Pervasive and Mobile Computing 5 (2009) 465–477

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

journal homepage: www.elsevier.com/locate/pmc

Fast track article

Human–battery interaction on mobile phones

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ARTICLE INFO

Article history:
Received 21 January 2008
Received in revised form 18 July 2008
Accepted 8 August 2008
Available online 17 August 2008

Keywords:
Mobile phones
Human–battery interaction
Batteries
Power management

ABSTRACT

Mobile phone users have to deal with limited battery lifetime through a reciprocal process we call human–battery interaction. We conducted three user studies in order to understand human–battery interaction and discover the problems in existing designs that prevent users from effectively dealing with the limited battery lifetime. The studies include a large-scale international survey, two long-term field trials including quantitative battery logging and qualitative inquiries, and structured interviews with twenty additional mobile phone users. We evaluated various aspects of human–battery interaction, including charging behavior, battery indicators, user interfaces for power-saving settings, user knowledge, and user reaction. We find that mobile phone users can be categorized into two types regarding human–battery interaction and often have inadequate knowledge regarding phone power characteristics. We provide qualitative and quantitative evidence that problems in state-of-the-art user interfaces have led to under-utilized power-saving settings, under-utilized battery energy, and dissatisfied users. Our findings provide insights into improving mobile phone design for users to effectively deal with the limited battery lifetime. Our work is the first to systematically address human–battery interaction on mobile phones and is complementary to the extensive research on energy-efficient design for a longer battery lifetime.

1. Introduction

Battery lifetime is a major usability concern to mobile phone users. Our recent survey (Section 2.1) showed that 80% of mobile phone users in our respondents took various measures to increase their battery lifetime. While significant research has been devoted to improving the battery lifetime, little is known regarding how human users deal with limited battery lifetime, which we call human–battery interaction (HBI). Human–battery interaction is a reciprocal process. On one hand, modern mobile phones provide users with indicators of the battery charge level, as well as user interfaces for changing power-saving settings such as display brightness reduction. We refer to these indicators and user interfaces collectively as the *battery interface*. On the other hand, human users can react to the dropping battery charge level by changing the power-saving settings, altering usage patterns, and charging the phone.

Understanding human–battery interaction will provide valuable insight into the effectiveness of the battery interface and how mobile users deal with limited battery lifetime, prioritize and make tradeoffs. Knowledge regarding human–battery interaction will essentially help design better battery interfaces that enable users to more effectively take advantage of the limited battery lifetime. However, understanding human–battery interaction on mobile phones is challenging, due to vast diversities in phone makes and user population.

To address this challenge, we have conducted multiple user studies including both quantitative inquiries and qualitative measurements. First, we surveyed more than 350 high school students from China, India, and the US to assess their knowledge regarding mobile phone power characteristics and their concerns about battery lifetime. Second, we conducted

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1574-1192/$ – see front matter
doi:10.1016/j.pmcj.2008.08.003

field trials with a commercial Pocket PC phone over multiple months. We conducted focus groups and interviews to assess our participants' subjective opinions and collect their stories of human–battery interaction. Third, we interviewed twenty additional mobile phone users on their experience with battery interfaces and how they deal with limited battery lifetime. These three studies collectively provided a comprehensive understanding of state-of-the-art human–battery interaction and offered insights into ways to improve it. Our results were first reported in *ACM Mobile HCI 2007* [10]. Since then, we have finished a much longer field trial (four months) and made several new findings, which are included here. To the best of our knowledge, our work is the first to systematically address human–battery interaction on mobile phones. Our technical contributions include:

- We presented four complementary user studies that address various aspects of human–battery interaction, and offered many interesting findings based on their results.
- We showed that mobile phone users take different strategies to deal with limited battery lifetime, which roughly fall into two categories.
- We showed that mobile phone users often have inadequate knowledge on the power characteristics of mobile phones and their features. However, they quickly adapt charging behavior to changes in battery lifetime.
- We showed the inadequacy in state-of-the-art battery interfaces. In particular, we found battery indicators are inaccurate, many of them provide insufficient information, and power-saving settings remain largely unutilized. Such inadequacy can prevent the user's very strategy from achieving their intended goal.

The implication of our work on human-centered design of mobile phones is multifold. First, the battery interface should be designed to impose minimal cognitive and technological challenges to mobile users. Second, mobile phones should provide users with battery knowledge through proper manual and user interface designs. Third, our findings regarding human–battery interaction provide foundations to energy management research that leverages user charging behavior to utilize battery energy for better services [3,14].

The rest of the paper is organized as follows. In Section 2, we provide the background for human–battery interaction. Then, in Section 3, we present the details of our research methods toward understanding human–battery interaction. Our methods include large-scale surveys, interviews, and long-term field trials with in situ logging and qualitative inquiries. In Section 4, we present our findings regarding human–battery interaction. We discuss related work in Section 5 and conclude in Section 6.

2. Background

We next provide the background for human–battery interaction on mobile phones: properties of modern phone batteries, the user interfaces provided to deal with limited battery lifetime, and our user model for the process of human–battery interaction.

2.1. Mobile phone batteries

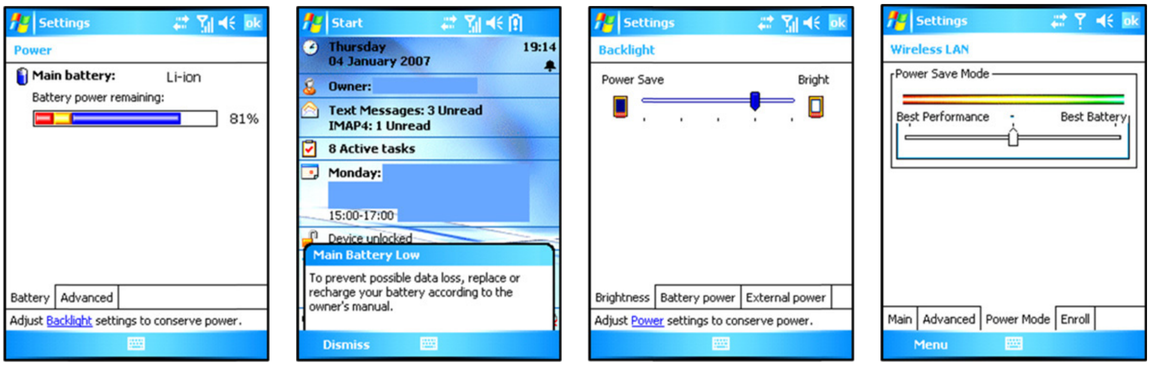
Rechargeable batteries power the operation of most mobile phones on the go. Its lifetime determines the availability of the portable services mobile phones provide. While new battery technologies have been intensively investigated, battery capacity, in terms of volumetric or gravimetric energy density, improves at a much slower pace than computing capacity [8], which has been governed by Moore's Law. To enjoy a decent battery lifetime, state-of-the-art advanced mobile phones often spend over 10% its weight on battery, e.g. 13% for the Nokia E90 and 15% for the HTC Wizard. Batteries have become an increasing usability challenge as phones progressively add more features while shedding weight. For example, the Nokia Communicator has lost close to half of its original weight in 10 years, from the 9000 model to the E90. Intensive research has been devoted to make the mobile phone more energy-efficient and thus elongate the battery lifetime. Yet little is known regarding how mobile users deal with the availability constraint set by the battery.

Most mobile phones employ rechargeable Lithium-ion (Li-ion) or Lithium-ion polymer (Li-poly) batteries, which enjoy improvements over previous generations, such as nickel-cadmium (NiCd) and nickel metal hydride (NiMH). One particular advantage is that they can be charged at any charge level without much harm to battery capacity. This leads to new charging behavior as mobile users can charge virtually any time of convenience. An important drawback of Li-ion and Li-poly batteries is that they start aging immediately after manufacture, even if not used [5]. Battery lifetime becomes noticeably shorter after several months of usage, and this was reported by participants in our four-month field trial.

Rechargeable batteries found in mobile phones usually provide remaining battery capacity through the smart battery interface [5]. The smart battery interface employs a *gas gauge* microchip that calculates the charge level with a pre-known battery model using measurable parameters, including temperature, voltage, and current flowing from or to the battery. It can supply information to the system through a serial data interface. Modern mobile phones treat the battery as a peripheral device and retrieve battery information through the battery driver. For example, Windows Mobile provides a function call (*GetSystemPowerStatusEx2*) for applications to retrieve battery information, including the estimated charge level as a percentage of the full capacity. Unfortunately, the sophistication of battery chemistry [9,11,12] and the simplicity of battery models mandated by the miniature computing capacity of the gas gauge microchip limit the accuracy of the charge level estimation. In particular, it is well known that the energy output of a battery depends on the discharging patterns and physical environment, e.g., temperature [11].

(a) i-mate K-Jam. (b) Cingular 2125. (c) T-mobile MDA. (d) Nokia 3220.

Fig. 1. Battery indicators on various mobile phones.



(a) Additional battery information. (b) Low battery alert. (c) Backlight brightness setting. (d) Wi-Fi performance setting.

Fig. 2. Battery interfaces on the HTC Wizard phone.

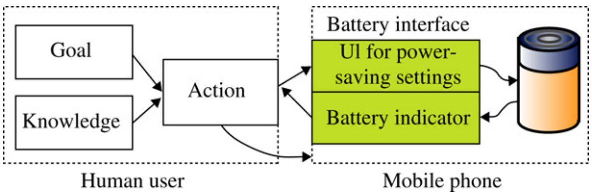


Fig. 3. Proposed conceptual model for human–battery interaction.

2.2. Battery interfaces

Modern mobile phones have interfaces to provide information regarding the remaining charge level and provide user interfaces for users to take actions.

2.2.1. Battery indicators

Battery indicators provide immediate information regarding battery charge level based on the gas gauge, described above. Fig. 1 presents battery indicators from four modern mobile phones. Some phones provide additional user interfaces to show more information about the battery, e.g., Fig. 2(a). Most mobile phones will alert the user for charging when the battery is extremely low, e.g., Fig. 2(b).

2.2.2. User interfaces for power-saving settings

Modern mobile phones provide user interfaces for users to make tradeoffs between battery lifetime and other aspects of usability, such as display brightness. They also allow users to turn off power-hungry system components, such as Bluetooth and Wi-Fi interfaces, to save power. Fig. 2(c) and (d) shows the user interfaces to trade display brightness and Wi-Fi performance for a longer battery lifetime on the HTC Wizard Pocket PC phone. The Wizard is commercially available under a variety of brands, including T-Mobile MDA / MDA Vario, Cingular 8125, Orange SPV M3000, O2 XDA Mini S, i-mate K-Jam, and Qtek 9100.

2.3. Human–battery interaction

We conceptualize human–battery interaction with a simple model illustrated in Fig. 3. The user reads the battery indication and evaluates the situation with their *knowledge* of system power characteristics and their *goal* in using the phone. The user then changes their usage pattern and the phone's power-saving settings, in hope to meet the goal. The model provides guidelines for our endeavor to understand human–battery interaction. It indicates that the study of human–battery interaction should include the investigation of user knowledge, how mobile users set goals in battery lifetimes and prioritize different aspects of usability, the design of battery user interfaces, and how users employ them. All these are studied in this work.

Our model also shows that human–battery interaction imposes perceptual, cognitive, and motor loads on mobile users. To help users deal with the limited battery lifetime effectively, such loads should be minimized. Our model suggests that good battery user interfaces should assume minimal knowledge on the user side, support effective ways for users to set goals and prioritize, and provide friendly means for users to take actions. We will extensively employ this model of human–battery interaction to analyze our user studies.

3. Research methods

In order to understand state-of-the-art human–battery interaction on mobile phones, we have conducted extensive user studies between summer 2006 and end of 2007. We next present our research methods in detail.

3.1. User surveys

In the summer of 2006, we surveyed mobile phone usage and ownership in two high schools in China (One in a rural county and the other in Tianjin, one of the largest cities in China), two high schools in Bangalore, India, and a summer school in Rice University. A total of 350 valid responses were collected from paper-based surveys. 41% of the respondents owned a mobile phone, their average age is 17 years old, and 59% were females. The survey included questions to assess the respondents' knowledge regarding mobile phone power characteristics and their concerns regarding battery lifetime. These questions are presented in [10]. The surveys in China and India were distributed and collected by our local volunteers. The survey in Rice summer school was included in the feedback packages distributed to all the students. While the surveys collected data from a massive number of mobile phone users, the method was limited in that we had no means to conduct follow-up interviews or focus groups of the same population. Nevertheless, the survey results did provide a sampled global view of the power and battery knowledge set of young mobile phone users.

3.2. User interviews

We interviewed twenty mobile phone users from Rice University who own a diverse set of phones. In order to assess possible differences in participants with different backgrounds, we recruited ten students from engineering and another ten from non-science/engineering majors. All participants had used mobile phones for at least six months prior to the interview. Each interview lasted about 30 min and was recorded with the interviewee's consent. The interviews were later manually coded and analyzed.

The interviews were structured and consisted of three parts. In the first part, the interviewee filled out a short survey with questions similar to the User Survey. In the second part, the interviewee was asked a series of questions regarding their interaction with the battery lifetime and battery interface of their phones. The conversation was kept in a casual fashion in order to solicit their stories and anecdotes. For some questions, such as agree/disagree ones, a 1–5 scale was noted down in addition to the interviewees' verbal response and comments. The question topics are listed in [10].

In the third part, the interviewee was shown two phones, the HTC Wizard Pocket PC phone and a smaller Smartphone, the HTC Tornado. The Wizard has a 2.8'' LCD with touchscreen and a slider QWERTY keyboard, while the Tornado has a smaller 2.2'' LCD and a multi-tap keypad. The interviewee was then shown multiple phone screen designs with different battery indicators, and asked for their opinion on each of the designs, and how they would rank the designs. Some of the battery indicator designs are presented in Fig. 4. We designed them based on our own experience and battery indicators from other mobile devices. The interviewee was also provided with paper so that they could draw whatever design they would recommend.

3.3. Field trials and data collection

To understand human–battery interaction in situ, we conducted two long-term field trials in 2007. In the field trial, we collected complete battery traces and complemented them with focus groups and interviews. At the end of the trials, we interviewed participants with the third part of the User Interview, described above.

3.3.1. Experimental phones and battery logging

We have used a popular Pocket PC phone, the HTC Wizard as the experimental phones for field trials. It is a GSM phone with Windows Mobile 5.0 and a standard battery capacity of 1250 mA h at 3.7 V. The phones used in our first field trial had a battery indicator with only two bars, while those used in the second trial had a battery indicator with four bars (Fig. 1(a) and (c), respectively).

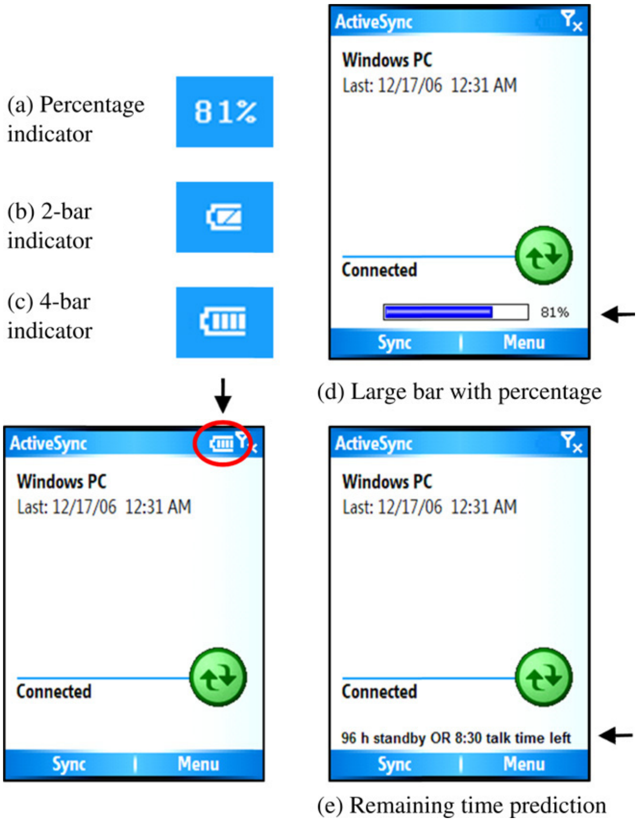


Fig. 4. Some of the battery indicator designs presented to user interview participants.

To quantitatively assess the charging habits of mobile users during real-life usage, we developed software, called SystemDiary, to perform in situ battery status logging on our experimental mobile phones in a non-intrusive fashion. SystemDiary was developed using Visual C++. It consumes about 140 kB memory and runs in the background, with minimal intrusion to the phone operation. It records the battery charge level and charging status every minute. SystemDiary reduces the standby battery lifetime from about five days to about two days in our first field trial, and to about three days in our second trial. Nevertheless, our participants had little experience with the HTC Wizard and were informed about the standby battery lifetime before participation. We assumed that they simply view it as a phone with a standby battery lifetime of two or three days.

3.3.2. First field trial (four weeks)

Ten volunteers from Rice University participated in our first field trial in early 2007. Their ages range between 20 and 26. All but one were males. In the following, we refer to them as P1 to P10. They used the HTC Wizard with SystemDiary from us as their primary mobile phones with their own SIM card inside for one month. While they were informed the phones were logging charge level and network signal strengths, they did not know that we were specifically interested in human–battery interaction.

To complement the logged battery traces, we conducted two 70-minute focus groups with the participants after the one month logging, each with five of the participants. In the focus groups, many topics regarding the phone features, battery life, and user interfaces were discussed. Among these topics were the participants' experience with the battery lifetime, battery interface, and their charging habits. The focus group discussions were recorded and later manually transcribed, coded, and analyzed. After the focus groups, we also interviewed each of the participants regarding any interesting comments they made during the focus groups.

3.3.3. Second field trial (four months)

We first reported the results from Field Trial One, User Survey, and User Interviews in *ACM Mobile HCI 2007* [10]. Since then, we have collected four months of data from a second field trial. The second field trial is similar to the first one except that participants are completely different, each focus group involves only half of the participants, and a participant joins a focus group approximately every three weeks. Moreover, since we conducted the second field trial with results from the first one, we were able to prepare new questions and formulate new hypotheses for focus groups and interviews. We also enhanced the SystemDiary to log the display status in order to infer how the phone is used. The second field trial not only provided additional evidence for our findings in [10], but also led to several new findings, as highlighted below.

The field trial involved 14 teenagers from Pecan Park, an underserved Houston community, in which an open outdoor 802.11 mesh network exists [2]. The network covers about 3–4 square km and registers over 3000 unique access devices during the field trial. Human–battery interaction is studied along with other human factors in the use of wireless broadband ready mobile phones. Our participants were between 15 and 18 years old. Similar to the first field trial, participants with their own GSM plans simply use the experimental phones with their own SIM cards. For those who do not have their own plans, we provided prepaid phone cards to be used with the experimental phones. At every focus group, we gave each of these participants a $25 refill card, worth for 130–150 min. Some participants also purchased additional refills on their own. We lost three participants in the first month due to phone robbery and theft. Therefore, we have meaningful data only for 11 participants, referred as Q1–Q11 below. In addition to the apparent demographic difference, the second trial is different from the first one in that most Pecan Park participants do not have regular access to personal computers while all Rice participants have regular access to either desktop or laptop computers that are Internet ready. We noticed a significantly higher level of non-voice usage of the experimental phones in the second field trial.

4. Results and implications

Our user studies gathered both quantitative and qualitative data regarding human–battery interaction on mobile phones. Analysis and cross examination led to many interesting findings, as we will present in this section.

4.1. User types in human–battery interaction

Our user studies provide strong evidence that our participants can be categorized into two types regarding their human–battery interaction:

- Those who regularly charge their phone, regardless of the charge level. For example, every 1 or 2 days, or whenever convenient. For Type-A, the human–battery interaction is minimal.
- Those who charge their phone based on charge level feedback from the battery interface.

Our field trials provide the strongest evidence. In the first field trial, four participants, P5, P7, P9, and P10, claimed they charge the phone once a day or two, rarely worried about the battery lifetime or battery indicator. They were clearly Type-A. The other participants, P1, P2, P3, and P4, claimed they charge their phones when the battery indicator shows one out of the only two bars. P8 mentioned that he regularly checks the additional battery screen, and charges when the remaining battery is around 40%. P6 mentioned that he usually charges whenever he gets the low battery alert, which occurs at 20%. They were clearly Type-B. The qualitative follow-up interview data was further corroborated by our quantitative battery traces: Type-A users have more random and flat histograms for battery charge levels upon recharge, while Type-B users have distinct peaks in theirs, as shown in Fig. 5. Our user interviews provide further evidence. Five of the twenty interviewees indicated they charge every day or two, irrespective of battery life, and do not care about battery life and its indicator. Type-A users may also explain about 20% of the mobile users from our user survey who indicated they did not care about saving battery. Participants in our second field trial also fall into these two types, with some variations as will be discussed later.

According to our human–battery interaction model in Section 2.3, Type-A and Type-B users take different strategies to optimize their perceptual, cognitive, and motor loads. Type-A users minimize the direct human–battery interaction loads at the cost of the extra cognitive and motor loads of faithfully charging phones more often than necessary. Therefore, they are not taking full advantage of their battery capacity. Type-B users minimize the cognitive and motor loads of charging, at the cost of extra perceptual, cognitive, and motor loads of direct human–battery interaction. It is important to note that Type-A behavior is possible only when battery lifetime is long enough to cover abundant charging opportunities.

One would expect Type-A users to charge more often than Type-B ones, which was indeed observed in our second field trial. However, on average among our first field trial participants, Type-B charged more often and at higher charge levels than Type-A. We believe this was caused by the 2-bar battery indicator of our HTC Wizards, as four out of six Type-B participants charged when they had one out of two bars left. This is addressed in detail in Section 4.4.

The categorization of mobile phone users has multiple implications to human–battery interaction research. First of all, knowing the type of a user, we can predict their human–battery interaction. For example, Type-A users care less about battery interfaces and will need less battery knowledge than Type-B ones, as our results suggest. Second, Type-A users make it possible for energy management systems such as Llama [3] to exploit the excessive energy left on the battery before recharging. Third, the existence of Type-A users provide indirect evidence that the existing battery interfaces may be so inadequate that some users simply give up on them. For example, in the follow-up interviews, one Type-A participant told us that he might change his charging habits and charge less often if the phone provided better battery feedback so that he could be sure he will not run out of battery. Further studies of Type-A users may provide insights into the optimization of battery interfaces.

4.1.1. Variations in user behavior

In [10], we conjectured that a mobile user may change their types of human-battery interaction under different usage scenarios. However, we did not observe such changes in the first field trial due to its short duration. Our second field study

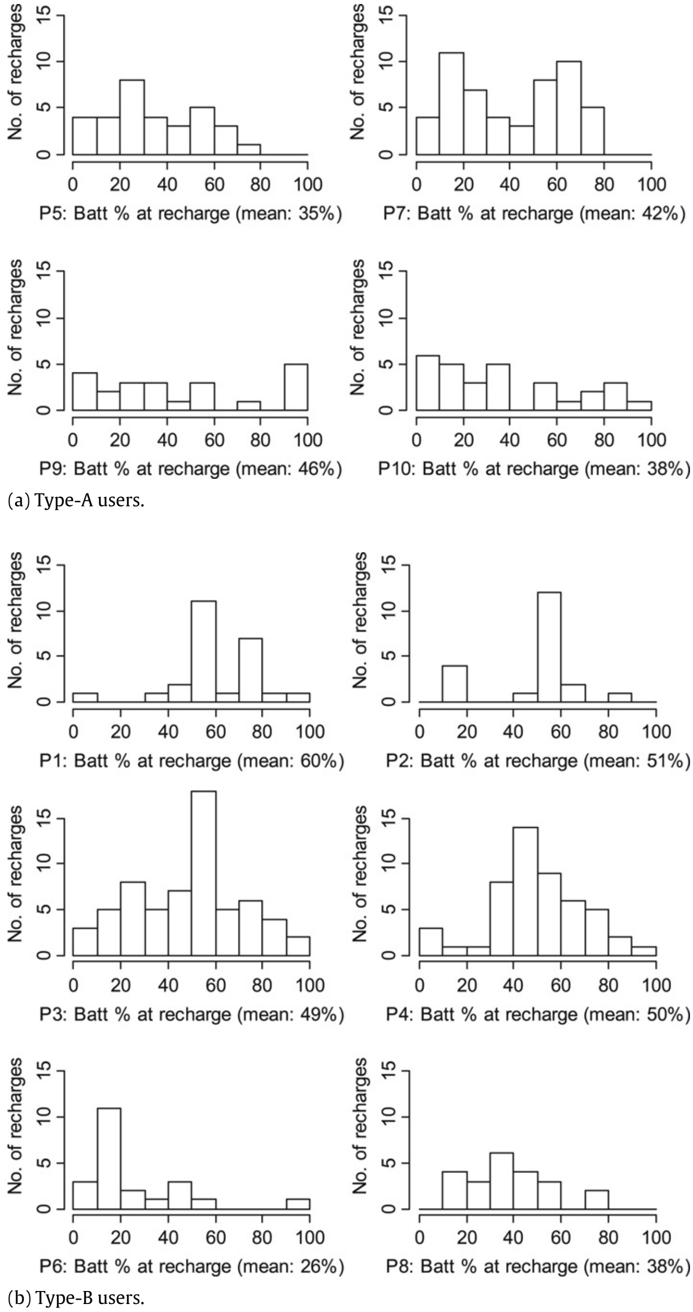
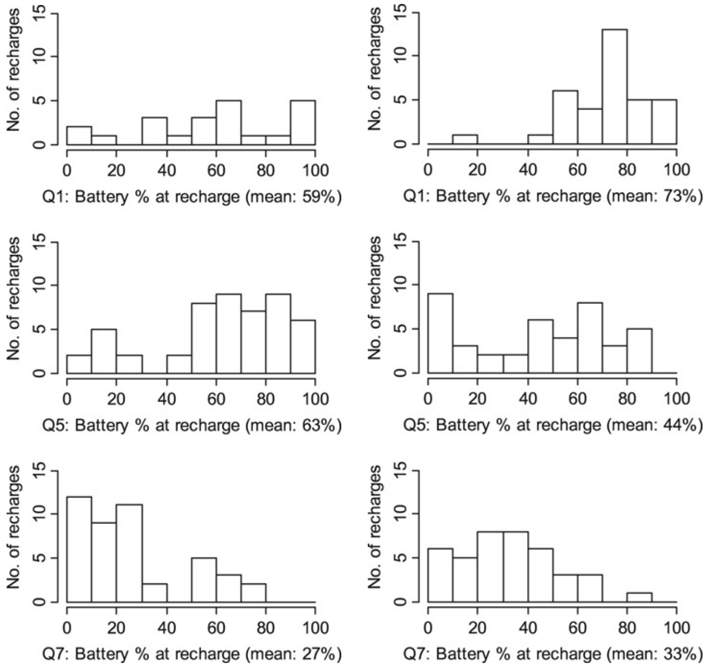


Fig. 5. Remaining battery charge level upon recharge.

enabled us to observe several behavior changes among our participants, engendered by the phones and/or the environment. We next present three distinctive examples for which Fig. 6 shows the histograms for the corresponding participants' battery charge levels upon recharge during the first and third month of the trial.

Type-B users learn the comfortable battery level for recharging. Q1, a Type-B user, became increasingly conservative. Interestingly, her battery logs, if used alone, might have suggested she was a Type-A. During the first month, she learns the battery characteristics; her logs show a wide range of battery levels upon recharge and a few low battery alarms (at 20%). In the first focus group approximately three weeks into the trial, she told us that she had found the battery to last three days, and she had to charge it on the second half of the third day at most. She also told us that she typically charged the phone without getting the low battery alarm. Indeed, in the third month, she rarely went below 50%. Later on, she told us that she always checks the extended battery information screen and charges the phone before it is down to 50%.



(a) First month of study. (b) Third month of study.

Fig. 6. Remaining battery charge level upon recharge for Participants Q1, Q5 and Q7.

Comfort with battery lifetime promotes Type-B behavior. Q5 started as a type-A. In the first focus group, approximately three weeks into the trial, he told us that he routinely charged the phone. Our battery logs show that he often charged with high remaining battery levels during the first month, with an average battery level of 63% upon recharge. Two months into the study, he told us:

> *"I charge it every time I get home. Or I try to charge it before I go to sleep so the next day it'll be charged. Unless I forget. Last night I forgot to charge it [but shows that it still works]."*

Our logs show that indeed he charged at reduced battery levels during the third month (on average at 44%), and suggest that he routinely forgot to charge the phone at night. We believe the reassurance of a long battery life that works for another day had enabled this originally Type-A participant to have more Type-B behavior: charging based on low battery alerts.

Changes in charging opportunities can engender type changes. Q7 started as a Type-B. However due to lifestyle changes that made charging opportunities increasingly rare, he changed into a Type-A. In the second focus group approximately six weeks into the trial, he told us:

> *"I used to charge when I got the low battery message, but since I'm home a lot less, as soon as I get home I charge it."*

His battery logs show an average battery level of 27% and 33% during the first and third month, respectively, which corroborates his claim.

4.2. User knowledge

Human–battery interaction is driven by the user's knowledge of battery and phone power characteristics, as illustrated by Fig. 3. Our user studies showed that mobile users obtain such knowledge from multiple sources. Personal experience, peer users, and the user manual are the three primary sources, while the user manual is supposed to be the most accurate and objective one. We asked our user interview participants if their phone and its manual provide adequate information on this topic. Most interviewees admitted they had not read the manual. However, many of them believed detailed information does exist in the manual, for example:

> *"Well, I haven't read the manual, but I'm sure the information is available 'somewhere' in the manual."*

4.2.1. Not all phone manuals provide adequate information

While many of our user interview participants believed the user manual contains detailed information on the battery and phone power characteristics, it is often the opposite. Take the user manual [1] for the T-Mobile MDA version of the HTC Wizard for example. The manual has a section devoted "To make the battery last longer", which only briefly mentions backlight settings and phone power-off timeout, and recommends a setting of three minutes or less for "optimum conservation''. Additional battery information is indeed scattered in other parts of the manual, including items such as turning off sound notifications, backlight flashing notifications, and Bluetooth to conserve battery power. In its Wi-Fi section, the manual mentions the Wi-Fi power-saving UI in Fig. 2(d), but only recommends to "move slider to a position that optimizes performance with the least power consumption'', without even naming the possible positions. It does not mention that Wi-Fi should only be enabled when necessary, and the idle battery lifetime is reduced to about 6 h when Wi-Fi is enabled. The manual falls short of even mentioning the extra power consumption due to low cellular signal strength, the vibrator, and running applications. As our interviews and surveys show, users have to learn from their experience and/or guess, and they are sometimes wrong.

4.2.2. Users have inadequate knowledge on system power characteristics

Only 31% of the mobile users in our user survey correctly pointed out voice communication as a large power consumer. From the remaining 69%, 39% chose text messaging as a large power consumer while text messaging is usually much more energy-efficient than a voice call to convey the same message, as our measurement indicated.

4.2.3. Many users are unaware of the mere existence of power-saving settings

Some of our user interview participants reported their phones do not have any display power-saving settings, while we knew their phones at least had a user configurable backlight timer and some even have UIs for display brightness. One participant even told us she was unhappy that her phone did not have such settings!

Moreover, settings that impact battery life *are often not advertised as power-saving settings*. For example, having vibration or Bluetooth enabled on a phone impacts its battery life. However, they are often not advertised as such by the phone manufacturer. Unsurprisingly, a majority of our interviewees, especially Type-A ones, were not aware of their power impact. It is interesting that we did not see a large difference between engineering and non-science/engineering participants in this regard.

For mobile phone designers and manufacturers, the implication of our findings is obvious. First, the user manual should provide information regarding the power characteristics of the phone in a user-friendly and readily applicable fashion. Moreover, the power impact of phone features should also be properly advertised in the user interfaces. Because of the limited display real estate on phones, the information can appear only for the first several times that a feature is accessed.

4.3. Battery indicator

4.3.1. Existing battery indicators are inaccurate and inadequate

Our user studies provide strong evidence that state-of-the-art battery indicators are inadequate. Eight of our twenty user interview participants, including one Type-A, commented that the battery indicator is non-linear or inaccurate. They usually complained that the battery discharges slowly when the battery charge level indicator is high and discharges fast when the charge level indicator is low.

Depending on phone design, additional battery information is rarely used. Our user interviews and field data collection suggest additional battery information is only used if it is easily accessible and provides significantly more information. Phones of seven of our user interview participants provided an additional screen with detailed battery information. Two of the seven were Pocket PC phones similar to the HTC Wizard, and the extra battery information (percentage display) was only a single touchscreen tap away. The two owners told us they "sometimes'' and "rarely'' check it, respectively. The battery information screen for the other five of the seven phones are three levels deep inside the menus and have six bars while their battery indicators have three bars. Three of the owners of these five phones were totally unaware of its existence and the other two indicated they never check it.

The HTC Wizard we used for the field data collection has an additional battery information screen, accessible with a single touch-screen tap. One field data collection participant told us he always checks the additional battery information screens. Two participants, both Type-A, told us they never check the additional screen. The other participants indicated they only check the additional screen when they are unsure about their future charging opportunities and whether the current remaining battery will enable them to meet their usage requirements.

Users welcome new designs with better feedback. To gain insights into mobile users' needs and preference in battery indication, we drew nine battery indicator designs based on battery indicators and additional battery information screens of various commercial mobile phones. We then asked our interviewees to comment on and rank them. While an accurate study requires the actual implementation and long-term use of the new interface, this preliminary study provides us with guidelines for future research in this area.

Among the designs, we included two new designs which we have not seen in any current phone. One new design was a simple percentage display in place of the normal battery indicator, shown in Fig. 4(a). Eight participants commented that they prefer to see some visual indication in addition to the number. Two complained it is not intuitive, and suggested to enclose the number in a battery sign. Even so, sixteen out of twenty participants preferred it over the standard 4-bar indicator in the same location. We also got a number of interesting comments such as:

> *"This is very good, since you know exactly how much battery is left.''*
> *"I don't like it. Even though it's rational, I don't know how much I can talk on, say*, 37% *charge.''*

The other new design was a single line of text, with the predicted remaining talk / standby time, such as "96 h standby time OR 8:30 talk time left", shown in Fig. 4(e). Eight engineering students and three non-science/engineering students selected it as the best format. Many of them were very excited about it, even though some mentioned they prefer to see some visual feedback along with the text. Two others ranked it as second best, and another two wanted it in another screen, accessible via a menu. A few participants were concerned about the screen space usage, and commented to abbreviate the sentence, for example "96h stdby, 8:30 talk". We also got a number of interesting comments such as:

> *"If my phone provided such feedback, I could charge less often."*
> *"This is great since* 50% *remaining battery capacity, even if it is linear, is so different between old and new batteries."*
> *"I don't like it because it would make me think about how much I talk on the phone."*

The fact that eight engineering and only three non-science/engineering participants selected this as the best format was the *only* significant difference we observed between engineering and non-science/engineering students. From the interviewees' responses about battery estimation accuracy, we conjecture that non-science/engineering students are more skeptical of the possibility of accurate battery estimations. For evidence, most of the participants who liked the remaining standby and talk time display added their concerns, e.g.,

> *"It would be great, but only if it could become reasonably accurate."*

However, non-science/engineering participants were even more skeptical and less convinced. One even took out her iPod and told us:

> *"My iPod claims* 12 h *playback time and doesn't deliver. How could I trust such an estimate?"*

The above findings highlight the importance of accurate battery estimation. Unfortunately, in the absence of adequate and uniform standards, battery life estimates for virtually all devices are only given for "ideal conditions". Even worse, different devices and manufacturers can have different "ideal condition" definitions that may be closer or farther from real-life conditions.

4.3.2. *Battery indicators of higher resolutions lead to higher user satisfaction*

Battery indicators on the phones of three of our twenty user interview participants had 7 bars; others had only 3 or 4 bars. All three participants with 7-bar indicators strongly agreed that the battery indicator feedback is sufficient to determine if it can meet their goals. On the contrary, only three out of the other seventeen had this opinion. Their average score is 3.5/5, as compared to the perfect 5/5 for the 7-bar battery indicators (1 being "strongly disagree" and 5 being "strongly agree").

Furthermore, the HTC Wizard phones used in the field data collection had only two bars, shown in Fig. 1(a). In the follow-up focus groups, all participants, including Type-A ones, stated their dissatisfaction with the indicator feedback, along with some angry comments such as:

> *"Who was the [...] who thought a* 2*-bar battery indicator is adequate. It's not a binary function you know!" — Type-A*
> *"It only shows it's full, empty or somewhere [unidentified] in between." — Type-B*

It is appealing to have an adaptive battery indicator that increases its resolution and prominence when the charge level decreases. Our participants mentioned that it is only necessary to display detailed battery life information in a prominent fashion when the charge level is relatively low. As one of our interviewees put it:

> *"It doesn't make a difference whether I have* 96 *or* 90 h *of standby time left! When the battery is low, however, I would like to know how much standby and talk time I have left."*

4.3.3. *A more accurate indicator with better feedback may enable users to charge phones more conveniently*

Virtually all Type-B users in our user interviews agreed that a better battery interface would enable them to charge less often or at more convenient times. The only exception owned a phone with a "four to five day" battery lifetime and a 7-bar indicator; he told us he had to charge only once or twice a week "when the indicator had one or two bars", and "had plenty of time after reaching two bars". This shows his phone already provides reasonable feedback. Therefore we conclude users welcome and may directly benefit from better battery feedback. As expected, most Type-A users did not care. The exception was the one who told us he might charge less often if he is sure he will not run out of battery. Therefore we conclude that a more accurate battery indicator can enable users to better take advantage of the limited battery capacity.

Our field data collection provides further evidence. As mentioned in 4.1, we expect Type-B users to charge their phones less often than Type-A users. However, on average among our first field trial participants, Type-B charged more often and at higher charge levels than Type-A. We believe the 2-bar indicator of our HTC Wizards is the cause, as four out of six Type-B participants charged when they had one out of the only two bars left. The average charge level upon recharging for those four participants was 52%, compared to 43% for our Type-A participants.

4.3.4. *Battery indicator design must consider usage patterns and user goals*

As noted in Section 3.3, participants in our two field trials had very different usage patterns. The Rice participants in our first trial had significantly less usage of non-voice features than our Pecan Park participants in the second trial. Such usage difference impacts their preferred location for battery indicators. While all participants unanimously preferred battery indicator designs with more feedback, among those who did care about the indicator location, Rice and Pecan Park participants preferred the battery indicator on the title bar and near the bottom of the phone, respectively. Pecan Park participants, with heavy usage of non-voice applications, stated their reasons such as "there is already enough stuff up there [on the title bar]" and "it takes space [on the title bar]". Indeed, the title bar is cluttered with many icons in addition to the start menu, leaving little space for the title of the foreground application. Rice participants, with much less usage of phone applications, were obviously less concerned with this.

4.4. Power-saving settings

While virtually all mobile phones provide user adjustable power-saving settings and other settings that impact battery life, they usually remain unused and ineffective. In this section, we present our observations and findings from our user interviews and field data collection regarding power-saving settings.

4.4.1. Power-saving settings remain largely unused

Only three out of our twenty user interview participants routinely changed phone settings to save power. All are Type-B. Two of them had Pocket PC phones. Pocket PC phones typically have more power-saving settings, a larger more power-hungry screen, and are more often used for non-voice communication than typical mobile phones. The other participant was mainly interested in reducing power consumption in critical battery situations where he didn't have access to a charger. Five others had set the display power settings only once. One of them explained to us that she changed the default setting because "the backlight turned off too quickly".

Our field data collection provides more evidence. As mentioned in Section 2, the HTC Wizard has multiple user-adjustable power-saving settings. Two out of our ten participants had not checked out the display brightness settings at all, both Type-A. The other eight had seen or set it only once.

4.4.2. Current UIs for power-saving settings are inadequate

Power-saving settings on mobile phones are typically limited in nature and scattered in different parts and levels of menus. For example, vibrator settings may be in the profiles menu, backlight may be in the display menu, and Bluetooth settings may be in the communications menu. This makes it hard for the user to employ them, and may contribute to the fact that power-saving settings remain under-utilized. One of our user interview participants suggested having a single option to select a maximum-battery mode instead of requiring the user to change a large number of settings for maximizing battery life in critical situations where there is no access to a charger.

Existing UIs assume users have significant knowledge on both computing and system power characteristics. This makes it difficult for the user to adjust power tradeoffs, even on those phones where such UIs are provided to the user. For example, the backlight power-saving setting of the HTC Wizard used in field data collection, shown in Fig. 2(c), allows users to reduce the display brightness to save battery. However, it offers no clue on how much battery lifetime a brightness reduction can save. When we asked our field data collection participants how they think it impacts their battery life, we got unconfident responses such as "*I don't know*", "*I think it is effective*", and "*it should be effective*".

The Wi-Fi power-saving setting, shown in Fig. 2(d), is even more problematic. It allows users to trade Wi-Fi "performance" for a longer battery lifetime; however, it offers no clue on what "performance" is. Two field data collection participants had seen this setting. One told us:

> *"I didn't change it because I didn't know what it did, and I didn't want to sacrifice performance. What is performance anyway? Is it the range? Speed? Does it auto-connect?"*

The other had set it to "performance", mistaking it for the processing speed. He told us:

> *"I chose best performance because performance is important, and the phone is slow anyway."*

When asked how much it impacts his battery life, he told us:

> *"I don't know, but I expect it to be linear: if it uses twice the power, it should become twice as fast."*

However, our measurements show that selecting modes other than "performance" introduces barely noticeable latencies in wireless Internet access, e.g., web browsing. On the other hand, power consumption in the "performance" mode is significantly higher than the other two modes.

The HTC Wizard phone represents existing battery interfaces on state-of-the-art commercial mobile phones: *they are technology-centered and overload users with cognitively and technologically challenging tasks*. As a result, they render power-saving settings less useful and make it hard for users to react effectively to the limited battery lifetime.

4.5. Phone usage changes

When our user survey participants were asked whether they had taken any steps to increase battery lifetime, 16% responded they stop using some features, 19% responded they turn off their phones, 13% had bought a new battery, and 20%, likely Type-A users, claimed they had never taken any steps.

Our qualitative findings from our user interviews also show that users reduce or change their phone usage when faced with low battery conditions. Many participants told us they reduce the number and length of their calls when faced with low battery conditions. Some told us they sometimes turn off their phones when faced with low battery conditions without access to the charger. One interviewee told us he would use text messages instead of phone calls in such conditions.

Usage changes due to battery lifetime limitations provide evidence that battery lifetime is critical to the usefulness of the phones. Improved human–battery interaction would enable users to correctly identify low battery conditions, take informed decisions, and/or specify their goals so the phone would gracefully conduct power management.

5. Related work

While human factors in various aspects of mobile phone design have been extensively studied, our work is the first to systematically address how users deal with limited battery lifetime on mobile phones. The work in [3] is the most related yet complementary to ours. The authors studied battery use and recharge behavior on laptop computers and mobile phones. They found that most recharges are driven by time and location, instead of low battery; in about half of all recharges, there is more than 50% battery left unused; furthermore, there is a great variation in battery use and recharge behavior between different users and between laptops and mobile phones. Based on these findings, they presented Llama, a user-adaptive system energy management policy that employs each user's charging statistics to exploit the excessive battery energy. In contrast, we have studied on human–battery interaction on mobile phones in general, with a focus on battery interfaces, user knowledge, and behavior beyond recharge. Our work not only provides evidence for the feasibility of Llama, but explains the variation between different users and supplies insights for how Llama can be better applied. Indeed, we conjecture that Type-A mobile users can greatly benefit from Llama.

Extensive research effort exists on improving the battery lifetime of mobile computing systems. In particular, human factors have been recently considered. For example, HP Labs researchers selectively darkened part of organic light-emitting diode (OLED) displays for energy reduction [7], and conducted user studies for this technology [4,6]. Vallerio et al. studied the effect of user-interface design on energy efficiency [13]. Our work is complementary to them, as we focus on improving human–battery interaction on mobile phones such that users can receive meaningful feedback on the battery life of the phone and be better informed on the effects of different usage patterns and system settings. These works all focused on improving battery lifetimes respecting or leveraging human constraints. Instead, our work focuses on understanding how users deal with the limited battery lifetime.

6. Conclusions

We presented the first work toward understanding how mobile phone users deal with the limited battery lifetime of their devices, which we call human–battery interaction. We reported results from four user studies, including a large-scale international survey, structured interviews with twenty mobile phone users, and two long-term field trials with quantitative battery logging and qualitative inquiries. We studied the various aspects of state-of-the-art human–battery interaction, including charging behavior, the battery interface (user interfaces for the battery charge level and power-saving settings), user knowledge, and user reaction to the limited battery lifetime. We found that mobile phone users can be categorized into two types regarding human–battery interaction. We showed the inadequacy of the state-of-the-art battery interfaces. In particular, we found that battery interfaces impose cognitively and technologically challenging loads to the user, leading to under-utilized power-saving settings, under-utilized battery energy, and dissatisfied users. Our study further suggested directions to improve human–battery interaction by providing intuitive and accurate battery interfaces, and proper information through the user interface and user manual.

The focus of this work is on understanding human–battery interaction and discovering the problems in existing mobile phone designs. While our participants and we ourselves made suggestions regarding how to improve their design, we believe further research is required to confirm them. Our work in understanding human–battery interaction provides a new approach for improving the usability of mobile phones by helping the user better deal with limited battery lifetime. Our work complements the extensive body of research that focuses on improving the battery lifetime itself.

Acknowledgements

This work was made possible in part through support from NSF grant IIS-0713249 and Enhancing Rice through Information Technology program, a seed grant funded by Sheafor/Lindsay from the Computer and Information Technology Institute at Rice University, and support from TI Leadership University Innovation Fund. We would like to thank Angela Qian, Mian Dong, Jiayang Liu, and Narendra Anand for assisting the international survey. We would also like to thank Jim Forrest from Technology For All for administrative assistance in our second field trial. Last but not least, we would like to thank the volunteers who participated in our user studies and surveys.

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