be tuned optimally in order to find a tradeoff between reducing energy consumption and maintaining user QoE.

Solutions for saving energy in WLAN can be broadly classified into two distinct classes. The first class represents traffic independent solutions, and the second class represents

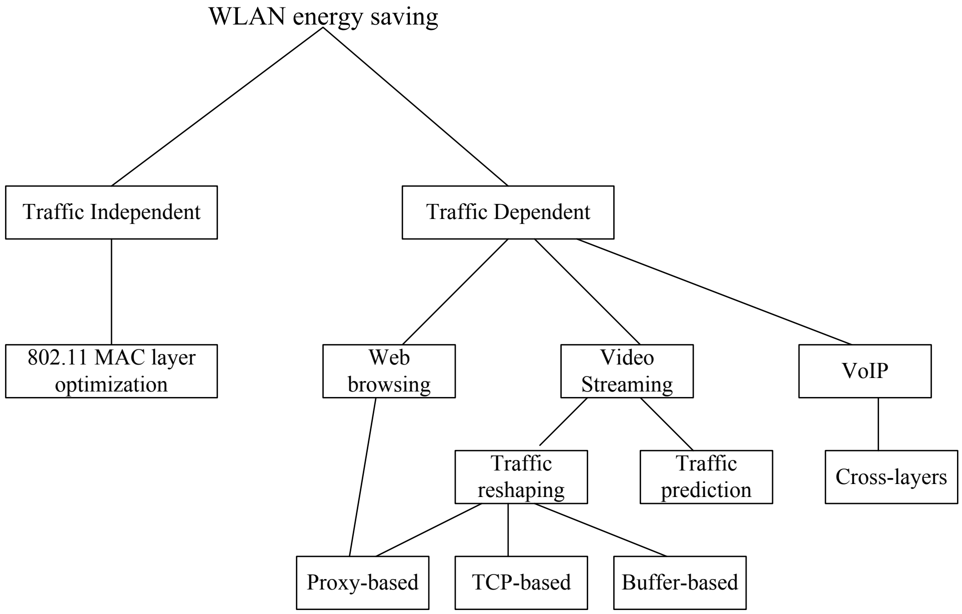

Fig. 13. Classification of power saving protocols in WLAN.

approaches relying on the traffic type (for instance, VoIP, video streaming, Web browsing, etc). Most of the solutions belonging to the first class are mainly based on MAC layer enhancements to reduce energy consumption. Meanwhile, traffic-dependant schemes consider cross-layer solutions or traffic prediction/reshaping in order to support the QoS/QoE requirements of real-time applications. Fig. 13 presents a classification of the proposed mechanisms for saving energy in WLAN. This figure shows the different solutions envisaged in the two classes. Mechanisms dedicated to VoIP use mainly cross-layer solutions to support QoS while maximizing energy consumption. They consider the application requirements in order to tune the sleep period. On the other hand, solutions for video streaming are based on traffic prediction and traffic reshaping in order to define the sleeping period.

Besides the standardization activities, there are other significant works on energy conservation for 802.11 networks belonging to the traffic independent class. Zhao [62] proposed a detailed mechanism regarding the MAC parameters to be considered for saving energy. This can be divided broadly into three main categories:

a **Conserving energy during contention**: In this category, the main idea is to reduce the contention period (i.e. waiting time before transmitting frames), by adapting the Contention Window (CW), in order to reduce the energy consumption.
b **Reducing power consumption at transmission or retransmission phases**: In this category, the main objective is to reduce the transmission time by:
  i Compressing packets
  ii Using the highest data rate allowed by the physical layer; which reduces the energy consumption.
c **Eliminating contentions, inter frame space (IFS) and acknowledgments**: In this category, the main idea is to reduce the waiting time before sending data frames or acknowledgment. Hence, the proposed solution tried to reduce the IFS and use a block of acknowledgments (as proposed for 802.11n).

In addition, the work in [63] proposed a modified version of 802.11's PSM called "SleepWell". It enables multiple APs in a network, which would normally have overlapping beacon-periods, to readjust their beacon intervals in order to eliminate unnecessary network contention.

Traffic-dependent solutions are related to the traffic type. In fact, there are solutions related to best-effort traffic, such as web browsing (HTTP), and solutions related to real-time traffic, such as video streaming as well as VoIP. In [64][65], the authors addressed the energy-saving for both applications (video and VoIP) by optimally tuning the *sleep-period*. Particularly, the work in [64] demonstrates that the wireless network can be turned off with periodic turn on messages. Moreover, the work in [65] considered the packet inter-arrival and the MAC layer delay variation to plan the duration of the sleep period. By considering a simple 802.11 analytical model as well as a 64 kbps continuous data connection, it was found that the optimal value of sleep period is 20 ms. In [66][67], the authors proposed to derive a dynamic sleep strategy to tune the sleep period and the application packet intervals according to the collision probability. By using the collision probability, a tradeoff could be found between maximizing network capacity and energy conservation. It was suggested that if the collision probability is low, the station could go to sleep for a period inversely proportional to this probability. However, if this probability is high, the station could be maintained as it is, in the *awake state*. The authors in [103][104] proposed a QoE-based power save mechanism for VoWLAN (VoIP over WLAN). The proposed solution is based on a cross-layer mechanism, which allows the network interface of a client device to sleep [105]. "GreenCall" dynamically calculates the sleep interval of the WNIC by comparing the latency involved in the transmission and decoding of packets, to the packets' play-out deadlines.

A pioneering solution to reduce energy for video streaming is based on predicting the traffic pattern produced by the video server. This is done by predicting the burst-based pattern that is followed by streamed video, so that the WNIC can sleep in silent periods and wake up for the burst periods. Works in [68][69] presented a client-side prediction scheme, wherein, they used history-based prediction and statistical linear prediction strategies to predict the occurrences and lengths of the no-data time intervals. These predictions were used to select the time periods during which the communication is suspended. However, the main weakness of such solutions is that they rely on the accuracy of the prediction. If the predicted duration is too short, then the energy saving is not perceptible. If the predicted sleeping duration is too long, then the end-to-end delays are increased which reduce the user QoE. The solution in [70] can reduce the complexity of the traffic prediction mechanisms by using traffic shaping with an intermediate proxy. The proxy groups the frames together in order to constitute a burst of packets. Thus, during the period where the proxy constitutes the burst of data, the WNIC at the mobile side can go to the *sleep* mode. The idea of using a proxy was introduced in [71] and [72]. In [70], the author proposed to adapt the HTTP-level Power Web Proxy (PAWP), which was initially dedicated to handle HTTP-based traffic, by proposing the Power Aware Streaming Proxy (PASP). PASP tackles the streaming traffic tunneled through HTTP. The main idea is to handle in-stream media transformations such as: (i) forwarding only the most appropriate video layers regarding the client rendering capabilities; (ii) selectively dropping B and P video packets. In [73], the proxy-based solution was used to reduce energy for audio streaming by reshaping the constant bit rate (CBR) server traffic into a burst-based traffic.

The authors in [74] proposed a client-centric approach to reshape the TCP traffic into bursts. However, this work is more dedicated to best effort traffic as the data transmission delays are highly increased, which is not acceptable for a TCP-based streaming application. PSM-throttling [75] is a novel scheme proposed to increase energy savings in the case of TCP-based video streaming applications. The authors exploit the unused Internet bandwidth raised from the principle of bandwidth throttling at the server-side to save energy at the WLAN client side. Since the effective data transmission is lower than the available bandwidth, the authors propose to exploit the unused network bandwidth to reshape the TCP traffic into periodic bursts with an average throughput equal to the server transmission rate. Therefore, the packet arrivals can be easily predicted at the client side, which allows the WNIC to enter into *sleep* mode. The PSM-throttling solution is considered as a client-centric solution since the TCP client controls the server transmission rate by using ACK choke and un-choke packets.

Recently a progressive streaming solution based on HTTP and P2P-based delivery has been proposed for efficient video streaming. In [76] the authors present an empirical evaluation of battery power consumption for streaming data to mobile devices. They compared 11 popular video streaming applications available on the Internet. These applications are based on different streaming protocols (HTTP, Chunk-based, RTSP, and P2P). The obtained results show that chunk-based streaming is the most power efficient as the traffic shaping mechanism is adopted to use PSM. Meanwhile, P2P streaming is not power efficient as this solution requires additional transmission of control traffic as well as uploading data, which means the WNIC stays predominantly in the *active state*.

2) Power Efficient Communication in 3GPP's Long Term Evolution (LTE) Evolution: 3G mobile networks, such as LTE and beyond 3G are mainly data centric and have significant multimedia traffic, which consumes the battery rapidly. In contrast to 802.11, the LTE standard supports the Discontinuous Reception (DRX) [77] mode for energy saving in both the *idle state* and *connected state*. In the *idle state*, the radio connection between the user equipment (UE) and eNodeB (LTE Base station) is released, while the UE context is still maintained by the mobility management element as well as by the serving and packet data network gateways. In the *connected state*, on the other hand, both the radio connection and the UE context are active. The DRX mode is activated by the UE after a period of time (t_1) from successfully transmitting/receiving a data packet. That is, the UE does not receive or does not have packets to transmit during the period t_1. The UE entering the DRX mode would be still in the connected state (i.e., the radio connection would be active). The UE begins by turning off the WNIC interface periodically for a duration known as the DRX *short cycle*. At the end of this cycle, the UE wakes up to listen the downlink control channel to check whether it would receive data in the uplink frame as well. If there is no transmission/reception scheduled, the UE goes into *sleep mode* for another DRX *short cycle*. After a period t_2 (i.e., from the beginning of the DRX procedure) where no transmission/reception is scheduled by the UE, it enters the DRX *long cycle* mode. In this cycle, the UE switches to the idle state and the RRC connection is released. In this state, the UE listens only to the downlink broadcast for paging procedures. Fig. 14 shows the basic DRX mode in LTE wireless network interface.

The major parameters affecting the DRX procedures (such as *short cycle* duration and *long cycle* duration) are announced by the eNodeB [77][78]. These parameters particularly impact the performance of the application, as there would be extended delays when the UE has to transmit/receive packets. If the UE is in the *idle state*, these delays occur mainly because the UE has to re-enter the network (establish new RRC connection) before transmitting/receiving data. If the UE is in the *connected state*, these delays are related to the duration of the sleep period (DRX long and short cycle duration). Like in the PSM mode of WLAN, the sleeping period has a direct impact on the delays. If this period is too long, the packets are buffered at the eNodeB, which increases the delay. Different studies [79][80] have suggested that the DRX cycle should be adjusted dynamically based on certain conditions. For instance, the authors in [81] proposed an adaptive DRX scheme where the DRX cycle is updated automatically based on available battery power in the mobile terminal. It is suggested by the authors that UE with available battery power

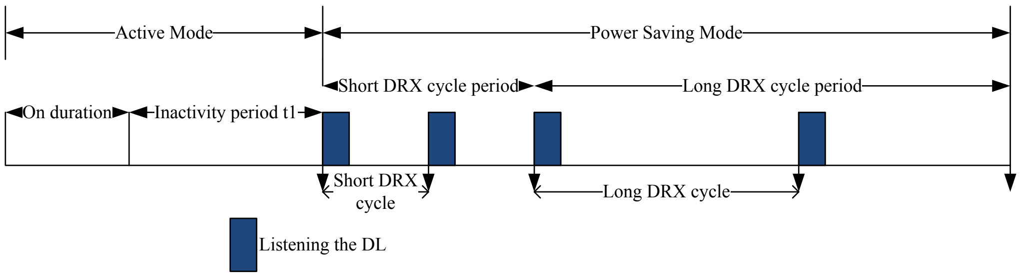

Fig. 14. Simplified DRX mode in LTE.

lower than a certain threshold can be assigned longer DRX periods than UE with higher available battery power, thus reducing power consumption. Another adaptive DRX scheme is presented in [82], where the DRX cycle is dynamically adjusted based on arrival pattern of data packets. It should be noted that DRX is not always feasible as rich media content transmission has different QoS requirements as compared to traditional data transmission. In [83] the authors proved the benefit of using a long DRX cycle and analytically presented that power saving performance and packet delay contradict each other. A tradeoff has to be established between power saving performance and packet delivery latency by optimally tuning the DRX cycle. In [84], the authors showed how the parameters of the DRX impact video streaming and VoIP. For video streaming applications with high data rate, the short DRX cycle does not affect the packet delay performance. However, for video with low data rate, the DRX time decreases which reduces the gain of DRX procedure in terms of energy conservation.

3) Power Efficient Communication in Heterogeneous Networks/Multi-hop based Transmission: This sub-section details adaptive energy-saving mechanisms in the device through careful selection of wireless networks, especially during multimedia streaming. There are two broad domains for minimizing the device energy consumption while continuously exchanging data through the network. These include: *'network selection and handover'* in the case of the availability of multiple wireless networks, and the *'use of multi-hopping for minimizing the energy consumption'*. Keeping these in mind, this section discusses work in each area by reviewing the most pertinent solutions.

Most mobile devices today are shipped with multiple heterogeneous wireless network interfaces, such as WLAN, UMTS, GPRS and Bluetooth [85]. Each of these networks has different energy consumption characteristics. For instance, measurements show the relationship between the energy consumption per unit time of communications in UMTS and IEEE 802.11b/g to be similar to each other[63][86]. However, the energy consumption as a function of the data transferred can be up to 300 times larger over the UMTS network interface as compared to other network interfaces. Trestian *et al.* [87] investigated new techniques in order to exploit these energy characteristics. In this work, a utility function has been proposed for ordering the vertical/horizontal handover between different networks within range, based on the predicted value of energy consumption across each network. Mahkoum *et al.* proposed a power management framework which enabled a device to maintain a network presence across multiple heterogeneous networks by powering off all-but-one of the network interfaces on a device [88]. The authors in [89] proposed a technique called "CoolSpots" for reducing the power consumption of wireless mobile devices with multiple radio interfaces. The solution proposed in [90] is similar to [91] but would not only work for heterogeneous network interfaces but also for different traffic patterns. The efficiency is achieved by utilizing proxies on each of the heterogeneous networks to feign the connectivity of the device's network interfaces. If a connection was made through the proxy for any of the sleeping network interfaces, the proxy would contact the device's active interface, which in turn would wake up the interface required. In [91], an algorithm is proposed for vertical handover between heterogeneous wireless networks in the scenarios where a device has multiple network interfaces. The algorithm balanced the load among the attachment points (base stations and access points) and would also maximize the network lifetime.

In [92] and [93], a video delivery model is proposed for transmitting video content to wireless mobile devices in a Bluetooth/Wi-Fi based *ad hoc* network, as compared to standard cellular networks. The model assessed the device characteristics and the battery life of a mobile device and then adapts the enhancement layers up or down, in an MPEG-4 SVC video. The result was that the life-time of the *ad hoc* network increased by 200%. While the proposed model is compatible with energy-aware routing protocols, they have not been further investigated in the literature. Similarly, the residual power of a device was the only characteristic that was monitored periodically. Aupet *et al.* presented a novel web service for Automatic Video Data Flows Adaptation (WAVA) which allowed adaptive video streaming across heterogeneous networks [94]. In [95], a conceptual framework based on utility function (UF) is introduced, which modeled video entity, amount of adaptation, resource utility, and the relationship between them. Instead of modeling the UF through analytical models, the proposed approach performed UF prediction based on the video content and classified the video clips into a number of clusters. Based on the predicted UF, the video transcoding parameters were applied. However, neither the transmission aspects of the video delivery nor the device's energy were considered in the algorithm.

Over the last decade, multi-hop networking has been a strong contender for energy-efficient transmission. In this scheme, the communication, between the source and the destination, takes place in multiple hops, whereby the communication distance between the individual hops is very small. This significantly reduces the required transmission power and thereby increases the probability of transmission over long distances. At the same time though, it increases the processing/computations due to increased overhead and re-transmission of information by each relay node. In a landmark paper, Banerjee and Misra investigated the minimum energy paths for reliable communication in multi-hop wireless networks [96]. Further, in [97], the authors proposed an energy-efficient broadcast and multicast routing mechanism for a multi-hop based wireless network. Similarly, there has been considerable work on different aspects of multi-hop networking [98][99], wherein the overall energy consumption has been shown to be reduced significantly. The multi-hopping mechanisms have been mainly considered to reduce the energy consumption of the network, rather than that of the device. With the advent of social media and substantial upload of images and videos by the users, multi-hopping could also become a potent tool for energy optimization in the device. Further, based on the multi-hop technique, the researchers in Aalto University in Finland have designed a network proxy that claims to cut the power consumption of 3G smart-phones up to 74%. The key idea behind these new energy savings is the network proxy which enhances performance of the device and reduces power usage through a planned reduction in the transmission distance and thereby reduces the power consumed by the flow of data between a mobile phone and the network [100]. However, apart from this Aalto University project, to the best knowledge of the authors, there has not been major research outcome in terms of energy optimization in the device through multi-hopping. This is a major research concern and needs to be addressed in the future.

E. Other Mechanisms Related To Joint Energy Savings Across Components/OSI Layers

It could be seen from the above work on network interfaces that optimizing energy consumption in the network interface involves changes in the processing unit. In an effort to jointly optimize the energy consumption in the CPU and the network interface Mochocki *et al.* introduced a novel approach to minimize the energy consumed by the network resource through careful selection of voltage and frequency levels on the CPU [101]. Their contribution leverages a network-aware Dynamic Voltage and Frequency Scaling (DVFS) algorithm and a CPU-centric DVFS algorithm for reducing the energy consumption in the network resource and also across the system. In a landmark paper, Mohapatra *et al.* [102] proposed a cross-layer framework for optimizing energy across different components, including the CPU and network interface. However, though the paper considered joint adaptations, it did not consider joint optimization of different parameters. In fact, to the best knowledge of the authors, a joint energy optimization across CPU, display and network interface is still an open research problem that needs to be tackled. The work in [106] presented a general framework of a cross-layer network-centric solution and then described the recent advances in network modeling, QoS mapping and QoS adaptation. Further, a novel quality-oriented adaptive media play-out scheme was proposed by Park and Kim [107]. In this paper, the proposed mechanism predicts the buffer occupancy and triggers the play-out adjustment when a play-out pause or skip was about to occur. Similarly, an advanced scheme has been proposed in [108] that retained the smoothness in the video play-out even while adapting to the channel conditions in real-time. An important area in energy savings research has been the idea of middleware frameworks. These allow a device to coordinate the adaptation of multimedia applications running on them and to dynamically manage their underlying hardware resources. In a significant work [109], the authors proposed a power management middleware for mobile devices, which not only considers energy savings for the processor but also optimized energy-savings for other device parts such as display unit, RF unit, keyboard, memory, etc. These represent the different energy saving mechanisms focusing on several layers of the network and importantly would be beneficial for optimizing energy consumption across several components in the device [110].

On the other hand, there are some works that addressed the joint network-mobile terminals optimization for saving energy. Indeed, they focus either on the process of user association and attachment to the network (mainly with the base station), or on introducing a proxy in the network infrastructure to help the mobile device reduce energy. In [122] authors propose to encompass dynamic BS operation and the related problem of user association in order to save energy. The authors formulate a total cost minimization for a flexible tradeoff between flow-level performance and energy consumption by coupling user association with turning ON/OFF the BSs. Generally speaking, the proposed framework: (i) switches the BS ON/OFF according to their serving traffic load and energy consumption, (ii) allows the mobile terminal to select the optimal BS (in ON state) that maximizes flow-level performance (in terms of delays, data rate, etc.) while maximizing the bits per joule. Based on the fact that switching off the BS to reduce energy is not very interesting for network operators, mainly due the challenge of the implementation process and the possible degradation of user experiences, the authors in [123] extend their previous work [122] in order to propose a component-level deceleration technique rather than switching OFF the BS. The deceleration technique, called *speed scaling*, is more conservative than totally shutting down the BS. Instead it involves switching over to a dynamic power manager during periods of low load while ensuring full coverage. The authors formulate the same total cost minimization solution as in [122], with the introduction of a decelerating coefficient. In [124], the authors propose to use dual access point association in order to help the mobile terminal conserve energy. Indeed, they placed the proposed solution in the context of wireless networks with Relay Stations (RS), and considered that RSs have different characteristics than the BSs in terms of transmission powers and physical coverage. The authors show with an example, where a mobile terminal is connected to the RS for the uplink communication (as usually the RS is near in distance) and to the BS for the downlink communication, which considerably reduces the energy consumption at the mobile side. Stateful proxy-based system for Control overhead Elimination and Payload reduction Through Elimination of Redundancy (Scepter), introduced in [125], is based on the observation that a reduction in the number of bytes transmitted over a wireless interface directly correlates to a reduction in the power consumed by the wireless interface. Scepter reduces the number of bits to communicate the same information between mobile devices and the network infrastructure. To do so, a stateful proxy is collocated with the AP, where its main functionality is to capture packets from or directed to a mobile device, and according to the communication direction, the proxy adds or removes information from the packet payload and the header. For instance, the mobile terminal can reduce the number of bytes to be sent, by using Robust Header Compression (RoHC), and the proxy reconstructs the entire initial header and sends the packet to the remote receiver.

IV. MAJOR GLOBAL RESEARCH INITIATIVES ON ENERGY OPTIMIZATION

There are several major global projects on general energy optimization investigating different energy-saving aspects in networks with some amount of energy optimization in devices. However, it should be noted that since the extensive growth of smart-phones has been over last 3-4 years only, the major research initiatives *on energy optimization in multimedia-centric* devices are limited to less than 3-4 years. This in turn results in few *energy-focused* projects on wireless devices. At the same time, these initiatives give a broad overview of how the research is headed in this domain.

Over the last few years, the European Union Framework Program (FP) has put lot of emphasis on the control of energy-emissions in next generation emerging technologies. A current European project *FIT4Green* aims at contributing to ICT energy reducing efforts by creating an energy-aware layer of plug-ins for data center automation frameworks [111]. Similarly, another current EU project *ECONET* aims at studying and exploiting dynamic adaptive technologies for wired network devices that allow saving energy when a device or even a part of it is not used [112]. However, this project mainly investigates the switching aspects in wired networks. Further, another related EU initiative, *Greenet*, is an Initial Training Network Marie Curie project that is focused on the analysis, design and optimization of energy efficient wireless communication systems and networks [113]. In an important development, an EPFL (École Polytechnique Fédérale de Lausane)-led EU research project, “Steeper” deals with increasing electronic device efficiency by a factor of 10X. This is a very significant European project designed with a long-term strategy, wherein the focus is to tunnel field effect transistors and semi-conducting nano-wires to improve the efficient use of energy in electronics [114]. In a related development, Mobile VCE, a collaboration partnership between companies and UK universities, has outlined a new research stream called “Green-Radio” to improve the power and spectral efficiency of wireless networks [115]. However, except for the EPFL-led “Steeper” project, all other solutions focus on large-scale energy optimization in the networks. Over the last three years, there have been several initiatives on energy optimization in wireless devices. A recent European FP7 project *C2POWER* (cognitive radio and co-operative strategies for power saving) focuses on developing and demonstrating energy saving techniques for multi-standard wireless mobile devices [116]. An interesting project, funded by the Finnish funding agency for technology and innovation (Tekes) under the Future Internet research program is the reduction in the energy consumption in the smart-phone while transmitting data to the network [100]. The key idea is to use a combination of a new software and network proxy hardware to dynamically alter the use of the phone’s cellular radio in order to optimize the energy consumption in the device. Currently, Ericsson has been coordinating a project called *ACTOR* (Adaptivity and Control of Resources in Embedded Systems) for better control of software resources in servers and mobile phones. The idea is to distribute the computer processing resources between applications in such a way that would make it possible to create software that can adapt itself to change in the environment [117].

Apart from European level initiatives, there have been a considerable number of research projects worldwide that deal with energy consumption in devices and networks. Prominently, the “Energy-Efficient Internet” project [118], investigated at the University of South Florida, focuses mainly on reducing energy consumption at the edge of the network. The project aims at minimizing energy consumption in wired networks by addressing energy use of the Ethernet links and by proposing to employ proxies to allow end-devices to sleep when idle. A proxy-based technique was also proposed by the “Energy-Efficient Digital Networks” project [119], which revolved around adapting the link rate based on the traffic level, in order to reduce the energy consumption. Another project initiative, *Nets-FIND* [120] investigated designs for new architectural components in order to provide better support for selectively-connected networking, by which sleeping hosts can retain their standing in the network or delegate agents to act on their behalf during their absence. Recently, under the national science foundation (NSF) sponsored program, a pair of researchers from USA have been working on designing a more energy-efficient processor for mobile embedded systems, a technique that could actually lower mobile device costs by simplifying the handhelds. In addition, a global consortium *“GreenTouch”* has been formed with 27 members including leading companies like Samsung, Alcatel and other academic and research institutions [121]. Their goal is to develop new architecture, specifications and roadmaps – and demonstrate key components needed to increase network energy efficiency by a factor of 1000 from current levels. The *GreenTouch* Initiative is stimulated by recent research that identifies a gap between rapid network growth rates today and historical equipment efficiency improvements – a gap that promises to increase over the decades ahead. Technologies in use today, even considering best-case projected energy efficiency improvement, are not expected to be sufficient to check the rate of energy consumption over the long term. At the same time, key technology energy limits associated with existing underlying components of ICT networks (optical, wireless, electronics, routing, architecture, etc.) are still many orders of magnitude below current operating levels. The vision of *GreenTouch* is to create ICT networks and technologies that enable a sustainable Internet, and serve as an open, collaborative platform that allows its members to make best use of their expertise and accelerate the creation of these new networks. It is anticipated that the initiatives of *GreenTouch* would deliver demonstrations of key components needed to realize a fundamental re-design of networks that dramatically improves their energy efficiency and reduces the overall carbon footprint [121].

V. SUMMARY AND OUTLOOK

This paper provides a comprehensive insight into the energy consumption behavior in a smart phone/high-end mobile device. In order to measure the energy consumption across the different functionalities and computations of a device, a particular model, the Android based HTC Nexus One phone, was used for extensive testing. In terms of energy consumption, the three components – *display screen*, *CPU* and *the network interface* were found to be most significant, while the energy consumption of the speakers was relatively negligible. Further, this paper surveyed different state-of-the-art energy-saving techniques and solutions that have been developed over the years and global research projects that are currently being developed.

To begin with, though the multimedia codecs, video compression techniques and efficient display screens would continue to become better over time, the battery depletion still remain as the biggest drawback of the electronic world in general; and smart-phone world in particular. In this context, there is a **fundamental problem in the energy consumption space that is still overlooked**. There are no sophisticated adaptive processes in the device that prolong the battery life in real-time, depending on the nature of the current application and current battery level. Secondly, implementing an image adaptation and importantly, a region-of-interest display adaptation in the device screen in real-time is an open problem that needs considerable attention. Further, the adaptive mechanism would involve significant design challenges in the middleware layer design and importantly, design of individual components for different aspects like – *color depth adaptation*, *image contrast adaptation* and importantly, *region-of-Interest based adaptation in the device* during streaming/browsing. Thirdly, even though there is a high amount of multimedia traffic due to Facebook, Google+ and other social media, there is no available mechanism for a device to optimize its energy consumption during multimedia streaming. The inability of today's systems to optimally integrate the features of the Internet technologies into multimedia-centric devices poses major challenges for mobile devices, especially since the vast majority of Internet traffic used by smart-phones corresponds to multimedia or video related information. These open research problems present excellent opportunities for researchers to solve them individually and build a framework for adaptively optimizing the battery consumption in the multimedia-centric devices in real-time. In this context, a combination of different adaptive power-saving technologies across different components of the device; and across different layers of OSI stack offer an enormous potential for energy savings in mobile multimedia.

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