Application of Wireless Power Transfer (WPT) in Smart Homes and Buildings

A CABA WHITE PAPER

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The Continental Automated Buildings Association (CABA) is an international not-for-profit industry association, founded in 1988, and dedicated to the advancement of intelligent home and intelligent building technologies. The organization is supported by an international membership of over 375 organizations involved in the design, manufacture, installation and retailing of products relating to "Internet of Things, M2M, home automation and intelligent buildings". Public organizations, including utilities and government are also members. CABA's mandate includes providing its members with networking and market research opportunities. CABA also encourages the development of industry standards and protocols, and leads cross-industry initiatives. CABA's collaborative research scope evolved and expanded into the CABA Research Program, which is directed by the CABA Board of Directors. The CABA Research Program's scope includes White Papers and multi-client market research in both the Intelligent Buildings and Connected Home sectors. www.caba.org

ABOUT CABA'S CONNECTED HOME COUNCIL (CHC)

Established in 2004, the CABA Connected Home Council initiates and reviews projects that relate to connected home and multiple dwelling unit technologies and applications. Connected homes intelligently access wide area network services such as television and radio programming, data and voice communications, life safety and energy management/control information and distribute them throughout the home for convenient use by consumers. The Council also examines industry opportunities that can accelerate the adoption of new technologies, consumer electronics and broadband services within the burgeoning connected home market. www.caba.org/chc

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1. INTRODUCTION

Wireless power transfer (WPT) provides a convenient non-contacting charging solution for everyday equipment, from low-power consumer electronics devices (such as mobile phones) to high-power systems (such as electric vehicles). WPT has great potential to revolutionize the way people charge and has aroused great interest in academia and industry over the past decade. Compared with conventional plugged-in charging, WPT brings a number of obvious benefits, including the elimination of electrical contacts (safer charging), enclosed design (dust protection and reduced risk of corrosion), a better user experience ("place and charge"), and a neater living environment (avoidance of messy wires).

Users have become ever more accustomed to connecting their home devices to the Internet—and to linking these devices together—to achieve cost savings and enhance aspects such as comfort, entertainment, safety and security. With the rise of Internet of Things (IoT) technologies, people now have different options in terms of how they choose to set up their living spaces. The development has not only made it easier to transfer information and data; it has made it more convenient to transfer power in a non-contacting manner, which can better support the sustainable operation of smart devices. As an emerging technology, WPT is expected to significantly change people's existing lifestyles at home. From bedroom lamps to kitchen mixers, many household appliances can apply the WPT technology, adding to convenience, efficiency and safety in the home.

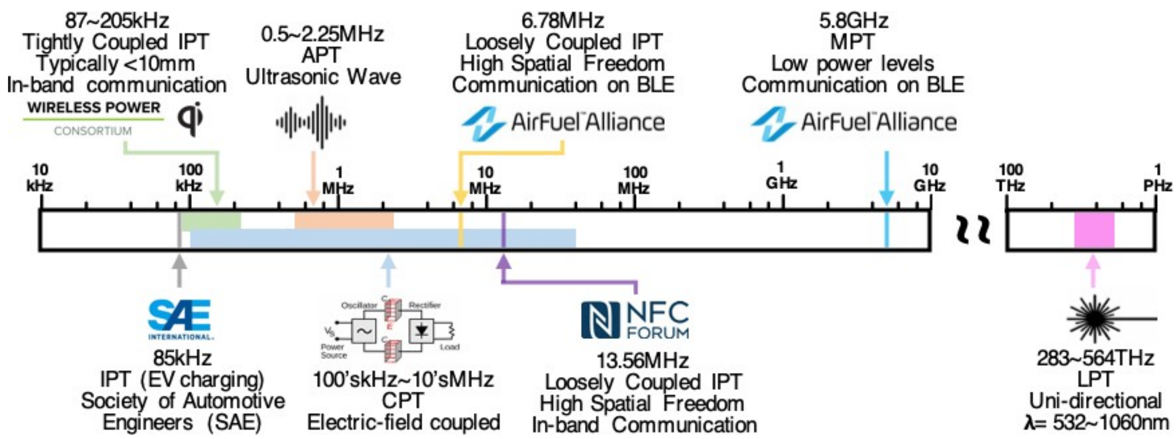
This White Paper provides an overview of WPT, its main technical and business aspects, and its application in smart homes/buildings. Integrating WPT into buildings and various household appliances can greatly improve the reliability, convenience and safety of power supplies in our lives. The purpose of this White Paper is help readers better understand the overall picture, advantages and design methods of WPT in smart home/building application scenarios.

2. OVERVIEW OF WPT

Maxwell's equations mathematically predict that electromagnetic waves can propagate in space as a carrier of energy, which has led to the revolutionary development of wireless communication and thus changed modern society in numerous ways. Based on the same physical principle, when compared to the transfer of digital bites in wireless communication, a much larger amount of energy can also be transferred wirelessly over a long distance. Nikola Tesla is a pioneer of WPT. Many of his discoveries have become the basis of today's WPT research. In the late 19th century, the proposed "Tesla Coil" served as an early demonstration of WPT (Uth, Robert, 2008). In particular, he discovered the importance of tuning both "the driving and the working circuits" to operate at the same resonance frequency, which has become the basic principle of today's non-radiative WPT (S. Y. R. Hui, et al, 2014).

Since then, WPT has experienced more than 100 years of development, and various WPT technologies have emerged. Figure 1 shows representative WPT technologies, depending on their different frequency bands, operating principles, and the organizations and standards followed.

Figure 1 Representative WPT technologies



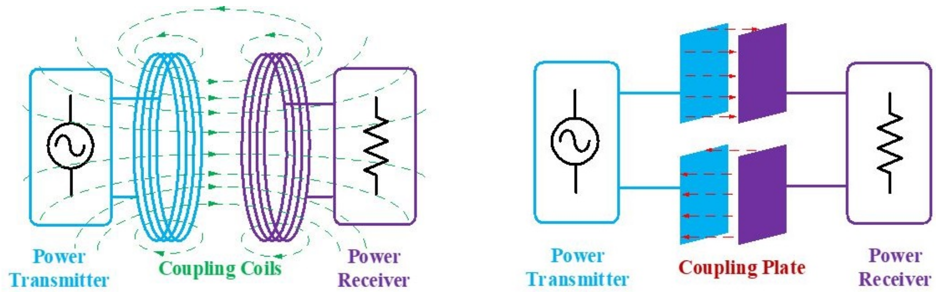
2.1 Technologies

Based on different operating principles, WPT can be realized by inductive power transfer (IPT), capacitive power transfer (CPT), microwave power transfer (MPT), laser power transfer (LPT), and acoustic power transfer (APT), respectively. These operating principles are described below, along with their key characteristics.

IPT – IPT uses coupling coils to transmit power over a relatively short distance [see Figure 2]. The transmitting coil is driven by alternating current to generate an alternating magnetic field in the surrounding area. The receiving coil placed near the transmitting coil then induces an alternating current. IPT is currently the most widely-used WPT technology, suitable for various power levels. Its effective power transfer distance is directly limited by the size of the coupling coils.

CPT – CPT normally uses two sets of coupled plates to transfer power through a certain distance. Compared to IPT, the power transfer distance of CPT is relatively short (J. Dai, et al, 2015). Both IPT and CPT can achieve relatively high efficiency (≥90%) at high power levels (up to kilowatt) (J. Dai, et al, 2015). CPT uses electric field coupling and therefore can transfer power through metal barriers. Meanwhile, there is a safety risk due to the electric field coupling.

Figure 2 Simplified Schematics of IPT and CPT. (Left – IPT, right – CPT)



MPT – Microwaves are emitted from the antenna into free space and propagate over a long distance (i.e., many times the size of the antenna). The receiving antenna collects and converts microwave energy. Because MPT has an omnidirectional characteristic, efficiency is usually significantly lower than that of IPT (S. Y. R. Hui, et al, 2014). In commercial applications, its output power is also small to avoid radiation level that may be hazardous to the human body or interfere other electronic devices (C. R. Valenta, et al, 2014).

LPT –The laser emitter generates a monochromatic beam. Then, a set of optics is used to shape the laser beam and direct it to a remote photovoltaic (PV) receiver through a beam guide/director. The PV cells that match the laser wavelength and beam intensity convert the laser back to electrical energy. For most research work, the wavelength is between 532 and 1060 nm. Note that the most efficient lasers work at near-infrared wavelengths in the retinal hazard region (K. Jin, et al, 2019).

APT – APT is a relatively new form of WPT that uses sound waves to transfer energy wirelessly, while all other WPT technologies rely on electromagnetic field/waves. A medium is needed between the transmitter and receiver to convey sound waves. This technology allows power to be transferred through metal. In most research, the frequency of sound waves is between 0.5 and 2.25 MHz (Maurice G. L. Roes, et al, 2013). APT operating frequency should be away from the resonance frequency of the ambient objects.

2.2 Organizations and Standards

This section provides an overview of the main organizations and standards supporting the development of WPT.

Wireless Power Consortium (WPC) – Established in 2008, WPC is a standard development group for low-frequency kHz WPT products. At present, WPC consists of more than 500 member companies worldwide. WPC developed the Qi (pronounced “chee”) standard, which is widely used in today’s commercial mobile devices, such as cellphones. Due to the maturity of the kHz power electronics technology, most existing WPT products adopt the Qi standard. Qi specifies interoperable WPT and in-band communication between wireless chargers and charging devices. Qi can now provide up to 15W of power, with an operating frequency range of 87 to 205 kHz (Qi Specification, 2017). Future expansion will also provide up to 60W of power to support large devices such as laptops (About WPC, 2020).

AirFuel Alliance (AFA) – AFA was established in 2015 by the merger of two leading wireless charging organizations-Wireless Power Alliance (A4WP) and Power Matters Alliance (PMA). AFA announced two WPT standards: "AirFuel Resonant" and "AirFuel RF". "AirFuel Resonant" specifies the IPT standard to transmit a moderate amount of power (several watts to tens of watts) at 6.78 MHz. Due to the increased operating frequency, “AirFuel Resonant” can achieve greater spatial freedom and multi-device charging. “AirFuel RF” allows any 3D item from the cup holder to the drawer or box to become a transmitter/charging station, and the charging area is up to 15 feet (AirFuel RF, 2020). Bluetooth Low Energy (BLE) is required for communication between the wireless charger and the charging device.

Society of Automotive Engineers (SAE) International – SAE International is a global professional association and standard- setting organization for engineering professionals in various industries. SAE International released "SAE TIR J2954 Wireless Power Transmission and Alignment Method for Light Plug- in/Electric Vehicles" in May 2016, in which 85 kHz (81.39-90 kHz) was declared as the common frequency band for WPT of all light duty vehicles. Three power levels of 3.7, 7.7, and 11.0 kW were specified, and two higher power levels will be released in the future, up to 22 kW (SAE, 2016). J2954/2 was announced alter to define more powerful 500 kW charging for heavy-duty vehicles (SAE, 2013).

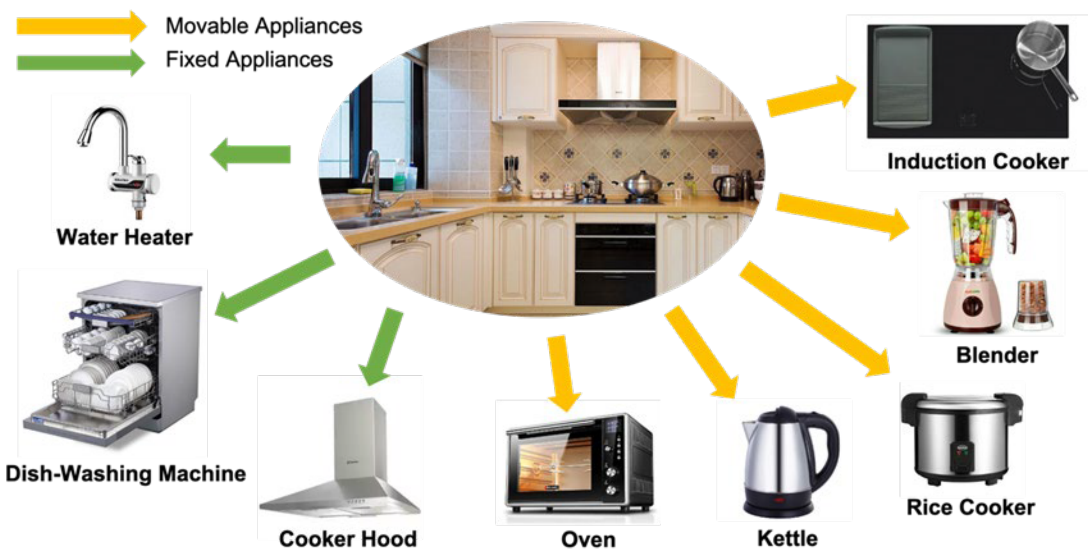
Near Field Communication (NFC) Forum – The NFC Forum is a global standard and advocacy association for near field communication (NFC) technology. The NFC specification uses the same 13.56 MHz-based frequency channel for both communication and WPT. A single NFC antenna is used to exchange information and to transfer power, at a rate of up to 1 W (NFC, 2020).

WPT is an interdisciplinary research field that combines power electronics, radio frequency and microwave, electromagnetics, optimization and control, etc. WPT applications are also required to adhere to multiple standards. In addition to the above organizations/standards, there are many other WPT standardization working groups, such as ITU (International Communications Union) (Report ITU-R, 2017), IEC (International Electrotechnical Commission), ISO (International Organization for Standardization), CISPR (International Special Committee on Radio Interference). Different organizations focus on different aspects of standardization, such as frequency bands, power levels, interfaces, electromagnetic interference (EMI), electromagnetic compatibility (EMC), etc. WPT products must also comply with the relevant standards enacted by each country/state/jurisdiction.

2.3 Applications in Smart Homes and Buildings

WPT technology has been widely used in consumer electronics devices such as smart phones, earbuds, and various wearable devices. The WPT market is growing rapidly every year, and its applications have been widely used in many household appliances: coffee machines, robot vacuum cleaners, electric kettles, and many other examples. WPT can be widely used in kitchens and bathrooms where electricity and water coexist. WPT enables these devices to have a closed structure, making them more waterproof and dustproof and eliminating the risk of electric shock. Figure 3 shows some potential WPT applications in kitchen appliances, including ovens, kettles, blenders, etc. These appliances can be charged by simply placing them on a transmitter installed beneath the kitchen countertops, which improves convenience and safety. WPC announced the "Ki Wireless Kitchen" standard in 2019, which can power cordless devices, from simple low-power juicers to high-power heating devices that require up to 2.2 kW of power (Ki Cordless Kitchen, 2019). The standard allows Ki wireless kitchen transmitters and appliances to work together regardless of their brand.

Figure 3 Concept of cordless kitchen: equipping WPT into various kitchen appliances



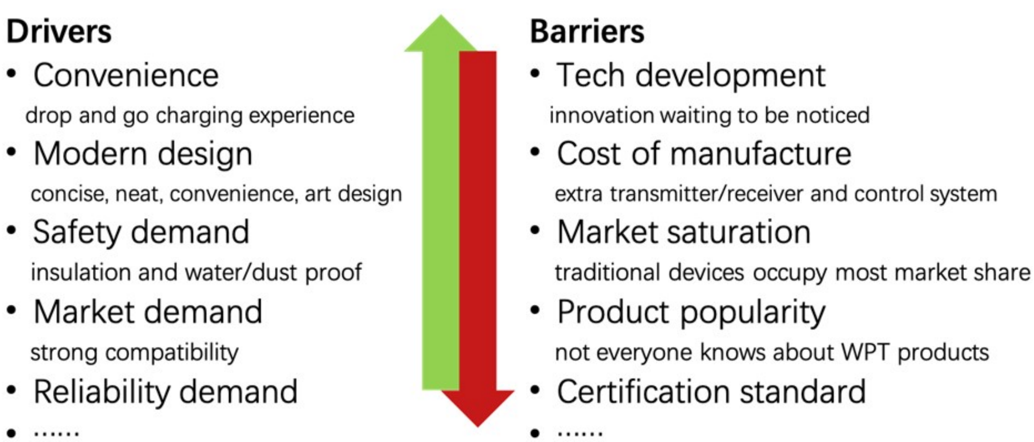
In addition to standardization bodies like WPC, many leading companies have also shown great interest in WPT and have invested heavily in developing their own WPT products. Haier is one example. According to information on the company's website, Haier has released many household appliances with WPT functions. Figure 4 shows some of them. Figure 4(a) shows the smart desk lamp WZDT502L-B equipped with a Qi wireless charger of cellphones. Regarding kitchen and house cleaning, Haier also released WJD-380A wireless blenders, WFD-30A wireless rice cookers and wireless sweeping robots (690RS) in 2019.

Figure 4 Wireless appliances from Haier: (a) smart desk-lamp WZDT502L-B, (b) wireless robot sweeper 690RS, (c) wireless rice cooker WFD-30A, (d) wireless blender WJD-380A

In addition to the above examples, WPT still has many potential applications in consumers' homes that need to be explored. Televisions, 5G and other telecommunications facilities and water heaters in bathrooms are all good examples of installations that can be transformed by WPT to create a tidier, safer and more convenient life for people. Although WPT has a series of advantages over the conventional plugged-in charging, there are still some obstacles that hinder its wide application. First of all, consumers always need time to adapt to new technologies.

Secondly, the hardware and software of WPT may bring extra costs to consumers, even though at the same time, changes in mass production have lowered the cost of the WPT system. Other obstacles include market saturation, product penetration and certification standards. Despite these obstacles, the WPT industry is still developing. In the next ten years, the application of WPT in connected homes and intelligent buildings is expected to grow exponentially.

Figure 5 Drivers and barriers of incorporating WPT into smart home/building design



3. INCORPORATING WPT IN SMART HOME/BUILDING DESIGN

As household appliances integrated with WPT become more and more popular and widely used, it is intuitive to incorporate the WPT system into the connected home/building right from the design stage. Typical examples include embedding the wireless charger for Roomba below the living room floor and embedding the wireless charger for EV underground in a garage. However, incorporating an WPT system into building projects may seem overwhelming to those who are approaching these projects for the first time. Some basic ideas and concepts for designing an efficiency WPT system are provided here as resources for architects, building owners, and designers. The basic considerations when designing an WPT system are listed as follows:

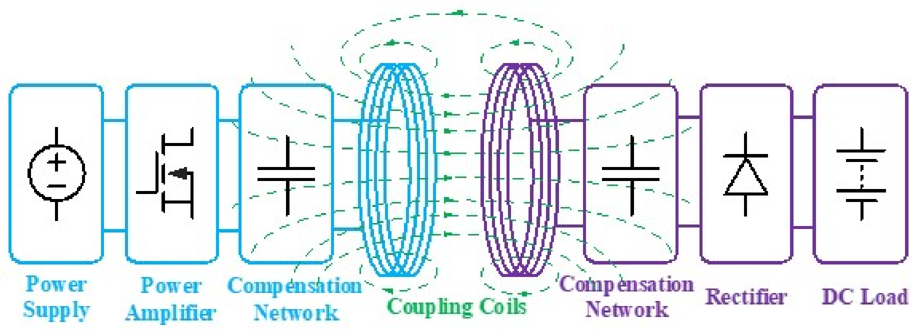
- Target power level;
- Target power transfer distance;
- Medium between the transmitting and receiving sides; and
- Target size and shape.

Once the above basic specifications are determined, the appropriate WPT technology can be determined. Please note that different WPT technologies have their own advantages and disadvantages, and are thus suitable for different applications.

Due to ease of implementation and early release, most of today's commercial electronic devices and household appliances comply with the Qi standard. However, the Qi standard operating at kHz presents some disadvantages, such as short transfer distance (typically <10mm) and sensitivity to coil misalignment, which hinders the further application of this technology.

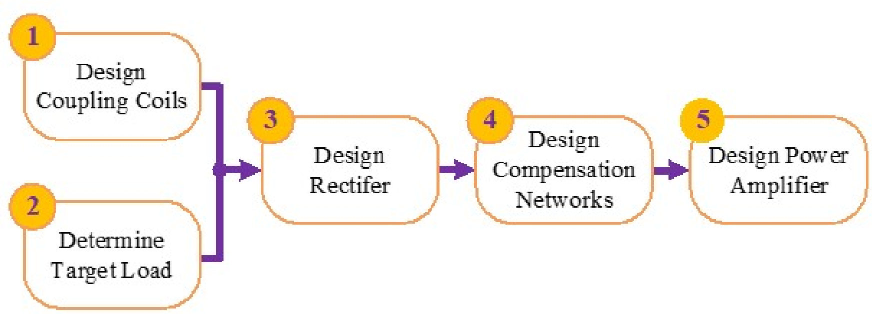
Compared with the Qi standard, the AFA standard operating at MHz has higher spatial freedom and other advantages. For example, in principle, no ferrite material is required, and it is easy to charge multiple devices at the same time (J. Song, et al, 2020). As the operating frequency increases, the required coil size will also become smaller. As a result, MHz WPT systems are generally lighter and smaller, and provide longer transfer distance and better coil misalignment tolerance. According to the standards issued by AFA, 6.78 MHz is the most recommended operating frequency for MHz WPT systems. A typical configuration of MHz WPT system is shown in Figure 6.

Figure 6 A typical configuration of MHz WPT systems



The power amplifier converts the direct current from the power source into alternating current that drives the transmitting coil. The compensation networks connected to the two coupling coils are used to achieve complete resonance of the coils. Power is wirelessly transferred through magnetic coupling between the two coils. The rectifier then converts the alternating current of the receiving coil into direct current again to charge the battery and other loads. Figure 7 illustrates the system-level design flow of the MHz WPT systems in a step-by-step manner (M. Liu, et al, 2020):

Figure 7 System-level design flow of MHz WPT systems



1. **Design of Coupling coils**: The design of the MHz WPT system usually starts from designing the coupling coil according to the target power transfer distance and size limitation. High- quality-factor (namely, low AC resistance) coupling coil is expected to improve power transfer efficiency. Several commercial electromagnetic simulation tools, such as Ansys HFSS and Maxwell, can help design the coupling coils.

2. **Target load calculation**: It is also important to determine the target load for the design of the WPT system. However, the load of the WPT system usually changes with time; for example, when charging a lithium ion battery. In this case, it is necessary to determine the load variation range in advance to guide the following system-level design.

3. **Rectifier design**: According to the target load and the characteristics of the coupling coil, the design of the rectifier can be determined. Resonant power conversion topologies such as Class E and Class EF are promising for MHz WPT rectifiers and power amplifiers, due to their soft-switching property, high efficiency and better EMI performance (M. Liu, et al, 2020).

4. **Design of compensation networks**: There are four basic compensation networks for the coupling coils, i.e., series- series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP). SS is the most widely applied compensation network in MHz WPTs. This topology has the main advantage of being straightforward in achieving the full resonance of the coupling coils and capable of providing a pure resistive load to the power amplifier.

5. **Power amplifier design**: Class E and EF topologies are also effective for power amplifiers used in MHz WPT. The impedance of the transmitter coil, i.e., the load of the power amplifier needs to be calculated to guide the design. Since WPT systems may operate under varying coupling and load conditions, robust design/control may be required in practical applications.

It should be noted that when incorporating a WPT system into a home/building, many non-technical issues need to be considered, such as cost, consumer demand, safety, and aesthetics. All of these require close cooperation among engineers, architects, building owners and designers.

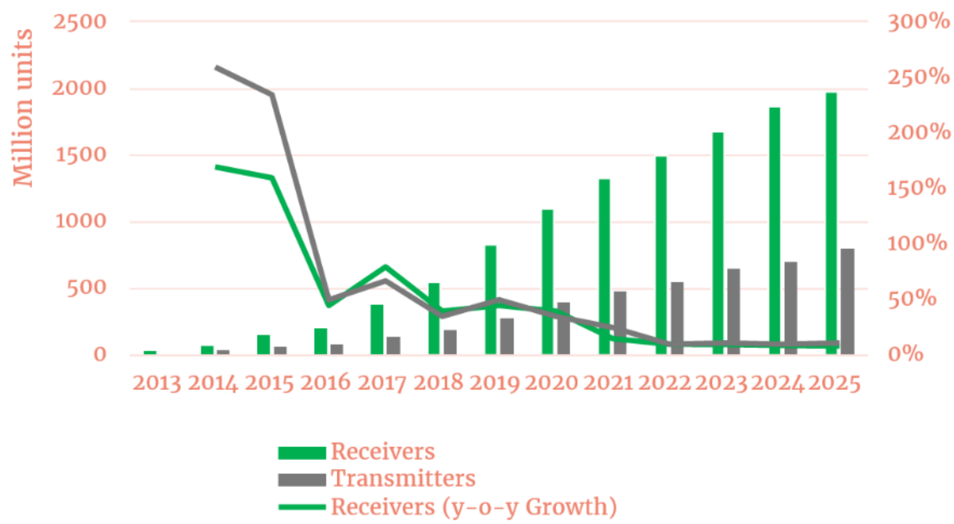
4. BUSINESS ASPECTS OF WPT IN BUILDING APPLICATIONS

4.1 Market Evaluation

Global WPT market is growing year by year. Driven by shipments in mobile phones, laptops and wearables, a nearly 300% increase over 2016 levels was achieved in 2019, according to a WPT market forecast from IHS Markit [see Fig. 8] (D. Kithany, 2017).

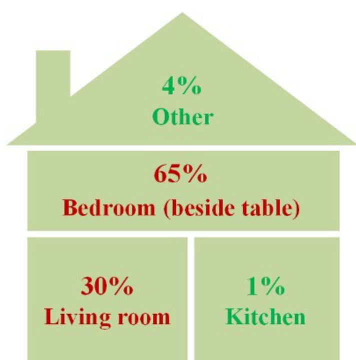
During these three years, more consumers experienced wireless charging for the first time. Today, almost all mainstream mobile phones have wireless charging capabilities. By 2022, the size of the market will reach 12 billion USD (Wireless Power Transmission Market, 2020). The number of devices enabled with wireless charging will reach 1,500 million units a year for the first time in 2022.

Figure 8 WPT market forecast by IHS Markit



Home is the most common place for people to charge their cellphones. According to a 2017 consumer survey by IHS Markit, 95% of users charge their cellphones in bedrooms and living rooms [see Fig. 9]. WPT is certainly a convenient solution for cellphone charging. Therefore, integrating WPT systems into smart homes/buildings will bring many benefits to consumers, such as 1) increased frequency of charging due to the convenience; 2) prolonged battery cycle life thanks to less over discharge; 3) improved sustainability of power supply; 4) non-contacting safe charging experience.

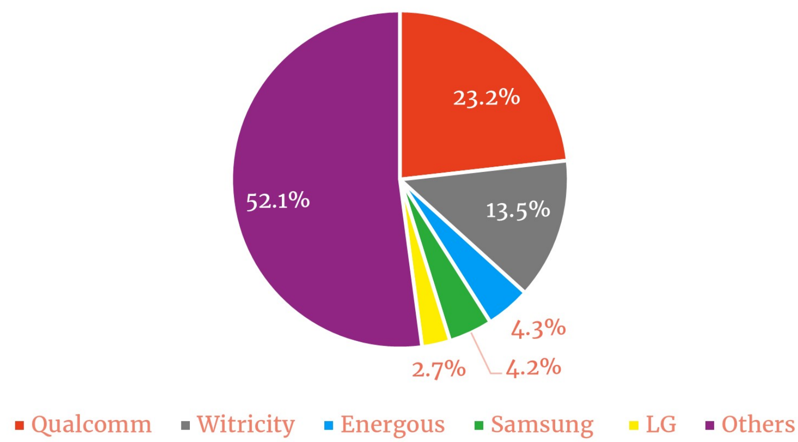
Figure 9 People most often charge their cellphones at home



4.2 Key Global Companies

Today, more and more companies are engaged in WPT R&D and commercialization. Figure 10 shows the companies with the most WPT patents, according to Google Patents. Leading companies Qualcomm, Witricity, Energous, Samsung and LG account for 47.9% of all patents. These five companies are briefly described below.

Figure 10 Companies with the most WPT patents, according to Google Patents (Google Patents, 2020)



Qualcomm - Qualcomm currently holds the most WPT patents, most of which focus on wireless charging of cellphones and electric vehicles. Qualcomm Halo EV wireless charging system is capable of charging an EV dynamically at, and in excess of, 100 km/h with 20 kW (Qualcomm, 2017).

WiTricity - WiTricity is a spin-off company of MIT, established in 2007. It provides wireless power transfer solutions for the automotive, consumer electronics, industrial and medical fields. In 2019, Witricity announced the acquisition of more than 1,500 WPT-related patents and patent applications from Qualcomm.

Energous - Energous Corporation is the developer of WattUp, which provides wireless power to multi-receivers using the near field, mid field and far field technologies. The company is best known for its Radio frequency (RF) based charging technology to charge electronic devices up to 4.5-meter charging distance.

Samsung – Samsung started research into WPT technology in late 2000 and released their first commercial wireless charging pad in 2011. Samsung's main WPT-related products today include smartphones, smart watches, wireless charging pads and wireless battery packs.

LG – Similar with Samsung, LG's WPT-related products include smart phones, smart watches and their charging pads.

CONCLUSION

In this White Paper, the fundamentals of WPT in connected home and building applications are introduced from a technical and commercial perspective. We began with an explanation of the background of WPT, including the possible technologies and standardization organizations. Secondly, we analyzed the application scenarios, driving factors and obstacles of WPT technology. We went on to introduce the design procedures of a typical MHz WPT system for reference purposes. In the closing section, we discussed the global WPT market and its principal players. Connected homes and intelligent buildings equipped with WPT facilities and equipment promise to add convenience and improve quality of life. After decades of academic research, WPT has reached the required maturity level to be used widely, but its application in smart homes/buildings will require early-stage cooperation between engineers, architects, building owners and designers.

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