Energy-efficient Device-differentiated Cooperative Adaptive Multimedia Delivery Solution in Wireless Networks

Ruiqi Ding, *Student Member, IEEE,*, Cristina Hava Muntean, *Member, IEEE*
and Gabriel-Miro Muntean, *Member, IEEE*

Abstract

There is very much interest in balancing remote delivered multimedia quality and energy consumption in a heterogeneous wireless network environment. This paper proposes a solution for Energy-efficient Device-differentiated Cooperative Adaptive Multimedia Delivery over wireless networks (EDCAM), a hybrid innovative approach which combines multimedia quality adaptation and content sharing mechanisms to save energy at client devices according to their different characteristics. EDCAM relies on an automatic application-aware device profiling, which is proposed to assess individual *device energy constraints*. These constraints along with QoS delivery scores are used as metrics for the multimedia delivery quality adaptation. Devices make use of content sharing partners with which retrieve the content cooperatively, reducing the usage of high energy consuming networks and therefore increase the delivery energy efficiency.

Simulation tests in a WiFi and LTE-based heterogeneous wireless network environment with increasing number of video flows and users show how the proposed EDCAM solution results in significant improvements of up to 40% in terms of energy efficiency in comparison with three other state of the art solutions, while maintaining the performance of multimedia content delivery and estimated user perceived quality at the highest levels.

Index Terms

Multimedia, Energy, Application Profiling, Wireless.

Ruiqi Ding and Gabriel-Miro Muntean are with the Performance Engineering Laboratory, Dublin City University, Ireland, e-mail: gabriel.muntean@dcu.ie

Cristina Hava Muntean is with the National College of Ireland, e-mail: cristina.muntean@ncirl.ie

I. INTRODUCTION

The latest developments of wireless communication technologies in terms of mobility and scalability enable mobile devices to inter-connect people and devices anywhere and at anytime. The global smart device market grew 25.3% year over year in the second quarter of 2014 alone and the number of mobile network-connected devices shipped in a quarter has exceeded the 300 million unit mark, representing an outstanding record for this industry to date [1]. It is expected that over 1.25 billion smartphones will be shipped worldwide in 2014, representing a 23.8% increase in comparison with the similar number in 2013 and more than 1.8 billion units in 2018, resulting in a 12.7% compound annual growth rate between 2013-2018 [2]. Cisco estimates handsets will generate in excess of 50 percent of mobile data traffic in 2014, and the video content will account for more than two thirds of the globe networking traffic by 2016 [3]. This trend is made possible by the multimedia capability support and ubiquitous network connectivity provided by the latest smart mobile devices.

As the number of increasingly powerful mobile devices such as smart phones and tablet PCs grows, and they run many and more diverse communication and rich media-based applications, they play increasing important roles in people's life. Mobile devices are used everywhere for example in airports, on the street, in coffee shops and conference centres, for work and entertainment, for communications, computations or presentations. Notably, recently more than half of the Internet searches were performed from mobile devices [4]; multimedia-based traffic accounts for 49 percent and 53 percent of the total data consumption over smartphones and tablets, respectively [5].

The latest mobile devices are designed to be complex, but compact, and therefore it is a requirement to be powered by slim and light batteries. These batteries have limited lifetime and consequently energy-efficiency is a key issue. Many energy saving solutions have been proposed, including communication-oriented mechanisms [6]–[10]. In the context of multimedia content delivery, adaptive solutions have been proposed to improve the energy efficiency of multimedia transmissions and remote playout, while also maintaining high levels of quality of service (QoS) [11]–[15]. Some of these adaptive solutions are specific to wireless deliveries to mobile devices [16]–[23].

There are various technologies (e.g. WiFi, WiMax, LTE) to support wireless networking in hot spots, at home or within company premises which establish a heterogeneous wireless network environment providing ubiquitous connectivity to smart devices, as illustrated in Fig.1. Different network interfaces are associated with these technologies and consequently they have different characteristics in terms of transmission bandwidth and energy efficiency. Therefore exchanging content between devices by utilising diverse network interfaces gives opportunity to improve the performance of wireless content delivery and multimedia content in particular. This is especially useful when multimedia is delivered to mobile devices in places with many people, where many individuals may require access to the same content.

In such scenarios, there are major challenges. Some networks are often congested when people density is high; others have lower bandwidth. Some solutions [24]–[29] propose using mobile ad-hoc networks (MANET) to form sharing groups to help overcome congestion or save energy. However very much effort is put into group management, which offsets the energy saving benefit on the client side. Additionally, multi-hop transmissions affect seriously the throughput [26] and solutions extend also in the wireless ad-hoc [30], [31] and wireless sensor networks [32], [33] space.

Other solutions save energy by performing quality adaptation based on device battery energy level and network conditions only [34], [35]. Park et al. [16] change the quantization parameter for blocks in the video decoder for energy saving. They develop a dedicated chip for scalable video coding content delivery [17]. ESTREL [22] and EVAN [23] adapt video quality to the remaining battery level of mobile devices. Adams et al. [18] reduce the frequency of client wake ups by buffering traffic at access point and changing the timing for sending data traffic. Trestian et al. [21] adjust video quality to remaining energy level and signal strength. Similarly Kennedy et al. [20] adapt video quality to the remaining energy level and video duration. The above solutions consider devices in the same context. Along with the video delivery application, devices may simultaneous run multiple applications with different power demands that propose different energy constraints on the devices. Hence a comprehensive application-aware energy modelling is needed. The modelling will assist the implementation of device differentiated multimedia content adaptation.

Devices with different energy constraints require content of different quality to prolong battery life. Even energy-oriented content sharing schemes [6], [24], [36] fail to address such issues. This is because they assume the available content is of the same quality, and allow a group of devices to share the content of the same quality among them. This assumption obviously does not perfectly suit current trends of offering content of multiple quality to suit various user preferences. Quality adaptation and device differentiation are not considered either.

Going beyond the existing state of the art, this paper introduces a novel *Energy-efficient Device-differentiated Cooperative Adaptive Multimedia Delivery Solution (EDCAM)* for heterogeneous wireless networks such as the one illustrated in Fig. 1. The proposed *device differentiated* solution includes application-aware device profiling and energy efficient quality adaptation to suit individual device characteristics. EDCAM considers both *interest in content* and *device required quality level* in its *adaptive*

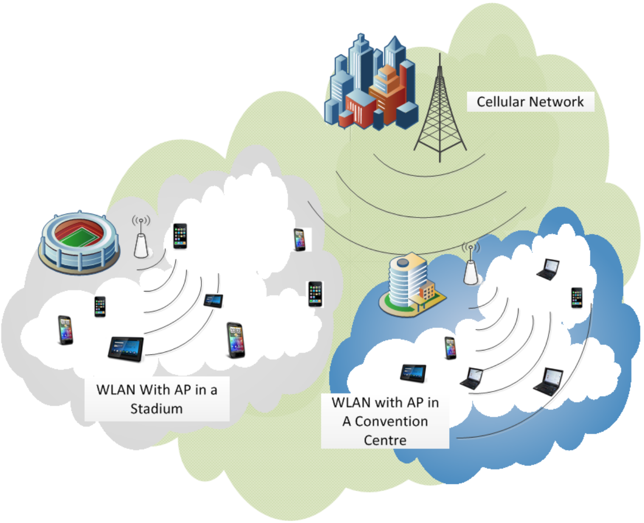

Fig. 1: An Illustration of A Heterogeneous Wireless Network Environment

cooperative delivery process.

EDCAM's multimedia delivery process employs a cooperative behaviour and uses one neighbouring device with the same interest in the content as partner for multimedia content sharing. The partner selection is based on energy-oriented device characteristics. EDCAM also uses a quality-based adaptation algorithm for further energy saving which adapts video quality based not only on network conditions, but also on an energy-oriented device profile.

EDCAM constructs an energy-oriented system profile including power signatures of various device components for each running application. This profile reflects the current energy constrains of the device and combines software and hardware-related aspects. Based on this profile, if neighbouring devices with the same interest on the content of the same quality exist, the most energy constraint device is selected as a partner for cooperative content download to maximise the benefit. Meanwhile an energy efficient content adaptation is performed for the content delivery.

This paper presents EDCAM in details, including its architecture, energy-oriented system profiling, co-operative content delivery with a partner device, and energy-efficient adaptive content delivery mechanism. Simulation-based testing in different conditions and with various load shows how EDCAM outperforms other state of the art solutions in terms of energy-efficiency and performance of delivery.

The structure of this paper is as follows. Section II discusses related works on energy-efficient wireless multimedia content delivery. Section III introduces EDCAM's principle, its architecture and algorithms. Section IV presents EDCAM performance evaluation in comparison with other approaches and section

V draws the paper's conclusions.

II. RELATED WORKS

Wireless multimedia content delivery to mobile devices involves large data transmission over wireless network interfaces, multimedia data decoding, and content (dis)play, which are high energy consuming tasks [37]. Increasingly complex mobile applications and fast, yet increasingly energy demanding hardware, make the energy efficiency a very important issue. Unfortunately, the latest improvements in battery technology could not keep up with the increasing energy demands of mobile devices and there is a need for energy-efficient solutions for wireless content delivery. In this context, the research performed worldwide mainly focuses on three avenues: traffic shaping (which makes network interfaces sleep longer to save energy), content sharing (which reduces networking traffic) and quality adaptation (which reduces the amount of data to be exchanged and processed).

Most traffic shaping solutions cache the content at the server and schedule content receiving for clients according to the traffic shape. By taking this approach, the clients can sleep longer, and receive data efficiently once they wake up. Yan et al. [7] introduces a client-centred TCP compatible scheme that tracks each TCP connection to determine the timing to transit wireless network interface card into sleep mode. The solution also shapes the traffic from the client side by requesting the server to send data bursts in order to prolong sleeping intervals. This work is limited to TCP-based applications, including web browsing and FTP downloads.

Buffering data at the access point (AP) can also increase the device sleep time. Adams et al. [18] buffer the data traffic at AP in order to hide the traffic when the client is in sleep mode. Thus the frequency of client wake ups is reduced, conserving energy at client devices. Based on this work, Adams et al. [38] propose a power save adaptive algorithm that works in all stages of multimedia delivery: reception, decoding and playing. In the reception stage, data traffic is buffered at the AP and sent to the client when it wakes up. Lower yet acceptable bit rates are used for power saving in the decoding stage. In the playing stage, screen brightness and speaker volume adaptations are applied for achieving energy efficiency.

Song et al. [39] have proposed a quality-oriented cross-layer solution for energy efficient multimedia delivery in wirelss network. Data is shaped into bursts at application layer to prolong the sleep interval of Wireless Network Interface Card (WNIC). While at MAC layer, a dynamic WNIC scheduling scheme is employed to predict the data arrival pattern so that the WNIC is waken up in time for data receiving. Cross layer information is utilised to provide high energy efficiency without compromising user experience.

Content sharing reduces the traffic from the server to the clients. For content sharing, the server transmits the original content to one of the users of a group of users requiring the same content. The content will be then shared within the group of devices. The server reduces the energy consumption to only a fraction of the group size. GroupDL [8] is a typical content sharing scheme using the above mentioned mechanism, but it cannot guarantee any energy reduction at the client. In fact, the total energy consumption on the client side is similar with that of traditional solutions. Chen et al. [6] introduce a scheme where devices can request other devices with higher energy levels to download content for them, then transfer it locally. Tests performed on an iPad showed how energy was saved because less 3G interface usage was required for the device with lower energy level. However, the device that performs the download incurs higher energy consumption. Other content sharing based energy efficient solutions [24], [26], [28], [36] take the similar route that offloads content to local wireless network. Yet they have very much the same limitation of not being practical when local networks are often congested, others have lower bandwidth or free AP is not available. Meanwhile the group management and mobility management have always been challenging.

Quality adaptation during multimedia content delivery is also an effective approach to energy saving. EVAN [23] and ESTREL [22] use this approach, adapting the video quality based on device characteristics and remaining battery levels. Scalable video coding such as MPEG-4 SVC [40] enables layer-based multimedia quality adjustments. Devices subscribe to enhancement layers only if their remaining energy levels are high. Otherwise they un-subscribe from some enhancement layers to reduce the amount of data to be received/transmitted and save energy. SAMMy [21] is a dynamic video delivery solution that adjusts content quality based on estimated signal strength and monitored packet loss rate. These parameters are utilised to make more efficient use of the wireless network resources, increase user perceived quality and save energy. DEAS [19] adaptively changes the video QoS level by monitoring the application holding on and the current residual energy. DEAS is the first adaptive streaming solution that considers application running environment (i.e. not only the current multimedia streaming application, but also other applications) and device features that put different energy constraints on the device. Alt et al. have proposed [13] that assess the level of movement between continuous frames. The frames with major difference than the previous frame have to be delivered as important information is lost otherwise. However it drops frames with little difference in movement to save energy. Park et al. [17] have proposed a SNR scalable architecture that trans-coding from H.264 to SVC for energy saving. They developed a dedicated chip for trans-coding in order to release mobile CPU from the computational complexity of trans-coding in adaptive content delivery scenario.

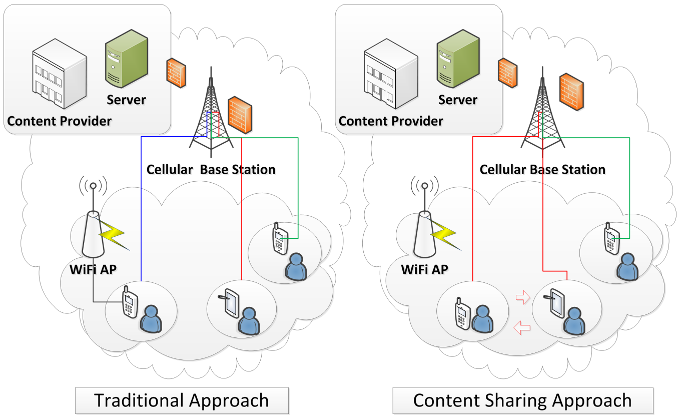

Fig. 2: Different Multimedia Content Delivery Strategies

As indicated by Martin et al [41], there is a need for a more sophisticated adaptive approach that takes the nature of the current application and current battery level, analyses and processes the data and adjusts the delivery process in an innovative manner in order to prolong the battery life in real time for mobile devices. This is a little researched area in the energy consumption space. In this paper, we addresses this issue and present a cooperative adaptive multimedia delivery solution for mobile devices that combines device-differentiated application-oriented energy modelling, cooperative content delivery and content quality adaptation approaches in order to save energy.

III. Energy-efficient Device-differentiated Cooperative Adaptive Multimedia Delivery Solution (EDCAM)

A. *EDCAM Principle and System Architecture*

The following subsections introduce the architecture of the three major elements of EDCAM: energy-oriented system profiling; energy-efficient content adaptive delivery mechanism; cooperative content delivery with a partner device.

Fig.2 illustrates the EDCAM-based multimedia content delivery. In the traditional approach, each device gets the whole content via the same network interface (e.g. cellular), independent from other devices. The new approach of EDCAM enables pairs of devices with the same interest in certain content to retrieve part of that multimedia content from the content provider via a network interface (e.g. cellular) and exchange it against the missing part from its pair via another network interface (e.g. WiFi).

1) Energy-oriented Device Profiling: One of the novel contributions of the EDCAM is the *energy-oriented device profiling*. This application-based energy-aware device profiling is used for quality adapta-

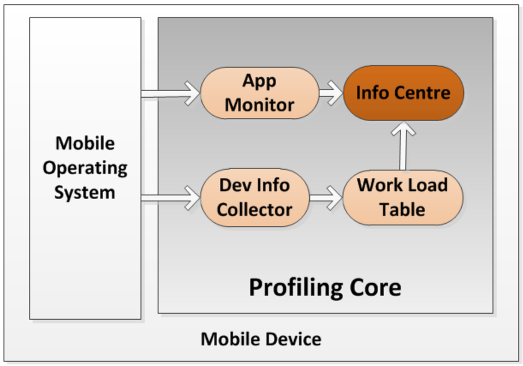

Fig. 3: Application-aware Device Profiling Mechanism

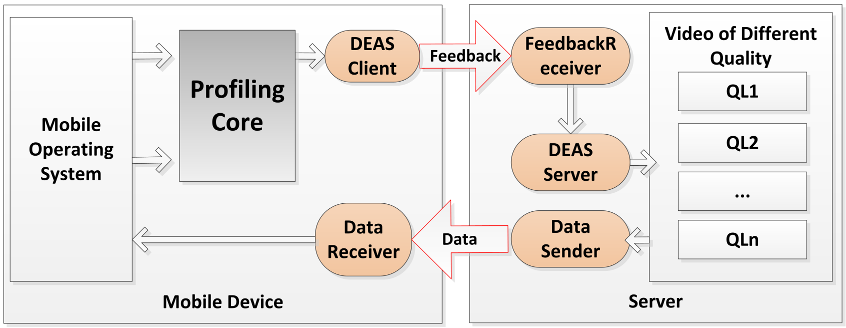

Fig. 4: Quality Adaptation Architecture

tion and partner selection of content sharing. It builds an energy model of the mobile device, records power signature of each hardware subsystem, and calculates energy constraint score in real time. The block-level components of this algorithm along with the information exchange mechanism are illustrated in Fig.3. Once a new application is launched, *App Monitor* identifies it as the current running application. From the *Mobile Operating System* readings of CPU workload, wireless network card load, cellular interface utilisation, as well as the resolution of the display unit, battery characteristics, and battery energy level. *Dev Info Collector* is in charge with doing these readings in order to form the power signature of the application on this device. Based on this information, *Profiling Core* stores device features, maintains different application profiles, evaluates the delivery QoS level, and calculates the expected battery life.

2) Energy Efficient Quality Adaptation: A content quality adaptation algorithm is in place for energy-efficient multimedia content delivery. The device can request degradation of the content quality level provided to the pair it belongs to, in order to reduce network traffic and importantly save energy. This adaptation enables devices to react to the dynamically changing network environments. The block level

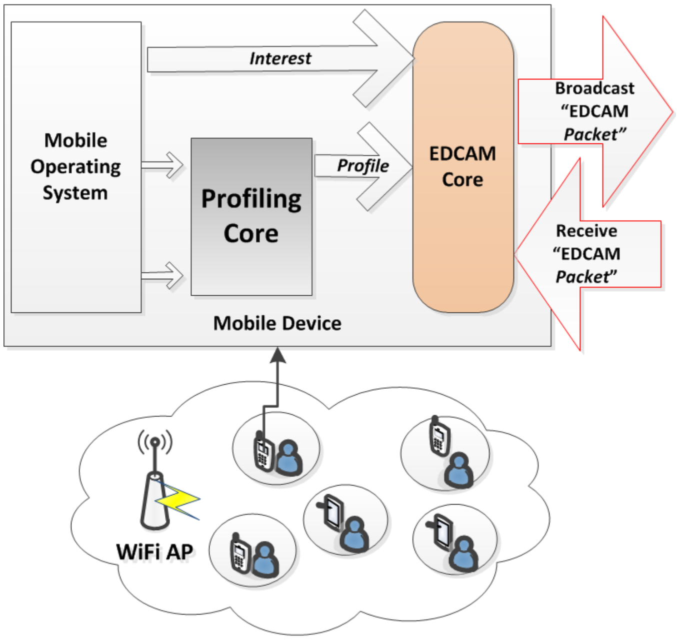

Fig. 5: Selection of the Sharing Partner

illustration of the quality adaptation mechanism is illustrated in Fig.4. The quality adaptation component of EDCAM is performed by DEAS [19]. DEAS monitors user perceived quality by calculating PSNR value, takes energy constraint score from *Energy-oriented Device Profiling* module, and makes quality adaptation request based on the above information. Based on the application profile from *Profiling Core*, *DEAS Client* makes video quality level adjustment requests according to the DEAS's video quality adaptation algorithm. On the server side, *Feedback Receiver* listens for adaptation requests from the mobile device, and *DEAS Server* handles the requests by dispatching video at certain quality level (QL). Data packets are transmitted by the server's *Data Sender* to the *Data Receiver* at the mobile device. When a device is demanding a quality change that is out of the threshold (QoS Energy) of the other device in the pair, the demanding device will search for another partner.

3) Partner Selection in Cooperative Content Delivery: If multiple devices sharing the same interest (including quality level and context) are at present in the same neighbourhood, the interest level in content along with required quality level is used for the selection of eligible sharing partners. As cellular networks incur higher energy costs and have relatively lower bandwidth and often variable connectivity, this cooperative downloading approach is designed to conserve energy by encouraging the usage of the WiFi network interface for communication instead of the cellular interface. The energy saving will be analysed in the ”Benefit Analysis” subsection and demonstrated in the test results section. Fig.5 shows the architecture of the sharing partner selection mechanism. *Profiling Core* provides ”profile” data that states the current energy constraint of the device to the *EDCAM Core*. The current application on the operating system provides the ”interest” level in the content to the *EDCAM Core*. *EDCAM Core* aggregates these two pieces of information in an ”EDCAM Packet” and broadcasts it. Among all the devices that listen to these broadcasts from the sources of the packets with the same ”interest”, the one with the most critical energy constraint is selected as the content sharing partner. The partner selection and partnership establishment mechanism will be explained in more details in the following subsections.

B. Application-aware Energy-oriented System Profiling

Application-aware Energy-oriented System Profiling constructs a ”profile” that includes the following two components: *Energy Model* takes workload of device components and calculates the corresponding battery discharge and *Application Profile Table* records application power signature, namely the typical work load on the hardware components for each application.

The principle of system profiling was first introduced in the application-aware energy model of AWERA [9], [10], [42]. DEAS [19] has extended the profiling techniques with multi-task support and used it for quality adaptation. The profiling in our previous work makes use of a *Component Workload Profile Table* and a special algorithm to map between the workload on each hardware component and the corresponding power level. This paper further develops the profiling technique with an online regression-based Energy Model for accurate power estimation. The regression technique performs energy modelling and was introduced in [43]–[45].

Compared with these existing energy models that also use regression technique, the proposed energy-oriented system profiling proposed in this paper has two contributions: application power signature-based power estimation and multi-task scenario support.

The use of application power signature enables an efficient energy constraint estimation without the expensive frequent power monitoring of the hardware. The energy model will produce the current energy constraint with little cost by knowing current application type and the corresponding power signature. On the contrary, devices’ build in energy model uses frequent I/O access on system configuration files that record hardware meter readings to calculate battery discharge. This approach obtains remaining energy while lacks the knowledge of energy constraint.

Moreover, existing solutions [43], [44], [46] focus solely on hardware usage while overlooking the importance of user preference and software aspects. While user’s habit of device usage dictates the

TABLE I: Component Workload Profile Table

Workload	L_{CPU}	L_{GRA}	L_{CELL}	L_{WLAN}	L_{SCR}	P_{SYS}
5%	$L_{CPU}5$	$L_{GRA}5$	$L_{CELL}5$	$L_{WLAN}5$	$L_{SCR}5$	$P_{SYS}5$
15%	$L_{CPU}15$	$L_{GRA}15$	$L_{CELL}15$	$L_{WLAN}15$	$L_{SCR}15$	$P_{SYS}15$
20%	$L_{CPU}20$	$L_{GRA}20$	$L_{CELL}20$	$L_{WLAN}20$	$L_{SCR}20$	$P_{SYS}20$
...	...	...	...	...	...	...
90%	$L_{CPU}90$	$L_{GRA}90$	$L_{CELL}90$	$L_{WLAN}90$	$L_{SCR}90$	$P_{SYS}90$
95%	$L_{CPU}95$	$L_{GRA}95$	$L_{CELL}95$	$L_{WLAN}95$	$L_{SCR}95$	$P_{SYS}95$
100%	$L_{CPU}100$	$L_{GRA}100$	$L_{CELL}100$	$L_{WLAN}100$	$L_{SCR}100$	$P_{SYS}100$

choice of application, the energy consumption of each hardware component shows distinctive features, and each typical application scenario (e.g. sending text message, watching video, etc.) shows distinctive energy requirements as well [47], [48]. Hence to keep record of applications power signature can ease the calculation of power constraint score from the energy model. This is because subsystem usage data can be collected less often than other solutions as application type can dictate the typical power demand. The power signature can be updated from time to time for more accurate estimation.

Additionally, in contrast with existing energy modelling approaches [43], [44], [46] which are not designed to deal with multi-task scenarios, our approach addresses this issue, as described in details next.

1) Initialization Phase: Since devices of different models have different hardware specifications, the same application does not necessarily results in the same amount of workload on the hardware components of different devices. Even the same percentage of workload does not necessarily show the same power readings on individual devices. Hence an initialisation phase is introduced to construct a *Component Workload Profile Table*, prior to the construction of application profiles in order to make the proposed algorithm device independent. The *Component Workload Profile Table* is illustrated in Table I.

In this phase, EDCAM runs a set of predefined tasks to put various loads on the different device components and monitors the corresponding power. For example, DEAS [19] runs a dedicated float point addition program to load the CPU to different degrees and monitors the corresponding power. Perrucci et al. [48] applied a similar approach to measure energy consumption of each hardware component of a smart phone with external circuitry. EDCAM takes the readings directly from the operating system and takes the value with better granularity. Although this phase introduces overhead, it is applied to each individual device once only. Besides, real tests show that online power monitoring and energy modelling can be realised with negligible overhead without affecting normal usage if designed carefully [44].

Among all the hardware components, the readings of the screen (SCR), the graphics processor (GRA), WLAN interface card, including WiFi (WLAN), cellular network interface module such as GSM for instance (CELL) and the processing chip set (CPU) are recorded only. This is because these components are the major energy consumers among the hardware components of the latest mobile devices (i.e smart phones or tablet PCs) and they show significantly higher energy consumption than the others [48].

The *Component Workload Table* is shown in Table I, where $\mathrm{L_{CPU}x}$, $\mathrm{L_{GRA}x}$, $\mathrm{L_{CELL}x}$, $\mathrm{L_{WLAN}x}$ and $\mathrm{L_{SCR}x}$ (x = 5, 15, 20,..., 90, 95, 100) are workloads at x percent for CPU, graphics processor, cellular module, WLAN interface and screen, respectively. And $\mathrm{P_{SYS}x}$ is the corresponding system power when the hardware components are at the workload of x percent. The workload of the system is represented as a vector in equation (1). EDCAM measures a small set of values to reduce the overhead.

$$\vec{L_{SYS}} = \begin{pmatrix} L_{CPU} \\ L_{GRA} \\ L_{WLAN} \\ L_{SCR} \end{pmatrix} \tag{1}$$

In equation (2), $\mathrm{P_{sys}}$ represents the utility function corresponding to the energy model of the current mobile system. The energy model is contributed by all the major device hardware components considered: CPU, screen, graphics, WLAN card and cellular module, respectively. $\mathrm{L_{comp_i}}$ represents the workload on the i-th device component. Weight values are used to balance the contribution of different hardware components on the overall utility function. Weight values $\mathrm{W_{comp_i}}$ are obtained by training the model with real workload and corresponding power values resulted from testing as shown in Table I. c is a constant value.

$$P_{sys} = \sum_{i=1}^{n} (W_{comp_i} \cdot WL_{comp_i}) + c \tag{2}$$

The error function of the energy model is represented by equation (3). The goal of the training process is to minimise the calculation error ”E” of the energy model. This is realised by comparing the calculated power value P_{cal} and the real value from the OS P_{real} while adjusting the weight values in order to reach the optimal solution.

While the predefined loading tasks loading the system variously, the profiling procedure records a large set of observed workload combinations. Initially the training method calculates P_{cal} with one record from the observed data sets in conjunction with the initial weight values. Next many rounds of calculation take one record by another from the observed data sets to calculate P_{cal}. In each round, weights values are redistributed for even smaller variation between P_{cal} and P_{real}. To avoid over-fitting, when error is

TABLE II: Application Power Signature

	L_{CPU}	L_{DISP}	L_{CELL}	L_{WLAN}
App_j	$L_{CPU}(j)$	$L_{DISP}(j)$	$L_{CELL}(j)$	$L_{WLAN}(j)$

lower than a threshold, the training stage finishes. The weight values are fixed for now to form an initial energy model for further energy constraint estimation. However this training stage takes place in ”Working Phase” as well in order to adapt to the change of device usage.

$$E = \frac{1}{2}\sum_{k}(P_{cal}(k) - P_{real}(k))^2 \tag{3}$$

In conclusion, the output of this phase is the energy model as in equation (2) with identified optimal weight values W_{comp_i}. In the following phases, the energy model will take workload as input and output the estimated power level.

2) Monitoring Phase: Monitoring Phase constructs the *Application Profile Table*. Once a new application with no previous record is launched, EDCAM records the extra workload on the mentioned hardware components on top of the exiting figure caused by the applications on hold. Once the application shuts down, the average value is calculated and recorded as a new entry in the *Application Profile Table*. A streaming application delivering different data rates is regarded as a separate record, so that the energy constraint imposed by delivering different multimedia quality content is calculated separately. Each application is assigned a vector of its typical workloads as its power signature. The following description explains: how to use a vector to represent the power signature, and how this application profile is used in conjunction with the energy model described in the above section for energy constraint calculation.

Table II shows one simple implementation of the *Application Profile Table*. For application j, $L_{CPU}(j)$ gives the workload of CPU. $L_{GRA}(j)$, $L_{CELL}(j)$ and $L_{WLAN}(j)$ follow the same idea. Notably, the workload of the screen is not recorded as the brightness is highly dependent to the illumination of the environment and user preference. The above work load values are represented in a vector as in (4), where PS_{APP_j} is the power signature of $application_j$. Consequently, the sum of the running applications gives the power signature of the system. When energy constraint value is needed, the result of computations from equation (5) is the input of the energy model described in equation (2). The output of equation (2) is the running power of the whole system.

$$\vec{PS_{APP_j}} = \begin{pmatrix} L_{CPU}(j) \\ L_{GRA}(j) \\ L_{WLAN}(j) \\ L_{SCR}(j) \end{pmatrix} \tag{4}$$

$$\vec{PS_{SYS}} = \sum_{j=1}^{n}(\vec{PS_{APP_j}}) \tag{5}$$

Compared with constant hardware level monitoring, the proposed application-aware energy profiling is an easy and inexpensive approach as deployed devices will recognise the applications and use the power signature records in conjunction with the energy model to calculate the current application energy constraint.

3) Working Phase: This phase focuses on improving the existing application profile. Once a device encounters an application with a previous record in the *Application Profile Table*, it references the table for data to be used in order to calculate the current energy constraint.

In the working phase the *Application Profile Table* is updated incrementally. EDCAM occasionally monitors by sampling the average power on each component for applications which already have records in the *Application Profile Table*. According to (6) and (7), the updated workload $\mathrm{PS}_{\mathrm{updated}}$ for an application is calculated by the old value $\mathrm{PS}_{\mathrm{old}}$ taken from the application profile and the new value $\mathrm{PS}_{\mathrm{new}}$ that has just been measured. Weight values $\mathrm{W}_{\mathrm{old}}$ and $\mathrm{W}_{\mathrm{new}}$, that distribute the effect of the two workload values, are determined by the running duration of the application. Each time an application is launched, new readings are used to update existing profile to enable adaptive self-learning.

$$\vec{PS_{updated}} = W_{old} \cdot \vec{PS_{old}} + W_{new} \cdot \vec{PS_{new}} \tag{6}$$

$$\frac{W_{old}}{W_{new}} = \frac{Duration_{old}}{Duration_{new}} \tag{7}$$

Importantly, the training process introduced in the Initialisation Phase is invoked periodically so that the energy model is able to perform accurately and adapt to the environment change of device usage. Although the device periodically needs to obtain the actual power value from the system for model training, the overhead reduction is substantial given that energy constraint is often updated and used.

C. Energy-efficient Quality Adaptation Algorithm

The Energy-efficient Quality Adaptation Algorithm requests the server to perform adjustments to the delivery rate according to two metrics: ”battery expected lifetime” that is calculated based on the data collected from System Profiling; and ”perceived quality” that is estimated using PSNR of the monitored active video application.

As revealed by extensive tests [49], [50] the variation of traffic volume and decoding effort caused by different video quality levels has major impact on energy efficiency when compared with that of link quality, network load and transport protocol. Consequently Energy-efficient Quality Adaptation Algorithm focuses on the above two metrics.

Assuming the video content of different quality is stored at the server side, RTP and stream switching algorithm are in place so that the video content is delivered at different quality levels based on client feedback. The multimedia data is transmitted via RTP, and the adaptation algorithm enabled device transmits feedback via RTCP packets to the server. This mechanism provides a user centric solution to address the challenges introduced by the heterogeneity of mobile devices in terms of software and hardware. Importantly, the same adaptation mechanism can also be applied using scalable video coding.

”Expected battery lifetime” is proposed as a metric that reflects device’s current energy constraints. This is based on the energy profiling introduced in the previous section. The expected battery lifetime is dependent on the energy-oriented device characteristics: battery residual, current system power, applications that are running or on hold.

Equation (8) is the utility function to calculate the ”expected battery life” based on the current applications and individual device features. $\alpha(B)$ is the compensation factor that reflects the depletion curve of the battery. $Residule_{battery}$ is the current residue energy of the battery, $Voltage_{battery}$ is the voltage value of the battery used. They are both obtained from the mobile operating system. P_{sys} is the estimated power that reflects the current energy constraints imposed by both active application and applications on hold.

$$Exp\_Life = \frac{Residule_{battery} * Voltage_{battery}}{P_{sys} \cdot \alpha(B)} \tag{8}$$

Expected battery lifetime is used to determine the maximum quality level upon which the adaptation performs.

PSNR is used to estimate user’s ”perceived quality” in the adaptation algorithm. Based on PSNR, DEAS client makes adaptation requests to best balance quality of experience and energy saving. Equation

(9) [51] represents the utility function, expressed in terms of PSNR and measured in decibells, where *AVG_BitRate* is the average bit rate of the video, *Exp_Thru* is the expected throughput, and *Thru* is the current throughput.

$$PSNR \quad = \quad 20 \cdot \log_{10}\left(\frac{MAX\_BitRate}{\sqrt{(Exp\_Thru - Thru)^2}}\right) \tag{9}$$

Given the above information, EDCAM performs *Energy-efficient Quality Adaptation* as described in Algorithm 1. When the smart device receives the first data packet, it starts a loop to send feedback to the server. The proposed adaptation algorithm first calculates the expected battery life *Exp_Life* and quality score (PSNR) for the current session. *Exp_Life* is compared with the threshold *Thre_Life*. If *Exp_Life* is shorter than the threshold *Thre_Life*, the maximum quality level *Max_Level* is reset to lower level if any. Otherwise, the maximum quality level is reset to higher level if any. Adaptation is caused by the change of energy constraint, for example, closing an application, opening a new application, battery depletion, etc. Quality score (PSNR) is compared with the threshold *Thre_PSNR*. If it is less than *Thre_PSNR*, the device will request a "Quality degradation" from the server. Otherwise, it will request a "Quality upgrade" from the server. The device will wait for a while before sending another feedback.

Algorithm 1 Energy-efficient Quality Adaptation Process

```
Since the Smart Device Received the First Data Packet:
while $True$ do
    $Calculate(PSNR, Exp\_Life)$;
    $Compare(Exp\_Life, Thre\_Life)$;
    $Reset(Max\_Level)$;
    if $(PSNR < Thre\_PSNR) \wedge (Quality > Min\_Level)$ then
        $Request(Degrade, Quality)$;
    else if $(PSNR >= Thre\_PSNR) \wedge (Quality < Max\_Level)$ then
        $Request(Upgrade, Quality)$;
    end if
    $Wait(Timeout)$;                                   ▷ Wait before sending feedback
end while
```

D. Two-party Cooperative Downloading

Cooperative downloading is a crucial element of this solution. If another device in the same neighbourhood is to acquire the same multimedia content at the same quality level, the device downloads a half of the content only and let the other device download the other half. Both parties can share the content they have downloaded with the other one. In this manner, the usage of cellular network interface is reduced to almost half. This can result in substantial energy saving and monetary benefit as will be illustrated in our analysis. However, if no other party is acquiring the same content, the device can directly proceed to perform energy efficient adaptive download that is to be introduced in the next section.

1) Motivation For Two-party Content Sharing: The cooperative downloading algorithm involves two parties in the sharing process, rather than multiple devices as proposed by other content sharing solutions [6], [24], [26], [29], [36]. The proposed design is backed by several facts.

The existing simple content sharing solutions assume the availability of WLAN, which is not realistic due to the limited deployment of free WiFi hot spot. Moreover the WiFi WLAN can be very congested, and consequently it is not suitable for multimedia delivery with high bandwidth demand and tight QoS restrictions.

Without existing WiFi AP, Ad hoc wireless LAN with corresponding routing algorithm is needed for multiple nodes content sharing. The relatively bigger overhead of group management brings challenges to the improvement of energy efficiency and system performance. The deployment of MANET itself is against the goal of energy saving, this is because the connection setup and group management need peer-to-peer information exchanges between all the parties. Once any device encounters difficulties in maintaining connectivity, the whole connection set-up process that introduces all the overhead has to be invoked all over again.

In addition, the download scheduling among devices is challenging and complex. Any distributed complex calculation will affect negatively the individual smart device, which is again, against energy saving principle. In terms of performance, the involvement of multiple parties pose challenges to the scheduling of downloading. Facing this challenge, a bigger buffer with intelligent buffer management algorithm is needed in the gateway device. Even if a dedicated gateway is deployed, instead of electing one device to act as a gateway, this approach introduces delay and difficulties in stitching partial content together.

Last, it is unlikely that a group of heterogeneous devices simultaneously demands the same quality level as there optimal choice. Hence re-clustering happens regularly to avail group quality adaptation. In contrast, it's a feasible and agile design that a device performing quality adaptation shares content with another individual device demanding for the same quality level.

In conclusion, regarding energy efficiency as the design philosophy, a two party content sharing is chosen for ease of deployment and less overhead in the sense of both connection management and download scheduling.

2) Content Sharing Mechanism: In the restricted space where people are densely distributed with relatively stable mobility pattern, for example, convention centres, sports stadiums and high speed trains, it is highly likely there are more than one device showing common interest in such scenario. The Content Sharing mechanism is described in Algorithm 2.

Algorithm 2 Content Sharing Mechanism

```
Device Needs to Request Content from the Server:
$Calculate(Quality, Exp\_Life)$;
$Broadcast(Quality, Content)$;
while $True$ do
    $Wait(Grace\_Period)$;
    if $Exist(Reply)$ then
        $Find(Minimal\_Exp\_Life, Replies)$;
        $Communicate(Partner)$;
        $Connect(Server, Quality)$;
        $Sharing\_and\_Adaptive\_Delivery$
    else if $NonExist(Reply)$ then
        $Connect(Server, Quality)$;
        $Adaptive\_Delivery$
    end if
    $Wait(Change\_Quality)$;
    $Calculate(Quality, Exp\_Life)$;
    $Broadcast(Quality, Content)$;
end while
```

When a device's energy constraint is tight, it can initiate a search of partner for content sharing-assisted adaptive multimedia delivery. Before downloading any content, a device will use the WiFi interface to broadcast its interests of content (the context and the corresponding quality level). A grace period is

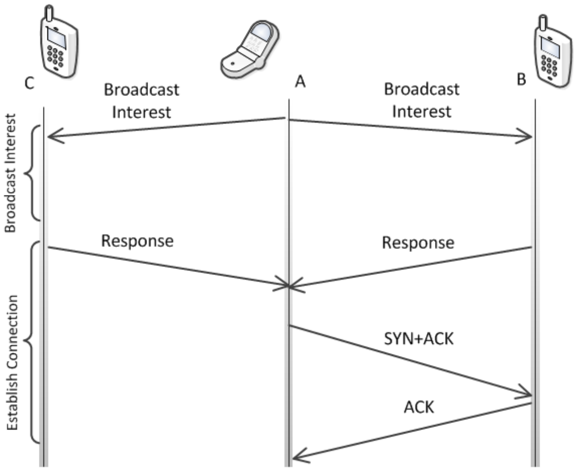

Fig. 6: Handshake Procedure to Establish a Connection with the Partner for Content Sharing

assigned to allow the device wait for any nearby device sharing the same interest to join and download together. Meanwhile the nearby devices demanding ”the same content” of ”the same quality level” will response the request with a control packet of its energy constraint information as in (8). If no device is joining by the end of this period, the current device will proceed to perform energy-efficient quality adaptive downloading alone.

Facing multiple replies as in Fig.6, the initiating device will establish a partnership with the most energy constraint device based on the energy constraint information retrieved from the received response packets. This design aims to maximise the benefit. When quality adaptation is needed, the device will first communicate with its partner for permission. If permission is granted, they will both request for quality adaptation at the same level. If they cannot come to an agreement because the QoS or ”expected life time” exceed the partner’s threshold, the device will search for another sharing partner or, if not available, will transfer the content alone. The criteria for quality adaptation has been discussed in the previous section.

Once a partner has been selected, a TCP-like three way handshake procedure is used to establish a WiFI connection with the sharing partner. The handshake procedure is demonstrated in Fig.6. Device A sends SYN-ACK control packet to the selected Device B to confirm its willing to corporately download. SYN-ACK control packet includes: ’SeqNo’ - the sequence number for device B to start with, and ’LEN’ - the length of each sharing unit ’LEN’. For example, A will download from SeqNo+LEN, B will download from SeqNo. Once B received SYN-ACK, it will sends ACK control packet to A to establish the connection. Next, they will both download their part of length ’LEN’ and exchange as soon as they

TABLE III: Parameter Definitions

Variable	Definition
α_{File}	Multimedia file size (bit)
α_{hs}	The amount of handshake traffic (bit)
β_{c}	Cellular interface bit rate
β_{w}	WiFi interface bit rate
γ_{c}	The amount of cellular traffic (bit)
γ_{w}	The amount of WiFi traffic (received and transmitted in bit)
ϵ	The price of transmit 1 bit over cellular network
P_{c}	The power of Cellular interface
P_{w}	The power of WiFi interface
E_{Total}	Energy consumption of device using proposed algorithm
E_{Tra}	Energy consumption of device using only cellular interface
$\text{E}_{\text{Benefit}}$	Energy efficiency benefit
$\text{M}_{\text{Benefit}}$	Monetary benefit

have it.

Once the bound is established, both devices use cellular interface to download the content corporately, and use their WiFi interface to share the content between each other.

E. Energy Benefit Analysis

This subsection presents the energy benefit analysis when employing cooperative downloading and quality adaptation. Table III presents the definition of parameters used in this discussion.

$$t_{Tra} = \frac{\alpha_{\text{File}}}{\beta_c} \tag{10}$$

$$E_{Tra} = P_c \cdot t_{Tra} \tag{11}$$

Equation (10) represents the transmission time of the required multimedia content via cellular interface using the traditional approach. Consequently, equation (11) shows the required energy for successful content transmission using the traditional approach.

$$\gamma_c = \frac{\alpha_{\text{File}}}{2} \tag{12}$$

$$t_c = \frac{\gamma_c}{\beta_c} \tag{13}$$

$$\gamma_w = \alpha_{hs} + \frac{\alpha_{\text{File}}}{2} + \frac{\alpha_{\text{File}}}{2} \tag{14}$$

$$t_w = \frac{\gamma_w}{\beta_w} \tag{15}$$

$$E_{Total} = P_c \cdot t_c + P_w \cdot t_w \tag{16}$$

As in (12), the cellular interface receives only half of the original multimedia content. Hence the data transmission time over cellular interface is shown in (13). As in (14), WiFi receives the other half of the original multimedia content, and sends the content received via the cellular interface to the other device in the sharing pair. In addition, WiFi interface delivers control traffic to the sharing partner for handshake. Equation (15) shows the data transmission time over Wifi interface. Since control traffic is only needed in the beginning of the transmission, the total content transmission time will not be longer than the traditional approach as long as the typical bit rate of WiFi is higher than that of the cellular interface. This assumption is true for a typical current infrastructure deployed.

Based on this assumption, as long as cellular interface's power-per-bit value is higher than the WiFi interface's, $\mathrm{E}_{\mathrm{Total}}$ from equation (16) will be less than $\mathrm{E}_{\mathrm{Tra}}$ from equation (11). This is usually true, for example, the cellular interface consumes 18 times energy than WiFi interface on Ipad [6]. Consequently, $\mathrm{E}_{\mathrm{Benefit}}$ from equation (17) is positive.

$$E_{Benefit} = E_{Tra} - E_{Total} \tag{17}$$

In addition, energy-efficient quality adaptation algorithm can further reduce the size of data to deliver, while maintaining the QoS level to satisfactory. According to our theoretical analysis, the proposed hybrid solution is able to conserve energy for smart mobile devices while receiving multimedia content.

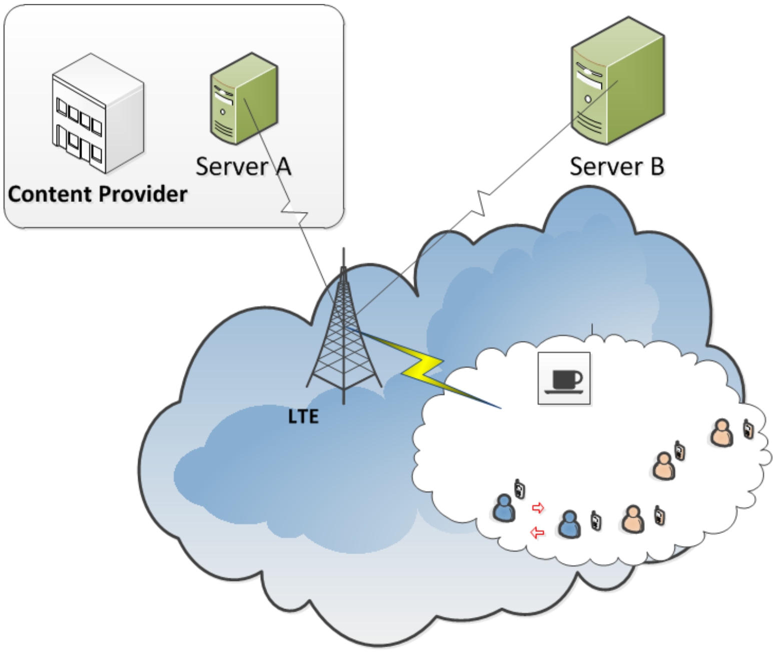

Fig. 7: Simulation Topology

$$M_{Benefit} \quad = \quad \epsilon \cdot \frac{\alpha_{\text{File}}}{2} \tag{18}$$

The monetary benefit $\text{M}_{\text{Benefit}}$ is demonstrated by equation (18), where ϵ symbolises the price of transmitting 1 bit of data over the cellular networks. Since the content α_{File} that is to be transmitted over cellular network is reduced to half, the expenses $\text{M}_{\text{Benefit}}$ are reduced to half. Notably, the handshake happens in WiFi interface, which is often free of charge.

IV. PERFORMANCE EVALUATION

A. *Simulation Model and Parameters*

A simulation model was developed in Network Simulator 3 [52] to test the proposed solution in terms of both energy saving on client devices and quality. Except for the parameters indicated explicitly in this sub-section, default NS-3 value settings were used. The topology deployed in the simulation is illustrated in Fig.7. A LTE cellular network, a fast wired network, and ad-hoc WiFi communication between devices comprise a heterogeneous networking environment.

A group of 10 mobile devices are evenly deployed in a 100 square meter area. All the devices are equipped with both WiFi and LTE interfaces. A LTE base station is located 1000 meters away from this area. The content provider delivers video content via the LTE base station to three LTE subscriber devices. Server B is transmitting background traffic to other devices via the LTE base station to load the LTE network.

Mobility is considered in this simulation; user device holders randomly walk in the bounded area with an average speed of 0.5 mps, a typical value for pedestrian walk. The simulations were run 15 times and the results were averaged.

H.264/MPEG-4 video content was stored at 5 quality levels with average bit rates of 1920 kbps, 960 kbps, 480 kbps, 240 kbps and 120 kbps, from the highest to the lowest quality levels, respectively. Three devices have subscribed to the above content.

The number of subscribers of background traffic differs in the six scenarios considered in the simulations as follows: A) 2 devices; B) 3 devices; C) 4 devices ; D) 5 devices; E) 6 devices; F) 7 devices. The growth of subscriber number yields the growth of number of flows participating in the LTE transmission in the cell. This is to find out how the compared solutions cope with the increasingly congested network environment.

Since there were 10 devices in total with 3 adaptive video content subscriber, the maximum number of flows is 7. In the simulations, the results with 1 and 2 background traffic flows are identical.

The simulation configuration limited the resources allocated to the cell, and the networks are overloaded in the above scenarios. The tests were conducted with background traffic bit rate set as 1Mbps and 2Mbps, respectively. These network conditions were set such as the adaptive solutions are still able to adjust the delivered quality above their minimum bitrate and take advantage of their adaptation algorithms. This setting fully explores how the solutions behave differently when facing different network conditions. The results obtained with different background traffic data rates are recorded separately for clear comparison.

In order to perform realistic modelling and simulations, the power settings are configured according to comprehensive measurements with a Google Nexus One mobile device in a real test bed. The power readings when playing video content at different quality levels locally and when delivered over the WiFi interface are recorded. The power settings on the LTE interface are set 4 times higher than those of the WiFi interface [53]. All power-related values are presented in Table IV. The initial battery capacity is 180 J. The simulation duration is 100 s. These are both reduced from real life values for simulation purposes; this does not affect the validity of the experiments.

EDCAM is compared against Non-adaptive traditional LTE, DEAS and ESTREL. ESTREL uses an energy saving mechanism based on adjusting streaming bit rate. Facilitated by the scalable video coding scheme, ESTREL unsubscribes enhancement layer data traffic when energy level is low in order to

TABLE IV: Power Settings for Testing

Scenario/Video Bitrate	1920 kbps	960 kbps	480 kbps	240 kbps	120 kbps
Local Playback	1157 mW	811 mW	673 mW	612 mW	560 mW
WiFi Interface	288 mW	211 mW	168 mW	152 mW	140 mW
LTE Interface	1445 mW	1022 mW	841 mW	764 mW	699 mW

conserve energy. ESTREL is configured as in [22]. DEAS takes energy metric and quality metric to best balance the quality and energy efficiency. In order to further improve the energy efficiency, EDCAM employs the cooperative mechanism that allows two devices share the downloaded content.

B. Simulation Results

The above delivery schemes are compared in terms of average values of delay, jitter and PSNR in order to illustrate their levels of quality of service and estimated user perceived quality. The performance of the solutions is assessed in terms of the device energy consumption. The results for EDCAM, DEAS, ESTREL and Non adaptive (NonAd) are shown in Table V, Table VI, Table VII and Table VIII, respectively.

These tables show how EDCAM outperforms the three alternative solutions in terms of both energy efficiency and user perceived quality levels. For instance energy savings of 22%, 35% and 40% have resulted when using EDCAM in comparison with when NonAd, DEAS and ESTREL were used in the least loaded network case tested, respectively. In this situation *Excellent* video quality levels were supported by all the adaptive solutions and *Good* level by NonAd. Lower energy savings of 16%, 29%, and 39% have been achieved when using EDCAM in comparison with when NonAd, DEAS and ESTREL were employed in the most loaded network conditions, respectively. However in this situation the benefit of EDCAM in terms of user perceived quality is outstanding as it maintained the *Excellent* level, whereas the other solutions have dropped it to *Good*, *Bad* and *Bad*, respectively.

Individual paired T-tests were performed comparing the results for EDCAM with each of the other three approaches in terms of energy consumption, delay, jitter and PSNR. In all situations it can be said with 95% confidence that there is a statistical difference between the compared results in favour of EDCAM.

Three key observations can be made from the simulation results as follows:

- adaptive solutions (ESTREL, DEAS, EDCAM) successfully save energy by reducing the traffic volume to be transmitted;
- QoS-oriented adaptation (DEAS, EDCAM) is effective in improving user perceived quality;

TABLE V: Simulation Results for EDCAM

Background Traffic Class	A 1Mbps	A 2Mbps	B 1Mbps	B 2Mbps	C 1Mbps	C 2Mbps	D 1Mbps	D 2Mbps	E 1Mbps	E 2Mbps	F 1Mbps	F 2Mbps
Energy Consumption (J)	84.48	92.70	86.29	92.72	89.33	94.33	92.06	95.28	92.12	95.29	91.64	94.33
Delay (Sec)	0.0027	0.0027	0.0030	0.0028	0.0027	0.0028	0.0028	0.0029	0.0030	0.0029	0.0031	0.0032
Jitter (Sec)	2.030	2.072	2.034	1.176	2.031	1.172	3.083	4.049	3.145	2.180	3.052	3.500
PSNR (dB)	38.54	36.67	38.54	36.67	38.53	36.67	37.90	36.67	36.66	36.67	36.67	36.67

TABLE VI: Simulation Results for DEAS

Background Traffic Class	A 1Mbps	A 2Mbps	B 1Mbps	B 2Mbps	C 1Mbps	C 2Mbps	D 1Mbps	D 2Mbps	E 1Mbps	E 2Mbps	F 1Mbps	F 2Mbps
Energy Consumption (J)	107.44	114.78	111.85	116.78	113.11	116.69	113.65	116.69	114.28	116.69	115.39	112.89
Delay (Sec)	0.0050	1.0030	0.0060	1.0100	0.0050	1.0120	0.0610	3.0500	0.0950	4.0190	2.0590	6.1410
Jitter (Sec)	3.020	5.095	3.040	5.070	3.033	5.079	5.040	7.080	6.120	8.060	8.116	9.168
PSNR (dB)	37.30	29.43	37.32	29.40	35.44	29.41	30.21	26.19	29.69	28.44	26.45	28.18

TABLE VII: Simulation Results for ESTREL

Background Traffic Class	A 1Mbps	A 2Mbps	B 1Mbps	B 2Mbps	C 1Mbps	C 2Mbps	D 1Mbps	D 2Mbps	E 1Mbps	E 2Mbps	F 1Mbps	F 2Mbps
Energy Consumption (J)	129.34	133.73	131.36	133.73	131.77	133.73	133.05	133.73	133.73	133.81	133.73	133.73
Delay (Sec)	0.0058	6.0792	0.0060	6.0600	0.0059	6.0792	2.0760	5.0373	4.0470	5.0420	5.0460	5.0304
Jitter (Sec)	6.060	4.058	6.180	3.180	6.038	4.058	6.013	5.037	9.060	11.120	11.114	12.115
PSNR (dB)	52.10	22.19	24.67	24.57	24.19	22.19	24.20	14.14	23.10	9.67	18.84	7.22

- the cooperative solution (EDCAM) achieves further energy saving due to the usage of the lower energy consuming network interface instead of the high energy consuming network interface during data transmission.

Fig.8 and Fig. 9 clearly show how EDCAM achieves substantial energy saving. For example it uses just over half of the energy than NonAd. Since ESTREL starts to adapt when energy level is already low only, the saving by ESTREL is not as high as that of DEAS and EDCAM. By introducing the WiFi interface sharing, EDCAM improves the performance of DEAS by 20 percent. Therefore cellular

TABLE VIII: Simulation Results for NonAd

Background Traffic Class	A 1Mbps	A 2Mbps	B 1Mbps	B 2Mbps	C 1Mbps	C 2Mbps	D 1Mbps	D 2Mbps	E 1Mbps	E 2Mbps	F 1Mbps	F 2Mbps
Energy Consumption (J)	135.86	155.61	137.00	155.62	155.61	145.75	155.61	155.61	155.61	155.52	155.62	155.61
Delay (Sec)	0.0087	5.0408	0.008	5.0400	5.0444	5.0400	5.0442	5.0482	5.1200	5.0300	5.0513	4.1238
Jitter (Sec)	9.129	2.106	9.120	2.130	2.134	2.130	14.097	5.100	12.130	6.080	13.164	11.091
PSNR (dB)	24.58	10.08	24.57	10.09	10.10	22.17	13.87	7.89	11.77	6.50	8.67	5.59

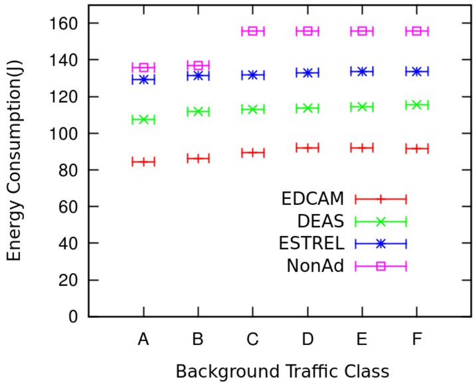

Fig. 8: Energy Consumption - 1Mbps Background Traffic

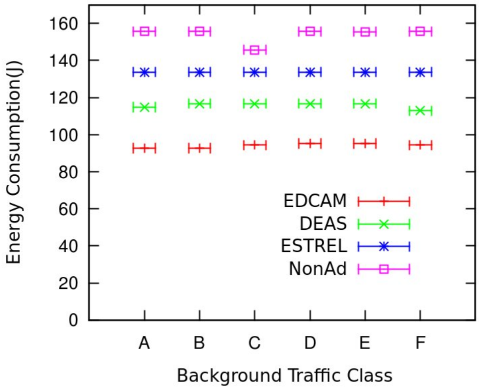

Fig. 9: Energy Consumption - 2Mbps Background Traffic

interface usage reduction is very useful in saving energy.

Since the recorded energy consumption is comprised of both local processing energy consumption and network transmission energy consumption, the energy saving is not proportional to the reduction of

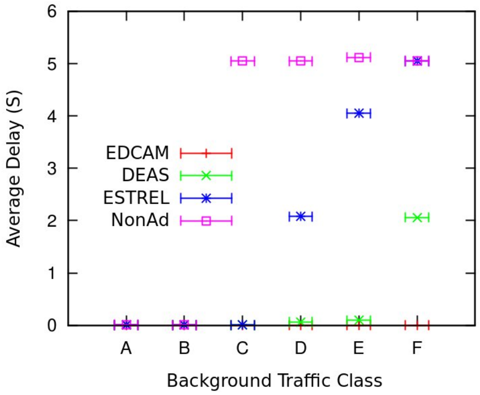

Fig. 10: Average Delay - 1Mbps Background Traffic

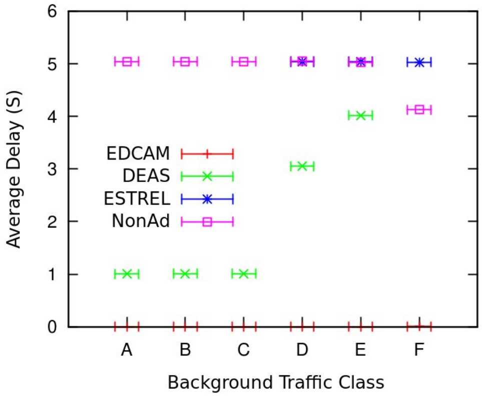

Fig. 11: Average Delay - 2Mbps Background Traffic

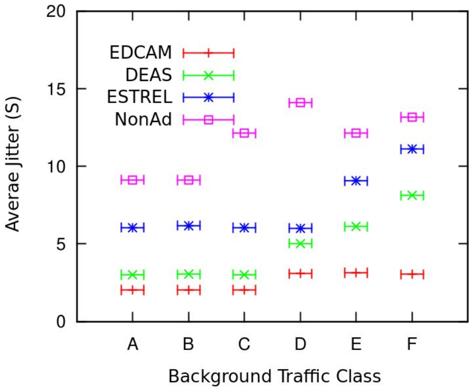

Fig. 12: Average Jitter - 1Mbps Background Traffic

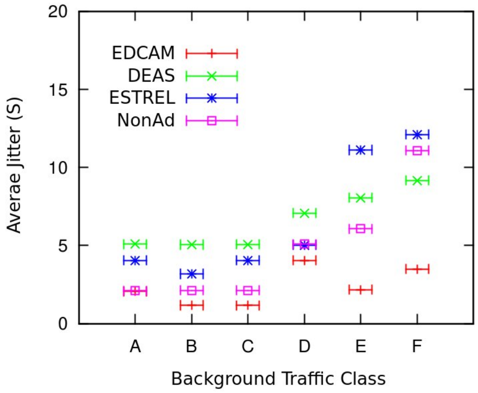

Fig. 13: Average Jitter - 2Mbps Background Traffic

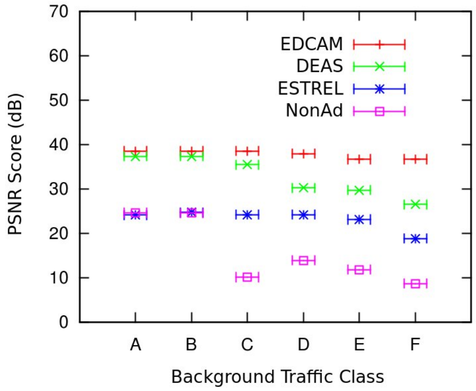

Fig. 14: Average PSNR - 1Mbps Background Traffic

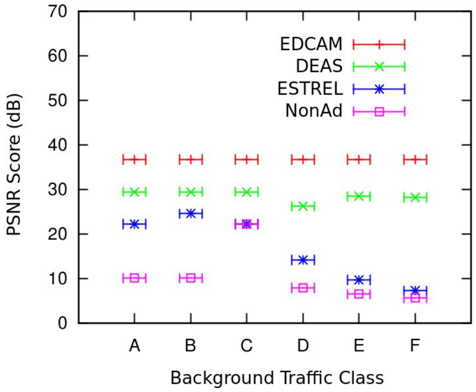

Fig. 15: Average PSNR - 2Mbps Background Traffic

networking traffic. Still network traffic reduction results in less local processing. In addition, despite the differences of energy efficiency between multiple network interfaces [53], the cooperative approach is not able to ease the decoding and display burden, namely the energy consumption of local playback.

The increased background traffic volume does not affect the energy consumption very much. This is because the traffic volume to the end user remains similar in the case when the adaptive solutions are employed and the network is fully loaded. On the contrary, the energy consumption of NonAd increased much in heavy traffic condition. However, the increased background traffic volume seriously affects the user perceived quality as discussed next.

Adaptively reducing traffic brings better performance. Reducing cellular interface usage boosts even better performance due to WiFi interfaces offload part of the data. From Fig.10 and Fig.11, Non-adaptive delivery had significantly higher delay than adaptive solutions. Meanwhile, EDCAM shows more consistent performance in all the scenarios. With 1Mbps and 2 Mbps background traffic, ESTREL struggles because ESTREL does not adapt until energy level is low. Therefore the total performance is inferior to that of DEAS and EDCAM. Although DEAS is designed to balance QoS and energy efficiency, DEAS failed to maintain low delay when facing 1Mbps background traffic and is affected more by 2Mbps background traffic. However, with half of the traffic shared in WiFi interface, EDCAM easily shows stable and very low delay in all the scenarios.

While high delay value is annoying for multimedia content receiver, high jitter value shows even worse effect on user quality of experiences levels. From Fig.12 can be seen how EDCAM is superior to the other adaptive solutions and much better than NonAd. Facing heavier background traffic in Fig.13, EDCAM demonstrated again stable and superior performance. DEAS suffered from relatively high jitter. This can be introduced by frequent adaptation. However, the jitter value from DEAS is more stable when heavier traffic was introduced.

In Fig.14 and Fig.15, the PSNR scores confirm the fact that EDCAM performance is superior to that of the other solutions in terms of QoS. First, the scores are stable in all the scenarios for EDCAM. DEAS is more stable in 2Mbps and ESTREL is more stable in 1Mbps. The adaptive solutions managed to achieve above ”good” in all the scenarios, while EDCAM and DEAS have reached the ”excellent” level. In Fig.15, ESTREL degraded to ”acceptable” and ”poor” levels in heavy traffic conditions. As expected, NonAd performed poorly except in very light background traffic as seen in Fig.14.

Unlike reducing traffic volume to be transmitted, cooperative downloading saves energy by taking advantage of the energy efficient, yet often idle WiFi interface. Hence energy efficiency is improved without losing video content. When the network is congested or energy constraint is tight, the QoS and energy efficiency oriented adaptive delivery best balances QoS and energy efficiency. EDCAM effectively combines these two elements and delivered superior performance in all the testing scenarios.

V. CONCLUSIONS AND FUTURE WORK

It is challenging to both deliver high quality of multimedia content and maintain high user perceived quality in heterogeneous wireless network environments. This paper presents EDCAM - a novel *Energy-efficient Device-differentiated Cooperative Adaptive Multimedia Delivery solution* for heterogeneous wireless networks. EDCAM considers both *user interest in content* and *device required quality level* in its *adaptive cooperative delivery* process in order to save energy and maintain high user perceived quality levels. Its major contributions include: an automatic application-aware device profiling process for device energy constraints calculation; an energy saving two-party cooperative downloading scheme that reduces group management overhead and utilises the multi-home capability of smart devices; a DEAS [19]-based energy efficient quality adaptation algorithm that adapts video quality for energy saving and high QoS in the ever changing device usage environment.

Extensive simulation-based tests have been performed involving H.264/MPEG-4 video content encoded at five different bitrates between 120 kbps and 1920 kbps and delivered to 10 users with devices of different types supporting both WiFi and LTE. Random mobility with an average speed of 0.5 mps was considered for the users. 12 different scenarios were defined, increasing number of video flows between 2 and 7 and each with two different levels of background load 1 Mbps and 2 Mbps, respectively. These scenarios have increasingly loaded the networks such that adaptive delivery solutions still support high user perceived quality levels. The proposed EDCAM was compared against three other solutions: NonAd - a non-adaptive delivery approach selected as baseline, and two state of the art adaptive video solutions DEAS and ESTREL. In particular ESTREL is an adaptive mechanism proposed for energy saving.

Testing results have demonstrated how EDCAM outperforms the three alternative solutions in terms of both energy efficiency and user perceived quality levels. For instance energy savings of 22%, 35% and 40% have resulted when using EDCAM in comparison with when NonAd, DEAS and ESTREL were used in the least loaded network case tested, respectively. In this situation *Excellent* video quality levels were supported by all the adaptive solutions and *Good* level by NonAd. Lower energy savings of 16%, 29%, and 39% have been achieved when using EDCAM in comparison with when NonAd, DEAS and ESTREL were employed in the most loaded network conditions, respectively. However in this situation the benefit of EDCAM in terms of user perceived quality is outstanding as it maintained the *Excellent* level, whereas the other solutions have dropped it to *Good*, *Bad* and *Bad*, respectively.

Future work will perform a detailed study of the comparative effect of speed and distance on the energy consumption of the different video delivery solutions. Potential deployment in a vehicular heterogeneous wireless environment [54] will also be considered.

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