Improving Wireless Charging Energy Efficiency of Mobile Phones: Analysis of Key Practices

Girish Bekaroo
Middlesex University (Mauritius Branch Campus)
Bonne Terre, Vacoas, Mauritius.
g.bekaroo@mdx.ac.mu

Amar Seeam
Middlesex University (Mauritius Branch Campus)
Bonne Terre, Vacoas, Mauritius.
a.seeam@mdx.ac.mu

Abstract— As human beings became dependent on mobile phones, the relationship of these devices with the natural environment became more significant to study. Mobile phones require energy to operate and this is stored within connected batteries. Recently, there has been a shift in the way batteries of mobile phones are charged, namely, from wired to wireless charging. Being regarded as a transformational technology in the mobile world, many smartphone manufacturers have been investing in this technology. However, current wireless charging mechanisms meant for mobile phones are recognized to be slow and energy inefficient as compared to wired charging. Such inefficiency can in turn worsen the adverse impacts that mobile phones already have on the environment. This paper addresses the energy inefficiency issue during wireless charging of mobile phones by comparing different charging practices in order to identify opportunities for energy savings.

Keywords—Wireless Charging; Trickle Charging; Energy Efficiency; Power Consumption;

I. INTRODUCTION

Recently in 2014, the number of active mobile phones on Earth has outnumbered the number of human beings for the very first time on this planet [1, 2]. Human beings are heavily dependent on mobile phones due to various reasons including communication, web surfing and entertainment, among others. These devices are dependent on batteries for their operation and the purpose of these batteries is to store energy and convert that stored energy into electrical form whenever needed. The traditional mechanism to charge the battery involves use of a wired charger which connects one end to a mobile phone and the other end to the power outlet. Recently, there has been the emergence of the wireless charging mechanism for mobile phones. Since its emergence, this technology has been regarded as a transformational technology in the mobile world by many big smartphone manufacturers including Samsung and Apple, among others [2]. This technology is expected to bring various advantages, including increased convenience, and elimination of the need to have multiple designs for charger ports.

A. Wireless Charging Technology

The concept behind wireless charging originates in 1981 when Nikola Tesla demonstrated wireless power transmission by lighting electric lamp without the use of wires [3, 2]. Wireless charging makes use of an electromagnetic field for the transfer of energy between two objects [4]. In this endeavor, an inductor is used, which is in the form of a loop of coiled wires around a magnet. When an electric current passes through the inductor, an electromagnetic field (EMF) is created around the magnet. This EMF can then be utilized to transfer a voltage, or charge, to a proximate object without actually touching it. Various wireless charging standards have emerged where the leading ones include Qi and Power Matters Alliance (PMA). These standards vary in terms of transmission frequencies and connection protocols utilized in the device communication process and power management control [5].

Even though the fundamental concepts behind wireless charging have been understood since over a century, it has been argued that scientists are yet to find ways to efficiently transfer large amounts of power via the use of this technique [6]. As such, current wireless charging mechanisms meant for mobile phones have been recognized to be slow and inefficient as compared to wired charging [7]. However, as the mobile industry is quickly migrating towards the wireless charging technology and that this technology has been actively penetrating the market during recent years, it becomes important to study how end users can make energy efficient use of this technology.

B. Wireless Charging and Energy Efficiency

Energy inefficiencies in wireless charging can worsen the adverse impacts that mobile phones already have on the environment [10]. This is because charging involves the use of electricity, which is predominantly being generated using non-renewable sources (e.g. coal or oil) [11]. Moreover, as energy has associated monetary costs, inefficiencies also have an impact on the utility bills. One recognized solution to diminish energy expenses while reducing environmental impacts is towards energy efficiency improvement [8]. Energy efficiency is defined by the Lawrence Berkeley National Laboratory (LBNL) as: "*the use of lesser energy to provide the same service*" [9]. Based on this definition, energy efficient wireless charging refers to the use of lesser energy to charge the mobile phone completely under same conditions.

In order to address the energy inefficiency of wireless charging, different studies attempted to efficiently transfer higher amount of power [12]. However, commercial solutions matching the energy efficiency of wired-based charging are yet to be released. Until such solutions are released, end users of wireless chargers need to efficiently utilize such technologies in order to save costs while also reducing associated environmental impacts. For this, wireless charging practices become important to study. Furthermore, it has been previously shown that quantitatively analyzing the energy consumption of mobile phone charging can help to identify opportunities for energy saving [13, 14]. As such, this paper quantitatively investigates energy efficient use of the wireless charging mechanism by comparing different charging practices to order identify energy saving opportunities.

II. Methodology

In order to quantitatively determine energy efficient practices during wireless charging, a list of common charging scenarios utilized by mobile phone users had to be prepared. Charging scenarios or practices here relate to the way end users charge their phone. However, due to the limited market research on charging approaches used by end users of mobile phones, the research team had to compile common scenarios about how mobile phone users charge their devices. Three such scenarios were considered namely, charging from the switched off and on states, in addition to charging in the on-state with Wi-Fi enabled. Additionally, to benchmark the energy performance of the wireless charging for each of these 3 scenarios, the scenario list was extended to consider wired-based charging. These 6 compiled scenarios under investigation are given in Table I.

TABLE I. Mobile Phone Charging Scenarios

No.	Scenario	Description
S1.	Wired-based charging under Switched off state	To charge the selected mobile phone from 1% to 100% under switched off state via the use of a wired charger.
S2.	Wireless-Based charging under Switched off state	To charge the selected mobile phone from 1% to 100% under switched off state via the use of a wireless charger.
S3.	Wired-based charging under Switched on state I	To charge the selected mobile phone from 1% to 100% under switched on state via the use of a wired charger when the phone is in idle mode.
S4.	Wireless-based charging under Switched on state I	To charge the selected mobile phone from 1% to 100% under switched on state via the use of a wireless charger when the phone is in idle mode.
S5.	Wired-based charging under Switched on state II	To charge the selected mobile phone from 1% to 100% under switched off state via the use of a wired charger when the phone is connected to the network.
S6.	Wireless-based charging under Switched on state II	To charge the selected mobile phone from 1% to 100% under switched off state via the use of a wired charger when the phone is connected to the network.

After having compiled the list of scenarios to be investigated, approach to be used to determine the most energy efficient wireless charging scenario among the list had to be determined. Based on the previous definition of energy efficiency from LBNL [11], energy consumption of each scenario had to be measured. For this, an electronic wattmeter was used due to its accuracy pertaining to power and energy measurement [15]. The electronic wattmeter has the ability to measure power consumption in Watts (W) at the interval of every second. It can also measure energy consumption in Joules or kilowatt hour (kWh). For this study, kWh has been chosen as metric due to its common use within utility bills.

A. Devices Under Test

For the experiment, a charger based on the Qi standard was preferred since over 80 phone models have embedded this standard in their wireless charger [14]. As such, for the device under test, the Samsung Galaxy S6 Edge with Android v5.1.1 Lollipop was utilized since the device has Qi standard embedded in its wireless charger. The device utilizes a Li-Ion 2600 mAh battery with a Quad-core 1.5 GHz Cortex-A53 CPU and has 3GB RAM.

The device under test was restored to factory settings and updated in order to minimize power fluctuations due to previously installed applications, while at the same time ensuring the phone is running up-to-date software. Moreover, since the strength of electromagnetic field during wireless charging is expected to drop sharply with distance, a device still needs to be close to the charger so as to benefit from maximum power [6, 2]. As such, the mobile phone needed to be in complete contact with the charging station. Furthermore, the cellphone was used without case or cover during the experiment so as to prevent further power loss during wireless charging.

B. Experimentation Procedures

The experiment was conducted within a lab environment and begun by selecting the first scenario in Table I. for investigation. The mobile phone was taken while ensuring that its battery level was 1%. A charger was then connected to the mobile phone on one end and the electronic wattmeter on the other. The electronic wattmeter was then in turn connected to the power outlet. Once ready, the electronic wattmeter was switched on, which also started charging the mobile phone. At the same time, a stopwatch was started. As the charging process started, power readings from the meter were recorded at the interval of every 5 minutes until the device was fully charged. It should be noted that the cell phone was left untouched during the charging process so as to avoid fluctuations in power. This also meant that the battery level could not be obtained at every 5 minutes interval as this would cause power fluctuations. Once the mobile phone was fully charged, energy consumption from the wattmeter was recorded in addition to the total time taken to charge the mobile phone. The experiment however continued for 15 more minutes so as to study whether and how much power is still being transferred from the charger to the phone. In case of the effect of trickle charging, the power reading from the electronic wattmeter is recorded at the same 5-minute interval. Once trickle charging power has been recorded, a single instance of the experiment for a particular scenario was marked as complete. The same scenario was then conducted three different times so as to ensure reliability of results. The average power and energy consumptions to fully-charge the phone were then computed. After the first scenario was completed, the next one from Table I was conducted until all scenarios were fully investigated. The collected data were statistically analyzed.

III. Results and Discussions

Once the charger was switched on for each scenario, it was observed that power readings started from 0W to progressively reach a maximum value. For all scenarios investigated, the maximum power recorded was at the 5th minute of the experiment with 9.3 W (for S6) for wireless charging and 16.9 W (for S1 and S3) for wired. This also highlights the low-power transfer characteristics of wireless charging discussed earlier [6]. The maximum power reached then stabilized in most scenarios before a sudden decrease. This decrease was more significant in scenarios related to wireless charging as compared to wired charging. After this decrease, power consumption in the different scenarios showed to be constant for the biggest part of the experiment. Then, for wired-based charging a gradual decrease in power readings was noted until the battery was fully charged. For scenarios related to wireless charging, an increase towards the initial maximum power was noted before the gradual power decrease until the battery reached 100%. The power consumption pattern over time for the different scenario investigated is given in Figure I.

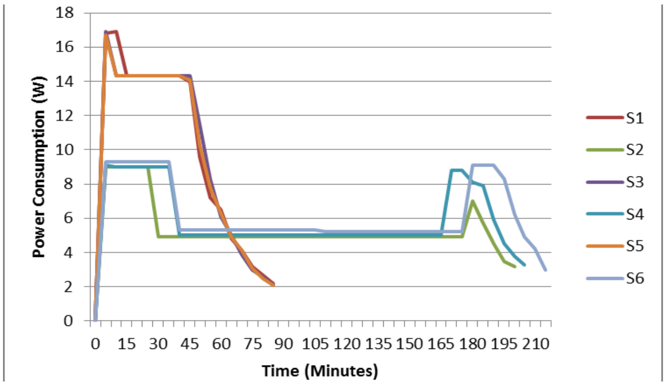

Figure I. Charging Patterns

The average power and energy consumption, in addition to the average duration of the different scenarios are given in Table II.

TABLE II. EXPERIMENTATION RESULTS

Scenario	Average Power Consumption (W)	Average Duration (Mins)	Average Energy Consumption (kWh)
S1.	9.86	85	0.014
S2.	5.37	201	0.018
S3.	9.66	87	0.014
S4.	5.85	205	0.020
S5.	9.66	87	0.014
S6.	5.92	213	0.021

In terms of duration, it took approximately 206 minutes to charge the phone wirelessly as compared to 86 minutes when using the wired charger. This result also shows that the wireless charger took more than twice the time taken to charge the phone via the wire interface. This is also due to the low power characteristics of wireless charger, as identified Table II. In turn, the low power is due to the number of coils present within the charger since theoretically, the amount of electric charge transferred is proportional to the number of coils present within the wireless charger [6]. Moreover, it was slightly faster to charge the phone under switched off state as compared to the other states. This is due to fewer background operations that take place when the mobile phone is switch off as compared to the other states investigated.

As expected, energy consumption of wireless charging was more than that of wired charging for all scenarios investigated. For wireless charging, results showed that there was minimal difference in energy consumption in the switched on (S4) and stand-by (S6) states of the phone. With the wireless charger, the lowest energy consumption was found to be during the switched off-state (S2) and highest when Wi-Fi was enabled (S6) on the phone. However, this result is different for the wired charger which showed no variance during the different scenarios investigated, where a constant value of 0.014 kWh was noted for S1, S3 and S5. The reason for the variance in results in wireless charging scenarios could be attributed to power losses and dissipated heat, among other factors. Figure II shows the bar-chart comparing the energy consumption of the different scenarios stacked by the type of charger used.

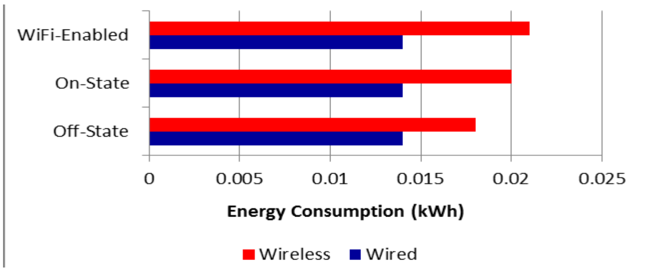

Figure II. Energy Consumption Comparison

Experiments also showed that the mobile device continued to consume power even when the battery was 100% charged. The power consumed by the wired charger was 2.0W for the 3 different states analyzed and 2.7W for the wireless charger. As such, scenarios involving the use of the wireless charger showed to consume more trickle power than that of the wired charger. The compiled results are given in Figure III. These results also imply that an important amount of energy could be consumed in case a charger remains connected to a mobile phone after that the device has been completely charged.

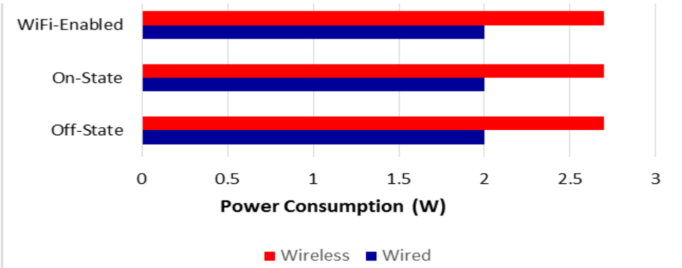

Figure III. Trickle Power

Overall, wirelessly charging under switched-off state was found to be more energy efficient than the two other states investigated to potentially save 0.003 kWh. Even though this figure seems to be small, its significance when considered at on an annual basis and with a large population size cannot be disregarded. The major challenge faced during the experiment was to drain the battery level to 1% so that the next scenario could be investigated. This was a lengthy process which involved performing various operations on the mobile device including switching on the torch, playing a high quality movie, turning on camera, among others. Another challenge was that the experiment was a time consuming one where readings were manually being taken at every 5-minute interval. An improvement could have been to automatically obtain measurements from the power meter; but this would necessitate further work.

IV. RECOMMENDATIONS

Although experimentation confirmed that wireless charging is less energy efficient as compared to wired charging, a few practices can be applied by end-users users so as to save energy during its use. These practices were compiled based on findings of this study and are as follows:

1. Switch-off phone when charging wirelessly

Experimentation results showed that an important amount of energy could be reduced when wirelessly charging in the switched-off state. As such, a good practice to save energy is to switch off the mobile phone when charging.

2. Unplug charger once fully charged

The experiment showed that even when fully charged, both types of charging continue to consume energy if the mobile phone remains connected to the power source. As a countermeasure for trickle charging, the mobile phone should be unplugged from the charger once the battery has been fully charged. However, it is often challenging to get to know instantly when a battery is fully charged. As a solution, mobile applications such as Full Battery & Theft Alarm could be used to notify the user once battery level has reached 100%.

3. Remove case when charging wirelessly

With some wireless chargers, literature showed that there is a need to remove the mobile cover/case so as to improve contact with the cellphone [17]. As such, to improve charging effectiveness, thick cases can be removed as to increase contact between the mobile phone and the wireless charger.

In the longer term, more effort is needed so as to enhance the energy efficiency of wireless charging. To start with, work could be done to first align the efficiencies of wireless charging with that of wired charging before investigating further improvements. For this, work could be done to increase the power supplied during wireless power transfer while maintaining the size of the charger. Also, more research is needed on how to reduce power losses during the wireless power transfer process. However, until these solutions are found, the above practices could be adopted.

V. CONCLUSIONS AND FUTURE WORKS

This paper addressed the energy problems related to wireless charging of mobile phones by investigating and comparing different charging practices. A lab experiment was conducted to compare the energy consumptions of three different charging practices while also benchmarking against wired based charging for same scenarios. Results showed that different wireless charging scenarios consumed different amount of energy and charging under switched-off state was found to be most energy efficient. Findings from this study could be used by end users to improve their wireless charging practices, in addition to researchers who can use the quantitative values of this study in their endeavor to improve the wireless charging process.

As future work, the experiment could be repeated using different mobile phones having wireless chargers that have the Qi standard embedded. For example, the latest Qi wireless chargers utilize fans to disperse excess heat produced during the wireless transfer of energy. Moreover, the variance obtained in wireless charging scenarios also needs further investigation.

VI. REFERENCES

[1] Z. Borren, "Active Mobile Phones Outnumber Humans for the First Time," International Business Times, 2014. [Online]. Available: http://www.ibtimes.co.uk/there-are-more-gadgets-there-are-people-world-1468947. [Accessed 3 Jan 2016].

[2] G. Bekaroo, C. Bokhoree and C. Pattinson, "Impacts of ICT on the natural ecosystem: A grassroot analysis for promoting socio-environmental sustainability," *Renewable and Sustainable Energy Reviews,* vol. 57, pp. 1580-1595, 2016.

[3] S. Curtis, "Wireless charging: everything you need to know," The Telegraph, 2015. [Online]. Available: http://www.telegraph.co.uk/technology/news/11434736/Wireless-charging-everything-you-need-to-know.html. [Accessed 5 Jan 2016].

[4] N. Tesla, The Transmission of Electric Energy Without Wires (The Thirteenth Anniversary Number of the Electrical World and Engineer), New York: McGraw-Hill, 1904.

[5] N. Shinohara, "Power without wires," *Microwave Magazine,* vol. 12, no. 7, pp. 64-73, 2011.

[6] H. Russel, "Qi or Powermat? What's the difference and which should you choose?," Android Central, 2015. [Online]. Available: http://www.androidcentral.com/qi-or-powermat-whats-difference-and-which-should-you-choose. [Accessed 5 Jan 2016].

[7] T. Ghose, "How Does Wireless Charging Work?," LiveScience, 2015. [Online]. Available: http://www.livescience.com/50536-what-is-wireless-charging.html. [Accessed 5 Feb 2016].

[8] K. Siddabattula, "Why Not A Wire? The case for wireless power.," Texas Instruments, 2015. [Online]. Available: https://www.wirelesspowerconsortium.com/technology/why-not-a-wire-the-case-for-wireless-power.html. [Accessed 15 Jan 2016].

[9] W. Sangprasert and C. Pharino, "Environmental impact evaluation of mobile phone via life cycle assessment," in *3rd International Conference on Chemical, Biological and Environment Sciences (ICCEBS'2013)*, 2013.

[10] S. Murugesan, "Harnessing green IT: Principles and practices," *IT professional,* vol. 10, no. 1, pp. 24-33, 2008.

[11] United Nations Environment Programme, "UNEP Handbook for Drafting Laws on Energy Efficiency and Renewable Energy Resources," United Nations Environment Programme (UNEP)., 2007.

[12] Lawrence Berkeley National Laboratory, "What's Energy Efficiency?," 2011. [Online]. Available: http://eetd.lbl.gov/ee/ee-1.html. [Accessed 4 Mar 2012].

[13] S. Lee and R. Lorenz, "Surface spiral coil design methodologies for high efficiency, high power, low flux density, large air-gap wireless power transfer systems," in *IEEE Twenty-Eighth Annual Applied Power Electronics Conference and Exposition (APEC)*, 2013.

[14] P. Ostendorp, S. Foster and C. Calwell, "Cellular phones: Advancements in energy efficiency and opportunities for energy saving," Natural Resources Defense Council, 2004.

[15] J. Ruutu, J. Nurminen and K. Rissanen, "Energy efficiency of recharging a mobile device," in *IEEE 5th International Conference on Next Generation Mobile Applications, Services and Technologies (NGMAST)*, 2011.

[16] G. Bekaroo, C. Bokhoree and C. Pattinson, "Power Measurement of Computers: Analysis of the Effectiveness of the Software Based Approach," *International Journal of Emerging Technology and Advanced Engineering (IJETAE),* vol. 4, no. 5, pp. 755-762, 2014.

[17] J. Perzow, "Wireless Charging of Consumer Electronics: Rubbish Heap or Mass Adoption?," Wireless Week, 2016. [Online]. Available: http://www.wirelessweek.com/article/2016/02/wireless-charging-consumer-electronics-rubbish-heap-or-mass-adoption. [Accessed 25 Mar 2016].

[18] Nexus, "How to use the Nexus Wireless Charger," Google, 2015. [Online]. Available: https://support.google.com/nexus/answer/6073618?hl=en. [Accessed 25 Mar 2016].