Towards Sustainability in Portable Computing through Cloud Computing and Cognitive Radios

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Abstract—It is imperative to consider the concept of sustainable portable computing as the role of such devices increases our lives. With the emergence of the cloud computing paradigm, there will be an increased reliance on wireless communication from portable computing devices to more powerful centralized servers. This paradigm shift to ‘thin-clients’ presents an opportunity to make portable computing more sustainable by shifting more functionality to centralized servers. Reduced functionality needed on these devices could mean a slower rate of hardware replacement. This could significantly cut the electronic waste that is currently attributed to the frequent replacements of these devices. One of the challenges in such a paradigm shift to thin portable clients through reduced local computation would be the additional burden imposed on the wireless communication technologies used. Wireless communication technologies must be improved to handle the additional burden that will be imposed. Any proposed wireless technology must also be energy-efficient to maximize the operating life time of these battery operated, energy-constrained devices. Software approaches to achieve energy-efficient operation are preferable as they reduce the dumping of existing hardware due to upgrades or replacements, and help reduce electronic waste. This paper discusses these challenges and describes one way to move forward towards sustainable portable computing by considering application scenarios based on cloud computing and communication through software-defined cognitive radios.

I. MOTIVATION FOR SUSTAINABLE PORTABLE COMPUTING

Computing devices are playing different roles in server farms, data centers, office equipment, among others. With the increased awareness in how the world consumes energy, and its impact on the planet, it is natural to thus think about the impact of computing on global energy consumption. There have been many studies that document this impact looking specifically at information and computing technology [1], [2], [3].

The world is, however, changing the way it accesses the Internet, and computing in general. There is increasing relevance of portable, battery operated devices in how we handle computing and communication tasks. The first phone call over a GSM cellular phone occurred in 1991. By the end of 2007, half the world population possessed such phones. This phenomenon is similar to the growth of computing devices in general where CPU processing power and capacity of mass storage devices doubles every 18 months. Such growth in both processing and storage capabilities fuels the production of ever more powerful portable devices. Devices with greater capabilities work with more data, and thus subsequently require greater capabilities to communicate data. This has resulted in a similar rapid growth of wireless communication data rates as well to provide adequate quality of service as shown in a study done by Novarum [4] and reproduced in Figure 1.

The increased role of portable devices has thus resulted in calls to look at sustainability in mobile computing [5], [6]. The work in [5] finds that computing devices including data centers, server farms, desktops and portable devices (laptops and mobile phones) account for about 3% of the global electricity usage. Surprisingly, portable devices were responsible for close to 20% of this share, with this share expected to grow as power-hungry smart phones proliferate the market. The study also found that computing devices (including portable devices) were responsible for 270 million tons of CO₂ annually – this number is equivalent to the emissions of 4.5 million vehicles on the road when driving 10,000 miles per year considering an average car giving 21 miles per gallon. The share of CO₂ emissions by the computing sector was found to be much

Average Cellular Downlink Performance 2007-2009

Fig. 1. Cellular downlink performance through various U.S. carriers [4].
larger than what was expected based on its share of global energy consumption. A big reason for this is the fact that most of the computing sector runs on electricity, most of which is produced from coal.

When it comes to looking at energy efficiency and the concept of sustainability in computing, the focus has invariably been data centers and mobile infrastructure like cell towers as they were considered the power hogs within the computing sector. However, the study in [5] dispels this notion and points out that portable devices consume comparable, if not greater energy than the devices/infrastructure believed to be power-hogs (reproduced in Figure 2). Thus, over the next few years, it is opportune to research ways to move towards sustainable portable computing.

II. ELEMENTS OF SUSTAINABLE PORTABLE COMPUTING

Before we can move towards sustainable portable computing, it is important to define what it entails in terms of portable devices.

- **Reduction in Electronic Waste**: A recent study by Ofcom (a UK based broadcast and telecom regulator) has concluded that a fundamental balance must be struck between the increasing environmental impacts of systems and services, and the social, economic and commercial benefits delivered by such systems and services. Achieving this balance is considered to be a key challenge for the communications industry going forward. That study also highlights that consumer equipment, where devices have small individual impact, often have very substantial impact overall due to the large volumes involved and shorter product life compared to infrastructure systems. Thus, significant efforts are being put into the manufacturing and recycling phases of mobile computing devices. An increasing number of portable devices touted as green are emerging made from recycled material [7]. A recent European law known as the WEEE Regulations (Waste Electrical and Electronic Equipment) assigns financial responsibility to producers of electronic and electrical for the collection, treatment, and recycling of their WEEE. A global recycling survey highlighted that only 3% of handsets are recycled [8]. In response to legislation and lack of recycling awareness by mobile phone users, handset manufactures have started promoting free-of-charge take-back programs. In spite of all these efforts, a major form of reducing electronic waste has gone largely unnoticed – reducing the rate at which these devices are replaced.

- **Energy-Efficient Operation**: As mentioned earlier in this section, portable devices consume energy that is not insignificant anymore due to the large number of such devices in use globally. Thus, an effort for sustainability in this area does require more attention to be paid by manufacturers in providing better information and ‘green’ options to users and better usage behavior by individual users. It is also the responsibility of researchers to improve existing devices through improvements in hardware and software that allow portable devices to do more with less energy, and reduce energy wastage. Energy-efficient operation of these typically battery-life constrained devices would further improve user satisfaction by providing greater operating lifetimes per battery charge, increasing the utility and thus the number of applications of such devices.

**Importance of Software Based Approaches**

Typically, computer equipment manufacturers rely on periodic hardware updates to achieve more energy-efficient operation. Unfortunately, achieving this one facet of sustainable portable computing comes at the cost of the other facet: reduced electronic waste. Periodic hardware updates result in consumers dumping their existing hardware and using new ones. Take, for example, the rate at which cellular phones are upgraded every 2-3 years. Each upgrade results in possibly improved performance for the consumer, but results in the old hardware becoming a waste. As mentioned above, very little hardware is actually recycled – a study by the U.S. Environmental Protective Agency (EPA) found that only about 10% of such waste is recycled in the U.S, while a recent Nokia study showed that only 3% of cell phones were recycled globally [8]. Thus, it is imperative to focus more on non-hardware, software approaches to achieve energy-efficient operation as it reduces the dumping of existing hardware. Note that we do not imply that energy inefficiency is the cause of e-Waste. Rather, we are stressing on how energy efficiency should be preferably achieved to get reduced e-Waste as a byproduct.
III. THE CLOUD COMPUTING APPROACH

A. Motivating Example:

Consider a smart phone being used to play the game of Chess by a person who is traveling. The game could be played locally on the device itself, or it could be played online. In the former version, all the computing required to make a move by the computer (the game opponent in a two-player format) is done using the device’s resources. In the latter, online version, all the computation is done through a powerful remote server and conveyed through communication to the device. It is easy to see that more communication is required in the latter scenario by the portable device, but possibly significantly less computation\(^1\). The latter scenario allows the user to play higher-level games without having to upgrade his/her device in the future. All the resources needed for improved performance are already at the server, or could be by an upgrade at only this one location. Thus, by just focusing on the energy efficiency of the communication done, we can significantly improve the sustainability of smart phones for this application scenario.

B. Cloud Computing

A Cloud is used as a metaphor for the Internet, where resources, information, software and hardware are transparently shared. The main advantages for using cloud computing are scalability, ubiquitous availability, and maintenance costs. The cloud computing concept is being furthered by a lot of major companies today like Google, IBM, Microsoft etc. Many of us are using cloud computing in our daily lives without actually noticing it. For example, you go on a trip and have an album of digital pictures to share on your local computer. Photo sharing web sites (for example Flickr or Picasa \(^9\), \(^10\)) make it easy to upload the pictures online and just send the link of the location as a URL for others to look at. This is cloud computing, where the album is stored in a data center online in a cloud and easily accessible from any location connected to the Internet. Another common cloud based application that is emerging is office productivity tools. Google’s Docs, and Microsoft’s Office Live are two examples. Such tools, apart from increased availability, also make collaboration easier.

Cloud computing is typically a client-server architecture, where the client can be any portable device like a laptop, phone, browser or any other operating system enabled device. Users of portable devices these days want to share documents, check email, surf the internet on the fly and represent an increasing segment of the population. A main issue with these portable devices is the constraints they present in terms of storage, memory, processing, and battery lifetime. By storing information on the cloud, and interacting with the cloud through communication, all these constraints can be easily met. An interesting point to note is that all these constraints of portable devices are based on hardware, and when using the cloud paradigm, hardware upgrades do not always present obvious advantages. For example, a higher powered processor and faster memory on the portable device do not seem as attractive anymore\(^2\). Frequent hardware updates are now done at the cloud’s servers, which are much fewer in number. Thus, many portable devices can be possibly utilized for many more years than what is typical now, and hence reduces the manufacturing and recycling costs associated with this large-scale segment of mobile computing.

C. Communication Challenge

The only possible downside is that all the burden is shifted onto the communication interface and the techniques it uses. With most of the portable devices currently using the wireless medium for communication, it is expected that the wireless spectrum will be highly congested, especially if cloud based applications become more popular \(^11\).

Why cognitive radios?
The state-of-the-art solution to wireless spectrum congestion is the cognitive radio (CR) paradigm as discussed next \(^13\). This paradigm can be implemented mostly with software techniques, maintaining our vision of sustainable mobile computing. The cognitive radio paradigm has its challenges as well, and one of those challenges (energy consumption) will be the focus of this paper so as to move towards sustainable mobile computing.

IV. CRITICAL CHALLENGE FOR PORTABLE CLOUD COMPUTING - ENERGY-EFFICIENT OPERATION OF COGNITIVE RADIOS

With an increased communication burden likely when portable devices rely on a cloud computing paradigm, next generation wireless communication radios will likely work on the software-defined, cognitive radio paradigm where the communication medium and parameters are continuously optimized to maximize performance. The central question that needs answering is:

Are cognitive radios energy-efficient in a cloud-computing scenario, and how should they be configured to allow energy-efficient operation of portable devices?.

A. Cognitive Radios and Related Work

Ever-increasing spectrum demands of emerging wireless applications and need to better utilize existing spectrum have led the Federal Communications Commission (FCC) to consider the problem of spectrum management. Under conventional spectrum management, much of the spectrum is exclusively allocated to licensed users. In the new cognitive radio (CR) paradigm, unlicensed users (a.k.a. secondary users) opportunistically operate in unutilized licensed spectrum bands without interfering with licensed users (a.k.a. primary or incumbent users), thereby increasing spectrum utilization efficiency. Cognitive radios have been seen as the way to minimize congestion

\(^1\) The amount of computation required could vary, for example, based on the size of the protocol stack employed and degree of encryption used

\(^2\) On the other hand, improving graphics processors and more demanding playback of media could still necessitate hardware upgrades. However, as a recent article explains, running graphics based on capabilities on the cloud is an increasing trend \(^11\)
by allowing multiplexing between primary users of a piece of spectrum with other opportunistic secondary users of the same spectrum. This allows each radio to watch for a less-congested spectrum to move to and possibly improve its communication performance. Research on the Cognitive Radio (CR) technique has mainly dealt with how spectrum can be sensed, the co-existence of primary and secondary users, and the channel access aspect.

**Sensing and Co-existence with Primary Spectrum Users**
The sensing aspect of CR mainly deals with finding the right spectrum to use for communication, as introduced in the seminal paper [14]. This involves finding spectrum that provides the best communication possibilities for the node in terms of metrics such as throughput, fairness, interference, and utilization. The channel assignment or allocation problem in CRs has been studied through different optimization formulations in [15], [16], [17], [18], [19], [20], [21], [22]. Further, the detection and avoidance of primary users (PU) of the spectrum is of utmost importance as they are the incumbent users who have priority on the spectrum. Secondary users must ensure that they detect PU signals at very low signal-to-noise ratio (SNR) and move to another channel or stop communication to avoid interference to PU’s. This detection process of a PU receiver and/or transmitters on the spectrum has been of considerable interest to researchers [23], [24], [25], [26]. Some important considerations include the determination of the duration to sense the channel [27], [28] and the duration to communicate packets on each spectrum [29].

**Channel Access**
The channel access aspect of CR can be classified based on the type of network architecture: infrastructure or ad-hoc.

MAC protocols for CR in *infrastructure networks* make use of the centralized base station to synchronize and conduct node access operations. The carrier sense multiple access (CSMA) MAC protocol proposed in [30] for infrastructure CR networks is a random-access protocol which relies on differentiated access to the medium for packets from or to primary users (PUs), with other CR nodes having a lower priority. IEEE 802.22 is a standard for Wireless Regional Area Network (WRAN) using white spaces in the TV frequency spectrum. The development of the IEEE 802.22 WRAN standard is aimed at using cognitive radio techniques to allow sharing of geographically unused spectrum allocated to the Television Broadcast Service, on a non-interfering basis [31]. The IEEE 802.22 standard for CR uses the notion of superframes and slots at the base station to control access to the medium. In the downstream direction, 802.22 MAC uses time-division multiplexing, while in the upstream direction, it uses demand-assigned time division multiple access (TDMA). In general, in an infrastructure network, the base station is in control of the network and dictates what frequency all nodes in its network should use. Nodes are, however, free to search for and associate with other base stations to satisfy communication requirements.

In *ad-hoc* CR networks, spectrum sensing and medium sharing are distributed in nature, along with responsibilities of forming packet forwarding routes and time synchronization, if required. Proposed protocols in literature can be classified further based on whether nodes have one or multiple radios. The dynamic open spectrum sharing (DOSS) MAC [22] proposes the use of three radios per node; one for data communication, one for control packets, and one for sending a busy tone. By
sensing the busy tone, nodes know about an active PU because each data channel is mapped to the busy tone channel as well. Even if a node does not recognize the signals on the data channel of the PU, the busy tone conveys its presence. Further reading on MAC protocols for CR can be found in the recent survey in [32].

The work in [33] focuses specifically on using CR techniques for WLANs to solve the performance degradation due to congestion. Like other work, energy consumption with regard to CR techniques is not considered. The work by [13] specifically points out that one of the biggest motivations for CR techniques is WLAN spectrum congestion and the continuing density increase of wireless devices. This is also our motivation to explore the issue of energy consumption of a cognitive radio beginning with the WLAN scenario.

Negatives of obtaining Cognition

The increased attention to develop CR techniques to find and use wireless spectrum, has however, resulted in researchers overlooking the importance of energy consumption in the devices that employ such techniques. Scanning for wireless spectrum, and possibly switching between frequency channels, is power-intensive and could result in a rapid depletion of the lifetime of energy-constrained devices like PDAs, laptops, smart phones, wireless sensors, among others. The fact that the success of the CR technique depends on such a power-intensive operation can undercut the very paradigm in such portable devices. Thus, research needs to be done to study the extent of energy consumption and its impact on device lifetimes.

Positives of having Cognition

On the positive side, the CR technique could also reduce the energy consumed for communication by finding spectrum that is less congested. This would enable communication with less contention for the medium, another major factor of energy consumption in wireless devices. Higher contention for the medium typically results in more packet collisions, more time spent backing off when using CSMA protocols, and more overheard packets from other nodes. Thus, the CR technique’s positive impact on energy consumption needs to be studied and quantified as well to understand how energy-constrained devices would fare in terms of operating lifetime.

The work in [34] presents techniques for reducing energy consumption of a cognitive radio. Their work targets only the physical-layer adaptations involving the power amplifier, modulation, coding, and radiated power. Our work, on the other hand, looks at the problem in a top down fashion. We study the impact of higher layer parameters such as scanning time per channel, number of contending nodes on the medium, and node distribution across channels in conjunction with physical-layer constructs like channel conditions.

V. PRELIMINARY RESULTS

In this section we look at some preliminary results on what can be expected when using cognitive radios in cloud computing scenarios. The first set of results is of a comparison between a cognitive radio and a conventional radio in terms of energy consumption. This would indicate whether cognitive radios are a good idea to start with when energy is a metric. The second set of results is for a comparative study of energy consumed by a commonly used application executed both locally as well as on a cloud. This would indicate whether cloud computing is more energy-efficient than traditional, local computing. Based on these two preliminary, fundamental results, we point out the next steps to be taken towards sustainable mobile computing.

A. Cognitive Radio Versus Conventional Radio

A cognitive radio differs from a conventional radio in that it can scan a pre-defined range of spectrum and pick a channel for subsequent communication. The reason for moving from one channel to another could be due to several reasons: the arrival of a primary user, unfavorable channel conditions, or an increase in load because of growth of number of users on the former channel. All these factors would have led to increased energy consumption by the radio if it had stayed on the former channel. Thus, a cognitive radio can ‘hunt’ for better channels that can reduce energy consumption. There are various possible scanning strategies, which must be evaluated and compared.

Optimal Scan

Doing a thorough, extensive scan of all available frequency spectra can guarantee a channel that is the best for communication in terms of minimizing energy consumption. Such a channel could minimize energy consumption for the following reasons: there are very few contending nodes on the chosen channel, or there exists a low-interference communication
environment, or a combination of both that results in minimal energy wasted due to packet collisions, backoff time, or packet losses. Such an optimal strategy, however, can be very energy-intensive in scanning all possible frequency spectra since the radio has to listen on each channel for some time, switch to another channel, and so on. Listening on a channel consumes almost as much power as communicating on a channel [35].

**Greedy Scan**

Another possible strategy is to greedily scan the spectrum until a satisfactory channel is found. A channel can be deemed satisfactory if it satisfies a certain threshold in terms of expected energy consumption for communication due to channel conditions and node contention. This scheme may not incur as much energy for scanning as the optimal strategy, but the found spectrum may not reduce energy consumption as much as an optimal channel either.

**Sticky Scan**

Another strategy is to stay put on a channel without scanning, until the expected energy consumption goes above a certain threshold, at which point a new channel is sought. This could particularly decrease lost energy in scanning and switching between channels, and make scheduling of communication with other radios easier. This would be more of a reactive strategy.

**Selective Scan**

Another strategy is to do a selective scan, where previously used, good channels are scanned with a higher probability over channels that were not found to be satisfactory. Such a strategy could minimize the number of channels scanned while, at the same time, ensuring some of the better channels are examined for future communication needs.

**Current Status:**

Preliminary work done with just the optimal and greedy spectrum scanning techniques showed that results were highly dependent on the application scenario and configuration parameters [36]. For example, for the optimal scanning technique, the results shown in Figure 5 were obtained that shows how various parameters like number of channels, node distribution across channels number of nodes on each channel, and time spent scanning each channel play in whether a cognitive radio can save energy over a conventional, non-scanning radio.

For the experiment results shown in Figure 5, node contention was chosen as the sole reason a cognitive radio changes channels. The number of nodes on a ‘current’ channel was \( n_c \) and spectrum scanning was done to find a channel that had fewer number of nodes contending. The conventional radio, of course, does not scan and stays put on the current channel. The energy savings shown thus compare the energy consumed by the conventional radio on the current channel, versus the energy consumed by the cognitive radio on a newly found channel (including energy consumed to find this new channel). The parameter node ratio is the ratio of number of nodes active on the eventual chosen channel through the scanning process to that of the current channel. Thus, if there is a tenfold reduction in the number of nodes on the chosen channel, the node ratio would be 0.1. The smaller the node ratio, the greater the reduction in contention by switching to this channel.

Further work needs to be done to examine the impact of application scenarios on various spectrum scanning schemes and configurations to better understand fundamental limits.

**B. Cloud Versus Non-Cloud**

The goal of our preliminary work with cloud computing was to study the energy consumption of portable devices over a cloud based application. For a representative device, we picked a laptop which we had experience doing energy measurements with previously. For a cloud based application, we picked office productivity tools.

**Application Scenario**

With traditional desktop office productivity tools, a copy of a software program is executed on each computer owned. The documents created are stored on the computer on which they were created. With cloud computing,
the office suite used isn’t run from a typical user’s personal computer, but is rather stored on servers accessed via the Internet, typically within a web browser. The browser accesses the web-based application and an instance of the application is opened within the browser window. Once launched, the web-based application operates and behaves like a standard desktop application; the only difference is that the application and the working documents remain on the host’s cloud servers.

Methodology

Our laptop used in the study was IBM Lenovo SL400 with a 14 inch display. The study was done on the Windows 7 operating system. We used Microsoft Office 2007 as the desktop application, while Microsoft’s Office Live was used as the cloud based application. Text was input into the word processing editor using an automated program at the same rate over a period of time on both versions. This was done multiple times to ensure reproducibility of results.

Results

The results obtained are shown in Figure 6. Three lines were plotted denoting how the battery lifetime decreases over time. The Idle line denotes how the laptop battery would have degraded over time if it was kept on and idle, with no applications running, and the WLAN interface switched off. The line denoted C denotes the energy consumed when the cloud based application is executed with the WLAN interface on. The line denoted NC denotes the energy consumed when the cloud based application is executed with the WLAN interface off. Clearly, Idle has the least energy consumption state among the three. What is interesting is that line C is lower than line NC, inspite of the latter’s communication interface being inactive4. This is a very encouraging result confirming our intuition that cloud based computing for portable devices can be more energy-efficient, apart from reducing the need for hardware upgrades.

More work is required to confirm the energy efficiency obtained by using cloud based applications. For example, our work here just looked at one type of application. Other applications could result in different outcomes.

C. Lessons and Next Steps

From the preliminary results, it is clear that greater reliance on communication by running applications in the cloud and using cognitive radios can have benefits in terms of reduced energy consumption of portable devices, along with the potential to reduce frequent hardware upgrades. For cognitive radios, they can save energy over conventional radios under a specific set of configurations and application scenarios. When comparing cloud based applications to those that are not, it is seen that energy could be saved at least for some applications.

What we need to understand is whether typical cloud application scenarios relevant to a wide range of users will allow such operating conditions under which energy-efficient wireless communication is possible. To this end, the preliminary work mentioned in this section must be continued to take into account other cognitive radio spectrum scanning techniques and application scenarios, and cloud-based applications like multimedia streaming. Most importantly, energy efficiency must be evaluated when using cognitive radios in cloud based application scenarios to current scenarios of conventional radios in non-cloud application scenarios.

REFERENCE