

Energy-Efficient Vertical Handovers

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Energy-Efficient Vertical Handovers

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Abstract

Recent studies have shown that there are currently more than 1.08 billion of Smartphones in the world, with around 89% of them used throughout the day. On average each of these users transfers more than 450 Mbytes per month via either a cellular network or a Wi-Fi network. So far it has been up to the user to decide which one of these two networks to use at each particular moment.

In this master's thesis, the potential energy savings that could be achieved by means of automating the choice of network interface are explored. This way, the user equipment itself would be able to initiate handovers from one radio access technology to another depending on each particular service and on the environmental conditions, and hence it could extend its battery life.

The work has focused in energy efficient vertical handovers (VHOs) between Long-Term Evolution (LTE) and Wi-Fi networks. The rapid growth and increasing interest in LTE networks have been the main reasons why these networks have been chosen over Third Generation Mobile Networks. Nevertheless this work can be easily extended to other radio access technologies such as WiMAX (Worldwide Interoperability for Microwave Access) or UMTS (Universal Mobile Telecommunication System).

During the thesis project, the potential energy savings via VHOs depending on the type of service have been studied, as well as the different processes involved in a handover decision process. In order to do so, an energy consumption profile of each interface has been built, the different services have been modeled, and a heterogeneous scenario with Wi-Fi and LTE networks has been simulated. The thesis presents how these savings change within each service and with the environmental conditions (network load, interferences).

The results show that large energy savings can be achieved. Nevertheless, the potential savings for each different user device can significantly differ. The VHO decision process includes two main aspects that need further study: investigating energy efficient ways of discovering accessible Wi-Fi access points and measuring the available throughput in each network at the moment of the decision.

In addition, within LTE-Advanced and HetNets (Heterogeneous Networks), a lot of research regarding how LTE operators can offload traffic to smaller networks is being performed. These smaller networks consist basically of LTE micro cells and Wi-Fi. Both the energy savings and the potential energy expenses of offloading different kinds of traffic to a Wi-Fi network were also studied in this master's thesis project, using the same approach described in the previous two paragraphs.

Keywords: *Vertical, Handover, Offload, LTE, 4G, WLAN, Wi-Fi, Energy consumption, Energy savings, Energy-efficient, IEEE 802.11, Smartphone, Battery life*

Sammanfattning

Enligt beräkningar så finns det nu mer än 1.08 miljarder smarta telefoner i världen, och ungefär 89% av dem används varje dag. Varje användare överför mer än 450 megabyte per månad i genomsnitt, antingen via cellulära mobilnät eller Wi-Fi. För närvarande är det användaren som avgör vilket av dessa interface som ska användas vid varje tidpunkt.

I detta examensarbete utvärderas vilka energibesparingar som kan uppnås genom att automatisera valet av nätverksinterface. På detta vis skulle den mobila enheten själv utföra handover från en radioaccessteknik till en annan beroende på aktiva tjänster och på radioomgivningen, och därmed utöka batteriets livstid.

Detta examensarbete fokuserar på vertikal handover mellan LTE och Wi-Fi nätverk. Den snabba tillväxten och det ökande intresset för LTE är den främsta anledningen till att LTE har valts istället för 3G. Det är dock möjligt att med små förändringar generalisera arbetet till andra radioaccesstekniker, till exempel WiMAX eller UMTS.

De potentiella energibesparingarna genom vertikala handovers för olika typer av tjänster har studerats, liksom de olika stegen i handover-beslutsprocessen. För detta syfte har en energikonsumtionsprofil skapats för varje interface, de olika tjänsterna har modellerats och ett scenario med Wi-Fi- och LTE-nätverk har simulerats. Denna rapport beskriver hur dessa energibesparingar ändras för varje tjänstetyp och med ändringar av omgivningen (nätverkslast och interferens).

Resultaten har visat att stora energibesparingar kan uppnås, även om dessa besparingar kan variera mycket för olika UEs. Beslutet om vertikal handover inkluderar två huvudsakliga aspekter som kräver fortsatta studier: energieffektiva metoder för att upptäcka tillgängliga WiFi-accesspunkter som går att ansluta sig till och mätning av den upplevda datahastigheten i varje nätverk före beslutet om vertikal handover tas.

Parallellt med detta examensarbete pågår omfattande studier om hur mobiloperatörer kan avlasta datatrafik till basstationer med kortare räckvidd. Dessa småskaliga nätverk förväntas bestå av LTE mikro/pico celler och/eller Wi-Fi nätverk. Detta examensarbete inkluderar även studier av de potentiella energibesparingar eller energikostnader för att avlasta olika slags trafik till Wi-Fi nätverk.

Nyckelord: *Vertikal, Handover, Avlastning, LTE, 4G, WLAN, Wi-Fi, Energiförbrukning, Energibesparingar, Energieffektiv, IEEE 802.11, Smartphone, Batteriets livslängd*

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List of Acronyms and Abbreviations

3G	Third Generation of Mobile Telecommunications Systems
3GPP	3rd Generation Partnership Project
4G	Fourth Generation of Mobile Communications Systems
AAA	Authentication, Authorization and Accounting
ANDSF	Access Network Discovery and Selection Function
AP	Access Point
BS	Base Station
DL	Downlink
DRX	Discontinuous Reception
eNB	Evolved Node B
EPC	Evolved Packet Core
E-UTRA	Evolved UMTS Terrestrial Radio Access
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
ETSI	European Telecommunications Standards Institute
FFT	Fast Fourier Transform
GPS	Global System Positioning
GSM	Global System for Mobile
HHO	Horizontal Handover
HN	Host Network
HO	Handover
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
LTE	Long-Term Evolution
MAC	Media Access Control
MIH	Media Independent Handover
MT	Mobile Terminal
PL	Path Loss
PRB	Physical Resource Block
PoA	Point of Attachment
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RRM	Radio Resources Management
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ratio
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VHO	Vertical Handover
Wi-Fi™	Wi-Fi is a trademark of the Wi-Fi Alliance and it concerns WLAN technology that is in compliance with IEEE 802.11 standards
WiMAX	Worldwide Interoperability for Microwave Access
WWAN	Wide Wireless Area Network
WLAN	Wireless Local Area Network

1 Introduction

Due to the huge growth of wireless networks and to the tendency of users wishing to be “always connected” [1], it is very common that, at any given location more than one Radio Access Technology (RAT) is available. For example, in a large city, there is cellular coverage almost everywhere from one or more different wide area cellular operators. Additionally, there will probably be multiple wireless local area network (WLAN) access points (APs) available anywhere in the city. Today all smartphones are capable of connecting to at least two different RATs, specifically wide area cellular networks and WLAN networks, but also to other technologies such as WiMAX (Worldwide Interoperability for Microwave Access).

Up until now, it has generally been completely up to the user to manage their device’s access to the different types of available access networks. The user must manually decide when to turn on and off the different wireless network interfaces in their device and when to connect to these different wireless networks. It is true that some systems where two RATs are seamlessly used have been proposed [2]. However these did never get much popularity.

It is obvious that the way these decisions are managed strongly affects the behavior of the mobile terminal (MT) in terms of battery power consumption or perceived Quality of Service (QoS). This issue has not gone unnoticed by the industry and a lot of research has been performed in the area. Many papers have been published in the recent years describing how changes between different RATs –also known as vertical handovers (VHO), can extend the battery life of the MT [3], can be used for load balancing by the network operators [4], or can improve the performance of the MTs [5]. This subject is indeed very important for the fourth generation mobile communications systems (4G). These systems will utilize all-IP architectures and to an increasing extent rely on several different radio access networks (RANs). Currently there is an increasing interest from operators and in 3GPP for efficient support of traffic offloading to WLAN.

During this master’s thesis the full details of VHOs will be analyzed in depth from an energy-efficiency perspective. After researching the different steps in the course of a VHO, different solutions will be proposed and evaluated using simulation, showing how VHOs may save energy and extend the battery lifetime of MTs.

1.1 Focus of this Master’s Thesis

The fast growth and development of Long Term Evolution (LTE) and fourth generation mobile networks (4G) has been the reason why this thesis work has focused on VHOs between these and IEEE 802.11* interfaces. Besides, there is an increasing interest regarding how LTE operators can use Wi-Fi networks in their benefit. Nevertheless, the algorithms and results can easily be extended to other wireless access technologies, such as WiMAX or 3G and to other types of handovers such as handovers to pico-cells and femto-cells.

It is widely known that the battery life of current MTs is a very important user concern [6] and a lot of research regarding ways to optimize an MT’s operating time has taken place in recent years [7]–[9]. This thesis project continues this trend by focusing on energy-efficiency. Different solutions and algorithms will be evaluated to see which offers the greatest energy-efficiency and to explore how VHOs can contribute to extend MT’s lifetime.

* Here after we will refer to these interfaces as Wi-Fi™ interfaces, as this represents the popular trade name for IEEE 802.11 compatible devices.

1.2 Scope of this Master's Thesis

Hence, the scope of this work is to analyze how VHOs can save energy in mobile devices and to assert if these energy savings are actually significant. In order to do so, different services such as Web surfing, VoIP calls or downloads are modeled and separately studied. Besides, other processes involved in VHOs are also covered from an energy efficient point of view, such as optimizing the threshold to leave and enter networks, defining preferable idle network or techniques to automate the VHO decision.

1.3 Structure of this Master's Thesis

During this first Introduction section the topic, focus and scope of this work have been introduced. The following sections of this report will go deeper into such concepts and will illustrate the work made during this Master's Thesis. Namely, the rest of this report is divided into these four sections: Background, Method, Analysis and Conclusions.

Chapter 2, Background, constitutes an extensive literature study which provides with a wide vision regarding the VHOs' state of the art and with a full understanding of the topic, which have been essential for the development of this thesis. The different algorithms and systems proposed are based on this previous research. In this section an overview of the RATs of interest is also given. Finally, nowadays usage of mobile devices is analyzed as well, justifying why the different services studied have been chosen.

The Method section presents the tools used to study the potential energy savings thanks to VHOs. These tools are firstly formed by the energy models employed. How the energy model of each interface was developed, how they have been combined and how they work is explained in detail. At the same time, the simulated scenarios are introduced. Such scenarios represent certain urban areas with the presence of the two RATs of interest, LTE and Wi-Fi. The used parameters and techniques to simulate then can be found in this section. Finally, the expected real world scenarios where VHOs may save energy are introduced thanks to some immediate conclusions extracted directly from the energy models.

In the following chapter, called Analysis, the simulations and experiments are carried out, covering the expected scenarios described in the Method section. The different processes that intervene in a VHO decision are covered. For each kind of traffic selected, the potential energy savings via VHOs are analyzed; showing how this new type of handovers can save significant amounts of energy given the proper circumstances.

Finally, the conclusions extracted from the conducted experiments are presented in the last section, which is called Conclusions. A discussion analyzing the results obtained in the different experiments is included here. This final section has another important subsection called Future Work, where a reflection regarding how the work made in this thesis can be continued and describing some possible lines of actions that will allow such extensions.

After the conclusions, the references used during this project are listed.

2 Background

Along the following subsections a deep literature study is presented. In this study, all the concepts covered in this Master's Thesis are described in detail to provide the reader with a full understanding of the topic.

2.1 LTE Networks

Long-Term Evolution (LTE) is a wireless data communication standard developed by the 3rd Generation Partnership Project (3GPP) [10] and documented in the 3GPP Release 8 and Release 9 specifications [10], [11]. It constitutes an evolution of the Global System for Mobile (GSM) and Universal Mobile Telecommunications System (UMTS) standards towards an all-IP broadband network. It was first proposed by NTT DoCoMo [12] of Japan in 2004 and it was the Swedish mobile network operator TeliaSonera [13] who launched the first publicly available LTE service in 2009.

These networks are also referred sometimes as Evolved UMTS Terrestrial Radio Access (E-UTRA) and Evolved UMTS Terrestrial Radio Access Network (E-UTRAN). The most important motivations for LTE have been the following:

- ✓ Need to ensure the continuity of competitiveness of the 3G system for the future
- ✓ User demand for higher data rates and quality of service
- ✓ Packet Switch optimized system
- ✓ Continued demand for cost reduction
- ✓ Low complexity
- ✓ Avoid unnecessary fragmentation of technologies for paired and unpaired band operation

At the same time, LTE networks are designed to support a huge variety of services, including web browsing, FTP, video streaming, VoIP, online gaming, real time video, push-to-talk and push-to-view [14]. Hence, some performance goals for these networks, listed in Table 2-1, were defined.

Table 2-1: LTE performance requirements [14]

Metric	Requirement
Peak Data Rate	DL: 100Mbps; UL: 50Mbps (for 20MHz spectrum)
Mobility Support	Up to 500 km/h but optimized for low speeds from 0 to 15 km/h
Control plane latency	Control plane latency (Transition time to active state)
User Plane Latency	< 5ms
Control Plane Capacity	> 200 users per cell (for 5MHz spectrum)
Coverage (cell sizes)	5 – 100 km with slight degradation after 30 km
Spectrum Flexibility	1.25, 2.5, 5, 10, 15 and 20 MHz

Regarding the overall network architecture, LTE uses a simplified single node architecture consisting of the evolved Node Bs (eNBs) which communicate with the Evolved Packet Core (EPC), which is purely IP (Internet Protocol) based. The eNB hosts the PHYSical (PHY), Medium Access Control (MAC), Radio Link Control (RLC), and Packet Data Control Protocol (PDCP) layers as well as Radio Resource Control functionality.

LTE is based on OFDMA (Orthogonal Frequency Division Multiple Access) to be able to reach even higher data rates and data volumes, up to 170 and 300 Mbps in the up and downlink respectively. Besides, the core network can work with other access technologies not developed by the 3GPP, like WiMAX and Wi-Fi.

In the LTE access network there is no centralized intelligent controller which helps to speed up the connection set-up and reduce the time required for a handover.

In an effort to support as many regulatory requirements as possible, the LTE frequency bands ranged from 800 MHz up to 3.5 GHz and the bandwidth is very flexible as shown in Table 2-1. Besides, LTE supports both the time division duplex technology and the frequency division duplex.

According to an IHS iSuppli Wireless Communications special report [15], LTE subscribers are expected to reach the 198 million in 2013, surpassing the 1 billion by 2016.

Further developments of LTE were presented in the 3GPP LTE Release 10, where LTE-Advanced was defined as major enhancement to LTE. In this case the focus was on higher capacity [16]:

- Increased peak data rate, DL 3 Gb/s, UL 1.5 Gb/s
- Higher spectral efficiency, from a maximum of 16bps/Hz in R8 to 30 bps/Hz in R10
- Increased number of simultaneously active subscribers
- Improved performance at cell edges, e.g. for DL 2x2 MIMO at least 2.40 bps/Hz/cell.

In the next several years it is expected that LTE operators will need to significantly increase the capacity of their networks [17]. At the same time, the available spectrum is expected to be very limited and expensive [17]. This provoked the development of techniques where both macro and small cells are used, creating a so called Heterogeneous Network (HetNet). Such techniques enable operators to deploy low power small cells in addition to macro cells in the same channel and therefore increase the capacity of their networks.

2.2 Wi-Fi Networks

Wi-Fi networks include any wireless local area network (WLAN) products that are based on the Institute of Electrical and Electronics Engineers' (IEEE) 802.11 standards, as defined by the Wi-Fi Alliance [18]. This Wi-Fi Alliance is the owner of the Wi-Fi trademark and “it provides a widely-recognized designation of interoperability and quality and it helps to ensure that Wi-Fi-enabled products deliver the best user experience” as they themselves assert [19].

Any device that uses Wi-Fi can make use of a wireless network access point (AP) to gain access to a network resource such as Internet. Such devices can be smartphones, televisions, cameras, music players, etc.

As mentioned, these networks are based on the IEEE 802.11 family standards, which implement wireless local area network (WLAN) computer communication in the 2.4, 3.6, 5 and 60 GHz frequency bands. The most important of these standards are the following [20]:

- 802.11a (1999): transmits in the frequency of 5 GHz with a maximum data rate of 54Mb/s. It uses an OFDM based interface.
- 802.11b (1999): it operates in the band of 2.4 GHz and has a maximum raw data of 11Mb/s
- 802.11g (2003): it transmits data at 2.4GHz but can transmit a maximum of 54 Mb/s as it also uses an OFDM coding.
- 802.11n (2009): it can transmit a maximum of 140 Mb/s and operates in both frequency bands (2.5 and 5 GHz). It added multiple-input multiple-output antennas which meant a significant improvement to previous standards.

The range of these networks depends on the standard. For a typical deployment using 802.11b and 802.11g, the ranges could be about 20 meters indoors and 70 outdoors. On the other hand, the 802.11n protocol can increase those numbers to double.

2.3 An overview of Wi-Fi Access Points

Within any big city, MTs are able to reach a Wi-Fi network almost everywhere. However, the fact that they can actually connect to that network is not so common. Therefore, it is considered that a brief introduction to the different kinds of Wi-Fi networks in terms of accessibility for an arbitrary MT must be performed.

There are two main categories of Wi-Fi networks: private and public. The private ones are those that are present at almost every home, those set up in an office for the employees, etc. Almost all these networks have a private password, so it is highly unlikely that an arbitrary MT will have access to them.

Public Wi-Fi networks are very common as well. These are for example Wi-Fi points installed by the city government in a famous square, or those provided by some restaurant in order to attract more customers. There are some important considerations that need to be made regarding these. For example, they can either have a password or not. If they do have it, some of them do not allow to the MTs to remember it, forcing the user to introduce it every time. Another aspect of these APs is that they are usually powered off at certain time in the day. For example, the free Wi-Fi available in a mall will probably be powered off when it closes.

The fact that these APs are free together with the better bandwidth Wi-Fi usually provides, makes them a very attractive solution for the users. This has not gone unnoticed and there are many web pages which have collected these Wi-Fi's within a certain area. For example, thanks to [21] it is possible to locate a large number of free Wi-Fi in several cities of Sweden. This tool is also very helpful to figure out how common these open APs actually are. Only in Stockholm, the webpage has information about more than 200 free Wi-Fi access points.

Finally, one last kind of Wi-Fi APs can be those where the access is possible thanks to the credentials stored in the MT SIM card. They were developed in order to simplify the authentication and access process. The Wi-Fi Alliance (WFA) [18] came up with this idea in an effort to integrate Wi-Fi hotspots seamlessly into the cellular networks. They were included in the Hotspot 2.0 program which finally derived in the PassPoint Certification [22]. The research regarding these Wi-Fi hotspots consists of another approach addressed in the LTE Advanced HetNet techniques mentioned in the previous section.

2.4 Vertical Handovers Overview

Along this section an overview of VHOs will be given. Different types of handovers will be presented and described as well as the different processes involved in their realization.

2.4.1 Different Approaches to Vertical Handovers

There are several different approaches to VHOs in terms of the degree of collaboration between the different entities. As this work will focus on VHOs between cellular networks (4G/LTE) and WLAN networks (Wi-Fi), we consider three different entities: the MTs, the cellular network, and the WLAN network.

These three entities can interact and communicate in different ways, thus leading to different VHO processes. We can characterize these different methods in terms of the degree of integration of different RANs. Typically, three different degrees of integration are considered [23]:

1. *Tight coupling*: where the integration between both networks is very strong. The cellular network tightly integrates the WLAN APs. In these systems the handover (HO) decision and/or execution can be made either by the MT or by the network. This type of approach is easier to carry out in WLAN networks owned by the cellular operators. This is followed in section 4.11.
2. *Loose coupling*: In this case the cellular network takes part in the VHO process, but it is not the main player. Here the HO is MT-driven, but the cellular network can provide some parameters, such as the network load or the coverage area, as input to the HO decision.
3. *No coupling approach*. In this case the VHO process is transparent to both the networks. The MT makes the HO decision and all the parameters are measured and evaluated by the MT *without* any collaboration with either of the networks.

Two immediate drawbacks of the tight and loose coupling approaches are the scalability and the (potentially unknown) operator's management policy. On the other hand, with the no coupling approach, the problem of resource management and network load balancing need to be addressed.

Many believe that tighter the integration, the greater the complexity of the system [23]. Some also believe that the tighter the integration the greater the energy efficiency, but this remains to be seen.

2.4.2 Reasons to perform a handover

The first question is: why should a HO occur? It is possible to characterize VHOs according to the reason why the HO was triggered [24]. Here it is important to note that handovers can occur both as VHOs and HOs between Points of Attachment (PoA) -evolved Node Bs (eNBs) in case of LTE and Access Points (APs) in case of Wi-Fi, of the same type of RAT. The latter are known as horizontal handovers (HHOs)*.

The first type of HOs is an imperative handover. This type of HOs are triggered when the received signal strength (RSS) falls below a certain threshold, hence the MT will (soon) be unable to communicate via this link. This is the traditional motivation for HHOs within cellular networks or within a WLAN. In this case a HO is necessary because there is not enough received power to maintain communication. Unless a new PoA is found in time an on-

* Sometimes handovers between different "layers" in a RAT are also referred to as vertical, e.g. handovers between macro-cell to/from pico cells.

going call/session will probably be dropped*. These HOs are always triggered by the MTs since they know their received signal strength from multiple base stations and hence they have the best information about the chance of having a better channel after a handover. Nevertheless, the connections may turn out to be limited by the UL in some cases, for example due to interference or imbalance between UL and DL coverage.

Imperative handovers can also be triggered by the network for load balancing purposes. This type of HO is triggered by the network in order to optimize the network's performance. This may negatively impact the MT, as the MT may need to expend more power both during the HO and after the HO.

A second type of HO is an alternative handover. These handovers are performed when there is another network that offers better service for the current activity of the MT. For example, if the current PoA offers only low bandwidth and a video VoIP call comes in, it may be wise to change to another PoA (either belonging to the same RAT or not) which offers higher bandwidth, if one is available.

There are two different approaches to managing alternative handovers. The first periodically monitors the available networks and checks if there is a more suitable one available. Alternatively, an alternative handover can be triggered by a certain event. For example, if a MT wants to download a large video clip and its current PoA offers only limited downloading bandwidth, then a process of access network discovery can be started. If a better PoA is found, then a handover will occur, otherwise the MT will stay with the current PoA.

Finally, there is another type of handover called a power-based handover. These are triggered when the battery power level of the MT is below a certain threshold. This threshold can be either fixed or adapted to the user's preference. This type of HO is meant to save battery power.

2.4.3 Access Network Discovery

Access Network Discovery is a fundamental process during a VHO execution. Before changing from one RAT to another, it is compulsory to find the different available wireless networks. Moreover, this must be made in the most possible energy-efficient way. This necessity has not gone unnoticed by the researchers and several energy-efficient Access Network Discovery solutions can be found in the literature nowadays. Most of these proposals are focused on the efficient discovery of Wi-Fi APs. Specifically, different ways of detecting these PoAs without continuously activating the Wi-Fi interface have been deeply researched. The next paragraphs constitute a review of some of these solutions.

One possible approach to find PoAs in an energy efficient way consists of using context information. This is the strategy followed in [25]. Information such as time, history, cellular network conditions or device motion is employed to estimate Wi-Fi network conditions without powering up such interface. Along the paper several methods to estimate the network conditions through context information are presented:

1. *Hysteretic Estimation*: the context information previously measured consists of the network conditions, which will be used until a new measurement or until a time-out runs out. It is more effective for shorter data transfer intervals.

* Note that in the first three generations of wide area cellular telephony, the emphasis was on calls – since the primary purpose of the system was to support telephony. However, there is a growing amount of packet traffic that is not session oriented.

2. *Time of Day Estimation*: it exploits the fact that network conditions at the same time on different days are statistically related.
3. *Cellular Tower Estimation*: cellular visible towers are used as the context information and the correlation between the network conditions and the geographical location is exploited. Excluding the GPS system due to its high energy consumption, two methods are proposed to figure out the position of the MT:
 - a. *Cell ID Estimation*: the Wi-Fi availability is calculated as a weighted sum probability of the possibility of Wi-Fi availability for when each cell tower is visible. Google has developed a system based on this approach which is nowadays available for any user of an Android device. It is called *Google's My Location* [26].
 - b. *Fingerprinting Estimation*: an ordered set of up to seven visible cell towers reported by the phone (i.e., the fingerprint) is used as the context. This is the method with best results but it also needs more memory and requires prior training at each location to be effective.
4. *Acceleration Estimation*: the acceleration data is used to measure how much a MT has moved. If such amount of movement is below a certain threshold, previous network conditions measurements are used.

The Hysteretic and Acceleration methods are very useful to predict a change in the network conditions. At the same time, thanks to Cell ID and Fingerprinting is possible to predict the network condition irrespective of previous measurements. With this in mind, the authors finally propose an algorithm that combines different estimation methods: it first estimates if a change in the network conditions is likely to occur; if it is, Cell ID or Fingerprinting is used; if it is not, the previously network conditions will be.

In [27], the Wi-Fi interface activation is controlled by monitoring the cellular signal quality. The authors have used the way the signal degrades when moving from an indoor to an outdoor location to design an algorithm to estimate WLAN area coverage. Such algorithm is completely terminal-driven and therefore it has the advantage that neither changes to existing networks nor the assistance of a server are required.

A loose coupling approach is designed in [28]. The authors of this paper propose to obtain the information about close WLAN APs through a server in the network. The protocol used for this exchange of data is the IEEE 802.21, presented in detail in section 2.5. Nevertheless, in the algorithm proposed the WLAN interface must be turned on sometimes. A similar solution is presented in [29]. In this case, the authors propose a location-based system where a database of WLAN APs depending on the geographic location is available for the MTs. Therefore, the MTs only activate their WLAN interface when there is at least one Wi-Fi AP within range. Location awareness is suggested to be achieved via GPS. This database is proposed to be sent by the BSs to the MTs; either periodically (passive schemes) or only when requested.

2.4.4 Radio Fingerprinting

This localization technique is a very interesting approach to solve the issue of energy efficient access network discovery. It consists of an energy-efficient solution which can have a wide range of applications.

As it was explained before, this technique consists of building a radio map and inferring the location of the MTs through best matching, using either deterministic or probabilistic algorithms [30]. Deterministic techniques store scalar values of average RSS measurements from the access points. Three relevant techniques in this group are:

- *Nearest Neighbor*: the estimated location is simply the one closer using an Euclidean distance approach
- *K-Nearest Neighbors*: the k top possible locations are identified. The centroid of that set is the estimated location.
- *Smallest M-Vertex Polygon*: selecting several nearest neighbors which will form various polygons and the centroid of the smallest polygon will be considered as the estimated location.

On the other hand, the location in the radio map with higher probabilities is the one chosen in probabilistic techniques. The RSS measurements are treated as random variables statistically related to the location.

Many technologies can be used for radio fingerprinting. The most common are cellular and Wi-Fi WLAN networks but solutions based on Bluetooth [31] or Digital TV [30] have been considered as well. In radio fingerprinting it is also common the usage of several of these technologies at the same time. For example, in [32], Wi-Fi, Digital TV and cellular communications are combined.

Considering that one of the main angles of this Master's Thesis is the energy-efficiency, the most attractive approach for us is the radio fingerprinting using cellular networks. In these cases, the radio map is usually built by combining RSS (Received Signal Strength) values from several base stations. Nevertheless, information such as signal time delay, channel impulse response or any other location-dependent parameter can be included as well. Some advantages of these approaches are the low energy-consumption and that they do not require external hardware and are easy to implement. However, the fingerprint database may not be easy to build and it needs to be periodically updated. Besides, exact matches are very unlikely and some errors are inevitable [33].

In [34], a low-cost fingerprint positioning system in cellular networks is proposed. The system consists on collecting RSS values from all the available BSs. These samples are preprocessed using a *Time Delay Neural Network* method which performs a linear averaging of the RSS values as they are collected. However the authors realized that the error was still big so they decided to perform a post-processing of the estimated location obtained from the neural network algorithm. This post-processing includes tracking using *Kalman* filter [35] algorithm and map matching. The final system has an average positioning error of 50 meters.

Another RSS-based positioning algorithm in GSM networks is designed in [36]. It uses probabilistic fingerprints built with the help of a grid. This method involves a small increase of computation compared to deterministic solutions but it outperforms them considerably: it provides a median error in urban areas of about 30 meters.

2.4.5 Leveraging the Parameters

The last process before making a HO is to decide upon which network the MT is going to associate with. At this point there are a large variety of parameters that can be considered. For example, if the intended purpose of the HO is to gain QoS and the MT is not moving, then the available bandwidth will be a dominant factor and the coverage area of the network will not have much importance. On the other hand, if saving battery power is the highest priority, then the expected power consumption when using the different available APs will need to be considered.

As has already been explained in previous sections, the traditional handover engines have primarily focused on RSS. However, there are many other parameters to evaluate given the variety of applications used in MTs nowadays.

Nevertheless, there are some important factors that will always need to be considered. One of them is a dwell timer to avoid a ping-pong effect in handovers, which consists of repeatedly changing between two networks [24]. Another aspect that should always be considered is the network load, as it has been proven that failed attempts to handover to a congested network are one of the most important reasons for call drops [24].

Once the decision of which parameters are most important and which are least important for specific HOs has been made, there are several alternatives regarding how to evaluate their importance. These have been summarized by Shen et al. in [37] and are briefly presented in following paragraphs.

The first algorithm is based on the traditional approach of HHOs: a HO is performed when the current connection is in danger, i.e. when there is not enough received signal strength to maintain such connection. The ping-pong effect in these *RSS-based* solutions can be reduced by introducing the hysteresis and/or the dwell timer method [38]. This is an easy algorithm to implement but it does not take into consideration important elements such as the battery life of the device or the network congestion, so its usage in heterogeneous networks is quite limited.

The second algorithm that will be analyzed here is based on *Cost Functions*. Once that the different parameters to be used have been decided, a cost function based on these is designed to evaluate the performance of each network. The form of this cost function can change completely depending on which factors are chosen to consider during the HO decision process. Using a cost function instead of a RSS-based algorithm offers the possibility of including many other factors in the decision process, hence better results can be obtained. However, these cost functions have an important drawback: their form is fixed and therefore they cannot be adapted to the different service traffics.

The *Multiple Attributes Decision Making* algorithms face this problem of adaptability. This approach consists of firstly calculating the quantitative value of each normalized parameter and afterwards evaluating the candidates' network through the weighted function of the quantitative values. The different importance of each parameter can now be reflected in the weights assigned to each one of them. This algorithm includes:

- *Simple Additive Weighting Based Algorithm*. They are the most common Multiple Attributes Decision Making algorithms. Different factors are assigned different weights. These factors can be dynamically changed so different traffic classes can be supported.
- *Analytic Hierarchy Process Based Algorithm*. This is a suitable algorithm for complicated Multiple Attributes Decision Making problems. It defines a visible hierarchical structure consisting of goal layer, criteria layer and alternative layer. In not so complicated environments, this algorithm provides similar results than the Simple Additive Weighting Based Algorithm which are considerably simpler.
- *Grey Relation Analysis Based Algorithm*. This is an analytical method used to calculate the correlation of different factors. It works fine with little data which makes it a suitable algorithm for dynamic network analysis. However its computation complexity is hard. It can also be combined with other methods such as Analytic Hierarchy Process Based Algorithm.

There are also algorithms whose primary intention is not finding the best available network for the MT but improving the performance of the whole network. These are the *Balancing Algorithms*. An example can be found in [39], where the aim of the proposed VHO

algorithm is to provide an efficient resource utilization through balancing the traffic load among the different APs and to extend the battery life of the MTs. Another example is available in [40], where the average RSS and blocking probability are used to improve the system performance.

The last algorithm that will be introduced in this section is the *Fuzzy Logic and Policy Based Algorithm* [41], which is used to manage fuzzy parameters in HO decision processes. These parameters are difficult to quantify. One of these fuzzy factors can be the user's preference for a specific network or other user requirements.

2.5 VHOs Existing Standards

There are several different vertical handover standards, two of them are introduced in the following subsections.

2.5.1 Media Independent Handover (MIH)

The Media-Independent Handover (MIH) standard is part of the IEEE 802.21 [42] and provides a common language to exchange link-layer information of different RANs and MT's battery-level information. It is therefore meant to optimize the HO process between heterogeneous networks. It uses both the MTs and the networks as information sources. Its most important entity is the Media Independent Handover Function which is an interface between the media specific technology and the MIH users. This entity provides three services to the higher levels [43]:

1. *Media Independent Event Service*: the MTs subscribe to events such as changing in the state of a link layer, HO completions, changes in link conditions, etc. These events can be predictive as well: decreasing in RSS can mean that the connection will get lost soon.
2. *Media Independent Command Service*: MIH users send commands to the Media Independent Handover Function and the Media Independent Handover Function send commands to the access network interfaces. These commands can cause event indications to other MIH users. Thanks to this service, the MIH users can get dynamic information about the situation on the link layer (SNR, bit error rate, ...). Besides, the Media Independent Command Service can be used to subscribe or unsubscribe of certain events, configure thresholds for report events, activate actions on the link layer and even for link layer resource reservation.
3. *Media Independent Information Service*: it facilitates the exchange of information between MTs and operators on possible HO network candidates. This information is usually static and it is provided through *Information Elements* which can be classified in three groups:
 - a. General information about the available access networks within an area: offered QoS, cost, used frequency bands, maximum data rate, etc.
 - b. Information concerning to the different PoAs available: channel range, link layer address and geographic location.
 - c. Access network-, service- or vendor specific IEs. They provide network information about the supported higher layer services on the available networks.

2.5.2 Access Network Discovery and Selection Function (ANDSF)

The Access Network Discovery and Selection Function (ANDSF) is an entity within the 3GPP standard 23.402 [44] to help in the detection of non-3GPP access networks. It can also provide the MT with information regarding policies and operator requirements to connect to these networks. The ANDSF can provide three types of information:

1. *Inter system mobility policy*: network selection rules for MTs with only one active access network connection. This may contain information such as access network preference for certain data.
2. *Inter system routing policy*: network selection rules for MTs with potentially more than one active access network connection. This information consists of a set of IP filter rules that define the different APs that shall or shall not be used by the MT to route a specific IP traffic.
3. *Discovery information*: list of available access networks (including access type technology, radio access network identifier, etc.).

2.5.3 ANDSF and MIH in VHOs' literature

There are a good amount of researchers who have proposed and designed several VHOs algorithms which make use of the ANDSF and of the MIH. It is clear that they can be very helpful and that they can facilitate certain processes during a vertical handover.

An example of one of these solutions can be found in [45]. The authors in this paper propose a VHO decision algorithm where the battery life and the offered QoS are important parameters. In order to include the battery life in the algorithm, the proposed solution uses the Media Independent Handover Function power management functionalities to obtain the necessary information for the VHO decision.

In [43], it is proposed a VHO algorithm where both the MIH and the ANDSF are used. In this paper a comparison between both standards is made and finally a solution which uses both of them is presented. The MIH is used to inform the source network of moving to the target network and to disconnect from it. In addition, the ANDSF is used to obtain the operator's policies which will contribute to PoA selection.

2.6 VHOs: Existing Solutions

As it has already been stated in previous sections, a HO depends on many factors which relative importance can be differently interpreted. Simultaneously, a VHO can be managed in many different ways: it can be triggered by the network, it can use GPS to predict when a VHO is going to be needed, it can be application-driven, and many others. Considering these factors, many solutions have been published along the recent years. A review of some of them can be found in the next paragraphs.

A first approach to HOs consists of only considering the RSS value. As it was explained in previous sections, this is the traditional approach for HOs which involves changing of PoA when the RSS is below a certain threshold and consequently the current connection is in danger. A classification of these approaches is made in [38]:

1. Relative RSS: if a candidate PoA has better RSS than the current one, then a HO is performed.
2. Relative RSS plus absolute RSS: if a candidate PoA has better RSS than the current one and at the same time the RSS of the current PoA is below a certain threshold, then a HO is performed.
3. Absolute RSS plus hysteresis: if the current RSS is below a certain threshold and the candidate's RSS is higher than the current one plus the hysteresis, then a HO is performed.
4. Dwell timer: when the decision of performing a HO has been taken, a dwell timer starts. If after this time, the candidate's conditions remains, then the HO will be finally made. This timer aims at avoiding the ping-pong effect. However, it also adds a certain HO delay.

Nevertheless, the RSS-based solutions do not react well to slow fading. A way to solve this issue is presented in [38], where a position aware vertical handoff decision algorithm is designed. In this algorithm, the MT's position is used as decision criterion. The functioning of the algorithm is the following. Firstly, the APs positions and coverage radius are broadcasted by the operators, for example in their webpage, and downloaded by the MTs. And secondly, the MTs use both the downloaded data and the information provided by their GPS to estimate when they are going to exit the area of coverage of their current AP. When they estimate so, the HO procedure is launched.

In contrast to the previous solution, a no coupling scenario is presented in [46]. In this paper, a low-complexity revision of the hybrid RSS/Goodput algorithm designed in [47] is proposed. In the original algorithm, it is necessary to compute the instantaneous goodput available at each network interface, which makes the practical implementation very challenging. Hence, two different modifications are presented:

1. RSS-based algorithm. Better service in terms of bandwidth and costs in the Wi-Fi interface is assumed. Therefore, the MT always connects to the Wi-Fi if available, regardless the services provided by the cellular interface. While in Wi-Fi, the MT only comes back to the other interface when the RSS is below a certain threshold.
2. Hybrid RSS/Goodput algorithm. This approach is closer to the original solution proposed in [47]. In this case, the MT only changes to Wi-Fi if its goodput is bigger than the goodput offered in the cellular network. In order to check that condition, two connections, one to each interface, need to be active at the same time, which makes of the MT a temporary multi-homed host. The authors themselves admit that how to manage these two connections is an open problem. Again, while in Wi-Fi, the MT only comes back to the other interface when the RSS is below a certain threshold.

The authors in [48] introduce a policy-based VHO decision algorithm where not only RSS measures are considered but also parameters such as the monetary cost, the network conditions or the system performance. In order to evaluate these set of parameters, a cost function is designed which includes a network elimination feature to reduce the delay and processing required in the evaluation of the cost function. This network elimination feature provides with the possibility of eliminating "bad" candidate networks at an early stage. It is specially meant for networks that cannot guarantee the necessary QoS constraints for a particular service. A multi-network optimization is also introduced to improve throughput for mobile terminals with multiple active sessions. Nevertheless, this cost function does not consider signal variations and cellular boundaries, which may derive in a problem with the ping-pong effect.

In [49], a seamless and proactive scheme for VHOs is proposed. In a VHO scenario, a proactive solution means to access to the network conditions and user's preferences before the VHO decision process. In order to provide such a system, two factors are considered as the most important: network condition detection and connection maintenance. The cited solution consists of a novel end-to-end mobility management system with two main parts. The first one is a connection manager used to detect the different network and their conditions. The handoff metric proposed is a QoS-based and includes available bandwidth and access delay and the connection manager accesses to them via WLAN media access control layer sensing. And the second part is a virtual connectivity based on the end-to-end principle and employed to maintain the connection.

A network-based approach can be found in [39]. In this proposal, load balancing across PoAs and MTs' battery life consideration coexist. It consists of a tightly-coupled system where a VHO decision controller placed in the access networks controls all the process. In

order to obtain the decision inputs, this controller uses the media-independent handover function. The VHO decision algorithm gives priority to the Wi-Fi access points and if one of these is available and can support the current connection, it will have preference over the cellular network PoAs.

Another example of a tightly coupling approach can be found in [50]. Considering a single operator with multiple RATs available, the authors propose a system able to perform load balancing and at the same time to satisfy as much as possible the application requirements and the users' preferences. The VHO decision is made in the MT by its Radio Resources Management (RRM) where the data is processed. The Common Radio Resources Management module in the IP core network simply translates the specific policies into an adequate configuration of the RRM algorithms and transmits them to the local RRM in each radio access interface. These local RRM are the responsible of exchanging the necessary information with the MTs for the HO decision process. Regarding the selection decision algorithm, several types of service are considered and parameters such as the network load, the battery life or users' preferences are adaptively weighted for each class of traffic.

In [51] the measurements of the HO metric are calculated in the visiting networks instead of in the MT. The considered parameters are the bandwidth, the cost per hour and dropping probability. Hence, they propose a Distributed Handover Decision scheme where the MTs receive the measures from the candidate PoAs and choose the most suitable network.

They are not so common, but MT-centric solutions can be also found in the current literature. An example of one of these is the proposal of [2], where the authors have designed an intelligent access selection mechanism where user's preferences, network conditions and applications requirements are considered.

2.7 Energy-Efficient VHO Approaches

Energy-efficient approaches are becoming very popular among the researchers during the recent years. The fact that the length of the MT's battery life is a very important concern for the user is widely known. Hence many solutions concerning VHOs from an energy-efficient point of view have been published lately. Some of them are analyzed in the next paragraphs.

A RSS-based approach can be found in [25], where an algorithm for optimizing the energy consumption during data transfers is designed. In such algorithm, the RSS in each candidate network is the only parameter used in the HO decision process. The estimated energy that will be consumed for the specific data transfer is calculated using the offered RSS in each available PoA and based on that the VHO decision will be taken.

In [52], a tight coupling approach is presented. They propose a scheme where a single operator manages both the UMTS and the WLAN network. In order to do this, a decision entity called Virtual Domain Controller is set up in the network side. This entity can initiate HOs if it is necessary for the overall network performance, and have the final decision over the HOs requested by the MTs. This is an energy-efficient solution because it saves a considerable amount of power by treating the uplink (UL) and the downlink (DL) separately: the MTs receive through the UMTS interface and transmit through the WLAN one. Nevertheless, as pointed in [16], this requires advanced signaling procedures, while the aggregated idle-time on both the DL and UL interfaces may result in higher overall energy consumption.

The researchers in [53] propose a tightly coupling approach as well. Their system avoids the energy consuming process of turning on the WLAN during the network discovery. In order to make this possible, the MTs access to location based information through cellular

paging channels and directly associates with a PoA. Regarding the HO decision algorithm, a VHO is only performed from the cellular network to the WLAN for long-lived bursty sessions.

Cellular paging channels are also used in [54]. The proposal in this paper consists of turning off the Wi-Fi interface after a certain time of inactivity. A paging signal through the cellular network will wake it up when some data need to be sent or received.

A similar philosophy is used in [55] where a simple power saving mechanism is used to turn off the Wi-Fi interface when not used. They compare the energy consumption of a tightly-coupled system where only one interface can be active at the same time with one where both can be. This latter approach can achieve better results but it is much more energy consuming as well. Nevertheless, thanks to that power saving mechanism, they manage to reduce that increase in energy consumption to 17-30%. However, they do not consider the power consumed for turning on and off the WLAN interface and for the association with the WLAN, with can be a determinant factor [16].

A strategy to turn on only the interfaces of the networks on the MT's vicinity is proposed in [24]. Thanks to the GPS system, the MTs send its location to their current PoA and this returns information about close PoAs using its own location aware functionality. The GPS also provides data about the velocity and direction of the MT. This information is used to elaborate an "estimated residence time" in the candidate network. For the HO to occur, this estimated residence time will have to be higher than the favorable residence time, which is the minimum time the MT needs to stay in the candidate network for the HO to be profitable energy-wise. Nevertheless, the use of the GPS already consumes a considerable amount of energy [25]. Finally, the authors suggest that the network should broadcast information concerning their coverage areas, services available and network load in their beacon signals. This way, the attempts to make a HO to a congested network can be reduced.

In [56] a MT-controlled VHO algorithm is designed. In an integrated UMTS/WLAN environment, the MT automatically selects the most power efficient interface for the current communication state while it turns off the idle interface; all this without degrading the network performance. However, things such as the VHO delay, throughput and energy overhead are neglected.

In [57], Xenakis et al. make use of the Cognitive Radio technology [40]. They propose a context-aware VHO framework towards energy-efficiency. In this paper it is considered that, in order to achieve an energy-efficient solution, context awareness is necessary. They take into consideration not only RSS measures and network congestion, but also battery lifetime, user's preferences, MT consumption at current PoA, charging policy and so on. The framework is service-oriented and MT-specific. The energy conservation is sought by incorporating QoS and energy-efficiency triggers in the network discovery process.

Finally, another very interesting paper regarding power efficiency is the one presented in [58]. The authors propose an adaptive algorithm for RANs selection. Their algorithm changes depending on the current application in the MT. Specifically, they consider two scenarios. The first one involves non real-time applications, where the energy consumption per bit is employed as the evaluation metric. In the second one, i.e. real-time applications, the RAN with lower power consumption while satisfying the required data rate is selected. Besides, in this paper it is considered that the HO overhead cannot be neglected. In order to take them into consideration, they use penalty functions mathematically derived for each application.

2.8 Mobile Terminals

In the following subsections we will look at the importance of power consumption by terminals, presenting existing studies that aimed to define energy consumption profiles for each RAT. This energy is also put into context by considering the power consumptions of tasks that are unrelated to VHOs. An introduction regarding current trends in Smartphones' usage will be given as well.

2.8.1 Contemporary Usage

As explained in Chapter 1, this Master's Thesis work aims at studying how handovers between different RATs can extend the battery life of mobile devices (which in most cases consist of smartphones or tablets). A company named GO-Gulf [59] recently published a very interesting infographic about the usage statistics in 2012 of these smartphones.

This study revealed that there are currently 1.08 billion of Smartphones in the world and that 9 out of 10 users use their phone on a daily basis. At the same time, the most common activities among these users in 2011 were: texting, Internet browsing, playing games, emails, used downloaded applications, social networking sites and music/videos.

Concerning the preferred platform, Android [60] has a 46.9% of the market share, followed by iPhone [61] (28.7%), RIM [62] (16.6%) and Microsoft [63] (5.2%).

Another aspect especially interesting for us involves the data consumption and the downloaded applications in each platform. According to the study, the users with an Android phone are the ones who consume the highest amount of data (582 MB/month), followed by the ones with iPhone (492 MB/month). However, the iPhone users download an average of 48 applications per month while the Android ones only 35.

Since this work has focused on handover between cellular networks and Wi-Fi, it is also interesting to obtain a general idea of the data usage trends in each one of these RATs. Concerning to this very same topic, Informa telecoms & media [64] published a white paper in 2012 called "*Understanding today's Smartphone user: Demystifying data usage trends on cellular & Wi-Fi networks*". One of the important conclusions extracted from the study is that Wi-Fi is the primary form of data connectivity, exceeding cellular networks by a ratio of four to one sometimes. They also state that operators have not paid enough attention to this Wi-Fi usage and advice them to look further into this potential market.

Finally, they also made an interesting distinction between the top 5 applications when using Wi-Fi or cellular networks, shown in Table 2-2.

Table 2-2: Top 5 Smartphone Applications

Cellular	Wi-Fi
Browsing	Browsing
Facebook App	YouTube
Tethering	Video and audio Streaming
YouTube	Downloads
Downloads	iPlayer

2.8.2 MTs Energy Profile

Designing an energy profile for a MT is essential in order to evaluate the performance of any VHO algorithm. In the existing VHOs algorithms in the literature, several approaches are followed concerning this issue.

Most of these approaches have focused in comparing 3G networks with Wi-Fi or Bluetooth. Nevertheless, in the recent years the interest for LTE has considerably grown and hence more papers have been published in the area.

Among the papers that have studied the energy consumption in LTE, the most interesting one corresponds to the work done by Huang et al [65]. In their work, they develop an energy model for mobile devices using real tests. This model has been of high importance in the development of this thesis and it is explained in detail in the section 3.2. The work by Dusza et al. [66], [67] has also been used in this work. In those papers experiments regarding the energy consumption of the LTE interface in the uplink were conducted. They are also described in detail in the section 3.2.

Other interesting study regarding LTE power consumption is found in the paper published in 2011 by Gupta et al. [68]. This work was one of the first studies showing power measurement data in a Smartphone. Thanks to their measures, they were able to infer the Radio Resource Control state machine used in LTE which is very useful to understand the power consumption of mobile devices in LTE networks.

Among the papers that consider 3G networks, one solution worth mentioning consists of using the power consumption values for each of the states from a particular interface card, as in [52] and [56]. In this approach the energy consumption rates of typical 3G and Wi-Fi cards are used to estimate the MT's power consumption. It is known that the actual power consumption depends on many factors. Nevertheless, this approach allows a researcher to obtain a general idea of the major differences between the energy consumption when using different RATs, which in turn can be very useful when designing a VHO algorithm.

A similar approach is followed in [55] and [69]. They use fixed energy consumption rates in Jules per second for each state of the network. In the case of [55], these values are extracted from [70]–[73]. They came up with some interesting values regarding the Wi-Fi energy consumption which are displayed in Table 2-3.

Table 2-3: Wi-Fi energy consumption

Measure	Value
Wi-Fi Power-on	29 mJ
Wi-Fi Power-off	24 mJ
Wi-Fi Transmit	2000 mJ/s
Wi-Fi Receive	900 mJ/s
Wi-Fi idle	800 mJ/s
Wi-Fi sleep	40 mJ/s

In contrast to the approaches described in the previous paragraphs, a more complex energy model for a MT could be created. If this strategy is followed, then the energy consumption of each interface is dynamically calculated based on the amount of data transfer or on the time the interface is being used. Some authors have proposed such models. A description of two of them can be found in the next paragraphs.

The first model was proposed in 2012 by Kalic, et al.[74]. They conducted a study of the energy consumption of the wireless communication technologies typically found in Android phones, i.e. Bluetooth, 3G, and Wi-Fi. Using a simple Android application that sends and receives data continuously and monitors the MT’s battery status, they developed an energy model for each technology. Such a model is linear and it predicts the percentage of battery consumed for a series of states for a given interface technology. This percentage can be calculated via two functions. The first function considers the amount of data transferred in gigabytes and the other uses the elapsed time of a transmission in units of hours. This model is shown in Table 2-4, where y is the percentage of power battery consumed, x in the amount of data transferred, and z is the elapsed time.

Table 2-4: Existing energy model in literature

	Download		Upload	
Bluetooth	$y = 24.58x + 0.8$	$y = 9.53z - 0.39$	$y = 17.09x - 0.53$	$y = 9.01z + 0.84$
Wi-Fi	$y = 17.01x - 0.93$	$y = 18.09z + 0.17$	$y = 17.31x - 2.28$	$y = 21.24z - 2.68$
3G	$y = 31.74x + 2.15$	$y = 20.59z - 1.09$	$y = 71.27x - 0.03$	$y = 15.31z + 2.67$

Another energy consumption model is presented in [75]. In this case Balasubramanian, et al. proposed a model that estimates energy consumption depending on the size of the transfer and the time between successive transfers. This mode is based on power measurements made on a Nokia N95 for 3G, GSM, and Wi-Fi. An interesting aspect of this paper is that the authors remark upon the importance of considering the tail energy in wide area cellular networks. In networks such as 3G and GSM, the interface is not automatically switched to a power saving mode after a transmission, but rather it stays for a while in the active state in order to anticipate subsequent transmissions. This habit consumes an amount of energy that should not be neglected. For example, in one of their experiments, the energy consumption of downloading 50KB over the 3G interface with a HTC Fuze [76] phone was measured. The results showed that 80% of the total energy consumption was the tail energy. As will be shown later in this report, this is the very same case of LTE, where the tail energies are of high importance.

The disadvantage of the two models described above is that the power consumption in a MT changes significantly with each MT. At the same time, a common practice among all these models consists of neglecting the energy consumed in the transitions between states. Such assumption has been confirmed by different authors [77], [78].

2.8.3 Power Tutor

As it has already been mentioned, the particular characteristics of each MT heavily affect the power consumption of such device. Therefore, any energy model used in a VHO decision algorithm should take this issue into consideration as far as possible.

A possible solution to do it consists of using an Android application called PowerTutor, available for free in Google Play [79]. Researchers from the University of Michigan in collaboration with Google Inc. proposed this tool in a paper published in 2010 [80]. Thanks to this application, it is possible to accurately estimate real-time power consumption for both cellular interfaces and Wi-Fi. The authors claim that the accuracy of the application is excellent, with at most 2.5% error for 10-second intervals. This application was specifically designed for the HTC G1 [81], HTC G2 [81], and Nexus One [82] phones, so it is expected that the accuracy will decrease in other Android phones.

This application has already been used by other researchers which needed information regarding the power consumption of Android devices such as Zahid et al. [9]. Two captures of this interface in a Samsung Galaxy SII [83] can be observed in the next figure.

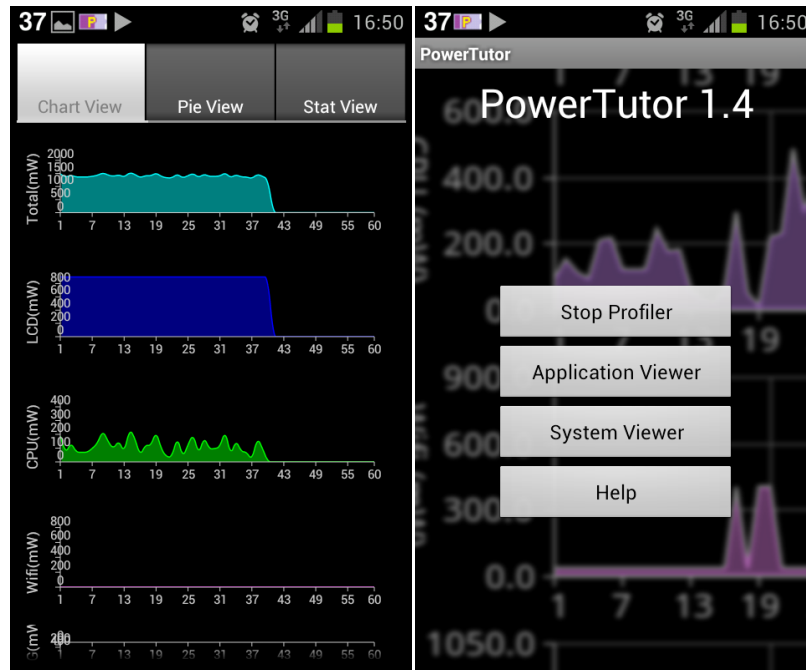


Figure 2-1, PowerTutor captures

2.8.4 Power Consumption of Tasks Unrelated to VHOs

In order to be able to judge if VHOs can save significant amount of energy for the MTs or User Equipments (UEs) it is necessary to obtain a general idea regarding how many Joules are actually significant for a UE nowadays. With this purpose in mind, listed below can be found an example of how much energy several activities in a UE consume. With the help of the Android application Power Tutor [79], such energy is calculated manually for a Samsung Galaxy SII [83]. Hence, these are the studied parameters:

- Total battery life (1650 mAh, 3.7 V [83]): $1.650\text{Ah} \times 3.7\text{ V} \times 3600\text{s/hr} = 21978\text{ J}$
- Screen –brightness 100%: $\sim 800\text{ mJ/s}$ (5 minutes = 240 J)
- Screen –brightness 50%: $\sim 300\text{ mJ/s}$ (5 minutes = 90 J)
- Music reproduction: $\sim 400\text{ mJ/s}$ (30 minutes = 720 J)

Taking these into consideration, in following sections it will be leveraged how significant the potential achievable energy savings are. Such will not be considered really important if they are under the several tens of Joules.

3 Method

In order to explore the potential energy savings by means of VHOs, the approach that has been followed has consisted of first assessing what an optimal access network choice would be when given very accurate information about the network load and future demand from applications running in the terminal. It was believed that starting from this initial oracle like assessment would help to identify the most important context information that could be used by the handover algorithm. The next step is to design realistic algorithms with respect to signaling and/or estimation of the relevant information. Where the relevant information was identified in the first step.

In cellular networks the decision about which cell a UE should connect to is typically based on the measured strength of some downlink reference signal. The network may also implement different policies about which cell UEs should connect to for example based upon offsets between the cells or by signaling to the UEs to change cell. Signaling one or more UEs to change cell can be used for the purpose of load balancing. Here we consider a scenario where the UE controls where it chooses to connect. The main reason for assuming that the UE has control is that currently the UE controls switching on and off its Wi-Fi and cellular radio interfaces. However, this choice of the locus of control will have implications on the criteria used to select the network to which the UE will attempt to connect to. Rather than optimize this network selection from a global perspective the UE will optimize its own perceived utility. This optimization can be based on both the expected link QoS and the expected remaining battery life time. Our goal is to minimize the terminal's energy consumption while maintaining the desired link QoS. This requires knowledge of the characteristics of the expected traffic, the expected radio coverage, and the expected energy consumption of the different interfaces if they were to be used for connectivity. Another factor that is critical to the performance of each interface is the load of the cell of the network to which the UE would connect. At high load the resulting throughput over the network in this cell for each user will be lowered if an additional UE connects to this cell, which leads to a lower energy efficiency for all the UEs in this cell.

To determine the most suitable interface for specific services we will use models of the energy consumption of the Wi-Fi and LTE interfaces. The actual energy consumption depends on many factors, such as the implementation of each interface and the UL and DL traffic service characteristics of the particular traffic that will utilize the newly selected interface. Since different terminals use different components the energy consumption will vary between them. In the extreme, an accurate model would have to be generated individually for each terminal model. Moreover, network parameters can have a significant impact on the energy consumption, for example the configuration of the DRX (Discontinuous Reception) parameters, beacon intervals, scheduling, and power control. Therefore, it is not obvious how detailed the model must be while remaining practical to use. Therefore, one task is to investigate how sensitive the handover decision is to the details of the energy model. Based on this sensitivity analysis we can design solutions that may use simple default models, application level measurements, or even component level hardware measurements depending on how important the accuracy of the model is.

Several models of the energy consumption of Wi-Fi and 3G interfaces have been published in the literature. However, for LTE not many models are yet available. We will utilize the model presented by Huang in 2012 [65] as starting point. This model is derived from application level measurements of two different LTE handsets and it is explained in detail in section 3.2. For the uplink power model, the work of Huang will be complemented

with the two papers presented by Bjoern Dusza et al. about energy efficiency in LTE devices [66], [67]

The potential for an energy aware vertical handover algorithm will be evaluated by means of simulations. A heterogeneous radio environment with LTE macro cells, Wi-Fi APs and moving UEs will be used. The radio models used are in agreement with those defined by the 3GPP [84]–[86].

3.1 Services Considered

The proposed vertical handover algorithm is connection-triggered. The term connection will be used repeatedly in this report. The concept of a (logical) connection involves the arrival/request to the UE for any of the targeted services. When such a request is made, the UE will decide if it should change RAT or not. This choice will depend on the environmental conditions and on the particular characteristics of the requested service.

The specific services that have been chosen because they represent a large fraction of a smartphones' usage nowadays [87] and because they represent distinct traffic behaviors. Nevertheless, the models and simulator can be used to analyze any other kind of traffic (given the details of the traffic model).

In the following sections the VHO decision criteria for each one of the target services will be studied, as well as how the decision criteria changes with the different characteristics of each service. How each service has been modeled will be covered in detail in subsequent sections.

The services that will be targeting in our studies are: VoIP Calls, High Quality Video Calls, High Definition Video Calls, File Uploads, Web Browsing, and Downloads. Each of these will be treated in detail in section 0.

3.2 Energy Model

The characterization of the interfaces of interest from an energy consumption point of view is one of the key parts in any VHO algorithm. It is essential to estimate how much energy will be spent when using each type of interface in order to determine which interface is preferable.

Therefore a model for each interface's energy consumption is proposed in this thesis. As a starting point, the work performed by Huang et al. and presented in [65] has been used. In their work, they aimed to study the performance and power consumption characteristics of 4G LTE networks. To do this they describe in detail the LTE Radio Resource Control state machine, propose a power model for an LTE interface, and make real world measurements and tests to determine the parameters of their model and whether the model was suitable. Afterwards, they compare their LTE results with models of interface for other existing networks; specifically 3G and Wi-Fi, and they draw some conclusions regarding how the different networks behave both in terms of performance (characterized by throughput) and power consumption.

Nevertheless they did not study VHOs and therefore the transitions between interfaces were not covered. The power consumed turning on and off each interface is not mentioned nor is the power control of the LTE interface described. Therefore, in this thesis we will address these neglected issues.

3.2.1 LTE State Machine

The experience with 3G UMTS networks has made clear that the Radio Resource Control states are important to look at when considering energy consumption. The relevance of the Radio Resource Control states has not changed with 4G networks.

Figure 3-1 illustrates the Radio Resource Control state machine in a LTE network. There are some small differences in this figure from the figure presented in [65]; as the Associating state has been added to deal with access network discovery and association with an eNB and the promoting time is treated here as another state. Details of these states are described in Table 3-1.

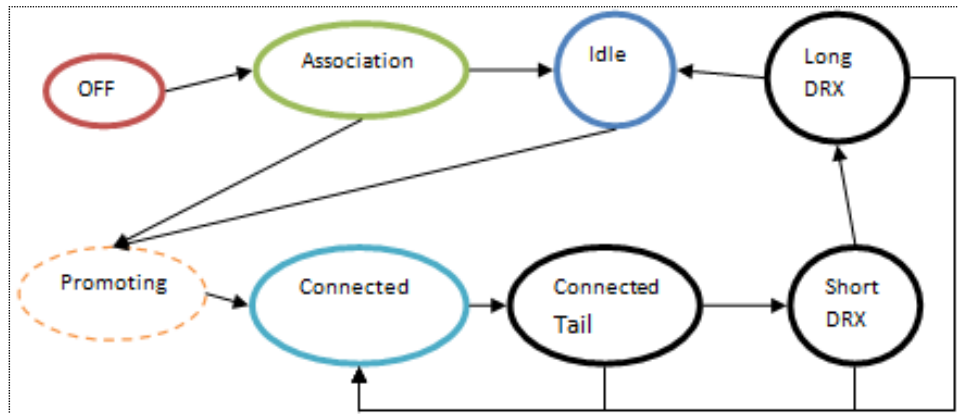


Figure 3-1 LTE States' Machine

Table 3-1: LTE terminal states

Off	The LTE interface is powered off. At some point it will be turned on and immediately the interface will go to the <i>associating</i> state.
Associating	While a UE is in the associating state, it is looking for an available eNB to connect to and it is trying to connect to it. If a network originated connection request arrives while the UE is in this state, the connection will be lost*. This state's timeout includes: time to turn the interface on, time to look for an accessible eNB, and the time needed to authenticate to the eNB.
Idle	A UE stays in the idle state while it is inactive. Most of the time while in the idle state the UE is in sleep mode; the rest of the time it wakes up to look for paging signals, i.e. connection arrivals from the network. If a connection arrives, the UE will transition to the <i>promoting</i> state.
Promoting	A UE enters in the promoting state when it was in the idle state and a connection request arrived. The UE will transition to the <i>connected</i> state after a certain period of time. This time required for this state transition represents the signaling time the network needs to assign the proper resources to the UE (i.e., a period of signaling processing).
Connected	While there is a connection ongoing, the UE stays in the connected state. Once the connection has terminated, the UE will transition to <i>connected tail state</i> .

* Note that if the user initiates the connection it should not be a problem for the UE to handle it although there would be some delay.

Connected tail	When a connection has terminated the UE enters in the connected tail state. If no connection has arrived after the connected tail timeout, then the UE will move to the short DRX state, otherwise it will return to the <i>connected state</i> . This state is similar to the <i>idle state</i> as it has a cycle time and an <i>on time</i> .
Short DRX	When the <i>connected tail</i> timeout expires, the UE enters in this state. If a request arrives before the timeout of this state, the UE will go again to the <i>connected</i> one; otherwise it will go to <i>long DRX</i> .
Long DRX	When the <i>short DRX</i> timeout expires, the UE enters in this state. If a request arrives before the timeout of this state, the UE will go again to the <i>connected</i> one; otherwise it will go to <i>idle</i> . The timeout of this state can be very long compared to Wi-Fi depending on the configuration of the network.

In all the states other than the *associating* state, if the LTE signal is lost, then the UE will lose connectivity and it will have to look for an accessible eNB, i.e. enter the *associating* state. The transitions between states are considered to be immediate (i.e., the state transition time is zero milliseconds).

Most of the parameters associated with timeouts, the on times, the cycle times, etc. are configured by each network and can vary significantly. Nevertheless, in the simulations carried out in this Master's thesis project that the values measured in [65] will be the used, unless stated otherwise. It will not be forgotten though that such parameters can change, taking it into consideration when drawing conclusions from these simulations.

3.2.2 Wi-Fi State Machine

The different states in the Wi-Fi networks are presented in Figure 3-2. These states are not explained more in greater detail because they are similar to the LTE states, with the exception that here there are no DRX states. The same observations made in the LTE case apply here.

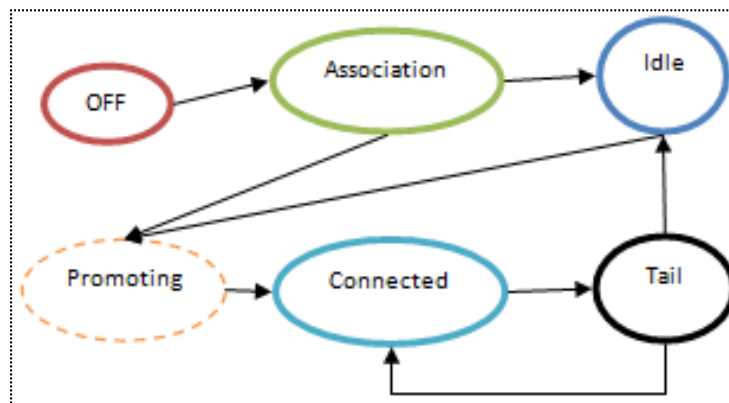


Figure 3-2 Wi-Fi State Machines

3.2.3 LTE/Wi-Fi State Machine

A similar approach to that in [88] has been followed. In order to perform a VHO, we assume that a UE is able to maintain the two interfaces in an active state, i.e. not in the *off* state, for some time and that the two state machines just described will run independently and concurrently. As a result some new states will be introduced. In the next paragraphs several examples are used to illustrate how this has been done.

If a Wi-Fi-connected UE perceives a SINR below a certain threshold for all of the WLAN APs, the UE will perform a VHO to LTE:

If the UE was in the idle state, it will go through the following states:

idle_Wi-Fi + associating_lte
idle_lte.

If the UE was in a connected Wi-Fi state, then it will go through these states:

connected_Wi-Fi + associating_lte,
connected_Wi-Fi + promoting_lte,
connected_lte.

A major assumption has been made that is important to note at this point. If a connection arrives, i.e. a VoIP call arrives a file download occurs, or some other connection needs to be set up, then if the decision to make a VHO is made the connection will start in the **old** network. Once the new network connectivity is established, i.e. after the associating time + promotion time, the remaining portion of the call, download, or whatever will be performed via this new network (and interface). For example, if a Wi-Fi-connected UE is in the idle state and a download of 10 Mbytes needs to be made, then the device will decide if it is better to go back to LTE to perform the request, i.e. to make a VHO. If it does decide to do so, then the UE will go through these states:

idle_Wi-Fi (the download is requested →)
promoting_Wi-Fi + associating_lte,
connected_Wi-Fi + associating_lte,
connected_Wi-Fi + promoting_lte, and
connected_lte.

After the LTE association time, the Wi-Fi interface will be turned off and the rest of the download will occur through the LTE network. This decision of turning off the other interface (the Wi-Fi interface in this case) will be analyzed in following sections of the thesis. It is not so obvious that turning the interface off is better than leaving it in the *idle* state in terms of both energy and performance.

All of the possible states that a UE may be in are listed in Table 3-2.

Table 3-2: UE Power Model States

LTE States	Wi-Fi States	LTE + Wi-Fi States
Associating_lte	Associating_Wi-Fi	Connected_lte + Associating_Wi-Fi
Idle_lte	Idle_Wi-Fi	Connected_Wi-Fi + Associating_lte
Promoting_lte	Promoting_Wi-Fi	Idle_lte + Associating_Wi-Fi
Connected_lte	Connected_Wi-Fi	Idle_Wi-Fi + Associating_lte
Conneted_tail_lte	Tail_Wi-Fi	Promoting_lte + Associating_Wi-Fi
Short_drx		Promoting_Wi-Fi + Associating_lte
Long_drx		Conneted_tail_lte + Associating_Wi-Fi
		Short_drx + Associating_Wi-Fi
		Long_drx + Associating_Wi-Fi
		Tail_Wi-Fi + Associating_lte
		Connected_Wi-Fi + Promoting_lte
		Connected_lte + Promoting_Wi-Fi

3.2.4 LTE Uplink Transmission Power Control

A very significant difference between LTE and Wi-Fi is the presence of the Transmit Power Control in LTE. This algorithm defined in the 3GPP TR 36.213 [89] defines the emitted power by the UE as the following:

$$P_{Tx} = \min (P_{max}, P_0 + 10\log_{10} M + \alpha \cdot PL + \Delta_{TF} + f) \text{ [dBm]} \quad (3-1)$$

Where:

- P_{max} is the maximum transmission power allowed for LTE. It depends on the UE power class; 23 dBm for class 3 UE [90]
- P_0 is cell specific; it can be seen as the target power received by the eNode-B [91], or as the reference power per PRB for the case of no Path Loss (PL) and no additional offsets [67].
- M is the number of physical resource blocks (PRB) allocated to the UE
- α stands for the path loss compensation factor. It is cell-specific.
- PL is the downlink path loss measured by the UE. It usually includes the shadow fading effects [92].
- Δ_{TF} is an offset specific to each UE/cell which depends on used the Modulation and Coding Scheme (MCS)
- f is an additional closed loop command from the eNodeB [91].

It can be easily deduced that the average consumed power by a LTE device is a function of its transmit power. As the previously presented formula suggests, such power depends both on the PL and on the number of allocated resource blocks.

At the same time, the achievable uplink throughput depends on the SNR at the eNode-B since, depending on it, a different MCS will be chosen. This SNR at the eNode-B is given by the following formula:

$$SNR \text{ [dB]} = P_{Tx} \text{ [dBm]} - PL \text{ [dBm]} - N \text{ [dBm]} \quad (3-2)$$

Where:

- P_{Tx} is the UE transmitted power introduced before
- PL is the uplink path loss
- N is the noise level

Extensive laboratory measurements on this achievable throughput in the uplink are made in [67]. Considering that they use a very similar parameters set up to the one used in this Master's Thesis, their conclusions are of high interest. Such configuration will be presented and explained in more detail later in the report. Nevertheless it is firstly introduced in Table 3-3.

Table 3-3: LTE Uplink important Parameters

Parameter	Value
Carrier frequency	847 MHz
Target SNR	30 dB
Channel bandwidth	10 MHz
Modulation and Coding scheme	Variable
Fast Fourier Transform (FFT) size	1024
Allocated PRB	50

With such a parameter configuration, they were able to observe that, for an Additive White Gaussian Noise channel, the maximum achievable throughput is 21 Mb/s obtained with SNRs above 25 dB. At the same time, they noticed that the throughput decreases quite fast with the SNR until the 7dB which is the minimum signal to noise ratio to establish a connection in the uplink. They also made these measurements for an Extended Pedestrian A Fading channel –defined in the 3GPP TS 36.104 [93], and observed a decrease of the achievable throughput of about 66%. This could be due to the fact that the device, i.e. a USB

stick, is not designed to work well in mobility cases.

These authors have conducted simulations regarding LTE devices' energy consumption in the uplink as well, which are presented in [66], [67]. They realized that, depending on the number of allocated PRB and on the transmitted power, a LTE device can be in *low* and *high* power mode. While in low power mode, the measured LTE devices consume an average of 1.5 J/s; in high power mode it grows with the transmission power from 2 J/s [66].

An important assumption made in this thesis is that in low power mode, the Transmit Power Control is able to compensate both the PL and the different interferences in the uplink. This implies that the effective SINR-throughput for this case is ~ 1 . The target SNR in the uplink will be set up to 30 dB; which is a value strong enough to support this assumption. Figure 3-5 shows that the SINR-throughput efficiency is indeed 1 for SINR above the ~ 23 dB.

They also noticed that for distances below 1 km and for the simple Additive White Gaussian Noise channel, the energy consumption per bit is almost constant [67]. In the scenario studied in this Master's Thesis, the LTE inter site distance will be 350 meters, so this assumption will be taken as a simplification.

3.2.5 Energy Model for data transmissions

To quantify the power model used during data transfers, Huang et al [65] proposed a linear model for both Wi-Fi and LTE. This model has the form:

$$P \text{ [J/s]} = \alpha_u t_u + \alpha_d t_d + \beta \quad (3-3)$$

Where:

- t_u is the uplink throughput,
- t_d the downlink throughput,
- α_u is a measured parameter; different for each RAT,
- α_d is a measured parameter; different for each RAT, and
- β is a measured parameter; different for each RAT.

This linear model is one of their most important contributions. It is important to note that they distinguish between data rates of the uplink and downlink. This formula describes the energy consumed when the UE is in the connected state (both for the Wi-Fi and LTE interface). Huang et al. conducted experiments to verify the accuracy of this model and observed an error of less than 6% with real applications.

There are some important considerations to note at this point. The downlink and uplink throughputs depend both on the amount of resources the network has assigned to the UE and on the radio channel conditions. Under ideal conditions, the UE would download/upload at this assigned speed. Nevertheless, for each particular environment's conditions, i.e. interference, shadow fading, etc., the perceived SINR will likely decrease and consequently the effective download/upload throughput will decrease as well. This will be discussed further in following sections.

In Wi-Fi there is not any power control system and hence the measured values and the proposed model by Huang et al. have been used.

This model is not so accurate for LTE though due to the presence of the Transmit Power Control; explained in section 3.2.4. With the values measured by Huang et al. of $\alpha_{u,LTE}$ and β_{LTE} , the average energy consumption (mJ/s) and the energy efficiency per bit (mJ/bit) by the UE is given by the following formulas:

$$E [\mu\text{J/bit}] = 0.438 + \frac{1,288}{\text{Throughput (Mb/s)}} \quad (3-4)$$

$$E [\text{mJ/s}] = 438 \cdot \text{Throughput} \left(\frac{\text{Mb}}{\text{s}}\right) + 1288 \quad (3-5)$$

As it was already mentioned, such measures were taken in unknown radio conditions (allocated PRB, distance to the eNode-B, etc.) probably from a single location, so it is not possible to know if the UE was in high or low power mode. However, comparing these measures to the ones in [67] and in [66], it is possible to state that, most likely, these values were taken when the transmission power were close to the maximum and hence the device was in the high power mode. Considering that the average upload throughput they obtained was 5.6 Mb/s, the distance between UE and eNB was probably quite big as well (>1km).

The transition from the low to high power mode heavily depends on each LTE device, on each network allocation policies and parameters and on the particular environmental conditions; it is therefore very difficult to predict. Considering this, along this report both modes will be studied independently.

For the high power mode, the model proposed by Huang et al. will be used. In this high power mode, the Transmit Power Control is no longer able to compensate the PL and therefore the effective upload throughput will decrease. How it will do so depends on the SINR at the eNode-B.

On the other hand, for the low power mode, the work of Dusza et al. will be the one used. In such mode, in [66] was shown that the average power consumed for the measured devices is in the interval of 1.4 to 1.6 J/s, depending on the uplink transmit power per PRB (given by formula 3-1) and on the number of allocated resources. Even though the LTE handset employed by Dusza et al. (Samsung GT-B 3730 [94]) is not the same than the one used by Huang et al., as a simplification, it is assumed that they have comparable consumption in this low power mode. Hence, a constant value of 1.5 J/s will be used.

Finally, the energy models employed for data transmission are summarized in the following figure:

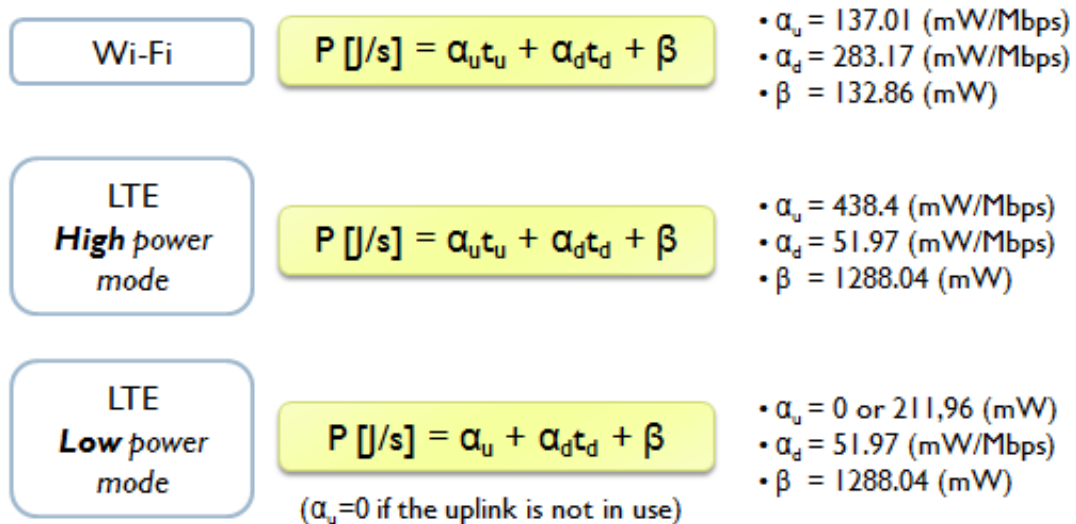


Figure 3-3: Energy Model for data transmissions

3.2.6 Energy Model Parameters Summary

The different parameters used in the energy models are presented in this section. Most of them were estimated in [65]. These parameters were measured for two different LTE handsets –Samsung Galaxy S [95] and Motorola Atrix [96], with the help of the Monsoon power meter [97] and averaged over repeated samples. It is not specified in the paper, but such samples seem to be taken from a single location, which means the averaging covers only a small range of channel conditions.

As was explained at the beginning of chapter, these parameters can significantly change from device to device, with different networks, for each interface configuration, etc. How much these potential variances may affect the VHO decision process will be examined later in this thesis.

The cited parameters are presented in Table 3-4 and Table 3-5. Some of them were also extracted from the work of Lampropoulos et al. [88].

Based upon these tables, certain conclusions can be drawn. The first and most important one is the fact that Wi-Fi idle is much less power consuming than LTE's idle mode. A simple calculation gives us the amount of energy in mJ/s via each network while in idle mode:

$$P_{\text{idle_Wi-Fi}} = \text{idle_on_power_Wi-Fi} * (\text{idle_on_time_Wi-Fi} / \text{idle_cycle_Wi-Fi}) = \mathbf{1.9 \text{ mJ/s}}$$

$$P_{\text{idle_lte}} = \text{idle_on_power_lte} * (\text{idle_on_time_lte} / \text{idle_cycle_lte}) = \mathbf{20.1 \text{ mJ/s}}$$

As a result we can see that when being inactive using only the Wi-Fi interface is more than 10 times less power consuming than when in idle mode and using the LTE interface. Considering that most of the time the UE is inactive, the UE should utilize the Wi-Fi interface as much as possible. This is a very important observation.

Another conclusion is that apparently the Wi-Fi interface is more energy efficient for transmission of large amounts of data. This will be studied in more detail later in the thesis.

Another observation is the large tail energy differences, with the tail time in LTE being huge when compared to that of Wi-Fi (around 11 seconds compared to 240 milliseconds).

Table 3-4: Wi-Fi Energy Model Parameters

PARAMETER	VALUE
Turn on	24 mJ
Turn off	29 mJ
Associating time	2 s
Associating power	120 mJ/s
Promotion power	124.4 mJ/s
Promotion duration	0.08 s
Tail power	119.3 mJ/s
Tail timeout	0.24 s
Idle on power	77.2 mJ/s
Idle off power	0 mJ/s
Idle on time	0.0076 s
Idle cycle	0.308 s
α (download)	137.01 (mJ/s) /Mbps
α (upload)	283.17 (mJ/s) /Mbps
β	132.86 mJ/s

Table 3-5: LTE Energy Model Parameters

PARAMETER	VALUE
Turn on	24 mJ
Turn off	29 mJ
Associating time	1 s
Associating power	250 mJ/s
Promotion power	1210.7 mJ/s
Promotion duration	0.260 s
Connected tail power	1060 mJ/s
Connected tail timeout	0.1 s
Short DRX on power	1680.2 mJ/s
Short DRX on time	0.001 s
Short DRX off power	0 mJ/s
Short DRX cycle	0.02 s
Short DRX timeout	0.02 s
Long DRX on power	1680.1 mJ/s
Long DRX on time	0.001 s
Long DRX off power	0 mJ/s
Long DRX cycle	0.04 s
Long DRX timeout	11.46 s
Idle on power	594.3 mJ/s
Idle off power	0 mJ/s
Idle on time	0.0432 s
Idle cycle	1.2802 s
α (download)	51.97 (mJ/s) /Mbps
α (upload –high power mode)	438.39 (mJ/s) /Mbps
α (upload –low power mode)	211.96 mJ/s
β	1288.04 mJ/s

3.3 Simulation Environment

The proposed VHO algorithms will be tested by means of simulation in a heterogeneous radio scenario with both LTE and Wi-Fi networks. In this scenario, certain mobile UE's will be placed and certain services will be utilized. The power models previously described will be used to quantify and to study how the different networks behave in terms of energy consumption.

Two different scenarios will be studied: an indoor and an outdoor scenario. The differences between each of them are described later in this section. In both cases, the simulated area represents a heterogeneous radio environment with both LTE and Wi-Fi networks, where the mobile UE receives specific connection requests. It is assumed that there is always LTE availability. All LTE cells have the eNB antennas placed above the rooftops to provide coverage, they are therefore considered as macro cells.

As was previously described, the most important input to the power models are the effective throughputs for the down and uplink.

3.3.1 Downlink Effective Throughput

The downlink effective throughput depends on the spectrum resources assigned to the UE by the network and on the perceived SINR. In real world environments the VHO algorithm can figure out such throughput by simply measuring and it will not care how this throughput is actually achieved and/or why it is higher or lower than it might expect. The UE can then make a VHO decision based upon the *measured* throughput. This will make it possible to implement the VHO algorithm without detailed knowledge about network load and detailed radio channel information.

However, the effective throughput and assigned resources must be modeled in the simulator. The following paragraphs describe how this issue has been approached.

Firstly, each network will provide the UE with a certain percentage of its available resources. For example, in a 1-user LTE network with resources corresponding to a maximum cell throughput of 80Mb/s, a UE that wants to perform a download will be assigned 100% of the resources, i.e. it would get a throughput of 80Mb/s in ideal channel conditions. This is called the *assigned throughput*.

In an ideal scenario, the UE would be able to make use of all these assigned resources and hence download at the associated throughput. However, the actual throughput will depend upon the SINR perceived by the UE; hence the UE will only be able to use a certain portion of the assigned resources. This proportion is given by a so called *Waterfall Curve*, which represents the achievable throughput as a function of the SINR. These curves are gotten as a result of a dynamic choice of the MCS depending on the SINR.

For the case of Wi-Fi these curves were extracted from the work of Katrina L. LaCurts in her Master's Thesis "*Measurement and Analysis of Real-World 802.11 Mesh Networks*" [98], where measurements of real IEEE 802.11b/g scenarios were made. In the case of LTE, the curves proposed in the 3GPP models [84]–[86] have been used. These curves are presented in Figure 3-4. Note that these curves depend on several factors such as the class of the UE or the number of antennas available for MIMO.

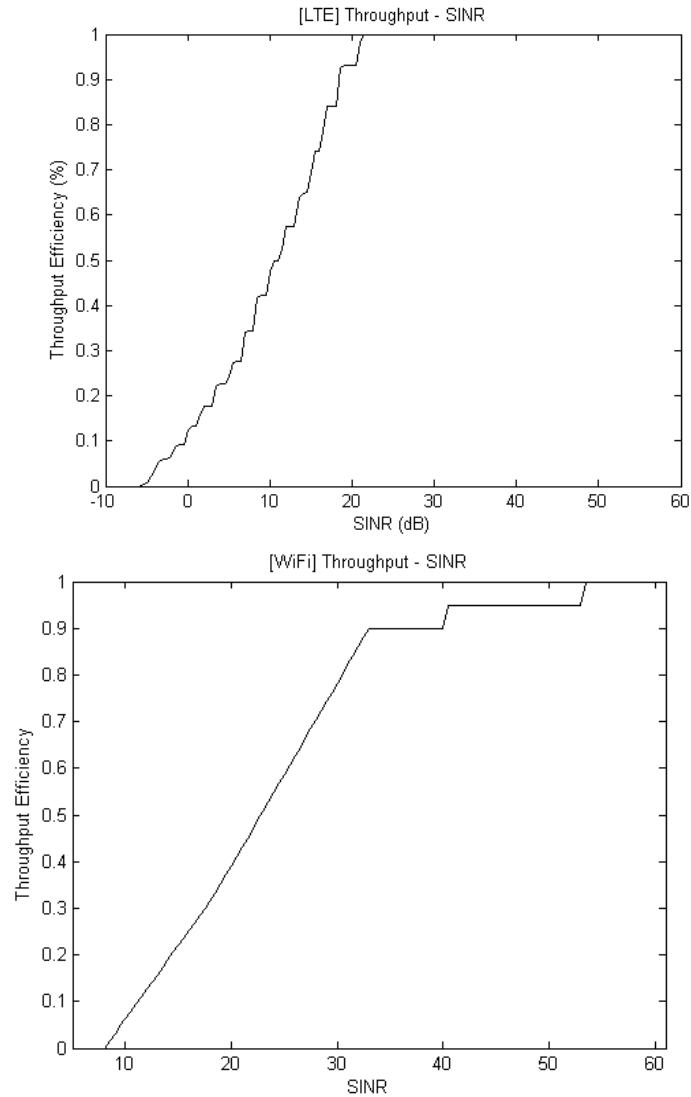


Figure 3-4: Waterfall Curves – LTE & Wi-Fi

As was just explained, measuring the SINR is a very important part of configuring the simulation environment. In order to do so, the first task is to calculate the Received Signal Strength (RSS) of each eNB for the case of LTE, and for each AP in the case of Wi-Fi. For this purpose radio propagation models are used. Their details can be found in subsections 0 and 3.3.5. Once these models have been obtained the SINR is easily calculated using the formula:

$$\text{SINR} = \text{RSS} - \text{Interference} - \text{Noise} \quad (3-6)$$

Where:

- RSS is the transmitted power from the eNB or AP to the connected UE, minus the propagation and penetration loss.
- Interference is the sum of the RSS of the other eNBs or APs,
- Noise is base noise level.

We assume that there is no interference between the LTE and the Wi-Fi network since they operate at different frequencies.

3.3.3 Uplink Effective Throughput

An analogue technique will be used to estimate the effective upload throughput. There are some small differences though.

Regarding the Wi-Fi network, the same waterfall curve as in the downlink is used. This simplification can be taken thanks to the fact that both links use the same frequency band and transmission scheme. At the same time, noise and interferences are assumed to be statistically the same and the transmission power of both the APs and the UEs is set equal. Hence, the SINR value is taken as the same as the one measured in the downlink, leading to the same throughput efficiency.

On the other hand, these assumptions cannot be made for LTE. The waterfall curve is now obtained thanks to the measures made in [67] and it is presented in the next figure.

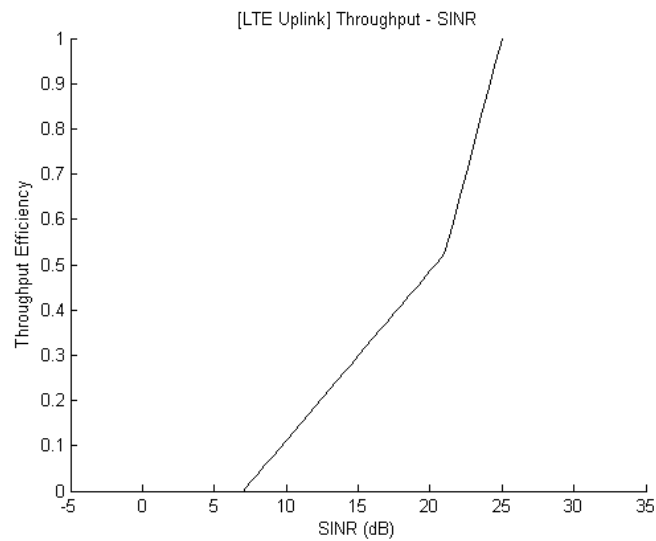


Figure 3-5: LTE Uplink Waterfall Curve

The interferences in this case are also different. They are now defined by the RSSs at the eNBs from the background active users. These active users can vary a lot with the time and hence a simplified model where these interferences will be considered constant has been used. The value chosen has been 20 dB as the total amount of interferences, i.e. the sum of the RSSs at the eNBs from all the background active users. Finally, the SINR changes as well since the transmission power of the eNBs and the UEs is not the same, neither the noise.

3.3.4 LTE Propagation Model

The LTE propagation model was built according to the model proposed by 3GPP in the technical reports TR 36.814 [84], 36.822 [85], and 36.839 [86].

Worth mentioning is the shadow fading model. A log-normal variable with mean 0 and standard deviation σ is used. This shadowing model is common for both LTE and Wi-Fi. The value of this standard deviation depends on the specific environment. How variances in this parameter affect the VHO decision algorithm will be covered later in the thesis.

The specific values used for each one of the previously described parameters are explained in detailed in following sections.

3.3.6 Wi-Fi Propagation Model

A logarithmic distance path loss model [99], [100] in combination with the shadow fading model described in the previous section is used to describe the radio signal propagation of Wi-Fi. Such a model is defined by the following formula:

$$P_{rx} \text{ (dBm)} = P_{r_0} - 10 \cdot \gamma \cdot \log_{10} \frac{d}{d_0} - X_{\sigma} \quad (3-7)$$

Where:

- P_{rx} is the RSS by the UE
- P_{r_0} is the power received at the reference distance d_0 (normally 1 meter). It is calculated using the Friis transmission equation, which is presented in the next paragraph.
- γ is the path loss exponent which depends on the environment conditions. The cases of interest are urban outdoor environments and indoor environments. More details regarding this value are given in following sections.
- X_{σ} is a log-normal variable with mean 0 and standard deviation σ which represents the shadow fading attenuation.

The Friis free space transmission equation is the following:

$$P_{r_0} = P_{tx} + G_{tx} + G_{rx} + 20 \cdot \log_{10} \frac{\lambda}{4\pi d_0} \quad (3-8)$$

Where:

- P_{tx} is the transmitted power by the AP
- G_{tx} and G_{rx} are the antenna gains in transmission and reception respectively, which would correspond to AP and UE respectively for the DL
- λ is the wavelength of the transmission, i.e. $300000000/\text{frequency}$.

The specific values used for each one of the previously described parameters are introduced in the next section.

3.3.7 Network Parameters

Some important parameters in the simulated scenario are listed below. In the case of LTE, the 3GPP recommendations were followed [84]–[86] and the typical and standard parameters were used. A similar approach was followed for the parameters in Wi-Fi where standard values have been used in order to represent a typical Wi-Fi scenario.

Table 3-6 and Table 3-7 show the most important parameters for LTE and Wi-Fi respectively in the simulated scenario.

Note that the maximum transmit output power for Wi-Fi APs in Europe is defined by the European Telecommunications Standards Institute (ETSI) [101] as 17 dBm. This work will use 14.47 dBm.

Table 3-6: LTE Network Parameters

PARAMETER	VALUE
Transmission power density per channel	43 dBm
Channel bandwidth	10 MHz
Maximum number of allocated PRBs per time slot	50
Inter site distance	350 m
MIMO	2x2
UL/DL MCS	Variable
FFT Size	1024
Maximum downlink throughput per PRB	730 kb/s
Maximum uplink throughput per PRB	420 kb/s
UE maximum transmitted power	23 dBm
Uplink target SNR	30 dB
Sectors per site	3
Number of macro cells	57
Antenna height	32 m
Antenna electrical tilt value	19 degrees
Antenna gain at main direction	14 dBi
Horizontal aperture angle of the antenna	70 degrees
Vertical aperture angle of the antenna	10 degrees
Power Control α	0.8
Shadow fading standard deviation	8 dB
Shadow fading correlation distance outdoor	50 m
Shadow fading correlation distance indoor	10 m
Penetration Loss (eNB outdoor – UE outdoor)	0 dB
Penetration Loss (eNB outdoor – UE indoor)	20 dB

Table 3-7: Wi-Fi Network Parameters

Parameter	Value
APs transmission power	28 mJ / 14.47 dBm
AP Transmission antenna gain	0 dB*
AP Reception antenna gain	0 dB*
Maximum bandwidth	48 Mb/s
UE transmission power	14.47 dBm
UE's SINR sensitivity	8 dB
UE Transmission antenna gain	0 dB*
UE Reception antenna gain	0 dB*
Shadow fading standard deviation	8 dB
Shadowing reference distance	1 m
Shadow fading correlation distance outdoor	50 m
Shadow fading correlation distance indoor	10 m
Path loss exponent outdoor	3 [100]
Path loss exponent indoor (distance between AP-UE <5)	1.7 [100]
Path loss exponent indoor (distance between AP-UE > 5)	5 [100]

* Antenna gains already covered in the transmission power in both the AP and the UE

3.3.8 Network Representation

Figure 3-6 presents the network topology. The red dots represent the LTE eNBs. The blue stars are the Wi-Fi APs. All distances are in meters. The right part of the figure is a zoom of the Wi-Fi AP of interest (where the analyzed UE will be placed in following sections; it will be placed in the center of the simulated area). The circle around this Wi-Fi AP represents a 20 meter perimeter.

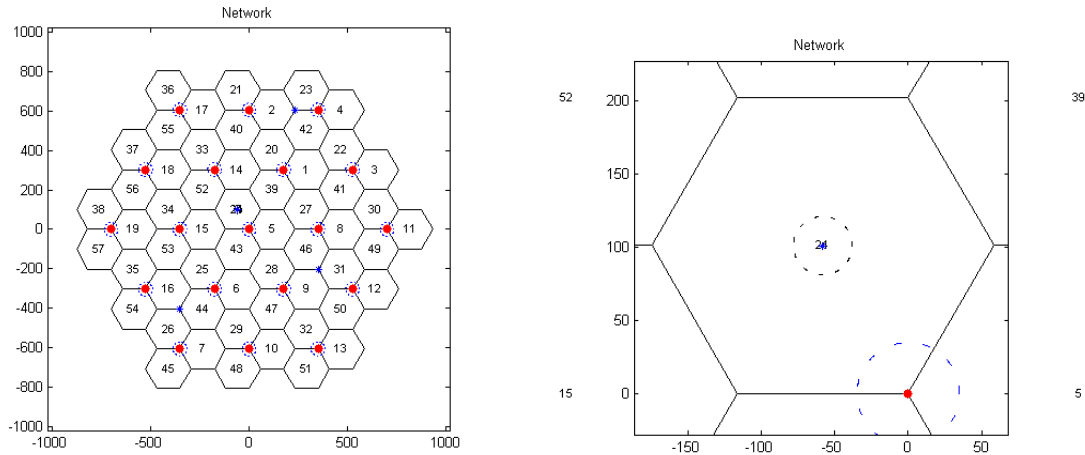


Figure 3-6: Network Topology.

Unless explicitly stated otherwise, in all the experiments shown in the following sections of the thesis shadow fading will **not** be considered (hence a standard deviation of 0 is used). This is not true in a real scenario, but due to the random nature of the fading attenuation this is the best way to analyze the behavior of the energy model and of the propagation models. Later in the thesis there will be specific sections which study the effects this random shadow fading generates in the different situations that are analyzed.

3.3.8.1 Outdoor Scenario

As was already explained, two scenarios where potential VHOs may occur will be studied. The first one is an outdoor scenario, where eNBs, APs and UEs are all placed outdoors. This section introduces the network topology for this case and the coverage area of the different networks.

Figure 3-7 shows the coverage area in terms of SINR for both networks. The figure is formed by four graphs:

1. In the first one the LTE downlink SINR distribution is presented.
2. In the second one the LTE uplink SINR distribution.
3. In the third graph, the black part represents the area where there is only LTE downlink coverage and the green part the area where there is both LTE and Wi-Fi coverage.
4. Finally, the last graph shows the Wi-Fi coverage and its SINR distribution. The Wi-Fi coverage for the outdoor case is **~50 meters** with the parameters described above.

Note that LTE coverage means a SINR greater than -5 and 7 dB in the down and uplink respectively and Wi-Fi coverage means a SINR greater than 8dB. The color bars are in dBs and the distances in meters.

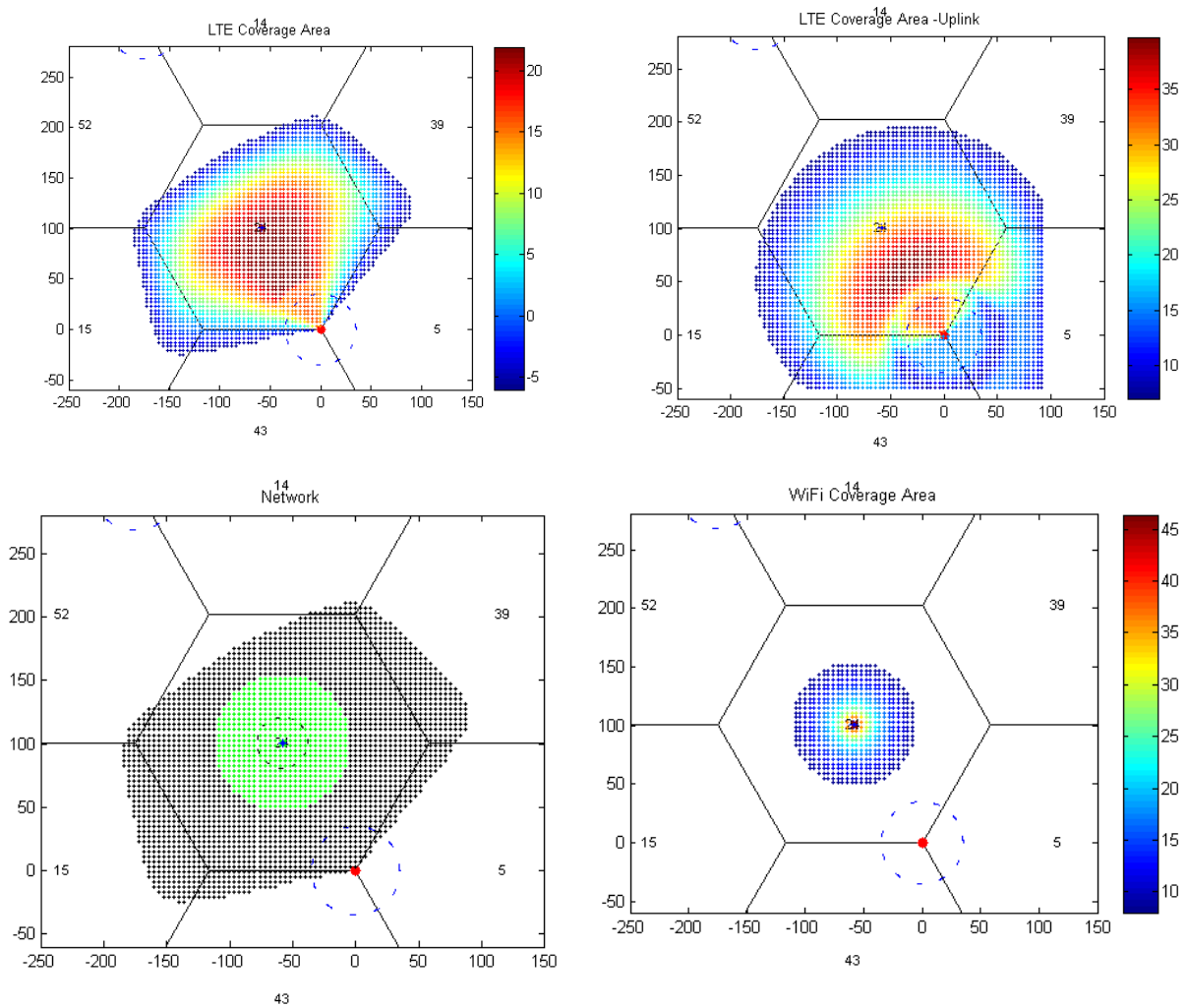


Figure 3-7: Outdoor coverage areas – colors scales in dBs

3.3.8.2 Indoor Scenario

In the indoor case, the Wi-Fi AP and the UEs are indoors while the LTE macro cells are outdoors. Figure 3-8 shows the Wi-Fi coverage in this case. Note that the SINRs figures for LTE do not change from the previous section and hence are shown here again. The Wi-Fi coverage for this new outdoor case is ~ 10 meters.

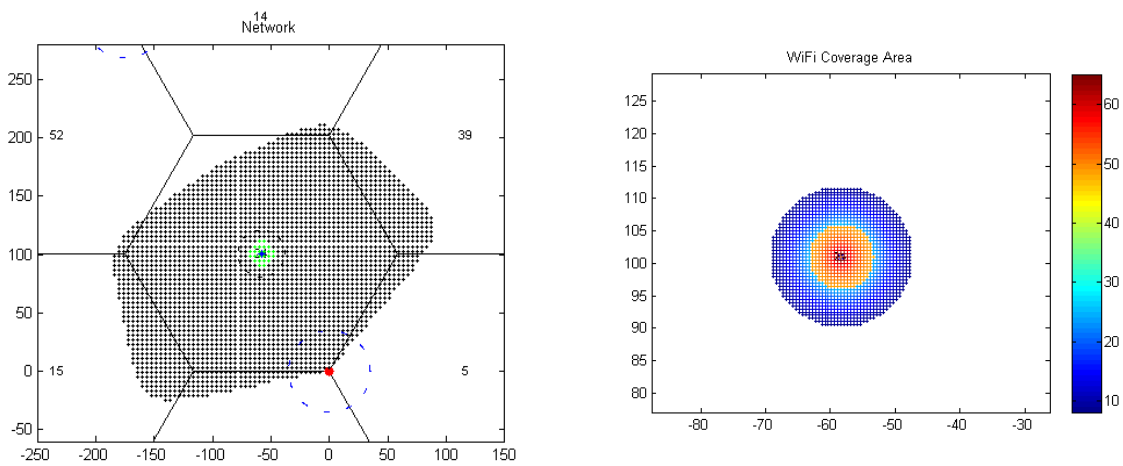


Figure 3-8: Indoor coverage areas– colors scales in dBs

3.3.9 Shadow Fading Effects

This section shows how the random nature of the shadow fading attenuation affects the results. The next figures show each network's coverage area for different values of the standard deviation. Only the outdoor scenario is shown here, but similar behavior is found for the indoor case.

In the shadow fading model used, there are two main parameters that affect its behavior:

- Standard Deviation
- Lognormal fading correlation distance

A value of 25-50 meters is accepted as a standard value for the lognormal correlation distance outdoors and a value of 10 meters indoors [86]. In contrast, the standard deviation depends heavily on the specific environment and it can range from 3 to 12 dB [100]. An average value is 8 dB. This value is recommended by the 3GPP [86].

The following subsections describe how the random nature of the shadow fading affects the coverage areas and the uniformity of the LTE or Wi-Fi availability. Three cases are represented with low, average, and high standard deviation. Only the LTE downlink is shown in this section; a similar behavior is expected for the uplink.

Looking at these graphs, it is fair to say that predicting how long the Wi-Fi availability will last in an unknown physical environment is very difficult, especially if the user is moving. Although the radio environment may look quite similar at the same place over time, the spatial changes in the radio channel become more frequent and harder to predict. This observation will be of great importance in the development of the VHO.

The legend of the figures in the next subsections is the following:

- | | |
|--------|------------------------------|
| Green | Both LTE and Wi-Fi coverage |
| Black | Only LTE coverage |
| Yellow | No coverage from any network |
| Blue | Only Wi-Fi coverage |

3.3.9.1 Low Shadow fading: standard deviation of 5dB

The four different simulation runs produced quite different results. These four graphs correspond to a standard deviation of 5 dB in both networks. All of these figures came from simulations with *exactly* the same parameters, but due to the random nature of the shadow fading attenuation, the coverage areas were different for each run.

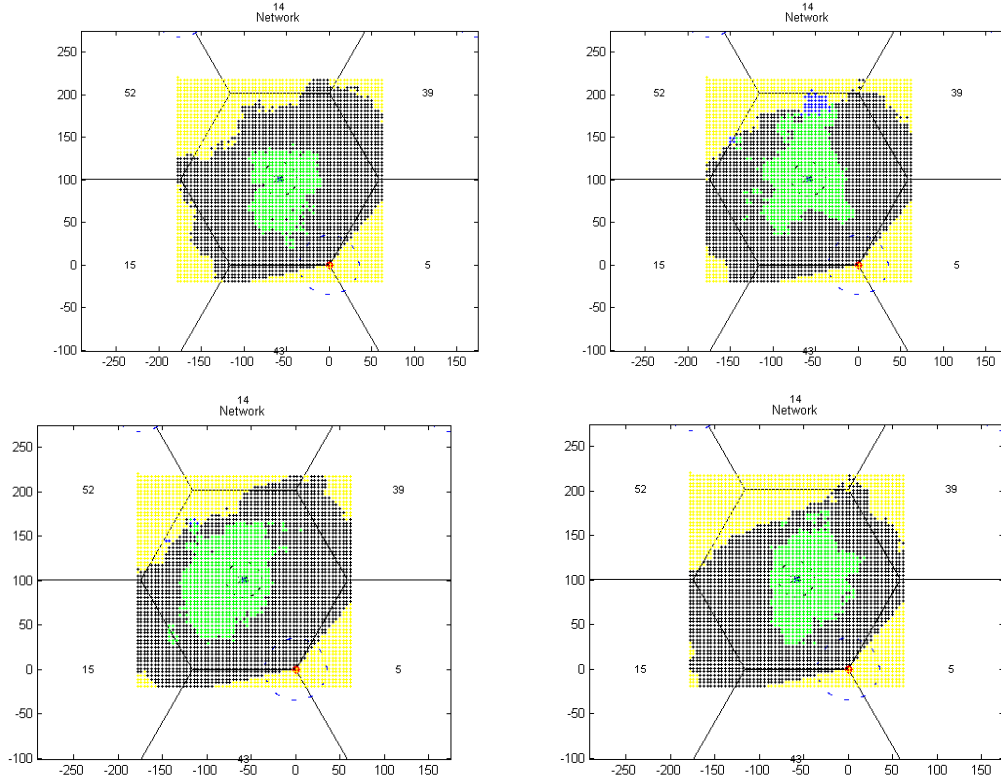


Figure 3-9: Outdoor [Shadow Fading] 5 dB Standard Deviation

3.3.9.2 Average Shadow fading: standard deviation of 8dB

Again four different simulation runs produced quite different results. These four graphs correspond to a standard deviation of 8 dB in both networks. All of these figures were from simulations with exactly the same parameters, but again due to the random nature of the shadow fading attenuation, the coverage areas changed with each run.

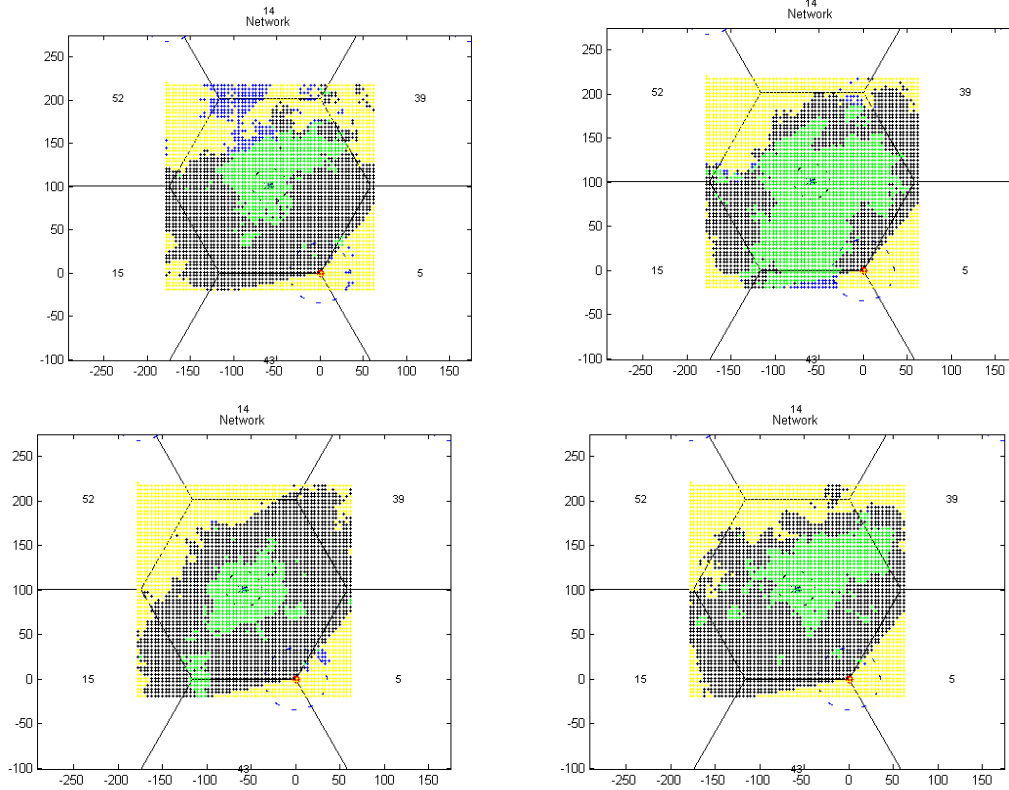


Figure 3-10: Outdoor [Shadow Fading] 8 dB Standard Deviation

3.3.9.3 High Shadow fading: standard deviation of 12dB

In this case the four different simulation runs also generated quite different results. These graphs correspond to simulations with a standard deviation of 12 dB in both networks. All the figures came from simulations with exactly the same parameters, but again due to the random nature of the shadow fading attenuation, the coverage areas changed with each run.

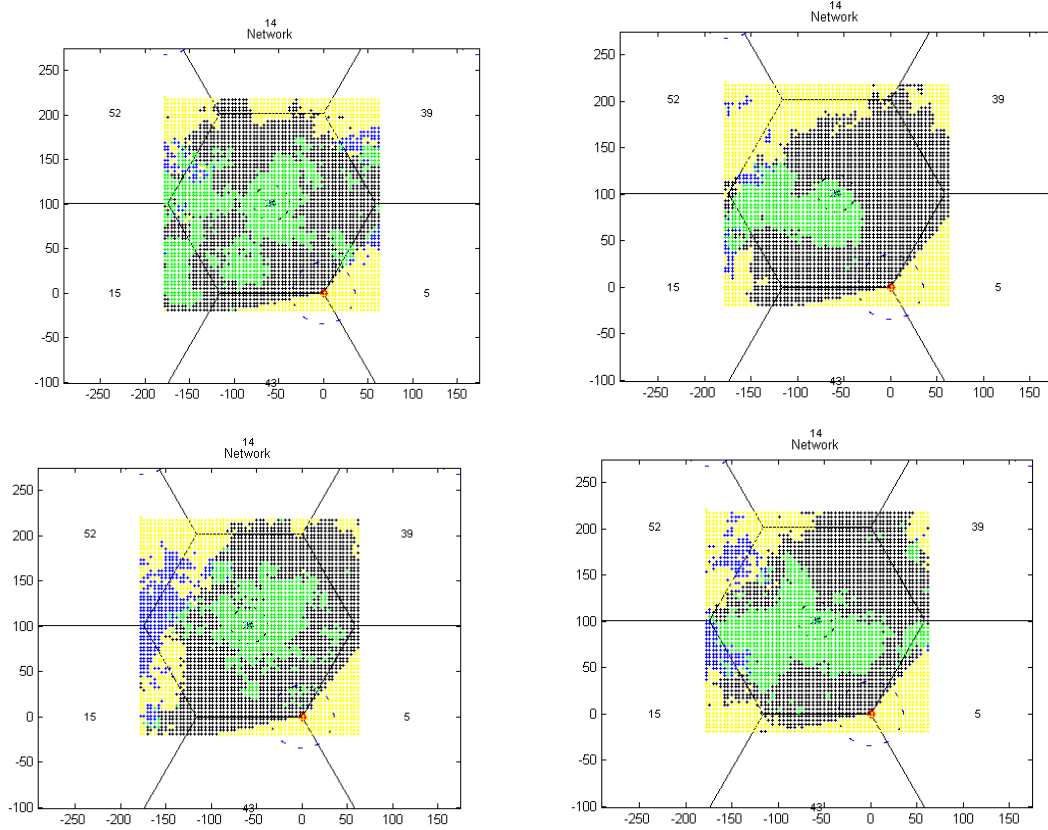


Figure 3-11: Outdoor – [Shadow Fading] 12 dB Standard Deviation

3.4 Real World Expected Scenarios

The power model suggests that being inactive in Wi-Fi is much less energy consuming than in LTE. Therefore, it is fair to say that a UE should connect via its Wi-Fi interface as soon as it is able to, if energy saving is the main goal. The veracity of this statement will be evaluated in later sections; however, it will be taken for granted in the next paragraphs.

With this assumption in mind, the VHO decision will almost always need to be taken in one of the situations shown in Table 3-8: Four VHO scenarios. Note that situations where, when a connection arrives, the UE is connected to LTE and there is already Wi-Fi availability at the same time, are not possible given the described situation: if the Wi-Fi AP was available before the connection request, the UE would have already connected to it.

One observation to be made here concerns the fact of turning the LTE interface off. It is not so clear that will be entirely possible in fourth generation networks and hence this alternative scenario is treated in detail in section 4.11.

Table 3-8: Four VHO scenarios

VHO Scenario	Description
1	The UE is inactive and connected to LTE. It starts moving and at some point it begins to perceive a Wi-Fi AP's signal. When the UE considers that this signal is strong and stable enough, it will change to Wi-Fi.
2	The UE is inactive and connected to Wi-Fi. At a certain instant a connection arrives and the UE must decide whether to utilize Wi-Fi or change to LTE. Here it is important to take into account that in most cases the UE will want to come back to Wi-Fi (if a VHO was actually made) once the transaction is finished*.
3	The UE detects that it may lose Wi-Fi coverage (due to low RSSI for example). A vertical handover will then be made to LTE regardless of whether the UE is inactive or not.
4	During a connection a LTE-connected UE begins to perceive a Wi-Fi AP's signal. If the AP is regarded as stable enough, then it can decide to move to Wi-Fi before the connection is finished.

* Ideally, the LTE would turn off the LTE interface right after the transaction is finished to return to idle in Wi-Fi. However, it is common that the network maintains blocks of resources for this UE until the long DRX timer expires. This may lead to poor resource management in the networks and must be addressed in the future.

3.4.1 VHO Scenario 1

The main task to perform in this scenario consists of detecting the Wi-Fi network as energy-efficiently as possible. It will be necessary to determine at the same time that this network is sufficiently stable so as to avoid an undesirable ping-pong effect. This process will be described in following sections as “acknowledging an accessible and stable Wi-Fi AP”. How to address this issue is covered in detail in section 4.10.1.

3.4.2 VHO Scenario 2

The decision of making or not making a VHO can depend on a variety of factors, such as interference, the load on the network, the bandwidth allocation policies of the operator, or the physical characteristics of the scenario. Hence, when a connection request arrives at the UE, these parameters must be considered. In order to do so, these parameters must be measured (perhaps periodically) or they must be measured when the connection is requested. More details regarding how and when to measure these parameters are given in section 0.

3.4.3 VHO Scenario 3

A detailed study regarding when to leave the Wi-Fi network depends on the speed of the mobile and on the characteristic of the network and device is presented in section 4.9.1.

3.4.4 VHO Scenario 4

Using the same approach as in the third scenario, a detailed study concerning when the Wi-Fi network is stable and good enough to connect to is performed in section 4.9.2.

4 Analysis

After describing the tools and scenarios that will be used, the potential energy savings of VHO are presented in this chapter.

In all but the last of the following subsections, the VHO scenarios described in Table 3-8 will be the ones being considered. A final section will cover the situation where a UE cannot turn the LTE interface off. It will be shown how, in such a case, the potential energy savings due to VHOs decreases significantly; nevertheless it represents a very interesting study for mobile network operators who may be very interested in offloading certain traffic into Wi-Fi networks.

In the following sections it will be discussed how the load of the network, the quality of the signal, the type of service, etc. affect the VHO decision and the potential energy savings. Before going into detail, it is important to make a small observation regarding the load of the LTE network. As presented in Table 3-6, the maximum number of usable PRBs per time slot for a 10 MHz bandwidth is 50. Each LTE network operator will allocate these PRBs depending on the cell's load and policies; giving more or less than 1 PRB to each UE in average (in a specific time slot it would give at least 1 PRB). This allocation is described in following sections as the "assigned resources" for the UE. For example, if the assigned resources are 10%, then the resulting maximum throughput would be the maximum throughput of the network multiplied by 0.1. The maximum throughput of the network is the total number of PRBs multiplied by the maximum throughput per PRB.

For both Wi-Fi and LTE networks, in the case of fair allocation bandwidth, 10% of assigned resources would mean that there are 9 additional active users at this moment. In the case of LTE, 5 PRBs would be allocated to each of these users.

Finally, note that in the LTE uplink power model, the number of PRBs influences in the transmitted power. Since the total number of PRBs in the configuration considered is 50, it will be assumed that, if the amount of assigned resources is lower than 2%, this number is 1; otherwise it will be the closest whole number to $50 \times \text{assigned resources}$ (rounded up). For example, for 31% of assigned resources, the number of PRBs is $50 \times 0.31 = 15.5 \rightarrow 16$ PRBs.

4.1 Turning off the old interface

Any VHO involves the change from one radio access technology to another one. A question arises here: Is it better to turn off the old network or to leave it in the idle state? There are some situations where the answer to this question is very clear. For example, if the UE is inactive and it decides to make a VHO because being inactive in the other network is more energy efficient, then it would not make any sense to leave the old network on in the idle mode.

On the other hand, if a connection arrives to an inactive Wi-Fi-connected UE, it is possible that the UE decides to change to LTE to carry out the requested service. At the same time and taking into account that being inactive in Wi-Fi is much more energy-efficient, it is very likely that the UE will want to return to using Wi-Fi once the transaction is finished, then the answer to the question is not so obvious.

* Note that the possibility of performing the requested service using both interfaces in parallel is out of the scope of this thesis. In such case, the performance would probably be increased as would the power consumption.

Leaving the Wi-Fi interface on in idle mode would imply extra energy consumption during the transaction time, but it would save as well the extra energy spent turning the Wi-Fi interface off and then on and during a new AP discovery and association process. Hence, depending on the transaction time and on the energy model parameters, the answer to the question will change.

At all times the UE will have to decide which alternative is less energy-consuming. This decision consists simply of comparing the consumed energy if it is left on to the energy that would be consumed if it is turned off:

If it is left on, the amount of power (in watts = joules per second) is the product of the energy consumed (in joules) while in idle mode by the Wi-Fi interface and the transaction time in seconds. As has already been mentioned in earlier sections, this Wi-Fi idle power depends on the network configuration (cycle time, on time) and on the UE characteristics (on power). Nevertheless we will assumed as values those measured in [65], which makes this power 1.9mJ/s*.

If the Wi-Fi interface is turned off, the power consumed would be the power to turn it off, to turn it on, and to find and associate again with an AP. Again these parameters change with each network and UE. The standard values used and already presented are the following: 24mJ (turn Wi-Fi on) + 29 mJ (turn Wi-Fi off) + 120mJ/s * 2 seconds (AP discovery and association), which makes a total of 293 mJ.

There is another factor to include in this sum, as during the 2 seconds the UE needs to find and associate with the AP, the LTE is consuming some energy, as it transitions through the following states:

1. Connected tail: $\text{connected_tail_timeout} * \text{connected_tail_power}$
2. Short DRX: $(\text{shortDRX_on_timeout} / \text{shortDRX_cycle}) * \text{shortDRX_power}$
3. Long DRX: $(\text{longDRX_on_timeout} / \text{longDRX_cycle}) * (2 \text{ seconds} - \text{connected_tail_timeout} - \text{shortDRX_on_timeout})$

Using the values reported by Huang et al., the total amount of the energy is 479.64 mJ. Hence given these values, we conclude that when the transaction time is going to be shorter than $479.64/1.9 = 252$ seconds (4.2 minutes), then it is more energy efficient to leave the Wi-Fi interface on.

Note that there is another possible scenario related to the previous one. It involves a situation where the Wi-Fi coverage is lost during the transaction. If the UE had decided to leave the Wi-Fi on during such a transaction, then all that idle energy was consumed needlessly. Unless it is explicitly stated, this situation will be neglected in following sections since it is considered that, if a UE has acknowledged a Wi-Fi AP, that this AP will remain available long enough to finish the transaction.

4.2 Idle Evaluation

As has already been discussed, simply by looking at the energy model it is possible to assert that being inactive in Wi-Fi, i.e. being in the *idle* state, is much more energy efficient than being in the idle state for LTE. In fact, it is more than ten times more efficient according to Huang, et al.[65]:

* Calculation already made in section 3.2.6 *Parameter Summary* and made again the next section 4.2 *Idle Evaluation*.

$$P_{\text{idle_Wi-Fi}} = \text{idle_on_power_Wi-Fi} * (\text{idle_on_time_Wi-Fi} / \text{idle_cycle_Wi-Fi}) = \mathbf{1.9 \text{ mJ/s}}$$

$$P_{\text{idle_lte}} = \text{idle_on_power_lte} * (\text{idle_on_time_lte} / \text{idle_cycle_lte}) = \mathbf{20.1 \text{ mJ/s}}$$

This difference makes it clear that it is better to be inactive when using Wi-Fi. Hence, if a LTE-connected UE acknowledges the presence of an accessible and stable Wi-Fi AP, it would be logical to perform a VHO and to change to using the Wi-Fi interface. Nevertheless that change would involve the consumption of some energy that would not be spent if the UE continued to utilize the LTE interface: the expected saved energy must be greater than the extra energy consumed for the change.

This extra energy consists of the following:

- Energy consumed in turning on the Wi-Fi interface +
- Energy consumed in turning off the LTE interface +
- Energy consumed during the AP discovery and association

At the same, the expected saved energy will depend on how long the UE stays inactive in Wi-Fi: the longer it does, the more energy will be saved. The following figure shows exactly how much energy is saved as a function of the time the UE remains inactive in Wi-Fi.

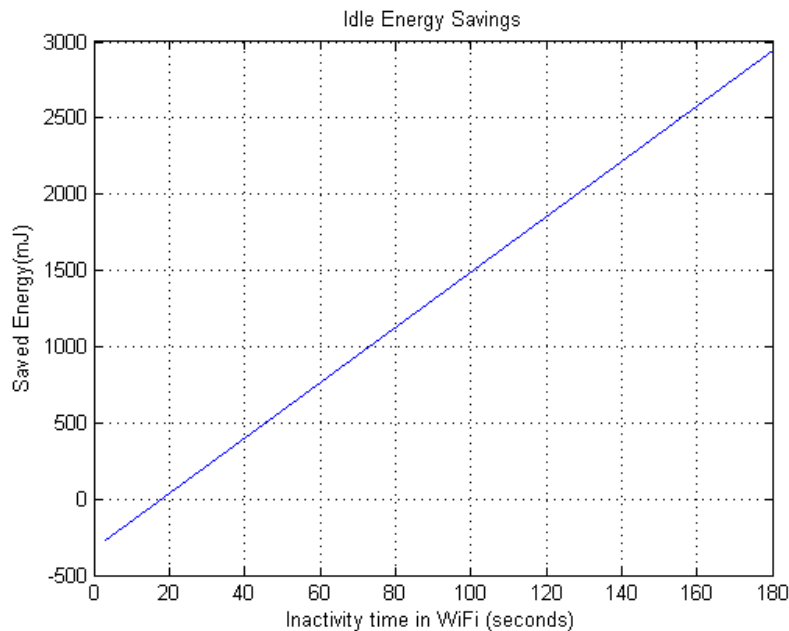


Figure 4-1: Idle energy savings; standard situation

This figure considers a scenario where the Wi-Fi AP discovery and association time is 2 seconds with an average consumed power of 120 mJ/s and the energy required to turn on the Wi-Fi interface and to turn off the LTE one are 24 and 29 mJ respectively. This figure shows that it is worth changing to Wi-Fi if the inactivity time is going to be longer than **18.2** seconds.

A much less favorable situation is shown in the Figure 4-2. In this scenario, the Wi-Fi AP discovery and association time is 4 seconds and the energy spent turning on the Wi-Fi interface is 48 mJ.

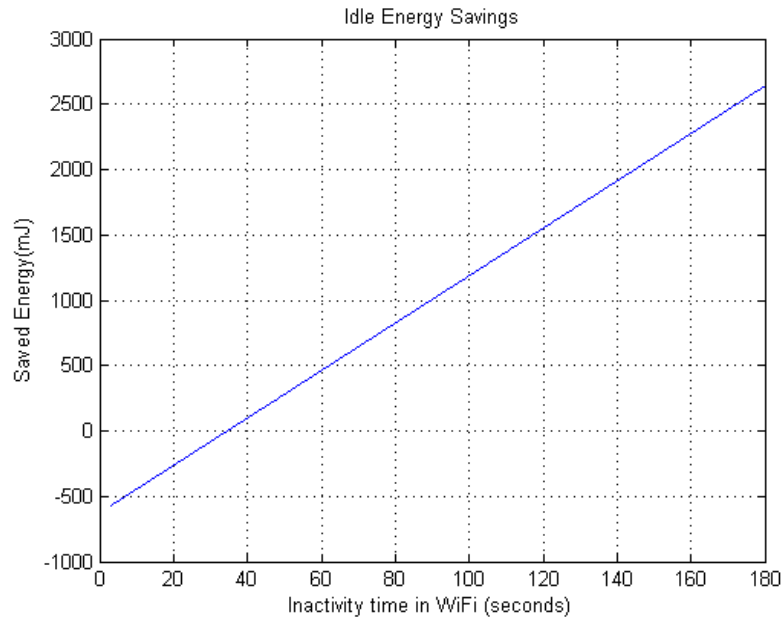


Figure 4-2: Idle energy savings; non-favorable situation

In this less favorable scenario, if the UE is only 34 seconds inactive in Wi-Fi, it will have already been worth the change in interface in terms of consumed energy. At the same time, if a Wi-Fi AP has been acknowledged as stable, then it seems safe to assume that it will remain available for much more than 34 seconds. In the literature it has been shown that most of the time UEs are actually inactive (around 70% of the time according to [53]), then in most cases no connection requests will arrive before those 34 seconds have elapsed. Hence, it can be stated that the most energy efficient decision is to **change to Wi-Fi as soon as possible** if the UE is/will be inactive.

There are two possible cases where this kind of VHO decision may occur. The first one occurs when a LTE-connected UE is inactive and at some point it acknowledges the presence of an accessible and stable Wi-Fi AP. In this case, the energy savings just shown are correct. It is also possible that a LTE-connected UE had just finished a connection and it has an acknowledged Wi-Fi AP, then the energy savings would be even greater due to the energy consumed in LTE during the connected tail, short DRX, and long DRX states.

4.3 VoIP Calls

The potential energy savings VHO can offer while making VoIP calls are studied in this section. VoIP calls have become very popular in smartphones and tablets. In fact the Android application for Skype [102](the world largest VoIP provider) is the third most popular application in Google Play [103] with millions of downloads every month.

In order to study how VHOs may help to save energy during VoIP calls it is necessary to model this type of service in order to include it in our simulated scenarios. These are the characteristics we have assumed for such a service:

1. In order to make a VoIP call, a UE will have to be able to transmit at a certain minimum throughput. The value of this required bandwidth changes within the used codec and bit rate [104]. According to the Skype Technical Support [105], the recommended throughput for calls is 100 kb/s and that will be the one used. Hence, the UE will need to have an effective throughput of 100 kb/s both in the up and downlink. At these rates the energy consumption is not so dependent on the data rates;

it is rather the active time that contributes most to the consumption. However, the simulation will be based on 100 kb/s.

2. For the downlink, the network will always assign to a UE that wants to make a VoIP call the necessary bandwidth for this UE to ensure the desired effective throughput, and no more. Obviously this assigned bandwidth will be equal or bigger than the effective throughput (100 kb/s). Note that the effective throughput (the 100 kb/s) is the input to the energy model as was explained in previous sections.
3. In the uplink, the UE will have to compensate for the loss of quality due to interference, path loss, and shadow fading. Hence, it will transmit at greater than or equal to 100 kb/s. How much faster will be determined by the uplink waterfalls curves described in section 3.3.2.
4. During a VoIP call, we assume that half of the time the user is using the downlink and the other half the uplink. This is achieved thanks to the use of the “Voice Activity Detection” (also known as silence suppression), which allows to prevent the transmission of silence packets [106].

4.3.1 Downlink and Uplink Limitations

The 100 kb/s limitation may not be achieved for two reasons: unavailable resources or insufficient SINR. For example, a UE with a SINR-throughput efficiency (obtained from the waterfall curves) of 0.5 would need the network to assign it resources corresponding to a bandwidth of 200 kb/s. However, if the available resources in the network are less, then the call will have to be rejected. Hence, depending on the load of the network (the amount of available resources) the UE will have to perceive a minimum SINR (have a minimum SINR-throughput efficiency) to be able to actually transmit at 100 kb/s.

As was explained in previous sections, the behavior of the up and downlink in Wi-Fi is the same. On the other hand, both the waterfall curve and the SINR change for LTE for each direction of the communication. Figure 4-3 shows how this minimum SINR changes with the load in both networks and for both the down and the uplink.

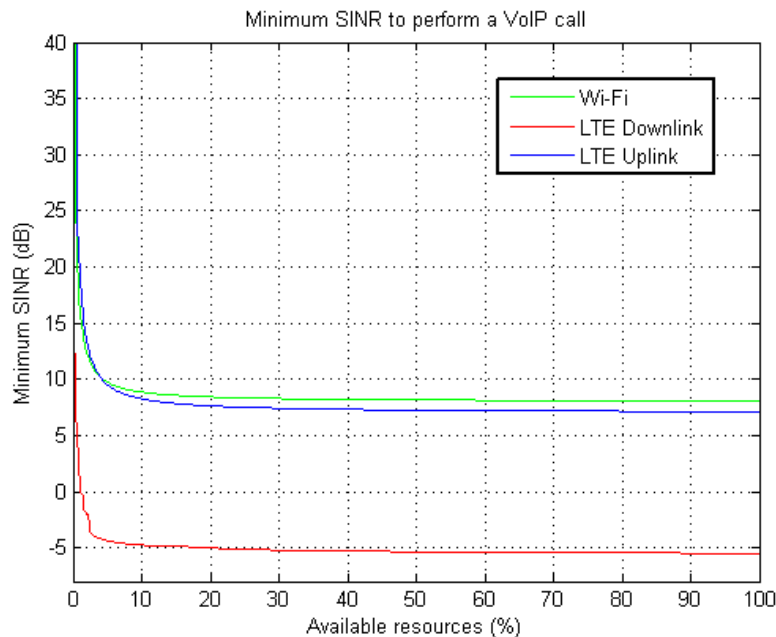


Figure 4-3: Min SINR to perform a VoIP

At this point is good to remember the minimum SINR to even have a connection in each network. For Wi-Fi, it is 8dB, for LTE downlink is -5 and for LTE uplink 7 dB. Observing the figure, it is possible to appreciate that only when the load of the network is above the 95%, does the necessary SINR need to perform a VoIP call differ from those values; and more over it does not significantly differ. Hence, a good signal is necessary with high loads, and with lower bit rate encodings even higher loads would not be any problem. In the case of a very high load it is therefore necessary to either have adaptive applications that reduce the rate by lower the encoding quality, or to use admission control to reject calls when an acceptable quality cannot be supported. The first of these approaches has been described in the Master's Thesis by Xiaokun Yi [107].

Another point to remember here is that we are assuming LTE is always available, i.e. that there is sufficient LTE SINR, so that VoIP calls will always be possible via LTE. For Wi-Fi, in order for the mobile to acknowledge and connect to an AP, its signal must be above a certain threshold, most likely greater than 2-3 dB above the minimum SINR to avoid a ping-pong effect.

4.3.2 VHO Decision: LTE uplink in “low power mode”

As has been discussed, the scenario of interest is the following: the user is connected to a Wi-Fi network and a VoIP call arrives. The UE must decide whether it should process the call in the Wi-Fi network or performing a VHO to LTE. In the following paragraphs this decision will be analyzed, along with the different factors and parameters that may change the outcome of this decision process.

Before performing the corresponding simulations, it is important to remember that in this “low power mode”, the energy consumption of the uplink in a LTE device is assumed constant (1.5 J/s, see section 3.2.5), regardless of the throughput, the number of PRBs assigned to the UE, or the SINR perceived at the eNB. At the same time, for the LTE downlink, the only input to estimate the energy consumption is the download effective throughput, which we will assume is constant for this type of service (at 100 kb/s).

Hence, for this “low power mode”, the energy consumption when making a VoIP call via the LTE interface varies linearly with the duration of the call. For a duration d , the energy consumed during the call via LTE would be:

$$\text{Energy LTE} = \frac{d}{2}(\text{s}) \cdot [\alpha_{u,\text{low,LTE}} + \alpha_{d,\text{LTE}} \cdot \mathbf{0.1} \text{ Mb/s} + 2 \cdot \beta_{\text{LTE}}] (\text{mJ/s}) = 1396,9 \cdot d(\text{s}) [\text{mJ}] \quad (4-1)$$

Where:

- d is the duration of the call in seconds, and
- $\alpha_{d,\text{LTE}}$ and β_{LTE} are the energy model parameters described in section 3.2.5. The value of 1.6 mJ/s was introduced in that section as well.

The same behavior occurs for the Wi-Fi interface, but the energy consumption only depends on the duration of the call:

$$\text{Energy Wi-Fi} = \frac{d}{2}(\text{s}) \cdot [\alpha_{u,\text{Wi-Fi}} \cdot \mathbf{0.1} \text{ Mb/s} + \alpha_{d,\text{Wi-Fi}} \cdot \mathbf{0.1} \text{ Mb/s} + 2 \cdot \beta_{\text{Wi-Fi}}] = 153,86 \cdot d(\text{s}) [\text{mJ}] \quad (4-2)$$

Where:

- d is the duration of the call in seconds, and
- $\alpha_{u,\text{Wi-Fi}}$, $\alpha_{d,\text{Wi-Fi}}$ and $\beta_{\text{Wi-Fi}}$ are the energy model parameters described in section 3.2.5

Hence, VHOs from Wi-Fi to LTE will only be made if the Wi-Fi is so loaded that it cannot process the call. Figure 4-4 shows the energy consumed during a call depending on the call's duration.

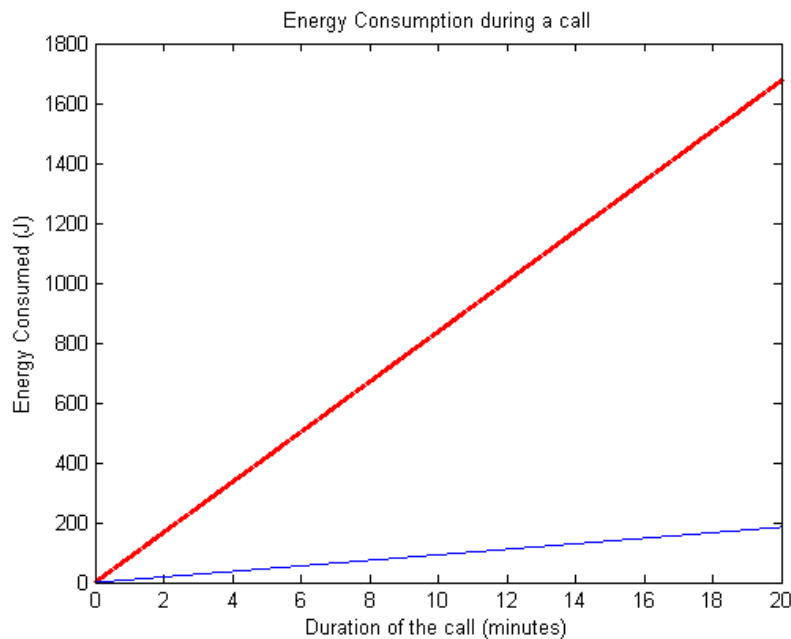


Figure 4-4: VoIP energy consumption; LTE in “low power mode”

There is another possible scenario worth mentioning. A call can easily last several minutes; during which time a LTE-connected UE may acknowledge the presence of an accessible and stable Wi-Fi AP. In this case the UE should consider making a VHO from LTE to Wi-Fi in the middle of the call. Such a VHO would imply some extra energy consumption that should be compensated for by the subsequent energy savings. This extra energy is due to the factors listed below and corresponds to 302.94 mJ with the current parameters and models. As discussed several times earlier in this thesis, this value can vary significantly with the networks' configuration, terminal, and environmental radio conditions. The relevant factors are:

1. Energy turning on the Wi-Fi interface (24 mJ)
2. Energy discovering and associating to the Wi-Fi AP (2 seconds * 120 mJ/s)
3. Energy in the Wi-Fi promotion state, necessary to establish the connection (124.4 mJ/s * 0.08 seconds)
4. Energy turning off the LTE interface (29 mJ)

The difference between the energy consumed in each network (~560mJ/s) per second is such that within 1 second of a call the extra energy (302mJ) is already compensated for. As a result VHOs from LTE to Wi-Fi are always advisable for VoIP calls.

4.3.3 VHO Decision; LTE uplink in “high power mode”

If the LTE is in “high power mode”, then the linear model proposed by Huang et al. and described in detail in section 3.2 is used. The effective throughput is still constant; hence the energy consumption will also be constant and can be expressed as:

$$\text{Energy LTE} = \frac{d}{2} (\text{s}) \cdot [\alpha_{d,\text{LTE}} \cdot \mathbf{0.1} \text{ Mb/s} + \alpha_{u,\text{LTE}} \cdot \mathbf{0.1} \text{ Mb/s}_{,\text{LTE}} + 2 \cdot \beta_{\text{LTE}}] (\text{mJ/s}) = 1312,5585 \cdot d(\text{s})$$

[mJ] (4-3)

Where:

- d is the duration of the call in seconds,
- $\alpha_{u,\text{LTE}}$, $\alpha_{d,\text{LTE}}$, $\alpha_{u,\text{LTE}}$ and β_{LTE} are the energy model parameter described in section 3.2.5.

For this kind of low data rate traffic the energy consumption in low and high power modes are almost the same, hence the same conclusions result: a UE should always switch to Wi-Fi when possible for a VoIP call.

4.4 High Quality Mobile Video Calls

Mobile video calls represent the next type of service that we will analyze. The popularity of this type of call has increased incredibly over the last 5 years and they have become a very popular service for smartphones and tablets. Some examples of service providers are Tango Mobile [108], Skype [102], and Google [109].

Tango Mobile offers a free video calling service over 3G, 4G, and Wi-Fi. Tango Mobile has more than 80 million active users. Skype, bought by Microsoft [63] in 2011 for \$8.5 billion, offers video calls and has already been downloaded 100 million times just for Android phones. Google offers a free video service, called Hangouts [111], which is able to support video conferences with up to 10 people.

The characteristics of this type of service are similar to VoIP calls. There are only two differences:

1. The required minimum and average rate are obviously greater since both voice and images are being transmitted. This rate depends on the quality of the video and may vary with each system or application. In this study we will considered a required throughput of 500 kb/s both in the up and downlink directions, which represents a face-to-face call with video of high quality, according to Skype’s Technical Support [105].
2. The second difference involves the up and downlink usage time. In this case both the up and down links are both active during the entire call.

The following subsections will analyze how VHOs may save energy for this type of traffic. Since this is a very similar service to the VoIP service introduced in the previous section, most figures and analysis are similar and hence some explanations are not given in detail.

4.4.1 Downlink and Uplink Limitations

As in VoIP calls, a high-quality video call may not be made if the load of the network is too high or if the quality of the received radio signal is insufficient. Figure 4-5 shows the minimum SINR needed given a certain amount of available resources, i.e. the minimum SINR to achieve an effective 500 kb/s throughput. Note that there are 3 lines in the figure: one for the LTE uplink that represents the minimum SINR at the eNB, one for the LTE downlink (SINR at the UE in a LTE connection), and one for the Wi-Fi communication which covers both up and downlink minimum SINRs*.

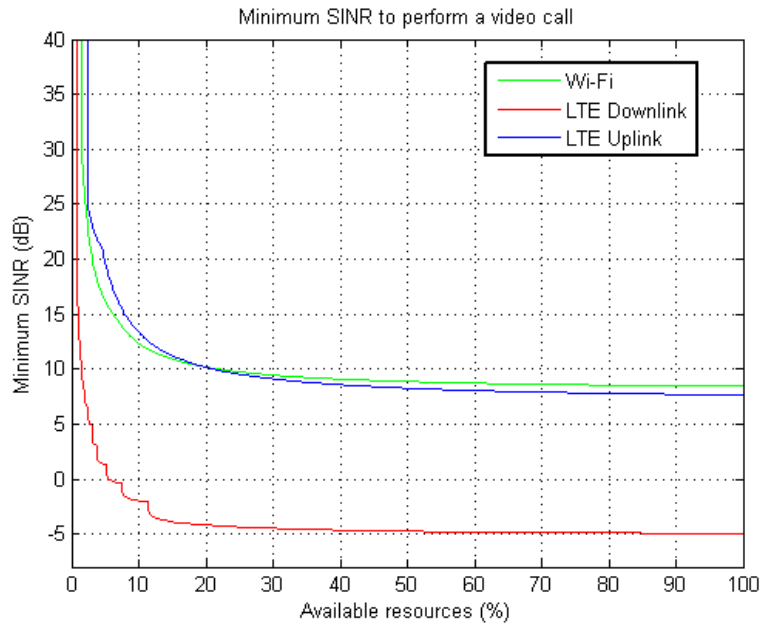


Figure 4-5: Min SINR to perform a video call

It is possible to appreciate in this figure that the network load is a more important factor than in for VoIP calls, as when the available resources are less than 20% the necessary SINR increases quite fast.

Via Wi-Fi a UE would need more than the 10% of the resources to make a high-quality video call if its SINR is less than 12.5 dB. Figure 3-7 and Figure 3-8 suggest that these may represent a significant fraction of the locations within the Wi-Fi coverage area.

In order to obtain a better idea of how important the load is for a video call, the positions where the Wi-Fi SINR is lower than 10 and 12.5dB are displayed in Figure 4-6, for the outdoor case. These two graphs correspond to shadow fading standard deviations of 0 and 8 dB, respectively. Note that the minimum Wi-Fi SINR needed to establish a connection is 8 dB and here it is being represented as being 10 dB. The reason for this has already been discussed and is due to the fact that a UE will leave a Wi-Fi network if its signal is below a certain threshold. This threshold will be 2 dB or bigger in most cases.

* As a simplification, the Wi-Fi SINR value in the up and downlink is considered equal as well as the waterfall curve in each direction. See section 3.3.2 for more details.

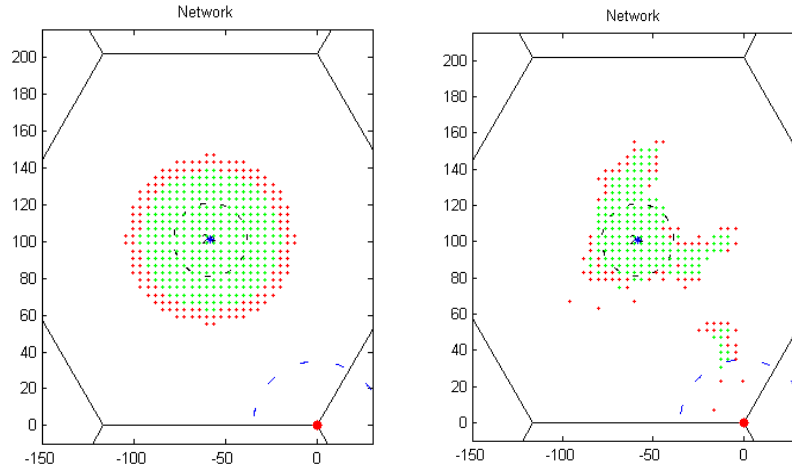


Figure 4-6: Positions where the Wi-Fi SINR is lower than 12.5 dB for standard deviations 0 and 8 dB; outdoor scenario

The red area represents the positions where the Wi-Fi SINR is between 10 and 12.5 dB and thus positions where the available resources would need to be larger than 10% to support a video call, and the green area the positions where the SINR is above 12.5 dB. Looking at the figure it is fair to say that these positions cannot be neglected, thus if the Wi-Fi network is significantly loaded (>90%), then there is a high possibility that a video call will be rejected, forcing the UE to make a VHO to LTE.

For the LTE downlink the load is not so critical: when the available resources are less than 5% the necessary SINR at the UE is still 0 dB. For the uplink, video calls are a bit more limited by the load of the network when the amount of interference is not low. As was shown in Figure 3-7, for 20 dB of interferences, the number of positions where the SINR is below 15 dB are significant; and the number of these positions will increase with the number of active users and hence the interference will increase as well.

In following sections it will be assumed that there are sufficient available resources to support the call. Given this assumption, the potential energy savings of performing a VHO will be studied.

4.4.2 VHO Decision: LTE uplink in “low power mode”

This section is analogous to section 4.3.2. The only difference is the required throughput (now 500 kb/s) and the uplink and downlink times. Hence, the consumed energy in LTE of a high-quality video call can be expressed as:

$$\text{Energy LTE} = d(s) \cdot [\alpha_{u,\text{low,LTE}} + \alpha_{d,\text{LTE}} \cdot 0.5 \text{ Mb/s} + \beta_{\text{LTE}}] \text{ (mJ/s)} = 1525,95 \cdot d(s) \text{ [mJ]} \quad (4-4)$$

Where:

- d is the duration of the call and
- $\alpha_{d,\text{LTE}}$ and β_{LTE} are the energy model parameter described in section 3.2.6

And energy for Wi-Fi is:

$$\text{Energy Wi-Fi} = d(s) \cdot [\alpha_{u,\text{WiFi}} \cdot 0.5 \text{ Mb/s} + \alpha_{d,\text{WiFi}} \cdot 0.5 \text{ Mb/s} + \beta_{\text{WiFi}}] = 342,9 \cdot d(s) \text{ [mJ]} \quad (4-5)$$

Where:

- d is the duration of the call in seconds and
- $\alpha_{u,\text{WiFi}}$, $\alpha_{d,\text{WiFi}}$ and β_{WiFi} are the energy model parameters described in section 3.2.5

As before, the energy consumed when using Wi-Fi is always smaller, hence VHOs to Wi-Fi may be made to save energy with this type of call. Figure 4-7 shows the total energy consumed as a function of the call's duration for both interfaces.

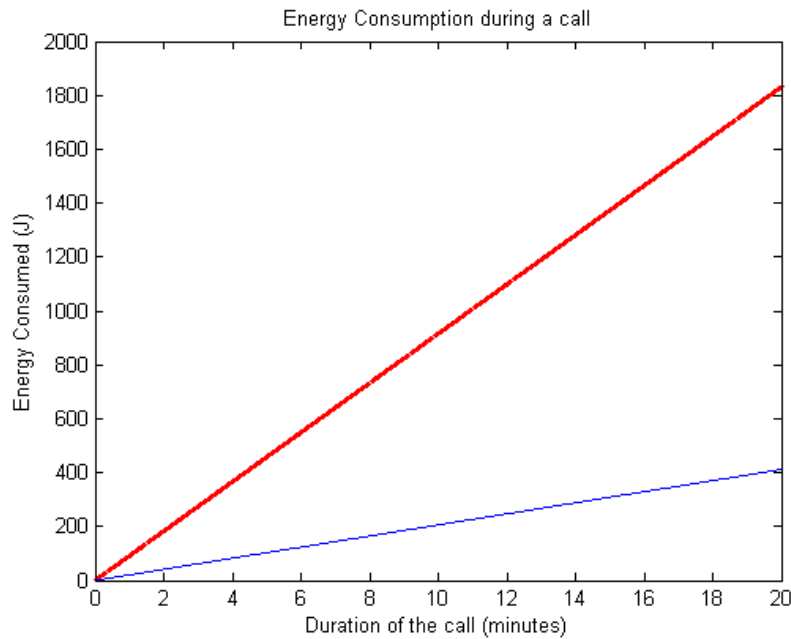


Figure 4-7: HQ Video call energy consumption; LTE in “low power mode”

As introduced in section 4.3.2, there is another possible scenario of interest: a call has already begun in LTE and a Wi-Fi AP becomes available. The VHO should now be made if the extra energy spent to complete the VHO is expected to be compensated afterwards. This extra energy is the same as in the VoIP case and corresponds to a value of 302.94 mJ with the current parameters and models; and this amount of energy will be compensated if the remaining time of the call is long enough. The same conclusions as before are drawn: that extra energy is very small compared to the energy consumed by the LTE interface and hence VHOs to Wi-Fi will always save energy.

4.4.3 VHO Decision: LTE uplink in “high power mode”

In high power mode, the LTE energy consumption can be expressed as:

$$\text{Energy LTE} = d \text{ (s)} \cdot [\alpha_{d, \text{LTE}} \cdot 0.5 \text{ Mb/s} + \alpha_{u, \text{LTE}} \cdot 0.5 \text{ Mb/s}_{, \text{LTE}} + \beta_{\text{LTE}}] \text{ (mJ/s)} = 1533.22 d \text{ (s)} \text{ [mJ]} \quad (4-6)$$

Where:

- d is the duration of the call in seconds, and
- $\alpha_{u, \text{LTE}}$, $\alpha_{d, \text{LTE}}$, $\alpha_{u, \text{LTE}}$, and β_{LTE} are the energy model parameters described in section 3.2.5

Here again the energy consumption in low and high power mode are comparable and much greater than the energy consumption via Wi-Fi, hence the same conclusions are made.

4.5 High Definition Mobile Video Calls

According to the Skype's Technical Support [105], the required throughput for high definition mobile video calls is 1.5 Mb/s. With this in mind and considering that these calls are very similar to the earlier video calls (but with a higher data rate), the following analysis has been performed.

4.5.1 Downlink and Uplink Limitations

Figure 4-5 shows the minimum SINR needed given a certain amount of available resources, i.e. the minimum SINR to achieve an effective 1.5 Mb/s throughput.

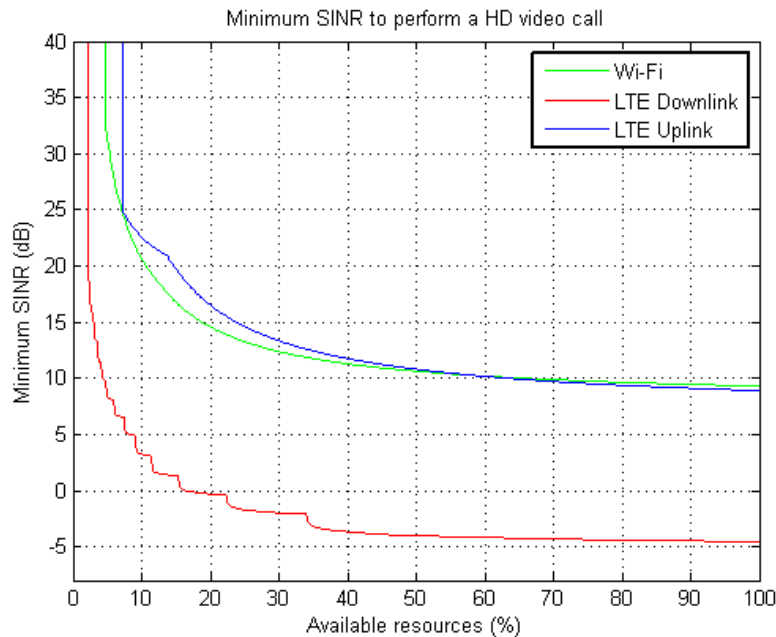


Figure 4-8: Min SINR to perform a video call

The minimum SINR is now considerably larger than in the previous cases, this will mean that in zones where the signal quality is not good it will not be possible to make this type of call. In Wi-Fi, if the available resources are lower than 20%, then the SINR will have to be above 15 dB, which represents a very significant increase in the number of positions within the coverage area, as shown in Figure 4-9, where the positions in the outdoor scenario where the Wi-Fi SINR is between 10 and 15 dB are shown in red. The two graphs correspond to shadow fading standard deviations of 0 and 8 dB, respectively.

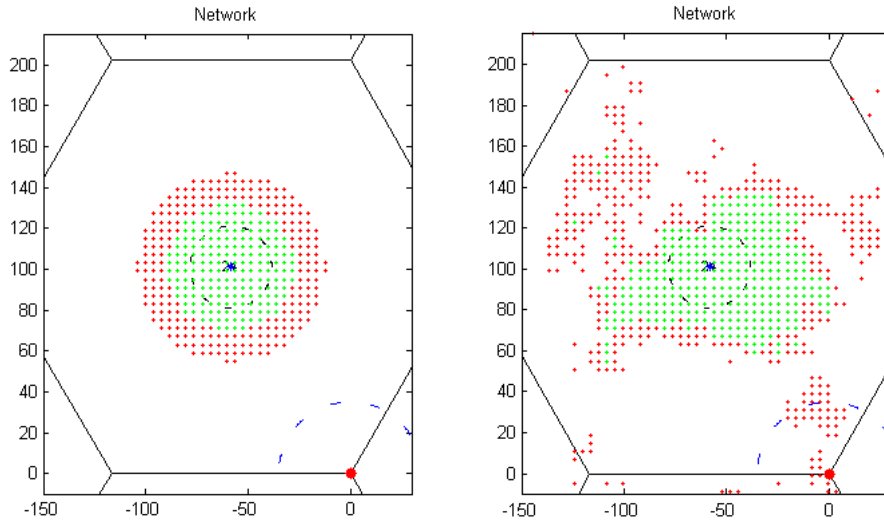


Figure 4-9: Positions where the Wi-Fi SINR is lower than 15 dB for standard deviations 0 and 8 dB; outdoor scenario

The red area represents the positions where the Wi-Fi SINR is between 10 and 15 dB – positions where the available resources would need to be larger than 20% in order to support the high definition video call, and the green area the positions where it is above 15 dB.

In the LTE case the load is an important factor as well, especially if the available resources are below the 20%. After that point, the minimum perceived SINR both in the up and downlink starts to grow quite fast, making these calls impossible in low coverage zones.

In following sections it will be assumed that there are sufficient available resources to process the call. Given this assumption, the potential energy savings of performing VHO in this case will be studied.

4.5.2 VHO Decision: LTE uplink in “low power mode”

This section is analogous to section 4.3.2. The only difference is the required throughput (now 1500 kb/s) and the uplink and downlink times. Hence, the consumed energy in LTE for a high-quality video call can be expressed as:

$$\text{Energy LTE} = d(s) \cdot [\alpha_{u,low,LTE} + \alpha_{d,LTE} \cdot 1.5 \text{ Mb/s} + \beta_{LTE}] \text{ (mJ/s)} = 1577,9 \cdot d(s) \text{ [mJ]} \quad (4-7)$$

Where:

- d is the duration of the call in seconds and
- $\alpha_{d,LTE}$ and β_{LTE} are the energy model parameters described in section 3.2.6

The energy for Wi-Fi is:

$$\text{Energy Wi-Fi} = d(s) \cdot [\alpha_{u,WiFi} \cdot 1.5 \text{ Mb/s} + \alpha_{d,WiFi} \cdot 1.5 \text{ Mb/s} + \beta_{WiFi}] = 763.13 \cdot d(s) \text{ [mJ]} \quad (4-8)$$

Where:

- d is the duration of the call in seconds and
- $\alpha_{u,WiFi}$, $\alpha_{d,WiFi}$, and β_{WiFi} are the energy model parameters described in section 3.2.5

As before, the energy consumed when using Wi-Fi is always smaller and hence VHOs should be made Wi-Fi in order to save energy with this type of call. As can be deduced from the energy models, with this higher required throughput, the energy consumption of both interfaces is closer than before. Figure 4-10 shows the total consumed energy for a given call duration via both interfaces.

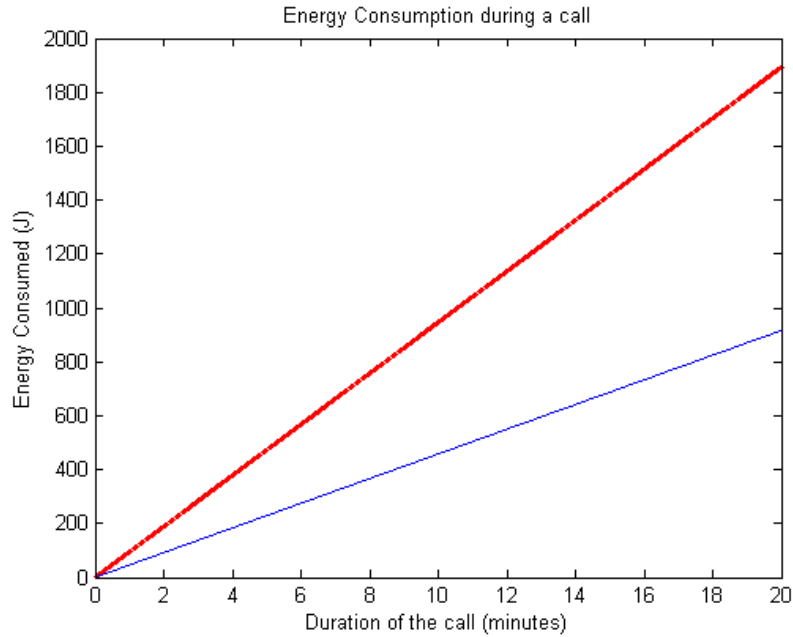


Figure 4-10: HQ Video call energy consumption; LTE in “low power mode”

As introduced in section 4.3.2, there is another possible scenario of interest: a call has already begun in LTE and a Wi-Fi AP becomes available. The VHO should be made if the extra energy spent during the VHO is expected to be compensated for afterwards. This extra energy is the same as in the VoIP case (302.94 mJ) with the current parameters and models. The same conclusions as before are drawn: that this extra energy is very small compared to the energy consumed by the LTE interface and hence VHOs to Wi-Fi will always save energy.

4.5.3 VHO Decision: LTE uplink in “high power mode”

The LTE energy consumption in high power mode can be expressed as:

$$\text{Energy LTE} = d \text{ (s)} \cdot [\alpha_{d, \text{LTE}} \cdot 1.5 \text{ Mb/s} + \alpha_{u, \text{LTE}} \cdot 1.5 \text{ Mb/s}_{, \text{LTE}} + \beta_{\text{LTE}}] \text{ (mJ/s)} = 2023.58 \cdot d \text{ (s)} \text{ [mJ]} \quad (4-9)$$

Where:

- d is the duration of the call in seconds and
- $\alpha_{u, \text{LTE}}$, $\alpha_{d, \text{LTE}}$, $\alpha_{u, \text{LTE}}$, and β_{LTE} are the energy model parameters described in section 3.2.5

The difference from Wi-Fi is now greater and hence the same conclusions are drawn: a UE will never make a VHO from Wi-Fi to LTE to save energy during these calls.

4.6 Downloads

In this section the VHO decision will be studied for the case of downloads. There are many reasons why a download may occur nowadays via a Smartphone or other mobile device. For example, a download will occur when a user wants to install a new application or game; when the user receives a photograph via a chat application, when the user receives an e-mail with attached files, when the user wants to download a document from the Internet, etc. Hence, studying how VHOs may save energy in such situations is very interesting as these downloads may occur frequently.

The files to download can be big or small. Their size will determine the energy consumed to perform the download in each network and therefore will be an important input to the VHO

decision. While in VoIP calls the equivalent parameter (the duration of the call) was unknown, the UE generally can know the size of the requested download. Note that this is not strictly true as the download might actually be a stream of indeterminate length. However, we will ignore this case in the remainder of this section.

The environmental conditions will also be very important in the VHO decision process, specifically parameters such as the load of the network and the perceived SINR will have to be considered.

We will begin throughput-based estimation. As has been discussed, the only input for the energy model is the throughput of the UE and therefore no simulation is needed. Note that in following paragraphs there is no consideration regarding the uplink traffic. Of course this is not strictly true, as the higher layer protocols may need to exchange flow control information, hence feedback is needed from the UE to the server which is providing the information for the download. Nevertheless, the UL traffic is neglected.

According to the earlier described power models, the energy consumed during a download via each interface is as follows:

For LTE:

$$\text{Energy LTE} = \frac{s}{t_{d,LTE}} (s) \cdot [\alpha_{d,LTE} \cdot t_{d,LTE} + \beta_{LTE}] \text{ (mJ/s) [mJ]} \quad (4-10)$$

Where:

- s is the size of the download,
- $\alpha_{d,LTE}$ and β_{LTE} are the energy model parameters described in section 3.2.6, and
- $t_{d,LTE}$ is the effective download throughput

And for Wi-Fi:

$$\text{Energy Wi-Fi} = \frac{s}{t_{d,WiFi}} (s) \cdot [\alpha_{d,WiFi} \cdot t_{d,WiFi} + \beta_{WiFi}] \text{ (mJ/s) [mJ]} \quad (4-11)$$

Where:

- s is the size of the download,
- $\alpha_{d,WiFi}$ and β_{WiFi} are the energy model parameter described in section 3.2.6, and
- $t_{d,WiFi}$ is the effective download throughput

Figure 4-11 shows the preferable network in terms of energy at a certain throughput. Note that this figure is based upon values measured using only two phones and are averaged over the unknown radio conditions during the measurements, so this figure only provides a suggestion of what a potential decision threshold could look be.

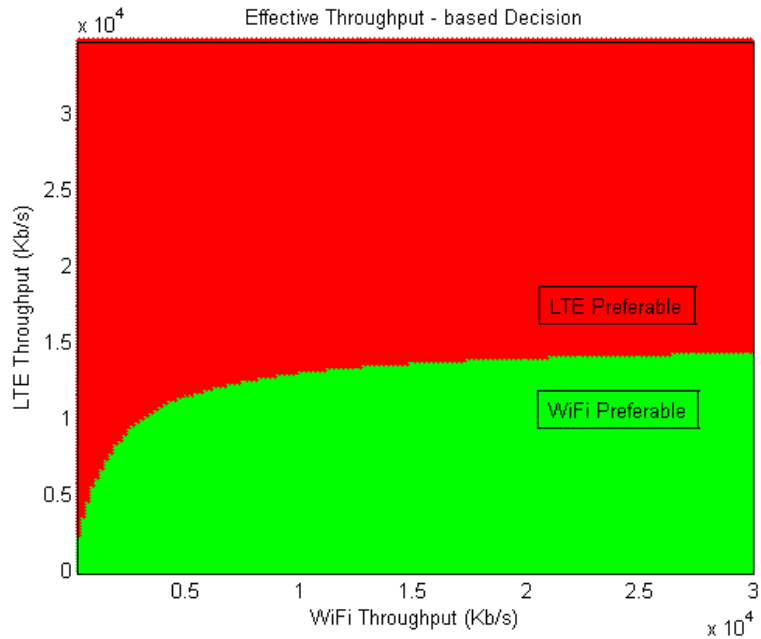


Figure 4-11: Download Throughput-based decision

It is possible to appreciate that if the LTE throughput is higher than approximately 14 Mb/s it is always less energy consuming to perform a download via LTE than in Wi-Fi. Fourth Generation networks are characterized by their high throughput, so this may not be an uncommon situation in the future. However, nowadays LTE networks offer a considerably lower throughput [65].

The next step consists of considering the expected scenario: the UE is connected to Wi-Fi and a download request arrives. Now the extra energy due to the VHO must be compensated for. As was discussed in section 4.1, the amount of this extra energy depends on whether the Wi-Fi interface is turned off or not during the transaction in LTE.

If the transaction time is expected to be shorter than 252 seconds (see section 4.1), the decision will be to leave the Wi-Fi interface on. This transaction time depends on the download size and on the throughput as is shown in Figure 4-12*.

* As it was explained in previous sections, in case of VHO, the download will start in the old network (Wi-Fi) and once the new one is prepared (after the association time plus the promotion time), the remainder of the download will be made in the new network. This fact is neglected in this case since the association time for LTE is just ~1 second.

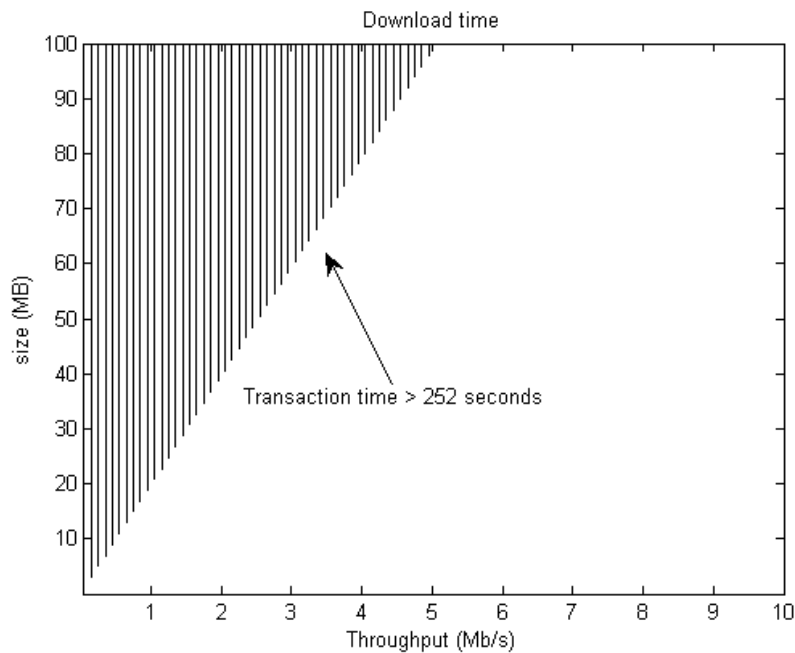


Figure 4-12: Download time, size vs. throughput

Looking at this figure we can say that only when the LTE effective throughput is quite low, is the transaction time long enough to be worth turning off the Wi-Fi interface. Taking into consideration that the main characteristic of LTE is its high data rates and that a very big percentage of downloads will not exceed the 10 MBs; it will be considered in following paragraphs that the UE leaves the Wi-Fi interface on. Nevertheless, since the file to download is something known to the UE at the beginning of the connection, the UE may decide to turn the Wi-Fi interface off if this would be advantageous.

In this case, the extra energy is due to the factors listed below. As has been repeatedly discussed, note that these are based on the current models and measured parameters; some of these values can change significantly with different device and network configurations.

1. Energy turning on the LTE interface (24 mJ)
2. Energy discovering and associating to the eNB (1 second * 250 mJ/s)
3. Energy in the LTE promotion state, necessary to establish the connection (1210.7 mJ/s * 0.260 seconds)
4. Energy spent in idle Wi-Fi while the file is downloaded in LTE
5. Energy turning off the LTE interface (29 mJ)

Figure 4-13 shows how the decision threshold changes with the size of the download. As expected, with large sizes the results tend to the division shown earlier in Figure 4-11.

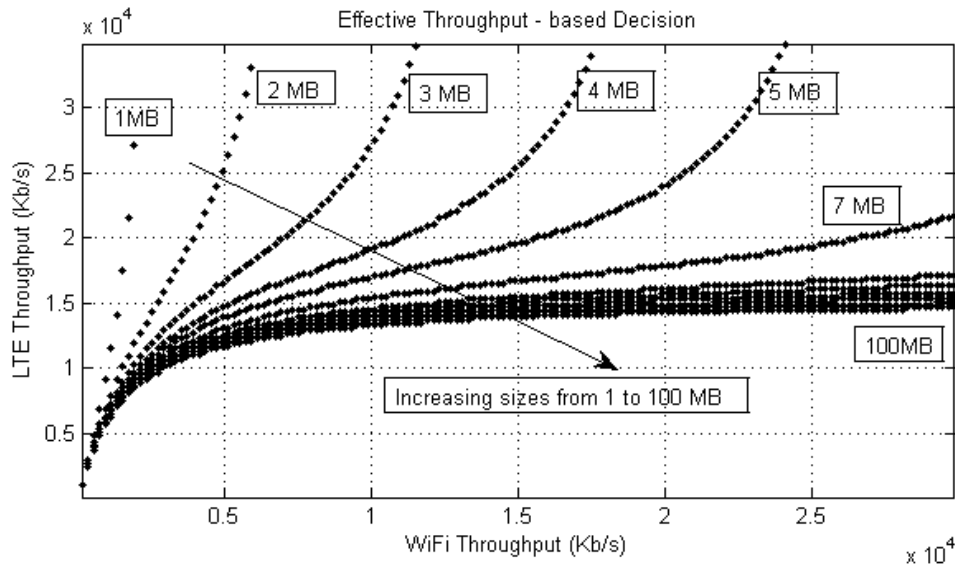


Figure 4-13: Size-dependant downloads' VHO decision

One important conclusion can be drawn from this figure. For big enough downloads (>10 MBs), the decision threshold stops depending on the download size but depends only on the effective download data rate. For smaller downloads, the decision must consider both the size of the download and the environmental conditions that will define the download data rate in each network.

The following paragraphs will study the effect of such environmental conditions on the VHO decision for this type of traffic, i.e. how the load and the perceived SINR affect the decision. Hence there are three variables that will determine if the VHO is made or not: the load of each network, the perceived SINR in each network and the download size.

4.6.1 Big Downloads (>10MBs)

As has just been discussed, the dependence on the download size disappears for large enough downloads. This simpler case will be analyzed first.

In order to appreciate how the load of the network affects the VHO decision, we assume that the LTE SINR is constant all over the Wi-Fi coverage area. This assumption is not so far from reality, since the LTE and Wi-Fi coverage areas differ so much in size. Following this approach, Figure 4-14 shows how bad the Wi-Fi signal quality would have to be to make the VHO to LTE energy worthwhile, depending on the load of each network, for an average LTE reception (LTE SINR = 15 dB). The color scale is in dBs.

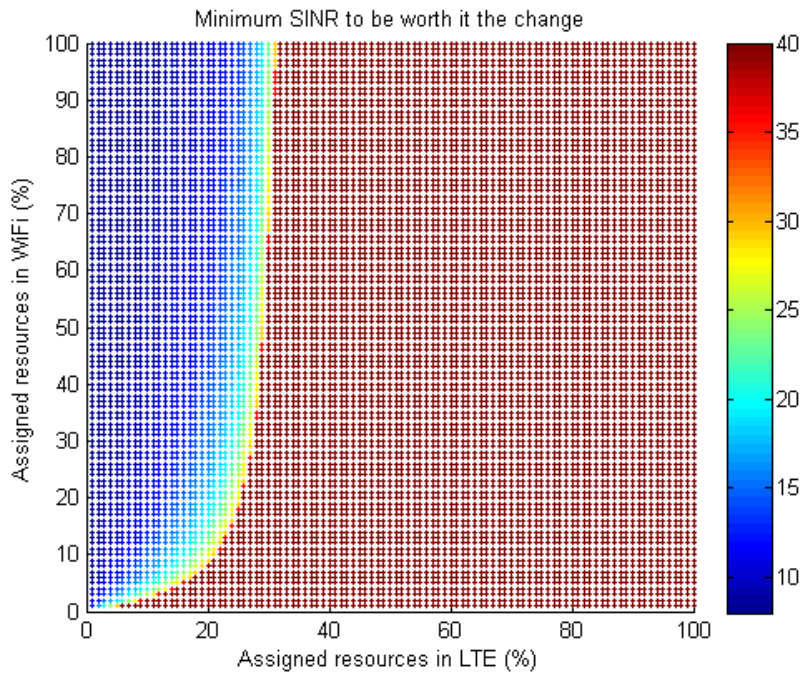


Figure 4-14: [Average LTE coverage] Minimum Wi-Fi SINR to change to LTE depending on the networks load

The blue part of the figure indicates that the UE needs to perceive a very poor Wi-Fi SINR in order to change network, i.e. a VHO is unlikely. On the other hand, as the color turns redder, the Wi-Fi signal would have to be better in order not to change. The right red area indicates that a VHO to LTE will be made regardless of the Wi-Fi signal SINR.

When the LTE SINR is equal to 15 dB, VHOs would not be made in most cases since it is likely that the assigned resources are above 20% (corresponding to 4-5 active users in a fair allocation of bandwidth). Nevertheless it is possible.

Figure 4-15 shows how the benefit of VHO would increase if the LTE coverage is the best possible. This occurs for an LTE SINR above 22 dB (see Figure 3-4).

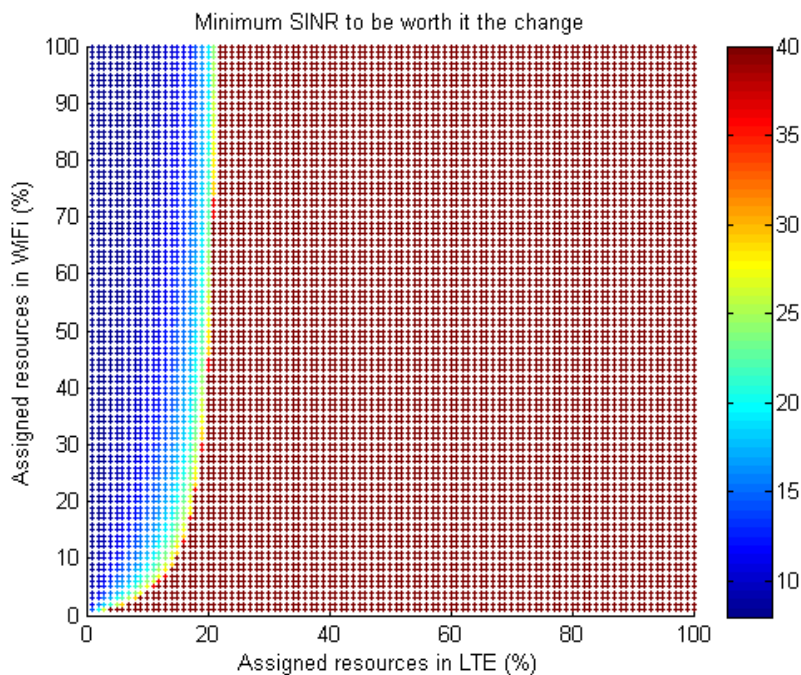


Figure 4-15: [Best LTE coverage] Minimum Wi-Fi SINR to change depending on the networks load

Similar conclusions can be drawn. Obviously in this case the scenario is more favorable to LTE and hence the VHO area is bigger. Nevertheless the assigned resources have to be still quite big (> 15%). Therefore it is expected that in areas where the LTE coverage is bad, VHOs will almost never be worthwhile. This is shown in Figure 4-16, where the LTE SINR in the Wi-Fi coverage area is 9 dB.

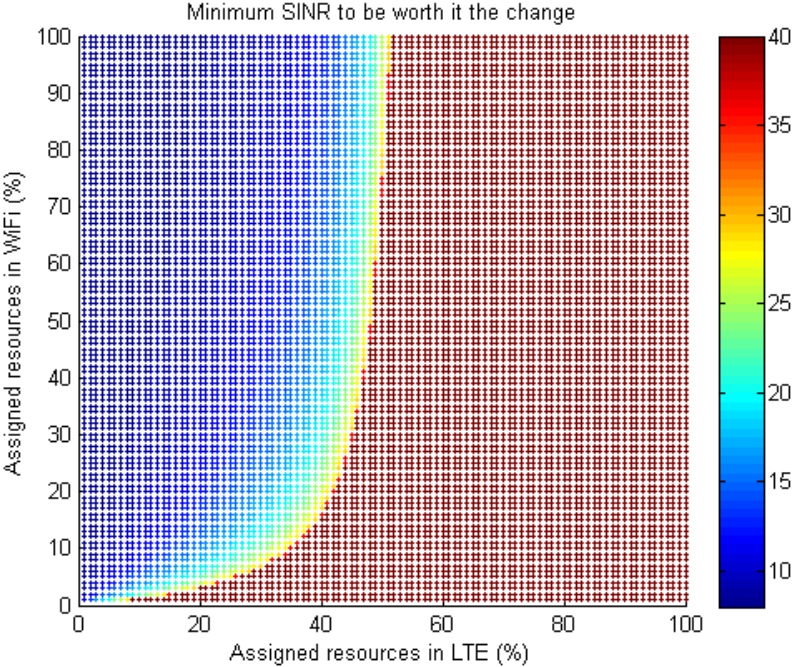


Figure 4-16: [Bad LTE coverage] Minimum Wi-Fi SINR to change depending on the networks load

In this case, the assigned resources must be above 40%. This means that, in a fair bandwidth allocation scenario, the number of active users cannot be more than 1-2, which is highly unlikely (or at least very unprofitable for the LTE operator).

Another interesting approach to investigate consists of actually measuring the potential amount of energy that may be saved due to VHOs. In this case the size of the download is important; as the larger the download the more energy that would be saved. Such savings are shown in two ways: as the percentage of energy saved and as the total energy saved.

The total saved energy and the percentage of saved energy are calculated as:

$$\text{Total Saved Energy (mJ)} = \text{Energy Wi-Fi} - \text{Energy VHO} \quad (4-12)$$

$$\text{Percentage of saved Energy (\%)} = \frac{\text{Energy Wi-Fi} - \text{Energy VHO}}{\text{Energy Wi-Fi}} * 100 \quad (4-13)$$

Where:

- Energy Wi-Fi is the total consumed energy if no VHO is made, i.e. the transfer is performed via the Wi-Fi network.
- Energy VHO is the total energy consumed if the VHO is made. This energy is calculated as described in the introduction of section 4.5.2.

In following figures, the non-colored positions are those positions where a VHO does not save any energy, i.e. staying in Wi-Fi is more energy efficient. The size of the downloads range from 10 to 200 MBs.

The first scenario presented in Figure 4-17 and Figure 4-18 consists of an average situation: the LTE SINR is 15 dB (considered constant in the Wi-Fi coverage area) and the percentage of assigned resources is 10% in both LTE and Wi-Fi. Under these circumstances, the energy saved depends on the size of the download and on the Wi-Fi SINR as shown in Figure 4-13.

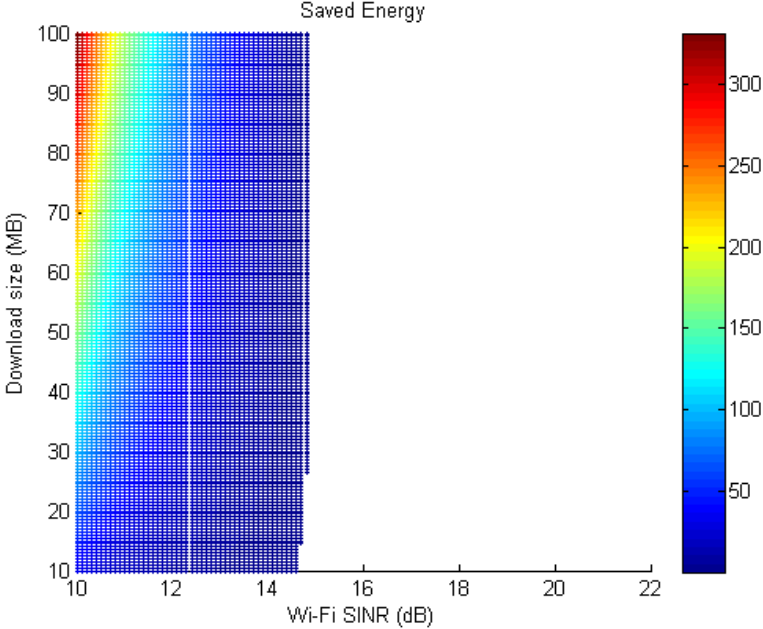


Figure 4-17: [Average scenario] VHO Energy savings in 10 to 100 MB downloads – Total energy in Joules

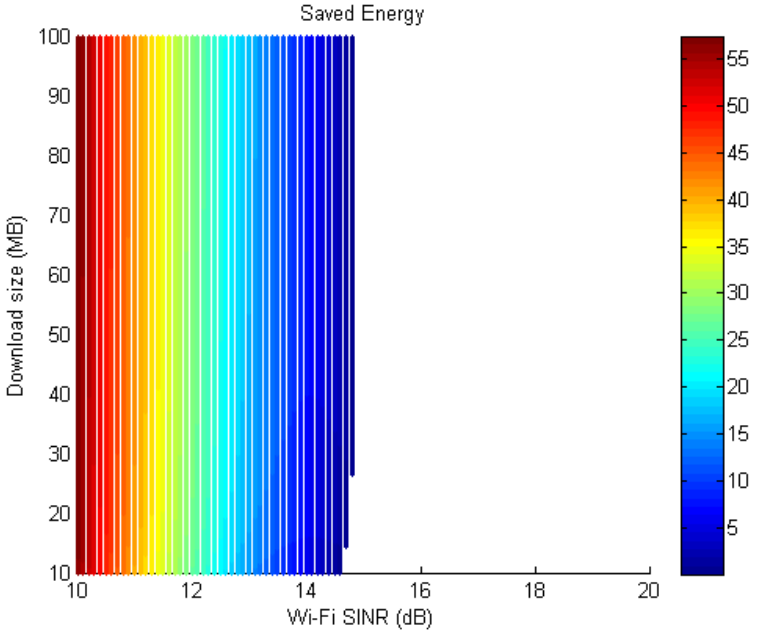


Figure 4-18: [Average scenario] VHO Energy savings in 10 to 100 MB downloads – Percentage of saved energy

It is important to note that these figures only present the results for a Wi-Fi SINR above 10 dB. The reason for this is that, since the minimum Wi-Fi SINR is 8 dB, a UE will leave the Wi-Fi network when its perceived SINR is lower than approximately 10 dB to avoid losing connectivity. This SINR threshold is studied in detail in section 4.9.2 and will be further analyzed in later sections of the thesis. This approach is used in the other figures in this section.

These figures show that, in the described scenario, if the Wi-Fi SINR is greater than ~15 dB, a VHO is **not** made regardless the size of the download. It can be appreciated as well that the percentage of saved energy is constant with the size of the download and that, in all cases, the amount of energy saved is very significant.

Figure 4-19 presents these results for a less favorable scenario for LTE: LTE SINR of 11dB, Wi-Fi assigned resources 10%, and LTE assigned resources 10%. In this less favorable scenario the potential energy savings are still significant. As expected a VHO will be made fewer times (only in positions where the Wi-Fi SINR < 12 dB), but when a VHO is performed large energy savings can be achieved.

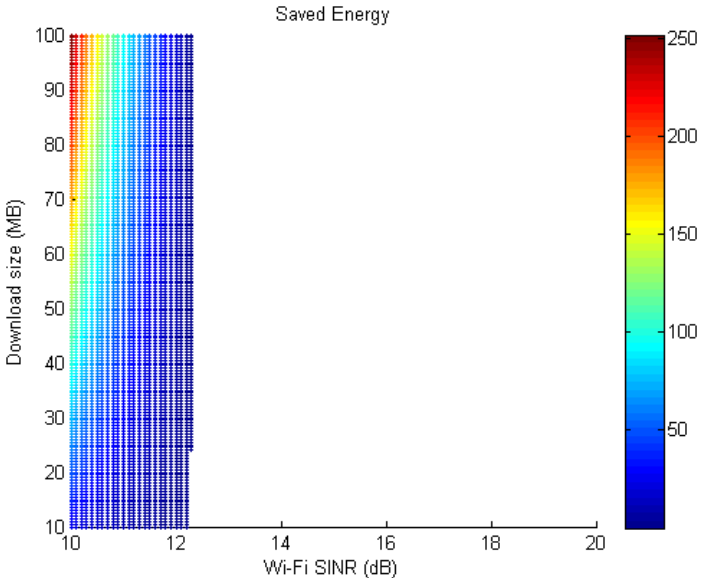


Figure 4-19 [Bad LTE Coverage] VHO Energy savings in 10 to 100 MB downloads – Total energy in Joules

Figure 4-20 shows how the load of the LTE network affects these VHO areas. In this figure, the assigned resources in LTE are 5% and in Wi-Fi 10%. The LTE SINR is average, i.e. 15 dB. Looking at this figure it can be deduced that the load heavily affects the VHO area, as now, only in positions where the Wi-Fi SINR is worse than ~11 dB is a VHO is advisable. Nevertheless, in such an area the potential energy savings are significant.

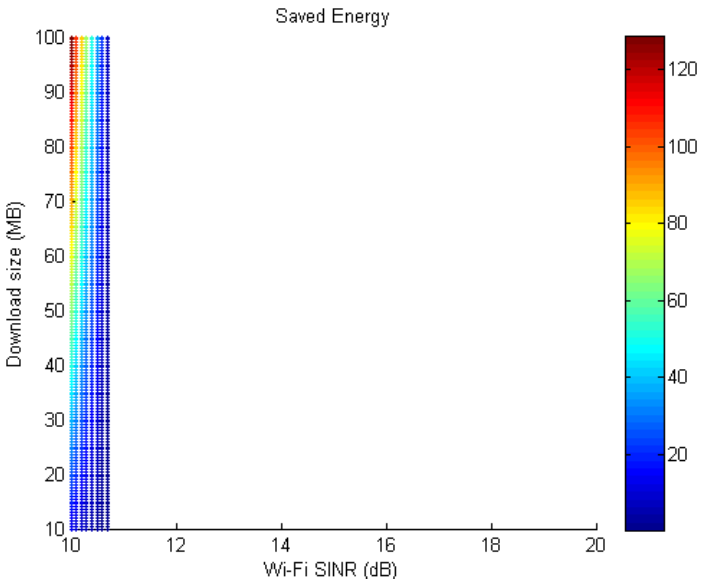


Figure 4-20 [LTE Loaded] VHO Energy savings in 10 to 100 MB downloads – Total energy in Joules

Figure 4-21 shows how the VHO area would increase if the LTE coverage is the best possible. This occurs for LTE SINR above 22 dB (see Figure 3-4). Again, large savings can be achieved. The positions where VHOs will be made in this case are those where the Wi-Fi is worse than ~18 dB, which represent a significant amount of the Wi-Fi coverage area as will be shown in following sections. The assigned resources in both networks are 10%.

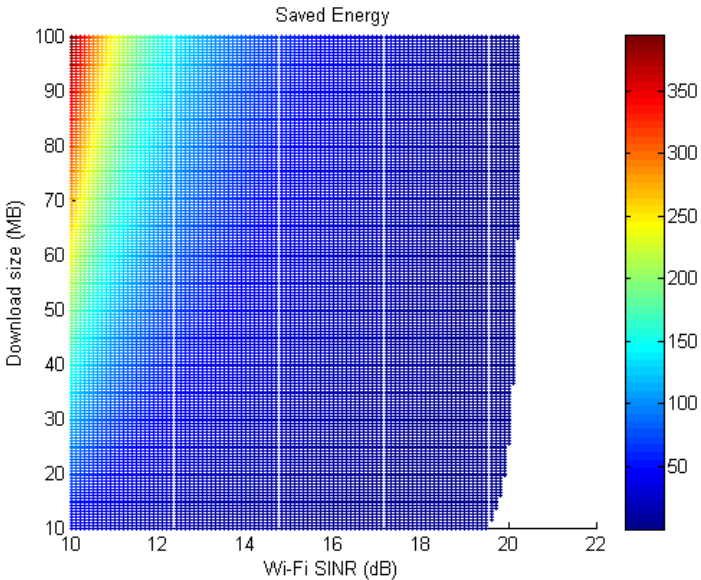


Figure 4-21 [Best LTE Coverage] VHO Energy savings in 10 to 100 MB downloads – Total energy in Joules

Summarizing the effects of the network load and the signal quality, it is possible to enumerate the following important conclusions for large downloads:

1. If the LTE network load is low enough, then a VHO to LTE will be worthwhile regardless of the Wi-Fi network conditions.
2. In positions where the Wi-Fi is very good (Wi-Fi SINR > 20 dB), VHOs to LTE will not be likely to occur unless the LTE network load is very low.
3. The potential energy savings are significant. Depending on the Wi-Fi SINR the energy saved with a VHO can be up to 55%, which corresponds to 600 J with the current energy model and measured parameters in average environmental conditions. In unfavorable conditions, a VHO can still save significant amounts of energy.
4. If the LTE network is highly loaded, then the VHO to LTE area decreases considerably.

4.6.2 Small Downloads (<10MBs)

From Figure 4-13 it was possible to conclude that the size of the download is an important factor in the VHO decision when the size was smaller than ~10 Mbytes. How the VHO decision changes taking into consideration this new variable and the load and quality of the signal is covered in following paragraphs.

At this point it is important to remember the observation made in section 3.2.3: when a download request arrives and it is decided to make a VHO, the download starts in the interface the UE is firstly connected to (Wi-Fi) and once the other one is ready, the remaining bytes are downloaded over the new interface.

Hence, in order to even consider a VHO, the download has to be big enough so that when the LTE network is ready there are still some packets to download. Apart from the Wi-Fi

throughput, the download time depends on the LTE association time and on its promoting time. Such times can vary with each different network as has been discussed. Nevertheless the parameters described in Table 3-5 provide us with a general idea regarding this issue. Such minimum size with the mentioned parameters is presented in Figure 4-22.

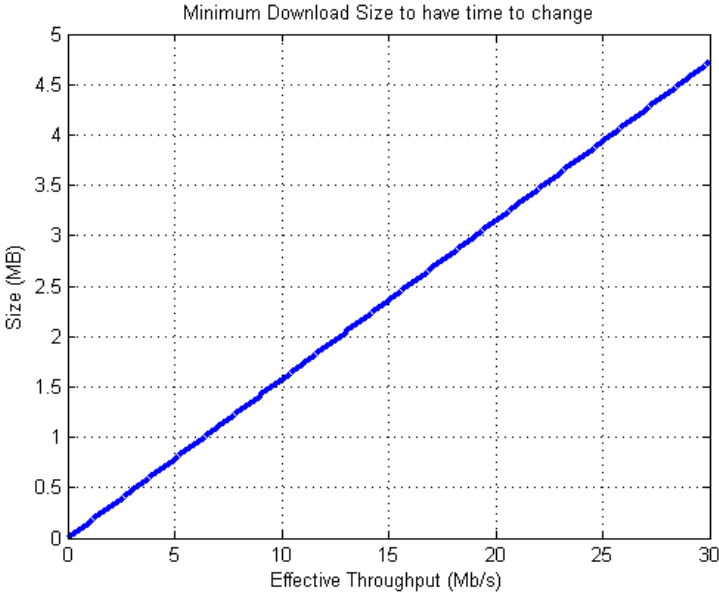


Figure 4-22: Minimum download size to consider a VHO

As has been discussed, the different parameters of the energy model and of the state machine heavily depend on each particular UE and on the network configuration. Hence, for small downloads the VHO decision can change significantly from one device to another. In the following paragraphs the results for the UE and network configuration studied will be presented.

The first step consists of showing the potential energy savings with small downloads. Firstly an average scenario is studied. This scenario is the same as the one in Figure 4-17 and Figure 4-18: LTE SINR 15 dB, assigned resources in LTE and Wi-Fi 10%. The next couple of figures show the percentage of saved energy and the total energy saved for downloads from 100 KB to 10 MB.

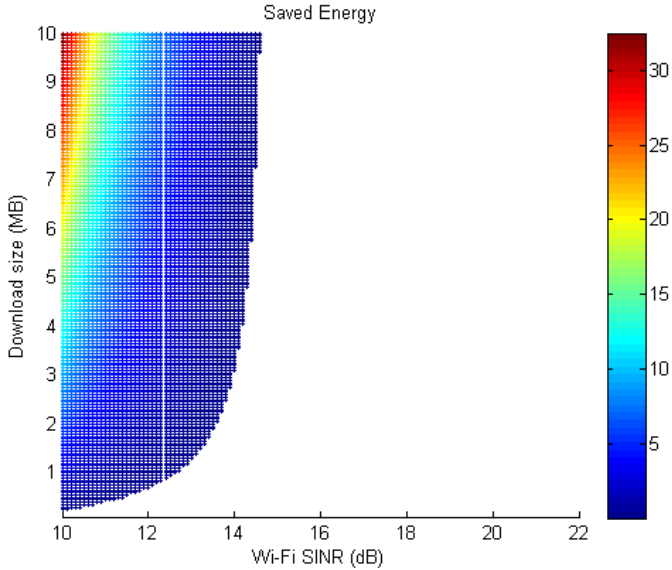


Figure 4-23 [Average scenario] VHO Energy savings in 0.1 to 10 MB downloads – Total energy in Joules

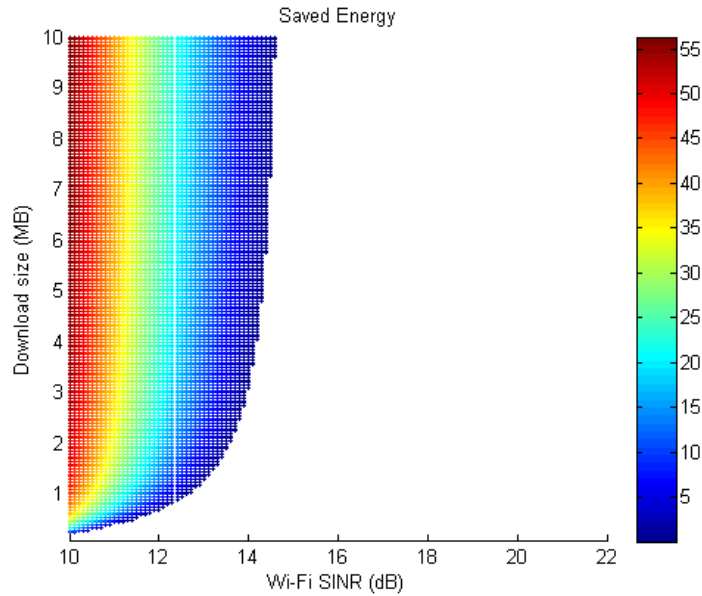


Figure 4-24 [Average scenario] VHO Energy savings in 0.1 to 10 MB downloads – Percentage of saved energy

The most important difference in this case is that the potential energy saved is not so big. In this standard scenario, it goes up to 30 Joules as shown in Figure 4-23. Obviously the smaller the download is; the less energy is saved.

After seeing these results, it is expected that, for a less favorable scenario for LTE, VHOs are not going to save significant energy. This can be appreciated in Figure 4-25 and Figure 4-26. In such figures, two scenarios are represented. In the first one, the LTE signal is quite poor (LTE SINR of 11 dB, assigned resources 10 % in both networks) and in the second one the LTE network is more loaded (LTE SINR 15 dB, LTE assigned resources 5%, Wi-Fi 10%).

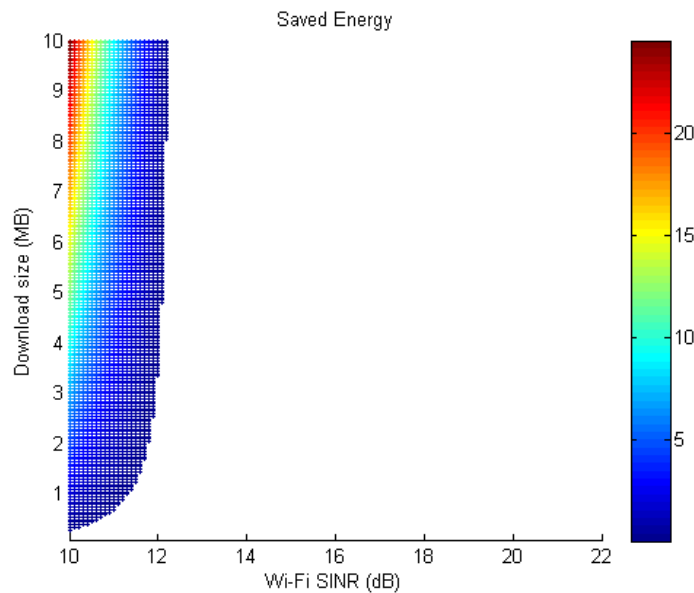


Figure 4-25 [Low LTE SINR] VHO Energy savings in 100 KB to 1 MB downloads – Total energy in Joules

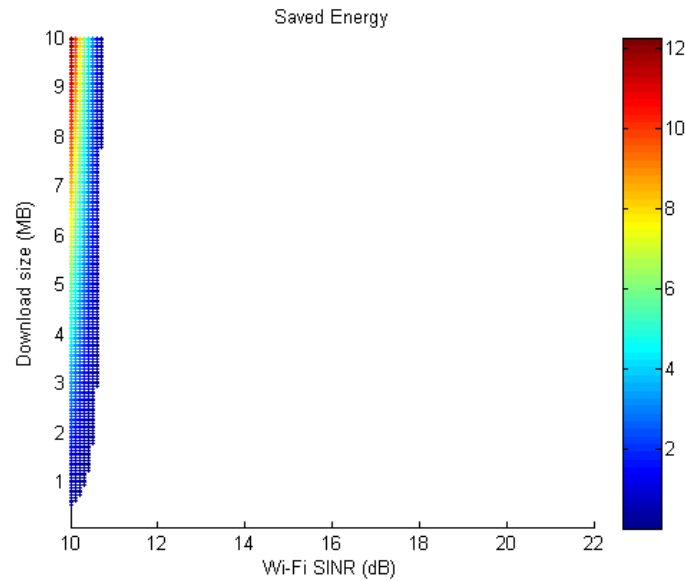


Figure 4-26 [Loaded LTE] VHO Energy savings in 100 KB to 1 MB downloads – Total energy in Joules

For this unfavorable to LTE situation, the energy savings are still low and at the same time VHOs are very unlikely; especially if the LTE network load increases.

Finally, a more favorable to LTE scenarios is presented. Figure 4-27 shows the total energy saved for VHOs due to small downloads when the LTE coverage is the best possible (LTE SINR > ~22 dB). The assigned resources both in LTE and Wi-Fi are still 10%.

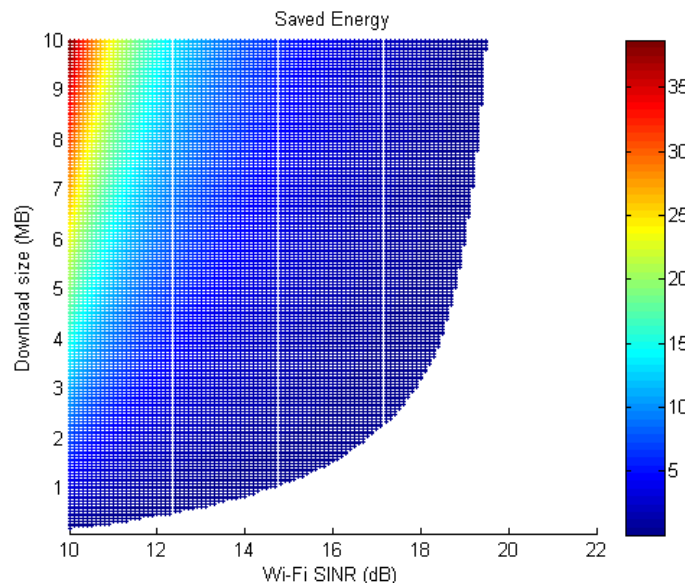


Figure 4-27 [Best LTE coverage] VHO Energy savings in 100 KB to 1 MB downloads – Total energy in Joules

The VHO area increases considerably since it now includes all the positions where the Wi-Fi SINR is worse than ~18dB; which are a lot of positions as it will be shown in following subsections. Nevertheless, the energy savings are not high (~15 Joules).

In smartphones it is a common practice to download small files (during a Web surfing session for example). Hence it is interesting to study if VHOs can save energy with downloads of even smaller files. Figure 4-28 shows exactly that: the total energy saved for downloads in the range of 10KB to 1 MB. The same average scenario as in Figure 4-23 and Figure 4-24 is considered.

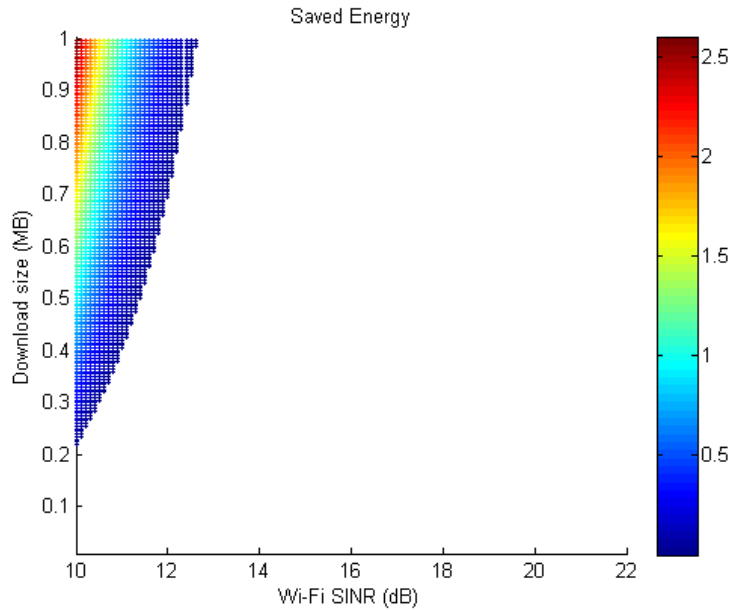


Figure 4-28 [Average scenario] VHO Energy savings in 10 KB to 1 MB downloads – Total energy in Joules

The VHO energy savings for downloads of files smaller than 1 MB are less than 2.5 Joules for the considered energy model parameters and scenario. Besides, the Wi-Fi signal needs to be quite bad (Wi-Fi SINR < ~13). For downloads smaller than 200 KB the VHO does not save any energy.

Considering the figures and results of this section, some important statements can be made regarding VHOs for small downloads:

1. The potential energy savings are low. This provokes that the different parameters both of the device and of the network will change the VHO decisions a lot for different UEs and networks, for each particular case. Anyways, the savings will still be insignificant in comparison with the energy consumed in other activities.
2. The energy savings are considerably smaller than with downloads of larger files. With the current parameters, there are no energy savings for files smaller than ~200KBytes unless the Wi-Fi conditions are extremely bad. This would include web traffic, where typically multiple small files would be downloaded and hence VHOs would not be advisable. See section 4.8 for more details.

4.6.3 Real Environment Scenarios

This section aims at providing with a general idea of how big or small the areas where VHO are advised actually are. Both the indoor and outdoor scenarios described in previous sections are covered. The situation of interest involves a Wi-Fi-connected UE and a download request. Like in previous sections, only the area where the Wi-Fi SINR is above 10 dB will be considered.

In all the figures in sections 4.6.3.1 and 0, the red area indicates the positions in the scenario where there are both Wi-Fi and LTE coverage and a VHO from Wi-Fi to LTE would save energy. Note that the shadow fading standard deviation in such figures is being considered 0 dB; that is the reason why the circles are so perfect. The Wi-Fi AP is located at the center of the LTE macro cell as shown in Figure 4-29 for example. This implies that the LTE signal quality is close to optimal; see Figure 3-7 for details. As the Wi-Fi AP goes to less favorable LTE positions, i.e. the LTE network is more loaded, the VHO areas will decrease as was shown in sections 4.6.1 and 4.6.2.

As was previously discussed it is considered that the Wi-Fi interface is left on in idle mode during the download in LTE.

4.6.3.1 Outdoor

The outdoor case is presented first. Following paragraphs and figures show the “changing areas” for different download sizes and network loads.

The first scenario involves an average load situation where both in Wi-Fi and LTE the assigned resources are 10%. How the VHO area changes with different download sizes is shown in Figure 4-29.

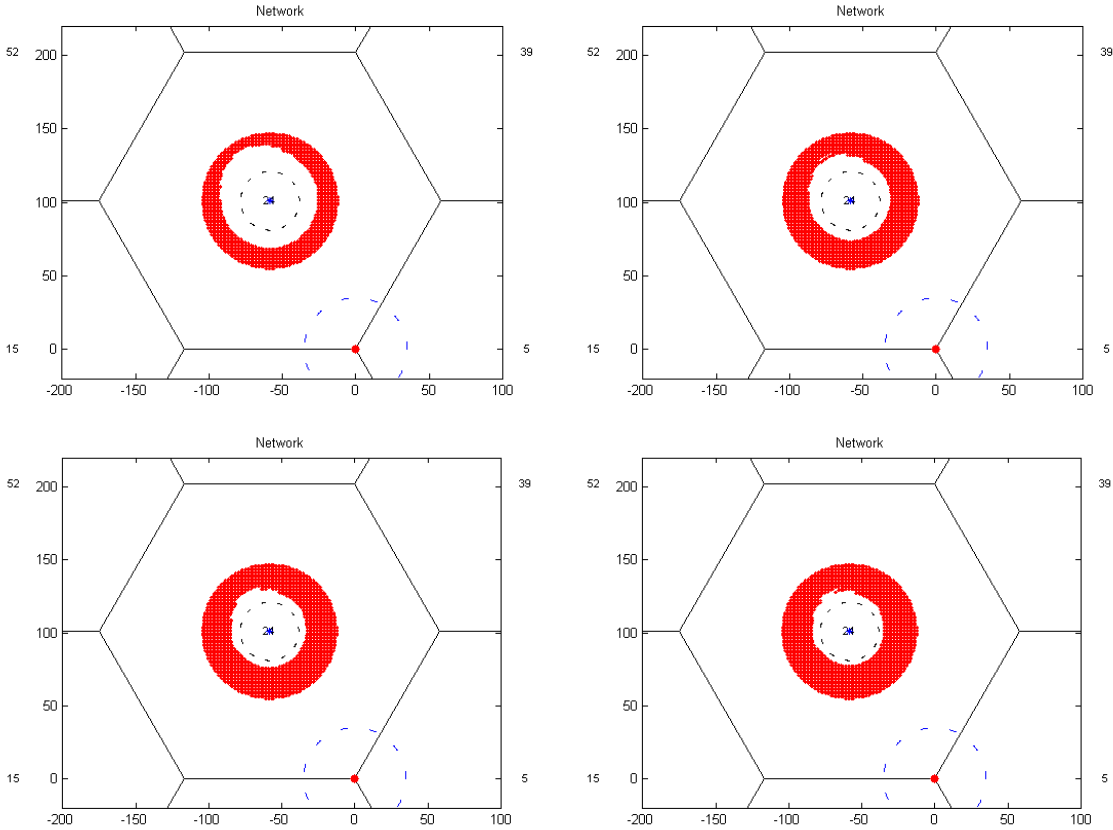


Figure 4-29: VHO area for downloads of 1, 3, 7 and 25 MB; average load situation; outdoors

It is important to remember that shadowing will break these perfect circles and the different areas will change a lot depending on each physical scenario and on the environmental conditions.

Now a situation where the LTE network is more loaded is shown. In this case, the assigned resources in LTE are 5% and in Wi-Fi 10% again. Now the convergence to the “big download” situation where the dependence with the size disappears is faster. As previous sections showed, the LTE load heavily affects the VHO area.

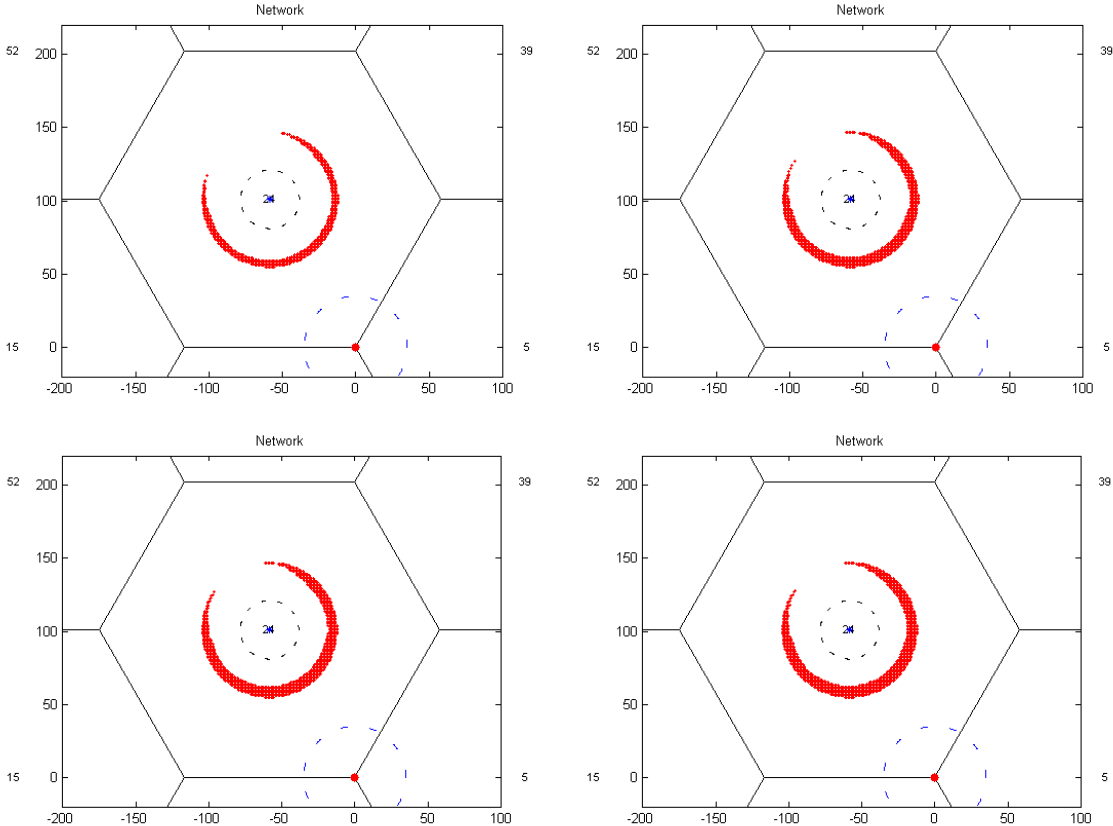


Figure 4-30: VHO area for downloads of 1, 3, 7 and 25 MB; LTE loaded; outdoors

Finally, a scenario where the load in the LTE network is lower is presented. In this case, the assigned resources for LTE are 20%. Again it is possible to appreciate how the load in LTE affects the VHO area a lot. In this case, for downloads bigger than 3 MB, it is always worth it to change to LTE regardless the Wi-Fi SINR.

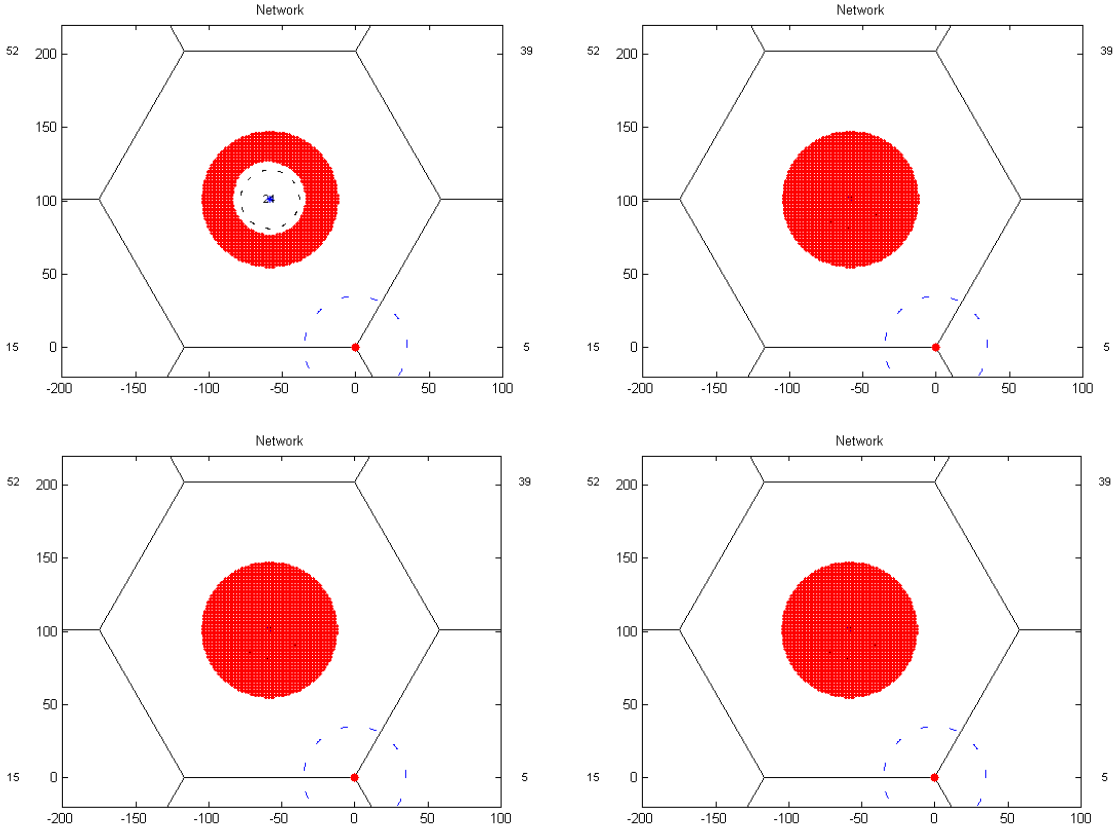


Figure 4-31: VHO area for downloads of 1, 3, 7 and 25 MB; LTE not loaded; outdoors

4.6.3.2 Indoor

The indoor case is presented now. The following paragraphs and figures show the “changing areas” for different download sizes and network loads. An analogue behavior as in the outdoor case is found.

The first scenario involves an average load situation where both in Wi-Fi and LTE the assigned resources are 10%. How the VHO area changes with different download sizes is shown in Figure 4-32Figure 4-29.

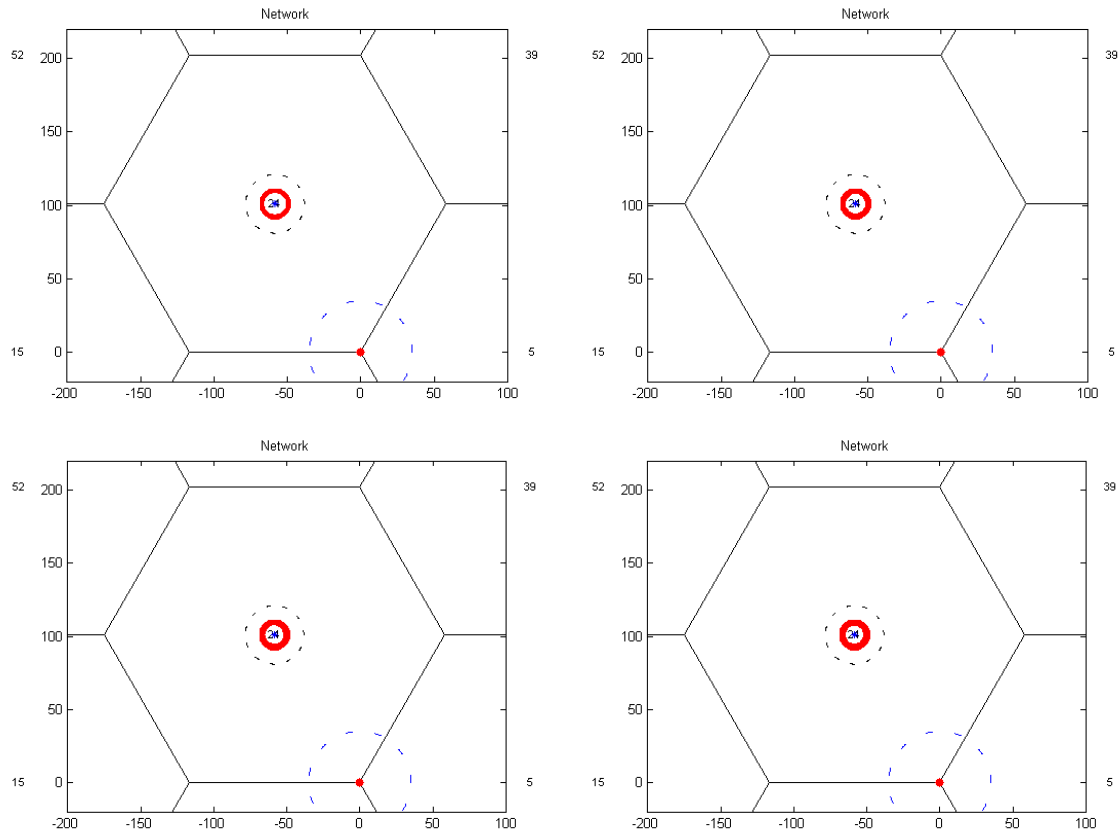


Figure 4-32: VHO area for downloads of 1, 3, 7 and 25 MB; averagely loaded situation; indoors

Now a situation where the LTE network is more loaded is shown (Figure 4-33). In this case, the assigned resources in LTE are 5% and Wi-Fi 10% again. Now the convergence to the “big download” situation where the dependence with the size disappears is much faster.

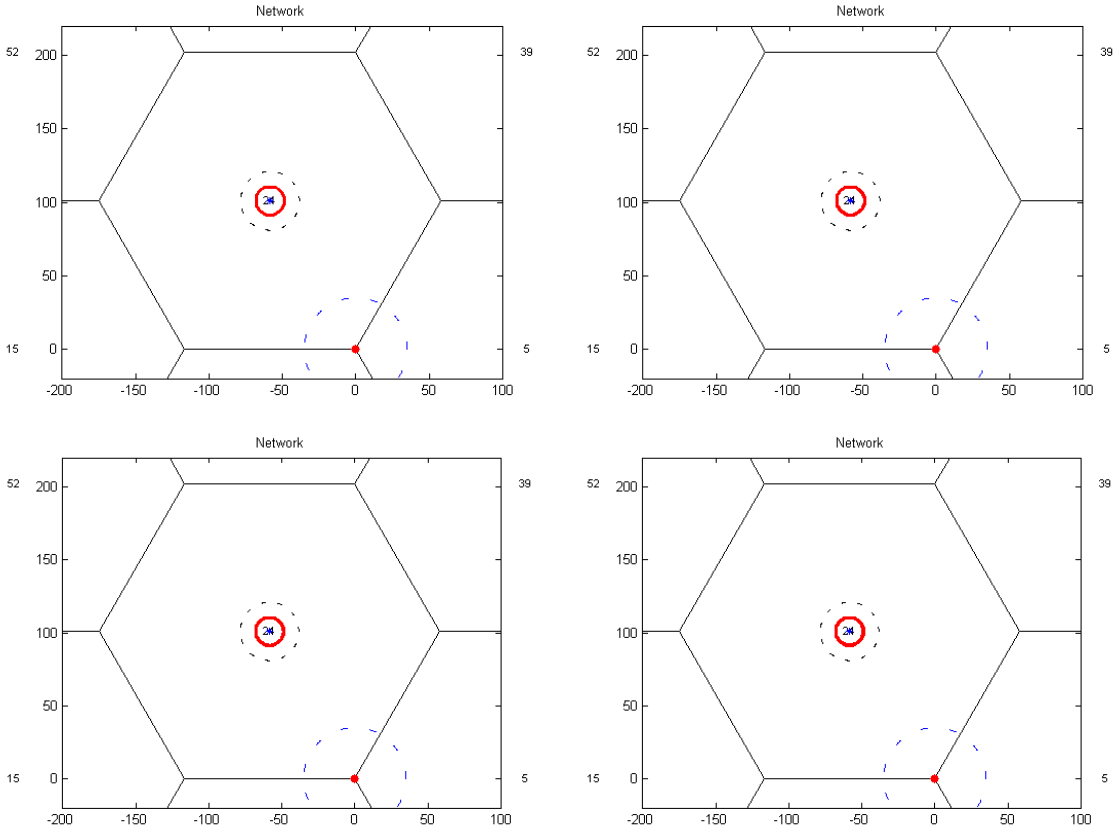


Figure 4-33: VHO area for downloads of 1, 3, 7 and 25 MB; LTE loaded; indoors

Finally, a more favorable scenario for LTE is covered. The LTE assigned resources are 20% (Figure 4-34).

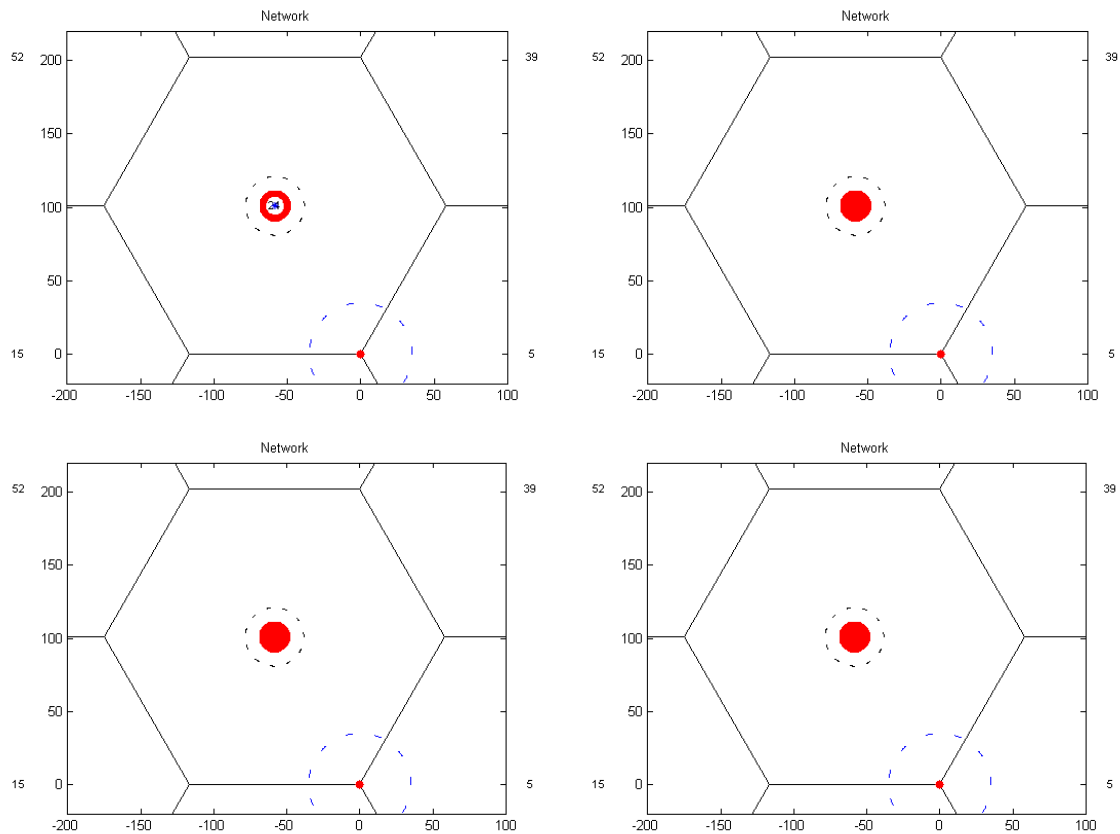


Figure 4-34: VHO area for downloads of 1, 3, 7 and 25 MB; LTE loaded; indoors

As expected, the same behavior as in the outdoor case is found. After a certain size, the VHOs always save energy regardless of the Wi-Fi SINR.

In this indoor scenario the positions where a VHO saves energy are not many in most cases. Nevertheless, a user at home will use its Smartphone while he or she is not moving. If he by any chance is in one of these positions a VHO can be made and some energy saved.

4.7 File Uploads

Another very common activity via mobile devices involves the upload of a file. For example, when a user takes a picture and wants to share it via their social network, he or she has to upload the image; when a file is attached to an e-mail message another upload is involved. Another example consists of applications such as Dropbox [112] that upload certain files automatically in the background.

In this type of service we will only consider the uplink. Again, we ignore the need for feedback to the sender for higher protocol layer's flow control, error correction, etc. In contrast to the VoIP and video calls, in this case there is no required minimum throughput; we instead assume that the users simply want to upload the file as fast as they can*. The effective upload data rate depends on two factors:

* Note that this need not be the case in background uploading, as in this case the user will trade off upload delay for greater energy savings.

1. The resources assigned to the UE by the network. These will change a lot depending on each network's resource allocation policies and on the load of the network.
2. The environmental conditions: path loss, shadow fading attenuation, and interference, will determine the quality of the signal, i.e. the SINR, the receiver – the eNB in LTE and the AP in Wi-Fi perceives. Depending on this SINR, the effective upload throughput will change. Note that the input to the energy model for the case of LTE in “high power mode” is this effective upload throughput.

Hence, in following subsections the potential energy savings due to VHOs will be studied. It is important to remember the main scenario of interest: a Wi-Fi-connected UE needs to upload a file. The UE will decide if it is worth changing to LTE for the upload, while taking into account that once the upload is finished, the UE will return to Wi-Fi to stay in idle mode. The VHO decisions will be analyzed, along with the different factors and parameters that may affect them.

Before going into details, the energy consumption of each interface during an upload will be described. For Wi-Fi, this can be expressed as:

$$\text{Energy Wi-Fi} = \frac{s}{t_{u,\text{eff,WiFi}}} (s) \cdot [\alpha_{u,\text{WiFi}} \cdot t_{u,\text{eff,WiFi}} + \beta_{\text{WiFi}}] (\text{mJ/s}) [\text{mJ}] \quad (4-14)$$

Where:

- s is the size of the file to upload,
- $\alpha_{d,\text{WiFi}}$ and β_{WiFi} are the energy model parameter described in section 3.2.5, and
- $t_{u,\text{eff,WiFi}}$ is the effective upload speed.

In the case of LTE, the energy consumption will depend on whether the UE is in “high power mode” or in “low power mode”. For the “low power mode”, the energy consumption can be expressed as:

$$\text{Energy LTE}_{\text{low}} = \frac{s}{t_{d,\text{eff,LTE}}} (s) \cdot 1500 (\text{mJ/s}) [\text{mJ}] \quad (4-15)$$

Where:

- s is the size of the file to upload,
- $\alpha_{d,\text{LTE}}$ and β_{LTE} are the energy model parameter described in section 3.2.5, and
- $t_{d,\text{eff,LTE}}$ is the effective upload speed

While in “high power mode”, this energy consumption is:

$$\text{Energy LTE}_{\text{high}} = \frac{s}{t_{u,\text{eff,LTE}}} (s) \cdot [\alpha_{u,\text{LTE}} \cdot t_{u,\text{eff,LTE}} + \beta_{\text{LTE}}] (\text{mJ/s}) [\text{mJ}] \quad (4-16)$$

Where:

- s is the size of the file to upload,
- $\alpha_{d,\text{LTE}}$ and β_{LTE} are the energy model parameter described in section 3.2.5, and
- $t_{d,\text{eff,LTE}}$ is the effective upload speed

Using these three formulas it is now possible to appreciate how the two factors described above affect the energy consumption of both interfaces:

1. The assigned resources will determine the upload speed of the UE.
2. Given this upload speed and the SINR –deduced from the environmental conditions, the effective upload throughput at the receiver will be calculated, using the waterfall curves described in sections 3.3.1 and 3.3.2.

Hence, a VHO decision for a file upload will depend on the size of the file to be uploaded, the load of each network, and the SINR at each receiver (i.e., the LTE eNB and Wi-Fi AP).

4.7.1 VHO Decision: LTE in “low power mode”

The first simulation aims to study the energy consumption in LTE and Wi-Fi. For this purpose, Figure 4-35 and Figure 4-36 show the $\mu\text{J}/\text{bit}$ consumed during a file upload in both interfaces. As discussed before, this throughput will vary depending on the SINR and on the resources assigned to the UE. The color bars are in $\mu\text{J}/\text{bit}$

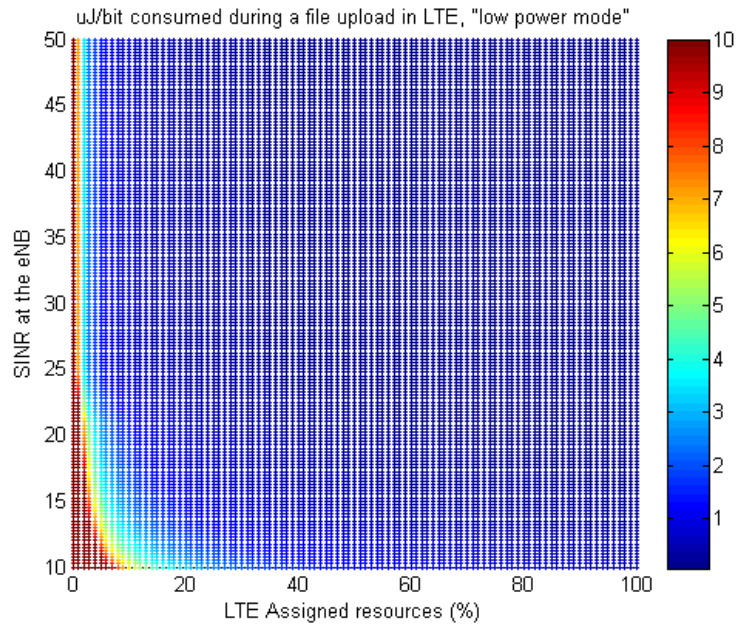


Figure 4-35: Joules per bit consumed during a file upload - LTE in low power mode

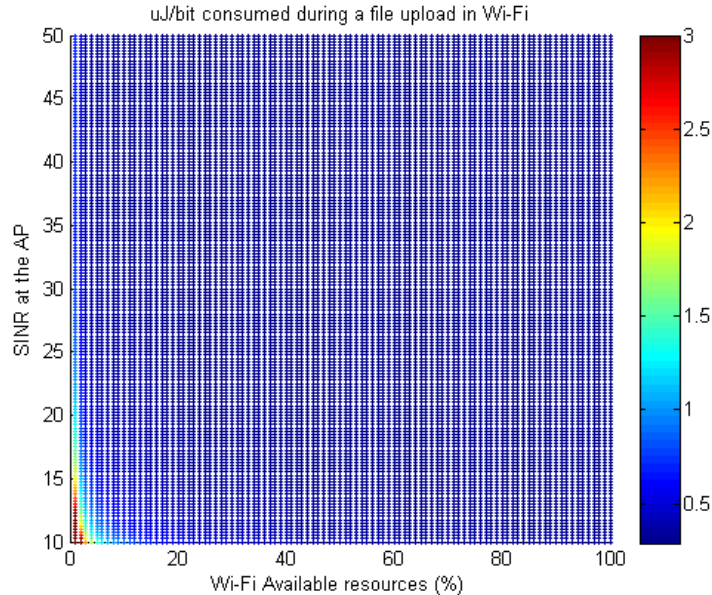


Figure 4-36: Joules per bit consumed during a file upload via Wi-Fi

Finally, the following figure shows the combinations of effective upload throughput in each network where a VHO may save energy, i.e., those points where the LTE power consumption is smaller than the Wi-Fi one. The color is such difference and it is in units of $\mu\text{J}/\text{bit}$.

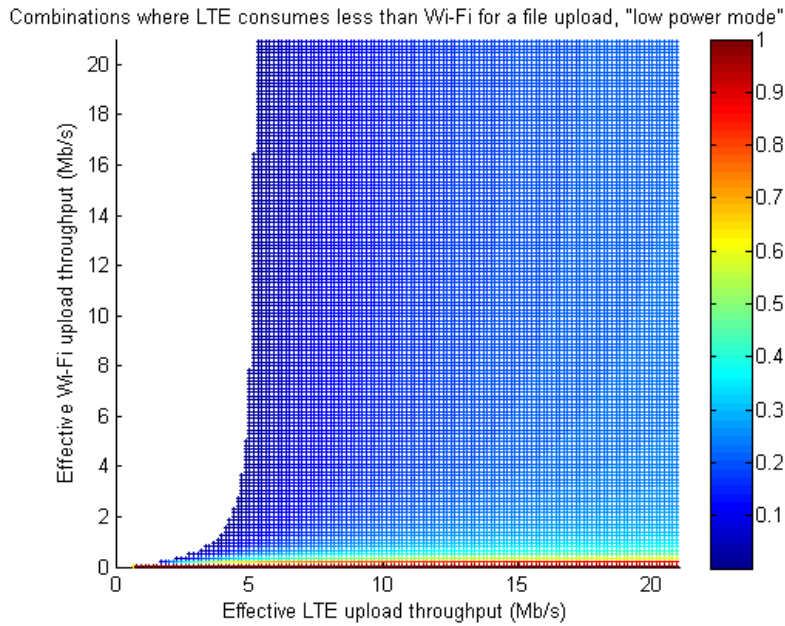


Figure 4-37: Combinations where LTE consumes less than Wi-Fi for a file upload, "low power mode"

Hence, as soon as the LTE upload effective throughput is higher than ~ 5 Mb/s, the LTE interface will consume less $\mu\text{J}/\text{bit}$ than the Wi-Fi one, regardless of the Wi-Fi conditions. Hence, if the file to upload is big enough, the extra energy derived from making the VHO will be compensated. Note that, in the scenario of interest, the UE is already connected to Wi-Fi and a file upload request arrives. This request can be originated from several sources (network, user, background application), but the decision to be made is always the same.

At this point the question of turning the Wi-Fi interface off or not during the upload must be addressed. Such a decision depends on the time the file uploaded will take: if this time is longer than 252 seconds, then the most energy-efficient decision would be to turn the Wi-Fi interface off; otherwise it is better to leave it on in idle mode. Figure 4-38 shows how large the file would have to be given a certain effective upload speed for this time to be longer than those 252 seconds.

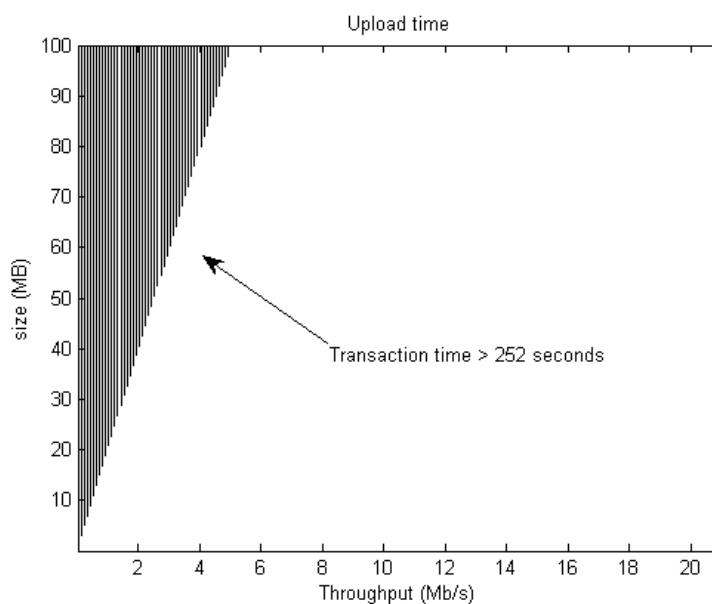


Figure 4-38: File upload time

As shown in the graph, most times this time will be lower than 252 seconds and considering that the files to upload in a Smartphone consist of pictures, documents, etc., they are usually going to be lower than 10 Mbytes. For these reasons, in the following paragraphs we assume that the UE always leaves the Wi-Fi turned on. Nevertheless, the size of the file to upload is sometimes known to the UE at the beginning of the connection and hence it may decide to turn the Wi-Fi interface off if this is advantageous. Once this decision is made, the energy consumption in the case of a VHO or non-VHO is as follows:

No VHO:

1. Wi-Fi promotion energy (0.08 seconds * 124.4 mJ/s)
2. Energy spent during the upload in Wi-Fi (Figure 4-36)

VHO:

1. Wi-Fi promotion energy
2. Energy spent during the upload in Wi-Fi*
3. Wi-Fi idle energy during the upload (1.9 mJ/s * upload time in LTE)
4. Energy to turn the LTE interface on (24 mJ)
5. Energy to associate to the eNB (1 seconds * 250 mJ/s)
6. Energy to establish the LTE connection (0.26 seconds * 1210.7 mJ/s)
7. Energy spent in LTE during the upload (see Figure 4-35)
8. Energy to turn the LTE interface off (29 mJ)

These two energies depend not only on the effective throughput at the AP and eNB respectively, but also on the file size. Figure 4-39 presents this minimum size for the VHO to be worthwhile in terms of energy consumption. The color bar is in units of MB.

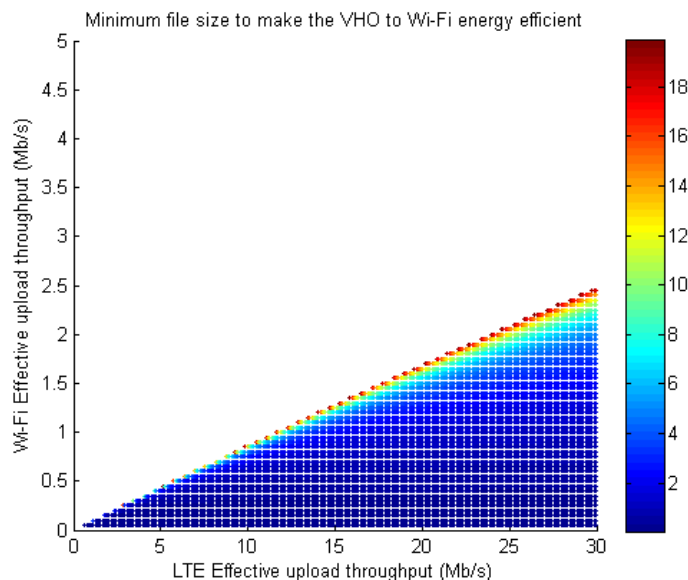


Figure 4-39: Minimum file size to make VHO – LTE in “low power mode”

* Note that, as explained repeatedly in the report, the upload starts in Wi-Fi and when the LTE is ready, the remaining packets are uploaded via this interface.

The picture shows that only when the Wi-Fi conditions are quite bad and at the same time the LTE ones are good, VHOs will be able to save some energy. The file needed for this to happen will not need to be big though. In order to appreciate if these savings are actually significant, Figure 4-40 shows the total savings depending on the Wi-Fi throughput for several LTE cases. The color bars are in Joules.

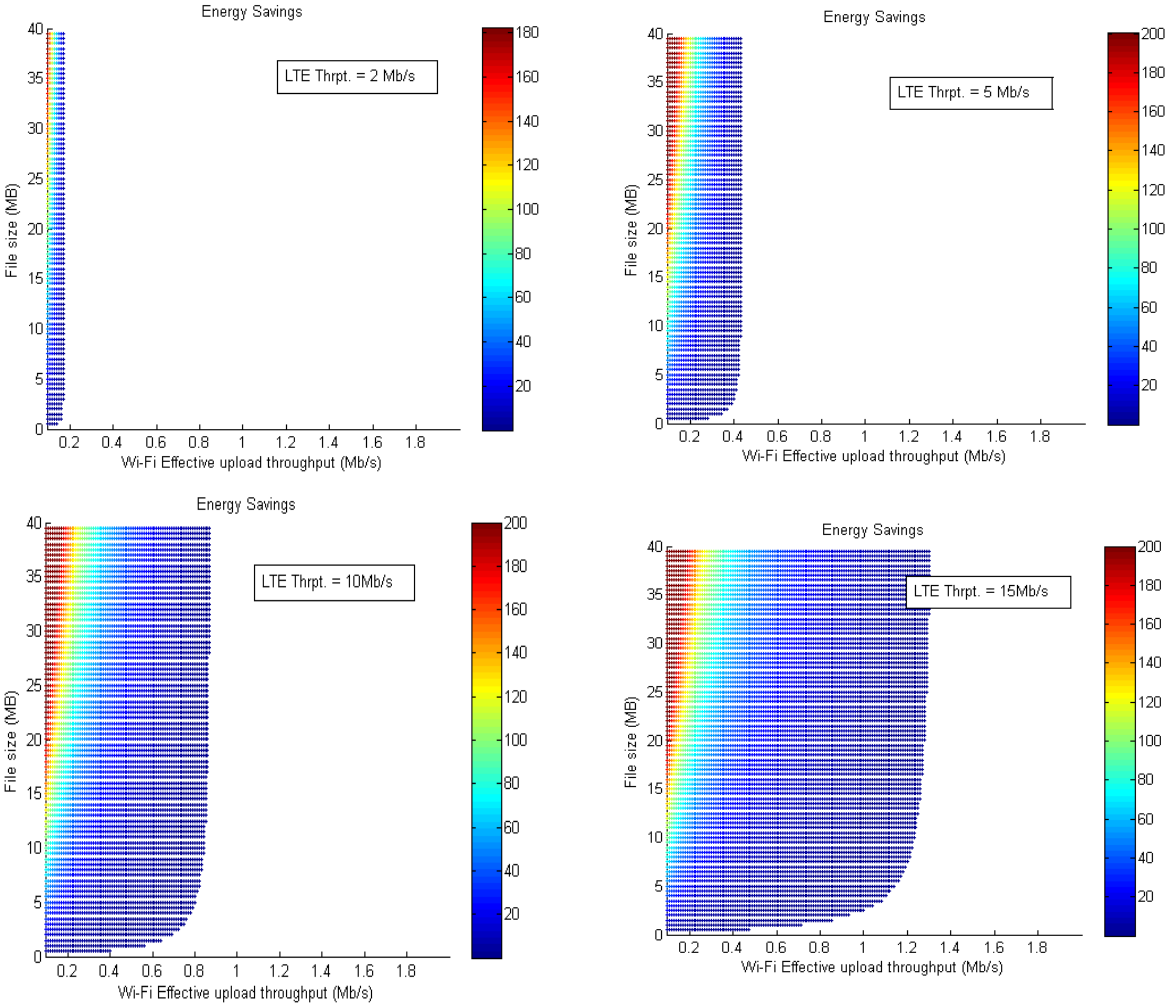


Figure 4-40: File Uploads VHOs energy savings – LTE in “low power mode”

The picture show than only significant savings are achieved when the Wi-Fi conditions are very poor and/or the LTE ones very good.

4.7.2 VHO Decision: LTE in “high power mode”

In Figure 4-36 the $\mu\text{J}/\text{bit}$ consumed by the Wi-Fi interface during a file upload is shown. According to this graph, this consumption is lower than $3 \mu\text{J}/\text{bit}$ except for very extreme cases. Therefore, potential VHOs cases will only be those where the LTE consumption is lower than this, otherwise a VHO should not be made. Figure 4-41 represents the $\mu\text{J}/\text{bit}$ consumed in LTE for a file upload, when the LTE uplink is in “high power mode”. As explained in the introduction to this section, this energy consumption depends on two factors: the SINR at the eNB and the resources assigned to the UE. Note that only the points where the $\mu\text{J}/\text{bit}$ consumed is lower than $3 \mu\text{J}/\text{bit}$ are colored. As shown in this figure there are many potential places where VHO is feasible. Nevertheless in this case the differences in energy consumption versus Wi-Fi are very low which cause the VHO decision to change for same file size depending on the environmental conditions (path loss, interferences, shadow fading, and load) and on the specific terminal and network characteristics.

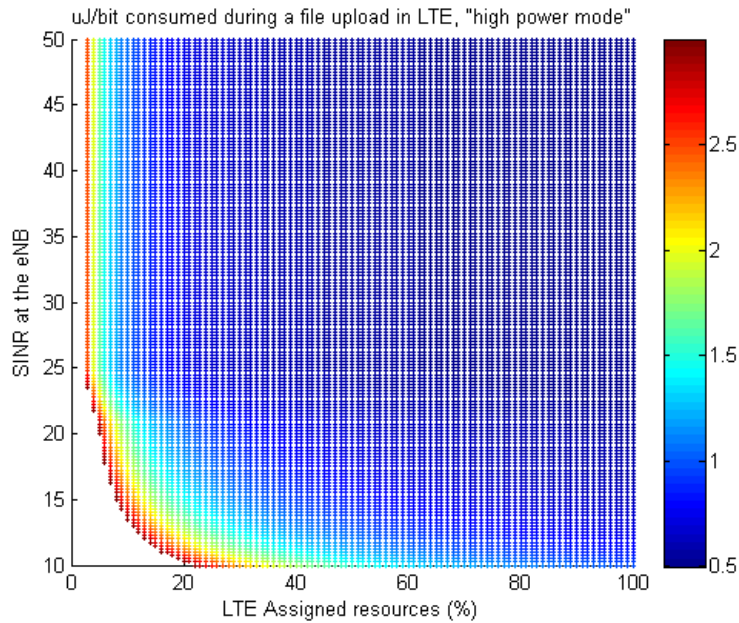


Figure 4-41: Joules per bit consumed during a file upload in LTE, “high power mode”

Assuming the best possible LTE scenario (LTE SINR at the eNB above 23dB, see Figure 3-5), Figure 4-42 presents the maximum Wi-Fi SINR such that it might be reasonable to make a VHO to LTE (as this would consume fewer joules per bit by using LTE lower than when using Wi-Fi), depending on the resources assigned in each network. The color bar is in units of dB. This figure shows that VHOs will never save energy unless the signal in Wi-Fi is extremely bad, even if the LTE signal is the best possible. For scenarios without worse LTE coverage, VHOs will be even more unlikely.

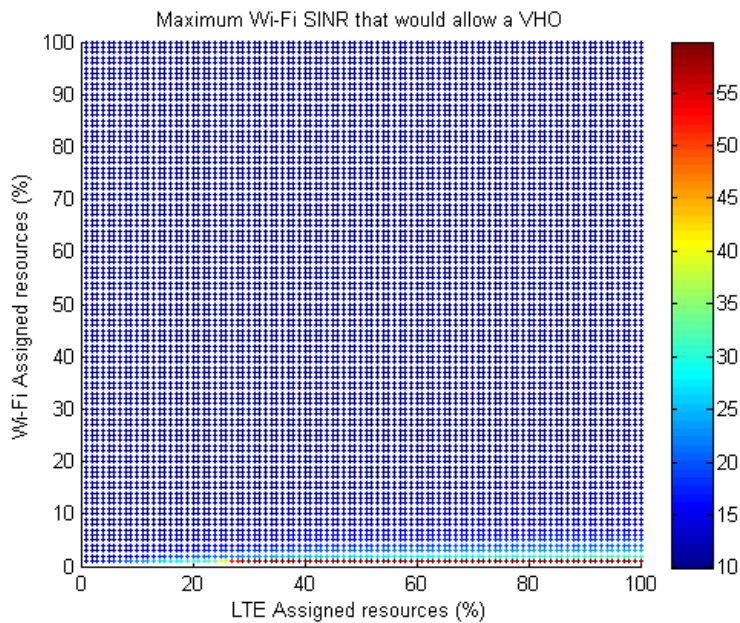


Figure 4-42: Maximum Wi-Fi SINR so a VHO may be made; best LTE coverage and “high power mode”

4.8 Web Browsing

Web browsing is another very common activity in mobile devices nowadays and therefore this scenario is interesting to study from an energy perspective. In order to do so, the HTTP (Hypertext Transfer Protocol) model presented in [113] will be used. In this model, the different parameters involved in a Web page request are described as the following:

- The reading time – the interval between two consecutive Web page requests. It answers to an exponential distribution with mean 30 seconds.
- The main object size in each request is given by a truncated lognormal distribution with mean 10710 bytes, standard deviation 25032 bytes, minimum 10, bytes and maximum 2 Mbytes.
- The number of embedded objects pair page is modeled using a Truncated Pareto distribution with mean 5.64, maximum 53, scale 2 and shape 1.1.
- The sizes of the embedded objects present a similar behavior as the main object sizes, with a mean 7758bytes, a standard deviation of 126168bytes, a minimum of 50bytes and a maximum of 2Mbytes.
- Finally, the Web page parsing time has an exponential distribution with 130ms as mean.

It is important to note that the model just described was presented in 2006. Since that time the size of both main and embedded objects had significantly increased. Therefore in following paragraphs two different cases will be analyzed, one using the parameters in [113], and a second one with those parameters (mean sizes, standard deviations, maximums and minimums) multiplied by 10. In order to be able to extract some conclusions, the figures and measures shown in the next paragraphs result from averaging 1000 randomly generated sessions.

Before getting into the VHO decision, there is one aspect to consider. If the VHO is made, there are two options: leaving the LTE interface on in idle between reading times or turning it off and then on again if there is a new request. Hence, the latter will be better if the energy to turn the interface on and off and to associate with an eNB is lower than the power in idle multiplied by the reading time plus the tail energy. Due to the huge tail energy in LTE* measured by Huang et al., it will be better to turn the interface off each time. Nevertheless, future implementations may change this.

Figure 4-43 shows the consumed energy during a web surfing session in the two cases just described. Note that, in case of making a VHO to LTE, according to the section 4.1 it would be better to turn off the Wi-Fi interface if the session is going to be longer than 252 seconds. For mobile Web surfing most sessions last less than 100 seconds according to Zhao et al. [114], so it is considered that the Wi-Fi interface is not turned off. In the graphs, it is represented Web surfing sessions of 8 requests. As it is possible to appreciate, VHOs to LTE will never save for this kind of traffic.

* Note that the long DRX timer is ~11 seconds, a smaller value would be more energy efficient at the cost of more signaling overhead and scheduling delay.

The energy in such graphs is formed by the following elements:

- If there is a VHO:
 1. (Web page request arrives) Energy to turn on the LTE interface (24mJ)
 2. Energy to associate with a eNB (250mJ/s * 1 second)
 3. Energy to obtain the channel in LTE (1210.7mJ/s * 260ms)
 4. Energy to download the first main object (see section 4.5.2)
 5. Energy in connected-tail during the parse time (1060mJ/s * parse time)
 6. Energy to download the embedded objects (see section 4.5.2)
 7. Energy to turn off the LTE interface.
 8. Energy in idle Wi-Fi during all the process
 9. After the reading time a new request arrives, back to point 1.

- If there is not a VHO:
 1. (Web page request arrives) Energy to obtain the channel in Wi-Fi (80ms * 124.4mJ/s)
 2. Energy to download the first main object (see section 4.5.2)
 3. Energy in connected-tail during the parse time (119.3mJ/s * parse time)
 4. Energy to download the embedded objects (see section 4.5.2)
 5. Energy in connected tail in Wi-Fi (240ms * 119.3 mJ/s)
 6. Energy in idle Wi-Fi during the rest of the time (1.9mJ/s * [reading time - 240ms])
 7. After the reading time a new request arrives, back to point 1.

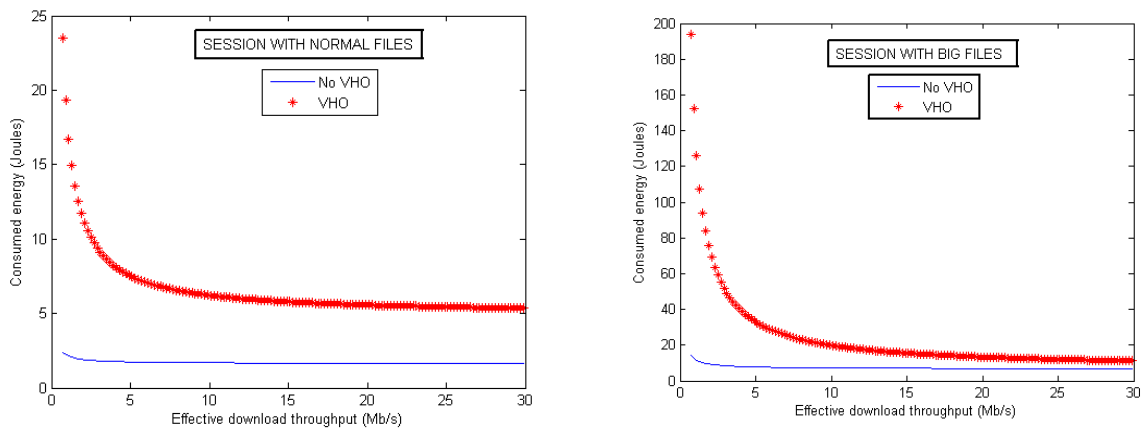


Figure 4-43: Energy consumed during a Web surfing session

4.9 Wi-Fi Leave and Recovery Threshold

The Wi-Fi leave and recovery thresholds were already introduced in section 3.3.9.1 and have been mentioned repeatedly in the earlier sections. The recovery threshold determines the minimum perceived Wi-Fi signal that needs to be received by the UE so it will connect to a Wi-Fi AP. As mentioned, there is a tradeoff between energy saved and the ping-pong effect: as the lower this threshold is, the sooner the UE connects to a Wi-Fi AP and starts saving energy. On the other hand, too low a value can provoke a very damaging ping-pong effect and consequently energy would be wasted, rather than being saved.

The leave threshold is the minimum Wi-Fi signal required for the UE to leave the Wi-Fi network. This value is usually lower than the recovery threshold in order to avoid the ping-pong effect. There is a similar tradeoff with this threshold: the lower it is, the more time the UE is utilizing Wi-Fi and hence saving energy; but if it is too low, the UE may lose connectivity with the Wi-Fi network before establishing a connection with LTE, which would lead to a period of complete unavailability. Note that this may not be bad. Since the time needed to associate to the eNB is very low (~1 second), the probability of receiving a service request in that time is very low and hence a possible approach could be just assuming this unavailability time. Nevertheless, this would not work if the Wi-Fi signal is lost during a connection because a period of unavailability would mean at least a temporary loss of the connection.

4.9.1 Leave Threshold

According to the measures used throughout this thesis, a UE needs 1 second to establish a connection with a LTE network. Hence, a UE must start a VHO from the Wi-Fi to the LTE at least 1 second before losing Wi-Fi connectivity (which is assumed to occur when the Wi-Fi SINR < 8 dB), otherwise there will be some time during which the UE will be completely unavailable via any network.

This leave threshold is the mechanism the UE utilizes together with the potential loss of Wi-Fi signal: when the received SINR is below this threshold, then the Wi-Fi connectivity is in danger of being lost and hence the UE must leave before completely losing connectivity.

The movement speed of the UE and the environmental conditions greatly affect this threshold. If the UE is stationary, then the signal will not change very much and if it does change it will do so very slow. If the UE is stationary, this threshold can be only 2 or 3 dB above the minimum Wi-Fi signal.

On the other hand, if the UE is moving rapidly, then the received signal strength can change completely in very few seconds. In this case a specific threshold value is not so obvious. In order to study the optimal value for this threshold while considering the random nature of the shadow fading attenuation, 300 simulations over different paths were made and the results for different leave thresholds were compared. The results in all the paths were averaged and are presented in following paragraphs.

Figure 4-44 shows such paths. The figure represents a moving UE that is leaving a Wi-Fi AP's coverage zone. The color bar is in dB and it shows the SINR at each position for one of the simulations out of the 300 that were done, for each path. The UE is moving at an average walking speed of 1.4 m/s, the standard deviation of the shadow fading is 8 dB, and the AP is placed outdoors.

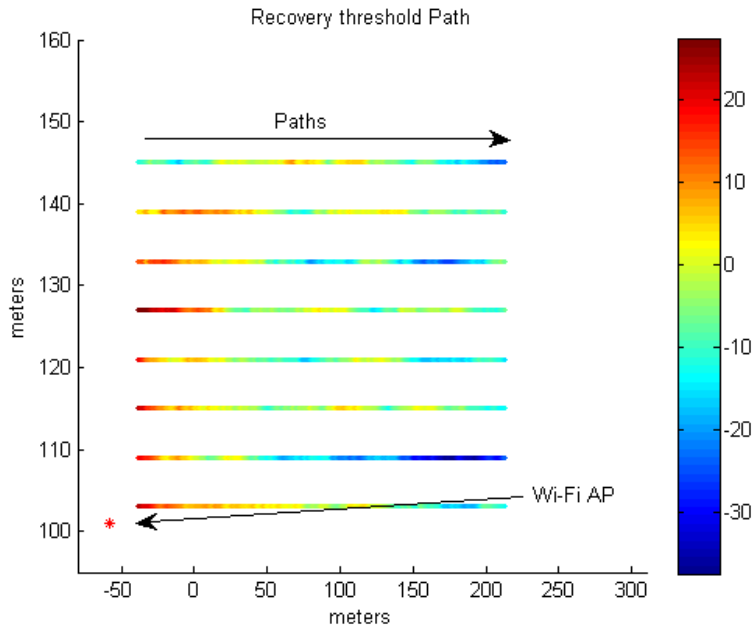


Figure 4-44: Wi-Fi Leave Threshold Path

Before going into the details of the simulations it is necessary to introduce a new concept. Depending on each UE and its configuration, the SINR will be measured periodically. If in one of these measurements the SINR falls below the change threshold, but it is still above the minimum received signal strength, then according to the previous paragraphs the UE will start a VHO to LTE. This will sometimes result in unnecessary VHOs. In order to avoid this, UEs wait to confirm that the signal is not getting better in the next X milliseconds. This time X has been called a “waiting time”*. Again there is a tradeoff: the longer the UE waits, the fewer unnecessary VHOs will be made; but if it waits too much, then it may lose connectivity. There is another approach regarding this timer just described: the switch can occur, but another switch will not be made unless things get considerably better or the dwell timer has expired.

Hence, depending on the change threshold and on this waiting time, the UE may move out of Wi-Fi coverage before having time to connect via LTE. Figure 4-45 shows in how many of those 300 simulations this happened for different leave thresholds and for different waiting times, in average for all the paths. Note that the leave threshold in the x-axis represents the amount in dB above the minimum signal (8 dB).

* Sometimes it is also referred in the literature as “dwell timer”

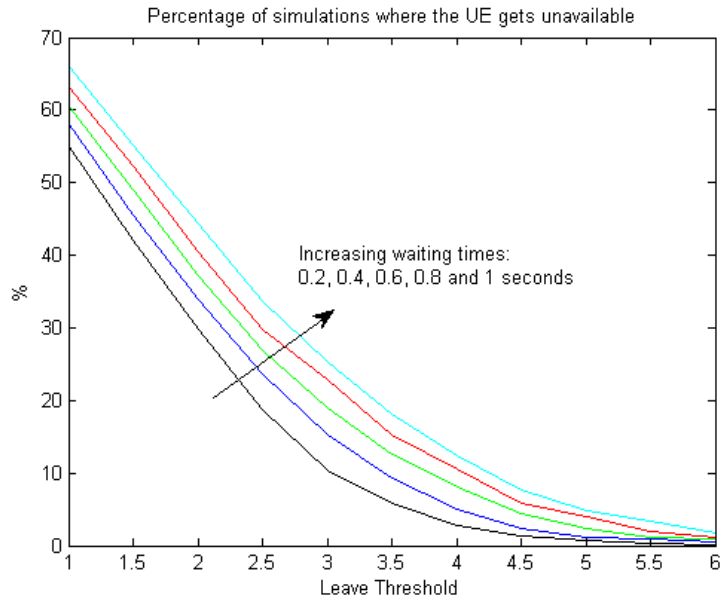


Figure 4-45: [Leave Threshold] VHOs % of simulations where the UE gets unavailable for different “waiting times”

In Figure 4-45 the UE required 1 second to establish a connection via its LTE interface. However, this time can vary a lot with different UEs, networks, and the environmental conditions. Figure 4-46 shows how these results change with a waiting time of 400 ms rather than 1 second.

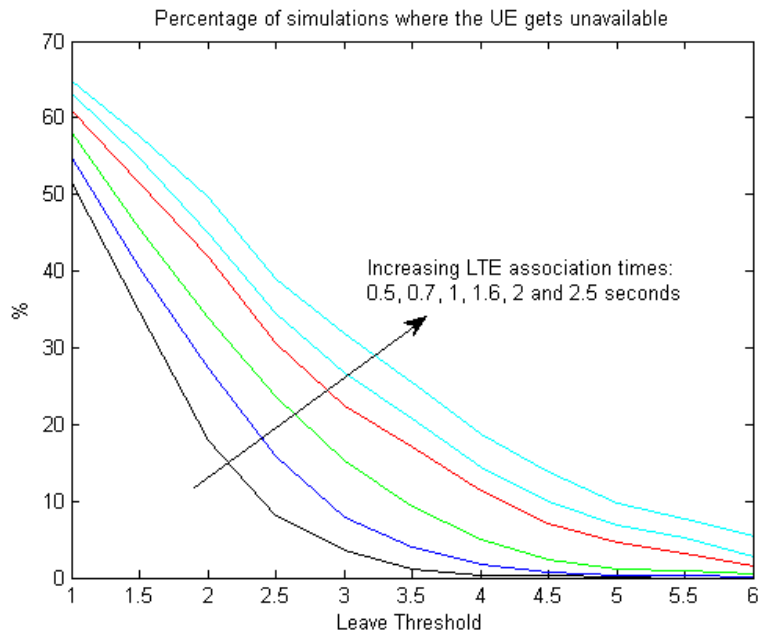


Figure 4-46: [Leave Threshold] VHOs % of simulations where the UE gets unavailable for different association times

With different configurations these unavailability points increase and decrease. It will be up to each UE manufacturer and network operator to decide upon the parameters that best satisfy their needs, while exploiting the different tradeoffs previously explained.

4.9.2 Recovery Threshold

In this subsection the optimal value of the minimum signal required to change to the Wi-Fi interface will be studied. Exactly as in the leave threshold there is a waiting time that the UE will wait before changing to the Wi-Fi interface. As mentioned in the introduction to this section, this value must be large enough to guarantee that the UE will remain stable for a certain amount of time. According to section 4.1, a UE will change to the Wi-Fi interface in order to stay inactive if the expected time that Wi-Fi connectivity will remain available is longer than 34 seconds in a very unfavorable to LTE scenario and longer than 18 seconds in the normal case.

The same approach as used in section 4.9.1 has been followed here. 300 simulations over different paths have been made, resulting in 300 vectors with the SINR value at each position per path. Afterwards, an experiment for each combination of recovery threshold and waiting time was performed, measuring the average time the Wi-Fi network remains available for each combination, i.e. the amount of time the SINR is above 8 dB. Finally, these have been averaged between all the paths.

Figure 4-47 shows the paths and the SINR evolution along that path for one of these 300 simulations. Such paths correspond to 180 seconds of a UE moving at a speed of 1.4 m/s. The color bar is in dB.

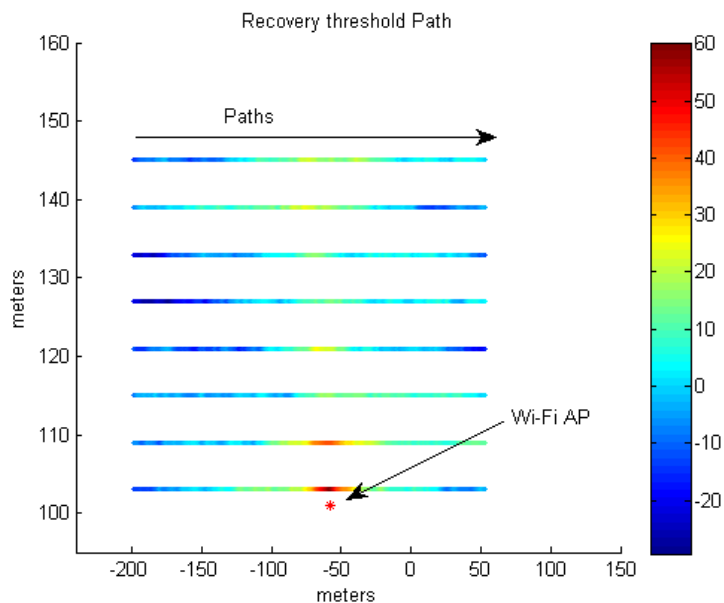


Figure 4-47: Wi-Fi Recovery Threshold Path

Figure 4-48 shows the results of these simulations. Note that if the recovery threshold is too high, then the UE will take longer to connect via the Wi-Fi interface. Since the UE is passing through a Wi-Fi coverage area, if it takes longer to connect to it, then the UE may exit the Wi-Fi area before establishing a connection. That is the reason why the average times decrease from a certain recovery threshold; which is the optimal value for this scenario. Again, each UE manufacturer and network operator must find an appropriate combination of these parameters that best satisfy their needs.

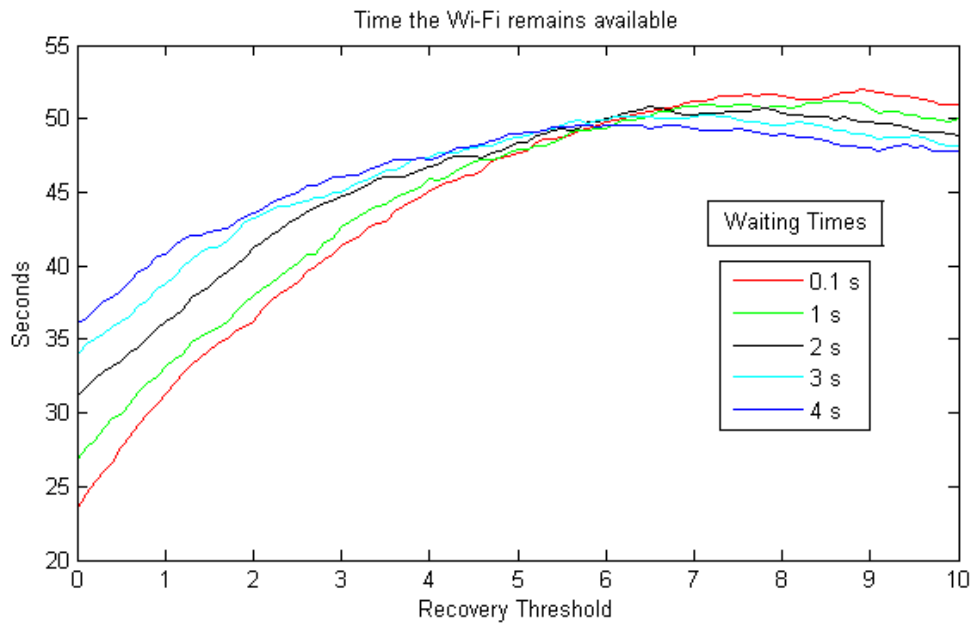


Figure 4-48: [Recovery Threshold] Time the Wi-Fi network remains available

Finally, in the Figure 4-49 it is shown the probability of not connecting to the Wi-Fi network in the entire path. As it was mentioned before, this can occur if the recovery threshold is too high and/or the dwell timer is too long. Hence, such figure shows how probable it is for this to happen given a certain threshold and dwell timer. The results are averaged from the 8 paths shown in Figure 4-47, with 300 random simulations per path. Note that the x-axis represents the amount of dBs above the minimum signal (8 dB), exactly like in the previous figures.

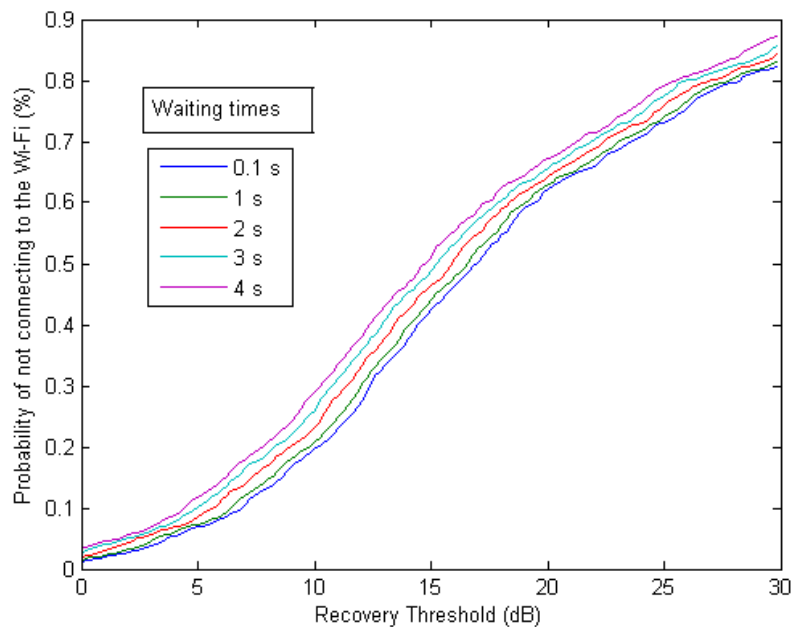


Figure 4-49: Not-connecting to Wi-Fi probabilities

4.10 Other processes involved during a VHO Decision

In this chapter we have studied how to make an optimal decision in order to save as much energy as possible by making a VHO. In these optimal decisions variables such as the load of each network, the assigned resources, or the interference have been considered and, depending on their values, different choices were revealed as being the most energy efficient choice.

However, all these parameters change with time, with each network and device, and with the environmental conditions, hence these parameters must be (periodically) measured. In the following subsections, some comments regarding how to do these measurements will be given. Due to the limited duration of this thesis project only some hints and recommendations are presented here. Future investigations in this area are needed to check the validity of the proposed solutions.

Note that the use of these proposed techniques and solutions imply a certain expenditure of energy which has **not** been taken into account in the previous sections. Nevertheless, all of the previous sections have shown how VHOs can potentially save energy and hence this extra energy is a price to pay in order to achieve greater savings. We will consider some of the additional expenditures of energy in the subsections of this section.

4.10.1 Wi-Fi AP Discovery

As explained in the section 3.3.9.1, the first task for a UE is to detect the presence of an accessible Wi-Fi network and to decide if its signal is stable and sufficient to connect to.

As a first approximation the UE can turn on the Wi-Fi interface and simply look for a Wi-Fi AP. However, this process is not automatic and it is typically up to the user to actually turn on the interface so that the device can look for available APs. Of course this process could be automated by the handoff algorithm.

In our scenario this process is to be transparent to the user, hence the device has to detect these APs on its own. In order to do so, several approaches could be followed:

1. Software could turn on the Wi-Fi interface periodically. This is not very energy efficient, but it can be worthwhile if the potential energy savings are large and the other methods are not sufficiently accurate.
2. Estimate the position of the UE. The UE could determine its position via some localization technique, i.e. GPS or radiofingerprinting. This approach implies some kind of offline phase or machine learning since the UE must know where the accessible APs are before arriving near them.
3. Sharing information between UEs. In this case either the LTE network helps distribute such information or an external server provides this service. The latter could imply a significant increase in the energy consumed if this information needs to frequently be downloaded in the field.
4. Combinations of any of the above.

The word *accessible* is especially important for a simple reason: in a city there are thousands of Wi-Fi APs, however a given UE will only have access to the Internet via a tiny percentage of them. Hence, only those APs that the UE can actually connect via are targeted in this localization. Such APs points can be divided into three categories:

1. *Private Wi-Fi networks*: these are typically Wi-Fi APs at the user's home, the one at the user's office, perhaps ones at a relative's/friend's/... house, etc.
2. *Free public Wi-Fi APs* in malls, restaurants, etc. The time a normal user spends in these locations is small in comparison to the first category of location and using most of these APs requires some kind of user intervention.
3. *APs which provide automatic security solutions, e.g. using Wi-Fi 802.11u/Hotspot 2.0*. The number of these types of APs is expected to grow significantly with an increasing interest from operators in offloading traffic from their wide area cellular networks.

Once the UE has identified the presence of an accessible AP, it has to determine if such an AP is stable, i.e. if it will be available for sufficient time to actually save energy. At this point it is important to remember the unpredictable behavior of shadow fading attenuation. If a user is moving, the UE can very easily lose the Wi-Fi signal from an AP because the UE enters/leaves a building, passes in front of a large wall, gets into an elevator, or some other reason.

Whether the UE is moving is not the only important factor that needs to be taken into account before making the decision to change to the Wi-Fi interface. Obviously, the UE has to measure the Wi-Fi signal from the AP and, unless this signal is above a certain threshold the UE will not even consider making a VHO to the Wi-Fi interface.

Taking into consideration the factors explained above, the following approaches were considered the most energy efficient ones and hence they are proposed to be used in combination with the VHO algorithm.

A radiofingerprinting technique will let the UE know if it enters into a zone with a potentially accessible Wi-Fi AP. For example, this zone could be a perimeter of 100 meters around the user's home. There is obviously an offline phase associated with this approach that will have to be considered. A very similar approach was followed in the work done by Delgado Romera [115]. In that paper was also shown how the GPS technique is much more accurate but at the same time consumes much more energy and it does not work indoors.

At the same time, the UE can monitor if it is moving or not (note that it is only important when it risks moving out of coverage, not its actual speed). Two examples regarding how to do so consist of examining the characteristics of the received radio signals or using an accelerometer. Nowadays an accelerometer is available in most smartphones.

A moving UE will eventually enter one of these predefined zones and it will start monitoring its movement. Once the UE has stopped for a certain time, it will be very likely that the UE has reached its destination. The UE will then turn on the Wi-Fi interface with the hope of finding the expected Wi-Fi AP. If it does find an AP and the received signal is strong enough, then it will connect via this AP. If it does not find an accessible Wi-Fi AP, then it will wait until the user moves again and the next time it stops, it will try again unless it has exited the predefined zone(s).

As explained at the beginning of this section, due to the limited duration of this thesis project these solutions could not be tested and validated and hence their energy efficiency and correct functioning cannot be assured. Nevertheless, based upon extensive background research, it is considered that these represent a potential good approach to address these issues.

4.10.2 Parameter Measurement

The UE is now connected to a Wi-Fi network and eventually a connection request will arrive, either mobile or network-originated. The UE must now decide if it is worth changing to the LTE interface in order to perform the requested activity or if it is better to remain connected via the Wi-Fi network.

Based upon the power models for each network, the UE will estimate the expected energy that would be consumed in both cases. These models have certain inputs which change with each network and with time, and hence they must be periodically updated. In particular the following parameters may change:

1. *Assigned bandwidth* in each network: this represents the amount of resources the network gives to the UE which changes with the load and the resource allocation policies.
2. *Perceived SINR* in each network and in each direction of the communication: the UE will not be able to actually transmit at the speed assigned by the network; if it has a poor SINR, there will be more retransmissions, which will decrease the throughput.

Therefore these parameters need to be measured, either periodically or prior to the VHO decision.

In the case of Wi-Fi, the SINR is very easy to measure since the UE is already connected via this interface. On the other hand, figuring out the amount of resources the network would allocate to the user is more problematic. There are two possibilities to solve this issue: making small tests periodically to measure these parameters or directly asking the AP. The latter would require some kind of communication protocol with the network which is not available today for most Wi-Fi APs.

For LTE there is an additional problem as this interface is powered off. The LTE signal is more stable than the Wi-Fi signal and the achievable throughput can be more or less constant during a short period of time. Therefore a possibility is to use the values of the parameters stored the last time the UE was connected to an LTE eNB, if this was not long ago and if the UE has not moved too much. The other option would imply turning on the LTE interface and making the necessary measurements. A tradeoff between energy and performance is presented here and further studies are needed to learn which approach is better.

Finally, other important inputs to the estimation of power are the characteristics of the required service: the length of the call, the size of the download, the duration of the web browsing session, etc. How these may affect to the VHO decision has been already covered in detail in previous sections.

4.11 LTE Always on

So far it has been assumed that a UE can turn off its LTE interface and still be available for every kind of service or communication. However, this may not always be true. Depending on the type of services that are used and how these are provisioned mobile UEs may be forced to leave their LTE interface always turned on. In particular operator specific services such as mobile telephony are currently built on this assumption. Indeed, it seems that Android APIs (Application Programming Interfaces) do not allow to switch off a cellular interface, and hence the UEs have to be rooted for this. This scenario is studied in this section.

As discussed in sections 2.1 and 2.3, recent studies in 3GPP are focusing on mechanisms to offload certain traffic to the Wi-Fi network, especially when the LTE network is more loaded. Hence, it is of great interest to investigate the energy expenses of VHOs in such cases. Depending on this “extra energy” derived from offloading such traffic to Wi-Fi, the LTE operators (or the UEs if it is they who decide) may change their decisions and algorithms.

As described in Chapter 2, together with such offloading techniques, research and standardization regarding automatic authentication to Wi-Fi networks via the SIM card have been extensively performed. Hotspot 2.0 and 802.11u networks are examples of the results of such studies.

The new scenario will consider a situation where a UE is connected to LTE and it will want to offload some services (downloads, calls, or any other service) via the Wi-Fi interface; leaving the LTE interface in idle mode. Another consideration is that LTE operators will only be interested in offloading services which represent a significant volume of traffic. This is the reason why only the cases of offloading high definition video calls, downloads, uploads, and Web surfing sessions are studied.

4.11.1 Idle Wi-Fi

As mentioned earlier, LTE operators will be particularly interested in offloading traffic when the LTE network is heavily loaded. In this situation, it is possible that, for almost every connection, the UE will utilize the Wi-Fi interface. If every time the UE finishes one of these connections it turns off the Wi-Fi interface, it will have to turn it on again the next time, again spending the energy this consumes.

Depending on the number of connections via the Wi-Fi interface it may be better to leave this interface in idle mode when not in use. Figure 4-50 and Figure 4-51 study this phenomenon. Assuming that the Wi-Fi is never turned off after the first connection, the figure shows the minimum number of connections during a 5 and a 15 minutes interval that make this decision worthwhile in terms of energy. Obviously, this number of connections depends on the time the Wi-Fi has been on, i.e. the offloading period (5 and 15 minutes respectively).

Note that the energy consumed turning on the interface and associating and authenticating with the Wi-Fi network heavily depends on each UE and network. According to the values used in this thesis that energy would be around the 264 mJ: 24mJ turning on the interface plus 120mJ/s during the 2 seconds the UE needs to associate to the network. Exactly the same happens with the mJ/s consumed during idle mode via the Wi-Fi interface: this value can significantly change with each device and network. In the measurements performed by Huang et al. this corresponds to a value of 1.9 mJ/s.

Hence, these variables were used in the calculations that resulted in these figures. The results are shown for two different periods of time during which the LTE operator offloads traffic, i.e. during this period the UE keeps the Wi-Fi on all the time. The figure shows the number of connections the LTE would have to offload to Wi-Fi to make the decision of not turning off the Wi-Fi interface after the first connection in order to be worthwhile from an energy point of view (for the UEs).

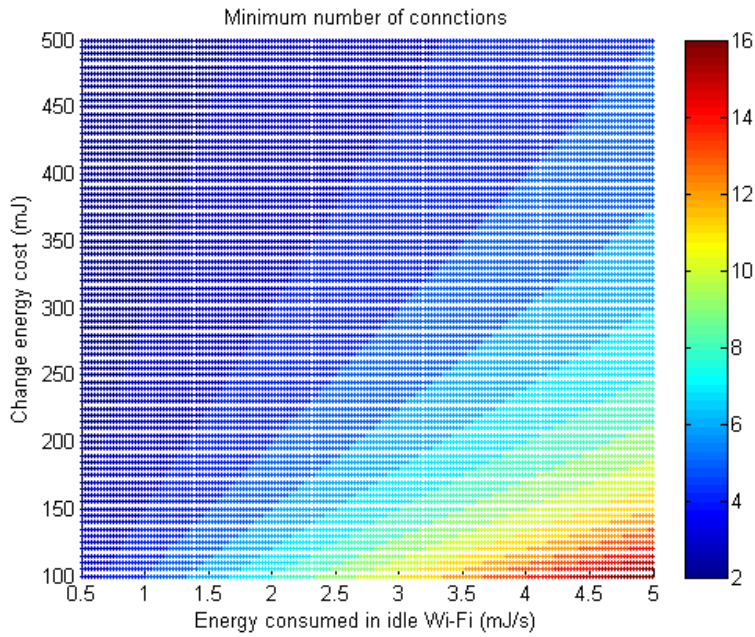


Figure 4-50: Number of connections to be worthwhile leaving the Wi-Fi interface on; offloading period of 5 minutes

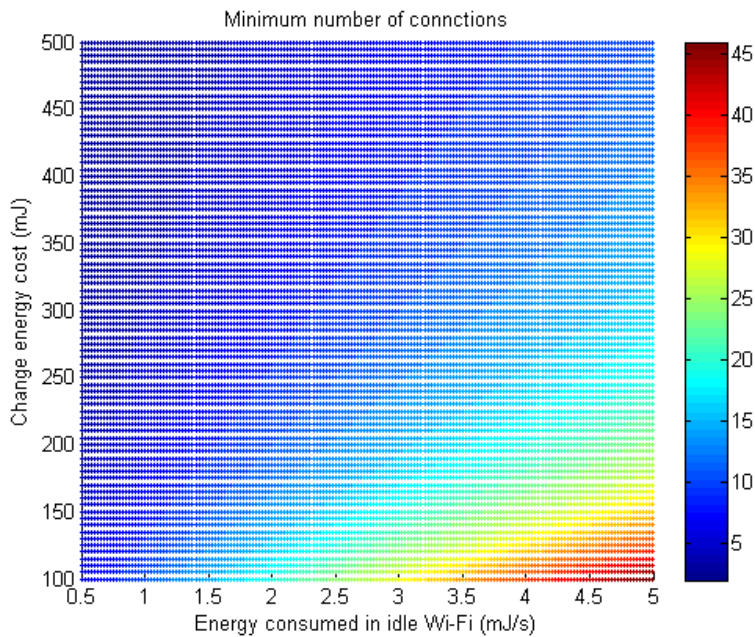


Figure 4-51: Number of connections to be worthwhile leaving the Wi-Fi interface on; offloading period of 15 minutes

Depending on the average number of connections the LTE operators decide to offload this decision will change. For each particular device the energy consumption will be different, potentially changing this decision as well. If the number of connections offloaded is below 2 in 5 minutes, then it will be worthwhile to turn the Wi-Fi interface off every time.

As a simplification and since we consider that receiving less than 2 connection every 5 minutes is very possible, in following sections it will be considered that every time a connection is offloaded to Wi-Fi, the Wi-Fi interface must be turned on and the UE must associate and authenticate to an AP. Once the service request is satisfied, the interface is turned off. Note that in this context, Web sessions are treated as a single “connection”.

4.11.2 High Definition Video Calls

In high definition video calls, the minimum required effective throughput is 1.5Mb/s. The following two subsections give a detailed analysis of both the low and high power mode in LTE when the LTE interface is always on. The same formulas utilized in section 0 are applied here.

4.11.2.1 LTE Uplink in "low power mode"

In the analysis in the section 4.5.2 it was shown that Wi-Fi consumes much less energy during a high definition video call than LTE. Hence it should be expected that VHOs from LTE to Wi-Fi will not only reduce the traffic in the LTE network but may save significant amounts of power. Figure 4-52 represents these savings. As discussed previously, the amount of savings will depend on the duration of the call. We calculate the energy savings as the energy spent in the call if it is not offloaded minus the energy if it is offloaded. We calculate these two terms as follows:

No offload:

1. LTE promotion energy (0.26 seconds * 1210.7 mJ/s)
2. Energy spent during the call ($1577,9 * \text{duration of the call}$; see Formula 4-7)

Within offloading:

1. LTE promotion energy (0.26 seconds * 1210.7 mJ/s)
2. Energy spent during the call while using the LTE interface ($1577,9 * (2+0.08 \text{ seconds})$)
3. LTE idle energy during the call ($20.1 \text{ mJ/s} * (\text{duration of the call}-2.08)$)
4. Energy to turn the Wi-Fi interface on (24 mJ)
5. Energy to associate with the Wi-Fi AP (2 seconds * 120 mJ/s)
6. Energy needed to establish the Wi-Fi connection (0.08 seconds * 124.4 mJ/s)
7. Energy spent by the Wi-Fi interface during the call ($763.13 * (\text{duration of the call}-2.08)$)
8. Energy to turn the Wi-Fi interface off (29 mJ)

Note that the differences in the tail energies are not taken into consideration here. These, especially in the LTE case, depend on the configuration by the user or network of parameters such as DRX timers or on cycles; which can change a lot and can be configured differently depending on the needs of UE and network. However, in general the LTE tail energy consumption is substantial.

Figure 4-52 (left part) shows that a large amount of energy can be saved. The Wi-Fi interface consumes so much less energy that, as soon as there are sufficient Wi-Fi resources, it is *always* a good idea in terms of energy to offload high definition video calls.

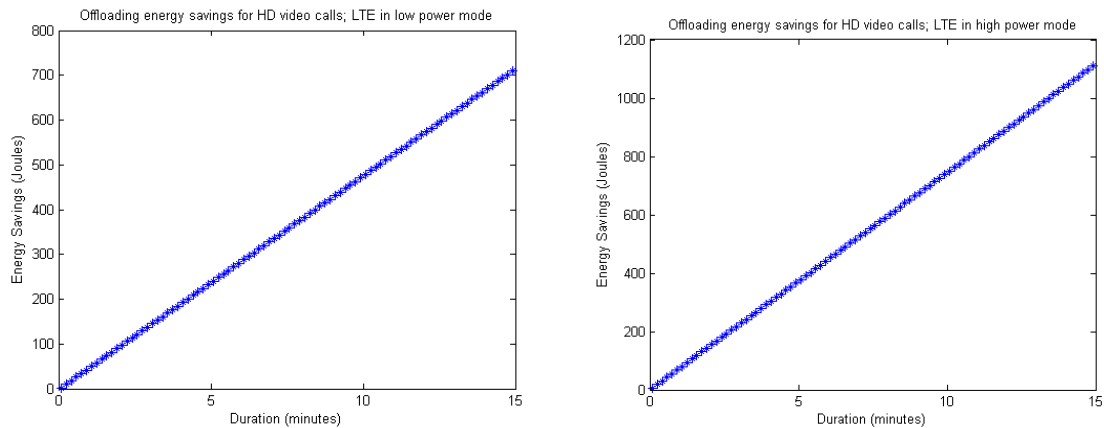


Figure 4-52: Offloading energy savings for HD video calls

4.11.2.2 LTE Uplink in "high power mode"

If the LTE is "high power mode", even more energy savings are expected. Using the formulas from section 4.5.3 and following the approach of the previous section, the energy savings are shown in Figure 4-52, right part.

4.11.3 Downloads

Based upon the analysis performed in the section 4.5.2, it is expected that, in some cases, offloading download traffic to Wi-Fi will save energy. This will happen when the energy consumption using the Wi-Fi interface is lower than when using the LTE interface and when the size of the download is large enough to compensate for the extra energy needed for the VHO to the Wi-Fi interface. Given a certain effective throughput at the UE (which will be determined by the resources assigned to the UE and by the SINR), Figure 4-53 shows the minimum size of the download which makes the VHO to Wi-Fi energy efficient. The color bar is in **kbytes** and the non-colored points are those where the VHO would never save energy.

Following a similar approach to the previous section, the energy of offloading the download and of not offloading is computed as follows:

No offload:

1. LTE promotion energy ($0.26 \text{ seconds} * 1210.7 \text{ mJ/s}$)
2. Energy spent during the download (see Formula 4-10)

With offloading:

1. LTE idle energy during the download via the Wi-Fi interface ($20.1 \text{ mJ/s} * \text{transaction time via Wi-Fi}$)
2. Energy to turn the Wi-Fi interface on (24 mJ)
3. Energy to associate with the Wi-Fi AP ($2 \text{ seconds} * 120 \text{ mJ/s}$)
4. Energy to establish the Wi-Fi connection ($0.08 \text{ seconds} * 124.4 \text{ mJ/s}$)
5. Energy spent using the Wi-Fi interface during the download (see formula 4-11)
6. Energy to turn the Wi-Fi interface off (29 mJ)

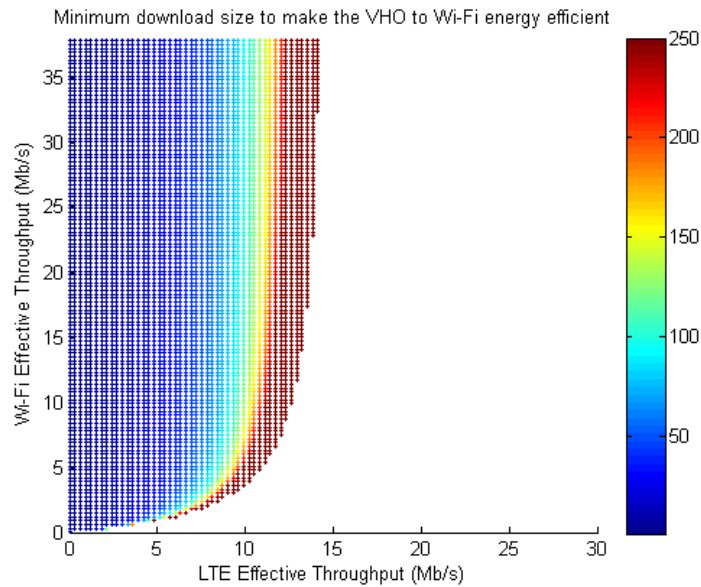


Figure 4-53: Minimum download size to make the VHO to Wi-Fi energy efficient

The figure shows that in any scenario where the LTE effective download throughput is less than ~13-14 Mb/s, VHO from LTE to Wi-Fi during downloads will save some energy if the download size is large enough. Today in LTE networks this situation is very possible. Huang et al. measured an effective throughput via LTE of ~13 Mb/s in real world scenarios.

As explained, the download throughput depends on the SINR at the UE and on the assigned resources. Figure 4-54 shows the combinations of these factors that make this throughput in LTE lower than 14 Mb/s. The color bar is in Mb/s.

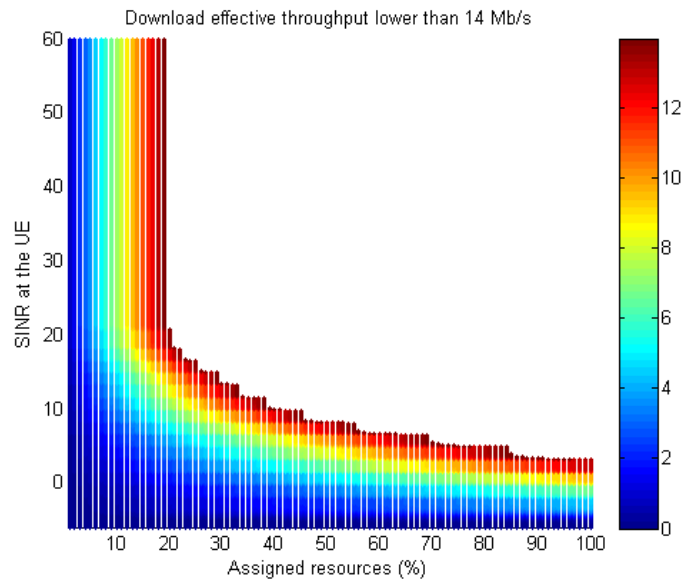


Figure 4-54: Download effective throughput lower than 14 Mb/s

Again, we can appreciate how these situations are very possible. Finally, Figure 4-55 shows the energy saved (positive values) and the energy wasted (negative values) for several sizes, given the effective download throughputs in both networks, when offloading downloads.

The figure shows that neither the energy savings nor the energy wasted when offloading a download is significant in most cases.

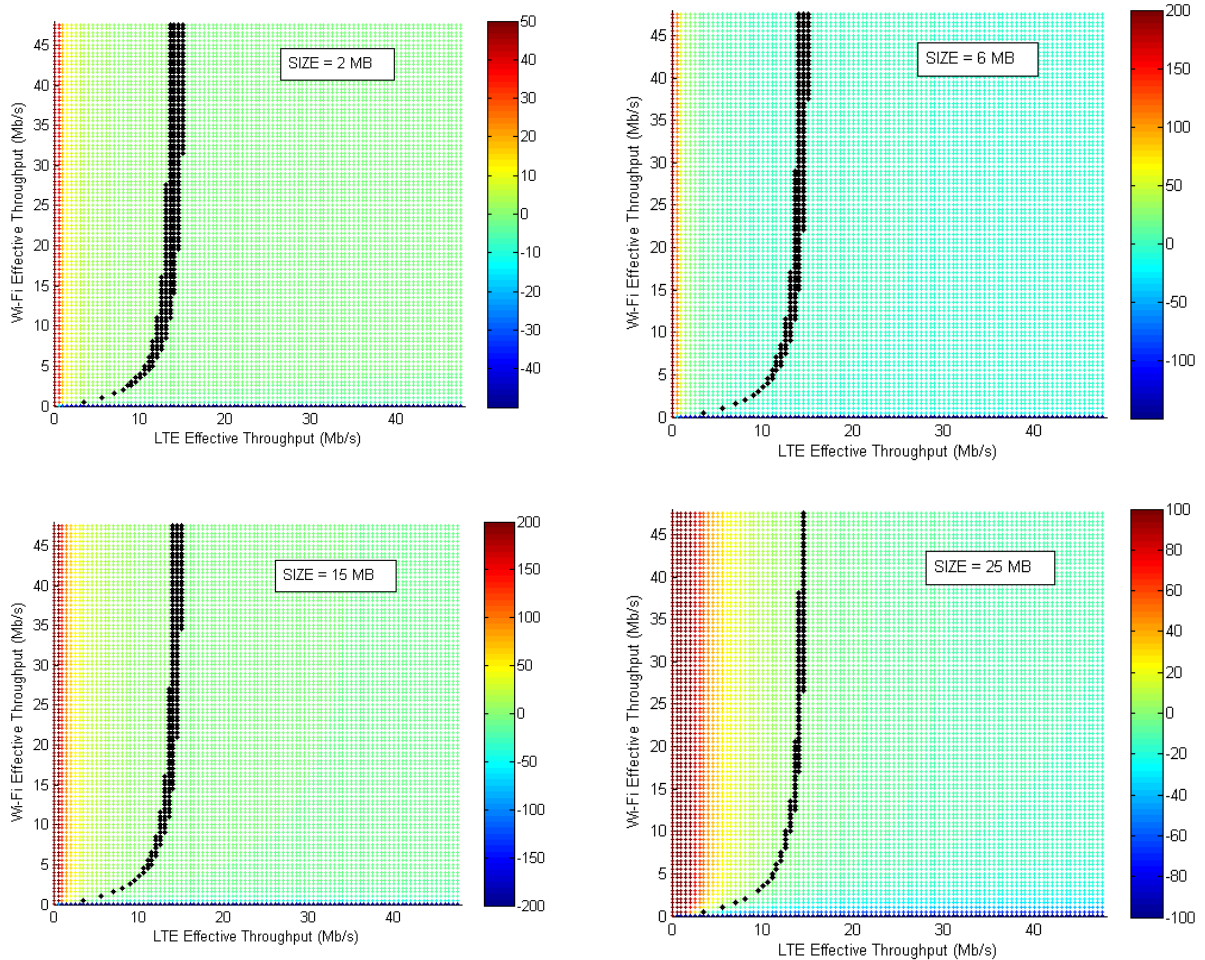


Figure 4-55: Energy savings & costs due to offloading a file download of several sizes

4.11.4 File Uploads

File uploads represent another interesting type of traffic for the operators to offload. Again, the scenario that is considered corresponds to a LTE-connected UE which needs to upload a file and decides to do so via the Wi-Fi interface, which was previously powered off.

4.11.4.1 LTE in "low power mode"

Section 4.7.1 showed that Wi-Fi is usually less power consuming than LTE for this type of service so some energy savings could be expected in this case. Figure 4-56 shows the energy saved (positive values) and the energy wasted (negative values) for several sizes, given the effective upload throughputs in both networks.

The color bar is the energy of not offloading minus the energy of offloading. Each one of them is formed by these elements:

No VHO:

1. LTE promotion energy (0.26 seconds * 1210.7 mJ/s)
2. Energy spent during the upload (Figure 4-35)

With a VHO:

1. LTE idle energy during the upload via the Wi-Fi interface ($20.1 \text{ mJ/s} * \text{transaction time in Wi-Fi}$)
2. Energy to turn the Wi-Fi interface on (24 mJ)
3. Energy to associate with the Wi-Fi AP (2 seconds * 120 mJ/s)
4. Energy to establish the Wi-Fi connection (0.08 seconds * 124.4 mJ/s)
5. Energy spent utilized by the Wi-Fi interface during the upload (see Figure 4-36)
6. Energy to turn the Wi-Fi interface off (29 mJ)

These figures show how, as soon as the LTE conditions get good, some energy will be always wasted. Nevertheless, these are not really significant under normal Wi-Fi conditions. The energy savings can be achieved when the LTE is loaded or its signal is poor, which in these offloading scenarios can be quite common as has been discussed in previous sections.

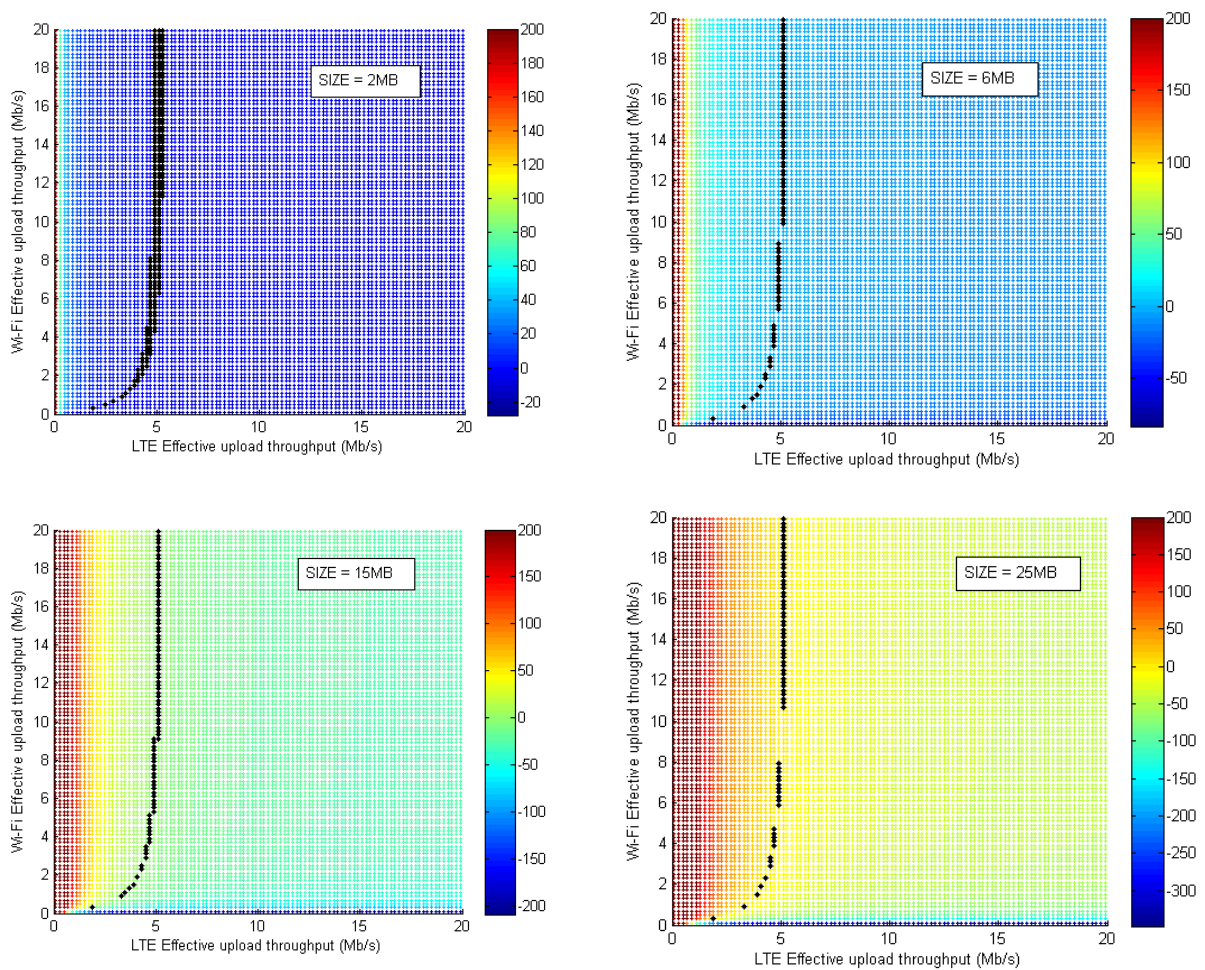


Figure 4-56: Energy savings & costs due to offloading a file upload of several sizes; LTE in "low power mode"

4.11.4.2 LTE in "high power mode"

The analogue figure to the previous one is presented here. In this case, the LTE is in "high power mode" and as can be appreciated, there will be savings almost always since the LTE consumes more energy now. Besides, for big files these can be quite significant.

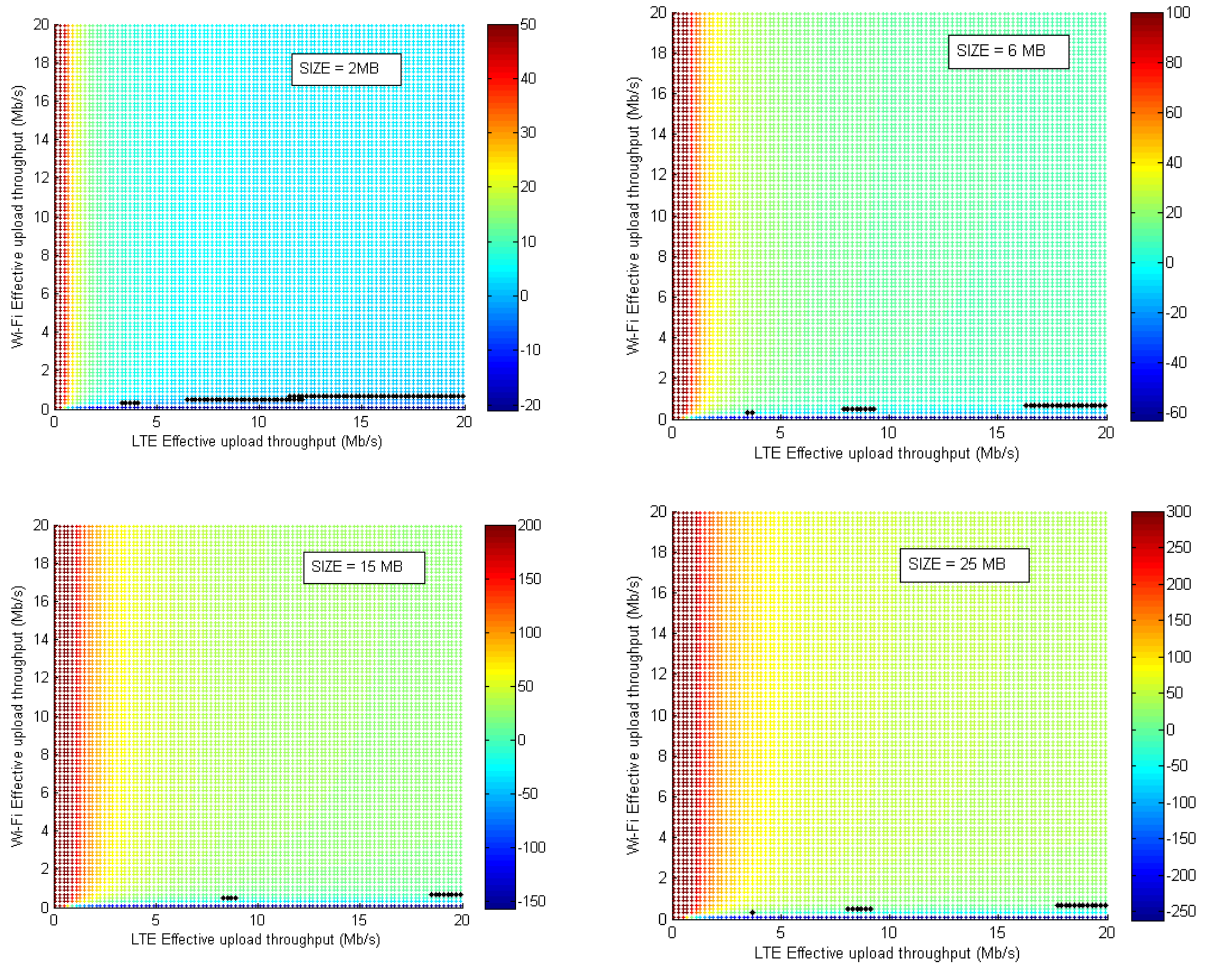


Figure 4-57: Energy savings & costs due to offloading a file upload of several sizes; LTE in "high power mode"

4.11.5 Web Browsing

Web browsing sessions is another type of traffic that the operators may want to offload to Wi-Fi. As shown in section 4.8, this type of traffic is always more energy efficient via Wi-Fi and hence offloading it may save energy under the appropriate circumstances.

Here again, if the session is offloaded, there are two options: leaving the Wi-Fi interface on between reading times or turning it off. Like in the case analyzed in section 4.8, the latter will be better if the energy to turn the interface on and off and to associate with an AP is lower than the power in idle multiplied by the reading time plus the tail energy. According to the measures used so far in this report, the reading time would have to be bigger than 140 seconds in order to be best to turn the interface off. The average reading time is 30 seconds so in following paragraphs it will be considered that it is not turned off.

Figure 4-58 presents the potential energy savings (positive values) and expenses (negative values). In the first figure, the main (mean: 10.7kbytes; std dev: 25Kbytes) and embedded (mean: 7.7kbytes; std dev: 126.16Kbytes) object sizes are the ones proposed in [113] while in the second one these are multiplied by 10 since such study is from 2006 and the Web pages sizes have increased considerably over the last years. The color bars are in Joules and the sessions are considered to contain 8 requests each, which is the average for mobile Web surfing according to [114]. The measures are averaged within 1000 different randomly generated Web surfing sessions. Note that the black points represent the frontier from where the VHO starts to save energy.

It is possible to appreciate in such graph that in few situations offloading these Web surfing sessions is going to save energy, especially in the case of bigger files. Besides, if the Wi-Fi conditions are very bad, the amount of energy wasted can be very significant. This is a little bit surprising considering the fact the Wi-Fi is more energy-efficient in this case (see section 4.8). However, the energy consumed in these sessions is very low and the big energy consumption in idle in LTE plays a very important role, resulting in these results.

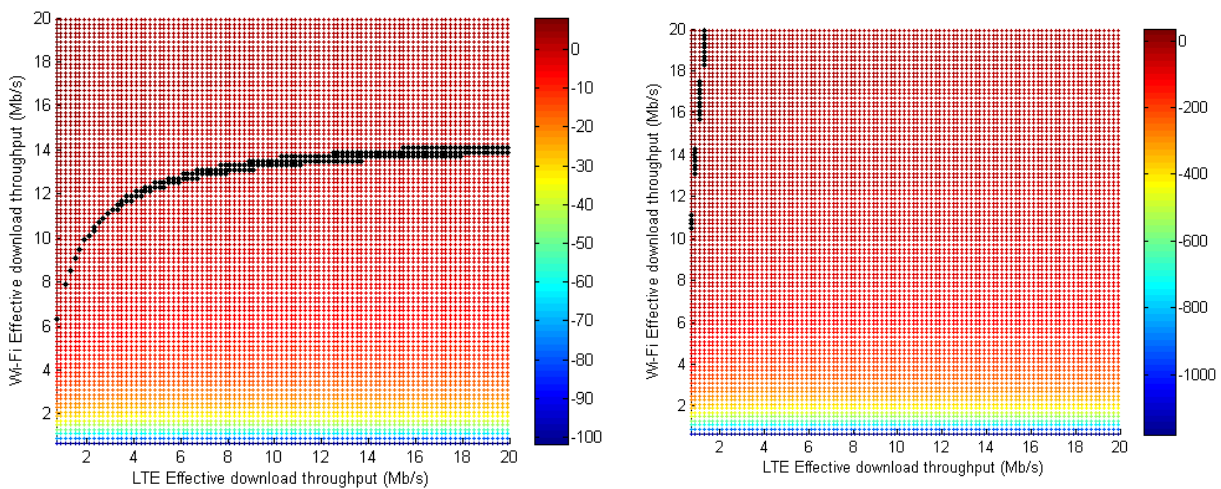


Figure 4-58: Energy expenses/savings when offloading a surfing session to Wi-Fi

5 Conclusions, Future Work, and some Reflections

5.1 Conclusions

The simulations have shown that extending the battery life of mobile devices is very possible by implementing VHO algorithms in mobile devices. In the approach followed, these automatic changes between LTE and Wi-Fi are service-driven: every time a VoIP call, a download or any other service is requested, the UE leverages the characteristics of such service, the environmental conditions (load, interferences) and its own characteristics and decides if changing RAT will save energy.

At the same time, it is possible to state that with current implementations, Wi-Fi is more energy efficient than LTE. Therefore, if the UEs can, they will leave this interface to stay in Wi-Fi and will come back momentarily to LTE only when some savings could be achieved. At the same time, WLAN offloading is no problem from an energy point of view.

Nevertheless, these potential savings heavily depends on the LTE RAN configuration, as appreciated in the big differences between [65] and [66], [67], for example. At the same time, it is expected to appreciate significant changes in the power consumptions in each interface over time with new implementations, probably in favor of LTE.

The services studied and the most important conclusions related to them are presented in the following subsections.

5.1.1 VoIP and Video Calls

According to the energy models used, VoIP calls are much more energy efficient in Wi-Fi. Hence, VHOs from LTE to Wi-Fi when these calls have to be processed are very likely to save energy; even if the LTE interface must be left on during the call. They need a very low bandwidth and hence are not really limited by high load or interferences. The drawback of Wi-Fi for VoIP is that the QoS is typically not guaranteed, therefore operator provided VoIP services are not suitable for offloading to Wi-Fi.

High Quality video calls present the same behavior as VoIP calls. Nevertheless, their required bandwidth is bigger and hence they will be rejected under poor coverage or high loads.

Similar conclusions can be drawn with High Definition video calls. In this case, the load and interferences play a more important role since the required throughput is considerably high.

5.1.2 Downloads

The first observation made was that, for downloads bigger than 10 Mbytes, the decision of making a VHO stops depending on the size but only on the effective download throughput at each network.

For these big downloads, it was appreciated that if the LTE conditions are good enough, this interface is always less energy consuming regardless of the Wi-Fi conditions. At the same time, if the Wi-Fi signal is good ($>20\text{dB}$), VHOs from Wi-Fi to LTE are very unlikely unless the LTE network load is very low. It was also observed that the load and the assigned resources have a large impact on the energy consumption and that big energy savings are achievable.

For small downloads, the potential energy savings decrease significantly, which provokes that the different parameters both of the device and of the network will change the VHO decisions a lot for different UEs.

Finally, in the case of offloading downloads to Wi-Fi some energy may be saved depending on the scenario. Nevertheless, in the cases where this does not happen, the energy expenses of offloading such service are usually not significant in comparison to the energy spent during other activities.

5.1.3 Uploads

VHOs from Wi-Fi to LTE will only save some energy in this case if the LTE uplink is in “low power mode” and only when the Wi-Fi conditions are quite poor. Nevertheless, under the appropriate conditions, some important savings could be achieved.

In the case of a LTE operator offloading file uploads to Wi-Fi it is found that neither the energy savings nor the wasted energy are significant in most cases unless the LTE network is heavily loaded and/or its signal is very poor. In this last case, offloading an upload to Wi-Fi could mean an important amount of saved energy, especially when the LTE is in “high power mode”.

5.1.4 Web Browsing Sessions

The most important conclusion is that VHOs are not useful neither from Wi-Fi to LTE nor from LTE to Wi-Fi. The reason for this consists of the fact that these sessions consume very few energy and hence the extra energy derived from the VHO plays a more important role than in other cases.

At the same time, in the second scenario where the LTE interface cannot be turned off, the potential wasted energy when offloading cannot be neglected, especially if the Wi-Fi conditions are bad. The reason for this is the energy consumed in idle mode by the LTE interface, which makes of these VHOs very energy consuming.

It was also observed that these Web surfing sessions are slightly less energy consuming in Wi-Fi. Thanks to this, some energy savings are achievable when the Wi-Fi conditions are good. Nevertheless, they are not really significant.

5.2 Future work

In order to complete and implement a VHO algorithm that actually saves energy, there are some aspects not fully covered in this Master’s Thesis work that require further analysis.

The first one involves the energy model of each interface. During the literature study, it was possible to observe how very different models have been proposed and how they offer very different results. In addition, during the experiments it was appreciated that variances in the energy model can change the VHO decision completely. Besides, there will be changes in the power consumptions in each interface over time with new implementations, probably in favor of LTE. These changes can be observed in Wi-Fi, comparing the different models published during along the years [65], [88] and how the energy-efficiency in this interface has improved.

For these reasons, it is considered that the different energy consumption parameters should be configured individually for each device towards a practical algorithm. However, one general question that remains to answer is whether it is worth doing that profiling, or if it is sufficient to use a very simple rule (“always use Wi-Fi when possible”). This would depend

on how important the battery life actually is for the users and it is something for the operators and manufactures to leverage.

At the same time, only some hints regarding an energy efficient way of discovering accessible Wi-Fi APs are given in this report. Such proposals have not been tested and therefore their performance cannot be guaranteed. Besides, there may be other solutions not mentioned more energy efficient. The same occurs with the process of measuring certain parameters needed during the VHO decision process. Specifically, when and how to measure the available throughput in each network at the moment of the decision in an energy efficient way must be further investigated.

5.3 Required reflections

Along this report it has been shown how the battery life of mobile devices can be optimized by means of service-driven VHOs. In order to so, mobile networks operators will have to implement certain algorithms in the UEs as well as device manufactures will probably have to provide certain information regarding the energy consumption of their products. Those companies that achieve these energy savings will be able to gain a very valuable competitive advantage and move forward in the industry.

This potential saving of energy has also a positive impact in the environment. If these savings are achieved on a large scale, a very significant amount of power can be saved every day. Besides, thanks to this Master's Thesis, users have the possibility to obtain a better understanding of their mobile device, helping them to make a better use of it.

Regarding the ethical issues related to this work, no violations of values and norms occurred. The experiments were done by means of simulation and all the external material used is properly referenced.

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