Energy–Quality–Cost Trade-off in a Multimedia-based Heterogeneous Wireless Network Environment

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***Abstract*— User mobility, heterogeneity of networks and network technologies, variety of mobile devices (e.g., different operating systems, display size, CPU capabilities, battery limitations, etc.), and wide range of video-centric applications (e.g., video on demand, video games, live video streaming, video conferences, surveillance, etc.) open up the demand for user-centric solutions that adapt the video application to the underlying network conditions and device characteristics. Additionally, the absence of battery improvements suitable to meet the growing power requirements, and the need for green ICT, provide strong motivation for researchers to develop energy efficient techniques to manage and reduce power consumption in next-generation wireless networks, while still meeting high user quality expectations. In this context we propose Adapt-or-Handover, a hybrid multimedia delivery solution, which balances the benefits of multimedia content adaptation and of network selection in order to decrease power consumption in a heterogeneous wireless network environment. The proposed solution is analyzed and comparatively tested through simulations. The results show how by using Adapt-or-Handover the users benefit from up to 31% energy savings with insignificant degradation in quality, in comparison with other energy efficient solutions.**

***Index Terms*—adaptive multimedia, network selection, heterogeneous environment, energy efficiency**

I. Introduction

THE latest advances in technologies and applications (e.g., improved CPU, graphics, display, etc.) and the mass-market adoption of the new multi-mode high-end devices (such as smartphones, iPhones, netbooks, and laptops), have determined a massive traffic increase for the mobile operators. There is a growing popularity of video-sharing websites such as YouTube, social networks like: Twitter, Facebook, Linkedin, MySpace, etc., entertainment services, mobile TV, etc., as well as increase use of gaming and video-based applications. It is expected that the use of mobile video will more than double every year by 2015 [1], representing the highest growth rate of any application category. The continuing growth in the amount of video content creates challenges for the network service providers in ensuring seamless multimedia experience at high end-user perceived quality levels, given the existing device characteristics and network resources. Adaptive multimedia streaming [2]-[7] represents one possible solution that aims at maintaining acceptable user perceived quality levels. Another solution which deals with this explosion of mobile broadband data is the coexistence of multiple radio access technologies with the use of network selection solutions [8][9].

In terms of energy conservation, Information and Communications Technologies (ICT) are seen as part of the solution (e.g., video-conferencing) in order to avoid large carbon footprints, but ICT itself needs to become more energy efficient. For example the EU Commission is pushing for reducing ICT's carbon footprint by 20% by 2015. This makes the understanding of the power consumption one of the key challenges in the next generation mobile multimedia networks in order to provide efficient power management. In this context, battery life of the mobile device is the key component that consumers care most about.

In this context, users are accessing video content on the move and via heterogeneous networks. For example, Figure 1 presents a scenario inspired from the daily life of Jack, a business professional who, while going from home to his office, wants to access multimedia services (e.g., watching the news, watching music video clips with his preferred band or watching movies, etc.) anytime and anywhere. On his path, Jack will have a number of available wireless networks (e.g., UMTS, WLAN A, WLAN B) to choose from. However, the major question is how an ordinary user, without any background knowledge in wireless networks and their characteristics, could know which is the best deal for him? In order to help Jack, this paper proposes an overall solution with several inter-linked algorithms.

The need for battery efficient devices and integrated power management tools motivates us to propose a hybrid **Adapt-or-Handover** solution, which makes use of both *adaptive multimedia delivery* [10] and *network selection* [11] in order to decrease power consumption in a heterogeneous wireless network environment as illustrated in Figure 1. Each component of the proposed solution has a role in helping Jack to be *'Always Best Connected'* on his commute. Figure 1 depicts this use-case with three reference location points (i.e.,

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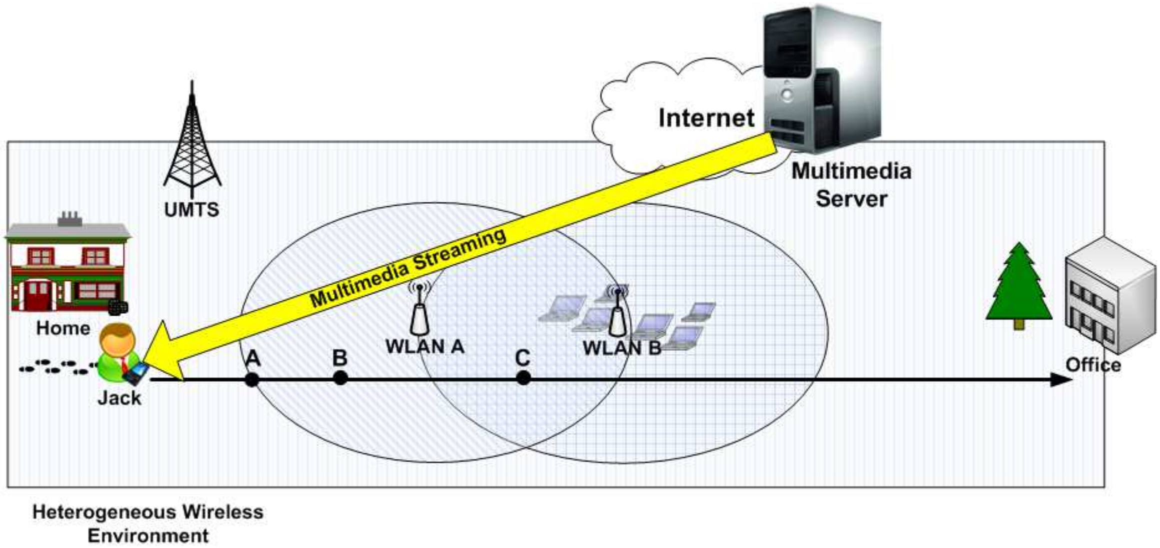

Figure 1. Heterogeneous Wireless Environment –Example Scenario of Jack's Daily Routine

A, B, C), as follows: *Point A* – Jack has the option to choose from a number of available Radio Access Networks (RAN) (e.g., UMTS and WLAN A). A network selection mechanism – ***PoFANS (Power-Friendly Access Network Selection Mechanism)*** [11] deployed in Jack's mobile device, will automatically perform the network selection for him, considering his preferences, application requirements, and network conditions. PoFANS indicates the best target network option and triggers the handover process. Note that the handover execution mechanism is not considered in this work. *Point B* – As Jack moves within a WLAN network, his device needs to cope with content delivery over the wireless environment and the adaptive multimedia delivery mechanism – ***SAMMy (Signal Strength-based Adaptive Multimedia Delivery Mechanism)*** [10] is employed. This mechanism will adapt the multimedia stream based on the network conditions in order to maintain good user perceived quality level for Jack. *Point C* – is a representative of a point where the ***Adapt-or-Handover*** solution can be employed. This solution will decide if it is better for Jack to handover to a new network (WLAN B) or it is better to adapt the multimedia stream, in order to conserve the mobile device energy. Note that the points marked in Figure 1 represent an illustrative example in order to better understand the roadmap of the overall proposed solution design phases, and they do not represent the exact location where the decisions take place.

We created a test-bed environment and studied the energy conservation benefits, gained by adapting the multimedia stream to different quality level under various network conditions and different network technologies. The user perceived quality was monitored for all video levels sent, in order to maintain a good trade-off between energy reduction and satisfactory end user perceived quality. The measurements from the real test-bed environment were used to build a model in the NS-2 simulation environment. The proposed Adapt-or-Handover solution was analyzed and comparatively tested through simulations.

II. Related Works

The existing energy efficient solutions were categorized into five wide categories: energy consumption surveys and studies, energy efficient network selection, operation modes-based energy efficiency, cross layer solutions for energy conservation, and energy efficient multimedia processing and delivery.

A. *Energy Consumption Surveys and Studies*

Zhang et al. [12] present a survey on the recent major advances in power-aware multimedia. The main focus of the survey is on video coding and delivery. The authors identify the main challenges that come when designing energy efficient mobile multimedia communication devices, as: (1) real-time multimedia is delay-sensitive and bandwidth-intense making it also the highest power consuming application, (2) the radio frequency environment is changing dynamically over time and space, (3) the diversity of mobile devices and their capabilities, (4) video quality does not present a linear increase with increase in complexity, and (5) the battery discharge behavior is nonlinear. The authors conclude that due to the dynamics involved, enabling power-aware mobile multimedia is extremely challenging. Many tradeoffs are involved in the process, for example using high compression techniques to reduce the amount of data to be transmitted and therefore the energy involved in data delivery, but higher compression involves higher computation both at the server and the client, and therefore increased battery usage.

A study on the energy consumption of YouTube in mobile devices was carried out by Yu et al. [13]. The authors measured the energy consumption of a Nokia S60 mobile phone for three different use cases (progressive download, download-and-play, and local playback) and for two access network technologies (WCDMA and WLAN). Even though the results show that the WCDMA network consumes more energy than WLAN, they do not consider the impact of fluctuating network bandwidth nor the quality of the video.

Correia et al. in [14] address the problem of energy efficiency for mobile cellular networks (e.g., WCDMA/HSPA, LTE). The authors look at the energy efficiency of the entire system on three levels: (1) component level – looking at the efficiency of the power amplifier; (2) link level – looking at the discontinuous or continuous transmission modes of the base stations; and (3) network level – looking at the deployment paradigm of the cellular networks. The authors conclude that potential energy consumption reduction could be made at the network level by taking into account daily load patterns as well as the network architecture type (e.g., multi-hop transmission, ad-hoc meshed networks, etc.).

Vallina-Rodriguez et al. [15] perform a study on collecting usage data from 18 Android OS users during a 2 week period (Feb. 2010) in order to understand the resource management and battery consumption patterns. The information collected from the mobile devices covers a wide range of parameters, more than 20 (e.g., CPU load, battery level, network type, network traffic, GPS status, etc.) being updated every 10 seconds. The study shows the importance of contextual information when designing energy efficient algorithms. For example, by identifying where and when some resources are in high demand (50% of the time the users were subscribed to one of their top three most common base stations) more energy efficient resource management can be proposed based on this information.

B. Energy Efficient Network Selection Solutions

Context information (time, history, network conditions, device motion) is also used by Rahmati et al. [16] in order to estimate current and future network conditions and automatically select the most energy efficient network (802.11b or GSM/EDGE). The authors collected usage information from 14 users (HTC Wizard Pocket PC, HTC Tornado, and HP iPAQ hw6925 phones) during a 6 month period. The authors argue that by using the context-based interface selection mechanism the average battery lifetime of the mobile device can be increased by 35% in comparison with the case of using the cellular interface only.

Selecting the most energy efficient network in order to prolong the lifetime of mobile devices was addressed in [17]-[20]. Petander et al. [17] propose the use of traffic estimation for an Android mobile device in order to select between UMTS/HSDPA and WLAN. The traffic estimation is done by the Home Agent of the Mobile IPv6 protocol and sent to the mobile device, which takes the handoff decision based on the estimate. The results show that the energy consumption for data transfer over UMTS can be up to three hundred times higher than over WLAN. The authors in [18] propose a network selection algorithm based on AHP and GRA which selects the best network between CDMA, WiBro, and WLAN. The authors consider a wide range of parameters: QoS (e.g., bandwidth, delay, jitter, and BER), the monetary cost, the Lifetime (transmission power, receiver power, and idle power) and user preferences. In [19] Liu et al. use a SAW (Simple Additive Weighted) function of available bandwidth, monetary cost, and power consumption to select between WiFi, WiMAX, and 3G. Whereas in [20], the authors make use of TOPSIS to solve the multi criteria (available bandwidth, RSS, velocity, load rate, and power consumption) problem and select between 802.11a, 802.11b, and UMTS networks.

C. Operation Modes-based Energy Efficiency Solutions

A state-of-the-art power management method for next-generation wireless networks with a focus on operation modes (e.g., sleep, idle, etc.) is presented by Kim et al. [21]. The authors provide a technical overview of power management in IEEE 802.16m and 3GPP LTE. 802.16m provides advanced power saving mechanisms based on enhanced versions of legacy IEEE 802.16 sleep and idle modes, whereas LTE adopts a discontinuous reception mechanism for power saving. The authors conclude that alternating available and unavailable intervals can provide an efficient and basic power saving method. However, in this way, extra power will be spent on activating and deactivating components, so the number of mode changes needs to be kept low.

Lee et al. [22] propose a Content-Aware Streaming System (CASS) that aims at improving the energy efficiency in Mobile IPTV services. CASS uses information from the network and makes use of the Scalable Video Coding scheme in order to reduce the transmission of unnecessary bit-streams. In order to further increase the energy efficiency, CASS reduces the operating time of the client wireless NIC by switching it ON/OFF based on the client buffer.

Perrucci et al. [23] investigate the energy consumption of a Nokia N95 while performing VoIP. The authors propose the use of a lower energy consumption interface (e.g., GSM) as a signaling channel to wake up the WLAN interface and run the VoIP service. The authors argue that by using the wake-up signals the energy consumption can be reduced significantly in a VoIP scenario. The use of sleep and wake-up schedules is used by Namboodiri et al. [24] for energy saving during VoIP calls. The authors propose a GreenCall algorithm that keeps the WLAN interface of a laptop in sleep mode for significant periods during the VoIP calls. The maximum delay that a user can tolerate during a call is used to compute the sleep periods.

D. Cross Layer Solutions for Energy Conservation

Li et al. in [25] propose joint optimization of video coder parameters, channel coder, and transmit power in order to minimize the power consumption in video transmission. Their results indicate that when transmitting over a slow fading wireless channel, the solution is very efficient and effective in terms of energy-efficiency. The consideration of more realistic channel models is part of their future work.

The authors in [26] propose a power savings cross layer solution for an adaptive multimedia delivery mechanism based on remaining battery level, remaining video stream duration, and packet loss rate level. The mechanism decides whether or not to adapt the multimedia stream in order to achieve power saving while maintaining good user perceived quality levels.

E. *Energy Efficient Multimedia Processing and Delivery*

Baker et al. [27] propose a power saving mechanism at the decoding stage. The power-aware technique aims at reducing the decoding computation required for H.264 streams by using macro-block prioritization. This is done by allocating block priority levels in each frame of the video content, and omitting them, based on the allocated priority, at the decoder side. In this way the low priority block will be ignored by the decoder leading to decrease in computational workload.

Another technique that explores the energy saving in multimedia streaming is brightness compensation [28]-[30]. The authors of [28][29] propose the use of a proxy server that performs on-the-fly transcoding and dynamic adaptation of the video content (brightness compensation) based on the feedback from the client. The proxy server will send back the control information to the client middleware which will change its system parameters (e.g., operating backlight level) accordingly. In [30] the authors propose a similar approach and model the problem as a dynamic backlight scaling optimization in order to determine the appropriate video content backlight level. The authors show that when the energy consumption presents a monotonic increase with the backlight level, their proposed algorithm is optimal in terms of energy saving.

Despite the amount of research done in the area of energy conservation, not much focus has been placed on the impact of the multimedia communication environment (e.g., location, technology, network load, etc.) on the energy consumption. It has been shown that by adopting an adaptive multimedia delivery mechanism we can obtain significant power saving [26], as well as by employing an efficient power-friendly network selection mechanism [11]. This provides us with the motivation to propose the hybrid **Adapt-or-Handover** solution in order to achieve increased power efficiency, while maintaining high user perceived multimedia quality.

III. Adapt-or-Handover Solution

The Adapt-or-Handover solution is proposed to combine the benefits of network selection (by employing PoFANS) with the adaptive multimedia mechanism (from SAMMy) in order to increase overall power savings.

A. *Adaptive Multimedia Delivery Mechanism*

The Signal Strength-based Adaptive Multimedia Delivery Mechanism (SAMMy) [10] makes use of IEEE 802.11k radio measurements in order to collect information on the radio interface and the location of the mobile node relative to the Access Point (AP). The adaptive mechanism bases its adaptation decision on received signal power prediction, user location and packet loss. The solution is distributed and consists of server-side and client-side components. On the server side the content can be encoded at *n* different quality levels (QL) which correspond to different bitrates for the multimedia data to be delivered. As the mobile node moves away from the AP, its received signal strength drops. The coverage area of the AP was divided into a number of different

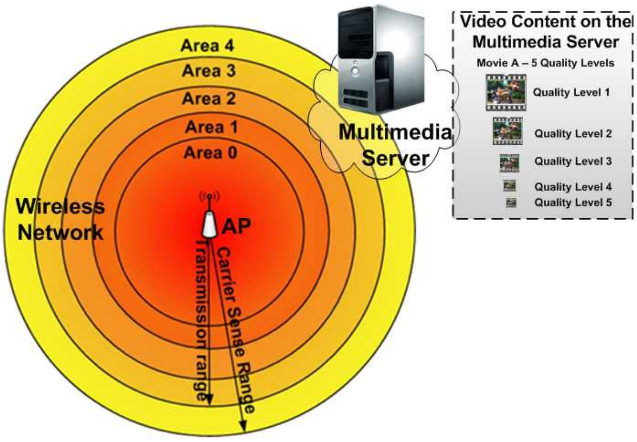

Figure. 2. Divided AP Coverage Area – Illustrative Example for 802.11b

areas (based on reduced signal strength) and then each area has an associated maximum QL, which corresponds to the maximum multimedia quality that a mobile user could avail of in that area. Based on the client feedback, client location, and signal strength-related readings, the server dynamically selects the most suitable QL and consequently adjusts the multimedia delivery rate. Positive feedback is used to indicate that no loss has been detected since the last received feedback, and conversely negative feedback indicates that loss has been detected. If the server receives two consecutive negative feedback reports, the QL is decreased by one. This ensures fast reaction to events which potentially affect user perceived quality. The QL will be increased again only after ten consecutive positive feedback reports are received. This more conservative approach increases the chance that the event which negatively affected the transmission quality has passed and aims to avoid the ping-pong effect of frequent quality increase-decrease decisions. The maximum achieved bitrate depends on the area the mobile user is located in.

Assuming that the multimedia server stores a movie (e.g., Movie A) encoded at five different quality levels (*n*=5) as illustrated in Figure 2 with Quality Level 1 (QL1) being the highest quality level and Quality Level 5 (QL5) the lowest quality level. For each defined Area there is a maximum QL, such that: Area 0 has QLmax = QL1, Area 1 has QLmax = QL2, Area 2 has QLmax = QL3, Area 3 has QLmax = QL4, and Area 4 has QLmax = QL5. This means that, for example, if a user is located in Area 1, then the maximum QL that the user can get in this area is QL2, and of course the minimum QL would be QL5 as SAMMy performs the adaptation between QL5, QL4, QL3, and QL2, only. The adaptive mechanism seamlessly adapts multimedia, decreases loss rate and increases user perceived quality for video streaming applications in wireless networks [10].

B. *Network Selection Mechanism*

As multimedia applications are high energy consumers and since the battery lifetime is an important factor for mobile users, the Power-Friendly Access Network Selection Strategy (PoFANS) [11] bases its selection decision not only on user preferences, application requirements, and network conditions, but also on the energy consumption of the mobile device. PoFANS enables the battery lifetime of mobile devices to last longer while running multimedia services and maintaining reasonable user perceived quality levels by selecting the most suitable least power consuming network choice. The solution is based on the multiplicative weighted score function presented in equation (1), which takes into consideration the estimated energy consumption of the mobile device when running real-time applications, the monetary cost of the network, application requirements, and estimated network conditions in terms of average throughput.

$$U_i = u_{e_i}^{w_e} \cdot u_{q_i}^{w_q} \cdot u_{c_i}^{w_c} \qquad (1)$$

In equation (1) U_i is the overall score function for RAN *i* and u_e, u_q, and u_c, are the utility functions defined for energy, quality in terms of received bandwidth, and monetary cost for RAN *i*. Additionally $w_e + w_q + w_c = 1$, where w_e, w_q, and w_c are weights for the considered criteria, representing the importance of a parameter in the decision algorithm. An important feature of any decision making scheme across multiple criteria is the chance given for the user to specify their preferences concerning the importance of the criteria. The users may give varying importance to each criterion. For example, if the user is on a strict budget, then the cost might be weighted higher, always looking for an affordable solution. If the user prefers to conserve the energy of his/her mobile device, then the energy will be given higher importance, meaning it will be weighted higher. If the user is more quality-oriented (high quality multimedia application), then the weight for quality will be higher. However, the aim is to find a good trade-off between the three weighted criteria.

There are many ways of collecting data from the user. Some of the proposed solutions probe the user for some required settings that are transformed afterwards into weightings for the networks parameters [31]. The solution proposed in [32] integrates a GUI in the user's mobile terminal in order to collect the user preferences on the following inputs: Service request class (Data, Video, Voice); Service preferred quality (Excellent, Good, Fair); and Service price preferences (Always Cheapest, Maximum service price). In this paper, it is assumed that the weights for cost, quality and energy are provided by the user (e.g., User Profile), and the user should be able to modify the weighting for each criterion, depending on his/her needs for each application in use and/or current environment.

PoFANS acts in user's best interest, computes the score function for each of the selected candidate networks and selects the network with the highest score as the target network. By making use of this network selection algorithm, significant power savings during multimedia transmissions can be achieved [11].

The utility functions for the three criteria are defined as follows:

1. *Energy Utility - u_e*

The energy utility is defined in equation (2). For low energy consumption values the corresponding energy utility (u_e) value is high, whereas for high energy consumption the utility is low. The energy utility value is in the [0,1] interval, and has no unit.

$$u_e(E) = \begin{cases} 1 & , \quad E < E_{\min} \\ \dfrac{E_{\max} - E}{E_{\max} - E_{\min}} & , \quad E_{\min} <= E < E_{\max} \\ 0 & , \quad otherwise \end{cases} \qquad (2)$$

E_{min} is the minimum energy consumption (Joule), E_{max} is the maximum energy consumption (Joule), and E is the energy consumption for the current network (Joule). E_{min} and E_{max} are calculated for Th_{min} and Th_{max} respectively. The energy consumption is computed using equation (3).

$$E_i = t(r_t + Th_i r_d) \quad (3)$$

In equation (3) E_i is the estimated energy consumption (Joule) for RAN *i*, *t* represents the transaction time (seconds), r_t is the mobile device's energy consumption per unit of time (W), Th_i is the available throughput (kbps) provided by RAN *i* and r_d is the energy consumption rate for data/received stream (Joule/Kbyte). The transaction time (length) can be predicted from the duration of the multimedia application. The parameters r_d and r_t are device specific and can be stored on/retrieved from the device. r_d and r_t differ for each network interface and they can be determined by running different simulations for various amounts of data and defining a power consumption pattern for each interface. In this work, a Google Nexus One device was used for the real experimental tests.

2. *Quality Utility – u_q*

A zone-based sigmoid quality utility function is defined to map the received bandwidth to user satisfaction for multimedia streaming application [33]. The utility is computed based on: the minimum throughput (Th_{min}) needed to maintain the multimedia service at a minimum acceptable quality (values below this threshold result in unacceptable quality levels i.e., zero utility); the required throughput (Th_{req}) in order to ensure high quality levels for the multimedia service; the maximum throughput (Th_{max}), values above this Th_{max} threshold result in quality levels which are higher than most human viewers can distinguish between and so anything above this maximum threshold is considered a waste. The mathematical formulation of this quality utility function is given in equation (4). The quality utility has values in the [0,1] interval and no unit.

$$u_q(Th) = \begin{cases} 0 & , \quad Th < Th_{\min} \\ 1 - e^{\frac{-\alpha * Th^2}{\beta + Th}} & , \quad Th_{\min} <= Th < Th_{\max} \\ 1 & , \quad otherwise \end{cases} \qquad (4)$$

In equation (4) α and β are two positive parameters which determine the shape of the utility function (no unit), *Th* is the predicted average throughput for each of the candidate networks (Mbps), Th_{min} is the minimum throughput (Mbps), and Th_{max} is the maximum throughput (Mbps).

3. *Cost Utility - u_c*

The cost utility u_c is defined as in equation (5), where C is the monetary cost for the current network (euro), C_{min} - minimum cost that the user is willing to pay (euro) and C_{max} – maximum possible cost that the user can afford to pay (euro). For small values of the monetary cost, the cost utility u_c has

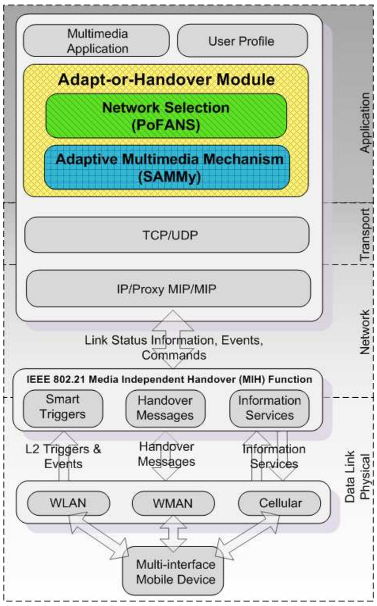

Figure 3. Adapt-or-Handover Overview Architecture

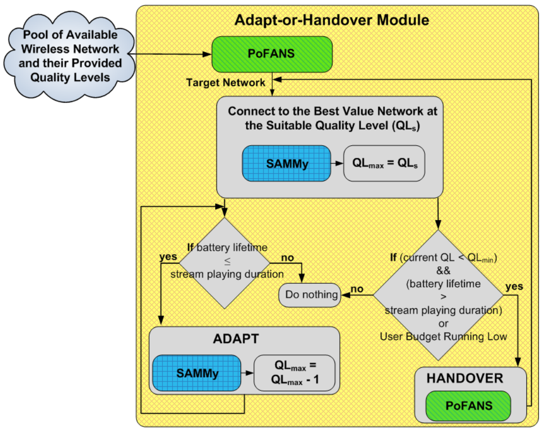

Figure 4. Adapt-or-Handover Basic Principle

high values, whereas for high monetary cost, u_c is small.

$$u_c(C) = \begin{cases} 1 & , \quad C < C_{\min} \\ \dfrac{C_{\max} - C}{C_{\max} - C_{\min}} & , \quad C_{\min} <= C < C_{\max} \\ 0 & , \quad otherwise \end{cases} \qquad (5)$$

The user can store his budget limit on his mobile device (e.g., User profile), which will be C_{max}, and of course the value of C_{min} is zero (e.g., free of charge services). In this work the monetary cost of each network, C, is a flat rate cost expressed in Euro/Kbyte. It is assumed that the flat rate charged is known in advance by the mobile user and does not change frequently (i.e., on a daily or weekly basis) and definitely will not change during a user-network session. The cost utility has values in the [0,1] interval, and no unit.

C. *Proposed Adapt-or-Handover Algorithm*

The need for battery efficient devices and integrated power management tools represents a strong motivation to propose a hybrid multimedia delivery Adapt-or-Handover solution. The

Algorithm 1 Adapt-or-Handover Decision Algorithm

START:
PoFANS Decision
Input:
M Available Wireless Networks;
N Quality Levels;
Procedure:
MxN Options;
Rank Options;
Output:
Connect to Target network;
Target QL;
SAMMy Decision
QL_{max} = Target QL;
ADAPT DECISION
if (battery lifetime ≤ stream playing duration) **then**
ADAPT - SAMMy Decision
$QL_{max} = QL_{max} - 1$;
end if;
HANDOVER DECISION
if (current QL < QL_{min}) && (battery lifetime > stream playing duration) || (User Budget running low)
then
HANDOVER - PoFANS Decision
Go to **START**;
end if;

Adapt-or-Handover solution balances adaptive multimedia delivery and network selection in order to improve energy conservation on the end-user mobile device, while maintaining acceptable user perceived quality levels.

Figure 3 illustrates the Adapt-or-Handover architecture based on the TCP/IP protocol stack model. The Adapt-or-Handover solution resides at the application layer, combining the two previously described mechanisms (SAMMy [10] and PoFANS [11]) and providing a middleware framework for multimedia delivery. The basic principle behind Adapt-or-Handover and a detailed description of the algorithm is further addressed in the next sections.

IV. Adapt-or-Handover – Basic Principle

Figure 4 illustrates the Adapt-or-Handover basic principle. In the first step the network selection mechanism (PoFANS) and the adaptive multimedia mechanism (SAMMy) are deployed in the mobile user device. Imagine again the case of Jack with a choice of available wireless networks as illustrated in Figure 1. Each of the available networks can deliver some or all of the offered multimedia server quality levels depending on network conditions. This list of available networks, together with the obtainable quality levels are input into PoFANS. PoFANS will score each network - quality level combination. For instance, if there are M available networks and each network can deliver any of the N Quality Levels set on the server, then the PoFANS mechanism would have MxN options to choose from. The output from PoFANS will be a ranked list of these MxN options. The option with the highest score is selected as the target network and quality level. Once Jack selects the target network, the adaptive SAMMy mechanism will set the maximum quality level to the provided target quality level. SAMMy works as previously described.

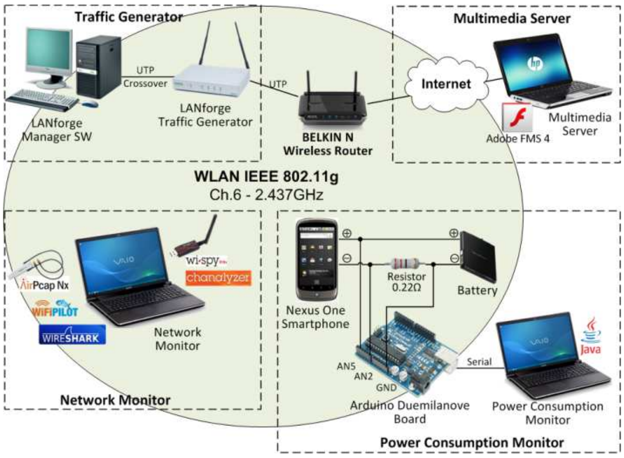

Figure 5. WLAN Test-Bed [34]

The Adapt-or-Handover solution will decide to adapt the multimedia stream only if the battery lifetime of the mobile device is less than the stream play-out duration. In which case, the maximum quality level set by SAMMy will be decreased by one.

A handover will only be triggered by the Adapt-or-Handover solution, if the current quality level is lower than the user's minimum acceptable level and the mobile device has enough battery lifetime to play the full stream, or if the user budget is running low so handover to a cheaper network is necessary. The user minimum acceptable quality and budget level could be taken from a user profile module integrated in the mobile device.

If the device does not have enough battery lifetime to handover to a new network, then the handover is cancelled and energy conservation will get a higher priority. In this case, SAMMy will adapt the quality level so that the stream will have enough battery to play until the end.

V. Adapt-or-Handover – Algorithm

As mentioned, the Adapt-or-Handover solution balances an adaptive multimedia delivery (SAMMy) and network selection (PoFANS) in order to improve energy conservation at the end-user mobile device. The pseudo-code of the decision process handled by the Adapt-or-Handover solution is described in Algorithm 1.

VI. Experimental environment and Results

A. *Test-Bed Environment*

This section investigates the energy consumption of an Android mobile device and the system efficiency in several video delivery scenarios over three different radio access technologies: IEEE 802.11g, UMTS and HSDPA. In our previous work [34] we presented an in-depth study on how the wireless link quality and the network load impact the energy consumption of an Android device while performing on-demand streaming over WLAN. The study offers a better understanding of the device's energy consumption on WLAN and demonstrates the necessity of considering network-related parameters (e.g., link quality, network load, transport protocol) when designing energy-efficient video transmission schemes.

TABLE I. Encoding Settings for the Multimedia Levels

Encoding Parameters					
Quality Level	**Video Codec**	**Overall Bitrate [Kbps]**	**Resolution [pixels]**	**Frame Rate [fps]**	**Audio Codec**
QL1	H.264/ MPEG-4 AVC Baseline Profile	1920	800x448	30	AAC 25 Kbps 8 KHz
QL2		960	512x288	25	
QL3		480	320x176	20	
QL4		240	320x176	15	
QL5		120	320x176	10	

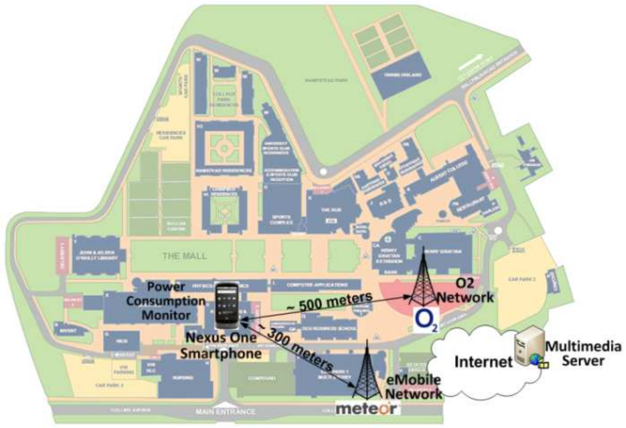

Figure 6. Cellular Test-Bed Setup [35]

The WLAN-based test-bed is illustrated in Figure 5. It consists of: an IEEE 802.11g *Wireless Router* running on channel 6 (freq. 2.437GHz), with no neighboring networks running on the same or adjacent channels; a *Multimedia Server* used to stream different multimedia quality levels to the mobile device; a *Traffic Generator* used to generate background traffic inside the wireless network; a *Network Monitor* integrating Wi-Spy DBx[1] and AirPcap Nx[2] used in order to monitor, capture, and analyze the traffic in the wireless network; an *Android Mobile Device* used as the client device and a *Power Consumption Monitor*.

The Power Consumption Monitor incorporates an Arduino Duemilanove[3] board connected to the Android mobile device and a laptop that stores the energy measurements. A Java application running on the laptop calculates the device power consumption (using Ohm's Law) based on the voltage values sent by the Arduino board at a frequency of 1Hz.

Adobe Flash Media Server 4[4] was employed for streaming using the proprietary application level streaming protocols RTMP (TCP) and RTMFP (UDP). The Blender Foundation's 10 minute long Big Buck Bunny[5] animated clip was used for testing. The video clip was encoded at five different quality

[1] Wi-Spy DBx - http://www.metageek.net/products/wi-spy/
[2] AirPcap Nx - http://www.metageek.net/products/airpcap/
[3] Arduino Duemilanove - http://www.arduino.cc/en/Main/ArduinoBoardDuemilanove
[4] Adobe Flash Media Server - http://www.adobe.com /products/flashmediaserver/
[5] Big Buck Bunny - http://www.bigbuckbunny.org/

TABLE II. CELLULAR NETWORK CHARACTERISTICS

Operator	Network Type	Downlink Rate	CID	LAC	MCC+MNC	SS
O2	HSDPA	7.2Mbps	2044410	36006	27202	-95dBm
eMobile	UMTS	384kbps	60902	3006	27203	-73dBm

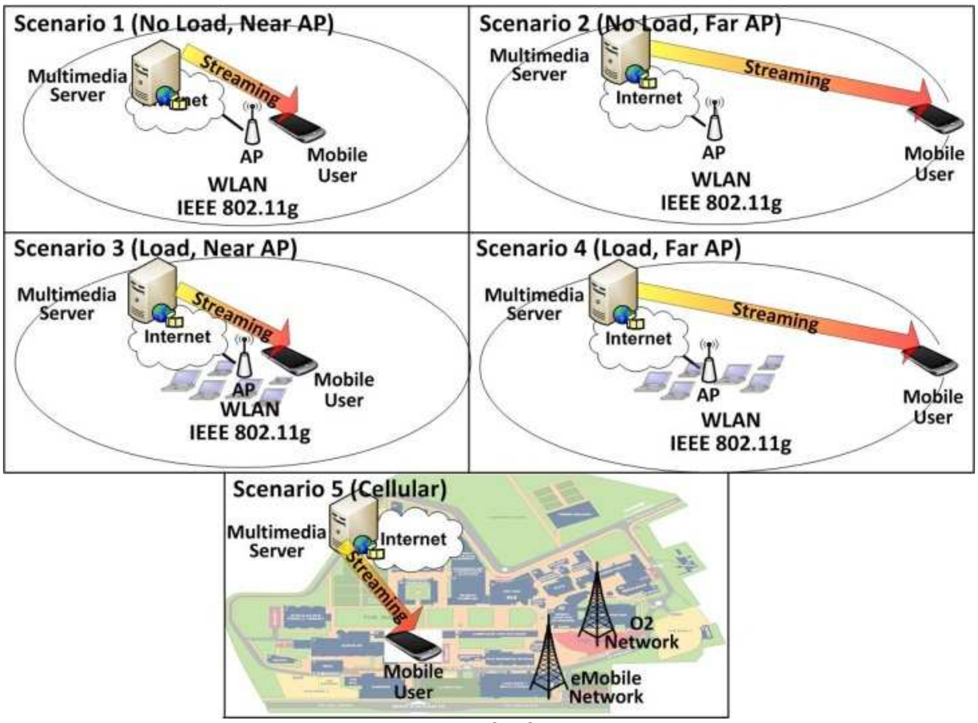

Figure 7. Considered Scenarios

levels, following the recommendations for encoding clips for multi-bitrate adaptive streaming[6] as illustrated in Table I. The video play-out is scaled to the device screen resolution. More details on the WLAN test-bed can be found in [34].

The test-bed used for gathering the cellular network power measurements is illustrated in Figure 6. The tests were run in Ireland within the Dublin City University campus, beside a second floor window inside the Engineering building over the cellular networks provided by two mobile internet service providers in Ireland: O2[7] and eMobile[8].

O2 offers HSDPA services nationwide, and is one of the leading mobile service providers in Ireland. eMobile is new onto the Irish market and offers UMTS services. Due to network operator data security, obtaining exact network related information (e.g. received throughput, network load, etc.) was not possible. The only information that could be gathered is the power consumption of the mobile device and generic network information (i.e., network type, maximum downlink rate, cell id (CID), location area code (LAC), mobile country code (MCC), mobile network code (MNC), signal strength (SS)) provided by the Network Signal Info Android application and listed in Table II. Only three quality levels were considered for cellular streaming due to the fact that cellular networks have lower transmission rates than WLAN (e.g., UMTS maximum rate is 384kbps, versus theoretically 54Mbps for IEEE 802.11g). The quality levels represent a subset of the five quality levels encoded for the WLAN test-bed. The three quality levels were streamed to the mobile device over the cellular networks. Unfortunately the O2 network blocked streaming over UDP, and therefore could only be tested for streaming over TCP. This was not the case for eMobile, where both protocols were enabled and full tests took place.

[6]Smooth Streaming Multi-Bitrate Calculator - http://alexzam belli.com /WMV/MBRCalc.html

[7] O2 Ireland - http://www.o2online.ie/o2/

[8] eMobile Ireland - http://www.emobile.ie/

B. *Test Case Scenario*

Five scenarios were considered as illustrated in Figure 7 and described below. In all the scenarios the Multimedia Server stores the *five ten-minute clips*, each corresponding to a different quality level as previously explained. The clips are streamed sequentially to the Android mobile device over either of two transport protocols (UDP and TCP).

1. Scenario 1 – No Load, Near AP

The first scenario considers the case of a mobile user, located near the AP (approximately within 1m), without any background traffic in the network, and where the received signal strength varies between -48dBm and -52dBm.

2. Scenario 2 – No Load, Far AP

In the second scenario the mobile user is located in an area with poor signal strength, varying between -78dBm and -82dBm. The tests were run without any background traffic in the network in order to study the impact of the link quality on the energy consumption of the Android mobile device.

TABLE III. RESULTS SUMMARY FOR UDP VOD STREAMING IN THE WIRELESS ENVIRONMENT

	WLAN							
	Scenario1 No Load, Near AP		**Scenario 2 No Load, Far AP**		**Scenario 3 Load, Near AP**		**Scenario 4 Load, Far AP**	
	Avg. Energy [J]	**Avg. Th. [Mbps]**	**Avg. Energy [J]**	**Avg. Th. [Mbps]**	**Avg. Energy [J]**	**Avg. Th. [Mbps]**	**Avg. Energy [J]**	**Avg. Th. [Mbps]**
QL1	862	2.07	875	3.32	897	2.27	1300	1.32
QL2	610	1.05	628	1.57	657	1.18	826	1.02
QL3	503	0.52	512	0.59	536	0.65	667	0.45
QL4	459	0.26	463	0.26	466	0.36	512	0.30
QL5	413	0.14	420	0.13	438	0.18	468	0.14

TABLE IV. SCENARIO 5 – UDP AND TCP VOD STREAMING

		Quality Level	**Avg. Energy [J]**	**Avg. Power [mW]**	**Dis-charge [mAh]**	**Battery Life [hrs]**	**Playout [s]**
O2 (HSDPA)	**TCP**	**QL3**	850	1330	64	3.70	**640**
		QL4	728	1173	55	4.19	**621**
		QL5	680	1119	51	4.39	**607**
eMobile (UMTS)	**UDP**	**QL3**	747	1254	56	3.92	600
		QL4	693	1160	52	4.24	600
		QL5	663	1110	50	4.43	600
	TCP	**QL3**	737	1230	55	4.00	600
		QL4	647	1078	49	4.56	600
		QL5	602	1004	45	4.90	600

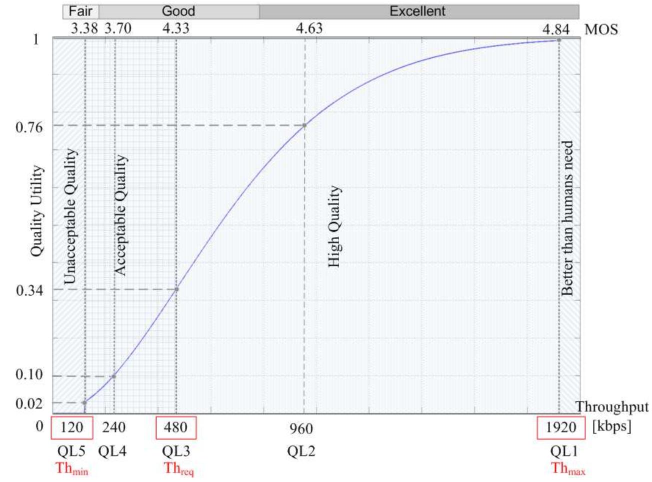

Figure 8. Quality Utility – Validation [31]

TABLE V. OBJECTIVE AND SUBJECTIVE RESULTS

Quality Level	**PSNR [dB]**	**Subjective MOS**	**Perceived Quality**	**Impairment**
QL1	-	4.84	Excellent	Imperceptible
QL2	47	4.63	Excellent	Imperceptible
QL3	41	4.33	Good	Perceptible but not annoying
QL4	36	3.70	Good	Perceptible but not annoying
QL5	31	3.38	Fair	Slightly annoying

3. Scenario 3 – Load, Near AP

The third scenario is similar to the first, except the addition of background traffic in order to load the network. It is used to study the impact of network load on the energy consumption of the Android mobile device. The LANforge traffic generator was used to create 25 to 28 virtual wireless stations, each generating traffic as previously explained. This background traffic was located near the AP with signal strength varying between -28dBm and -32dBm.

4. Scenario 4 – Load, Far AP

Scenario 4 is similar to Scenario 2 except that background traffic was added as in Scenario 3 (Load, Near AP). In this way the impact of both poor link quality (-78dBm - -82dBm) and network load, on the energy consumption of the Android mobile device can be studied.

5. Scenario 5 – Cellular

Scenario 5 considers the case of the mobile user performing VoD over the cellular networks previously discussed: O2 (HSDPA) and eMobile (UMTS) networks. In this scenario the impact of the network technology on the energy consumption of the Android mobile device is studied.

C. Results

An in-depth study and a more detailed view of the results within the wi-fi environment (Scenario 1 to Scenario 4) are presented in [34]. The study shows how the network related parameters (e.g., link quality, location, and network load) impact the power consumption of an Android Mobile device. A summary of the results is presented in Table III. Each test was repeated three times and the average values were considered. The average energy consumption of the Android Mobile device was measured while performing VoD Streaming over UDP for the different quality levels. The actual average throughput (Avg. Th.) received by the mobile device on the wireless network, was captured with Wireshark.

For Scenario 5, all the tests were performed with minimal background activities as for WLAN, and with the wireless interface disabled. The results are presented in Table IV [35]. It can be noticed that although O2 offers HSDPA (7.2Mbps theoretical data rate) which is an enhanced version of UMTS, some video motion loss is experienced, with re-buffering periods representing 6% for QL3, 4% for QL4, and 1% for QL5, respectively. On the other hand, when streaming over UMTS (384kbps theoretical data rate) the play-out is smooth without interruptions and more energy efficient.

O2 is one of the top mobile service providers in Ireland, owning 32.6% of the total market[9] while eMobile is new in the market (Sept. 2010). A realistic assumption is that the O2 network has more customers sharing bandwidth resources. This is reflected on the multimedia streams' play-out duration.

D. Modeling the Quality Utility

One of the important aspects of the multimedia delivery is user perceived quality. There are two methods which can be used in order to assess video quality: objective and subjective methods. The most widely used objective metric is the full-reference Peak Signal-to-Noise Ratio (PSNR). In order to estimate the human perceived visual quality offered by the five

[9] Europe mobile network operators - http://en.wikipedia.org/wiki /List_of_mobile_network_operators_of_Europe#Ireland

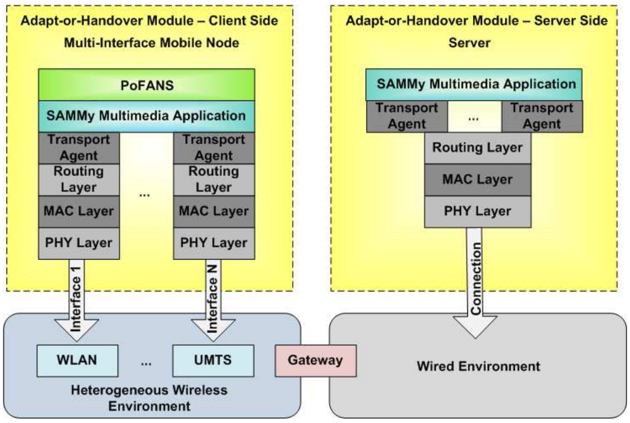

Figure 9. NS-2 Adapt-or-Handover Solution: Client Side and Server Side - Layered Model

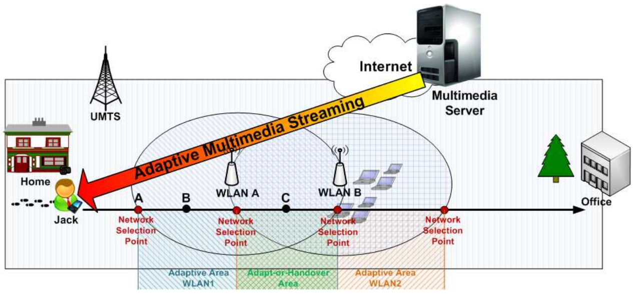

Figure 10. Example Scenario – Jack's path from Home to Office

encoding settings, the MSU Video Quality Measurement Tool[10] was used for computing the objective PSNR values.

A subjective study was also conducted as presented in [31]. For this purpose, four 20 seconds long test sequences with different spatial and temporal characteristics were extracted from the original 10 minute long multimedia clip of each quality level. A total number of 20 test sequences were used for the subjective study.

The objective PSNR and the subjective MOS results are listed in Table V together with the perceived quality and impairment mapping. Figure 8 shows the relationship between the quality utility, received throughput (Quality Levels) and MOS. The results obtained through subjective testing for the five quality levels, validate the choice of the sigmoid function. The detailed validation and modeling of the quality utility function is presented in [31].

Based on the quality levels' characteristics, the quality utility is modeled as in equation (6).

$$u_q(Th) = \begin{cases} 0 & , \quad Th < 0.120 \\ 1 - e^{\frac{-\alpha * Th^2}{\beta + Th}} & , \quad 0.120 <= Th < 1.920 \\ 1 & , \quad otherwise \end{cases} \qquad (6)$$

where α and β are two positive parameters that are determined knowing that: (1) for Th_{max} (1.920Mbps) the utility has its maximum value (e.g., u_{max} = 0.99 in order to avoid *ln(0)* which is invalid); (2) the second order derivate of u_q equals 0 for Th_{req} (0.480Mbps). In this particular case the values for α and β, after solving all the mathematical computations, are 5.72 and 2.66, respectively. For any other choice of quality levels, the procedure of identifying the parameters of the quality utility function is similar.

[10]MSU Video Quality Measurement Tool - http://compression.ru/video/quality_measure/video_measurement_tool_en.html

VII. Simulation Testing Environment

A. Enhanced Network Simulator

The simulation environment is based on the NS-2 Network Simulator (v2.33) [36]. The standard version of the simulator provides support for the simulation of different protocols (e.g., UDP, TCP) over wired and wireless networks (e.g., IEEE 802.11b). In order to test the proposed solutions, the basic NS-2 allinone v2.33 simulator was enhanced to create the necessary heterogeneous environment and to simulate as realistic an environment as possible.

For the WLAN environment, the No Ad Hoc (NOAH) wireless routing agent [37] was integrated in order to allow direct communication between mobile users and the AP only. This NOAH package was updated to work with NS-2.33.

The standard version of NS-2 only supports the simulation of 802.11b wireless channels, with no support for 802.11g included. The standard channel propagation model provided by the simulator does not consider the impact of interference, different thermal noises, or employed channel coding when determining the correct reception of frames. This means that the transmission range of a mobile node was modeled to be the same regardless of the data transmission rate. This is not realistic for 802.11 WLANs. The wireless update patch provided by Marco Fiore in [38] was used in order to improve the support for wireless communications scenarios by adding realistic channel propagation, multi-rate transmission support and Adaptive Auto Rate Fallback (AARF) [39].

The NS-2 source code was modified in order to add support for IEEE 802.11g. To obtain a more realistic behavior of the IEEE 802.11g channel, the wireless update patch provided by Marco Fiore was extended, and the multi-rate transmission support was updated for IEEE 802.11g.

In order to create a heterogeneous environment, the EURANE patch [40] was used. EURANE adds the support for the UMTS network and is available for NS-2.30. The patch was modified to work with NS-2.33. The wireless environment in NS-2 uses hierarchical addressing, this enables the grouping of nodes into clusters and domains in the same way as in the Internet IP addressing. However the EURANE patch comes with flat addressing making it incompatible to work with other IEEE 802.11g networks in a heterogeneous wireless scenario. For this reason EURANE was enhanced by adding support for hierarchical addressing. The UMTS scenarios use some input trace files that can be generated with Matlab. The trace files can be created for different realistic environments, modifying some of the physical layer parameters, like: environment (e.g., rural, urban, hilly terrain, etc.), velocity of the mobile user, distance from the BS, duration of the simulation, etc. The trace files provide the BLER (Block Error Rate) values and are meant to create a more realistic simulation environment.

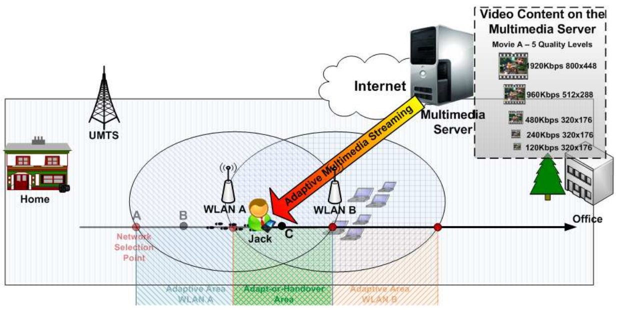

Figure 11. Adapt or Handover Scenario

TABLE VI. ADAPT-OR-HANDOVER RESULTS: COST FUNCTION VS. POFANS

	WLAN2		WLAN3		UMTS	
	No Load, Far AP		Load, Near AP		e-Mobile Network	
	Cost Function	PoFANS	Cost Function	PoFANS	Cost Function	PoFANS
QL1	**-0.3929**	0.4445	-0.3805	0.3968	N/A	N/A
QL2	-0.2088	**0.7005**	-0.1933	0.6804	N/A	N/A
QL3	0.0313	0.5433	0.0494	0.5323	0.2208	0.3847
QL4	0.3147	0.3230	0.3346	0.3174	0.5285	0.2394
QL5	0.6264	0.1709	0.6474	0.1704	0.8544	0.1306

B. Models and Algorithms Integration

As mentioned previously the proposed overall solution is structured into three main components: *(1) the Power-Friendly Access Network Selection Mechanism (PoFANS)* which performs the selection of the best value network, based on user preferences, application requirements, and network conditions; *(2) the Signal Strength-based Adaptive Multimedia Delivery Mechanism (SAMMy)* which adapts the multimedia stream based on network conditions in order to maintain acceptable user perceived quality levels; *(3) the Adapt-or-Handover* mechanism which decides whether to adapt the multimedia stream or to handover to a new network in order to conserve the energy consumption of the mobile device.

The Adapt-or-Handover solution makes use of both PoFANS and SAMMy, and was deployed in NS-2 as an application containing both server-side and client-side components. A schematic of the solution architecture integration within NS-2 is illustrated in Figure 9. As the Adapt-or-Handover solution requires a multi-interface mobile node that can be connected to different wireless networks (e.g., WLAN, UMTS), the standard implementation of the wireless node in NS-2 had to be updated.

As shown in Figure 9, each interface (one for each network) will use a separate transport agent for multimedia delivery. The transport agent from the client-side will be connected to its corresponding agent at the server side. The Adapt-or-Handover mechanism will make use of PoFANS in order to compute the score for each of the available networks and determine the corresponding interface and the suitable quality level for video delivery. All the input data required by PoFANS is assumed to be available at the client side.

The SAMMy-enabled multimedia application, at the client side, will make use of the transport agent and its corresponding connection in order to receive the adaptive multimedia traffic from the server. This SAMMy module sends feedback reports to the server containing: location information, packet loss information, received signal strength, maximum and minimum acceptable quality level (provided by the PoFANS module).

The server side is represented by a wired node that has a single high bandwidth wired connection. The Gateway is represented by a node that connects the wired network to the wireless network. The SAMMy server side component determines the quality level (based on the received feedback) that has to be delivered to the mobile client over the existing connection. Note that in the simulation scenarios individual simulations for each interface were conducted.

VIII. TESTING RESULTS AND ANALYSIS

In order to analyze the performance of the proposed solutions, the scenario with Jack is employed again. Recall the business professional who accesses multimedia content on his daily walking commute with a number of networks available as illustrated in Figure 10.

As Jack leaves his home he starts up a mobile multimedia session. In this call initiation phase, the selection of an access network is simple as there is only one available RAN (i.e., UMTS). As he moves further, he enters the coverage area of another RAN (i.e., WLAN A). At Point A, Jack's device should detect the second RAN and the possibility to handover from UMTS to WLAN A. The handover decision is made according to the PoFANS suggested solution, and it is very likely that the multimedia session will transfer to the WLAN A. Once on the WLAN A Jack's device may enable the adaptation of the multimedia stream based on the different rates offered by the WLAN A network in his approach towards and then away from the AP. The Signal Strength-based Adaptive Multimedia Delivery mechanism copes with the wireless errors in order to maintain an acceptable user perceived quality level for Jack's multimedia session.

By the time Jack enters the coverage area of WLAN B, his mobile device battery lifetime may be at risk. In which case, he faces the decision of whether it is better to adapt the multimedia stream to a lower quality level or it is better to handover to a new network in order to complete his viewing. In this situation, the Adapt-or-Handover mechanism will help Jack by taking the best decision.

A. Performance Analysis of Adapt-or-Handover (Point C)

At point C (Figure 11), Jack's smartphone has a choice of WLAN A, WLAN B, or the UMTS network. The decision has to trade-off between energy efficiency, user perceived quality, and playing out to the end of the clip within the battery limit. That is, is it better to adapt the multimedia quality to the current RAN or to handover to a new network and possibly quality level? In this situation, the Adapt-or-Handover mechanism will help Jack in taking the best decision.

This section presents the analysis of the performance of the Adapt-or-Handover solution in terms of energy efficiency. Two scenarios are considered: *(1) Critical Test-Case Scenario* – in which Jack's mobile device is running out of battery; *(2) Regular Test-Case Scenario* – in which Jack has recently

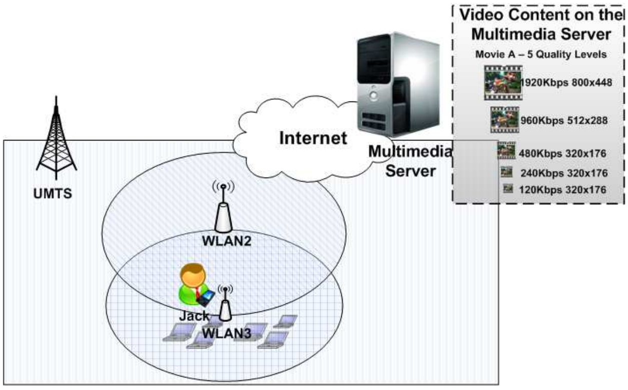

Figure 12. Adapt-or-Handover – Critical Test-Case Scenario

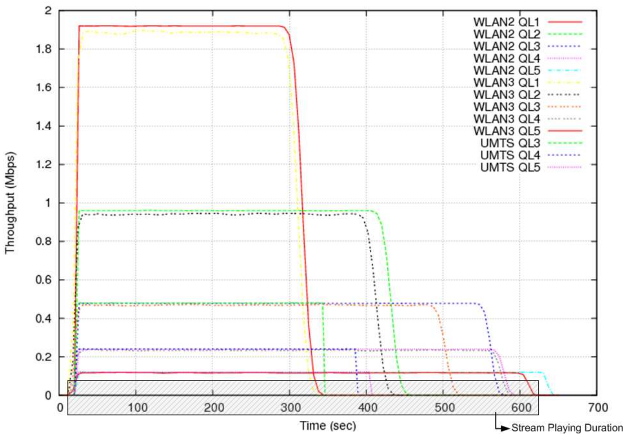

Figure 13. Stream Playing Duration for different QL and networks

TABLE VII. ADAPT-OR-HANDOVER COMPARISON OF STREAM PLAYING DURATIONS

	WLAN2	WLAN3	UMTS
	No Load, Far AP	**Load, Near AP**	**e-Mobile Network**
	Stream Playing Duration [min:sec]	**Stream Playing Duration [min:sec]**	**Stream Playing Duration [min:sec]**
QL1	4:57	4:51	N/A
QL2	6:52	6:33	N/A
QL3	8:26	8:05	5:26
QL4	9:19	9:15	6:09
QL5	**10:16**	9:51	6:27

charged his battery, and instead his full travel path is analyzed in terms of energy efficient decisions for the device.

The proposed Adapt-of-Handover solution is compared against the solution provided by Liu et al. [19]. The reason for using Liu's et al. solution as the comparison is that it also represents an energy dependent solution, and considers the same main parameters: available bandwidth, monetary cost, and the power consumption. This enables a fair comparison between the two schemes. Liu et al. propose the use of a SAW function (Cost Function *C*) given in equation (7).

$$C = w_B \ln \frac{1}{B} + w_P \ln P + w_c \ln c \qquad (7)$$

where *B* represents the available bandwidth, *P* represents the consumed power, and *c* represents the monetary cost. Note that when the monetary cost is zero (free network) then $\ln c = -\infty$. In order to allow for the Cost Function computation, in the simulations, it is assumed that a free network has a minor cost of c=0.01 and therefore $\ln c = -4.6$. As can be seen, the main difference between the two approaches is the choice of score and utility functions, Liu et al. making use of logarithmic functions and PoFANS makes use of the previously defined utility functions. For the overall decision score function, Cost Function *C*, follows the principle '*the smaller the better*', while PoFANS (equation (8)) follows the principle '*the larger the better*'. In order to compare the two it is assumed that *B* can be linked to the received throughput and *P* to the energy consumption (E), as described by equation (3) in Section IIIB.

$$U_i = u_{e_i}^{\ \ w_e} \cdot u_{q_i}^{\ \ w_q} \cdot u_{c_i}^{\ \ w_c} \qquad (8)$$

where: *U* – overall score function for RAN *i*; u_e, u_q, and u_c are the utility functions defined for energy, quality in terms of received bandwidth, and monetary cost for RAN *i*, respectively. Also $w_e + w_q + w_c = 1$, where w_e, w_q, and w_c are the weights for the considered criteria, representing the importance of a parameter in the decision algorithm.

The available three RANs used in the simulation scenarios, are set based on the information from the experimental test-bed networks, that is: WLAN1 – No Load, Near AP; WLAN2 – No Load, Far AP; WLAN3 – Load, Near AP; WLAN4 – Load, Far AP; UMTS – eMobile network. It is also assumed that WLANs can provide any of the five quality levels (three quality levels in case of UMTS) of the multimedia stream stored at the server side without difficulties.

1) Critical Test-Case Scenario – Low Battery Lifetime

The sub-scenario with Jack at point C where he has three available networks to choose from is illustrated in Figure 12. Assuming that Jack is willing to pay any amount within his budget limits, in order to ensure a good quality-energy trade-off, the weights for the three parameters are set to: $\boldsymbol{w_e = 0.5, w_q = 0.5, w_c = 0}$. This section assumes a critical scenario in which Jack's mobile device is running low on battery. The battery lifetime of his device is just enough to play five minutes of the ten-minute QL1 video clip stored on the server, in ideal network conditions (e.g., No Load, Near AP – from the experimental test-bed). In this situation the efficiency of the Adapt-or-Handover mechanism is analyzed.

The first step is for the network selection mechanism, PoFANS, to select the best network and quality level. The results of the PoFANS mechanism in comparison with the Liu et al. Cost Function for a choice of WLAN 2, WLAN 3 and UMTS, are listed in Table VI.

As seen in Table VI, PoFANS will select QL2 WLAN2 while Liu et al. Cost Function, will select QL1 WLAN2. Because the solution provided by Liu et al. Cost Function, does not provide a dual adaptation approach (network selection and video delivery adaptation), after the best network is selected the session is transferred at the corresponding quality level (i.e. QL1).

In the case of PoFANS, immediately after the selection of the best quality level and network combination, the Adapt-or-Handover algorithm kicks in by checking if the *Battery Lifetime* of the mobile device will meet the *Stream Playing Duration*. If the battery will not last at the current quality level,

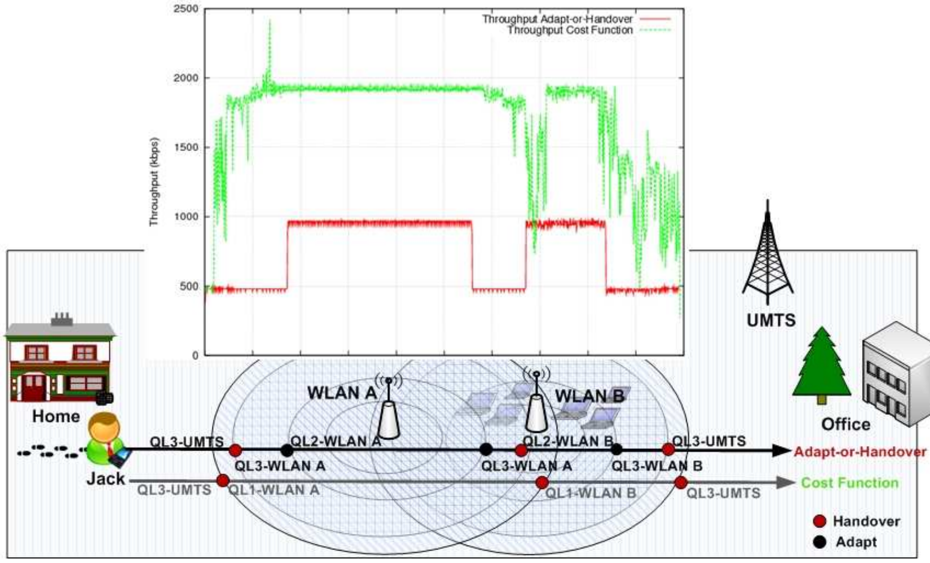

Figure 14. Throughput Jack's Full Travel Path: Adapt-or-Handover vs. Cost Function Analysis

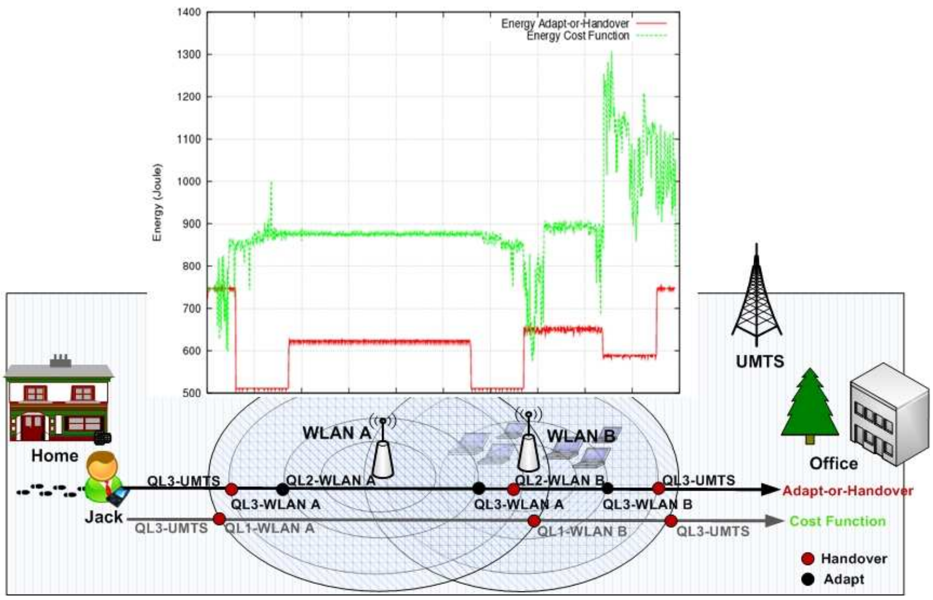

Figure 15. Energy Consumption Jack's Full Travel Path: Adapt-or-Handover vs. Cost Function

the energy conservation gets higher priority over the quality so that the device's battery lifetime will last longer (ideally until the end of the multimedia playout). The adaptive video delivery mechanism, SAMMy, is employed to reduce the current video quality level to a suitable quality level which will consume less battery power and offer the closest battery duration (preferably in excess of the stream play-out duration).

In the particular case of Jack's mobile having only five minutes battery charge left for a ten minute video stream at QL1, the Adapt-or-Handover mechanism will adapt the quality level such that the Jack's smartphone's battery lifetime will be last for the full stream play-out duration, QL5 in this case.

Figure 1 3 and Table XV illustrate the remaining battery lifetime for each of the quality levels in each network. The results are estimated based on the results obtained in the previously described real experimental test-bed scenarios. The battery duration for play-out at QL1 near the AP, with no background traffic, is taken as a reference. Figure 13 illustrates the throughput (quality level) for each situation, with the throughput falling to zero when the device runs out of battery. The results show that Jack will be able to finish watching the multimedia stream only when transmitting at QL5 in WLAN2. By employing the Liu et al. Cost Function the multimedia will be streamed at QL1 on WLAN 2. As seen in Table VII, in this situation Jack's mobile device battery lifetime will only last for 4:57 minutes, so Jack can watch less than half of the clip.

From Table VII it can be seen that, by employing the adaptation mechanism (SAMMy) in this situation, the Adapt-or-Handover solution, will more than double the battery lifetime of Jack's mobile device in comparison with the Liu et al. Cost Function-based solution.

TABLE VIII. ENERGY-QUALITY TRADE-OFF RESULTS: COST FUNCTION VS. POFANS

	WLAN1		**WLAN2**		**WLAN3**		**WLAN4**		**UMTS**	
	No Load, Near AP		**No Load, Far AP**		**Load, Near AP**		**Load, Far AP**		**e-Mobile Network**	
	Cost Function	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**
QL1	**-0.4005**	0.4706	-0.3929	0.4445	-0.3805	0.3968	-0.1950	0	N/A	N/A
QL2	-0.2166	**0.7103**	-0.2088	0.7005	-0.1933	0.6804	-0.1375	0.5960	N/A	N/A
QL3	0.0232	0.5480	0.0313	0.5433	0.0494	0.5323	0.1032	0.4957	0.2208	0.3847
QL4	0.3064	0.3253	0.3147	0.3230	0.3346	0.3174	0.3580	0.3104	0.5285	0.2394
QL5	0.6180	0.1709	0.6264	0.1709	0.6474	0.1704	0.6805	0.1656	0.8544	0.1306

2) *Regular Test-Case Scenario*

This section analyzes the performance of the proposed Adapt-or-Handover solution in terms of energy efficiency, over Jack's full travel path (from Home to Office). In this case the mobile battery is considered to be charged and well able to last the journey. The Adapt-or-Handover solution is compared against the Liu et al. Cost Function-based solution. Figure 14 and Figure 15 illustrate the received throughput and the energy consumption of Jack's mobile device, respectively. The weights for the three parameters are: $\boldsymbol{w_e = 0.5, w_q = 0.5, w_c = 0.}$ A weight for quality of 0.5 will result in minimum acceptable video quality above QL4.

In both Figure 14 and Figure 15 WLAN A is not loaded, whereas WLAN B is loaded. The results provided in Table VIII, considers the measurements from the test-bed for all five experimental network scenarios. For example, WLAN A incorporates WLAN2 (No Load, Far AP) when Jack is located far from the AP, and WLAN1 (No Load, Near AP) as he goes towards the AP. The same applies for WLAN B (WLAN3 - Load, Near AP and WLAN 4 – Load, Far AP). These aspects were considered when computing the energy consumption for this scenario. The network conditions from the experimental test-bed for all five networks were modeled in the NS-2 simulator. In this scenario, initially Jack receives video at QL3 over the UMTS network, and as he walks further, he enters the coverage area of WLAN A (with no load).

The Liu et al. Cost Function performs a handover to WLAN A (corresponding to QL1 – WLAN2) whereas Adapt-or-Handover solution decides to stay in UMTS. This is because, Jack would be located in an area with poor signal strength within WLAN A (Area 3, far from AP), meaning that SAMMy could provide QL4 as the maximum QL in that area, which is not acceptable for Jack who prefers a video quality above or equal to QL3. As soon as Jack enters Area 2 of WLAN A, the maximum QL of SAMMy increases to QL3, and the Adapt-or-Handover mechanism will handover. A smooth handover to WLAN A (corresponding to QL3- WLAN2) is assumed. Moving near the AP, SAMMy will adapt to the better conditions available and stream at QL2. QL2 is the maximum quality level that Jack could receive as decided by PoFANS (see Table VIII).

When Jack leaves the Area 0-1 near the AP and crosses back into Area 2 of WLAN A, SAMMy will adopt a lower quality level (corresponding to QL3-WLAN2). Note that since WLAN B is loaded, Adapt-or-Handover will detect this with Area 3 and Area 2 on WLAN B having lower selection scores than the WLAN A areas 0-2. On leaving WLAN A Area 2, the Adapt-or-Handover mechanism will trigger PoFANS, which will result in a handover to WLAN B (corresponding to QL2-WLAN3) since Area 3 of WLAN A is not acceptable in terms of quality. Once Jack moves away from the WLAN B AP, SAMMy will adapt the multimedia stream to a lower quality level (corresponding to QL3-WLAN4), and when leaving Area 2 of WLAN B, PoFANS will decide to handover to the UMTS network (since QL4 in Area 3 of WLAN B is not a favorable option).

The Liu et al. Cost Function has three handover decision points, when entering and leaving the coverage area of an AP, only. It does not take any adaptation decision and transmits the highest video quality level at all times.

The average throughput and average energy consumption for both Adapt-or-Handover solution and Liu et al. Cost Function –base solution, in this scenario, are listed in Table IX. It can be seen how Jack, by using the Adapt-or-Handover solution, can reduce the energy consumption of his mobile device by 31% in comparison with when the Liu et al. Cost

Function is employed. Note that the cost of handover in terms of energy consumption has been neglected in this scenario. However it does not have any impact in the comparison of the methods as both methods have the same number of handover executions.

B. *Energy-Quality-Cost Trade-off*

In order to analyze the energy-quality-cost trade-off two additional scenarios were considered: (1) **high budget user case** - where Jack cares most about his quality and energy usage and he is willing to pay a certain amount while maintaining a balance between the quality level of his received content, and the resulting energy consumption. Thus, the weights for the three parameters are selected to be: $w_e = 0.4$, $w_q = 0.4$, and $w_c = 0.2$; (2) **low budget user case** - where Jack cares most about his budget and uses the following weight distribution we = 0.1, wq = 0.1, and wc = 0.8.

Consider Jack with the same choice of three networks as before: WLAN2 – No Load, Far AP, WLAN3 – Load, Near AP, and UMTS. For testing, the network costs are set as: WLAN2 – 0.2 cents per unit of data, WLAN3 – free hot-spot, and UMTS – 0.9 cents per unit of data. The results for the two user case scenarios are presented in Table X.

For the first high budget user case, with PoFANS enabled on Jack's mobile device, he will end-up selecting QL2 on WLAN2. If the Liu et al. Cost Function had been in use, then Jack would end-up with QL1 on WLAN3. It can be seen that the Liu et al. Cost Function selects the highest quality level

TABLE IX. REGULAR TEST-CASE SCENARIO – JACKS'FULL TRAVEL PATH RESULTS

Solution	Average Throughput [Kbps]	Average Energy Consumption [Joule]
Adapt-or-Handover	740	610
Liu et al. Cost Function	1710	891

TABLE X. RESULTS: COST FUNCTION VS. POFANS

		WLAN2		WLAN3		UMTS	
		No Load, Far AP		Load, Near AP		e-Mobile Network	
		Cost Function	PoFANS	Cost Function	PoFANS	Cost Function	PoFANS
High Budget	*QL1*	-0.6362	0.5119	**-1.2244**	0.4774	N/A	N/A
	QL2	-0.4889	**0.7365**	-1.0746	0.7349	N/A	N/A
	QL3	-0.2969	0.6010	-0.8805	0.6039	0.1556	0.4132
	QL4	-0.0701	0.3965	-0.6524	0.3993	0.4017	0.2827
	QL5	0.1792	0.2382	-0.4021	0.2427	0.6625	0.1741
Low Budget	*QL1*	-1.3661	0.7816	**-3.7561**	0.8312	N/A	N/A
	QL2	-1.3293	0.8560	-3.7187	**0.9259**	N/A	N/A
	QL3	-1.2813	0.8136	-3.6701	0.8815	-0.0401	0.5120
	QL4	-1.2246	0.7332	-3.6131	0.7949	0.0214	0.4657
	QL5	-1.1623	0.6455	-3.5505	0.7019	0.0866	0.4126

(QL1), which in terms of energy conservation is the most power consuming, while PoFANS selects QL2 (WLAN2) achieving a 30% decrease in energy consumption as compared to QL1 (WLAN1).

In terms of the cost parameter, PoFANS first choice is QL2 from the paid network (WLAN2) followed by QL2 from the free loaded network (WLAN3). By selecting QL2 provided by WLAN2 Jack achieves 5% energy savings, when compared with QL2 from WLAN3. If Jack's mobile device was required to choose QL1, then the device would select the paid network over the free network. This is because for paying a small amount (0.2 cents per unit of data) Jack will get a better received quality (over the free loaded network) and energy savings (2.5%). For the lower quality levels (QL3-QL5) Jack willingness to pay is lower and thus PoFANS will select the free network for these levels. Looking at the results provided by the Liu et al. Cost Function, QL1 is the first choice followed by QL2-4 on the free network (WLAN3), QL2 on WLAN2 is the 6th choice. The Liu et al. selection function is not willing to accept a small cost in order to save energy and improve the quality level, it is only when the quality level is really beyond QL4 that this selection function will accept cost and select QL1 on WLAN2.

In the low budget user case it can be seen that the Liu et al. Cost Function again selects the highest quality level on the free WLAN3, whereas PoFANS also takes the no cost option of WLAN3 but finds a trade-off between quality and energy by selecting QL2. While both solutions select the free network, the benefit that Jack gets by using PoFANS vs. Liu et al. Cost Function is a 26.6% decrease in energy consumption (according to Table III), while still maintaining an 'Excellent' quality level for the delivered content.

IX. CONCLUSION AND FUTURE WORK

With the rapid growth in the multimedia traffic, adaptive multimedia streaming solutions have become common in the Internet video world in order to enable videos to play smoothly as network bandwidth fluctuates. Moreover with the increasing number of mobile users and their bandwidth demands, network selection solutions will be part of the next-generation of wireless multimedia networks. This paper proposes a hybrid multimedia delivery solution, Adapt-or-Handover which performs an energy-quality-cost trade-off by employing a combined adaptive multimedia delivery mechanism working in harmony with a network selection solution. The Adapt-or-Handover solution makes use of user preferences, location-based and network related information in order to decide whether to adapt multimedia delivery or handover to a new network.

The Adapt-or-Handover solution was analyzed in terms of energy efficiency and compared against another solution that considers energy, proposed by Liu et al. [19] and referred to as Liu et al. Cost Function. Two sub-scenarios were considered: (1) a critical test case scenario in which the battery lifetime of the mobile device is running low, and (2) a regular test case scenario that combines the use of PoFANS and SAMMy. The Adapt-or-Handover represents a dual-adaptation solution that makes use of PoFANS and SAMMy, whereas the Liu et al. Cost Function only performs network selection. The benefit of combining PoFANS and SAMMy into the Adapt-or-Handover solution has been analyzed. The results for the first scenario have shown that the Adapt-or-Handover solution can increase the battery lifetime of the mobile device up to 122%, in comparison with Liu et al. Cost Function, when considering a critical scenario in which the battery lifetime is at risk. In a regular scenario the Adapt-or-Handover solution could reach up to 31% energy savings in comparison with the Liu et al. Cost Function.

This paper demonstrates the efficiency of the proposed combined mechanism and shows the necessity of such a solution in real world scenarios. Nowadays network operators consider that if they offer high throughput that is translated into satisfied users. However, as shown here excellent perceived quality of service does not always result from a high throughput especially when the battery is low, and a good trade-off between quality and energy is needed in order to keep the user satisfied. Network operators need to integrate adaptive mechanisms in order to cater for the user preferences and enable a good balance between energy and quality.

In terms of future work, additional parameters and improvements could be integrated into the current solution in order to enhance the mobile user experience. Different studies have shown that the overall user experience may be affected by a wide range of factors, such as: Operator – considering different pricing models for various class of services, this can be achieved by predicting the economic behavior of the user [43] and by taking into account the user attitude towards risk [43] while performing service delivery; Connection –

considering the impact of the connection environment on service delivery and user satisfaction, e.g., the set-up of the connection, signal strength, reliability, coverage area, network conditions [34], wireless technology [35] etc.; Device Type – considering the impact of the various access devices [45] on service delivery and user satisfaction, e.g., various ranges of operating systems, capabilities, battery level, familiarity, etc.; Application – considering the impact of different content, tasks on service delivery and user satisfaction [46] e.g., video call, text/SMS, chat, online shopping, streaming, social interaction, entertainment, etc.; Activity/Mobility – considering the impact of different user locations and environments (noisy/quiet) on the service delivery [47] e.g., airport, on the street, coffee shop, office, at home, etc.

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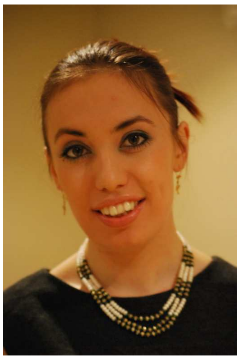

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