Research Assessment Exercise 2020
Impact Case Study 3

University: City University of Hong Kong
Unit of Assessment (UoA): 12 - Electrical & Electronic Engineering
Title of case study: World's First Industrial Standard for Wireless Charging

(1) Summary of the impact

The research team led by Prof. Ron SY Hui from 2000 to 2011 at CityU EE had laid the foundation on wireless charging. The team has made significant contributions to wireless power transfer technologies, generating a suite of important patents that underpinned the key dimensions of the ***Qi Standard***.

- **Wireless Power Consortium** for the standard was founded in 2008 initially with 8 companies that included the licensee company of the patents. The number of companies in the consortium was increased to nearly 600 by the year 2019.
- ***Qi Standard* became the world's first industrial standard** for certifying wireless charging through [redacted]. The inventions have brought in license fee revenues of [redacted] which is the highest record for the university.
- **Millions of mobile devices**, including more than 3000 products from popular smartphone brands such as Apple, Samsung, Huawei, and Xiaomi, have adopted the *Qi Standard* wireless battery charging feature. Notably, Apple has returned to the consortium in 2017 and has adopted the standard for iPhones.

(2) Underpinning research

The team led by Prof. Ron SY Hui from 2000 to 2011 at CityU made significant pioneering contributions to wireless charging, creating tremendous impact via the *Qi Standard* that is now used by millions of popular smartphones and mobile devices. Prof. Hui received the prestigious IEEE William E. Newell Power Electronics Award (2015) for his impactful innovations in power electronics, including his pioneering work on planar wireless charging technology and patents featured in the **world's first wireless charging standard** for low-power electronics, which "will help to reduce hundreds of millions of units of electronic waste per year considering the plethora of non-compatible charging devices produced in the past." He was also elected Fellow of Royal Academy of Engineering (UK) and Fellow of National Academy of Inventors (US) in 2016 and 2018, respectively.

Wireless charging is highly beneficial and has rapidly become the standard charging mode for a number of applications. Without the need of using electrical cables, there is significantly less wear and tear on the socket of the device, no need to constantly plug and unplug the device, and no contact with moisture or oxygen in the atmosphere for ensuring safety and reliability. In other words, since the electronic equipment is totally enclosed, frequent connections and disconnections are avoided and so the risk of short-circuit faults is reduced significantly.

At CityU, the team led by Prof. Hui pioneered the wireless charging technology as documented in more than 55 patents and a number of influential publications [R1-R6]. The research started with the development of using coreless printed-circuit-board (PCB) transformers for transferring signal and energy [R1]. Thorough investigations into the high-frequency characteristics of PCB transformers were carried out and optimal operating conditions for minimum input power requirement and maximum efficiency operations were identified. The main advantages of coreless PCB transformers include low cost, very high power density, absence of limitations associated with magnetic cores, absence of magnetic losses, and ease in manufacturing, based on which further development into microcircuits becomes possible. As a result, the technology developed at CityU by the team of Prof. Hui features: (a) free-positioning, (b) localized charging, and (c) compatibility checking.

(2a) Free-Positioning To enable free-positioning of electronic devices for charging, Prof. Hui extended the research investigation by using resonance via magnetic field to transfer energy wirelessly, as described in a series of patents filed at CityU [R2]. While the source (primary side) and load (secondary side) must have induction coils, a planar structure was proposed and developed for

the primary winding. Over the planar charging surface, uniformity of the magnetic flux generated by the primary winding is substantially improved. In this way, the precise position and orientation of the electronic device on the charging surface are no longer critical. Additionally, when the charging module comprises a plurality of primary windings in the form of an array, multiple devices can be placed on a sufficiently large planar charging surface for simultaneous charging [R3].

(2b) Localized Charging To provide safe localization of power, an effective shielding technique and a simple structure for PCB transformers were developed. The performance was evaluated using thin ferrite plates and copper sheets. A much greater shielding effectiveness has been achieved without affecting the energy efficiency [R4]. Such a technique is essential for enhancing safety in eliminating fire hazards due to cigarette lighters when deploying the invention. This is of great importance for indoor applications in a variety of venues including hotels, offices, and most public places.

(2c) Compatibility Checking In addition to the winding structure, the electronic controls used in driving the primary winding and controlling the power received on the secondary winding are also critical. An electronic control method for a planar inductive battery charging apparatus was invented by the team [R5-R6], thereby providing a wireless power transfer technique for simultaneously charging different electronic loads such as mobile phones, tablets, audio devices, and so on. The power control circuit of the charging pad consists of two power conversion stages. Depending on the nature of the input power supply, the first power stage is an AC-DC power converter with variable output voltage control, whereas the second stage is a DC-AC power inverter with constant current control. The combination of the two stages provides power control of the charging pad and generates an AC magnetic flux of ideally constant magnitude over the charging areas within a group of excited primary windings.

These research works laid the foundation for the *Qi Standard*. A wireless charging system according to the standard contains two main components: the base station and the mobile device. The base station generates high-frequency AC magnetic fields with a transmitting coil for wireless power transmission. It has a flat interface surface, on which the mobile device is to be placed. The mobile device couples the magnetic field and converts the AC power into DC power for charging. The success of the *Qi Standard* is attributed to its simple set of structural and electrical requirements, making it universally adoptable by all portable devices. The same charger can be used for devices from many different manufacturers. It is designed for simple integration, requiring the addition of only a few extra components in the entire system, thereby avoiding the extra expenses in using different chargers for different devices in a marketplace.

(3) References to the research

[R1] SC Tang, SY Hui, and H Chung, "Coreless Planar Printed-Circuit-Board (PCB) Transformers – A Fundamental Concept for Signal and Energy Transfer", *IEEE Trans. Power Electron.*, vol. 15, pp. 931-941 (2000).[Cited 139 times].

[R2] U.S. patents by SY Hui with CityU as the assignee in relation to "Inductive Battery Charger System with Primary Transformer Windings Formed in a Multi-Layer Structure": 7,164,255 B2 (2004), 7,872,445 B2 (2009), 8,269,456 B2 (2010), 8,917,057 B2 (2011), 8,299,753 B2 (2012), and 8,519,668 B2 (2012). The patents have been granted. They were filed in the years shown in the brackets.

[R3] SY Hui and WWC Ho, "A New Generation of Universal Contactless Battery Charging Platform for Portable Consumer Electronic Equipment," *IEEE Trans. Power Electron.*, vol. 20, pp. 620-627 (2005). [Cited 487 times].

[R4] SC Tang, SY Hui, and H Chung, "Evaluation of the Shielding Effects on Printed-Circuit-Board Transformers Using Ferrite Plates and Copper Sheets", *IEEE Trans. Power Electron.*, vol. 17, pp. 1080-1088 (2002). [Cited 207 times].

[R5] US Patent 7,576,514 B2: SY Hui, "Planar Inductive Battery Charging System". Filed in 2006. Granted in 2009. [Cited 326 times].

[R6] US Patent 8,228,025 B2: WC Ho, CK Lee, SY Hui, and H Chung, "Electronic Control Method for a Planar Inductive Battery Charging Apparatus". Filed in 2007. Granted in 2012. [Cited 130 times].

(4) Details of the impact

Of the [redacted] patents for wireless charging technology filed by the team at CityU, [redacted]. Most of the patents [redacted] Ltd., which is a major start-up company on wireless charging based in HK [E1]. These inventions have brought in license fee revenues of [redacted] by 2018, which has set the record-high licensing revenue for the university [E2].

The start-up company, [redacted], was instrumental in the founding of the Wireless Power Consortium (WPC) [E3]. Starting with only 8 companies in 2008, the consortium has now grown to about 600 company members worldwide, with an open membership of Asian, European, and American companies that are committed to the standardization of global wireless charging technologies. Members of the consortium include all major popular brands of smartphones and consumer electronics such as Apple, ASUS, Belkin, Bosch, Canon, Dell, Google, Haier, Huawei, IKEA, Lenovo, LG, MediaTek, Mophie, NXP, Panasonic, Royal Philips, Samsung, Sony, TDK, Verizon Wireless, and Xiaomi.

As one of the founding members, [redacted] As an open standard for use by the members of WPC, the ***Qi Standard* became the world's first industrial standard for certifying wireless charging** [E4]. The wireless charging technology possesses the following merits:

(a) great convenience for users because no cables are required,
(b) significantly reduced wear and tear on the sockets of devices and cables,
(c) reduced risk of short-circuit faults as the electronic equipment is entirely enclosed and shielded from moisture and oxygen in air, and
(d) reduced risk of infection caused by wiring of medical devices (e.g. pacemakers).

Moreover, the *Qi Standard* enables charging different mobile devices simultaneously on a charging plate, which is more convenient, efficient and environmentally friendly, as it helps to significantly reduce the number of different chargers which consumers would otherwise use for different brands. These merits resulted in the wide adoption of the standard by many smartphone manufacturers.

The *Qi Standard* is being adopted by millions of mobile devices around the world including 3000 products of major manufacturers. Notably, the *Qi Standard* is adopted for the built-in wireless charging circuitry for iPhones because Apple has returned to WPC since 2017. Wireless charging with *Qi* chargers has been included for iPhone 8, iPhone 8Plus, iPhone X, and iPhone 11, as listed by Apple (e.g. https://www.apple.com/iphone-11/specs/).

The standard is easy to implement for a multitude of real-world applications requiring different ranges of power. It provides a perfect solution for hazardous, humid, or dirty environments where frequent maintenance might impose cost and safety concerns, rendering it ideal for medical, industrial, scientific, and commercial applications. Thus, wireless charging platforms with the *Qi Standard* were quickly adopted in restaurants, hotels, vehicles, and other venues including:

- **Starbucks**: phone charging stations on coffee tables [E5],
- **ZENS**: cordless kitchen appliances for homes [E6],
- **KIA**: in-cabin phone charging and infotainment systems for vehicles [E7], and
- **IKEA**: integrated furniture and lighting for entirely wireless homes [E8].

Originally designed for low-power applications at the level of 5 W for charging mobile devices, the *Qi Standard* has been applied at an increased power level of up to 120 W for laptops or displays. Recently, WPC has demonstrated a high-power specification for applications up to 1 kW, suitable for high-power wireless charging of electric vehicles, which provides an automated and cordless alternative to plug-in charging. With the ever-growing interest on autonomous driving, such wireless charging between roads and vehicles is becoming very important for allowing vehicles to run indefinitely. It allows the elimination of heavy battery banks and the extension of travel distance, which are beneficial in increasing energy efficiency and meeting consumer demands.

With his ground-breaking research on power electronics, Prof. Hui was elected Fellow of the Royal Academy of Engineering (UK) and Fellow of the National Academy of Inventors (US) [E9]. He received the prestigious IET Crompton Medal for achievements in power electronics in 2010 and then the IEEE William E. Newell Power Electronics Award, a top award of the IEEE Power Electronics Society, in 2015 [E10]. These recognitions exemplify the impact of the research developed by Prof. Hui between 2000 and 2011 at CityU, which provided the underlying technologies that have become the cornerstone for the *Qi Standard*. The standard testifies to the success of the research that greatly impacted the industry and beyond.

(5) Sources to corroborate the impact

[E1] Patents by Prof Ron SY Hui at CityU [redacted]

- US Patents as attached in [R2]:
  (a) 8,299,753 and 8,519,668: Inductive battery charger system with primary transformer windings formed in a multi-layer structure,
  (b) 7,872,445: Rechargeable Battery Powered Portable Electronic Device,
  (c) 8,269,456: Secondary Module for Battery Charging System, and
- Europe Patent EP 2685594(B1): Planar Inductive Battery Charger.

Other licensed patents include UK Patents GB2399466 and GB2389720.

[E2] Press release regarding the significant license fee revenues for the wireless charging technology.
https://newscentre.cityu.edu.hk/media/pr/2018/07/08/significant-license-fee-revenues-cityus-technologies-including-globally-applicable-wireless-charging-technology

[E3] (a) Wireless Power Consortium (WPC) and (b) the approximately 600 members of the consortium as of 2019.
https://www.wirelesspowerconsortium.com/
https://www.wirelesspowerconsortium.com/members/

[E4] The *Qi Standard* for wireless charging.
https://www.wirelesspowerconsortium.com/qi/

[E5] Starbucks: Phone charging stations at coffee tables.
https://www.theverge.com/circuitbreaker/2017/9/14/16307832/starbucks-powermat-wireless-charging-qi-pma-iphone-x-8

[E6] ZENS: cordless kitchen appliances for homes.
https://www.makezens.com/wireless-charging-solutions/kitchen/

[E7] KIA: in-cabin phone charging and infotainment systems for vehicles.
https://www.air-charge.com/aircharge-for-business/automotive/kia-wireless-charging

[E8] IKEA: integrated furniture and lighting for entirely wireless homes.
https://www.imore.com/ikea-shows-wireless-charging-furniture-iphone-8-iphone-x

[E9] With his ground-breaking research on power electronics, Prof. Hui was elected (a) Fellow of Royal Academy of Engineering in 2016 and (b) Fellow of National Academy of Inventors in 2018.
https://www.raeng.org.uk/about-us/the-fellowship/new-fellows-2016/fellows/ron-hui
https://academyofinventors.org/wp/skin/search-fellows.php

[E10] The 2015 IEEE William E. Newell Power Electronics Award of the IEEE Power Electronics Society was conferred to Prof. Hui for his impactful innovations in power electronics, including his pioneering work on planar wireless charging technology and patents featured in the world's first wireless charging standard for low-power electronics.
https://www.ieee.org/about/awards/bios/newell-recipients.html#2015---shu-yuen-ron-hui