Sudden Drop in the Battery Level? Understanding Smartphone State of Charge Anomaly

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ABSTRACT

Battery State of Charge (SOC) estimation is a fundamental component of today's smartphones that affects the internal processes and observable behavior of the devices. This article systematically investigates and analyzes the SOC estimation techniques in smartphones. First, we discover that the voltage curve of a given smartphone implicitly captures the usable capacity of the battery while charging the mobile device. Second, we observe that today's SOC estimation techniques do not model battery capacity loss sufficiently to accurately capture the usable capacity. Finally, we report findings based on battery analytics of 2077 devices that validate the relationship between battery voltage and the usable capacity of a device. The presented results enable the development of more accurate battery gauges and metering solutions thus resulting in better power-saving decisions, recommendations for the users, and most importantly more reliable systems.

CCS Concepts

•**Hardware** → **Power and energy; Batteries; Power estimation and optimization;** •**Computer systems organization** → *Embedded systems; Reliability;*

Keywords

usable capacity; battery level; open circuit voltage; charging rate; battery voltage; lithium ion battery; SOC estimation.

1. INTRODUCTION

The SOC metric defines the remaining capacity of a device, before the battery has been completely discharged. SOC estimation is a fundamental component of today's smartphones that affects the internal processes and observable behavior of the devices. Smartphone manufacturers have recently introduced battery replacement programs that cover batteries that have a reduced capacity below 80%[1].

Erroneous SOC/battery level estimation can have significant adverse effects on the usability of a device and it can potentially result in data loss. For example, sudden drop in the battery level is a common issue reported by the users in different Internet blogs [7], and this problem affects both old and new devices. The level of dissatisfaction can be even higher when a sudden shutdown of the smartphone occurs, or damage to the device due to the battery failing.

The ongoing debate pertains to the following questions; *why does the battery level fluctuate?, is the battery faulty?, and is the device having a battery related problem?* Therefore, a good understanding of the performance of batteries would immensely improve user satisfaction and most importantly the reliability of the smartphones.

This article takes the first step towards the root cause analysis of the SOC estimation error in mobile devices. We investigate the performance of smartphones to estimate SOC and the usable capacity, C_{usable}, by analyzing the Android BatteryManager updates. To the best of our knowledge, we are the first to uncover the relationship between the battery voltage and C_{usable}. C_{usable} decreases as the battery ages. The capacity also decreases with suboptimal charging and discharging with higher voltage, current, and temperature than the recommended configuration [2]. It is also possible that a device is delivered with a substandard battery [1].

Through measurements, we discover that there is a correlation between the voltage curve of a battery determined while charging via AC and the usable capacity of the battery. Today's smartphones rely on charging cycle based capacity models and therefore, they are not able to capture such characteristics at runtime resulting in unreliable SOC estimation. We further investigate SOC anomalies in a large-scale crowdsourced battery analytics system. The findings in this work enable accurate SOC estimation, and also to gauge the usable capacity of the battery more accurately, and ensuring more reliable systems and improved user satisfaction. This paper contributes the following.

- We demonstrate that SOC estimation in modern smartphones cannot capture the usable capacity of the battery, and thus have unreliable SOC estimation. This inaccuracy manifests as sudden jumps in the battery level, and can result in the early shutdown of a device.
- We investigate the behavior of the battery voltage of

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[1] http://www.engadget.com/2015/06/30/apple-will-replace-your-battery-once-it-hits-80-percent-health/
http://www.pcmag.com/article2/0,2817,2481605,00.asp

smartphones as a function of the usable capacity with different charging and discharging conditions, and reveal the relationship between battery voltage and the usable battery capacity. We specifically investigate the battery voltage curve while charging, and discover that the battery voltage increases faster or reaches the maximum at lower SOCs as the capacity decreases. At the same time, the charging rate also increases. These observations serve as steps toward runtime usable battery capacity estimation.

- Our preliminary analysis with the battery analytics of four popular Android models based on 2077 users further validates the relationship between the battery voltage and the usable capacity. The study of in the wild devices suggests that mobile SOC anomalies are widespread and not limited to the experiments carried out in the laboratory environment.

The rest of the paper is organized as follows. Section 2 describes SOC and the usable battery capacity estimation techniques. In section 3 and 4, we investigate the performance of smartphones to estimate the SOC.

2. STATE OF CHARGE AND CAPACITY

The SOC metric defines the runtime estimate of the battery charge. A SOC value of 0 and 100 imply an empty and fully charged battery respectively. The most widely SOC estimation technique relies on open circuit voltage (OCV). The OCV is the voltage between two terminals of the battery without any system load [3]. Figure 1 shows an example behavior of battery OCV while charging Galaxy S4 via AC. We notice that OCV increases linearly until the battery is charged to approximately 76% ($0 \rightarrow 100\%$). During this period the charging current is constant, and after that the rate is trickled until the battery is fully charged. This charging mechanism is also called the constant current-constant voltage (CC-CV) charging. In this case, the battery is charged to a maximum $4.2 \pm 0.05V$. A variation of CC-CV is called Double Loop Control (DLC) that charges the battery to $4.35 \pm 0.05V$. In the case of discharging ($100 \rightarrow 0\%$), the OCV decreases as the SOC decreases. However, OCV curves for the charging and discharging vary and a device may maintain two separate look-up tables to estimate SOC.

The actual capacity of a battery decreases as the battery ages through an irreversible fading process. This capacity loss occurs both with active use, correlated with charging cycles, and with inactivity through self-discharge. The amount of loss is linear with time [5, 4] and accelerates with increasing temperature [3]. Smartphones do not typically employ sophisticated techniques for estimating the usable capacity with the basic solution basing on simple charge cycle estimation and then using an offline calibrated lookup table to find the SOC given the charge cycle. A charging cycle is equivalent to discharging the battery 100%. This 100% discharge can happen in multiple discharge events as shown in Figure 2. A battery is considered to be usable until the capacity is reduced by 20% [8].

In this paper, we observe that modern smartphones do not employ any sophisticated mechanism to estimate the usable capacity runtime. Therefore, the SOC estimation error manifests as the steep changes in the SOC and even shutdown of the device. While OCV is widely used to estimate SOC, we

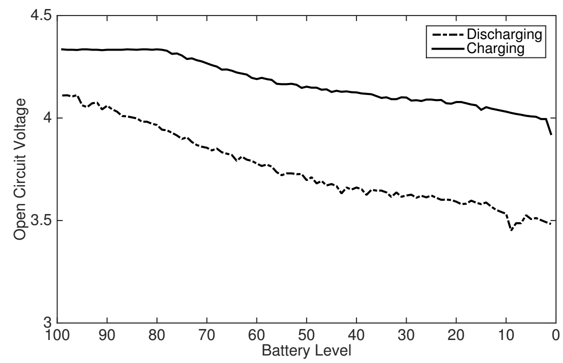


Figure 1: Battery voltage and SOC of Galaxy S4 while charging and discharging.

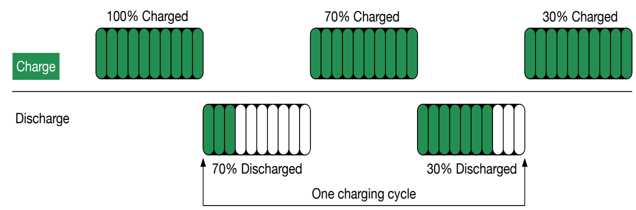


Figure 2: A Charging cycle of a Lithium-Ion battery.

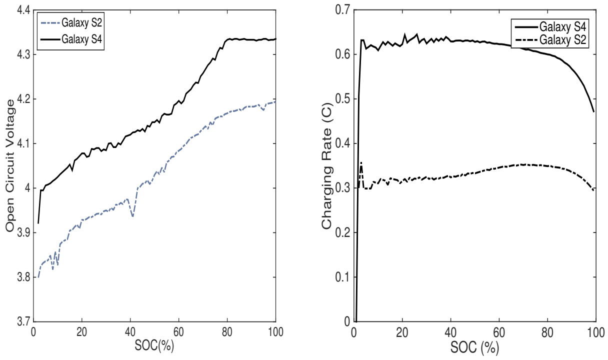
demonstrate that OCV, while charging via AC, can capture the usable capacity of the battery. Therefore, our observations serve as the steps toward deployable runtime capacity estimation.

3. SMARTPHONE PERFORMANCE

In this section, we study the battery performance of Android smartphones with three different types of batteries, namely new batteries, new batteries with lower capacity (substandard), and long used batteries. Two different Android models are utilized in the experiments, Samsung Galaxy S2 and S4, for estimating SOC while charging and discharging. The aim of the experiments is to be able to characterize suboptimal battery capacity first in the lab and then utilize the experimental results in assessing Android smartphone batteries in the wild.

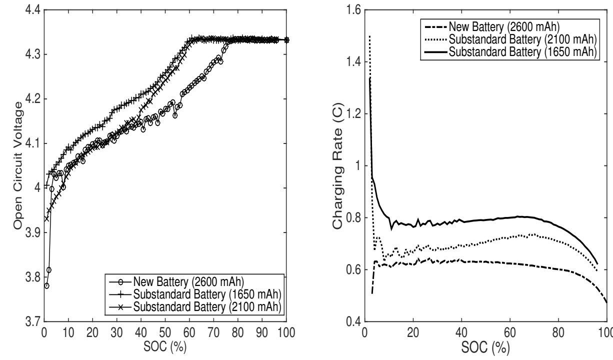
During the charging measurements, we keep the smartphones idle and in airplane mode in order to minimize the system load. Therefore, we present the battery voltage measurements as OCVs. Our methodology is similar to the one followed in the PowerBooter proposal [10].

We collect battery voltage, charger information, and the battery temperature for every SOC update. From the updates, we correlate OCV with the SOC. In the experiment, we used five batteries of models EB-F1A2GBU (1650 mAh), B600BE (2100 mAh), and EB-L1G6LLU (2600 mAh). The measurements were conducted in February and March 2015, and each was repeated four times. The maximum difference of the charging voltage and time was ± 0.04 V and ± 8 s respectively. The measurement scenarios are presented according to the following order. In section 3.4, we present the discharging measurements.



(a) OCV (b) Charging Rates

Figure 3: OCV and the cumulative charging rate of Galaxy S2 and S4 with new battery.



(a) GS4 OCVs (b) GS4 Charging Rates

Figure 4: OCV and cumulative charging rate of Galaxy S4 with lower capacity batteries.

3.1 Charging New Batteries

In this scenario, the Galaxy 2 and S4 devices were charged with their standard charger, cables, and new batteries. The initial battery capacity of Galaxy S2 and S4 are 1650 mAh (EB-F1A2GBU) and 2600 mAh (EB-L1G6LLU) respectively. These two batteries were manufactured in September 2014 and first used in this experiment.

Figure 3(a) shows the relation between battery voltage and the state of charge as charging proceeds; Galaxy S2's battery is charged to 4.2V maximum and S4 is charged to 4.35V. This is related to the charging algorithm used by the devices as explained in Section 2. We observe that battery voltage increases almost linearly as the SOC increases until they are charged to some level. This phase is called the constant current or CC phase, as the batteries are charged at some constant rate. The initiation of the CV phase is model specific and the charging time increases exponentially, as the rate is trickled during this phase.

Since the BatteryManager does not provide the charging rate, we estimate the rates from the timestamp of the SOC updates from the BatteryManager. We estimate rates relative to the battery capacity, called the C rate. If the capacity of the battery is 2600 mAh, then it will take one hour to charge 100% at 2600 mA. In this case, 2600 mA rate is equivalent to 1 C. At 0.5 C the rate will be 1300 mA. The C rates from the BatteryManager updates are computed according to the following,

$$R = \frac{36 \times n}{t_{i+n} - ti} \ , \tag{1}$$

where 36 is the time to charge one percent at 1 C rate. We take the rate for a cumulative SOC or battery level, for example the C rate to charge 1% to 10%. Figure 3(b) shows the charging rates of the devices during the CC and CV phase. We also notice that Galaxy S4 is charged at approximately 0.6 C which is equivalent to 1560 mA. In addition, Galaxy S4 has the highest C rate, and consequently, the inclination of the OCV is more aggressive compared with Galaxy S2. However, we did not observe sudden jumps in the battery level during this measurement scenario.

3.2 Charging Lower Capacity Batteries

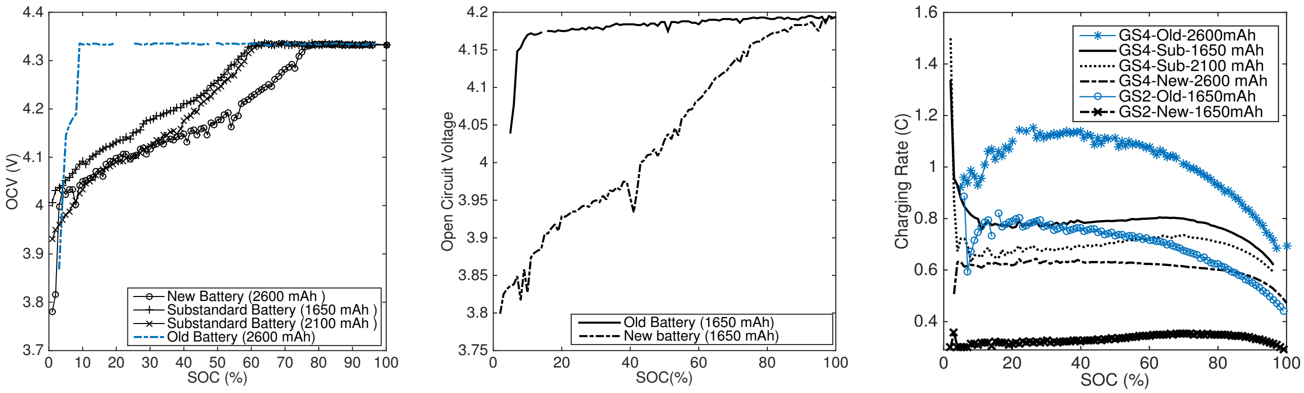
We next replace the new battery of Galaxy S4 with the lower capacity batteries. This experiment emulates the behavior of the battery as the capacity decreases. We denote 2600 mAh as the initial capacity, $C_{initial}$, of Galaxy S4. We study the performance when the usable capacity, C_{usable}, reduces from an initial 2600 mAh to 2100 and 1650 mAh respectively. Figure 4 illustrates a number of interesting observations for Galaxy S4.

First, as the battery capacity of Galaxy S4 decreases, the OCV of the battery increases sharply and the OCV reaches to the maximum voltage earlier compared with the standard charging scenario. For each capacity reduction scenario, there is a unique voltage curve (see Figure 4(a)).

Second, Figure 4(a) clearly shows that OCV varies for the same SOC with the reduced capacity. For example when the SOC is 60%, the observed OVCs are 4.2 and 4.33V. Third, the charging rates of the batteries vary with the capacity and the phase of charging. We compute the rates according to the equation (1), and compare the rates with usable capacities with the initial capacity in Figure 4(b). We can see when the capacity decreases, C rate of the battery increases, and as a result, the rate is maximum when the usable capacity reduces to 1650mAh. Finally, there are sudden jumps in the battery level. For instance, when the usable capacity were 2100 and 1650 mAh, there were sudden jumps of battery level from 96 to 100% over very small intervals.

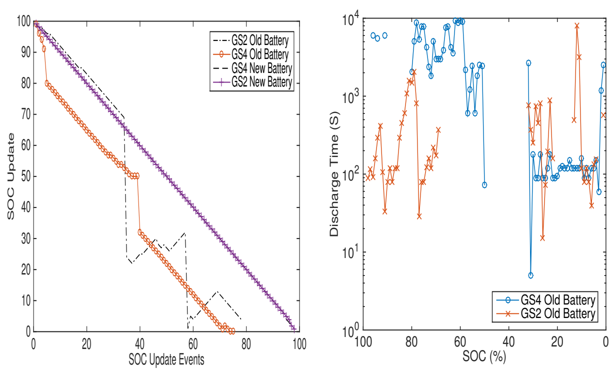
3.3 Charging Long Used Batteries

The charging measurements presented in the previous section suggest that the OCV increases faster as the capacity of the battery becomes reduced. Since such behavior has not been reported earlier, we investigate the devices further with their old batteries to make sure that our observations are not an artifact of using different batteries. We collected old batteries of Galaxy S2 (18 months old) and S4 (14 months old) and charged them with the AC charger. Figure 5(a) and 5(b) compare the voltage curves of old batteries with the other measurement scenarios. We observe that the voltage of the older batteries increase more sharply. The charging rates are also higher compared with the standard/substandard batteries (see Figure 5(c)). In other words, the older batteries have



(a) Galaxy S4 (b) Galaxy S2 (c) Cumulative Charging Rates

Figure 5: OCV and the rates for Galaxy S4 and S2 with new, new lower capacity, and very old batteries while charging.



(a) SOC Fluctuations (b) SOC Update Time

Figure 6: SOC behavior while discharging old batteries.

even less capacity, and the behavior of the battery voltage and charging rates are consistent as the C_{usable} decreases.

3.4 Discharging

While the charging scenarios presented in Sections 3.2 and 3.3 provide evidence that there are sudden jumps in the SOC or battery level, we also investigated the performance while discharging. We discharged Galaxy S2 and S4 after charging with the new and long used batteries. We let the devices discharge with the normal usage, such as checking emails, browsing, and watching videos 4 or 5 times in a day. In Figure 6(a), we notice that SOC updates are in the decreasing order, as expected, and the updates are consistent for the new batteries, whereas the old batteries have sudden drops in the battery level. For instance, the Galaxy S2 experiences a severe battery level drop from 70 to 20% within less then 20 minutes and similarly, the Galaxy S4 suffers a sudden drop from 50 to 30% within 45 minutes (see Figure 6(b)). We also observed unexpected shutdown of the devices even when the battery levels were above 15%. These observations were consistent when the old batteries were being used by their actual devices.

3.5 Summary

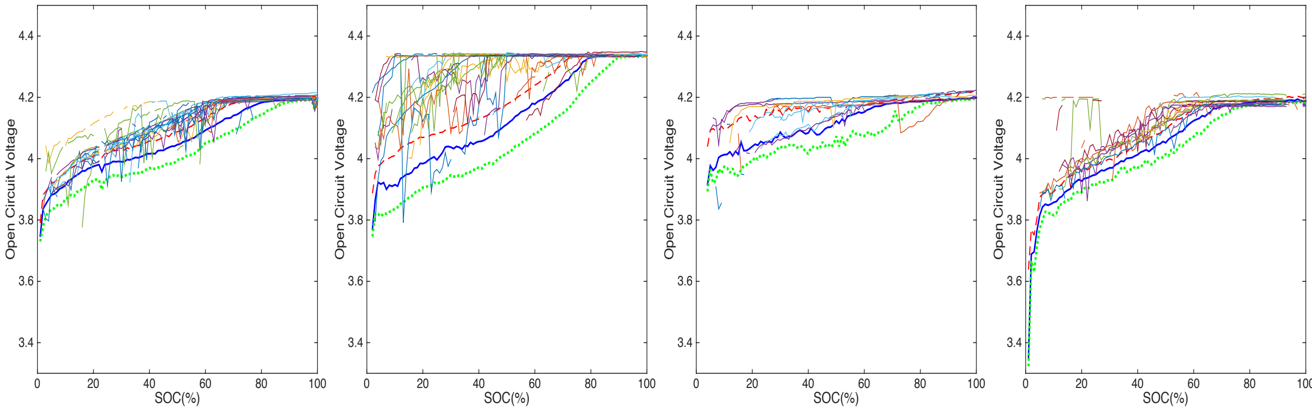
The investigations in this section reveal a number of interesting behavior of battery.

- Smartphones fail to estimate the SOC with old or suboptimal batteries. We observed sudden drops or changes in the battery level while charging and discharging mobile devices. Figure 6(a) shows that Galaxy S2 suffers from approximately 60% sudden drop and Galaxy S4 suffers from 50% drop in the battery level and therefore, it is likely that the old batteries had 60% and 50% less capacity, respectively.
- A battery with reduced capacity exhibits different behavior than a battery that has a near optimal usable capacity. First, the OCV increases more sharply compared to a new battery or it approaches the maximum voltage with a smaller SOC/battery level when the capacity reduces further. The OCV varies as the relative charging rate increases. Second, the relative charging rate increases as the capacity decreases, and it takes less time to charge.

4. CHARGING CURVES IN THE WILD

In order to assess the implications of our laboratory based findings pertaining to the usable capacity of smartphone batteries, we conducted a preliminary investigation of in-the-wild smartphone battery data obtained from the crowd-sourced Carat energy profiler [6]. Our crowdsourced data contains battery traces of 2077 Android devices of the following models: Galaxy Nexus (942), Galaxy S4 4G (727), Sony Xperia P(77), and HTC One X(331).

From the dataset, we first computed the median charging curve for the four models (see Figure 7) and their 25 and 75th percentiles. We took the median voltage for every SOC. Statistically, this median curve represents the charging curve of a particular model. The charging curve of an individual device is also constructed similarly and thus represents the actual battery status of that device. In figure 7,



(a) Galaxy Nexus (b) Galaxy S4 4G (c) Sony Xperia P (LT22i) (d) HTC One X

Figure 7: The red, blue, and green dashed charging OCV lines are for the 75th, 50th (median), and 25th percentiles respectively. The others are the charging voltage curves of individual users.

we notice that battery voltage behavior is similar to the observations in Section 3. The voltage curve of an individual device deviates from the median curve and the curves incline to the maximum voltage faster and at earlier SOCs. Our earlier experiment results suggest that those devices have lower battery capacity and therefore, the relation between OCV and usable battery capacity is not device specific.

5. CONCLUSION AND FUTURE WORK

The capacity loss of Lithium-Ion batteries has been studied from the age, temperature, and the memory effect perspectives [5, 4, 9]. The commonly employed solution to account for the capacity loss of a battery is an offline calibrated lookup table based on the charging cycle count of the battery. Therefore, if the capacity is reduced before the specified cycle or time, the devices may be unable to determine this loss and consequently may provide unreliable SOC measurements. Modern smartphones provide erroneous SOC measurements as they are unable to estimate the usable capacity of the battery at runtime. This article demonstrates that the battery voltage curve and the charging rates together capture the usable capacity of the battery at runtime. As a result, our findings pave the way not only for developing more reliable power management for mobile devices, but also for other Lithium-Ion battery-powered devices as well.

The accuracy of SOC estimation is an important issue for Lithium-Ion batteries, as the reliability of the battery powered systems depends on SOC. Our future work includes finding such voltage and SOC behavior among a large number of devices with various models. In addition, we would like to investigate a capacity and SOC estimation model that depends on the instantaneous open circuit voltages and rates rather than the charging cycles to estimate the usable capacity.

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