1.1 Mobile Clients Space

Mobile clients, specifically smartphones have become inseparable from day to day life of one and all. *Smartphones* are cellular phones that are also programmable mobile computing devices. Primary communication channel for mobile clients are wireless channel and the primary source of power is battery. In battery powered mobile clients such as, smartphones, laptops, tablets, mobile sensor nodes (*motes*), power consumption directly affects the usability or availability of mobile services.

The first Operating System(OS) platform which had a technical architecture optimized for smartphones was *Symbian OS* [7]. It was the most popular smartphone OS platform in the past decade among the enterprise and professionals. When considering both architectural control and attracting third-party complements to the platform, a key decision made by platform developers is the degree of vertical integration. One option for the developer is to integrate to produce the entire platform, while primarily relying on third parties for complements, called *vertically integrated approach* (VIA). For example, Apple and RIM blackberry smartphone platforms follow vertically integrated approach. Another approach would be for a firm to concentrate on one core layer of the platform architecture and rely on external partners to implement the
remainder of the platform, called open innovation approach (OIA). Symbian, Google Android and Microsoft Windows Phone platforms follow open innovation approach.

Early Symbian OS smartphones were primarily used as enterprise devices in the last decade and were prohibitively expensive for most consumers. But, the introduction of iPhone has popularized smartphones in the mass market, and has redefined its compute capability and user-experience. Apple’s phones are Internet enabled smartphones with capabilities similar to personal computer’s Internet access. Through vertical integration approach, Apple’s devices seem to provide better performance and user experience.

The follow-up, Android platform from Google, further popularised smartphones. Google followed open innovation approach and partnered with several Original Equipment Manufacturers (OEMs), to manufacture smartphones using its OS. Hence, the growth rate of Android devices accelerated at higher rate and surpassed the growth rate of iPhone in a short period. Many OEMs are supporting Android platform in order to maintain their market share, thus it greatly increases the penetration of smartphone among phone-users. According to International Data Corporation, smartphone shipment volume reached 491.4 million units in 2011, up from 304.7 million units shipped in 2010, recording a strong 61.3% growth, and Android and iPhone phone are claiming for nearly 53% of worldwide market share of all phones. According to Credit Suisse, the smartphone sales is expected to touch 1 billion mark in year 2014.
1.2 Mobile Applications

There are thousands of applications in the application stores of Apple and Google. Among these applications, games, messaging, social networks, web surfing and location based services are the most desired. In our study, we have mostly used mobile games as, mobile games is one of the most rapidly growing areas in todays consumer market and to our knowledge, there is no prior work dealing with game energy issues on smart phones. Games alone account for more than 50% of current iPhone application downloads [8]. There are several reasons for this phenomenon.

- Firstly, the introduction of iPhone has popularised smartphones among common people with rich set of useful applications. There is a paradigm shift from smartphone as a business device to common man’s communication and entertainment device.

- Secondly, today’s smartphone are capable of running 3D games which were possible only in PCs and proprietary game consoles in the past. As these games use various built-in sensors of the phone for user interaction, the games become very convenient to play. The cost of smartphone game is very low due to short development cycle and well streamed delivery and business model provided by platform developers (Apple Applicaion Store, Google Application Store, etc..) to cover mass market. An average game in Apple application store cost only about US$ 1 which is very low when compared to the selling price (approximately, US$ 40) of console games. The best-selling game Angry Birds clocked 648 million downloads in 2011 with 200 million active monthly users which are an impossible number for any console game.
Thirdly, the advent of social network sites has enabled people to connect with friends at all times. One of the activities people do most on social network sites is to play games. Modern smartphones offer just this. With 3G network, people can play social network games anywhere.

Finally, inclusion of Canvas in HTML5 [9] standard eliminates the dependency on plug-ins such as, Flash for browser based games. Google’s ChromeOS [10] may become popular for cost effective devices for browsing and casual gaming due to its early support for HTML5 and minimalist approach in OS design.

As games are so prevalent on smartphones, many researchers are now working on enhancing the game play experience on smartphones. One of these directions is to improve power efficiency of games, so as to stretch the game play for longer period.

1.3 Saving Energy

Emergence of bigger display, higher CPU frequency, additional CPU/GPU, multiple sensors, and powerful network interfaces supporting Wifi, 3.75G, 4G networks to provide better user experience has escalated demand for energy. Unfortunately, the advances in battery technologies are not catching up with the rest of the technologies in a smartphone [11]. Battery lifetime (talk time and standby time) of typical phones in each platform is given in Table 1.1. Irrespective of the platform, the battery lifetime of all these phones are close to each other.

As slim form factor gives competitive advantage, OEMs cannot increase the physical size of the battery. Current batteries are typically based on Lithium-Ion (Li-Ion) or Lithium-Polymer (Li-Po) technology, sometimes, NickelCadmium (Ni-Cd)
Table 1.1. Battery Lifetime in Modern Smartphones

<table>
<thead>
<tr>
<th>Platform (Phone)</th>
<th>Type</th>
<th>Battery Type</th>
<th>GSM talk, standby</th>
<th>WCDMA talk, standby</th>
<th>Quake III play</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbian (Nokia X7 [12])</td>
<td>OIA</td>
<td>1200 mAh Li-Ion</td>
<td>6h 30min, 450h</td>
<td>4h 30min, 450 h</td>
<td>-</td>
</tr>
<tr>
<td>Apple iOS (iPhone 4 [13])</td>
<td>VIA</td>
<td>1420 mAh Li-Po</td>
<td>14h, 300h</td>
<td>7h, 300h</td>
<td>-</td>
</tr>
<tr>
<td>Android (Google Nexus S [14])</td>
<td>OIA</td>
<td>1500 mAh Li-Ion</td>
<td>14h, 713h</td>
<td>6h 42 min, 427h</td>
<td>-</td>
</tr>
<tr>
<td>Android (HTC Desire HD [15])</td>
<td>OIA</td>
<td>1230 mAh Li-Ion</td>
<td>8h 10 min, 420h</td>
<td>5h 20 min, 490h</td>
<td>*1h 50min</td>
</tr>
</tbody>
</table>

* - To estimate this, we played Quake III Arena on a HTC Desire HD smartphone, for 5 minutes, and determined the percentage of battery power drained.

or NickelMetal Hydride (Ni-MH) cells are also still in use. The relative advantages and disadvantages of these technologies (in particular, capacity, recharging duration, memory effect, weight, robustness, and costs) are well known. A key metric is the energy density, expressed as Watt hours per kilogram or as Watt hours per litre. For Li-Ion technology, is around 150-250 Wh/kg (540 to 900 kJ/kg) [16]. However, the rate of increase is rather modest: as predicted earlier it is about 10% to 15% increase per year [11].

For a given technology/architecture, there is a close relation between the performance provided by a system and the power it consumes. As shown in Table 1.1, 3D games such as Quake III demands more CPU cycles resulting in higher amount of power consumption than voice communication. For a simple visual example, the power consumption increases as we increase the brightness of the display. There is a linear relationship as shown in Figure 1.1.
1.3.1 Why is saving energy in mobile clients important?

Much of the world has become completely reliant on electrical energy. In fact, without electricity much of the modern-day comforts we enjoy would no longer be possible. Using the energy conservatively and efficiently has highest priority in making the earth sustainable. There are several initiatives around the globe in this direction spearheaded by governments and international agencies. Here, we discuss the benefits of conserving energy in two key perspectives.

**Environmental and Financial Perspective.** Conservative use of energy lowers the energy bills. According to Google, every query consumes about one KJ [17]. Estimates put the annual electricity consumption figures of Google because of these data farms up to US $38 million [18].

Greenhouse gases, such as carbon dioxide and methane, trap heat in the atmosphere, contributing to global problems such as climate change, states the Environmental Protection Agency. Hence, current research focuses on conservative and
efficient use of energy and generation of renewable energy (solar, wind mills....) across all areas from domestic to industrial setups to reduce green house gases. A significant portion of energy is consumed by mobile devices. There is a rapid increase in number of mobile devices globally, resulting in them becoming another major consumer of electricity.

**Contribution of mobile devices to global energy consumption** - According to UN telecommunication agency, the number of mobile phone subscriptions worldwide has reached six billion by end 2011 [19]. The growth rate of smart phone users is continuously escalating [20]. As reported by Nokia, annual electricity consumption for a mobile phone 11 KWh per year [21]. This comes out to be around 1 W (1.2 W to be precise) per phone. This should be higher in modern smart phones [22]. For 6 billion phones the annual electricity consumption is 66 million MWh. Estimated overall ICT energy consumption including data centre server farms, desktops, laptops, mobile phones and mobile infrastructure is 452.3 million MWh [23] in year 2009. (Note: This study on overall ICT energy consumption did not include embodied energy or energy $^1$ [24]). Out of 452.3 million MWh, 168.8 million MWh is attributed to data centre energy consumption. The study estimates global data center power consumption from US data centre power consumption by assuming 50% of the global data centers are based in US. However, another study by Koomey [25] shows that global data centre power consumption ranges between 271.8 million MWh to 203.4 million MWh for the year 2010. A recent statistical report from British Petroleum estimates that global energy consumption grows every year by an average

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$^1$the energy required to build the devices and infrastructure
of 2.5% [26]. If we assume the same rate of increase for ICT energy consumption per year and use the upper bound of data centre energy consumption estimated by Koomey [25], it results in 506.3 million MWh ICT energy consumption for the year 2011. As estimated above mobile devices consume 66 million MWh per year which is about 13% of the energy consumed by all computing devices. In the attempt to estimate Internet power consumption, Ragavan et al. [24] tabulated about 4.13 GW power consumption for one billion smart phones (that can access Internet in some form) out of 170 GW overall energy consumption by Internet (including embodied energy). If we consider 6 billion phones, it results in 14.6% energy consumption by mobile phones which is close to our estimations. Considering the growth rate of mobile phones and its increasing functionalities, it is very important to design power efficient algorithms and techniques for mobile phones.

Usability Perspective. Along with call quality, a cell phone’s battery life is one of the most important considerations when choosing a mobile phone. It’s never fun to watch your cell phone die when you’re in the middle of an important call or an interesting game. And it’s no fun either to have little power when you’re nowhere near a charger. Typical mobile phone battery provides 8 hrs of talk time, while it provides only 1hr 50min game play for 3D networked games (Table 1.1). Though the modern smartphones are equipped with power full hardware to play 3D games, such a short battery life will make the phone unavailable for communication needs. On the other hand, it prevents the user acceptance of higher end games in the mobile devices. Hence, in this report we focus on energy efficient techniques for highly power consuming applications such as, 3D games.
1.3.2 Current Status & Challenges

In modern smartphones, the three main sources of power consumption are, 1) the CPU, 2) the display, and 3) the network interfaces. We found that the wireless interface and display components dominate the power consumption.

For example, on a HTC Magic Android smartphone, with all components running at peak levels (Figure 1.2), the Liquid Crystal Display (LCD) display and 3G mobile network interface consumes 45 to 50% and 35 to 40% of the total system power respectively. The remaining power is consumed by the CPU and memory subsystems [1].

![Component Power Consumption (HTC Magic)]

Figure 1.2. Component Power Consumption (HTC Magic) [1]

Most of the prior power management solutions target power efficient hardware design, power aware link layer protocols and OS level optimizations. Unfortunately, their one size fits all solutions do not exploit the nature and requirements of the applications that run on the hardware. Recently, researchers have started focusing
on power management solutions which use application specific knowledge resulting in very efficient power saving [27] [28] [29] [30] [31].

In this research work, we focus on the ways and means of saving power on mobile clients including smartphones and tablets. We focus primarily on the wireless network interface and display components.

1.3.2.1 Display Power Conservation

**LCD.** Major power consuming component in LCD displays is backlight. Backlight level can be reduced by compensating it by brightening the content. This technique is known as backlight luminance scaling technique. LCD displays are inefficient in displaying darker contents. More energy can be saved for darker contents. There are several works on backlight luminance scaling [32] [33] [34] [35]. In general these techniques suffer from the following issues, hence these are not suitable for computationally intensive mobile applications such as games and real-time video playback.

- To enhance the content brightness, each pixel of the frame need to be accessed and brightened individually by equal amount. It is time consuming activity. This will work for images or slide shows, whereas for videos and games in desktops, which require a refresh rate of around 30 frames per second, these schemes fails to meet the frame deadline. It becomes even worse in mobile devices.

- The power required by the CPU for the additional computations for pixel by pixel transformation results in negative power saving or minimum power saving in mobile clients.
• **Tone mapping** is a technique used in image processing to map one set of colours to another according to a given objective. Brightening each pixel by equal amount (linear tone mapping), results in faster saturation of pixels, resulting in either drop in quality or less energy saving. Non-linear tone mapping approach proposed in Iranli et. al [36] promises better quality and good power saving. However, such non-linear tone mapping functions are not readily available at hardware level.

• Evaluation of the quality in the above referenced works consider either saturation of pixels or loss of contrast. However, these alone are not enough to determine the quality. More advanced quality metrics are required to match the human perceived quality [37].

**OLED.** Pixels are individually illuminated in Organic Light-Emitting Diode (OLED) displays and they do not use backlight. Power consumption of these displays depend on the colour and luminance of contents being displayed. There are some significant amount of work on converting the colours of contents to energy efficient colours [4] [28] [38]. These existing approaches suffer from the following issues.

• Changing the colours of the contents to significantly different colours may be suitable for GUI components, however loss of colour fidelity is not acceptable for images and videos.

• As green being the lowest power consuming colour in many OLED mobile phones, colours of the web pages are mapped to shades of green for these phones.
However, viewing everything in monotonous shades of green makes the contents less informative and uninteresting.

- For web pages legibility and brand identity are very important. Previous works fails to consider brand colors and legibility. In addition, current methodologies require significant amount of changes to the web broswer’s source code.

1.3.2.2 Wireless Interface Power Conservation

A wide range of recent research focuses on power aware protocols and techniques for mobile environments. While several of these works are on power management at network interface level [39] [40] [41], and focus mainly on latency agnostic applications such as mobile web based applications and mobile audio/video streaming applications.

Mobile games pose more challenges than these delay tolerant applications. Mobile games are highly time sensitive. Packets must reach the client within the bounded latency and jitter, otherwise, it becomes useless. For example, our observations with Quake III [42] and the results reported in the literature [43] show that round trip network delays beyond 180ms makes the game not playable for twitch games such as first person shooting games. Dead-reckoning based schemes [27] [30] takes this delay constraint into account. However, they cannot save much energy as they are based only on one characteristic of the game. If there are multiple entities contolled by dead-reckoning algorithm they save very low amount of energy.
1.4 Thesis Contribution

From the above discussions we notice that, there is an increasing trend in applying application aware strategies to optimise power consumption. In this work, we build and demonstrate intelligent techniques to manipulate different types of media contents (eg. 3D graphics, images and texts) in mobile games and web pages to increase the energy efficiency of mobile phones. In addition we discuss ideas to adapt these techniques to other types of contents such as video. In general we address the following set of challenges in this thesis.

1. LCD backlight power management for mobile games: Our approach answers the following key questions -

- **Performance**: How to brighten the contents without affecting frame rate?,
- **Quality**: How to brighten the contents with minimum distortion to quality?,
- **Tone Mapping**: How to estimate the relationship between tone mapping (which is non-linear) backlight level (which is linear) and,
- **Power Saving**: How to achieve maximum possible power saving under the given quality constraints?.

In contrast to the previous works, we used tone mapping function (specifically, Gamma correction function) to enhance the content brightness. As the Gamma correction function is easily realisable at hardware level, and as it is already a part of many of the modern 3D games and GPUs, the computational cost of our algorithm is negligible. Hence, our approach is highly suitable for computationally intensive 3D mobile games. We can save maximum energy without affecting
the frame rate in a gameplay. By use of non-linear tone mapping function we preserve quality of the contents better than linear functions by reducing pixel saturation. We have evaluated the final quality of the contents using advanced metric Structural SIMilarity Index (SSIM) which takes the characteristics of Human Visual System (HVS) into account. In addition, we have done a careful user study to supplement our findings.

2. OLED power management for web contents (texts and images): Our approach answers the following key questions -

- **Brand Identity**: How to map the colour of a webpage to power efficient colours while maintaining the brand colours and legibility of the contents?,

- **Content Fidelity**: For any image colour transformation algorithm retaining the fidelity of the images is important. How to map the image colours to power efficient colours while maintaining the image fidelity?,

- **Games**: How to adopt these techniques for videos and mobile games?.

We have used fevicon (or corporate logo or key image) based colour transformation to retain the brand colours and identity of the pages. Our colour transformation for images (adaptable for videos and games) is based on the non-linear response of the HVS to colour luminosity and contrast of the objects viewed. In addition, we present the trade-off between quality of the contents and power saving requirements with a large scale user study.
3. Wireless interface power management: Given the strict real-time constraints of mobile games, especially, twitch games such as First Person Shooting (FPS) games and some Massively Multiplayer Online Games (MMOGs), how to decide,

- When to put the wireless interface into sleep mode? and,
- How long it can be in sleep mode without affecting the game play quality?

We decide these intelligently by predicting the importance of near future game state for the mobile client. Previous works use dead-reckoning alone to make power management decisions. To make more efficient and robust power management decision, we consider multiple parameters (client’s visibility, distance, angle of view...) of the game. As most of these parameters are already existing in today’s commercial games, we achieve good results with minimum effort. We turn-off the wireless interface when the estimated near future game state is not important. We describe three algorithms to estimate and predict the game state to achieve significant amount of power saving (up to 40% of wireless energy) without effecting the game play quality adversely.

4. For an algorithm to be efficient in power saving and yet retaining quality, it should be dynamic and adaptive to runtime characteristics of the game and game state.

Our algorithms (both display and network power management) continuously monitor the game state during runtime and tunes the power saving parameters for preserving game play quality.
1.5 Thesis Organisation

The remaining part of the thesis is organised as follows.

There is a rich body of research works that propose novel architectures, strategies, methodologies, and techniques to make handheld devices energy efficient. Chapter two provides a survey of related works divided in to four areas - LCD power efficiency, OLED power efficiency, network interface power efficiency and processor power efficiency.

Chapter three describes an adaptive backlight control approach for LCD display energy saving. The approach uses gamma-correction function to brighten the display contents with minimum computational overhead. Gamma-correction function is a common tone mapping function already available at hardware level in modern mobile devices.

Brand colour and HVS based colour transformation of web pages (texts and images) for energy efficient browsing in OLED displays including a description on how these color transformation techniques can be applied to other contents such as videos and games is discussed in Chapter four.

The game state based power management for network interface is discussed in Chapter five. To estimate the game state three different approaches are described - distance based approach, visibility based approach and renderer’s view based ap-
approach. Each approach has its own merits that make it suitable for a specific game genre and game map.