# Enhanced Power-Friendly Access Network Selection Strategy for Multimedia Delivery over Heterogeneous Wireless Networks

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*Abstract*— **The continuing growth in video content exchanged by mobile users creates challenges for the network service providers in terms of supporting seamless multimedia delivery at high quality levels, especially given the existing wireless network resources. A solution which deals with this mobile broadband data growth is to make use of multiple networks supported by diverse radio access technologies. This multi-access solution requires innovative network selection mechanisms to keep the mobile users "always best connected" anywhere and anytime. Additionally, there is a need to develop energy efficient techniques in order to reduce power consumption in next-generation wireless networks, while meeting user quality expectations. In this context, this paper proposes an Enhanced Power-Friendly Access Network Selection solution (E-PoFANS) for multimedia delivery over heterogeneous wireless networks. E-PoFANS enables the battery of the mobile device to last longer, while performing multimedia content delivery, and maintains an acceptable user perceived quality by selecting the network that offers the best energy-quality tradeoff. Based on real test-bed measurements the proposed solution is modeled and validated through simulations. The results show how by using E-PoFANS the users achieve up to 30% more energy savings with insignificant degradation in quality, in comparison with another state-of-the art energy efficient network selection solution.**

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

## I. INTRODUCTION

THE *Always Best Connected* [1] vision emphasizes the scenario of a variety of radio access technologies working together in order to form a global wireless infrastructure in which the end-users benefit from optimum service delivery via the most suitable available wireless network(s). Figure 1 illustrates such a heterogeneous wireless environment, which can be defined as a multi-technology multi-terminal multi-application and multi-user environment within which mobile users can roam freely.

Some of the advantages of such an environment are as follows: it makes use of existing infrastructure, eliminating the cost of new technology deployments; it provides increased wireless capacity ensuring seamless mobility; it provides backward capability and adds support for high data rates and low latency; and it enables seamless use of work and home WLANs integrated with public wireless networks.

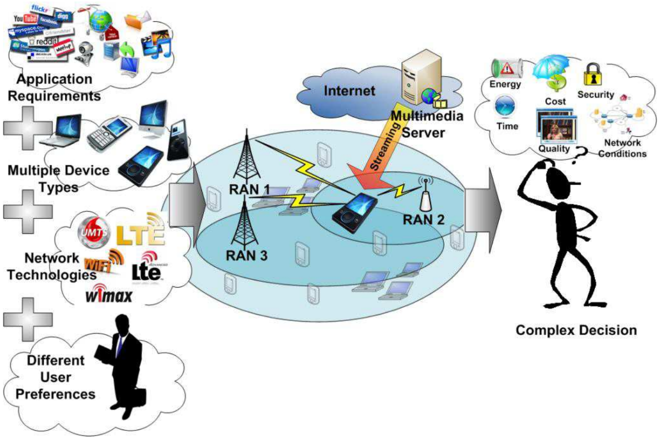


Figure 1. Heterogeneous Wireless Environment

However, in order to achieve seamless connectivity within the heterogeneous wireless environment a suitable interworking solution is needed. All of the existing solutions are built on the vision of an all-IP based infrastructure, having IP as the common network layer protocol. A variety of applications (e.g., voice, video, data, etc.) using different transport protocols (e.g., TCP, UDP) are run on top of the IP layer, which in turn is run over a number of access technologies (cellular, WLAN, Ethernet, etc.).

The Media Independent Handover Working Group IEEE 802.21 [2] has considered the interoperability aspects between heterogeneous networks, and developed a new standard referred to as IEEE 802.21. The standard enables the optimization of handover between heterogeneous IEEE 802 networks and facilitates handover between IEEE 802 networks and cellular networks by providing methods and procedures to gather useful information from both the mobile device and the network [3]. This information can contain: user profile, application requirements, network policy and type, link quality, etc.

However IEEE 802.21 only facilitates handover and does not specify the network selection algorithm, which is a major part of the handover process.

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Lately there is a significant trend towards proposing energy efficiency solutions, including in terms of network operation and content delivery. This paper proposes the **Enhanced Power-Friendly Access Network Selection solution (E-PoFANS)** which increases the energy efficiency of content delivery and prolongs the mobile device battery lifetime by selecting the network that offers the best energy-quality trade-off. E-PoFANS extends the power-friendly network selection mechanism proposed in [4] by including an energy consumption equation modeled based on real test-bed energy consumption measurements involving an Android mobile device, while performing video content delivery over different network types and under various conditions. The data from the real test-bed environment was used to create the simulation environment in NS-2, where the proposed solution was evaluated through simulations. Test results show how E-PoFANS achieves up to 30% more energy savings with insignificant degradation in quality in comparison against another network selection mechanism that also considers energy.

## II. Related Works

With the increasing popularity of the new smart devices and their applications, mobile users are demanding more interactive and personalized multimedia services at higher quality. The continuing growth in 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 [5]-[10] 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 [11][12].

However, it is known that real-time applications, and in particular the ones based on multimedia, have strict Quality of Service (QoS) requirements, while they are also the most power-consuming. In this context, one of the impediments of progress is the battery lifetime of mobile devices.

Energy conservation has become a critical issue around the world and presents a strong motivation for researchers to propose and develop more energy efficient techniques in order to manage the power consumption in next-generation wireless multimedia networks. Various studies were performed in order to determine the energy consumption patterns for different mobile devices. Researchers investigated the energy consumption in various conditions (e.g., different radio access technologies, time, device motion, etc.) trying to identify the main parameters that contribute to the energy consumption. In the research literature there are a number of different solutions which attempt to limit power consumption by means of adaptive streaming, decoding, reception, display (brightness compensation), transmission modes (ON/OFF/Sleeping), and interface switching (handover/network selection).

A study on the energy consumption of YouTube in mobile devices was carried out by Xiao 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). Although the results show that the WCDMA network consumes more energy than the WLAN, they do not consider the impact of fluctuating network bandwidth, nor the quality of the video.

Lee et al. [14] propose a Content-Aware Streaming System (CASS) that aims to improve the energy efficiency of Mobile IPTV services. CASS uses information from the network and makes use of a 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.

Vallina-Rodriguez et al. [15] perform a study on collecting usage data from 18 Android OS users during a 2 week period in order to understand the resource management and battery consumption pattern. The information collected from the mobile devices covers more than 20 parameters (e.g., CPU load, battery level, network type, network traffic, GPS status, etc.), with the data 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 their time the users were subscribed to their top three most common base stations) a more energy efficient resource management can be proposed.

Context information (i.e. time, history, network conditions, and 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 (holding HTC Wizard Pocket PC, HTC Tornado, and HP iPAQ hw6925 phones) during a 6 months period. The authors argue that by using the context-based interface selection mechanism the average battery lifetime of the mobile device can reach 35% increase comparing 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]-[21] as well. Petander et al. [17] propose the use of traffic estimation of 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 will take 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), monetary cost, lifetime (e.g. transmission power, receiver power, and idle power) and user preferences. In [19] Liu et al. use a SAW 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 (i.e. available bandwidth, RSS, velocity, load rate, and power consumption) problem and select between 802.11a, 802.11b, and UMTS networks. Fan et al. in [21] make use of fuzzy logic to ensure the optimal selection of the best value network. The selection decision is done using the information related to bandwidth, reliability, cost and estimated energy consumption.

In terms of multimedia delivery, Kennedy et al. in [22] propose a power savings cross layer solution that decides whether or not to adapt the multimedia stream in order to achieve power saving while maintaining good user perceived quality levels.

Different studies have looked at the overall user experience and have identified a wide range of factors that could affect the users Quality of Experience (QoE): the impact of different pricing models of the operators for various service classes - this can be achieved by predicting the economic behavior of the user [23] and by taking into account the user attitude towards risk [24]; the impact of the connection reliability and the environment, e.g., connection set-up, signal strength, coverage area, network conditions [25], wireless technology [26] etc.; the impact of the access device type [27], e.g., various ranges of operating systems, capabilities, battery level, familiarity, etc.; the impact of the application content, tasks [28] e.g., video call, text/SMS, chat, online shopping, streaming, social interaction, entertainment, etc.; the impact of the user location [29] e.g., airport, on the street, coffee shop, office, at home, etc.

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. This provides us with the motivation to propose an Enhanced Power-Friendly Access Network Selection Strategy (E-PoFANS) in order to achieve increased power efficiency, while maintaining high user perceived multimedia quality.

## III. E-PoFANS Solution

### *A. E-PoFANS Architecture*

As multimedia applications are known to be high energy consumers and since the battery lifetime is an important factor for mobile users, E-PoFANS bases its selection decision on user mobility, user preferences, application requirements, network conditions, and energy consumption of the mobile device. E-PoFANS enables the battery lifetime of the mobile device to last longer, while running multimedia services and maintaining good user perceived quality levels by selecting the least power consuming network choice.

Figure 2 illustrates the E-PoFANS architecture based on the TCP/IP protocol stack model. E-PoFANS resides at the application layer, providing a middleware framework for multimedia delivery. For example, a video application which uses the proposed E-PoFANS mechanism can employ a transport layer protocol such as UDP, a network layer protocol such as Mobile IP, and classic MAC and PHY layer protocols for delivery such as IEEE 802.11g.

E-PoFANS selects the best value network from the available networks based on information which includes network conditions, monetary cost of each network, energy consumption, and user preferences. This information is gathered by the mobile device by employing various mechanisms for monitoring the available networks, or by obtaining the required information from external entities or agents. For example, the new standard IEEE 802.21 provides three main services, as illustrated in Figure 2: *(1) Media Independent Event Service* – triggered when changes occur at the physical layer (i.e., link parameters change, new networks available, interrupted/established session); *(2) Media Independent Command Service* – enables the higher layers to control the link layer by reconfiguring or select an appropriate link*; (3) Media Independent Information Service* – provides an interface for the handover policy in order to gather information about the available networks.

E-PoFANS makes use of the IEEE 802.21 standard in order to gather information about the available wireless networks (e.g., available throughput, monetary cost, etc.). This information, combined with data about the multimedia application requirements and user preferences, enables E-PoFANS to best select a target network.

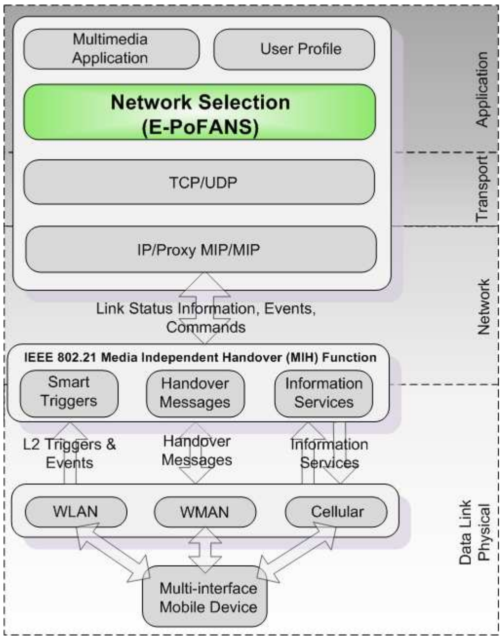


Figure 2. E-PoFANS Stack Overview

A detailed block architecture of E-PoFANS is presented in Figure 3. E-PoFANS is a client-side module which comprises four main sub-modules: *Data Collector*, *Network Filter*, *E-PoFANS Energy Prediction*, and *E-PoFANS Score Generator*. Next these four modules are described in details.

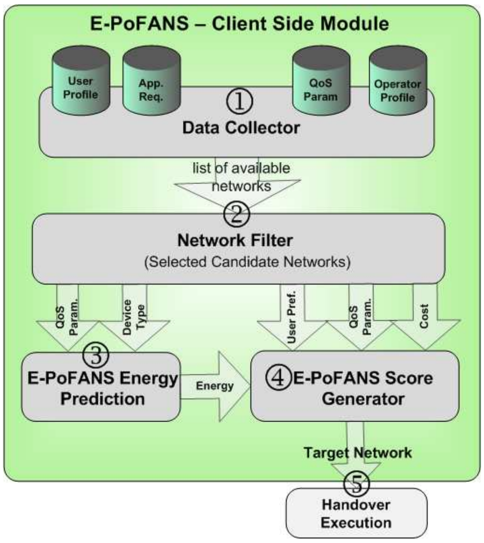



Figure 3. E-PoFANS Architecture

*1. Data Collection*

Data Collection provides all the information required by E-PoFANS to take its decisions. As already mentioned, E-PoFANS bases its decisions on five main parameters: user mobility, user preferences, available throughput, energy consumption, and monetary cost. The data collected is stored in databases. Figure 3 illustrates the Data Collector module and its four databases: **user profile**, **application requirements**, **QoS parameters**, and **operator profile**.

The main goal of using E-PoFANS is to satisfy the user. In this context, the **user profile** provides information about user preferences. Moreover, the profile can also exploit location information available on the mobile device to store user mobility patterns. There are many ways of collecting data from the user. However, frequent user interaction is undesirable because it can become tedious and also interrupt the user. One solution is to collect data on a one-time basis (e.g., when the user sets up his/her mobile device for the first time). However, the user should be able to change his/her preferences whenever they wanted. This can be done by integrating a GUI (e.g., user profile) in the user's mobile device. In order to obtain and manage information about **user mobility**, three user categories are defined: *(1) high speed user* – for example, a user in this category travels at a typical vehicular speed (i.e. values above 5.3 km/h); *(2) low speed user* – for instance, this category contains a user walking (i.e. speed values below 5.3 km/h); and *(3) stationary user* – for instance, a user using their internet connection in fix positions (e.g., hotspots).

**User preferences** play an important role in the decision making. The decision making of E-PoFANS is based on three main criteria of importance to the user: *quality, energy,* and *cost.* 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. As mentioned, this information could be provided in the user profile, and the user should be able to modify the weighting for each criterion, depending on his/her needs.

Different applications have different **application requirements.** For example a multimedia application has a minimum transmission bandwidth requirement that will ensure a minimum acceptable quality level to the user. These application requirements can be provided in the metadata of the application, and sent to the Data Collector module at runtime.

The IEEE 802.21 standard is used in order to gather all the information about network **QoS parameters** (e.g., available throughput) provided by the available wireless networks.

In this work it is assumed that dynamic pricing is not used by the networks and so the monetary cost of using a network is known in advance of the call. This monetary cost information may be stored on the mobile device in the **operator profile**. This information may be updated if there are any changes in pricing. For example, when one arrives in a new country a Short Message Service (SMS) is received informing about the call charges on the local networks; this information can be used to update the operator profile. Monetary cost could also be obtained by interrogating corresponding services located at the provider side (through the use of IEEE 802.21). The monetary cost represents the cost involved in using the services of a certain network and is expressed in Euro/Kbyte.
After collecting all the required information about the available wireless networks, the Data Collector module will provide the list of available wireless networks plus their associated information to the Network Filter module.

*2. Network Filtering*

Network Filtering performs a performance-based elimination step of some of the networks from the network candidate list. After receiving the list of the available networks, their characteristics (e.g., throughput, monetary cost) and all other information (e.g., application requirements, user profile) from the Data Collector module, Network Filtering eliminates all the networks which do not meet minimum/maximum criteria. For example, if the user has a strict budget, defined in the User Profile, all the networks which provide the required service for a monetary cost that goes above the user's budget will be eliminated from the decision. If the available bandwidth provided by some networks is below the minimum bandwidth level required by the transmission application to work, those networks are also eliminated. Only the networks that pass the parameter thresholds will be considered as candidate access networks for the network selection algorithm, reducing both the computation complexity and decision time.

After this filtering process, the Network Filter module sends the list of candidate networks to E-PoFANS Energy Prediction and E-PoFANS Score Generator modules.

*3. E-PoFANS Energy Prediction*

E-PoFANS Energy Prediction computes the estimated energy consumption of the running application for each of the candidate networks.

The estimated energy consumption for the real time application under consideration is computed using equation (1) as defined in [30].

$$E_i = t(r_t + Th_i r_d) \qquad (1)$$

where: $E_i$ - 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 $i$; $r_d$ is the energy consumption rate for data/received stream (Joule/Kbyte). Note that in the equation presented in [30] a constant $c$ was used. Following the calculations presented in this paper, constant $c$ was 0, so it is not considered anymore.

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 the device in the *user profile*. $r_d$ and $r_t$ differ for each network interface and they can be provided by the device manufacturer in the device specifications. Otherwise, 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 and real experimental tests were carried out, in order to build an energy consumption pattern. These experiments are introduced in the next section.

After the E-PoFANS Energy Prediction module has estimated the energy consumption for each of the candidate networks, the information is sent to the E-PoFANS Score Generator module for further processing.

*4. E-PoFANS Score Generation*

E-PoFANS Score Generator computes a suitability score for each candidate network and the network with the highest score is selected as the target network. After the target network is selected, the handover execution is triggered. As can be seen in Figure 3, the handover execution is not part of E-PoFANS and consequently the handover process is not detailed in this work. The focus is instead on the network selection decision.

The E-PoFANS proposed network selection score function makes use of the multiplicative exponential weighted (MEW) method and is defined in equation (2). The function considers four criteria: energy consumption, quality of the multimedia stream, monetary cost, and user mobility. These criteria can be divided into two classes: **(1) the larger the better** – higher values of the criteria metrics are considered to be better than low values of the criteria metrics (e.g., throughput); **(2) the smaller the better** – smaller values of the criteria metrics are considered to be better than high values of the criteria metrics (e.g., energy consumption, monetary cost). Because each criterion presents different ranges and units of measurement, they need to be normalized. The goal of the normalization process is to map all criteria metrics onto non-dimensional values within the [0,1] range and therefore make them comparable. In order to do this, each criterion is scaled with the help of utility functions.

$$U_i = u_{e_i}^{w_e} \cdot u_{q_i}^{w_q} \cdot u_{c_i}^{w_c} \cdot u_{m_i}^{w_m} \qquad (2)$$

In equation (2) $U_i$ is the overall score function for RAN $i$ and $u_e$, $u_q$, $u_c$, and $u_m$ are the utility functions defined for energy, quality in terms of received bandwidth, monetary cost for RAN $i$, and user mobility respectively. Also $w_e + w_q + w_c + w_m = 1$, where $w_e$, $w_q$, $w_c$, and $w_m$ are the weights for the considered criteria, representing the importance of a parameter in the decision algorithm. The weights are given by the Data Collector module, according to the *user profile*, as previously explained. If the user does not provide the weights, default settings assume the preference towards always selecting the cheapest network. As noticed in equation (2) the score function is built based on the utility functions defined for each criterion: energy utility, quality utility, cost utility, and mobility utility. The overall score function has also values in the [0,1] interval and no unit. Each utility function is further described below in details.

*a) Energy Utility - $u_e$*

The energy follows the principle "the smaller-the better" meaning that for small values of energy consumption the value of the energy utility, $u_e$, is high, whereas for high values of energy consumption, the utility is low. The energy utility is based on the estimated energy provided by the E-PoFANS Energy Prediction module and is defined in equation (3). The energy utility has values in the [0,1] interval, and no unit.

$$u_e(E) = \begin{cases} 1 & , \quad E < E_{\min} \\ \dfrac{E_{\max} - E}{E_{\max} - E_{\min}} & , \quad E_{\min} <= E < E_{\max} \\ 0 & , \quad otherwise \end{cases} \qquad (3)$$

In equation (3) $E_{min}$ is the minimum energy consumption (Joule), $E_{max}$ - the maximum energy consumption (Joule), and E – the energy consumption for the current network (Joule). $E_{min}$ and $E_{max}$ are calculated for throughputs $Th_{min}$ and $Th_{max}$ respectively. The energy consumption is computed using equation (1).

*b) Quality Utility – $u_q$*

In order to map the throughput to user satisfaction for multimedia streaming applications, a zone-based sigmoid quality utility function is defined, and illustrated in Figure 4 [31]. The utility is computed based on: *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), *required throughput* ($Th_{req}$) in order to ensure high quality levels for the multimedia service, and *maximum throughput* ($Th_{max}$), values above this threshold result in quality levels which are higher than most human viewers can distinguish between and so anything above this maximum threshold is a waste. The mathematical formula for 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) $\alpha$ and $\beta$ 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).

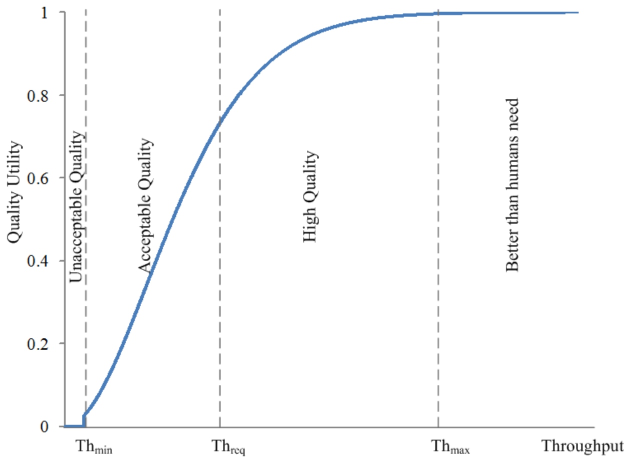



Figure 4. Zone-based quality sigmoid utility function [31]

In order to determine the exact shape of the utility function, the values of α and β need to be calculated. For this, two equations are needed. The first equation can be obtained from knowing that when the throughput reaches $Th_{max}$ the corresponding utility *u* will be equal to $u_{max}$. Thus, the first equation is defined as follows:

$$1 - e^{\frac{-\alpha * Th_{\max}{}^2}{\beta + Th_{\max}}} = u_{\max} \qquad (5)$$

From equation (5) a relationship between α and β can be obtained as follows:

$$\alpha = \frac{\ln(1 - u_{\max})(\beta + Th_{\max})}{-Th_{\max}^2} \qquad (6)$$

Now that the relationship between α and β is defined, a second equation is needed in order to calculate exactly their values. The required throughput, $Th_{req}$, illustrated in Figure 4 can be defined mathematically as the throughput before which the utility function is convex and after which the utility becomes concave. This means that the second-order derivative of the utility function is zero at this point. After computing the second-order derivate and replacing α with equation (6), equation (7) is obtained:

$$\begin{aligned} & [1 + 2\ln(1 - u_{\max})(\frac{Th_{req}}{Th_{\max}})^2]\beta^3 + [Th_{req} + 2\ln(1 - u_{\max})\frac{Th_{req}^2}{Th_{\max}} \\ & + 2\ln(1 - u_{\max})\frac{Th_{req}^3}{Th_{\max}^2}]\beta^2 + [2\ln(1 - u_{\max})\frac{Th_{req}^3}{Th_{\max}} + \ln(1 - u_{\max})\frac{Th_{req}^4}{2Th_{\max}^2}]\beta \\ & + \ln(1 - u_{\max})\frac{Th_{req}^4}{2Th_{\max}} = 0 \end{aligned} \qquad (7)$$

The positive solution of equation (7) represents the value of β. The values used for $Th_{min}$, $Th_{req}$, $Th_{max}$, α, β, and the modeling of the quality utility function are further detailed in the next section.

*c) Cost Utility - $u_c$*

Because there is a natural tendency to reduce the monetary cost, the cost parameter follows the principle "the smaller-the better". This means that for small values of the monetary cost, the cost utility, $u_c$, has high values, whereas for high monetary cost, the cost utility is small. Consequently the cost utility, $u_c$, is defined as in equation (8):

$$u_c(C) = \begin{cases} 1 & , \quad C < C_{\min} \\ \frac{C_{\max} - C}{C_{\max} - C_{\min}} & , \quad C_{\min} <= C < C_{\max} \\ 0 & , \quad otherwise \end{cases} \qquad (8)$$

In equation (8) C is the monetary cost for the current network (euro), $C_{min}$ - minimum cost that the user is willing to pay (euro) and $C_{max}$ – the maximum possible cost that the user can afford to pay (euro). The values for C, $C_{min}$, and $C_{max}$ are provided by the Data Collector module as previously described. The user can store his budget limit on his mobile device (i.e., *user profile*), which will be $C_{max}$, and of course the value of $C_{min}$ is considered to be zero (e.g., free of charge services). In this work the monetary cost of each network, C, is considered to be 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.

*d) Mobility Utility - $u_m$*

Information about user mobility is obtained from the Data Collector module as previously described. Based on the corresponding user mobility category, the mobility utility $u_m$, is defined as follows:

$$u_m = \begin{cases} 0 & if \quad high\ speed\ user\ \&\ WLAN \\ 0.5 & if \quad high\ speed\ user\ \&\ WMAN\ /\ Cellular \\ 1 & if \quad otherwise \end{cases} \qquad (9)$$

The user mobility has an impact on the utility function only for the case of high speed users. Since a high speed user may be in the coverage area of a short range network for a few seconds/minutes only, there is no need for handover and therefore for network selection. The mobility utility has values in the [0,1] interval, and no unit.

*B. E-PoFANS Algorithm*

As already mentioned, E-PoFANS selects the best value candidate network that fulfills user requirements, while maintaining the user 'always best connected' for multimedia delivery. The network selection is based on the user preferences, application requirements, quality of the multimedia application, energy consumption of the mobile device, monetary cost of the network, and user mobility. E-PoFANS is deployed as a client-side module that computes a score for each of the candidate networks. The outcome of E-PoFANS is a ranked list of the candidate networks, and the network with the highest score will then be selected as the target network.

Changes in the networks available, current network conditions (including network congestion, interference, etc.), user preferences, and/or efficiency of the energy consumption may trigger the network selection process. Changes or variations in these parameters, may determine a change in the ranking list of the candidate networks provided by E-PoFANS. E-PoFANS may be used no matter what types of networks are available, nor their number.

The pseudo-code of the decision making process of E-PoFANS is described in Algorithm 1.

The computational efficiency is an important concern when dealing with network selection algorithms. In this particular case a number of different processes are executed. For example, let us consider the case of one mobile user with the E-PoFANS network selection algorithm enabled on his/her mobile device and located in the coverage area of a number of available wireless networks. First, the algorithm will start an elimination process and from the list of available wireless networks only the networks that pass the required thresholds will be further processed as candidate networks. The elimination process should reduce the computational load. For each remaining candidate network the energy consumption, energy utility, quality utility, cost utility, mobility utility, and the overall score function are computed. The network that has the maximum score is selected as the target network. The process is repeated every time the current network fails to fulfill the user requirements or another better network becomes available.

**Algorithm 1** E-PoFANS Network Selection Algorithm

**<u>INPUT:</u>**

$w_e$; - *energy weight*
$w_q$; - *quality weight*
$w_c$; - *cost weight*
$w_m$; - *mobility weight*
} user preferences

$Th_{min}$; - *application requirements – the minimum acceptable throughput*
$C_{max}$; - *user's budget – the maximum cost the user is willing to pay for the services*
$Th_i$; - *the available throughput of RAN i*
$C_i$; - *the monetary cost of RAN i*

**<u>PROCEDURE:</u>**
i = 0;

**ELIMINATION PHASE**
**Input:**
List of Available Networks;

**Procedure:**
**for** i = 0 **to** number of available networks **do**
  **if** $Th_i \le Th_{min}$ or $C_i > C_{max}$ **then**
    **eliminate** *RAN i*
  **end if**
**end for**

**Output:**
List of Candidate Networks;

**ENERGY PREDICTION PHASE**
**Input:**
t; - *the transaction time (seconds) – the duration of the multimedia stream*
$r_t$; - *the mobile device's energy consumption per unit of time (W)*
$r_d$ ; - *the energy consumption rate for data/received stream (Joule/Kbyte)*
List of Candidate Networks;

**Procedure:**
**for** i = 0 **to** number of candidate networks **do**
  $E_i = t(r_t + Th_i\, r_d)$ ;
**end for**

**Output**
$E_i$;

**SCORE GENERATION PHASE**
**Input**
List of Candidate Networks;

**Procedure:**
**for** i = 0 **to** number of candidate networks **do**
  **compute utilities:** $u_{e_i}$ , $u_{q_i}$ , $u_{c_i}$ , $u_{m_i}$ ;
  **compute score:** $U_i = u_{e_i}^{w_e} \cdot u_{q_i}^{w_q} \cdot u_{c_i}^{w_c} \cdot u_{m_i}^{w_m}$
**end for**

**Output:**
Ranked List of Candidate Networks;

**<u>OUTPUT:</u>**
Ranked List of Candidate Networks;
with
the **Target** first choice **RAN** – the network with the highest score ($U_i$)

## IV. Experimental Environment and Results

### A. *Test-Bed Environment*

This section presents the experimental test-bed environment used to investigate the energy consumption of an Android mobile device while performing video delivery over one IEEE 802.11g and two cellular networks (e.g., UMTS and HSDPA). Our previous work [25] presents an in-depth study on how the wireless link quality and the network load impact the energy consumption of the Android device.

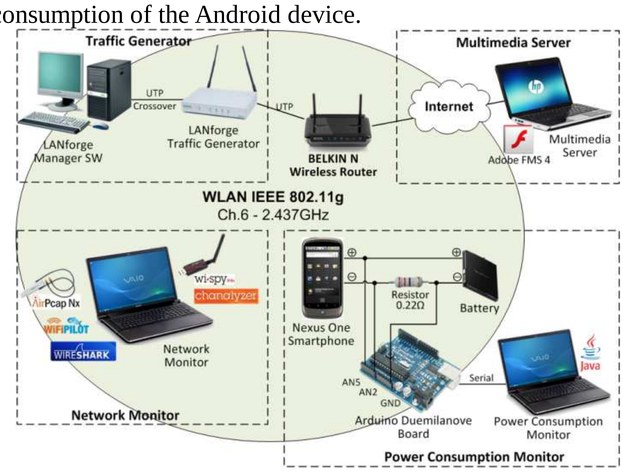



Figure 5. WLAN Test-Bed [25]

Figure 5 illustrates the WLAN test-bed that consists of: an IEEE 802.11g *Wireless Router*; 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

[1] Wi-Spy DBx - http://www.metageek.net/products/wi-spy/
[2] AirPcap Nx - http://www.metageek.net/products/airpcap/

network; an *Android Mobile Device* used as the client device and a *Power Consumption Monitor* that integrates an Arduino Duemilanove[3] board connected to the Android mobile device and a laptop that stores the energy measurements. The device power consumption is calculated (by using Ohm's Law) using the voltage values sent by the Arduino board with a frequency of 1Hz. The proprietary application level streaming protocols RTMP (TCP) and RTMFP (UDP) from Adobe Flash Media Server 4[4] ware used for streaming the Blender Foundation's 10 minute long Big Buck Bunny[5] animated. The video clip was encoded at five different quality levels as listed in Table I.

Figure 6 illustrates the cellular network test-bed used for running the power measurements. The tests were run over the cellular networks provided by two mobile internet service providers in Ireland: O2[6] and eMobile[7].

TABLE I. MULTIMEDIA LEVELS ENCODING SETTINGS

| 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 | |

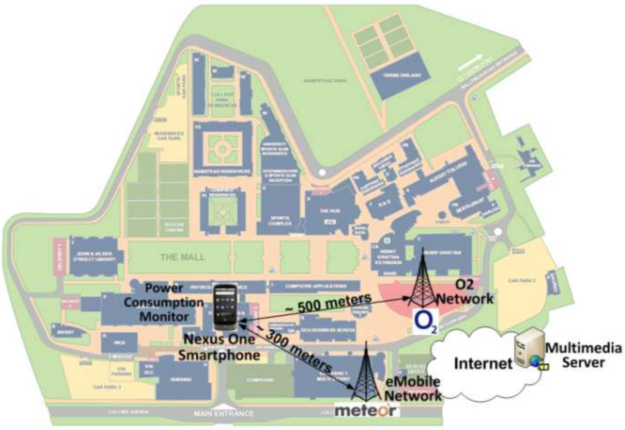



Figure 6. Cellular Test-Bed Setup [26]

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 |

The information related to the cellular networks is listed in Table II. As cellular networks have lower transmission rates than WLAN (e.g., UMTS has maximum 384kbps, whereas IEEE 802.11g has a maximum theoretical of 54Mbps), a subset of three quality levels from the five quality levels encoded for the WLAN test-bed were considered for streaming.

### B. *Test Case Scenario*

Figure 7 illustrates the five scenarios considered for the experiments: *(1) Scenario 1 – No Load, Near AP* – the mobile user is located near the AP (~ 1m away) with a signal strength varying between -48dBm and -52dBm. No background traffic is considered. *(2) Scenario 2 – No Load, Far AP* – the mobile user is located with poor signal strength varying between -78dBm and -82dBm. No background traffic is considered. *(3) Scenario 3 – Load, Near AP* – mobile user is located near the AP as in Scenario 1. Background traffic was added, 25 to 28 virtual wireless stations located near the AP with the signal strength varying between -28dBm and -32dBm, are used to generate traffic into the network. *(4) Scenario 4 – Load, Far AP* – mobile user is located in an area with poor signal strength as in Scenario 2. Background traffic as in Scenario 3 was added. *(5) Scenario 5 – Cellular* – mobile user is performing VoD over the cellular networks (O2 si eMobile).

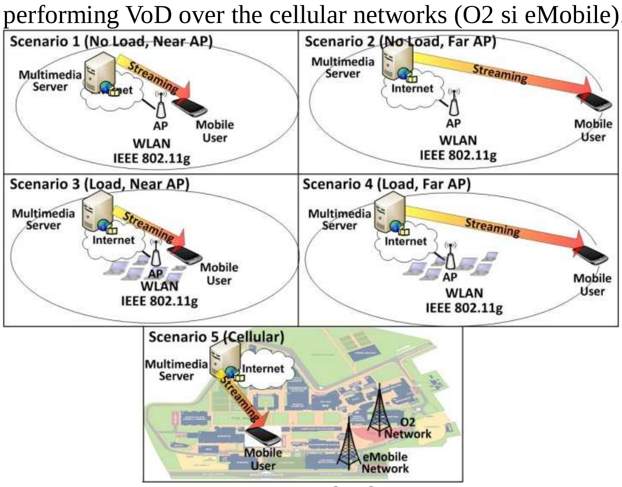



Figure 7. Considered Scenarios

### C. *Results*

The Multimedia Server stores the *five ten-minute clips* corresponding to different quality levels and the clips are streamed sequentially to the Android mobile device using either UDP or TCP. The results of the study [25] show how the network related parameters (e.g., link quality, location, and network load) impact the power consumption of an Android Mobile device within the WLAN environment (Scenario 1 to Scenario 4). Table III presents a summary of the results including the average energy consumption of the Android Mobile device while performing VoD streaming over UDP for different quality levels, and the actual average throughput (Avg. Th.) received by the mobile device on the wireless network captured with Wireshark.

The results for VoD streaming over the cellular networks are presented in Table IV [26]. Even though O2 offers HSDPA (up to 7.2Mbps data rate), the VoD session experiences video motion loss with re-buffering periods of 6% for QL3, 4% for QL4, and 1% for QL5, respectively. When streaming over eMobile that offers UMTS (up to 384kbps data rate) the

[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/

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

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

playout is smooth and enables more energy savings. A realistic assumption would be that O2 network has more customers sharing bandwidth resources, thus affecting the playout duration of the multimedia streams.

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 |

### D. *Modeling the Quality Utility*

The user perceived quality is one of the most important aspects of VoD. Two methods were used to assess the video quality: objective method in terms of Peak Signal-to-Noise Ratio (PSNR) and subjective tests. MSU Video Quality Measurement Tool[8] software was used for computing the objective PSNR values for each of the five encoding settings of the quality levels. A subjective study using 20 test sequences was also conducted [32]. The results of the objective PSNR and the subjective MOS tests are listed in Table V together with the perceived quality and impairment mapping.

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 |

The relationship between the proposed sigmoid quality utility, the received throughput (Quality Levels) and the MOS values from the subjective is listed in Figure 8. An in-depth study on the validation and modeling of the choice of the sigmoid quality utility function is presented in [32].

Using the characteristics of the quality levels, the sigmoid quality utility function is modeled as in equation (10) with α and β two positive parameters computed knowing that: (1) for $Th_{max}$ (1.920Mbps) the utility has its maximum value (e.g., $u_{max} = 0.99$ avoiding the invalid value of *ln(0)*); (2) the second order derivate of $u_q$ is 0 for $Th_{req}$ (0.480Mbps). Consequently, after solving all the mathematical computations the values for α and β are 5.72 and 2.66, respectively. The procedure of computing the quality utility parameters is similar for any other choice of quality levels.

$$u_q(Th) = \begin{cases} 0 & , \quad Th < 0.120 \\ 1 - e^{\frac{-\alpha * Th^2}{\beta + Th}} & , \quad 0.120 <= Th < 1.920 \\ 1 & , \quad otherwise \end{cases} \quad (10)$$

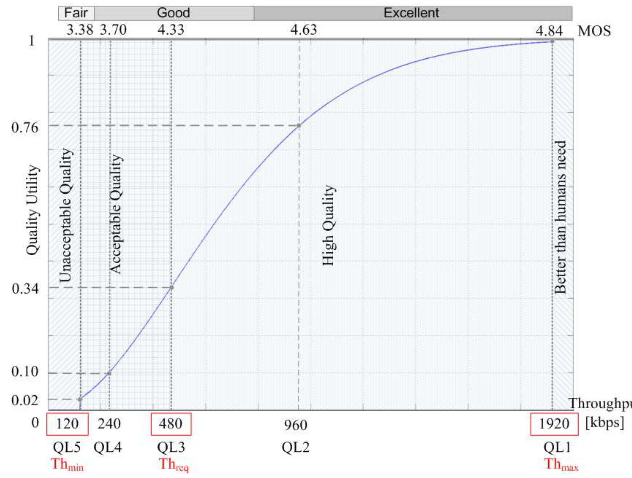



Figure 8. Quality Utility – Validation [32].

## V. SIMULATION TESTING ENVIRONMENT

### A. *Enhanced Network Simulator*

The simulation environment is based on the NS-2 Network Simulator (v2.33) [33]. In order to test the proposed solutions, there was a need to build a complex simulator-based testing environment. 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). The basic NS-2 allinone v2.33 simulator was enhanced in order to create the necessary heterogeneous environment and to be able to simulate as realistic environment as possible. For the WLAN environment, the No Ad-Hoc (NOAH) wireless routing agent [34] was integrated in order to allow direct communication between mobile users and the AP only. The NOAH package was updated to work with the NS-2 v. 2.33.

The standard channel propagation model provided by the NS-2 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 is 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 [35] was used in order to improve

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

the support for wireless communications scenarios by adding realistic channel propagation, multi-rate transmission support and Adaptive Auto Rate Fallback (AARF) [36]. The patch, computes the Signal to Interference plus Noise Ratio (SINR) in order to add the effect of interference and different thermal noises. The Bit Error Rate (BER) is also considered when deciding whether the frame was transmitted correctly or not and whether it has to be discarded. BER is taken from the empirical BER vs. SNR (Signal to Noise Ratio) curves measured for IEEE 802.11b PHY modes and provided by Intersil HFA3681B chipset as illustrated in Figure 9 [37]. The wireless update patch, initially built for NS-2.29 was updated in order to work with NS-2.33.

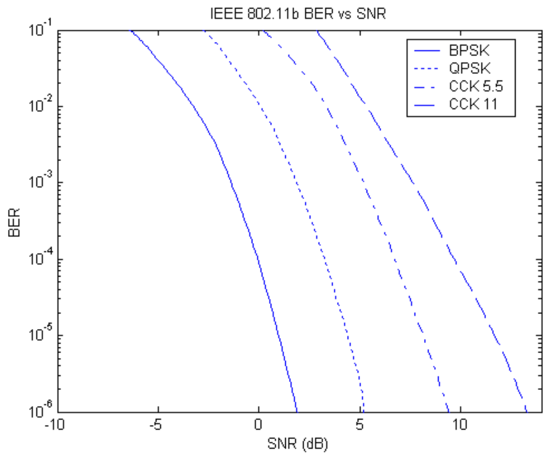



Figure 9. IEEE 802.11b BER vs. SNR [37]

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 and integrated into the NS-2 simulator.

IEEE 802.11g supports 12 data transmission rates (IEEE 802.11b + IEEE 802.11a) with the corresponding modulation scheme. As IEEE 802.11g uses the transmission rates and modulation schemes from both IEEE 802.11b and IEEE 802.11a, the values for BER were taken from the empirical BER vs. SNR curves provided for IEEE 802.11b [37] as in Figure 9 and IEEE 802.11a illustrated in Figure 10 [38]. The characteristics of the IEEE 802.11g physical layer integrated in the simulator are taken from Cisco Aironet 802.11a/b/g Wireless Card [39] and they are illustrated in Table VI.

TABLE VI. CHARACTERISTICS OF THE IEEE 802.11G PHY LAYER

| Rate [Mbps] | Modulation | Receive Sensitivity [dBm] |
|---|---|---|
| 1 | *DSSS/BPSK* | -94 |
| 2 | *DSSS/QPSK* | -93 |
| 5.5 | *DSSS/CCK* | -92 |
| 6 | *OFDM/BPSK* | -86 |
| 9 | *OFDM/BPSK* | -86 |
| 11 | *DSSS/CCK* | -90 |
| 12 | *OFDM/QPSK* | -86 |
| 18 | *OFDM/QPSK* | -86 |
| 24 | *OFDM/16QAM* | -84 |
| 36 | *OFDM/16QAM* | -80 |
| 48 | *OFDM/64QAM* | -75 |
| 54 | *OFDM/64QAM* | -71 |

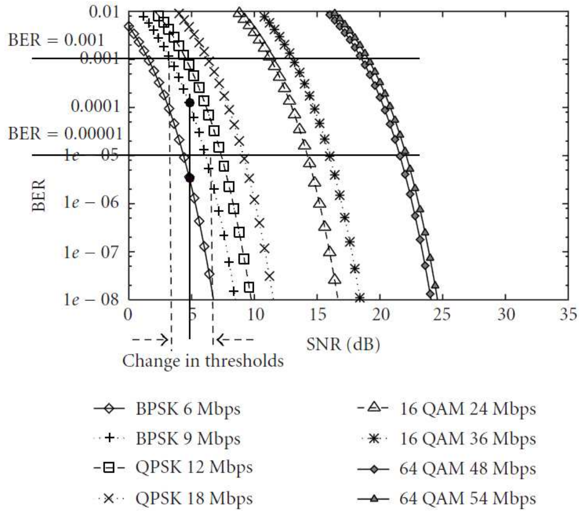



Figure 10. IEEE 802.11a BER vs. SNR [38]

The values of the physical parameters for the modulations schemes of 802.11b and 802.11g used in NS-2 are presented in Table VII.

TABLE VII. IEEE802.11B AND IEEE 802.11G PHY PARAMETERS

| Parameter | Value 802.11b | Value 802.11g | Description |
|---|---|---|---|
| ***MAC dataRate_*** | 11Mbps | 54Mbps | *Theoretical Data Transmission Rate* |
| ***MAC basicRate_*** | 1Mbps | 6Mbps | *Theoretical Transmission Basic Rate* |
| ***CWmin*** | 31 | 15 | *Minimum Contention Window* |
| ***CWmax*** | 1023 | 1023 | *Maximum Contention Window* |
| ***SlotTime*** | 9µsec | 20µsec | *Slot Time* |
| ***SIFSTime*** | 16µsec | 10µsec | *Short Interframe Space Time* |

In order to create a heterogeneous environment, the EURANE patch [40] was used. EURANE adds the support for UMTS network and it is available for NS-2.30. The patch was modified in order to work with NS-2.33. The wireless environment in NS-2 uses hierarchical addressing, this enables grouping of the 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 the 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.

## *B. Validating the Wireless Environment*

In order to validate the wireless environment integrated in NS-2, a simple scenario was created as illustrated in Figure 11.

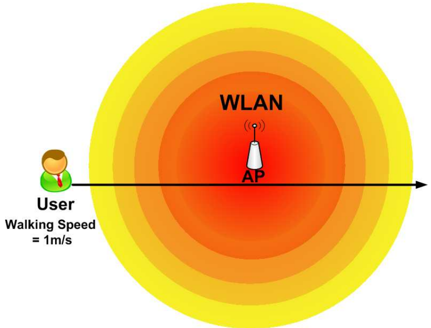


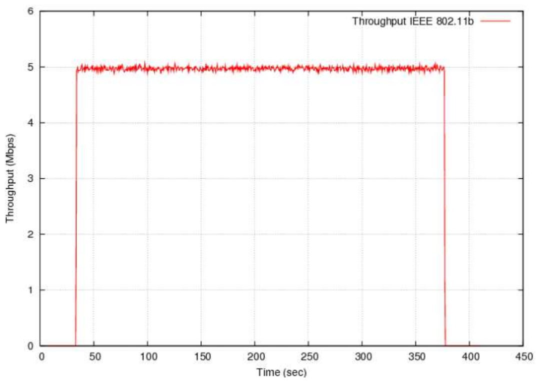

Figure 11. Validation Scenario – User moving towards and away from AP

The scenario is run for both IEEE 802.11b and IEEE 802.11g network types. A mobile user moves, at a walking speed of 1m/s, towards the AP and then away from the AP. The mobile user receives CBR (Constant Bit Rate) traffic at the highest data rate that can be provided (theoretically) by each network (i.e., 11Mbps for IEEE 802.11b and 54Mbps for IEEE 802.11g).

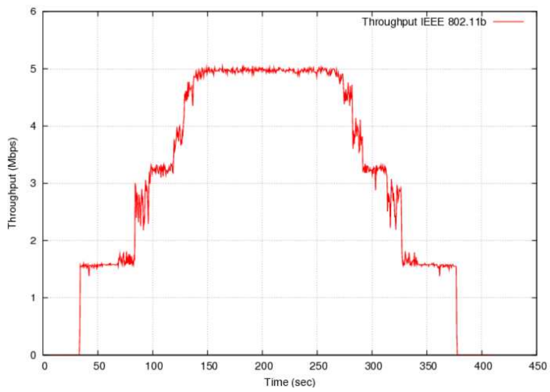
Figure 12 illustrates the user's received throughput during his/her path when simulating an IEEE 802.11b network using the standard version of NS-2.33 and when using NS-2.33 with the wireless update patch [35] integrated.

It can be noticed that the wireless update patch provides a more realistic model of an IEEE 802.11b wireless environment. As the mobile user moves towards and then away from the AP, in the standard version of the simulator the received throughput maintains the same value for the entire user's path, until the user moves out of the AP's coverage area. Whereas in the patched version of the simulator (with the wireless update patch), the throughput presents a step-wise increase as the user moves towards the AP and a step-wise decrease as the user moves away from the AP. The results are according to the IEEE 802.11b standard [41]. As noticed, the maximum throughput that can be achieved by the user in this scenario is 5Mbps even though the theoretical data rate for IEEE 802.11b is 11Mbps[9].

After the integration of the IEEE 802.11g network in NS-2.33, the same scenario was considered for its validation as for IEEE 802.11b (see Figure 11). Figure 13 illustrates the user's received power and received throughput as he/she is moving towards and then away from the AP at a constant speed of 1m/s. As noticed in Figure 13(b), as the user is moving away from the AP, his/her received throughput is step-wise decreasing, as described in the standard [42]. The maximum received throughput in this scenario goes up to 22-23Mbps, even though the maximum theoretical throughput for IEEE 802.11g is 54Mbps[10].

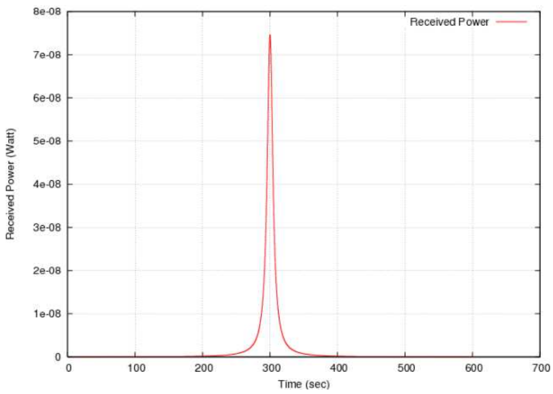



a) Standard NS-2.33

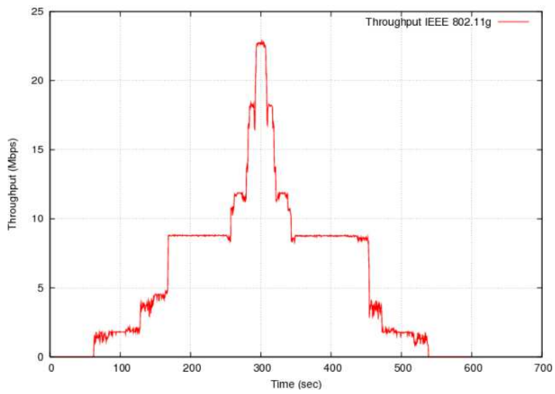



b) NS-2.33 plus wireless update patch

Figure 12. Received Throughput for User Moving Towards and then Away from an IEEE 802.11b AP




a) Received Power




b) Received Throughput

Figure 13. User Moving Towards and then Away from an IEEE 802.11g-based A

## VIII. TESTING RESULTS AND ANALYSIS

### A. Simulation Scenario

In order to analyze the performance of the proposed solutions, we consider the case of Jack, a business professional that likes to access multimedia content while walking every day from Home to Office. On his travel path there are a number of available networks (e.g., UMTS, WLAN, etc.) that he can use as illustrated in Figure 14. As Jack leaves his home he starts up a multimedia session on his mobile device.

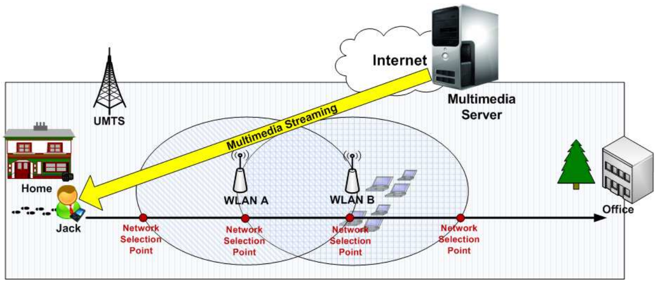



Figure 14. Example Scenario – Jack's path from Home to Office

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). At that point, Jack's device should detect the second RAN and the possibility to handover from UMTS to WLAN. The decision is made according to the E-PoFANS suggested solution, and very likely the multimedia session is transferred to the WLAN because of the increased rate offered by the WLAN network in comparison with UMTS. When Jack enters the coverage area of a second WLAN and his mobile device battery lifetime is at risk, he will be facing the problem whether it is better to remain in the current network or it is better to handover to a new network, in terms of energy efficiency. In this situation, E-PoFANS will help Jack again in taking the best decision.

### B. Simulation Environment Configuration

The simulation environment was configured so that the radio access networks used in the real experimental test-bed from Section IV were mapped to the access networks used in the simulator. Consequently, each wireless network form the simulation environment is mapped to a scenario form the experimental test-bed, that is: WLAN1 – No Load, Near AP; WLAN2 – No Load, Far AP; WLAN3 – Load, Near AP; WLAN4 – Load, Far AP. The cellular network used in the simulations, UMTS is mapped to the eMobile network from the experimental test-bed. The mapping and the characteristics of each access network used in the simulation environment are detailed in Table VIII. A multimedia server is used to store the quality levels of the video streams (five quality levels in case of WLAN and three quality levels in case of UMTS). It is assumed that each access network can provide any of the quality levels of the video stream, without difficulties as per the experimental test-bed. The performance assessment is done in terms of energy savings benefits and the quality level. The energy consumption is computed using the energy equation previously introduced in Section III, and the quality levels are mapped to the MOS obtained from the subjective tests.

TABLE VIII. SIMULATION ENVIRONMENT

| Network (Simulation) | Mapping (Experimental Test-Bed) | Characteristics |
|---|---|---|
| WLAN1 | *No Load, Near AP* | IEEE 802.11g network, MS located near the AP with no other background traffic in the network |
| WLAN2 | *No Load, Far AP* | IEEE 802.11g network, MS located far from the AP with no other background traffic in the network |
| WLAN3 | *Load, Near AP* | IEEE 802.11g network, MS located near the AP, background users located near the AP generating traffic at 20-21Mbps |
| WLAN4 | *Load, Far AP* | IEEE 802.11g network, MS located far from the AP, background users located near the AP generating traffic at 20-21Mbps |
| UMTS | *eMobile network* | MS located 300m away from the NodeB, Rayleigh fading environment, NodeB Transmission power 38dBm, NodeB antenna gain 17dBi, MS speed 1m/s |

### C. Performance Analysis of E-PoFANS

This section analyzes the performance of the Enhanced Power-Friendly Access Network Selection Mechanism (E-PoFANS) under two aspects: (1) the *energy-quality trade-off* and (2) the *energy-quality-cost trade-off*. Two test case scenarios are considered: *(1) Test Case 1 Energy-Quality Trade-off* – where Jack has a number of available wireless networks from which he can select. The networks differ only in terms of Quality Levels provided and Energy Consumption. All the networks are assumed to be free of charge. The trade-off between energy and quality is analyzed; *(2) Test Case 2 Energy-Quality-Cost Trade-off* – the monetary cost parameter is also introduced so that the trade-off between energy, quality, and cost is analyzed.

The proposed network selection mechanism (E-PoFANS) is compared against the solution provided by Liu et al. [19]. The reason for using Liu's et al. solution for the comparison is that it also represents an energy efficient 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 (referred to as a Cost Function *C*) as given in equation (11).

$$C = w_B \ln \frac{1}{B} + w_P \ln P + w_c \ln c \qquad (11)$$

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 a free network to have a cost of c=0.01 and therefore $\ln c = -4.6$.

(1

TABLE IX. TEST CASE 1 ENERGY-QUALITY TRADE-OFF RESULTS: COST FUNCTION VS. E-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 | E-PoFANS | Cost Function | E-PoFANS | Cost Function | E-PoFANS | Cost Function | E-PoFANS | Cost Function | E-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 |

As noticed, the main difference between the two approaches is the choice of score and utility functions, Liu et al. making use of logarithmic functions and E-PoFANS makes use of the utility functions defined in this paper and combined in equation (12). Liu et al. Cost Function *C*, follows the principle '*the smaller-the better'*, while E-PoFANS 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 (1) in Section III.

$$U_i = u_{e_i}^{\;w_e} \cdot u_{q_i}^{\;w_q} \cdot u_{c_i}^{\;w_c} \quad (12)$$

where: *U* 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*, 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. As noticed the utility mobility is not considered, this is because Jack is moving at a walking speed meaning that $u_m$=1. This value will be further considered for the rest of the simulation scenarios.

*1) Test Case 1 Energy-Quality Trade-off: Network Selection – Choice of Five Networks*

In this first test case scenario Jack is confronted with the problem of selecting the best network for his current application preferences from five available RANS as illustrated in Figure 15.

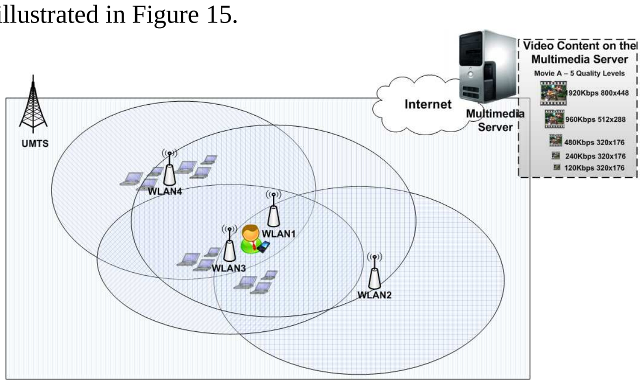



Figure 15. Test Case 1 – Network Selection – Choice of Five Networks

The available RANs are set as the five networks from the experimental test-bed, 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 each of these RANs 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.

Whenever new networks are available, Jack's device should detect a change in the candidate networks list and a network selection can be performed. Thus, the selection decision could be done between five (quality levels) x four (WLAN networks) + three (quality levels) x one (UMTS networks) = 23 options.

In order to compare the performance of the two network selection mechanisms in terms of the trade-off between quality and energy consumption, the weight value for the cost parameter, $w_c$, is set to zero. This means that Jack does not care about the monetary cost of the networks and is more interested in the quality of the multimedia stream and the energy consumption of the mobile device. For this reason the values for the three weights are set to: $\boldsymbol{w_e = 0.5}$, $\boldsymbol{w_q = 0.5}$, $\boldsymbol{w_c = 0}$. Considering these settings, the test-bed values for quality and energy were used to calculate the scores for both the Liu et al. Cost Function and E-PoFANS. The scores are illustrated in Table IX. Looking at the results, from the 23 available options, when using E-PoFANS, Jack's device first choice is QL2 on WLAN1, whereas when using the Liu et al. Cost Function, the first selection choice is QL1 on WLAN1. This shows that E-PoFANS provides a better trade-off between quality and energy consumption than the Liu et al. Cost Function. In this situation, Jack equally cares about the energy consumption of the mobile device and the quality of the multimedia stream he is watching, so by selecting QL2, representing 'Excellent' quality, Jack can save up to 28% in energy consumption in comparison with selecting QL1. Jack's benefit for using E-PoFANS vs. Liu e al. Cost Function is highlighted in Table X.

TABLE X. TEST CASE 1 ENERGY-QUALITY TRADE-OFF: USER'S BENEFIT COST FUNCTION VS. E-POFANS

| | Energy [Joule] | Quality Level/MOS |
|---|---|---|
| ***Liu et al. Cost Function*** | 861.8 | QL1/Excellent |
| ***E-PoFANS*** | 622.48 | QL2/Excellent |
| ***Benefit*** | 28% | none |

The energy component was computed using equation (1). In terms of quality there is no significant perceived benefit as both QL1 and QL2 can be mapped to the 'Excellent' quality level on the ITU-T P.910 scale.

Moreover, looking at the selection scores for each network separately E-PoFANS selects QL2 before QL1 as QL2 will provide sufficient user-perceived quality. For example, WLAN1, QL1 will only be the third choice, whereas QL1 will be the first choice for Liu et al. Cost Function. That is, for WLAN1-3 the order of selection for E-PoFANS will be: QL2, QL3, and only then QL1, while the order of selection for the

TABLE I. TEST CASE 1: QUALITY-ORIENTED AND ENERGY-ORIENTED RESULTS: COST FUNCTION VS. E-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 | E-PoFANS | Cost Function | E-PoFANS | Cost Function | E-PoFANS | Cost Function | E-PoFANS | Cost Function | E-PoFANS |
| *Quality* | ***QL1*** | -4.6962 | 0.7397 | -4.6932 | 0.7230 | -4.6883 | 0.6909 | -4.6140 | 0 | N/A | N/A |
| | ***QL2*** | -4.2068 | 0.7437 | -4.2037 | 0.7396 | -4.1975 | 0.7310 | -4.1751 | 0.6933 | N/A | N/A |
| | ***QL3*** | -3.6950 | 0.4135 | -3.6918 | 0.4121 | -3.6845 | 0.4088 | -3.6630 | 0.3973 | -3.6159 | 0.3589 |
| | ***QL4*** | -3.1658 | 0.1673 | -3.1625 | 0.1668 | -3.1546 | 0.1657 | -3.1452 | 0.1642 | -3.0770 | 0.1480 |
| | ***QL5*** | -2.6253 | 0.0592 | -2.6219 | 0.0592 | -2.6135 | 0.0591 | -2.6003 | 0.0585 | -2.5307 | 0.0532 |
| *Energy* | ***QL1*** | 3.8953 | 0.2994 | 3.9074 | 0.2733 | 3.9272 | 0.2279 | 4.2241 | 0 | N/A | N/A |
| | ***QL2*** | 3.7736 | 0.6783 | 3.7861 | 0.6635 | 3.8109 | 0.6333 | 3.9002 | 0.5124 | N/A | N/A |
| | ***QL3*** | 3.7414 | 0.7261 | 3.7543 | 0.7162 | 3.7832 | 0.6933 | 3.8694 | 0.6185 | 4.0576 | 0.4122 |
| | ***QL4*** | 3.7786 | 0.6324 | 3.7919 | 0.6254 | 3.8237 | 0.6082 | 3.8612 | 0.5869 | 4.1340 | 0.3872 |
| | ***QL5*** | 3.8613 | 0.4932 | 3.8747 | 0.4932 | 3.9083 | 0.4909 | 3.9613 | 0.4692 | 4.2396 | 0.3210 |

Liu et al. Cost Function will be: QL1, then QL2, and QL3. For the UMTS network both algorithms ranked choice list will be the same, i.e., QL3, QL4, and then QL5.

Two further situations were considered: **(1)** for **Quality-oriented** users, the weight for quality will have a higher value, for example: $\boldsymbol{w_e = 0.2, w_c = 0, w_q = 0.8}$; **(2)** for **Energy-oriented** users, the energy weight is higher than the quality weight, for instance: $\boldsymbol{w_e = 0.8, w_c = 0, w_q = 0.2}$. The results for these two situations are presented in Table XI. It can be seen that in the case of Quality-oriented users the ranked list for target quality level and network are the same as when equal Quality-Energy orientation was considered (e.g., $w_e = 0.5$, $w_c = 0$, $w_q = 0.5$).

This means that the E-PoFANS users would choose QL2 over QL1 as the first choice in comparison with the Liu et al. Cost Function, which still chooses QL1 as the first choice. The benefits of using E-PoFANS are the same benefits as presented in Table X. The Quality-oriented users will benefit from an ‘Excellent’ quality level and a 28% decrease in energy consumption when compared with the case when the Liu et al. Cost Function is employed.

In the case of Energy-oriented users both selection solutions provide similar ranking results starting with QL3 on WLAN1-3 as the first choice.

The results show that E-PoFANS score function more accurately models a good trade-off between quality and energy consumption in comparison with Liu et al. Cost Function for different user preferences on quality and energy. This is because Liu et al. Cost Function is based on the SAW method whereas E-PoFANS is based on the MEW method. The main disadvantage of SAW is that a poor value parameter can be outweighed by a very good value of another parameter, whereas MEW penalizes alternatives with poor parameters values more heavily. This can be noticed here in case of WLAN4, when the network is loaded and the mobile user is located in an area with poor signal strength. From the experimental test-bed measurements presented in previously, it has been seen that in this situation, streaming QL1 will significantly increase the energy consumption of the mobile device and will additionally more than double the playout duration of the multimedia stream (introducing re-buffering periods) which consequently will reduce the Mean Opinion Score. This makes QL1 (WLAN4) the worst option among the different QLs. This situation is captured by E-PoFANS which gives a zero score to QL1, Liu et al. Cost Function end up selecting QL1 as the fifth choice.

The results show that a weight of 0.5 for $w_q$ can be mapped to a minimum quality level which is above QL4 (‘Good’ on the ITU-T P.910 scale). This means that with these settings, Jack’s minimum acceptable quality would be QL3, so the options for QL4 and QL5 can be eliminated from the selection decision as they do not meet the minimum criteria. In this case E-PoFANS eliminates a number of candidate network choices reducing the list from 23 options to 16 options. This improves the performance and reduces the computational complexity of the solution in comparison with Liu et al.

*2) Test Case 2 Energy-Quality-Cost Trade-off: Network Selection – Choice of Three Networks*

Consider in this case, Jack as having a choice of three networks: WLAN2 – No Load, Far AP, WLAN3 – Load, Near AP, and UMTS, as illustrated in Figure 16.

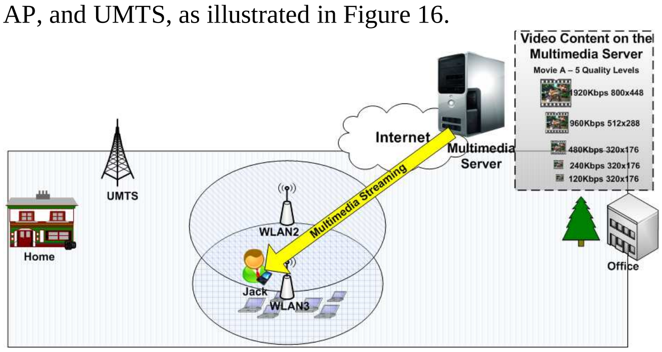



Figure 16. Test Case 2 – Network Selection – Choice of Three Networks

As the cost parameter is also considered additional to energy consumption and quality, for testing, the costs for each of the three networks are set to: WLAN2 – 0.2 cents per unit of data, WLAN3 – free hot-spot, and UMTS – 0.9 cents per unit of data. In this situation Jack cares also about his budget and he is willing to pay a certain amount while also maintaining a balance between the quality level he is getting the content at, and the energy consumption. However, he is not willing to pay anything if his requirements are not fulfilled. In these conditions the following weights for the three parameters are considered: $\mathbf{w_e = 0.4, w_q = 0.4}$, and $\mathbf{w_c = 0.2}$. The results for this test case scenario are presented in Table XII.

TABLE XII. TEST CASE 2 ENERGY-QUALITY-COST TRADE-OFF RESULTS: COST FUNCTION VS. E-POFANS

| | WLAN2 | | WLAN3 | | UMTS | |
|---|---|---|---|---|---|---|
| | No Load, Far AP | | Load, Near AP | | e-Mobile Network | |
| | Cost Function | E-PoFANS | Cost Function | E-PoFANS | Cost Function | E-PoFANS |
| ***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 |

If Jack has enabled E-PoFANS on his mobile device, he will end-up selecting QL2 on WLAN2. If the Liu et al. Cost Function is enabled, then he will end-up with QL1 on WLAN3. It can be seen here the same phenomena as in Test Case 1 where the Liu et al. Cost Function selects the highest quality level (QL1), which in terms of energy conservation is the most power consuming, while E-PoFANS selects QL2 (WLAN2) achieving a 30% decrease in energy consumption as compared to QL1 (WLAN1). This shows again that E-PoFANS provides a good balance between quality level and energy consumption. When the cost parameter is also considered, E-PoFANS will select only QL2 and QL1 from the paid network (WLAN2) relative to QL2 and QL1, from the free network (WLAN3), respectively.

Thus, Jack will be willing to pay the 0.2 cents per unit of data only if he is getting the 'Excellent' quality. If this quality level is not provided, then Jack is better off going for the free network (WLAN3) for QL3 to QL5. Looking at the results provided by the Liu et al. Cost Function, the free network will be always selected. Comparing the decisions for the quality levels from WLAN2 relative to the same quality levels provided by WLAN3, the Liu et al. Cost Function will never select the quality levels provided by the paid network. Even though for example for QL2 provided by WLAN2 there can be a 5% decrease in energy consumption when compared to QL2 provided by WLAN3. This shows that E-PoFANS finds a good trade-off between energy-quality-cost. Table XIII highlights the benefit obtained by Jack while using E-PoFANS in comparison with the case when he would use the Liu et al. Cost Function.

As it can be noticed, the benefit in terms of energy is 30%, while there are no evident benefits in terms of quality, as both QL1 and QL2 are mapped to the 'Excellent' level on the ITU-T P.910 quality scale. When looking at the benefit in terms of cost, Jack will have to pay an additional amount of 0.2 cents per unit of data in order to get the 30% decrease in energy consumption.

TABLE XIII. TEST CASE 2: USER'S BENEFIT: COST FUNCTION VS. E-POFANS

| | Energy [Joule] | Quality Level/MOS | Cost [cents/unit of data] |
|---|---|---|---|
| ***Liu et al. Cost Function*** | 897 | QL1/Excellent | 0 |
| ***E-PoFANS*** | 632.3 | QL2/Excellent | 0.2 |
| ***Benefit*** | 30% | none | -0.2 |

Other two situations are considered: **(1)** for users with **Equal Interest** in energy, quality, and cost, the weights are set to: $w_e$ = ***0.33***, $w_q$ = ***0.33***, and $w_c$ = ***0.33***; **(2) Cost-oriented** users which could use, for example, the following weight distribution $w_e$ = ***0.1***, $w_q$ = ***0.1***, and $w_c$ = ***0.8***;

The results for the two above situations are listed in Table XIV. For both situations the outcome is the same. It can be noticed that the Liu et al. Cost Function has a stronger quality-orientation by selecting the QL1 on WLAN3, whereas E-PoFANS finds a trade-off between quality and energy by selecting QL2 on WLAN3. However both solutions select the free network in both situations. The benefit that Jack gets by using E-PoFANS vs. Liu et al. Cost Function is 26.6% decrease in energy consumption, while maintaining an 'Excellent' quality level for delivered multimedia content.

TABLE XIV. TEST CASE 2 RESULTS: COST FUNCTION VS. E-POFANS

| | | WLAN2 | | WLAN3 | | UMTS | |
|---|---|---|---|---|---|---|---|
| | | No Load, Far AP | | Load, Near AP | | e-Mobile Network | |
| | | Cost Function | E-PoFANS | Cost Function | E-PoFANS | Cost Function | E-PoFANS |
| ***Equal Interest*** | ***QL1*** | -0.7904 | 0.5656 | **-1.7691** | 0.5434 | N/A | N/A |
| | ***QL2*** | -0.6689 | 0.7636 | -1.6456 | **0.7756** | N/A | N/A |
| | ***QL3*** | -0.5105 | 0.6457 | -1.4854 | 0.6596 | 0.1110 | 0.4370 |
| | ***QL4*** | -0.3234 | 0.4581 | -1.2972 | 0.4689 | 0.3140 | 0.3195 |
| | ***QL5*** | -0.1177 | 0.3009 | -1.0907 | 0.3110 | 0.5292 | 0.2142 |
| ***Cost - Oriented*** | ***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 |

## VI. CONCLUSION

Increasing numbers of mobile users together with corresponding growth in user throughput and content quality demands, and also energy consumption awareness will determine that energy-efficient network selection solutions be part of the next-generation heterogeneous wireless network environments.

**E-PoFANS – the Enhanced Power-Friendly Access Network Selection Mechanism** is proposed, and when integrated in user mobile devices it will automatically perform energy-efficient network selection for the users, considering user preferences, application requirements, and network conditions. E-PoFANS indicates the best target network option and triggers the handover process.

In this paper, E-PoFANS has been analyzed in terms of energy efficiency and compared against another energy efficient solution proposed by Liu et al. [19]. Two main scenarios are considered: *(1) Energy-Quality Trade-off* –where the networks differ only in terms of quality levels provided and energy consumption. All the networks are assumed to be free of charge. The trade-off between energy and quality is analyzed; *(2) Energy-Quality-Cost Trade-off* – the monetary cost parameter is also introduced so that the trade-off between energy, quality, and cost is analyzed. The results show how the proposed E-PoFANS solution could achieve up to 30% more energy savings in comparison with Liu et al.'s solution.

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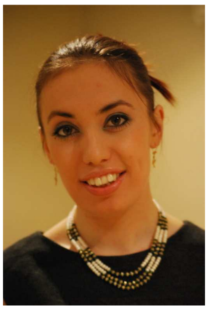

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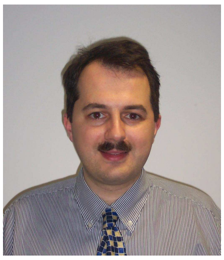

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