Revisiting Human-Battery Interaction with an Interactive Battery Interface

Denzil Ferreira[1], Eija Ferreira[1], Jorge Goncalves[1], Vassilis Kostakos[1], Anind K. Dey[2]
[1]Department of Computer Science and Engineering, University of Oulu, Finland
[2]Human-Computer Interaction Institute, Carnegie Mellon University, USA
{denzil.ferreira, eija.ferreira, jorge.goncalves, vassilis}@ee.oulu.fi, anind@cs.cmu.edu

ABSTRACT
Mobile phone user interfaces typically show an icon to indicate remaining battery, but not the amount of time the device can be used for, often forcing users to make faulty estimates and predictions about battery life. Here we report on two studies that capture users' experiences with a user-centered battery interface design. In Study 1, we analyze 12 participants' use of mobile phones, demonstrating that mobile phone users do not know how or what to do to extend their mobile's battery life. We further identify the information they rely on to assess battery life. In Study 2, we use this information to design, prototype and evaluate an *interactive battery interface* (IBI) with another 22 participants. Our findings describe how users *perceive* battery life and how we used their mental models of mobile phone batteries to create IBI. Lastly, we report on the users' experiences and IBI's effect on battery lifetime, showing gains of approximately 27% over the course of a day.

Author Keywords
Battery Monitoring; Context-Awareness; Mobile Computing; Battery Explanations; Range Anxiety.

ACM Classification Keywords
H.m. Information Systems: Miscellaneous.

General Terms
Design; Reliability; Experimentation; Human Factors.

INTRODUCTION
The workplace is increasingly mobile, where mobile devices such as tablets and mobile phones are being used to replace the desktop at home or at the office [8]. A key to these mobile devices is the notion of *mobility*: the ability to use the mobile device without having to surrender it to a battery charger. The limitation of the battery on mobile devices poses challenges for both usability and mobility, as users have limited understanding about *how* they can manage the battery life of their devices [6, 13]. In this paper we focus on understanding the effect that users' interactions with their devices have on their devices' mobility and on how to design a battery user interface that supports users in managing their expectations of battery life. The battery interfaces of the two most popular commercially available mobile operating systems, *i.e.*, Android and iOS are by default, reduced to an icon (Table 1).

Android	0%	15%	30%	40%	60%	80%	Full
1.6-2.2							
2.3.x							
3.x-4.x							
iOS	N/A						

Table 1: Evolution of the battery interface icon on Android (1.6-4.x) and Apple's iOS devices.

This minimal interface is not sufficient for the user to understand what is happening to the battery nor to take action based on that information [10, 11]. While Ferreira *et al.*'s work [6] has focused on how people charge their mobile phones, here we focus on what happens before charging takes place: the events that *lead up* to the need to charge. We explore whether providing information about such events in the form of a battery interface will empower users to better manage their devices' battery life.

We must revisit our current understanding of users' attitudes towards battery life. The reference research on people's perception of battery life was conducted in 2006-7 [10,11], before the iPhone was first introduced. In recent years, the increasingly pervasive use of smartphones, and the existence of application stores have significantly changed how users use their mobile phones (*e.g.*, as a music and video player, a navigation device, a gaming platform) [5]. As a consequence, users expect more from their devices, and we question how that affects their usage experiences.

Our goal is not to create a perfect battery interface, but instead to report on users' experiences with a user-centered battery interface design, refining our knowledge of human-battery interfaces, and providing insight for future battery interfaces. We start by investigating how users' interaction with a mobile phone can affect its mobility. We do so to gain an understanding of users' mental models of battery usage, and which applications users care about from a battery depletion perspective. We further explore how users' perceptions of their device usage correlate with actual battery depletion. We aim to understand better how

UbiComp '13, September 08 - 12 2013, Zurich, Switzerland
Copyright 2013 ACM 978-1-4503-1770-2/13/09…$15.00.
http://dx.doi.org/10.1145/2493432.2493465

we can help users decide what applications to keep running, thus more effectively managing their devices' battery life.

We start with an overview of popular manufacturers' mobile battery interfaces, and previous research on improving battery interfaces and understanding battery consumption. We follow with a description of our first study to understand how users *conceptualize* mobile phone battery usage and how they *actually* use mobile phones. We then present IBI, an interactive battery interface designed based on the results of the first study, and follow up with a second study to evaluate IBI and report on users' experiences of power management, thus providing an up-to-date assessment of human-battery interaction assessment.

RELATED WORK

The battery has consistently been a limiting factor for mobility in mobile devices. New technology employed to produce batteries has struggled to keep up with the advances in mobile computing. Faster processors, multitasking, and more built-in sensors have resulted in higher demand for more efficient and higher capacity batteries. Although recent manufacturing advances in battery technology seem promising, it will take some time until they are widely integrated in consumer batteries [2]. Regardless, managing battery life is a real, *everyday* concern for the majority of mobile phone users.

More informative battery interfaces are becoming available on the mobile phone. Newer Android devices (as of 2012) have a battery depletion history interface, in the Battery menu under Settings (Figure 1).

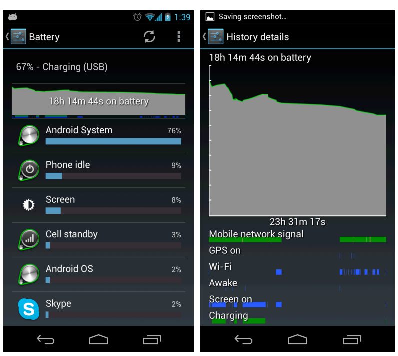

Figure 1: New battery's history interface in Android OS.

In this particular interface, users are presented with a plot of the battery percentage over time, the percentage of the battery that each application consumed and the amount of time that an application, the device's sensors or operating system has been active. This interface however, does not display *active* applications, but applications that have run recently, both active and not. Selecting a list item allows users to terminate active user-installed applications, or view usage statistics (*e.g.*, Android System, Android OS, Phone idle, Cell standby, Mediaserver) or view a hint to minimize battery consumption (*e.g.*, Screen). This *heterogeneity* in actions that can be taken and the *lack of real-time* information about what is currently running on the phone is potentially confusing to users. Since Android 4.2, the battery icon also includes the battery percentage if the user expands the notification bar. Revealing less information, iOS users can view a summary of the amount of time the device was on standby or in use, in the Usage Menu (Figure 2). Since iOS 4.0, iPhone users can also show the percentage together with the battery icon.

Figure 2: Apple's iOS battery information.

Also available on application stores are battery applications and widgets (an interactive mini-application) that either display an oversized icon with a battery percentage, or provide more technical information (*e.g.*, battery technology, health status, temperature, voltage) of their mobile phones' battery.

Researchers have tackled the management of one's battery life with mainly three approaches: hardware, software, and leveraging user routines. Here we will focus on the last two approaches. In terms of software, the battery interface has been shown to influence users' behavior [10]. In terms of user routines, Android mobile phone users frequently charge their battery when it reaches 30%, as the battery icon changes from green to yellow and again at 15% when the phone prompts users to charge the device [6]. Ravi *et al.* [12] explored location traces and call logs to predict how much battery life the user needs for the day.

Task-Centered Battery Interface (TCBI) focused on providing battery information based on current mobile phone usage [13]. TCBI's interface grouped applications in five popular application usage categories: none (phone left on without any visible application), video, music, Skype, GPS and browser. For each *category* it provided a breakdown and estimated time remaining of battery life. However, the recent proliferation of mobile application stores and the ability to run multiple applications at once have expanded the range of application categories that can be in use simultaneously. It may also be hard to categorize applications that can inherently be placed into multiple categories (*e.g.*, Google Maps can be used for navigation as well as social networking (Latitude)). With the emergence of new applications tailored for ubiquitous computing, the number of application categories will only increase, thus TCBI's approach of application categorization does not scale well in displaying application usage to the user.

Carat [9] is a passive battery interface that takes a black-box, collaborative battery estimation approach. Currently running applications, device model and operating system information are uploaded to a remote server where deviations from the average battery use are classified as "energy bugs." Carat provides *post-hoc* reports, which require one week of data collection to produce, on expected improvements for taking user-personalized actions: terminating or restarting an application and upgrading the operating system. For now, Carat does not provide real-time recommendations for managing battery life.

Focusing on application developers, Zhang *et al.* [14] introduced PowerBooter, an automated power model construction algorithm, and PowerTutor to provide power estimations in real-time on the device. Despite an accuracy of up to 97.5%, PowerBooter and PowerTutor require information on the device battery capacity and historical hardware measurements to provide battery estimations, which is challenging to obtain without physical access to the mobile devices.

Previous research has mostly focused on extending battery life, or optimizing its use and little attention has been given to studying and understanding how mobile phone users view and react to their devices' mobility. Smartphone users expect a longer battery life than currently supported by their handheld device, and have requested a 2-3 times increase in their battery life so that they can confidently complete a full day of work with the device and recharge it at night [3].

Rahmati *et al.*'s user studies on Human-Battery Interaction (HBI) [10, 11] is the reference literature on understanding the limitations and users' perceptions of mobile battery interfaces. Since 2006, however, mobile phones have evolved and, with them, mobile phone usage. In this paper, we revisit their findings and provide an updated understanding on the limitations and users' perceptions of mobile battery interfaces. We confirm that interfaces *still* do not inform users on how the devices' batteries should perform, and do not fully support users' mental models in understanding what happens while using their devices. As a result, and as also reported by our participants, users *expect more* from their mobile phones' battery life. However, if provided with an adequate battery interface, 80% of mobile phone users would take actions to improve their battery life [11]. To support users *while using* their devices, we focused on a user-centered battery interface design and evaluation process.

STUDIES

Our primary goal is to understand how a mobile phone's battery life is affected by the user's interaction with the device (Study 1). More specifically, we focus on the human factors aspects of a battery interface, and the aspects that impact the users' perception and understanding of their devices' battery life. As our second goal, we want to use our newly found understanding to prototype a battery interface to manage battery life, IBI (Study 2). This interface provides a descriptive state of the battery life, allows the user to quickly identify the current status of the battery, identify what is draining the battery and allows the user to act upon this information, thus giving users control over their battery life.

Study 1 - Understanding Mobility Requirements

We recruited 12 participants (7 male, 5 female), aged 20 to 45 years old, with a variety of occupations and daily routines, owning diverse Android mobile devices, by placing flyers around bus stops and our campus main library. All our Study 1 participants had relatively new devices, from a range of manufacturers, with an average age of 1.3 years (SD=0.7), so that aging effects of the battery are unlikely to affect our data analysis of battery life. The study lasted 4 weeks and participants were compensated with $80 US for completing the study. We conducted two sets of interviews, one before and one after the study was completed.

Data collected

We implemented an automated logging mobile application with AWARE [1] to collect *in-situ* mobile phone usage data. Rahmati's study collected *battery usage* from a *single* device that was given to the participants. Here, we deployed on participants' *own* mobile phones (thus capturing more authentic use) and collected a wider range of data that captures mobile phone usage. The data was stored locally on the mobile phone and retrieved from the devices before the last interview. We collected the following data continuously:

- *Battery usage*: battery charging duration, how long the battery lasted and battery level changes over time.
- *Network usage*: when, how long and in which application the network was used. In the network category, we collected GPS, Airplane, Wi-Fi, Bluetooth, and Carrier Network usage sessions. For the Carrier Network, we collected the nature of the connection (*i.e.*, GPRS, EDGE, UMTS, HSDPA, *etc.*) We characterized GPS as network usage since Android devices use Wi-Fi and Network triangulation to quickly acquire approximate GPS location coordinates before acquiring a satellite location.
- *Processor usage*: amount of processing (CPU time) dedicated to user, system and idle CPU status, number of processing sessions per application (background and foreground).
- *Application usage*: when, for how long and which applications were used by the user, both in the background and foreground. By background, we mean services and processes that run without user interaction. As foreground, we collected information about all the currently active and visible applications to the user.
- *Phone usage*: when calls were made/received (incoming, outgoing, missed), for how long, and how many; when messages were sent and received and how many.

The data was passively collected without interfering with the usage of the device. AWARE and the Android operating system are event-driven and we did not add any form of processing on the device itself, with limited impact on the device's battery life.

Revisiting Human-Battery Interaction

Mobile phone usage has changed rapidly since Rahmati's findings and we need to revisit our understanding of how users are using these devices, and how battery interfaces have supported this change. For example since 2006, we have witnessed the widespread adoption of smartphones due to the iPhone and Android OS, the proliferation of application stores [5] (ad-hoc increased functionalities), the increased availability of device sensors, network speed and processing power which has considerably reduced the expected battery life of mobile phones [13]. Because of this, on average a mobile phone's battery life lasts a single day [6]. We report and focus our analysis to battery usage similar to Rahmati's work and extend it with application usage, prominent today.

The goal of the first interview was to assess participants' mental model of how well their mobile device supported their mobility. Eight of our 12 participants confirmed that they charged the device *multiple times a day*. Their *charging routine varied*, with 8 out of the 12 participants preferring to perform their main device charge overnight, while 3 charged in the evening, and another charged in the morning.

All participants consistently reported using email, navigation (*e.g.*, Google Maps), browser, text messaging, games, and social network applications (*e.g.*, Facebook). The applications participants thought *depleted* their battery the most were: maps, games and social networking applications. Interestingly, one participant noted that the operating system was the one to blame.

During the study, the battery level was recorded every time it changed. We also collected events such as the phone being shut off, the moment the user started charging the device, and when the participant unplugged the device from the charger. We collected a total of 415,421 raw battery data points, with an average of 34,618 data points per participant (SD=824 data points) during the four-week study deployment. By overlaying the battery levels during the course of every day of the study, we saw that participants exhibited a variety of battery draining patterns (Figure 3).

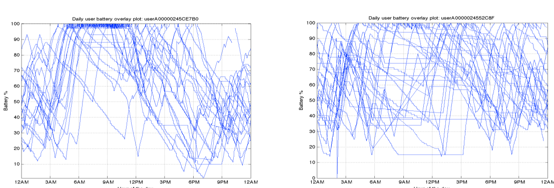

Figure 3: Daily battery levels for two different participants.

More importantly, Figure 3 exemplifies the diversity and variability in participants' mental model of how the battery behaves and how it should be recharged. While some participants kept the phones from reaching low (<30%) battery values, others ran out of power before recharging again. In addition to differences between users, there was a tremendous variability over time for the *same* user. This variability in each participant's own use makes it difficult to form an accurate mental model about battery depletion.

The amount of time the participants' device ran on a single charge also varied, depending on the device usage and charging opportunities in different locations (as reported in the initial interviews and previously in [2]) (Figure 4).

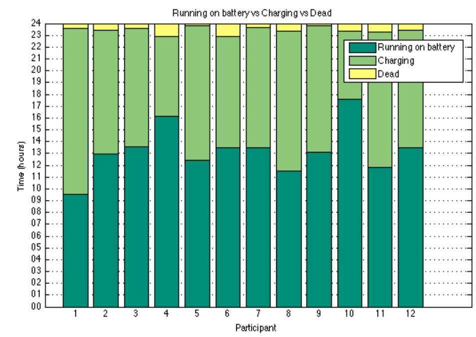

Figure 4: Daily average time the mobile phone ran on battery, was charging, and was dead.

In Figure 4 we considered the phone to be dead, *i.e.* without battery, for the periods when there was no data logged. On average, the mobile phones ran on battery for 12h54 minutes (SD=1h32m) and charged for 4h27 minutes (SD=2h13m) per day. When on battery, our participants' mobile phones ran applications in the background on average 76.6% of the time, *i.e.*, 10h28 minutes (SD=1h13m), while 23.4% of the time was dedicated to foreground applications, *i.e.*, 2h41 minutes (SD=1h42m).

As expected, different participants exhibited different device usage (Figure 5). On average, 51% of daily processing is dedicated to *user*-launched applications, while 23% is dedicated to the operating *system* applications. The remaining 26% of the processing, the phone is *idle* (*i.e.*, waiting for incoming calls, messages and notifications).

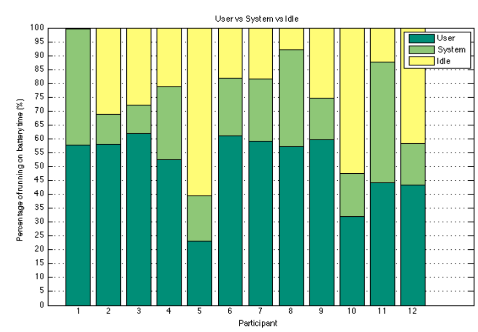

Figure 5: Daily average of processing dedicated to user, system and idle, when running on battery [1].

In the initial Study 1 interviews, users reported between 8h and 14h of battery life, which suggests that users have a

[1] In Figure 5, participant 1's device has very short idle time possibly due to his installed software. As a consequence, he charges his device the most and has the shortest running on battery time (See Figure 4, participant 1).

reasonable understanding of their device's daily battery lifetime. Moreover, contrary to previous findings [10, 11], our interviews suggest that participants nowadays *do* recognize that the use of *GPS, network* and *applications* affects the device's battery lifetime. However, the *operating system, calls, messages* or *airplane mode* are *still not* a part of most participants' battery mental model.

Understanding battery depletion

In the second interview, conducted at the end of Study 1, we jointly inspected the logged data with each participant, where we first discussed the different wireless and network capabilities of the devices, then interaction with the mobile phone (*i.e.*, phone usage – calls and texts; applications usage), management of battery life, and their reflections on the data. Particularly, we discussed whether and how the information helped them understand what was happening on their device and ultimately their device's battery life.

GPS was used very often for navigation, traffic information and social networking applications (9 of the 12 participants). Most of our participants do have a data plan active on their device. With the exception of two participants, the network provider data access was considered as "very good" and a reliable Wi-Fi replacement. Our participants rarely used airplane mode. Our participants did not use it for energy savings, but instead to be perceived as unavailable or when traveling.

"I turn it on at night, I'm unavailable" – P6
"I use it when I fly [...] I fly often [...]" – P10

The participants were presented with a list of the top-20 most processor intensive applications they used. This list was regarded as *very useful* for the users to *evaluate* which applications are likely to be draining their device's battery. The list also presented processor time allocated to background (*i.e.*, operating system) services, highlighting applications that the users reported to not be aware of, but that were consuming processor cycles nonetheless.

"I don't use [application], what's it doing there?!" – P8
" [manufacturer] applications are running a lot…" – P1

Overall, after the study the participants had a clearer overview of *which applications* were depleting the battery and they valued the *opportunity to reflect* on the application list.

"[...] had the feeling that games seemed to drain battery the most. This just confirmed it!" – P10
"Listening to music drains more battery than I anticipated!" – P12

The participants *associated* more easily the battery drain with *applications they used on a daily basis*. However, they struggled to identify *manufacturer* applications (*e.g.*, Mediaserver, Social Hub, AllShare, ChatOn, Days, Game Hub, Group Cast, Memo), *i.e.*, applications that *they did not install* and are *pre-installed* on their devices. Furthermore, our participants did not associate calls/messages with battery life, perceiving it as the phone's core functionality.

Managing battery life is part of the daily routine for our participants, where 10 out of 12 participants consistently charged their devices during the day and again overnight. When asked whether they had any strategy for increasing battery life, a few participants reported charging again and turning off the Wi-Fi and/or Bluetooth. However, most participants confessed to *not knowing what else to do* in order to increase the battery life, other than *recharging*. *All* participants felt "unhappy" about the longevity of their device's battery, and three of them reported that their device dies frequently during the day.

Summary from Study 1

The collected data was invaluable in providing us with a better understanding on how battery life was affected by users' interactions with their devices:

a) Individual users exhibit very *diverse* patterns of behavior, and it is challenging to capture this diversity to predict or explain battery usage in a battery interface;
b) Users have a reasonable battery mental model to explain their phone's battery lifetime and correlate the impact of their actions with *foreground application* usage, but not operating system processes or phone usage;
c) Despite this reasonable mental model of battery lifetime, some participants' phones died frequently. In addition, users reported not knowing *what to do* to increase battery life, other than simply recharging their device or turning on/off the Wi-Fi and Bluetooth;
d) When presented with a list of applications running on their phones, users more easily identified applications they *installed* from the application store, than manufacturer applications.
e) Users are unable to assess reliably the battery left with the battery icon (Table 1), on the notification bar.

Participants' device usage diversity, and issues we discovered with forming good mental models about battery life gave us design insights and motivated us to prototype and evaluate a *personalized* battery interface, IBI (a). As participants were able to correlate application usage with their phone's battery life, we will support their battery life mental model by listing *currently running* applications (b). IBI will also allow participants to *terminate* applications that are currently running, thus supporting the correlation and providing an alternative for battery management (c). Furthermore, participants easily recognized applications they installed from the application store, but did not recall manufacturer applications. Thus we decided to *hide* these applications in the design of IBI (d). The participants reported using their device's to check the current time. This motivated us to explore these short span interactions to display battery information to the participant on the lock screen (e).

Study 2 – Experiencing An Interactive Battery Interface

For Study 2 we recruited a new set of 22 participants (17 male, 5 female), aged between 22 and 40, with varied technical skills and professions, to study the usability and perceived usefulness of IBI. Participants were recruited via email and flyers, and each was compensated with two cinema tickets. We deployed IBI on their own Android phones for 3 weeks, and conducted 3 semi-structured interviews, one before the study, one halfway through the study, and one on the last day of the study.

Estimating battery life and application impacts

The estimations in IBI (*i.e.*, battery time left and application impact) provided application-granularity time estimations. For each application usage session (*i.e.*, time from when it is visible until it is closed or sent to the background) we recorded the active application, the amount of time it was active for, the other applications concurrently running in the background and how much the battery was depleted during this application session (Δ battery). A new application session is started every time the user changes applications.

Using linear regression, we calculated the weight of each application (w_{app}) on battery life as percentage/second (%/s) when running in the foreground (*i.e.*, visible) and when in the background (*i.e.*, invisible) individually for each application session (*i.e.*, the elapsed time is the same for all applications per session), as follows:

$$\Delta\, battery\ (\%) = \sum_{i=1}^{n} w_{app\ i}\ (\%/s) \times elapsed\ time\ (s)$$

Every time the user turned the screen on, used IBI or launched an application, we re-calculated the estimated battery time and application battery impacts. Given the remaining battery level and current running applications ($w_{running\ app}$), we can estimate the remaining battery life, assuming the set of running applications will not change, as follows:

$$Estimated\ time\ (s) = \frac{remaining\ battery\ (\%)}{\sum_{i=1}^{n} w_{running\ app\ i} (\%/s)}$$

The battery impact for each application is the amount of battery life that would be saved by terminating that application. This was calculated using the estimated battery time for the set of currently running applications minus the estimation time for the set of current applications with the application in question removed.

Similar to Caret [9], IBI provided estimates 1 week after it was deployed, in order to gain enough historical data with which to make reasonable estimates. Please note, producing an *accurate* estimate of battery life is *not the focus* of this work; rather we wanted to prototype a better battery interface and understand users' experiences in using it.

IBI is a functional prototype, using actual device information from each unique user on application and battery usage. Users were able to actively manage battery life immediately after installation, using the list of currently running applications and the current battery percentage.

Design and functionality

IBI was developed for Android 2.1 or higher and takes into consideration Rahmati's [10] recommendations for future battery interfaces and the insights from Study 1 (Figure 6).

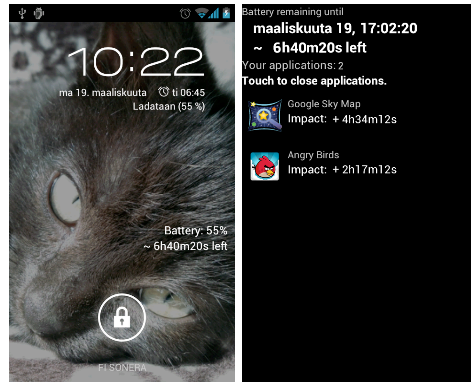

Figure 6: IBI prototype interface: locked screen (left), interactive battery manager (right).

Our interactive battery interface prototype allows users to:

- *Quickly glance* at the current battery life and see for *how much time* they can expect to use their device based on their current device usage (Figure 6, left);
- *Identify* currently running applications and *terminate* recognizable applications on demand, to potentially increase battery life (Figure 6, right);

From the final interviews in Study 1 we learned that users often use their mobile phones as a replacement for a watch and to check for new notifications. Therefore, we augmented the lock screen interface (Figure 6, left), which normally shows the current time and date, with a descriptive status of the battery without much detail, so as to be glanceable. It displays the current battery percentage as well as an estimate of the remaining battery time. The battery percentage is acquired from the operating system. IBI's main interface (Figure 6, right), when launched by the user, uses two different ways to present the remaining battery time: at the top, the date when a charge will be needed (month, day and time of day), and the remaining battery life (days, hours, minutes and seconds). This is followed by a count and list of the currently running applications.

TCBI [13] grouped applications into categories thus hiding specific applications users would recognize. From Study 1, participants reported more easily *recognizing* applications they installed from the application store, rather than the manufacturer applications. Thus, to improve application *recognition*, a scrollable list of only *user-installed* and *currently running* applications is provided (in contrast with the standard Android battery interface), displaying the application icon, name, and estimated battery impact.

Showing the battery impact helps users make an informed decision about how to manage their battery, by updating them about what is currently running on their device and what impact terminating an application would have on battery life. In fact, the user can select an application and, upon confirmation, terminate it, giving them the ability to make actionable decisions about battery life. As such, in addition to the data collected in the previous study, we also collected data on which applications the users decided to terminate and when.

Evaluating battery management with IBI

In our initial interviews in Study 2, for consistency we again asked the users how long their device's battery lasted, which applications they used on a daily basis, and which ones consumed the most power, in order to validate Study 1 findings about participants' perception of their devices' battery life and how they thought it was being drained. As in Study 1, participants in Study 2 reported that the battery life varied each day, between 8h and 14h on average. The most used applications were email, browser, calendar, games and Facebook. The most battery draining applications were the Internet browser and games.

In our second interview, halfway through the study (12th day), we asked our participants if they noticed any change in how they used their device since they started using IBI. In general, the participants reported that their understanding of the battery life on their device had been *augmented* by the new battery interface.

"Having a real number [%, estimation] is easier to read than this icon. Funny thing is seeing 41% and the icon still shows the battery as half-full." – P21
"With IBI, I know now that my phone's battery lasts for about a day or so. Before, I would wait for it to tell me it was about to die. I hated that [dying silently]" – P22

In the last interview, the participants discussed the limitations of IBI, how often and why they used IBI and if it had affected their device use in any way. Finally, we asked them to rate how useful IBI was in comparison to the standard battery interface, on a 5-point Likert scale (1=least useful, 5=most useful). The average reported usefulness of IBI was 4.7 (SD=0.5), whereas participants rated the standard battery interface with 2.5 (SD=1). For the 5 participants whose standard battery interface showed a battery percentage, the reported usefulness was 3.5 (SD=0.5).

In terms of limitations, one participant wished he could see the effects of the network and the display on battery life. Six of the 22 participants expressed that they wished that they could also see the manufacturer applications, not just the ones they installed. While manufacturer applications cannot be terminated (a known limitation of Android), viewing them would allow users to manage battery life by altering their usage of these applications.

"I also use […] the browser and Gmail. I wish I could see how much they affect my battery life." – P4

Although 6 participants saw hiding manufacturer applications as a limitation, the operating system task manager manages these applications automatically. Should the user decide to terminate such applications, the operating systems' task manager would restart the application immediately, thus giving the impression that IBI did not work or failed to respond to their command. Similarly to Figure 1, manufacturer applications are hidden (*e.g.*, Browser, Mediaserver, AllShare, Contacts).

All participants reported checking the battery level throughout the day, whenever they checked the current time from the locked screen interface. Six participants reported checking the battery by looking at the locked screen each night, before going to bed, to make sure they would have enough battery life the following day.

Two participants reported using IBI's main interface if the battery was running low and they wanted more battery life. Another reported using IBI if the device was performing "slow". Otherwise, in the majority of times, all participants used IBI to close applications they no longer required or were running without their knowledge.

In our final interviews from Study 2, participants were *surprised* to find running applications that they did not *explicitly* launch. The *most terminated* applications were *social* applications (*e.g.*, Facebook, WhatsApp, Skype, Twitter), *information retrieval* applications (*e.g.*, Pulse, Washington Post, Yahoo Mail) and *leisure* applications (*e.g.*, Endomondo, Spotify). Coincidently, *all* the most terminated applications are applications that intermittently pull or push updates from and to the Internet.

On average, each participant terminated 11 applications (min=4.3; max=22.5; SD=4.2) each day using IBI. We further assessed if using IBI influenced users' behavior, *i.e.*, motivated them to terminate applications. There is a positive correlation between application termination and IBI's application usage (r^2 = .5359, $p < .0001$), where participants terminated one or more applications for every six times they used IBI's main interface (Figure 7).

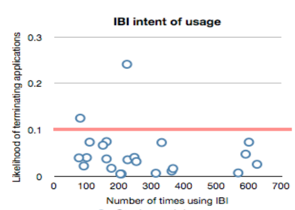

Figure 7: Likelihood of users terminating applications.

Twenty out of 22 participants demonstrated less than 10% likelihood of terminating an application when using IBI, with 4 of those using IBI more often (above 500 times). On the other hand, 2 participants demonstrated a higher likelihood (above 10% - horizontal line) of terminating applications when using IBI.

To assess IBI's effect on battery life, we calculated the average battery depletion rate (BDR), *i.e.*, how fast the battery is running out, as follows:

$$BDR\ (\%/h) = \frac{1}{n}\sum_{i=1}^{n}\frac{battery\ change_i}{elapsed\ time_i}$$

where n is the number of battery uptime intervals, *battery change* is the difference in battery percentage and the *elapsed time* is the length of the uptime interval in hours. We compared the BDRs for the first week (before introducing IBI's main interface) versus the following weeks, per participant (Table 2).

Participant	Before (%/h)	After (%/h)
1	6.93 (SD=1.63)	4.28 (SD=2.87)
2	7.55 (SD=2.53)	7.22 (SD=3.14)
3	4.60 (SD=1.52)	2.64 (SD=0.98)
4	9.35 (SD=1.43)	7.51 (SD=1.89)
5	7.94 (SD=2.85)	2.76 (SD=1.14)
6	3.28 (SD=0.61)	2.39 (SD=1.56)
7	6.57 (SD=2.52)	5.55 (SD=1.67)
8	5.79 (SD=1.99)	2.71 (SD=1.48)
9	3.44 (SD=1.41)	3.04 (SD=0.87)
10	5.79 (SD=3.43)	4.55 (SD=1.76)
11	8.50 (SD=2.01)	7.69 (SD=2.25)
12	8.85 (SD=2.34)	5.68 (SD=1.72)
13	5.18 (SD=2.64)	2.17 (SD=0.86)
14	8.94 (SD=3.15)	5.03 (SD=2.78)
15	3.83 (SD=0.65)	3.37 (SD=1.92)
16	5.33 (SD=2.13)	2.44 (SD=0.17)
17	6.35 (SD=2.59)	4.63 (SD=2.18)
18	4.97 (SD=1.29)	3.93 (SD=1.37)
19	4.69 (SD=1.35)	3.99 (SD=1.96)
20	5.74 (SD=2.98)	3.56 (SD=1.82)
21	6.11 (SD=2.41)	3.61 (SD=1.44)
22	3.56 (SD=1.17)	2.88 (SD=0.10)

Table 2: Battery depletion rates for all participants.

All participants' battery depletion rates *decreased* when we introduced IBI. This decrease is statistically significant ($t(21) = 6.887$, $p < .0001$) with mean 1.89% per hour (95% confidence interval [1.32, 2.47]). In other words, battery life increased from 12h21 minutes (SD=2h21) to 15h42 minutes (SD=1h15) on average per day, a statistically significant 27.1% increase. Moreover, Figure 8 shows evidence of improvement in our participants' mobile phone battery life and reduced frequency of charging, especially after our second interview (vertical line).

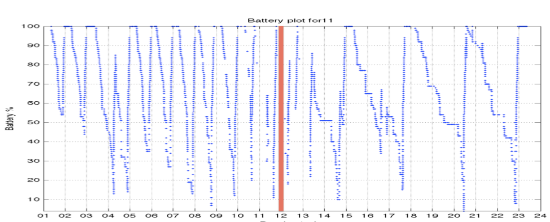

Figure 8: Battery plot for one participant in the study.

To validate that this improvement is due to IBI, we analyzed the applications used during the first week, and during the following week, and found that participants did not avoid battery-using applications. In fact, their daily average number of applications used significantly increased ($t(21) = 3.858$, $p < .0001$), from 49.0 (min=14.6; max=108.5; SD=27.3) to 59.3 (min=17.3; max=158.5; SD=32.9).

ANALYSIS & DISCUSSION

Human-battery interaction today

In their study of batteries, Rahmati *et al.* [10, 11] report the following points that we now revisit:

1. There are two sets of users: those who charge sporadically and those who follow the battery interface feedback;
2. Users' battery charging is diverse;
3. Users have inadequate knowledge of system power characteristics;
   a. Current UIs for power-saving settings are inadequate;
4. Existing battery indicators are inaccurate and inadequate;
   a. Battery indicators of higher resolutions lead to higher user satisfaction;
   b. Better feedback may enable users to charge phones more conveniently.

Similarly to [4, 6], we found that each user is unique in their use of their phone and that device usage also varies over time (Figure 3), where we confirm the duality in battery management of our users, validating point (1). This diversity in device usage is nowadays fomented by i) new applications that can be installed from application stores on an *ad-hoc* basis and ii) mobile phones' ability to run multiple applications that simultaneously share devices' built-in sensors, where collectively they may have significant impact on battery life. The mobile phone is no longer *just* a phone.

For recharging the battery, we found evidence that there were other relevant factors, in addition to location [2]. Users recharge their devices whenever *convenient* for them, often several times a day (Figure 3), thus validating point (2). Despite increased charging opportunities (*e.g.*, availability of USB and multiple power chargers), users do follow a preferred charging schedule routine, often overnight, also reported in [6].

We suspect that point (3) may no longer be as pertinent, as some of our users indicated disabling Wi-Fi or Bluetooth to save power, *i.e.*, point (3a). Despite users not associating calls and messages to battery life, users do acknowledge GPS, network and applications as being power-hungry. From our interviews, users consider calls and messages as core to the mobile device, and do not consider their impact on battery life. In general, users do have some idea of *which applications* consume the most battery on their device. For example, games, maps, navigation and social networking applications were the ones to blame for a shorter battery life. In the interviews in Study 1, users confessed to not knowing what to do in order to increase the battery life, other than recharging. This leads us to conclude that users struggle to *manage* their devices' battery life and that the standard battery life interface on their devices is *still* not helpful, *i.e.*, validating point (4).

Lastly, the standard battery interface has changed, and it is increasingly common to find percentages associated with the battery icon (Table 1), and the top-2 mobile manufacturers provide further details on battery life (Figure 1, Figure 2). Although useful in capturing a snapshot of the device's current uptime (amount of time running on battery), these interfaces do not provide an up-to-date battery life status and are mostly focused on the inner workings of the operating system with users failing to recognize the elements it displays (*e.g.*, what is the difference between Android OS and Android System in Figure 1?) and are unable to affect or control most of the elements (*e.g.*, phone idle, cell standby). Simpler still, but even more ineffective, is Apple's iOS battery status interface (Figure 2), with the amount of time the device is on standby and in use.

Manipulating HBI with an interactive battery interface

Our goal was not to create a *perfect* battery interface, but instead to study the users' experiences with a user-centered battery interface design. In the initial interviews from both studies, participants reported that their device would last between 8 and 14 hours before needing to be recharged. Our data analysis revealed that the average running on battery time was within this range, with an average of 12h54 minutes (SD=1h32m) for Study 1 (Figure 4), and 12h21 minutes (SD=2h21m) during the first week in Study 2. Despite evidence that mobile phone users create their own mental model of how their devices' battery should perform, which can be reasonable for some users, when we asked participants if they were happy with their device's battery life, *all* thought that it did not last long enough for their needs. The phones often died during the day, or simply required constant recharges throughout the day. This leads us to believe that although it may be true that some users have a satisfactory mental model for evaluating the current state and future state of their device's battery life, it is inaccurate for the majority of mobile phone users.

Despite running on battery for 30% more time than recharging, we found that participants only actively used their devices 23.4% of the time it was running on battery. This suggests that even though the user was not using the device *per se*, the battery is still being used on applications and services running in the background. Processing-intensive user applications and system services keep the phone busy 74% of the time, when averaged over each day (Figure 5). We found that the idle time is directly correlated with the running on battery time ($R^2 = .232$, $p < .0001$), which means that participants with higher idle times have higher running on battery times, but no battery interface has exploited allowing users to *manage idle time*.

One of IBI's interface goals was to augment the standard battery interface with information that could help explain the current battery state to the user, without information overload (Figure 6). Users do not associate the impact of the operating system, calls or messages on battery life, but instead *understood application usage*. With this in mind, we emphasized user-installed applications' battery impact in IBI's interface and hid manufacturer applications, because in the final interviews from Study 1 participants reported not knowing what some applications were (all of which were applications introduced by the mobile device manufacturer). In the final interview from Study 2, 16 out of 22 participants were happy with only showing applications they installed. However, it made a minority of the users feel they did not have control over their device.

Seventeen out of the 22 participants reported that the amount of time left was easier to understand than a specific date, as it is sometimes hard to remember what day it is. However, having the seconds in the estimations was misleading, as participants reported that they would wait and see if the seconds would decrease. In order to minimize battery life impact, IBI would only update if: the user turned the screen on (to update the lock screen UI), the battery value changed (which is not frequently), or when the user explicitly opened IBI or terminated an application from the running application list.

In the last interview in Study 2, participants revealed using IBI for various purposes: to *know* the current status of the battery level; to *control* what was running on the device; and finally, to *assess* if the battery level was high enough for the day ahead. While usage varied across participants, participants used IBI's main interface to manage their battery life, terminating one or more applications for every six times (on average) that they used it (Figure 7). The positive correlation between the frequency of user-terminated applications and IBI's usage frequency suggests that participants were able to decide which applications should be left running or terminated. In fact, each participant terminated eleven applications daily, on average. Despite battery life estimation errors, participants were able to successfully use the battery impacts to identify applications that were depleting the device's battery life.

The most frequently terminated applications intermittently update their content (social, information retrieval) or run in the background (entertainment). Social applications and information retrieval often pull or push the latest information to the user. Despite devices' built-in support for disabling background syncing, most of our participants were unaware of this setting. This contributes to participants' surprise in finding applications running without their explicitly using them, extending issue 3(a) to power-saving settings for application synchronization.

Participants with longer idle times run on battery longer (Figure 5). As IBI terminates applications, it increases the idle time, so we expected an increase in battery lifetime. There is evidence of an *increased* mobile phone battery life and a *decrease* in the frequency in charging when our participants used IBI (Figure 8), therefore reinforcing point

(4b). Our results show that our participants gained 1.89% of battery uptime per hour with IBI (Table 2), resulting in an increase of the average daily battery lifetime for the last two weeks of Study 2 from 12h21 minutes (SD=2h21) to 15h42 minutes (SD=1h15), a statistically significant 27.1% increase ($t(21)=4.066$, $p < .0005$).

This increase was not due to a reduction in application usage, as our participants' average daily application usage actually increased ($t(21) = 3.858$, $p < .0001$). Together, these results are indicative of *improved* mobility for our participants. Our results provide evidence that a descriptive and interactive battery interface will help users understand and adapt to the limitations of their device's battery life. They will also understand how their interactions with the mobile phone ultimately affect when and for how long they have to recharge, and therefore, gain control over their mobility, validating point (4a).

Study limitations

Both our studies were deployed on participants' own devices to ensure diversity of behavior and reduce bias. Nonetheless, we must acknowledge the limitations of an evaluation with 34 participants and that our observations might not be representative of a larger sample. Users' batteries age, usage diversity and variability makes estimation of battery life challenging and therefore requires further research that goes beyond the scope of this work.

Future work

From the feedback we received on IBI, it is not enough to provide an estimate of the amount of time the device will be alive for. The reader could argue for an automated approach [2, 3, 7] to reduce the burden of battery management. However, our work demonstrates that such an approach would deprive the users from deciding what to keep running or not. However, we could allow users to create rules to partially automate IBI. Allowing the user to take action on the currently running applications and knowing which applications have the most impact on battery life, will enable them to make more informed decisions on how to manage their battery life. In future work, we will investigate the value of providing suggestions on which applications should be terminated [9], crowd-sourcing application battery impacts to further enhance the battery estimations, recommending charging based on previous usage patterns and an even more descriptive battery interface, to further improve mobile phone users' expectations of battery life.

CONCLUSION

Nowadays, mobile device battery interfaces display an icon (and optionally, a percentage number), which, as reported from our interviews, still fail to adequately inform users about the status of their device. As a consequence, all 34 of our participants expected more from their battery life. To address this, we explored users' perceptions of mobile phone battery life and designed a new user-centered battery interface. The contributions of our work are: an up to date understanding of how mobile users are using their devices; an understanding of how mobile user's believe their interactions with the device affect battery life; and the development and evaluation of an interactive battery interface that resulted in a daily increase of 27% in battery uptime.

ACKNOWLEDGEMENTS

Funded by the Academy of Finland, InfoTech, TEKES, Nokia Foundation, Tauno Tönningin Säätio Foundation, KAUTE and the Portuguese Foundation for Science and Technology (FCT) grant CMU-PT/HuMach/0004/2008 (SINAIS).

REFERENCES

1. AWARE: Android Mobile Context Framework. www.awareframework.com.
2. Banerjee, N., Rahamati, A., Corner, M.D., Rollins, S. and Zhong, L. Users and Batteries: Interactions and Adaptive Energy Management in Mobile Systems. *UbiComp '07*, 217-234.
3. Bloom, L., Eardley, R., Geelhoed, E., Manahan, M. and Ranganathan, P. Investigating the Relationship Between Battery Life and User Acceptance of Dynamic, Energy-Aware Interfaces on Handhelds. *MobileHCI '04*, 13-24.
4. Falaki, H., Mahajan, R., Kandula, S., Lymberopoulos, D., Govindan, R. and Estrin, D. Diversity in smartphone usage. *MobiSys '10*, 179-194.
5. Ferreira, D., Dey, A.K., Kostakos, V. Lessons Learned from Large-Scale User Studies: Using Android Market as a Source of Data. *Mobile Human Computer Interaction (IJMHCI) 3*, 4 (2012), 28-43.
6. Ferreira, D., Dey, A.K. and Kostakos, V. Understanding Human-Smartphone Concerns: A Study of Battery Life. *Pervasive '11*, 19-33.
7. Harter, T., Vroegindeweij, S., Geelhoed, E., Manahan, M. and Ranganathan, P. Energy-aware User Interfaces: An Evaluation of User Acceptance. *CHI 2004*, 199-206.
8. Karlson, A.K., Meyers, B.R., Jacobs, A., Johns, P. and Kane, S.K. Working Overtime: Patterns of Smartphone and PC Usage in the Day of an Information Worker. *Pervasive '09*, 398-405.
9. Oliner, A, Iyer, A, Lagerspetz, E, Tarkoma, S and Stoica, I. Collaborative energy debugging for mobile devices. *HotDep '12*.
10. Rahmati, A. and Zhong, L. Human-battery interaction on mobile phones. *Pervasive and Mobile Computing 5, 5* (2009), 465-477.
11. Rahmati, A., Qian, A. and Zhong, L. Understanding Human-Battery Interaction on Mobile Phones. *MobileHCI '07*, 265-272.
12. Ravi, N., Scott, J., Han, L. and Iflode, L. Context-aware Battery Management for Mobile Phones. *IEEE PerCom '08*, 224-233.
13. Truong, K.N., Kientz, J.A., Sohn, T., Rosenzweig, A., Fonville, A. and Smith, T. The Design and Evaluation of a Task-Centered Battery Interface. *UbiComp '10*, 341-350.
14. Zhang, L., Tiwana, B., Qian, Z., Wang, Z., Dick, R.P., Mao, Z.M. and Yang, L. Accurate online power estimation and automatic battery behavior based power model generation for smartphones. *CODES/ISSS'10*, 105-114.