

Chapter 1

History, Present and Future of WPT

1.1. Theoretical predictions and the first trial in the 19th Century

In 1864, James C. Maxwell predicted the existence of radiowaves by means of a mathematical model. The so-called Maxwell equations are the most famous and most successful formulas. In 1884, John H. Poynting realized that the Poynting vector would play an important role in quantifying electromagnetic energy. In 1888, bolstered by Maxwell's theory, Heinrich Hertz first succeeded in showing experimental evidence of radiowaves using his spark-gap radio transmitter. The prediction and evidence of radiowaves toward the end of the 19th Century was the beginning of wireless power transfer (WPT).

During the same period, when Marchese G. Marconi and Reginald Fessenden pioneered communication via radiowaves, Nicola Tesla suggested the idea of wireless power transfer and carried out the first WPT experiments in 1899 [TES 04a, TES 04b]. He said "This energy will be collected all over the globe preferably in small amounts,

ranging from a fraction of one to a few horse-power. One of its chief uses will be the illumination of isolated homes". Tesla actually built a gigantic coil that was connected to a 200 ft high mast with a 3 ft diameter ball at its top. The device was called the "Tesla Tower" (Figure 1.1). Tesla fed 300 kw of power to the coil that resonated at a frequency of 150 kHz. The radio frequency (RF) potential at the top sphere reached 100 MV. Unfortunately, the experiment failed because the transmitted power was diffused in all directions using 150 kHz radiowaves, whose wavelength was 21 km. After this first WPT trial, the history of radiowaves has been dominated by wireless communications and remote sensing.

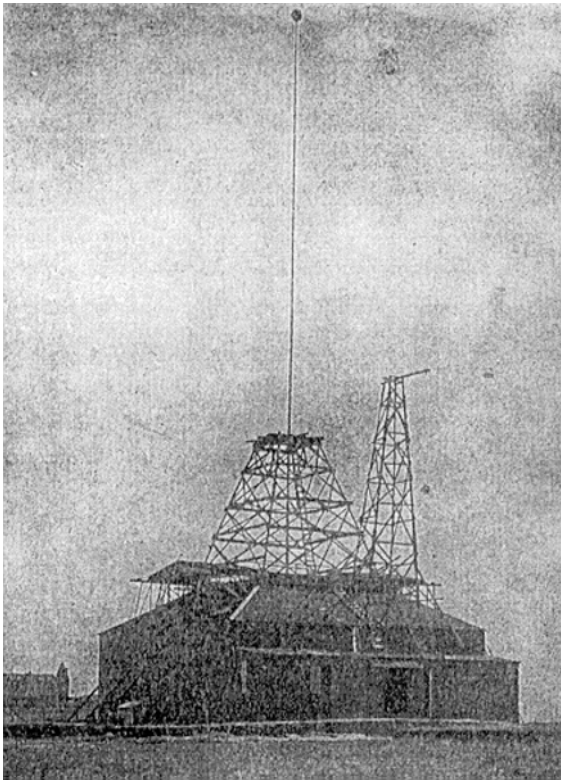


Figure 1.1. *The Tesla tower*

1.2. Rejuvenated WPT by microwaves in the 1960s

To focus on the transmitted power and to increase the transfer efficiency, a higher frequency than that used by Tesla is required. In the 1930s, a great deal of progress in generating high-power microwaves in the 1–10 GHz range was achieved by the invention of the magnetron and the klystron. After World War II, high-power and high-efficiency microwave tubes were advanced by the development of radar technology. The power delivered to a receiver can be concentrated with microwaves. WPT using microwaves is called microwave power transfer (MPT).

On the basis of development of microwave tubes during World War II, W.C. Brown introduced the first MPT research and development in the 1960s. First, Brown developed a rectifying antenna, which he named a “rectenna” for receiving and rectifying microwaves. The efficiency of the first rectenna developed in 1963 was 50% at an output of 4 WDC and 40% at an output of 7 WDC, respectively [BRO 84]. With the rectenna, Brown successfully applied MPT to a wired helicopter in 1964 and to a free-flying helicopter in 1968 (Figure 1.2). In the 1970s, Brown attempted to increase the total DC–RF–transfer–RF–DC efficiency using 2.45 GHz microwaves. The overall DC–DC efficiency was only 26.5% at an output of 39 WDC in the Marshall Space Flight Center tests of 1970 [BRO 73a]. In 1975, the overall DC–DC efficiency finally attained 54% at an output of 495 WDC using the Raytheon Laboratory magnetron (Figure 1.3) [BRO 84]. In parallel, Brown, Richard Dickinson and his team succeeded in the largest MPT demonstration up to that time in 1975 at the Venus Site of the JPL Goldstone Facility (Figure 1.4). The distance between the transmitting parabolic antenna, whose diameter was 26 m, and a rectenna array, whose size was 3.4 m × 7.2 m, was 1 mile. The transmitted 2.388 GHz microwave signal was 450 kW from the klystron and the rectified DC power achieved was 30 kW DC with a 82.5% rectifying efficiency. On the basis of

Brown's work, P.E. Glaser proposed a solar power satellite (SPS) system in 1968 [GLA 68].

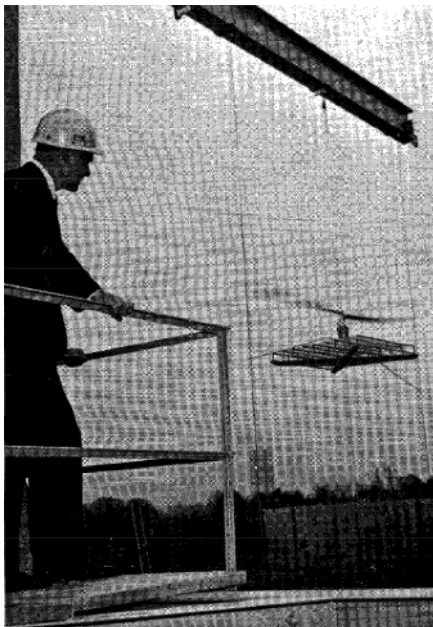


Figure 1.2. *MPT Helicopter demonstration by W.C. Brown in 1964 [BRO 84]*

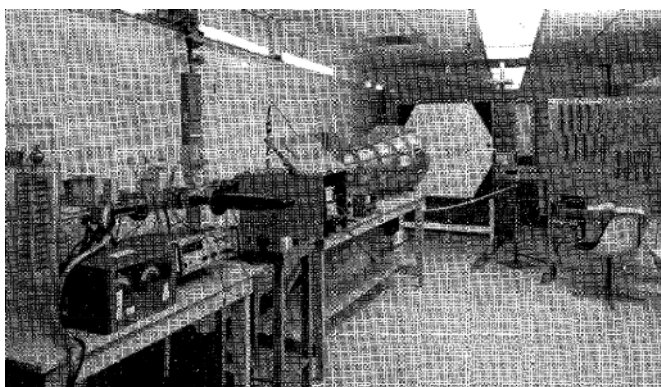


Figure 1.3. *MPT laboratory experiment by W.C. Brown in 1975 [BRO 84]*



Figure 1.4. *First ground-to-ground MPT experiment in 1975 at the Venus Site of the JPL Goldstone Facility*

But after the MPT experiments of the 1960s, SPS applications have led the field in MPT research [MCS 02, MAT 02a]. Because of the theoretical calculation, the large antenna size required to achieve high-beam efficiency to a far distant target, an MPT system designed for SPS did not seem to be suitable for commercial applications. However, even if the antenna size was to become larger, there would be the other merits of the space-based SPS. The SPS is designed as a huge SPS in geostationary orbit, 36,000 km above the Earth's surface, where there is no cloud cover and no night throughout the year. Microwave energy is not absorbed by air, cloud and rain; therefore, it is possible to obtain approximately 10 times the solar power, a stable and CO₂-free energy source, from the SPS using MPT technology than that from terrestrial solar sources. As a result of the high benefits expected, MPT research mainly focused on SPS applications during the late 20th Century.

Numerous Japanese scientists developed MPT technologies and research throughout the 1980s [MAT 95a, MAT 02a]. In 1983 and 1993, Hiroshi Matsumoto's team carried out the first MPT experiment in space. The rocket experiment in 1983 was called the microwave ionosphere nonlinear interaction experiment (MINIX) (Figure 1.5), and International Space Year – Microwave Energy Transmission in Space (ISY-METS) was conducted in 1993. These experiments focused on the nonlinear interaction between intense microwaves and ionospheric plasmas. In the MINIX experiment, the researchers used a cooker-type 800 W, 2.45 GHz magnetron for a microwave transmitter. New wave–particle interaction phenomena were observed during the MINIX study. Plasma theory and computer experiments supported the observations [MAT 95b, MAT 95c]. These rocket experiments were directed toward SPS applications.

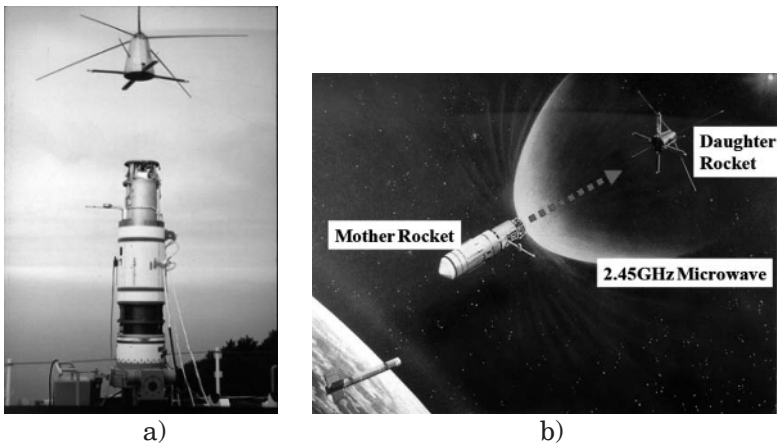


Figure 1.5. *The first rocket experiment by Matsumoto in Japan in 1983, called the MINIX project: a) image of mother and daughter rockets; b) image of the experiment*

During the 1990s, numerous MPT laboratory and field experiments were carried out all over the world. This

research was not only for SPS but also for other commercial MPT applications. Researchers often used 2.45 or 5.8 GHz frequencies of the industry, science and medical (ISM) band for MPT systems. A Canadian group of the Communication Research Centre (CRC) successfully conducted a fuel-free airplane flight experiment using MPT in 1987, which was called stationary high-altitude relay platform (SHARP) (Figure 1.6) [SCH 88, SHA 88]. They transmitted a 2.45 GHz, 10 kW microwave signal to a model airplane, having a total length of 2.9 m and a wing span of 4.5 m, flying more than 150 m above ground level. In the United States, a great deal of MPT research and development continued after Brown. For instance, retrodirective microwave transmitters, rectennas, new devices and microwave circuit technologies were investigated [BRO 88]. In Japan, several field MPT experiments were conducted, such as fuel-free airplane flight experiments with MPT phased arrays operating at 2.411 GHz for the microwave lifted airplane experiment (MILAX) project in 1992 (Figure 1.7) [MAT 93], ground-to-ground MPT experiments operating at 2.45 GHz were conducted by power companies and universities in 1994–1995 (Figure 1.8) [SHI 98a], and fuel-free light airship experiments using MPT operating at 2.45 GHz in 1995 [KAY 96]. The target system used in the MILAX project was the Japanese SHARP. Kobe University and Communications Research Laboratory (CRL; present National Institute of Information and Communications Technology (NICT)) group in Japan succeeded in an MPT field experiment involving a flying airship in 1995. They called it the Energy Transmission toward High-altitude long endurance airship Experiment (ETHER) project. This research group transmitted 2.45 GHz, 10 kW microwaves to a flying airship 35–45 m above ground level. In these experiments, except in those of the MILAX project, researchers adopted a parabolic antenna MPT system using a microwave tube. A phased array system was used only in the MILAX project, and this project was the first MPT field experiment to use it. In parallel with developments in Japan,

varieties of microwave transmitters, retrodirective microwave transmitters and, especially, rectennas were also developed. In Europe, some unique technologies are presently being developed. Researchers had planned ground-to-ground MPT experiments on Réunion Island (Figure 1.9) [CEL 97, CEL 04], but the project has not yet been carried out.



Figure 1.6. *The Canadian SHARP flight experiment and the 1/8 model airplane in 1987 [SHA 88]*



Figure 1.7. *The MILAX project airplane experiment showing the model airplane and the phased array used in Japan in 1992*



Figure 1.8. *Ground-to-ground MPT experiment in Japan in 1994–1995*

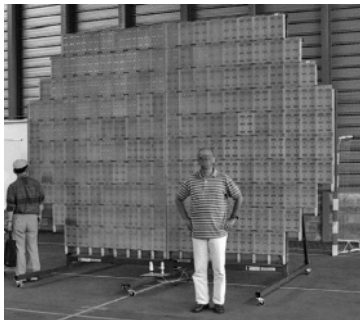


Figure 1.9. *Grand bassin, Réunion, France and their prototype rectenna [CEL 04]*

1.3. Inductive coupling WPT projects in the 20th Century

Maxwell integrated Ampere's law and Faraday's law into his equations. Prior to Maxwell's equations, it was known from Ampere's Law and Faraday's Law that a current creates a magnetic field and a changing magnetic field recreates a current. Two conductors are referred to as mutual-inductively coupled or magnetically coupled when they are configured such that a change in the current flow through one conductor induces a voltage across the ends of the other via electromagnetic induction. The phenomenon is called inductive coupling and is applied for power generators and transformers. Contrary to WPT via radiowaves, lower frequencies in the kilohertz to megahertz range are typically used for inductive coupling WPT.

Parallel to Tesla's first WPT experiments, M. Hutin and M. Le-Blanc proposed an apparatus and method for powering an electrical vehicle (EV) inductively in 1894 using an approximately 3 kHz AC generator [HUT 94]. EVs were developed shortly after the development of the steam engine, approximately 100 years ago. However, the EV became less popular with development of the internal combustion engine. As a result, after Hutin and Le-Blanc, the EV inductive coupling WPT charger was forgotten like Tesla's dream of WPT.

Professor Don Otto of the University of Auckland in New Zealand proposed an inductively powered vehicle in 1972 using the power generated at 10 kHz, by a force commutated sinusoidal silicon controlled rectifier inverter [OTT 74]. He adopted two circular cross-section conductors of copper, one of which was placed on the road as a transmitter and the other was placed on the body of the EV at a position 20 cm above the road surface. In 1978, the USA group of J.G. Bolger, F.A. Kirsten and S. Ng carried out the first EV-WPT application in the United States. They used a 180 Hz and 20 kW WPT system whose size was 60 cm × 1.52 m and its

air gap was 2.5 cm (Figure 1.10). In the 1980s, another WPT project was conducted in California, USA. It was called the Partner for Advanced Transit and Highways (PATH) project (Figure 1.11) [BOL 78, ZEL 82]. The work achieved a 60% efficiency powering a bus using machine-generated electric power at 400 Hz coupled across an air gap to drive the bus at a distance of 50–100 m [SYS 94]. Researchers in France and Germany conducted EV-WPT projects in the 1980s–1990s known as TULIP (*Transport Urban, Individuel et Public – Public and Individual Urban Transport*) and Inductive Power Transfer (IPT), respectively.

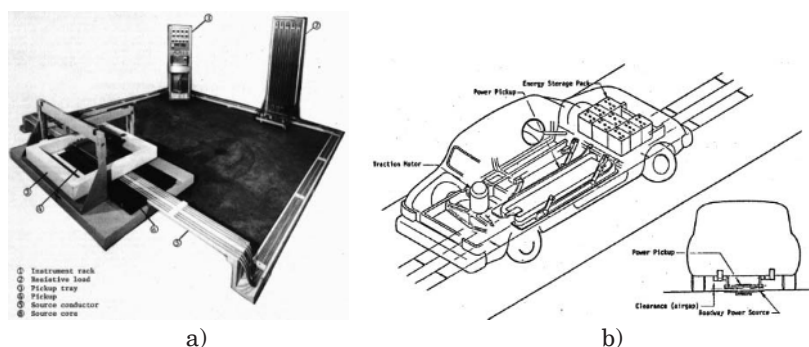


Figure 1.10. a) *Experimental setup of the first U.S. EV-WPT experiment; b) image of the experiment*

Inductive coupling is not only used for EV-WPT research projects but also for commercial, non-attached power supply of an electric kettle, an electric shaver, an electric toothbrush, etc. The integrated circuit (IC) card is one of the most famous applications of inductive coupling. In 1995, Sony proposed and developed the Felica system in Japan that used the IC card and adopted an inductive coupling wireless power supply with a 13.56 MHz signal. These inductive coupling WPT applications are used globally. However, there has yet to be any global standard developed for WPT technology and WPT systems vary considerably.



Figure 1.11. *Experimental setup of the PATH project in the U.S. in the 1980s*

1.4. WPT as a game-changing technology in the 21st Century

The other recent trend in WPT began with the use of resonant coupling in the United States by the Massachusetts Institute of Technology (MIT) [KUR 07] in 2006. The resonant coupler is well known as a microwave band-pass filter (BPF). The team at MIT applied the BPF to wireless power transfer. With this technique, a large amount of power (from watts to kilowatts) can be transmitted without radiation over mid-length distances (more than a few meters) at low frequencies (less than 10 MHz) using simple resonant circuits. It became evident that resonant coupling WPT is more suitable for commercial needs. Resonant coupling is based on the inductive coupling of magnetic fields. As shown in section 1.3, various research projects and

products using inductive coupling WPT technology have been pursued prior to MIT's revolution. This research and resulting products have supported both theory and development of resonant coupling WPT technology.

The Wireless Power Consortium (WPC) was established in December 2008 to develop wireless charging of mobile phones. They established the "Qi" standard for inductive coupling WPT in December 2010. Although there were some wireless charger developments for mobile phones with inductive coupling WPT, the work did not bear any commercially successful products. The "Qi" standard spread quickly in the world and wireless chargers using this standard have been able to be purchased of late. In addition to the WPC, various alliances, consortiums and forums for establishing a WPT standard and for promoting commercial applications have arisen as follows:

- WPC that established the "Qi" standard for inductive coupling WPT (established in December 2008, 166 member companies) [WPC 13].

- Alliance for Wireless Power (A4WP) to promote resonant coupling WPT (established in May 2012, 60 member companies) [A4W 13].

- Power Matters Alliance (PMA) to promote inductive coupling WPT, which is supported by IEEE-SA (established in March 2012, 95 member companies) [PMA 13].

- Broadband Wireless Forum (BWF) in Japan (established in July 2009, 55 member companies) [BWF 13].

- Wireless Power Consortium for Practical Applications (WiPoT) in Japan for MPT and other WPT technologies (established in April 2013, 28 member companies, 30 universities) [WIP 13].

- Wireless Power Management Consortium (WPMc) in Japan for direct current resonant coupling (established in July 2013, 21 member companies) [WPM 13].

– Energy Harvesting Consortium (EHC) in Japan for energy harvesting, which includes power generation from vibration, heat, light and radiowaves (established in May 2010, 60 member companies) [EHC 13].

– Korean Wireless Power Forum (KWPF) (established in 2011) [KWP 13].

(Data as of September 2013)

The initial targets of the above forums and alliances are wireless charging of mobile phones and/or in-house applications of WPT. These groups aim to establish a global standard for commercial WPT and to expand commercial WPT applications in the world.

Resonant coupling WPT not only represents a coil system in a magnetic field but also an electrostatic induction coupling system with coupled conductors. In Japan, a wireless charger using resonant electrostatic induction coupling WPT technology has been commercialized for tablet charging. Additional research in Japan has been directed toward resonant electrostatic induction coupling WPT, which will be applied to free positioning electrical points [HAR 11]. This application uses 600 kHz, 1.2 MHz and 2.0 MHz signals selectively and has succeeded in 150 W of wireless power transfer with over 95% efficiency.

Many other high-power WPT activities exist. As an example, inductive coupling WPT has been applied to wireless charging of an electric bus by Hino Motors Ltd. [HIN 13] and Showa Aircraft Industry [SHO 13] in Japan. This so-called “inductive power transfer” was demonstrated and an inductive power transfer hybrid system was operated from April 13 to 27, 2009 (Figure 1.12).

There have been some studies on the application of resonant coupling WPT for electric vehicles [IMU 09, IMU 10]. Toyohashi University of Technology in Japan

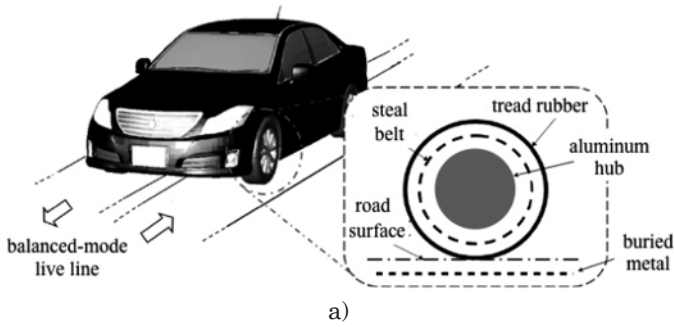


Figure 1.13. a) Diagram of the power transfer system proposed by Toyohashi University of Technology, Japan [HAN 11]; b) experimental setup

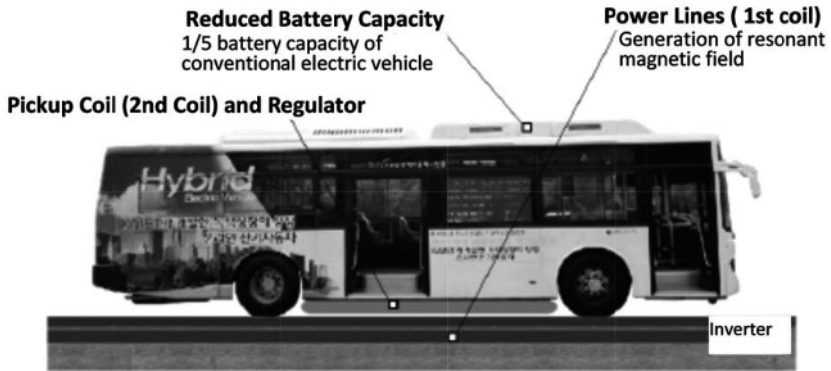


Figure 1.14. Wireless power supply for an online electric vehicle (OLEV) in Korea [AHN 11]

In the early 21st Century, G. Covic's group in New Zealand continued to develop EV-WPT systems with inductive coupling. The group conducted research on a system composed of a multiphase track with multicoil receivers in 2003–2005, and IPT road pads with multicoil receivers in 2009–2010 [COV 12]. The German company Bombardier developed 250 kW WPT railways until 2012 [MEI 12]. Bombardier, BS-Verkehrs-AG, BS-energy and TU-Braunschweig began an EV-WPT project called Elecrobis in Branschweig in May 2012 [MEI 12]. It is a field EV-WPT experiment in downtown Branschweig.

In addition to these EV-WPT research activities, some companies, for example Evatran Co., Audi Co., SEW-EURODRIVE Co. and UniServices Co., introduced inductive coupling wireless power transmission systems for EV applications as commercial products. HaloIPT/Qualcomm Co. adopted resonant coupling WPT and began field experiments in London in 2012. Evatran Co. introduced a plugless level 2 EV Charging System using inductive coupling technology as a commercial product in 2013 [PLU 13]. To date, various WPT systems for robots and vehicles based on inductive coupling WPT technology have been installed in factories all over the world.

Contrary to inductive coupling and resonance coupling WPT, MPT applications seem to have been delayed because of radiowave regulation problems. Inductive coupling and resonance coupling produce less radiation as compared to MPT systems. However, MPT research groups have proposed advanced MPT systems as being acceptable for commercial use.

One such advanced MPT system is the phased array system. The phased array, with which a highly directional power beam can be formed and controlled, is an important aspect in the development of a practical MPT system. The phased array is typically used for radar or remote sensing. For example, a phased array in the S-band, which was

composed of 4,000 phased shifters/array and 936,000 manufactured elements, is used in the AEGIS radar system [BRO 06]. A Japanese group, whose members come from the National Institute of Polar Research, the University of Tokyo, Kyoto University, many universities, national institutes and companies, is building a mesosphere/stratosphere/troposphere (MST) radar/incoherent scatter (IS) radar in the Antarctic to measure atmospheric phenomena. This project is called the Program of the Antarctic Syowa MST/IS radar (PANSY). This project uses approximately 1,000 antenna elements. The center frequency is 50 MHz and the diameter is approximately 160 m.

In the early 21st Century, in Japan, some trials as part of the development of high-efficiency phased arrays were carried out mainly for SPS applications. The Japanese SPS committee conducts development of the phased array. In FY2000, the SPS committee of the JAXA conducted a phased array experiment using solar cells for SPS called the solar power radio integrated transmitter (SPRITZ), which was developed mainly by Mitsubishi Heavy Industry (Figure 1.15) [MAT 02a]. Transmission was facilitated at a frequency of 5.77 GHz and the total number of elements was 100.

The other phased array field experiment was carried out by a team from Kobe University, Japan and John Mankins from Hawaii, USA in 2008. This group transmitted approximately 20 W of microwave power toward a target 150 km away using a phased array. Even though the microwave power in the experiment was not received, the transfer scheme has formed the basis of follow-up work.

A recent MPT project by Kyoto University's group in 2009 involved a field MPT experiment from an airship to the ground using two phased-controlled magnetrons (Figure 1.16) [MIT 10]. The experiment aimed to demonstrate an emergency wireless power source via MPT. The first phase-controlled magnetron was developed by Brown in the 1960s

[BRO 88]. The Kyoto University group revised the phase-controlled magnetron in the 1990s [SHI 00] and applied it to the airship experiment. Two magnetrons placed onboard the airship over 50 m above ground level were used as 2.45 GHz transmitters, and a mobile phone was charged with the wireless power.

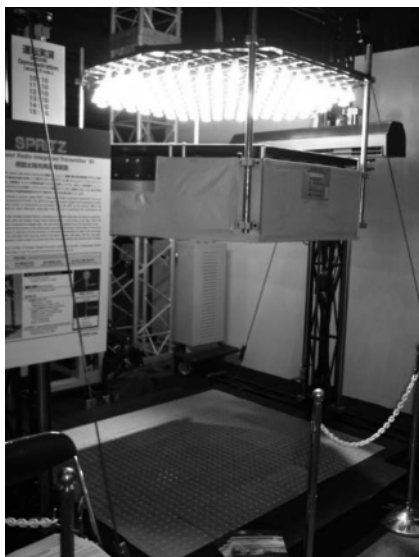
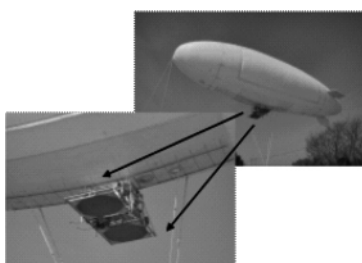
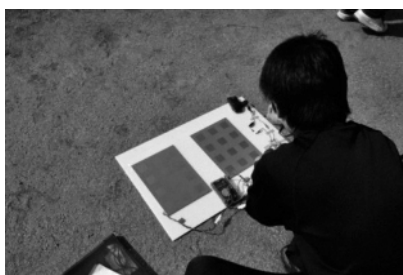


Figure 1.15. SPS demonstrator “SPRITZ” with 5.8 GHz transmission (demonstration in IAC2005)



a)



b)

Figure 1.16. a) Emergency MPT experiment in Japan and b) wireless charging of a mobile phone on the ground [MIT 10]

In addition to these MPT research projects, various kinds of MPT applications have been proposed, developed and commercialized worldwide. Details are described in Chapter 4.

The history of WPT is summarized in Figure 1.17. But there is little difference between the history of WPT and that of wireless communications. In fact, the history of WPT is largely based on the history of wireless communications.

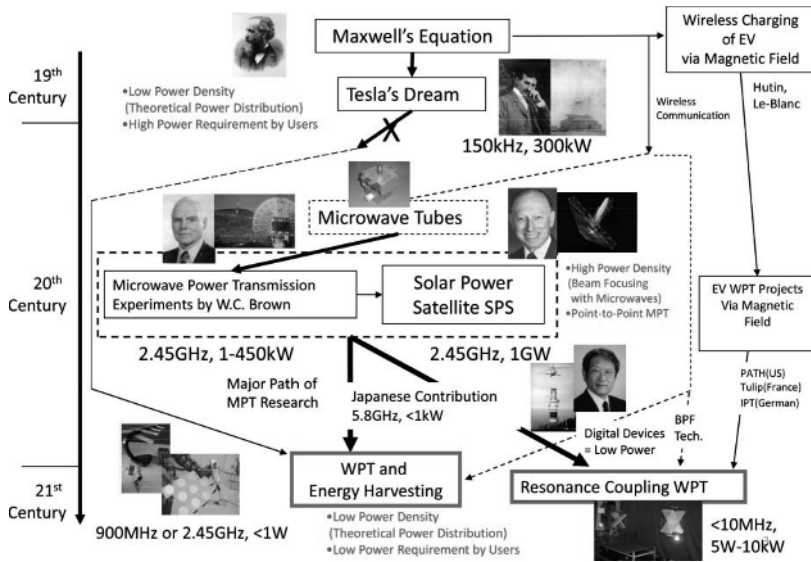


Figure 1.17. Historical summary of WPT