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Thin is green: Leveraging the thin-client paradigm for sustainable mobile computing ☆

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A B S T R A C T

Progress in the area of environmental sustainability for the mobile computing industry could be achieved by making advancement on two fronts: reducing the energy consumed by individual devices throughout their life cycle and reducing the rate at which these devices are discarded. In this work, to address both fronts, we propose the use of a thin-client approach, whereby a mobile device relies mainly on the resources at a remote server to carry out application tasks. To assess the benefits of the proposed approach, this work develops an analytical model as well as performs an empirical evaluation of performance and energy consumption on Android-based smartphones. In terms of energy, a reduction of approximately 11% in the average life cycle energy (LCE) is seen by increasing the device's usage life by even three months through a thin-client approach. In terms of performance, a thin-client device is shown to improve execution by 57% compared to a self-reliant device.

1. Introduction

The exponentially increasing demand for smartphones, tablets, and laptops has transformed the mobile communications sector into one of the fastest growing industries. The first phone call over the Global System for Mobile Communications (GSM) occurred in 1991, and presently 77% of the global population uses cell phones [1]. About 174 million smartphones were sold globally in 2009. It has been forecasted that smartphone sales will increase at a compounded rate of 30% by the year 2016. The *ANALYST* foresees that smartphones would contribute to a $320 billion market by 2016 [2]. In 2011, there were nearly five billion global mobile users, and 85% of these devices were capable of accessing the World Wide Web. The progression in mobile device technology also has brought a great deal of mobility and global connectivity. Accessing the Web and social networks through smartphones is becoming popular day by day. It is known that 61% of mobile subscribers in the United States have smart mobile devices [3].

The features and functionality of these mobile devices improve with time, but unfortunately their lifespan is very short, with most users upgrading their devices every 18–24 months [4]. This short lifespan leads to millions of cell phones and other mobile devices being discarded every year, thus contributing to a significant part of electronic waste, or e-waste. It was reported in [5] that nearly 19,500 tons of mobile devices were discarded in 2010, of which merely 2240 tons were recycled and the remaining 17,200 tons contributed to e-waste. Additionally, the increase in features and functionality of

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these smart devices is also responsible for a significant increase in their global energy consumption. Of the total energy consumed by information and communication technology (ICT), mobile devices are responsible for 10–20% [1,6,7].

In view of developing a reliably green and sustainable solution, we propose a model for reutilization of old mobile devices with the help of a cloud-based thin-client approach. This thin-client paradigm primarily operates on the concept of offloading a majority of computations to a remote server for executing the application logic. In most cases, the client is used for displaying the graphical output only. In this work, we propose an analytical model based on various critical parameters, such as life cycle energy (LCE), or energy consumption at various levels of the life cycle and performance improvement of old mobile devices. We further evaluate the performance improvement, end-user quality of the experience, and energy savings that could be achieved by reusing old or discarded mobile phones under a thin-client paradigm. The novelty of our work is accentuated via the LCE model for mobile devices, which provides a comprehensive insight into where and how energy savings could be achieved in the device's overall life cycle. Additionally, the life cycle model provides a clear path for steering the design towards a fully sustainable structure.

The specific contributions of this work include the following:

- A proposal for and evaluation of an analytical model for LCE consumption of mobile devices in order to understand energy consumption during various phases of a mobile device's life cycle.
- A derivation of the theoretical conditions for energy savings under a thin-client paradigm.
- A comparative empirical evaluation of performance and energy consumption of old and new Android-based smartphones operating under the thin-client paradigm.

Results of this work provide insight into the impact on LCE consumption of mobile devices due to an increase in number of usage phases. It is shown that a reduction in the average LCE of approximately 11% can be achieved with just a three-month increase in the duration of a device's usage phase. The proposed thin-client approach for smartphone reutilization was experimentally implemented by means of a laboratory-based setup of the thin-client scenario. Through our experiments, we show that an older device using the thin-client approach could execute tasks 90% faster than a newer device with greater capabilities.

The remainder of this paper is organized as follows: Section 2 presents related work. Section 3 presents an analytical model for a mobile device over its life cycle and associated numerical evaluations examining the relation between energy consumption and reutilization. Section 4 derives conditions for a device using the thin-client approach to save energy compared to a conventional device. The methodology employed for empirical evaluations of energy savings and performance of devices employing the thin-client approach is then described in Section 5 followed by the results discussed in Section 6. Finally, Section 7 presents the conclusions of this work followed by a discussion of future work.

2. Background

The ongoing expansion in the number of smart mobile devices has created multiple environmental challenges such as e-waste as a consequence of a device's shorter lifespan and a significant increase in global energy consumption. The driving factor for a shorter lifespan of 18–24 months is due to advancement in the technology and telecom provider contract plans. For instance, some of the largest telecom providers in the United States are now introducing newer mobile phone contracts where users can upgrade their smartphone devices after just one year of usage [8]. On the other hand, the central processing unit (CPU) processing power and mass storage capacity doubles every one and a half years, which also drives consumers to opt for newer devices [1].

Important factors such as features, capabilities, and upgrade opportunities, as discussed above, are some of the major driving elements for the short lifespan of smart mobile devices. However, a small percentage of these discarded devices are recycled and the rest (nearly 75%) contribute to electronic waste [5,9]. An additional impact on the global environment and human health comes from several toxic materials that are present in most of these mobile devices, including arsenic, lead, mercury, cadmium, nickel, copper, and zinc [9,10].

Although features and functionality of smartphones have significantly improved with time, these devices still lack processing capabilities, compared to desktops, and they have a limited battery life. A consequent upsurge in features and functionality of these devices has also led to greater levels of energy consumption. Such an increase in energy consumption impacts user productivity and convenience through faster depletion of the limited battery life. The collective global energy consumption by mobile devices is another major characteristic of the mobile communications domain. This type of consumption has increased proportionally with proliferation in features and functionality. Hence, the creation of a more energy-efficient model of mobile devices has been a primary focus for many researchers in the mobile communications sector.

In this paper, we propose a thin-client–server approach for mobile devices to make these devices more energy efficient in order to maximize their battery lifetime. An extension of the power-consumption model we proposed in [16] via energy savings by mobile devices during the usage phase under a thin-client paradigm is presented in the next sub-section. A thin-client–server model for mobile devices is primarily based on its operating in conjunction with a remote server for resource sharing, accessibility of features, and functionality [11].