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Radiocommunication Sector of ITU

Report ITU-R SM.2392-0

(08/2016)

Applications of wireless power transmission via radio frequency beam

SM Series

Spectrum management

International Telecommunication Union

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R SM.2392-0

Applications of wireless power transmission via radio frequency beam

(2016)

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1 Introduction

Wireless power transmission (or transfer) (WPT) technology is considered as one of game changing technologies. We will be able to become free from lacking electric power when electric power will be supplied wirelessly. Power transmission by radio waves dates back to the early work of Nikola Tesla in 1899. Tesla carried out his first attempt to transmit power without wires in 1899. He used low frequency power of 150 kHz, but his attempts failed. 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 during the period of time shortly after the steam engine, approximately one hundred years ago. Both inductive WPT which is called 'non-beam type' and the WPT via radio frequency beam which is called 'beam type' were started in the early 20th century.

The present development of the WPT via radio frequency beam owes to William Brown in 1960s using microwave technology developed during the World War II. He transmitted the microwave power from a transmitter to a receiver (point-to-point) with the overall (DC-microwave-DC) efficiency of 54% in his laboratory [BRO73]. When we use the microwave frequency, the WPT via microwave is called a microwave power transmission (MPT). A lot of the inductive WPT research projects for a wireless charging of EVs were carried out in 1980s and 1990s [SHI 14]. Commercial products of contactless cables are produced after 1900s. A turning point of the inductive WPT was in 2006, when Massachusetts Institute of Technology (MIT) demonstrated non-beam wireless power technology called resonance coupling WPT [KUR 07]. Nowadays, resonant WPT technologies are coming out to consumer market. Automotive industry looks at WPT for EV applications in near future. Information about WPT using technologies other than radio frequency beam, as partial answers to the Question ITU-R 210-3/1 was published as Report ITU-R SM.2303 in 2014. After the MIT's demonstration, a variety of WPT technologies including magnetic induction, resonance coupling, transmission via radio frequency beam, etc. are paid attention as game changing technologies.

This Report provides introductory information mainly about WPT using radio frequency beam. It also covers wider genre of power transmission by radio waves, which can include non-beam applications like energy harvesting but does not include magnetic induction, magnetic resonance, nor capacitive coupling technology, which are treated in the Report ITU-R SM.2303.

Further studies for the impact between such WPT systems and existing other systems, and safety aspects such as human exposure to electromagnetic fields are necessary in order to realize these applications.

[BRO 73] Brown, W.C., "Adapting Microwave Techniques to Help Solve Future Energy Problems", 1973 G- MTT International Microwave Symposium Digest of Technical Papers 73.1, pp. 189-191, 1973.

[HUT 94] Hutin, M. and M. Le-Blanc, "Transformer System for Electric Railways", US Patent Number 527,875, 1894.

[KUR 07] Kurs, A., A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances", Science, Vol. 317, pp. 83-86, 2007.

[SHI 14] Shinohara, N., "Wireless Power Transfer via Radiowaves (Wave Series)", ISTE Ltd. and John Wiley & Sons, Inc., Great Britain and United States, 2014.1

2 Applications developed for use of WPT technologies via radio frequency beam

Major characteristics of the WPT via radio frequency beam are: 1) long distance WPT, 2) no electromagnetic coupling between a transmitting antenna and a receiving antenna, which is different from an inductively coupled WPT and a resonance coupling WPT, and 3) various applications, e.g. weak powered sensors, high power wireless chargers, huge power transfer from power station, etc.

2.1 Wireless powered sensor network (App ID[1]: a1)

Recommendation ITU-T Y.2221 [ITU10] defines sensor network as: A network comprised of interconnected sensor nodes exchanging sensed data by wired or wireless communication. Wireless sensor networks (WSNs) are one of the most rapidly developing information technologies and promise to have a variety of applications in next generation networks (NGNs) based on ITU-T Technical Paper Y.2000 [ITU14]. Energy efficiency is quite important. This paper states as follows:

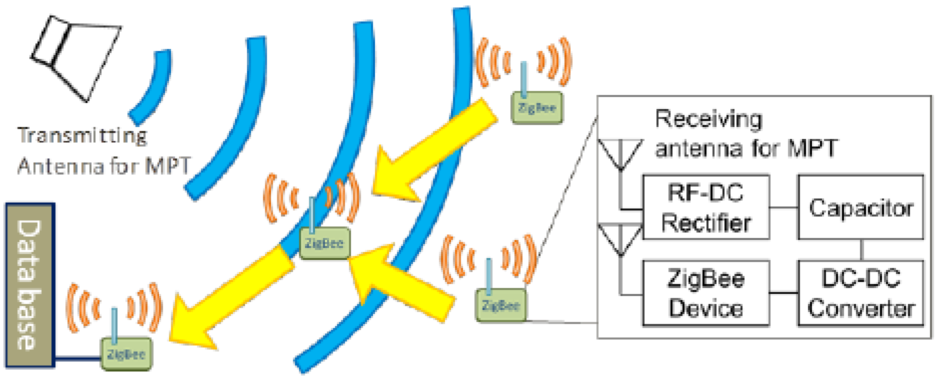
> "The WSN parts may be spatially distributed on the area of many kilometres, especially if a WSN user is managing it via the Internet. At the same time, sensor nodes can be located in the inaccessible places, or the concrete location of each sensor node can be unknown. Also, a WSN may consist of dozens, hundreds or even thousands of sensor nodes. Under these conditions charging of sensor nodes by the user is out of question. That is why a sensor node must have high energy efficiency in order to keep working on small and inexpensive battery for a few months and even years. This ultra-low-power operation can only be achieved by using low-power hardware components."

2.1.1 Situation of Japan

Microwave power can drive a wireless sensor without a battery. Wireless power can be actively transmitted to sensors requiring electricity (Fig. 2.1.1). This system could solve the above problem. A rectenna, which consist of an antenna and rectifying circuit with diodes, receives and rectifies a radio wave to direct current (DC). Radio frequency (RF) – DC conversion efficiency is theoretically 100%, and reaches approximately 90% at 2.45 GHz for a developed rectenna.

FIGURE 2.1.1

Image of wireless powered sensors (ZigBee) [ICH12]



The ZigBee/IEEE802.15.4 sensor represents a potential wirelessly powered sensor. The ZigBee network is configured as a coordinator, router, and an end device. The coordinator is just one device in the network and coordinates the network. The router has the function of relaying data from other

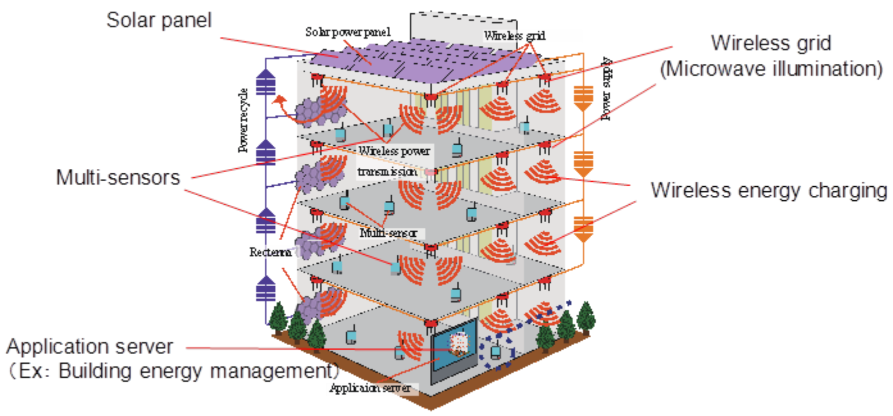
1 "App ID" means application ID and refers to different applications of WPT Beam technology and these applications are summarized in Table 3.1

routers and end devices as well as sensing information. The end device sends data only; otherwise it sleeps. Therefore, power consumption of the end device is lower than the other devices. The router and end device send a total of nearly 2 ms of data every 1.14 s. The coordinator drops either device from its network if it does not receive data from either for 15 s. The out of network device must perform the necessary routines to rejoin the network. When the end device and the router rejoin the network and communicate with each other, they expend 9.46 mW and 57.4 mW, respectively, to do so. When they do not join the network and sleep, they expend 61.8 mW and 57.1 mW, respectively [ICH12]. The electricity consumption is one example that indicates we can drive the ZigBee sensor strictly with microwave power.

Another Japanese proposed wireless powered sensor network is called wireless grid or microwave illumination whose concept is shown in Fig. 2.1.2 [SAK 10] [MAE 13]. The system provides wireless power and wireless information of active RF-ID in the 920 MHz band. The system uses 4 channels (1 W) without carrier sensing for passive RFID for wireless power. 77 channels (1 mW) for active RFID are used for the sensor network. Instantaneous received power should be larger than the power consumed by the sensor. The average consumed power is controlled by changing the duty cycle. A multi-power transmitter is used in the room and a carrier shift diversity is proposed in which multi frequencies are used to reduce standing waves in a closed room. The carrier shift diversity effectively reduced standing waves and created an approximately uniform power density in the room.

FIGURE 2.1.2

Concept of the wireless grid (microwave illumination) [SAK 10]



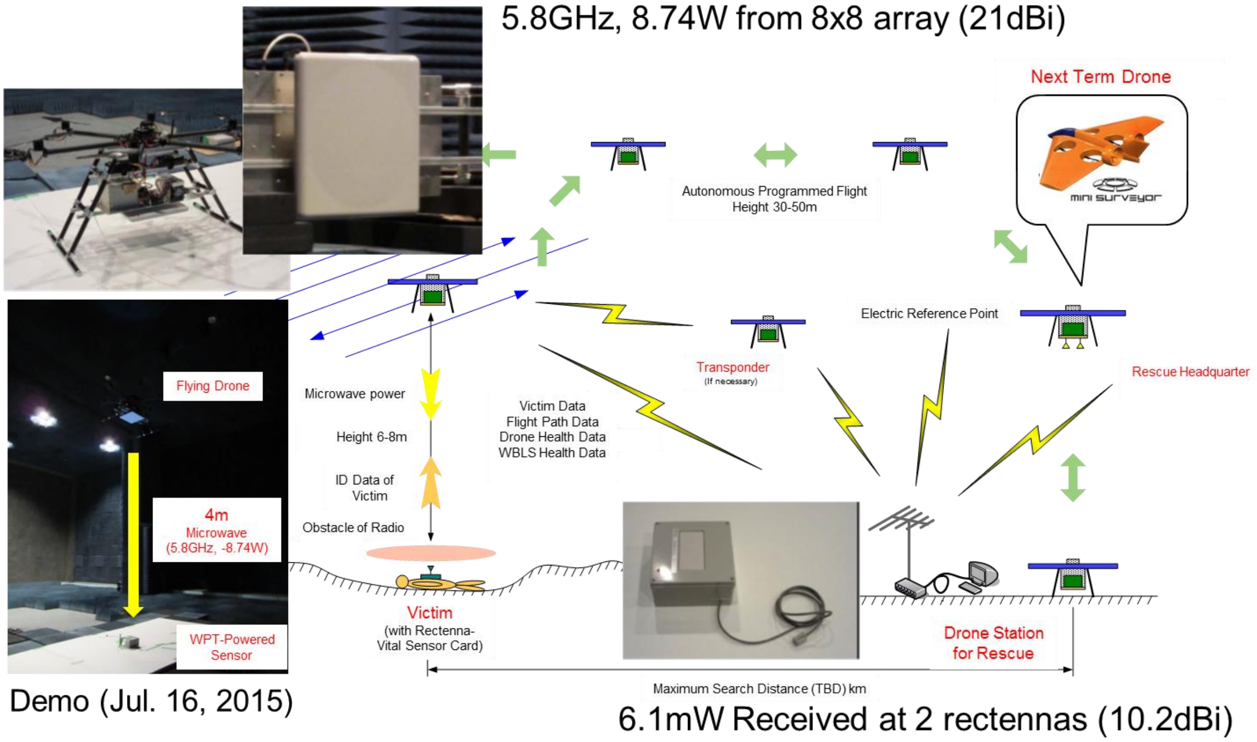
Japanese company provides a commercial wireless sensor using WPT in the 920 MHz band [DEN 13]. The distance of application is less than 5 m. The RF-DC conversion efficiency is approximately 60%. The company proposes applications of the wireless sensor for sensing in high temperature environments (85-120°C), sensing on a rotating or moving object, and sensing in severe environments; for example, in outdoor or marine environments, etc. They have developed a high efficiency rectenna whose RF-DC conversion efficiency is approximately 91.6% at 8W, 2.45 GHz and 7 W [FUR 13].

A wireless sensor application by using a flying drone is proposed in Japan in 2015. One of weak point of the WPT is a miss match between a required power and system size of the WPT which includes an antenna size and a transmitting radio wave power. When a distance between a transmitting antenna and a receiving antenna of the WPT becomes longer, beam efficiency becomes lower than a user expectation. Even for the WPT sensor, it sometimes happens. By using the flying drone, the distance between a transmitting antenna and a receiving antenna of the WPT becomes shorter and WPT system can be smaller than that without the drone. The proposed WPT system is named a ‘Multicopter Assisted Wireless Batteryless Sensing System (WBLS)”. The first experiment was carried out on July, 2015 at Kyoto University by WiPoT, Kyoto Univ., Mini-Surveyor Consortium, and

Autonomous Control Systems Laboratory Ltd. 5.8 GHz, 8.74W microwave power was transmitted from 8 × 8 array antenna (21 dBi) on a flying drone (multicopter) as shown in Fig. 2.1.3. Received and rectified 6.1 mW DC power drives a sensor. Hopeful applications of the Multicopter Assisted WBLS are rescue of victims, WPT-powered sensors at volcano, and inspection of infrastructures (bridges, tunnels), etc.

FIGURE 2.1.3

Concept of Multicopter Assisted WBLS and its demonstration on July, 2015 in Japan



[ICH 12] Ichihara, T., T. Mitani, and N. Shinohara, "Study on Intermittent Microwave Power Transmission to a ZigBee Device", Proc. of 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS-IWPT2012), pp. 209-212, 2012.

[ITU 10] "Requirements for support of ubiquitous sensor network (USN) applications and services in the NGN environment." Recommendation ITU-T Y.2221 (2010).

[ITU 14] "Applications of Wireless Sensor Networks in Next Generation Networks," ITU-T Technical Paper Y.2000 (2014).

[DEN 13] DENGYO Corporation http://www.den-gyo.com/solution/solution10_b.html (in Japanese).

[FUR 13] Furukawa, M., T. Minegishi, T. Ogawa, Y. Sato, P. Wang, H. Tonomura, M. Teramoto, and N. Shinohara, "Wireless Power Transmission to 10kW Output 2.4 GHz-band Rectenna Array for Electric Trucks Application (in Japanese)", IEICE Technical Report, WPT2012-7, pp. 36-39, 2013.

[MAE 13] Maehara, D., R. Akai, G.K. Tran, K. Sakaguchi, S. Sampei, K. Araki, and H. Iwai, "Experiment on Battery-less Sensor Activation via Multi-point Wireless Energy Transmission", Proc. of 2013 IEEE 24th Annual Int. Sympo. On Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 2346-2350, 2013.

[SAK 10] Sakaguchi, K., R.P. Wicaksono, K. Mizutani, and T. Khanh, "Wireless Grid to Realize Ubiquitous Networks with Wireless Energy Supply (in Japanese)", IEICE Tech. Report, Vol. 109, No. 442.

2.2 Wireless charger of mobile devices (App ID: a2)

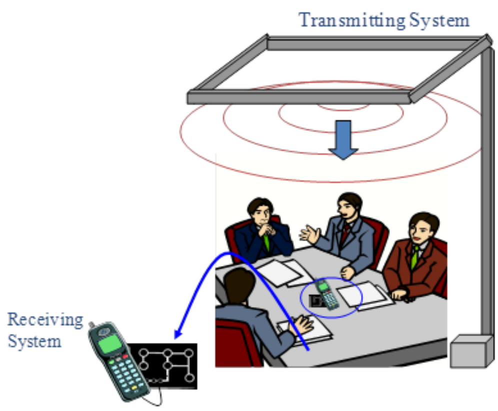
2.2.1 Situation of Japan

Sensors are suitable devices to take advantage of WPT via radio waves because they are very low power devices. However, various kinds of mobile devices exist that operate using battery storage and WPT should be applied for wireless power feeding or wireless charging of these various mobile devices. For this purpose, a concept termed ubiquitous power source (UPS) was proposed near the end of 1990s [SHI 04] [SHI 05] and is based on the concept that microwaves are everywhere at all times (ubiquitous) and are always available for WPT.

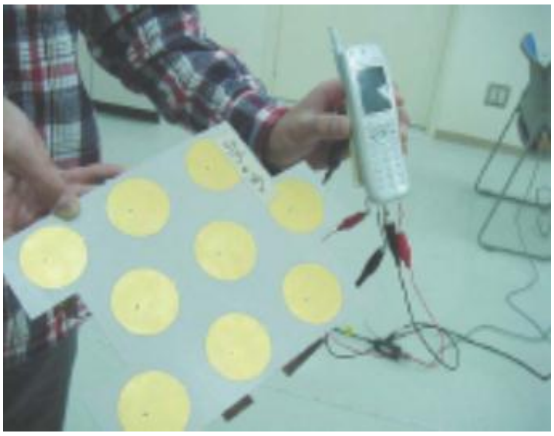
The concept of UPS is shown in Fig. 2.2.1(a). Microwave power at 2.45 GHz (industrial, scientific, and medical (ISM) band frequencies reside in the 2.40-2.50 GHz range) is transmitted from the edges of a ceiling to charge mobile phones. It is quite possible to create a uniform microwave power density in a UPS room with antennas installed at the ceiling edges. Slot antennas are selected as the transmitting antennas because of their reduced cost. For the same reason, a frequency stabilized and phase controllable magnetron is used. However, because the UPS concept is based on a “wireless power source all the time and everywhere,” the design of UPS is limited by safety issues associated with prolonged exposure to microwaves by human beings. The safety level set is under 1 mW/cm^2 for continuous exposure over the entire human body. For an experimental room of 5.8 × 4.3 m, approximately 150 W of microwave power was transmitted from a magnetron to create a uniform microwave power density of 1 mW/cm^2 or less. High-efficiency rectennas are also necessary for operation at a microwave power density of 1 mW/cm^2 or less. Under these conditions, an experiment was successful at charging mobile phones, as shown in Fig. 2.2.1(b). Furthermore, a mobile phone can still be used in the UPS room because of the difference between the 2.45 GHz microwave power and the 1.9 GHz communication system frequencies.

FIGURE 2.2.1

(a) The ‘Ubiquitous Power Source’ Concept



(b) Wireless mobile phone charging experiment using a UPS [SHI 04]

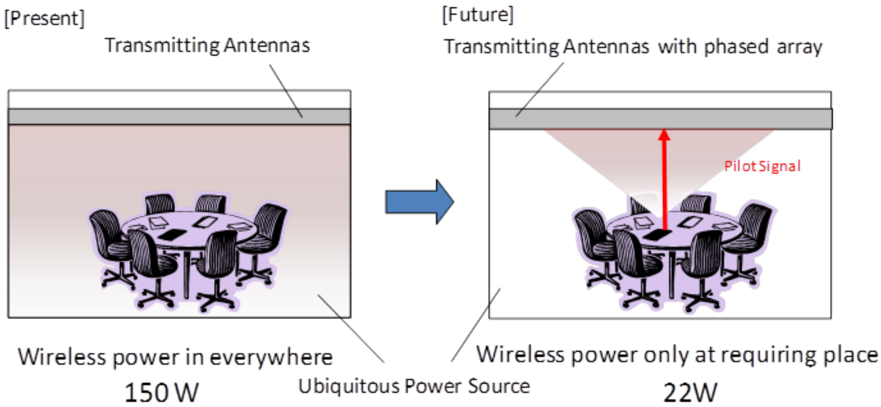


As an extension of UPS systems, a phased array should be used to reduce the total transmitting power and to reduce unexpected radiation at positions where power is not needed (Fig. 2.2.2). For directional UPS in a room size equivalent to the UPS experiment described above, only 22 W of microwave power (versus 150 W for the conventional UPS system) is required if the power density around a device is to be 1 mW/cm^2. The phase array is still expensive for commercial WPT and UPS. The cost of the array depends on component costs, especially the phase shifter.

Therefore, systems without phase shifters are proposed to reduce the total microwave power necessary for UPS while lowering the cost [HAS 11].

FIGURE 2.2.2

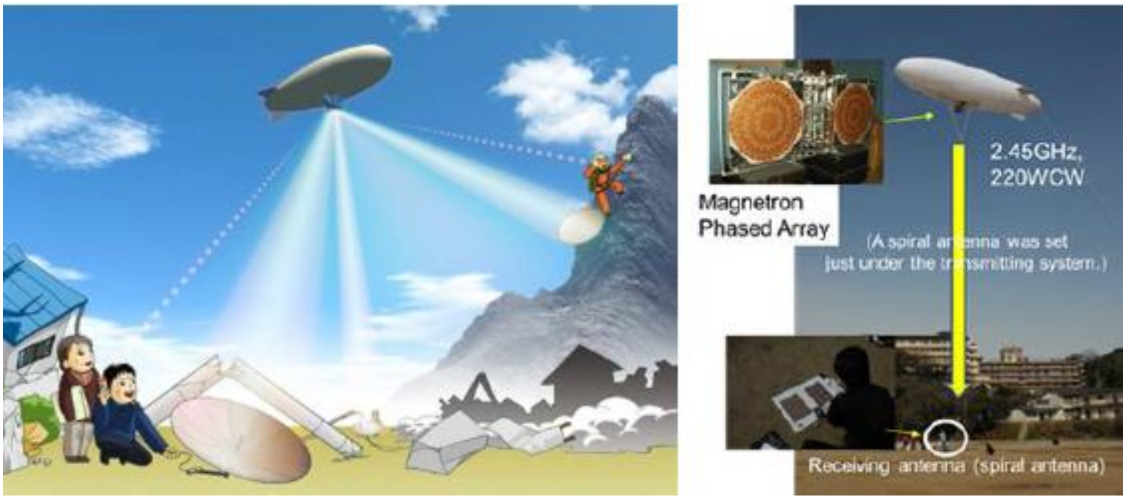
Present UPS vs future UPS using a phased array



Emergency UPS was proposed and an experiment was carried out in 2009 in Japan [MIT 10], as was discussed in Section 2.4. An image if the experimental system is shown in Fig. 2.2.3. Worldwide, there are some research projects involving emergency base stations for mobile phones by balloon or by airship. However, even if a base station for mobile phones is established for emergencies, a mobile phone cannot be used without electricity. So an emergency UPS system is proposed for rapid and periodic recovery of electricity by wireless power. In the experiment from 2009, a mobile phone was charged using only wireless power from an airship.

FIGURE 2.2.3

Image of an emergency UPS system and photo of experiment (2009)



2.2.2 Situation of U.S.

At the TechCrunch disrupt 2013 technology conference, a U.S. based company proposed a commercial wireless charger of a mobile phone using MPT whose frequency is the same frequency as that of WiFi [AOL 13]. It is called ‘Cota’ and can wirelessly deliver 1 W of power at a distance of 30 ft. In the conference, they showed an iPhone 5 being remotely charged from a prototype WPT system. The company claimed that the commercialized version of Cota is ready to ship in 2013-14 and a consumer version will be ready to ship before 2015. The other U.S. company starts to produce a wireless charger of a mobile phone called ‘Wattup’ in 2015. They use two frequencies; 2.4 GHz (unlicensed) for Bluetooth low energy communication and 5.7-5.8 GHz (Unlicensed Industrial, Scientific & Medical, ISM) band for power transfer.

[AOL 13] Aol Tech. http://techcrunch.com/2013/09/09/cota-by-ossia-wireless-power/.

[HAS 11] Hashimoto, K., T. Ishikawa, T. Mitani, and N. Shinohara, "Improvement of a ubiquitous power source", *Proc. of International Union of Radio Science (URSI) General Assembly 2011*, CD-ROM CHGBDJK-1.pdf, 2011.

[MIT 10] Mitani, T., H. Yamakawa, N. Shinohara, K. Hashimoto, S. Kawasaki, F. Takahashi, H. Yonekura, T. Hirano, T. Fujiwara, K. Nagano, H. Ueda, and M. Ando, "Demonstration Experiment of Microwave Power and Information Transmission from an Airship", *Proc. of 2nd International Symposium on Radio System and Space Plasma 2010*, pp. 157-160, 2010.

[SHI 04] Shinohara, N., H. Matsumoto, T. Mitani, H. Shibata, T. Adachi, K. Okada, K. Tomita, and K. Shinoda, "Experimental Study on "Wireless power Space" (*in Japanese*), *IEICE Tech. Report*, SPS2003-18, pp. 47-53, 2004.

[SHI 05] Shinohara, N., T. Mitani, and H. Matsumoto, "Study on Ubiquitous Power Source with Microwave Power Transmission", *Proc. of International Union of Radio Science (URSI) General Assembly 2005*, CD-ROM C07.5(01145).pdf, 2005.

2.3 Wireless power transfer sheet (App ID: b1)

2.3.1 Situation of Japan

A MPT operating through closed waveguides is a good potential application under present radio wave regulations. Another MPT operating through closed waveguides was proposed and developed in Japan. It is called the "two-dimensional waveguide power transmission (2DWPT) system or surface WPT system" [SHD 07]. In 2DWPT systems, the microwave propagates along a waveguide sheet and is selectively received by special receiving devices on the sheet (Fig. 2.3.1). The 2DWPT system also has an inevitable trade-off between the safety and power transmission capacity. Figures 2.3.2(a) and (b) illustrate an improved waveguide surface which has been demonstrated to enhance electro-magnetic compatibility (EMC) performance [NOD 11] [NOD 12]. The microwave is received at a waveguide-ring resonator (WRR) coupler which extracts the power from the waveguide across a thick insulator (Fig. 2.3.2(c)). Extraneous objects near or even touching the sheet are not exposed to the strong electromagnetic fields. The WRR coupler has a significantly high quality factor (high-Q) in the resonant state, which is essential to support the selective power transmission. The WRR is connected to a rectifying circuit which is driven in class F. The total efficiency, defined as the ratio of the DC output of the rectifying coupler to the microwave input into the sheet, was 40.4% at maximum where the microwave input was 1 W in the 2.4 GHz band with a 6.4 × 3.6 cm^2 coupler on a 56 × 39 cm^2 sheet (nearly 100 times the area of the coupler) [NOD 12].

FIGURE 2.3.1

Photographs of the 2DWPT system

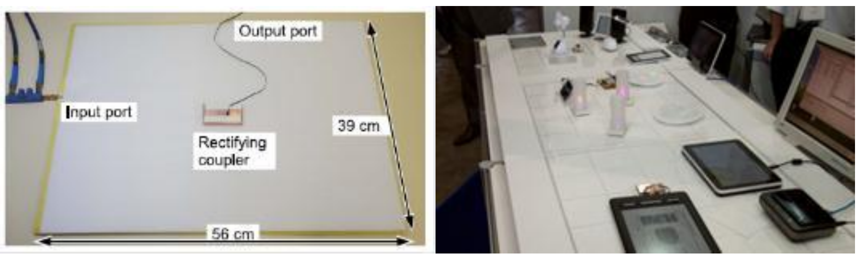


FIGURE 2.3.2

Wireless power transfer sheet

(a) Upper view of the waveguide sheet around its edge **(b) Schematic drawing of its cross section** **(c) Receiver of wireless power [NOD 11] [NOD 12]**

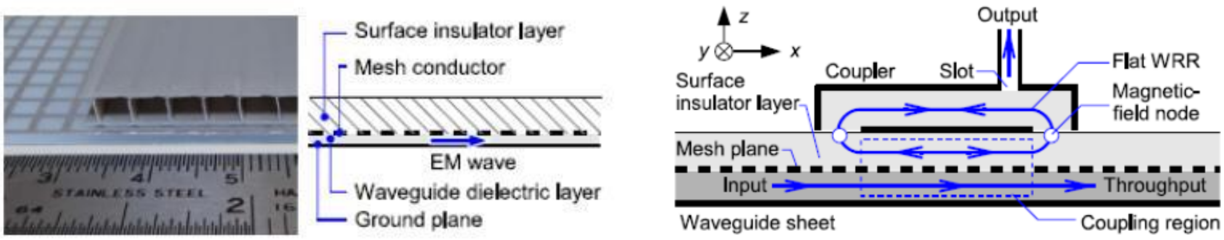
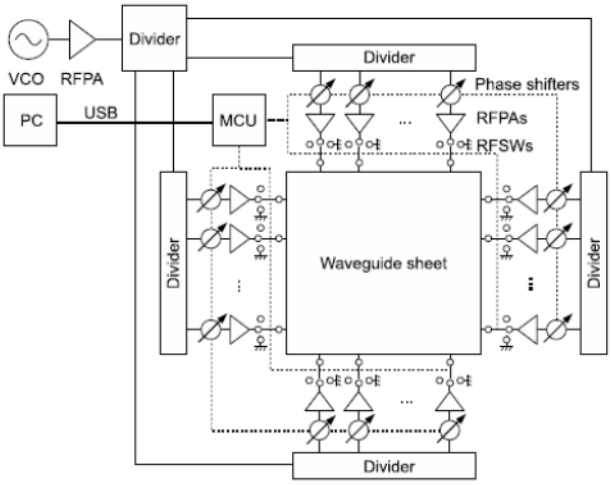


FIGURE 2.3.3

Block diagram of the microwave power supply system using a phased array which has seven RF amplifiers along each edge [NOD 13]



Microwaves are used in the 2DWPT system and the microwave diffuses in accordance with Maxwell's equations even if the dimension decreases from 3D to 2D. To suppress unexpected radiation, a phased array can be applied to the 2DWPT system, which is equivalent to a 3DWPT system [NOD 13]. Figure 2.3.3 presents a proposed experimental 2DWPT system using a phased array at the University of Tokyo. Results of the experiment indicated that the variation of the efficiency at a receiving point on the sheet using the phased array is suppressed within 2 dB, wherein the variation was more than 10 dB without the phased array system.

The 2DWPT system has been standardized in ARIB (Association of Radio Industries and Business) as ARIB STD-T113[ARI15]. Frequency is 2.498GHz±1MHz and its power is below 30W.

[ARI15] ARIB STD-T113 http://www.arib.or.jp/english/html/overview/doc/1-STD-T113v1_0.pdf (in Japanese).

[NOD 11] Noda, A., and H. Shinoda, "Selective wireless power transmission through high-Q flat waveguide-ring resonator on 2-D waveguide sheet," *IEEE Trans. MTT*, Vol. 59, No. 8, pp. 2158-2167, 2011.

[NOD 12] Noda, A., and H. Shinoda, "Waveguide-Ring Resonator Coupler with Class-F Rectifier for 2-D Waveguide Power Transmission", *Proc. of 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS-IWPT2012)*, pp. 259-262, 2012.

[NOD 13] Noda, A., and H. Shinoda, "A Phased Array Feeding System for 2-D Waveguide Power Transmission (*in Japanese*)", *Proc. of IEICE*, BSC-1-8, March 2013.

[SHD 07] Shinoda, H., Y. Makino, N. Yamahira, and H. Itai, "Surface sensor network using inductive signal transmission layer," *Proc. of Int. Conf. on Networked Sensing Systems (INSS) 2007*, pp. 201-206, 2007.

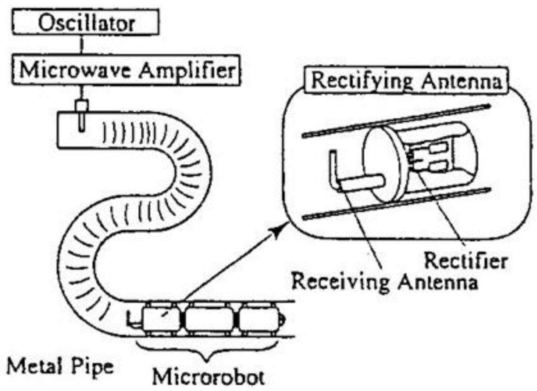
2.4 MPT in a pipe (App ID: b2)

2.4.1 Situation of Japan

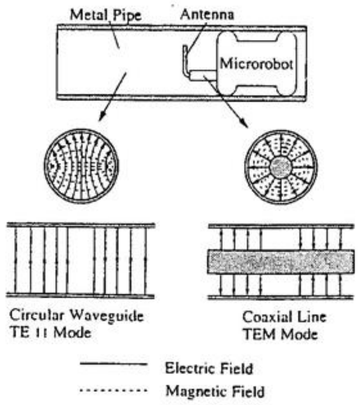
In the 1990s in Japan, a micro robot moving in a pipe and powered by MPT in a pipe was developed. The concept is shown in Fig. 2.4.1(a). The MPT in a pipe system was developed at 14 GHz microwaves, as shown in Fig. 4.4.1(b) [SHB 97], propagating down a 15 mm diameter circular pipe, as a circular waveguide, in the TE_{11} mode (Fig. 2.4.1(b)) with a transmission loss estimated to be < 1 dB/m. The rectenna which was composed of a monopole antenna and a rectifying circuit received the microwave power and fed the rectified DC power to the robot's inertial drive system composed of a piezoelectric bimorph cell to drive the microrobot. The microrobot received 50 mW of microwave power and was able to move at a rate of 1 mm/sec in the pipe when 1 W of microwave power was transmitted through the pipe.

FIGURE 2.4.1

(a) The concept of a robot in a pipe powered by MPT



(b) Conventional method of power conversion from a circular waveguide to a coaxial cable [SHB 97]



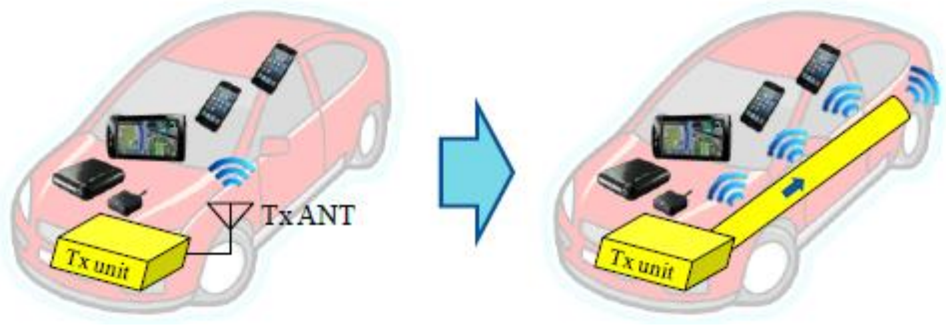
In the 1990s, an MPT system was proposed in Japan for powering an observation robot in a gas pipe [HIR 97] [HIR 99]. The diameter of the gas pipe was approximately 155 mm, which was suitable for propagation of microwaves operating at a frequency of 2.45 GHz. The problems associated with this particular MPT application were (1) an unknown propagation loss in rusty gas pipes, and (2) the complex branching of the gas pipe network. The propagation loss was estimated by experiments and theory and was on the order of −0.1 to −1.0 dB/m. It was concluded that the loss was sufficiently low to propagate microwave power in the gas pipe.

The complexity of the pipe branch network posed a bigger problem. Theoretically, radio waves cannot propagate to all branches of the waveguide, and some branches would not be serviced with radio waves. Experimental results supported the theory, which indicated that the proposed MPT in a pipe system had limited application.

A new radio wave hose for a WPT application is proposed and developed in 2015 in Japan [ISH15-1][ISH15-2]. The radio wave hose is plated and processed into a resin hose with a conductive coating. They constructed an experimental system for wireless power transmission using the radio wave hose and confirmed the possibility of wireless power transmission of a 100-mW class on a 5.8-GHz band. The radio wave hose will be applied for harnessless car as shown in Fig. 2.4.2.

FIGURE 2.4.2

Concept of a harnessless car with radio wave hose of the WPT in pipe [ISH15-1]



[HIR 97] Hirayama, K., N. Shinohara, K. Hashimoto, H. Matsumoto, T. Nakauchi, and Y. Yoshida, "Fundamental Study of Microwave Power Transmission to a Robot Moving in Gas Pipes (*in Japanese*)", *Proc. of IEICE Comm.,* p. 116, March 1997.

[HIR 99] Hirayama, K., N. Shinohara, H. Matsumoto, and I. Nagano, "Study of Microwave Power Transmission to a Robot Moving in Gas Pipes (*in Japanese*)", *Proc. of IEICE Comm.,* p. 25, March 1999.

[IHI15-1] Ishino, S., A. Kishimoto, Y. Takimoto, Y. Arai, Y. Huang, and N. Shinohara, "Study on WPT System Using a Radio Wave Hose as a New Transmission Line", *Proc. of 2015 IEEE Wireless Power Transfer Conference (WPTc2015),* P4.1, May 2015.

[ISH 15-2] Ishino, S., T. Miyagawa, and N. Shinohara, "A New Slotted Waveguide Using a Resin Hose with Metallic Coating", *Proc. of 2015 Asia-Pacific Microwave Conference (APMC)*, Dec. 2015.

[SHB 97] Shibata, T., Y. Aoki, M. Otsuka, T. Idogaki, and T. Hattori, "Microwave Energy Transmission System for Microrobot", *IEICE Trans. Electr.,* Vol.E80-C, No. 2, pp. 303-308, 1997.

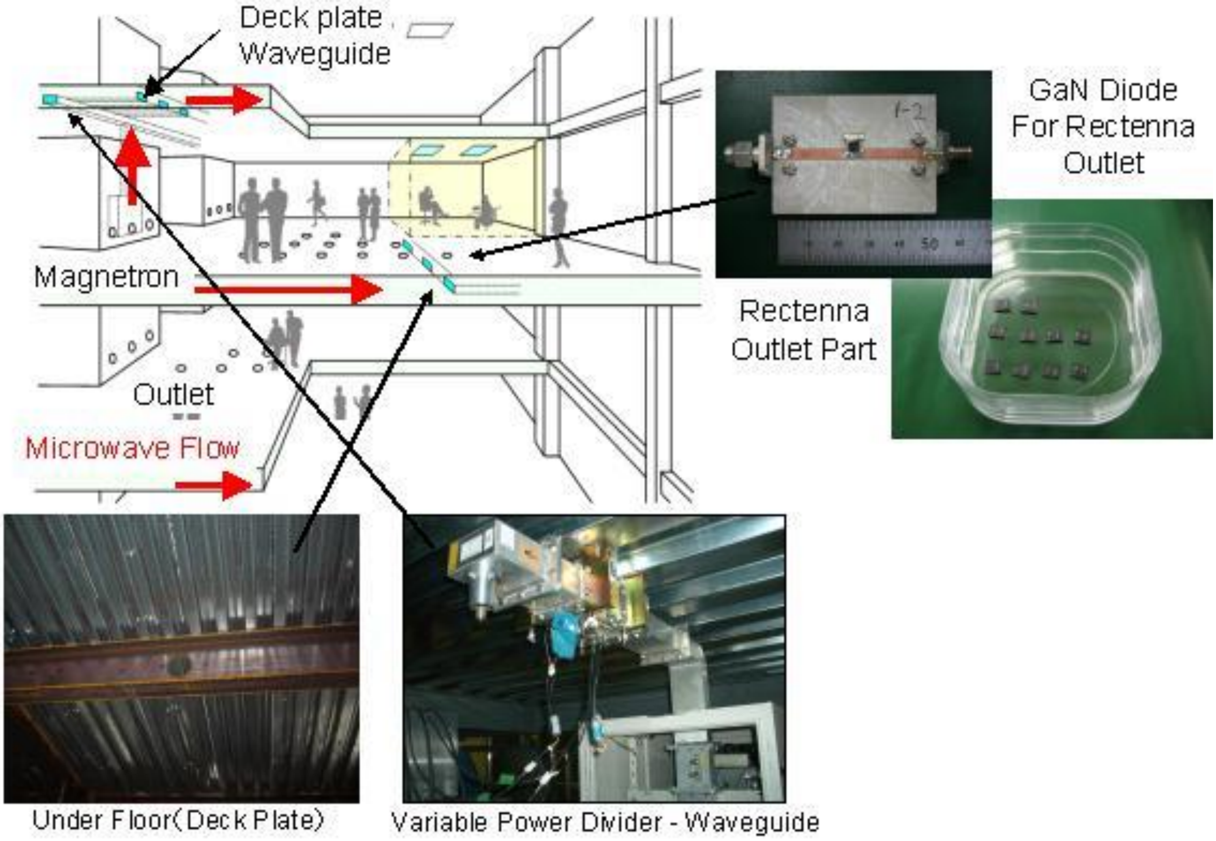
2.5 Microwave buildings (App ID: b3)

2.5.1 Situation of Japan

A Japanese building company jointly proposed with Kyoto University a wireless building using microwave power technology [SHI 14]. The proposed power system is shown in Fig. 2.5.1. This system wirelessly supplied electric power using a deck plate consisting of extra cover boards that acted as microwave transmission waveguides. A frequency of 2.45 GHz was selected on the basis of size limitations of the conventional deck plate and a magnetron was used as the microwave transmitter to reduce cost. The flow of microwave power could be controlled by variable power dividers that supplied microwave power only to users requiring it and blocked flow to places where there were no users. Rectennas as DC converters and as DC power sources were placed under the floor. Adjusting the position of the rectenna was quite easy because microwaves were present practically everywhere under the floor. Total efficiency from electricity to DC via microwave transfer was assumed to be 50%. Although the day by day running costs of electricity for the microwave building system is approximately twice that of a conventionally wired home, the initial cost of the building is reduced because of reduced construction costs. Therefore, it was estimated that the overall life cycle cost of the building can be reduced by using the microwave building system.

FIGURE 2.5.1

Wireless building using microwave power transmission



In the initial phase, the wireless system was considered for office buildings where DC-driven computers and other OA instruments are mainly used. It is estimated that one DC converter requires < 50 W, and > 3 kW of microwave power is provided to a single room, indicating that the system provides sufficient power to run a number of typical electrical devices per room. The microwave traveling through the waveguide in this application serves as a UPS system.

[SHI 14] Shinohara, N., N. Niwa, K. Takagi, K. Hamamoto, S. Ujigawa, J.-P. Ao, and Y. Ohno, "Microwave Building as an Application of Wireless Power Transfer", Wireless Power Transfer, pp. 1-9, 2014.4.

[TAK 09] Takahashi, K., J.-P. Ao, Y. Ikawa, C.-Y. Hu, H. Kawai, N. Shinohara, N. Niwa, and Y. Ohno, "GaN Schottky Diodes for Microwave Power Rectification", *Japanese Journal of Applied Physics (JJAP)*, Vol. 48, No. 4, pp. 04C095-1 - 04C095-4, 2009.

2.6 WPT to moving/flying target (App ID: c1)

2.6.1 Situation of Canada

The WPT via radio frequency beam is suitable for a WPT to a moving/flying target. A Canadian group of the Communication Research Centre (CRC) successfully conducted a fuel-free airplane flight experiment using MPT in 1987, which was called SHARP (Stationary High Altitude Relay Platform; Fig. 2.6.1) [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.

2.6.2 Situation of Japan

In Japan, a fuel-free airplane flight experiments with MPT phased arrays operating at 2.411 GHz for the MILAX project was succeeded in 1992 (Fig. 2.6.2) [MAT 93]. It was the first MPT experiment with the phased array beam forming in the world. The MPT experiments conducted during the SHARP and MILAX projects aimed at a stationary high altitude relay platform in the stratosphere.

FIGURE 2.6.1

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

FIGURE 2.6.2

The MILAX project airplane experiment showing the model airplane and the phased array used in Japan in 1992

In the early 21st century, the MPT to micro aerial vehicle (MAV) [MYS 12] and Mars observation airplane [NAG 11] [NAG 12] projects, which were MPT systems directed towards small airplanes, were proposed and developed in Japan (Fig. 2.6.3). The MPT to the MAV was proposed by the University of Tokyo. Researchers transmitted 5.8 GHz microwave power to a flying MAV from which a pilot signal of 2.45 GHz was transmitted as a signal for target detection. Rectennas were installed on the body of the MAV. Initially, five horn antennas were used as a phased array. The diameter of the phased array was 330 mm and its element spacing was 2λ. Microwave power from the horn antennas was 4 W each.

For the base system, a phased array using 8 microstrip antennas whose element spacing was 1.36λ was adopted. Microwave power from the microstrip antennas was 8 W each.

FIGURE 2.6.3

First concept of a MPT to micro aerial vehicle [MYS 12]

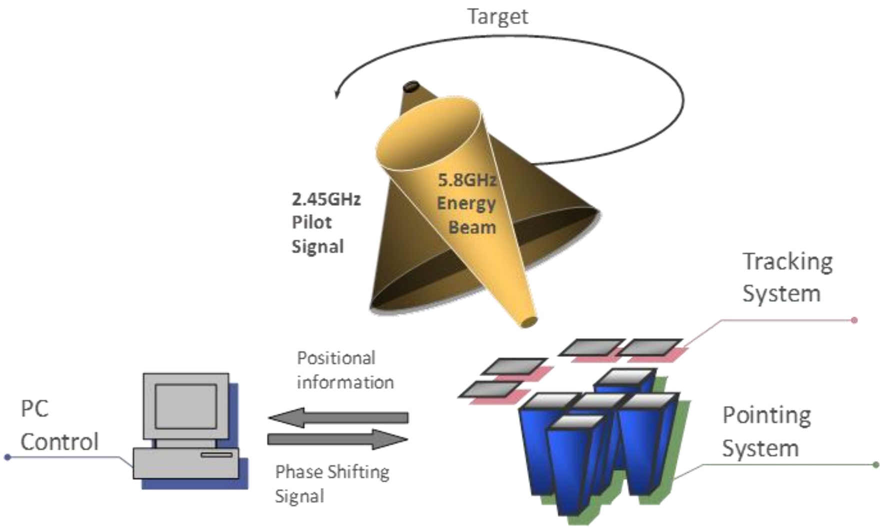
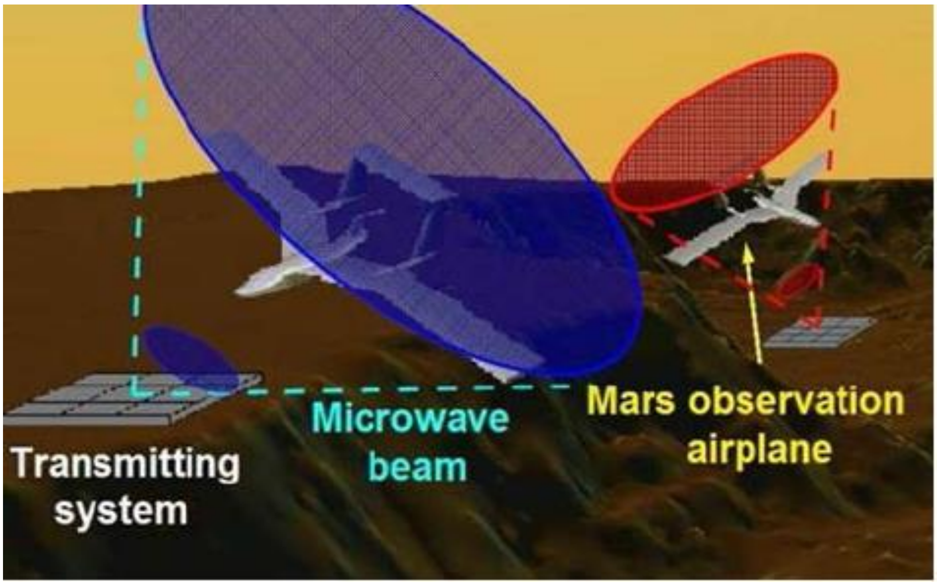


FIGURE 2.6.4

A description of the MPT to Mars observation airplane [NAG 11] [NAG 12]

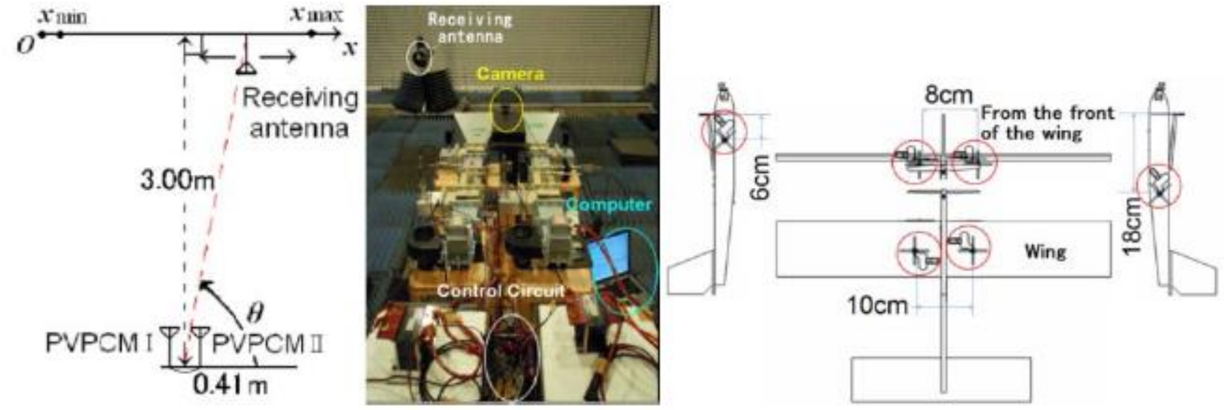


The Mars observation microwave airplane system was proposed by Kyoto University and Kyusyu Institute of Technology, Japan. Wide-ranging, continuous observation of the surface of Mars is of interest for understanding the physical properties of that planet. The Mars surface has been mainly observed by a rover, which can neither move rapidly nor observe bumpy areas. Therefore, small airplane observation is receiving attention as an alternative to the rover. In order to realize stable flight in the greatly reduced atmosphere of Mars, the weight of the airplane must be reduced.

MPT is an excellent possible technology to reduce or even eliminate the fuel requirements of an airplane. A description of a possible future Mars observation airplane is shown in Fig. 2.6.4 [NAG 11] [NAG 12]. An experimental setup is shown in Fig. 2.6.5. The MPT system using a phased array antenna composed of “power-variable phase-controlled magnetrons (PVPCMs)” was used in the experiment. The PVPCM is a derivative technology from the phase-controlled magnetron (PCM) developed at Kyoto University. A PVPCM can transmit 2.45 GHz, 61 dBm microwave power and can control the beam direction using phase control [NAG 11]. The transmitter traces the airplane's location with a camera using an image processing application [NAG 12].

FIGURE 2.6.5

(a) Schematic diagram and photograph of the magnetron-based phased array **(b) Alignment of the six rectennas on the airplane body for ground experiments [NAG 12]**



MPT to a moving rover is another potential application as shown in Fig. 2.6.6. From 2004 in Japan, MPT using active integrated antenna (AIA) technology was developed [SHI 07]. The target of this project was (1) development of very light power-to-weight-ratio microwave power transmitter using AIA technology (with a target below 50 g/W), (2) advancement of the power management of the rectified microwave power at the rectenna, receiver, and rectifier of the microwave power, especially against changes in the connected load, and (3) fundamental experiments of the coexistence of 100 W microwaves and 10 mW wireless communication waves. For the target of the project, MPT to a moving rover was chosen. The microwave transmitting sub-system was composed of a 32 element AIA with a linear polarized rectangular microstrip antenna array and 4 W output 3-stage GaAs high power amplifiers on a bent di-electric base for an expanded cooling area, whose total power is 120 W at 5.8 GHz. The system uses no phase shifter. A photograph of the MPT experiment in an anechoic chamber is shown in Fig. 2.6.7. The rover moved only by means of the microwave power provided by MPT.

Ritsumeikan University's group in Japan carried out a WPT demonstration to flying drone in 2015 (Fig. 2.6.8) [NIS15]. They used 430 MHz frequency band and approximately 30 W radio wave power to supply a power to the drone. A weight of the drone model was 25 g and it required 2WDC to fly. Presently, the drone could fly above a transmitting antenna at distance of approximately 10 cm. The system is under revision.

US group in University of Colorado and ISAE, France, are developing a WPT system to flying micro-UAV (unmanned vehicle) in 2015 (Fig. 2.6.9) [Dun15].

FIGURE 2.6.6

Experimental system of MPT for the moving rover [SHI 07]

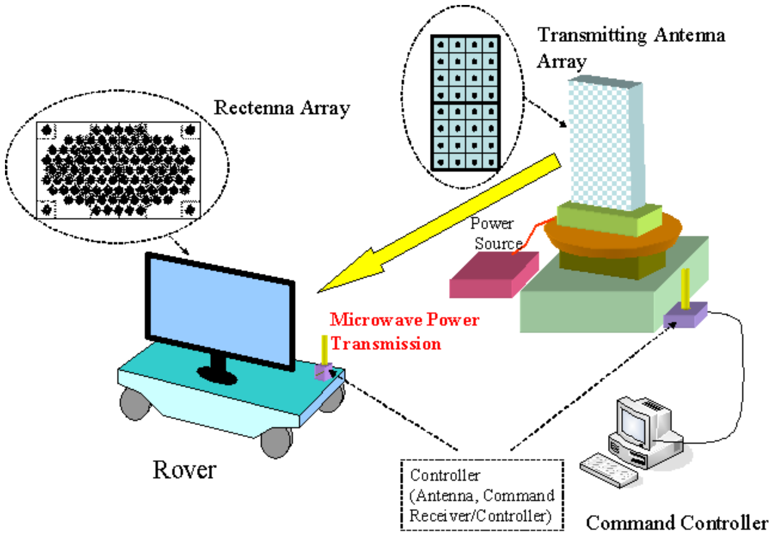


FIGURE 2.6.7

Photograph of the MPT rover experiment [SHI 07].

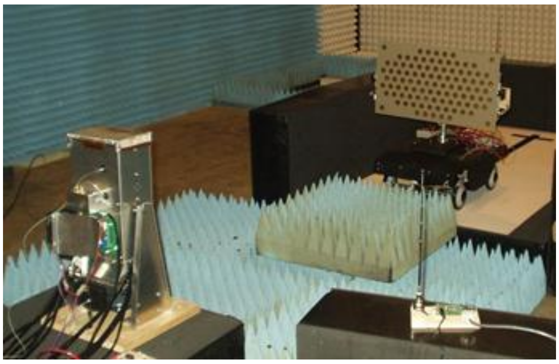


FIGURE 2.6.8

Experimental system of WPT to flying drone [NIS 15] and its demonstration in Japan (March, 2016, in Japan)

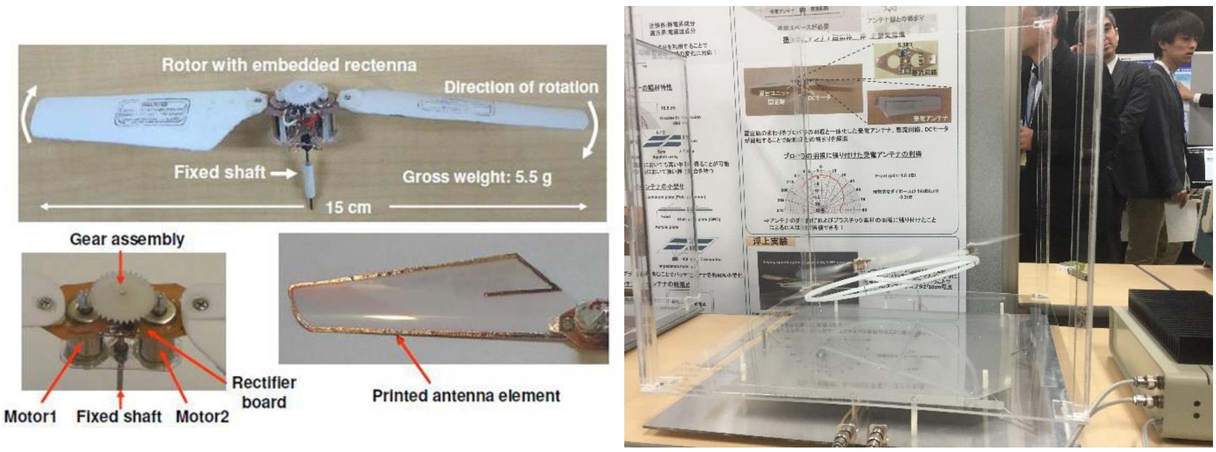
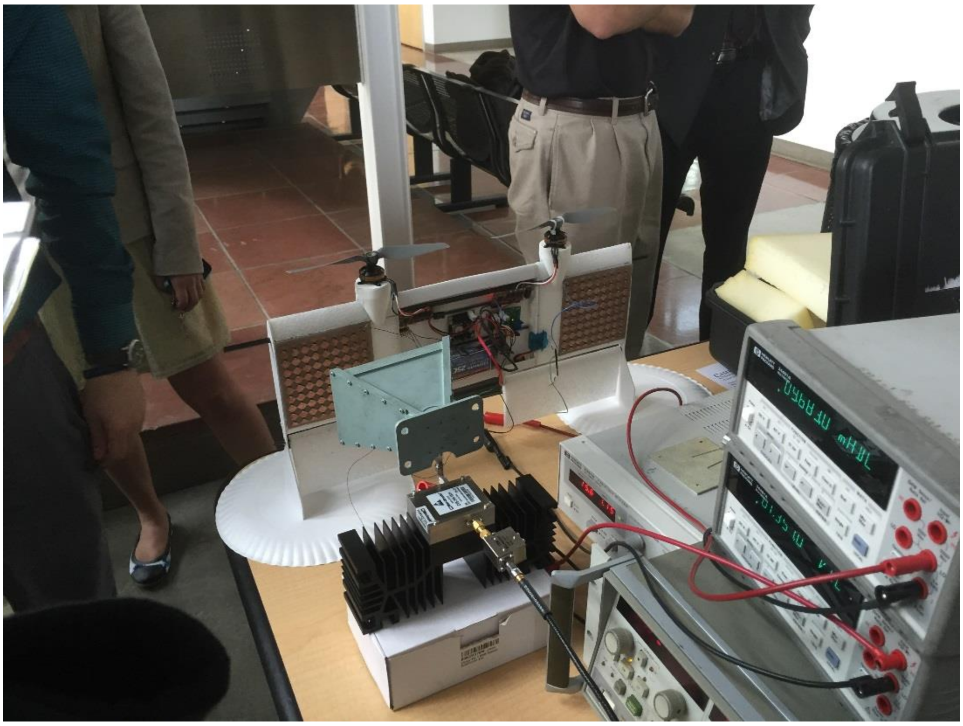


FIGURE 2.6.9

Experimental system of WPT to Micro-UAV



[DUN 15] Dunbar, S., F. Wenzl, C. Hack, R. Hafeza, H. Esfeer, F. Defay, S. Prothin, D. Bajon, and Z. Popovic, "Wireless Far-Field Charging of a Micro-UAV", *Proc. of IEEE Wireless Power Transfer Conference (WPTc),* T1.2, May 2015.

[NAG 11] Nagahama, A., T. Mitani, N. Shinohara, N. Tsuji, K. Fukuda, Y. Kanari, and K. Yonemoto, "Study on a Microwave Power Transmitting System for Mars Observation Airplane", *Proc. of 2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS-IWPT2011),* pp. 63-66, 2011.

[NAG 12] Nagahama, A., T. Mitani, N. Shinohara, K. Fukuda, K. Hiraoka, and K. Yonemoto, "Auto Tracking and Power Control Experiments of a Magnetron-based Phased Array Power Transmitting System for a Mars Observation Airplane", *Proc. of 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS-IWPT2012),* pp. 29-32, 2012.

[NIS 15] Nishikawa, H., Y. Kiani, T. Furukoshi, H. Yamaguchi, A. Tanaka, and T. Douseki, "UHF Power Transmission System for Multiple Small Self-rotating Targets and Verification with Batteryless Quadcopter having Rotors with Embedded Rectenna", *Proc. of IEEE Wireless Power Transfer Conference (WPTc),* T1.1, May 2015.

[MYS 12] Miyashiro, K., F. Inoue, K. Maki, K. Tanaka, S. Sasaki, and K. Komurasaki, "Sequentially Rotated Array Antenna for Wireless Power Transmission to an MAV (*in Japanese*)“, *IEICE Tech. Report,* WPT2012-30, pp. 59-61, 2012.

[SHI 07] Shinohara, N., K. Nagano, T. Ishii, S. Kawasaki, T. Fujiwara, S. Nakayama, Y. Takahashi, S. Sasaki, K. Tanaka, Y. Hisada, Y. Fujino, S. Mihara, T. Anzai, and Y. Kobayashi, "Experiment of Microwave Power Transmission to the Moving Rover", *Proc. of Int. Sympo. on Antennas and Propagation (ISAP2007),* 3B1-1, 2007.

2.7 Point-to-Point WPT (App ID: c2)

It is easy to image a point-to-point WPT via radio waves in over km distance instead of a wired power transfer (Fig. 2.7.1). In the 1960s, point-to-point WPT operating in the km range via microwaves was highly expected for WPT application. Brown and Dickinson carried out MPT experiments at JPL in 1975 (Fig. 2.7.2) [BRO 84]. However, the size of the transmitting and receiving antennas was decided by theory and they were too large to realize a commercial point-to-point MPT application with reasonable cost as an alternative to wired power transfer. Point-to-point MPT systems were revised and further experiments were proposed in the 1990s (Fig. 2.7.3) [SHI 98] [CEL 97]. They have developed a rectenna array. Under certain conditions, such as providing electrical power to an isolated mountain top or an island where the cost of a wired power supply is too expensive and/or electric power needs are sporadic, the point-to-point MPT system has a distinct advantage over wired power transfer.

FIGURE 2.7.1

Image of point-to-point WPT

FIGURE 2.7.2

1 Mile point-to-point MPT experiment with 26 m parabolic antenna and 450kW-2.388 GHz Klystron as a transmitter and 3.4 × 7.2 m Rectenna array as a receiver

FIGURE 2.7.3

50 m point-to-point MPT experiment with 3 kW-2.45 GHz magnetron in Japan (1995)

2.7.1 Situation of Japan

On February 2015, two long distance WPT experiments were carried out in Japan. One is 55 m distance WPT experiment with 5.8 GHz, 1.8 kW microwave (Fig. 2.7.4). The microwave was transmitted from 2.5 cm thickness phased array with GaN MMIC amplifiers and 5-bit MMIC phase shifters. Efficiency of the GaN high power amplifier is approximately 70% at 7W, 5.8 GHz. The thin phased array and GaN amplifiers were developed by Mistubishi Electric Corp and a rectenna was developed by IHI Aerospace. In this experiment, a recto directive target detecting and rotating electromagnetic vector (REV) method was adopted to detect a position of a rectenna and to control a microwave beam. The target detecting and beam forming system was developed by JAXA and Mitsubishi Electric Corp. The other long distance WPT was carried out at 500 m distance with 2.45 GHz, 10 kW from magnetron phased array by Mitsubishi Heavy Industries (Fig. 2.7.5). Both experiments were conducted by JSS (Japan Space Systems) and supported by METI (Ministry of Economy, Trade and Industry). These were field experiments as results of six year R&D project for a Solar Power Satellite. The R&D project by METI continues until 2017 and more.

FIGURE 2.7.4

55 m point-to-point MPT experiment with 1.8 kW-5.8 GHz phased array with GaN MMIC amplifiers in Japan by JSS and METI (2015)

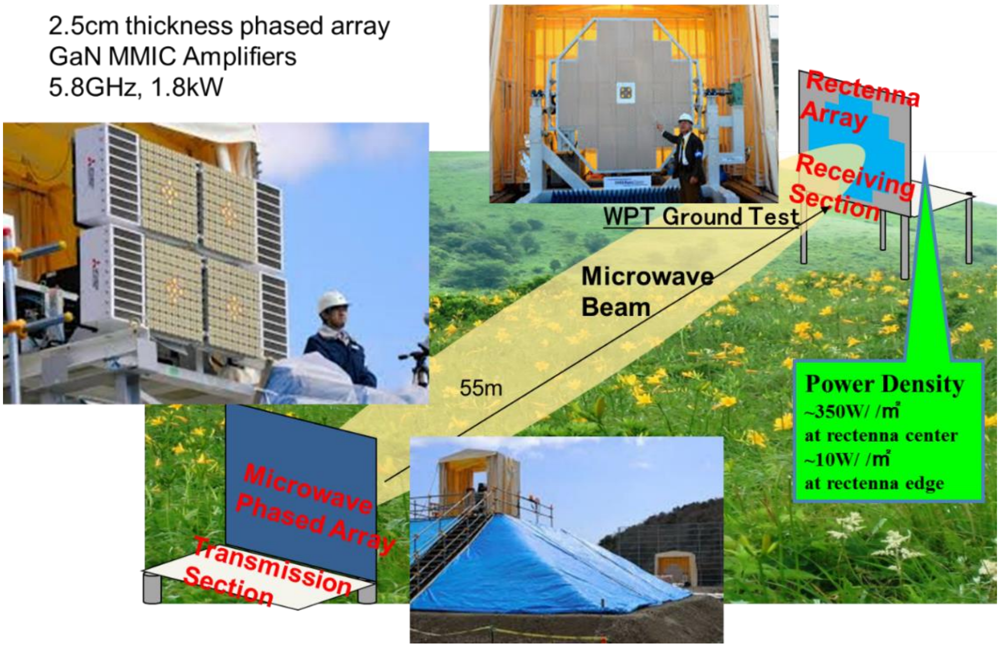
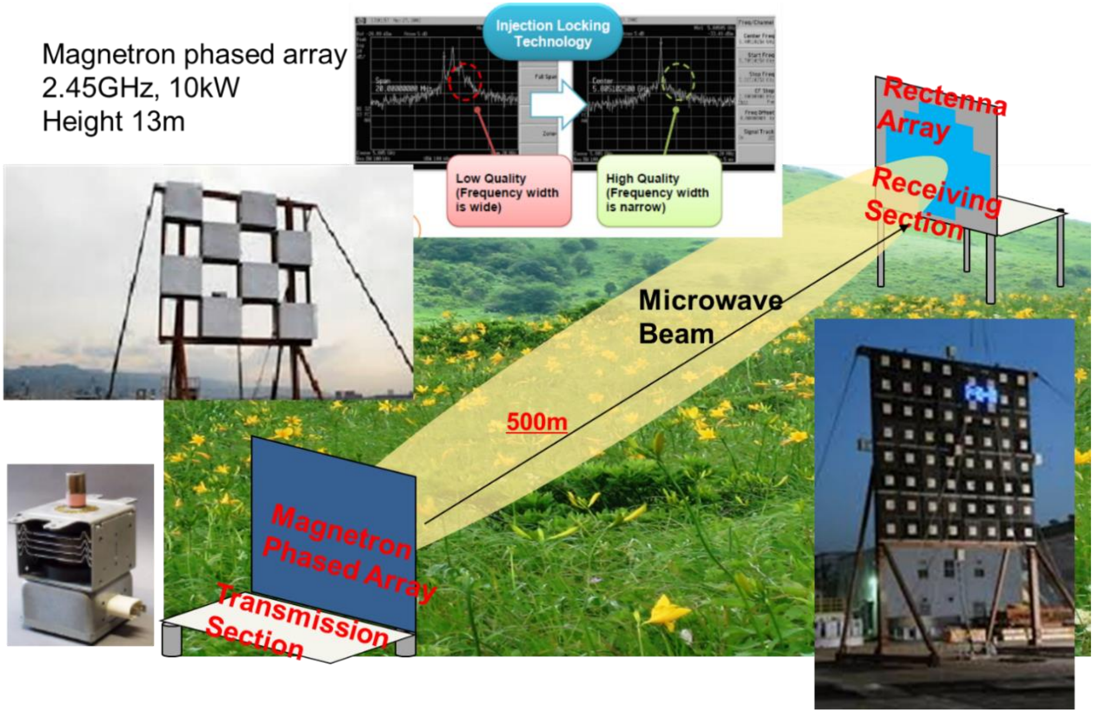


FIGURE 2.7.5

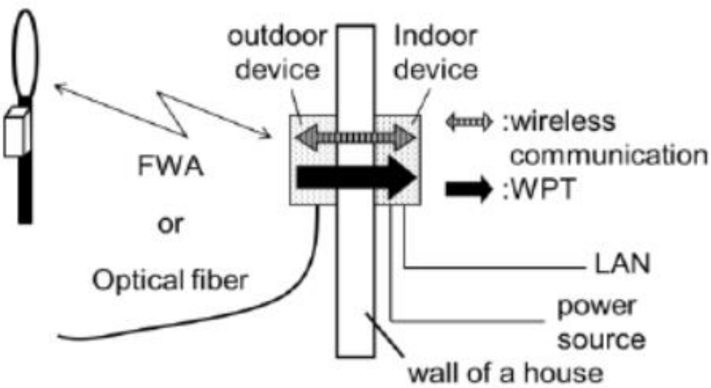
500 m point-to-point MPT experiment with 10 kW-2.45 GHz magnetron phased array in Japan by JSS and METI (2015)



The size of the antenna and the expense of an MPT system depend on the MPT's intended range. In Japan, a short-distance point-to-point MPT system has been proposed by NTT Corp. and Kyoto University, which is called MPT for fixed wireless access (FWA). Fig. 2.7.6 shows an image of the proposed system [HAT 12]. The outdoor device communicates with the Internet by the FWA or an optical fiber. The inside device and the outside device wirelessly communicate with each other. The inside device transmits power to the outside device by microwave. The outside device can operate without a battery. For the system, it is preferred that both information and power are carried by the same microwave carrier to reduce the size of the system. At first, a frequency of 24 GHz was selected and a MMIC rectenna with a class-F load output filter was developed, as shown in Fig. 4.5.18 [HAT 13].

FIGURE 2.7.6

Concept of a microwave-driven FWA system [HAT 12].



In 2015, Kyoto University and MHI group developed a wireless charging system for small electric cart with 2.45 GHz, 100W microwave (Fig. 2.7.7). This is one of point-to-point WPT at short distance. In 2016, the WPT system are investigated for daily use in Kyoto University.

FIGURE 2.7.7

Wireless charging system for small electric cart

[BRO 84] Brown, W.C., "The History of Power Transmission by Radio Waves", *IEEE Trans. MTT,* Vol. 32, No. 9, pp. 1230-1242, 1984.

[SHI 98] Shinohara N. and H. Matsumoto, "Dependence of dc Output of a Rectenna Array on the Method of Interconnection of Its Array Element", *Electrical Engineering in Japan,* Vol. 125, No. 1, pp. 9-17, 1998.

[CEL 97] Celeste, A., J-D. L.S. Luk, J.P. Chabriat, and G. Pignolet, "The Grand-Bassin Case Study: Technical Aspects", *Proc. of SPS'97,* pp. 255-258, 1997.

[HAT 12] Hatano, K., N. Shinohara, T. Mitani, T. Seki, and M. Kawashima, "Development of Improved 24GHz-Band Class-F Load Rectennas", *Proc. of 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS-IWPT2012),* pp. 163-166, 2012.

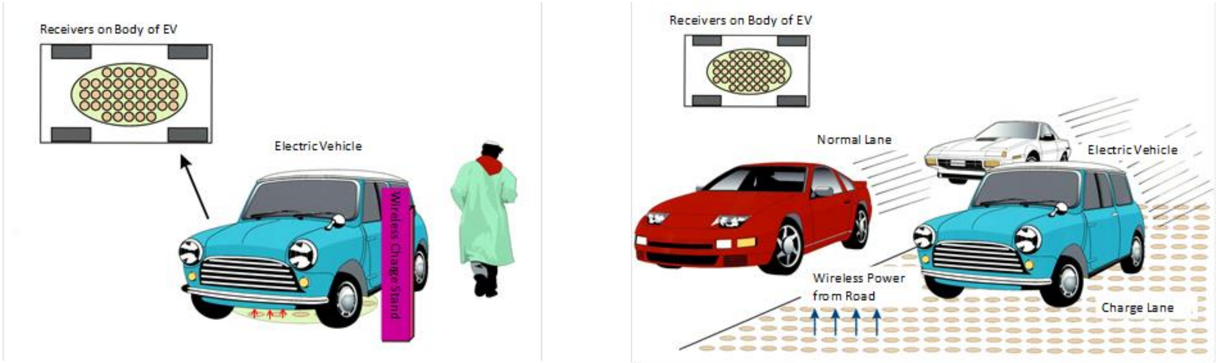
[HAT 13] Hatano, K., N. Shinohara, T. Seki, and M. Kawashima, "Development of MMIC Rectenna at 24 GHz", *Proc. of 2013 IEEE Radio & Wireless Symposium (RWS),* pp. 199-201, 2013.

2.8 Wireless charging for electric vehicles (App ID: c3)

Highly efficient MPT can be applied not only through closed waveguides, but also over short distances with smaller antennas. Photographs of the wireless charging of an EV using MPT are shown in Fig. 2.8.1. It is convenient to apply MPT for wireless charging both for parked EVs and for EVs in motion because the transmitting and receiving antennas are not coupled. The impedance of the antennas is not changed by a change in the position of the EV nor is the efficiency of MPT changed. Problems of safety and interference by microwaves are diminished for both MPT in a closed waveguide and over short distances because there is almost no diffusion of unexpected microwaves. In short-distance power transfer systems, the magnitude of wireless power can be also increased to the kW range because the transmission does not interact with humans or other living things between the transmitting and the receiving antennas.

FIGURE 2.8.1

Images of wireless charging of EVs (a) for parked EVs, and (b) for EVs in motion



(a) (b)

2.8.1 Situation of Japan

A MPT system for EVs was proposed and implemented (Fig. 2.8.2) [SHI 04]. From 2003 to 2008, the collaborative research between Japanese car company and university was carried out to develop a MPT system between the road and the body of an EV using a microwave frequency of 2.45 GHz (Fig. 2.8.3) [SHI 11] [SHI 11-2]. Magnetrons and slot antennas were used to reduce the system cost. The distance between the transmitting and the receiving antennas was approximately 12.5 cm, a distance of 1 λ at the 2.45 GHz frequency. The battery on the electric vehicle can be effectively charged using microwave transmissions having a theoretical beam efficiency of at least 83.7% and an experimental beam efficiency of at least 76.0% [SHI 11-2]. This efficiency is sufficiently high to realize the transmission of wireless power using microwaves. For this application, a new GaN Schottky diode was utilized to increase the rectified power and to reduce the EV charging time.

In 2000, a scaled MPT model for running an EV was developed [SHI 04]. To reduce power loss, the position of the model EV was detected by positioning sensors and microwave power was transmitted only to the position of the model EV.

FIGURE 2.8.2

Short-distance wireless microwave charging road system for EVs [SHI 04]

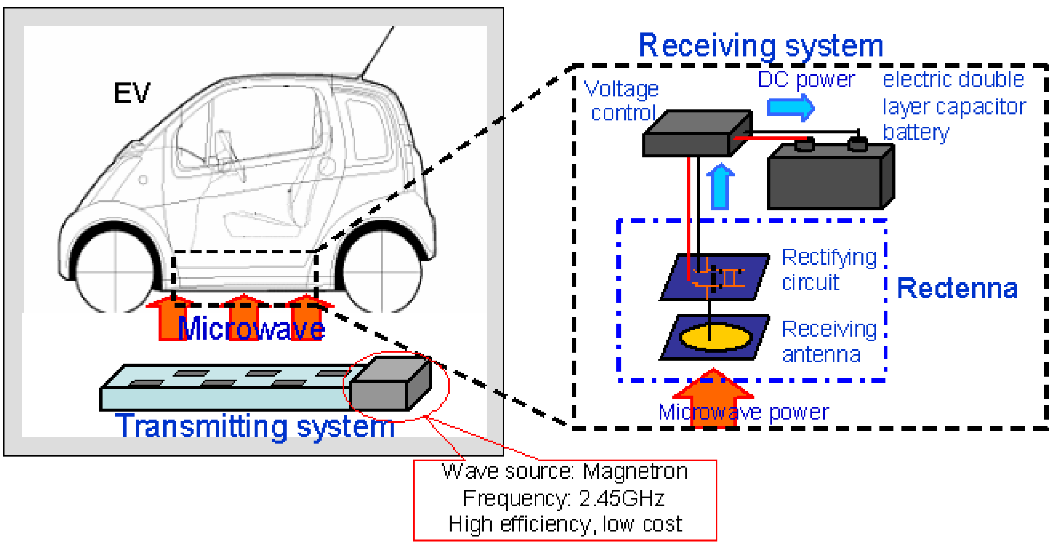
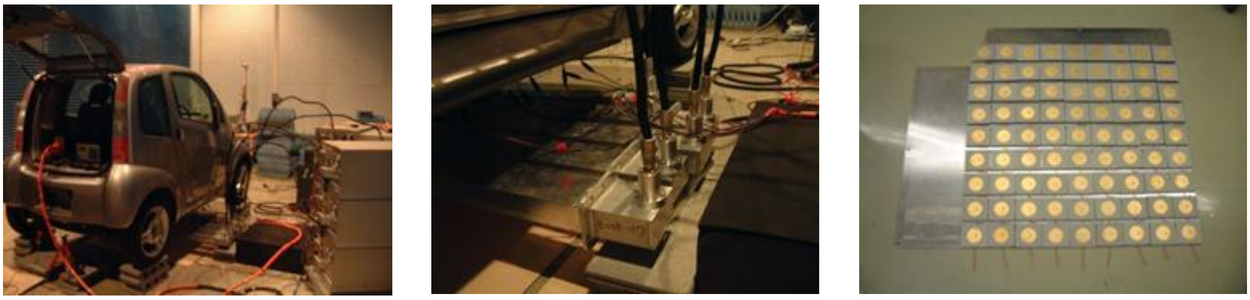


FIGURE 2.8.3

Wireless charging experiment with microwaves by Kyoto University, (a) the System, (b) Microwave transmitting antenna on the road, (c) Rectenna array on the body of the EV [SHI 11-2]



(a) (b) (c)

From 2006 to 2008, Japanese company conducted a MPT R&D project for EVs with Japanese three car company [SHI 13-2]. To reduce the power loss, they used (1) 6.6 kV directly to drive the 2.45 GHz magnetrons as microwave transmitters, (2) a blocking wall around which microwaves pass between the transmitting antennas and receivers, and (3) a heat recycling system. The total efficiency, including the heat recycling, was approximately 38% with an output power of 1 kW at a distance of 12.5 cm. The prototype released in 2009 is shown in Fig. 2.8.4.

In 2012, a Japanese branch of Swedish automotive company and Japanese company began to develop a new MPT system for an electric truck. The former system led to mutual coupling problems between the transmitting and receiving antennas because the MPT distance was too short; therefore, the new MPT system was changed from a road-to-body to a top-to-roof configuration (Fig. 2.8.5) [SHI 13-1] [SHI 13-3] to take advantage of the MPT as long distance WPT. The distance between the transmitting antennas and the receiving antennas on the roof-top of the EV was 2-6 m, depending upon the type of the EV used. To keep a high efficiency over the varying distance, a phased array system that can create a flat beam on the receiving antennas was proposed.

On 6th July 2012, they released a 10 kW rectenna array with an efficiency of 84% operating at a frequency of 2.45 GHz for the mid-distance WPT system (Fig. 2.8.6) [FUR 13]. The received microwave power density was over 3.2 kW/m^2 at a distance of approximately 4 m from the transmitter.

FIGURE 2.8.4

Wireless charging experiment with microwaves by Mitsubishi Heavy Industries' group in 2009 [SHI 13-2]

FIGURE 2.8.5

Proposed mid-distance wireless charging for EV and the FDTD simulation of the microwave beam [SHI 13-1]

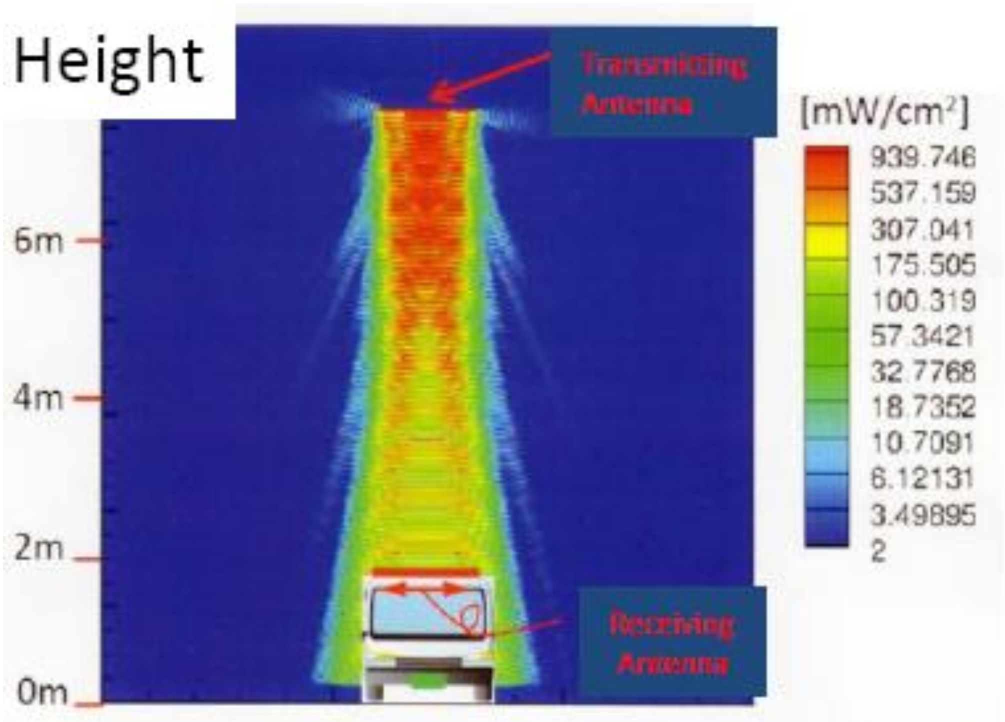


FIGURE 2.8.6

Photograph of the 10kW Rectenna operating at 2.45 GHz for wireless charging of EVs [FUR 13]

[FUR 13] Furukawa, M., T. Minegishi, T. Ogawa, Y. Sato, P. Wang, H. Tonomura, M. Teramoto, and N. Shinohara, "Wireless Power Transmission to 10kW Output 2.4 GHz-band Rectenna Array for Electric Trucks Application *(in Japanese*)", *IEICE Tech. Report,* WPT2012-47, pp. 36-39, 2013.

[SHI 04] Shinohara, N. and H. Matsumoto, "Wireless Charging System by Microwave Power Transmission for Electric Motor Vehicles *(in Japanese*)", *IEICE Trans. C,* Vol.J87-C, No. 5, pp. 433-443, 2004.

[SHI 11] Shinohara, N., "Beam Efficiency of Wireless Power Transmission via Radio Waves from Short Range to Long Range", *Journal of the Korean Institute of Electromagnetic Engineering and Science,* Vol. 10, No. 4, pp. 224-230, 2011.

[SHI 11-2] Shinohara, N., "Wireless Charging System of Electric Vehicle with GaN Schottky Diodes", *Proc. of Int. Microwave Sympo. (IMS) Workshops,* WFA "Wireless Power Transmission", 2011.

[SHI 13] Shinohara, N. and Yuta Kubo, "Suppression of Unexpected Radiation from Microwave Power Transmission System toward Electric Vehicle", *Proc. of 2013 Asia-Pacific Radio Science Conference (AP-RASC),* E3-4 (No. 290450), 2013.

[SHI 13-2] Shinohara, N., "Wireless Power Transmission Progress for Electric Vehicle in Japan", *Proc. of 2013 IEEE Radio & Wireless Symposium (RWS),* pp. 109-111, 2013.

[SHI 13-3] Shinohara, N., Y. Kubo, and H. Tonomura, "Mid-Distance Wireless Power Transmission for Electric Truck via Microwaves", *Proc. of 2013 International Symposium on Electromagnetic Theory (EMT-S2013),* pp. 841-843, 2013.

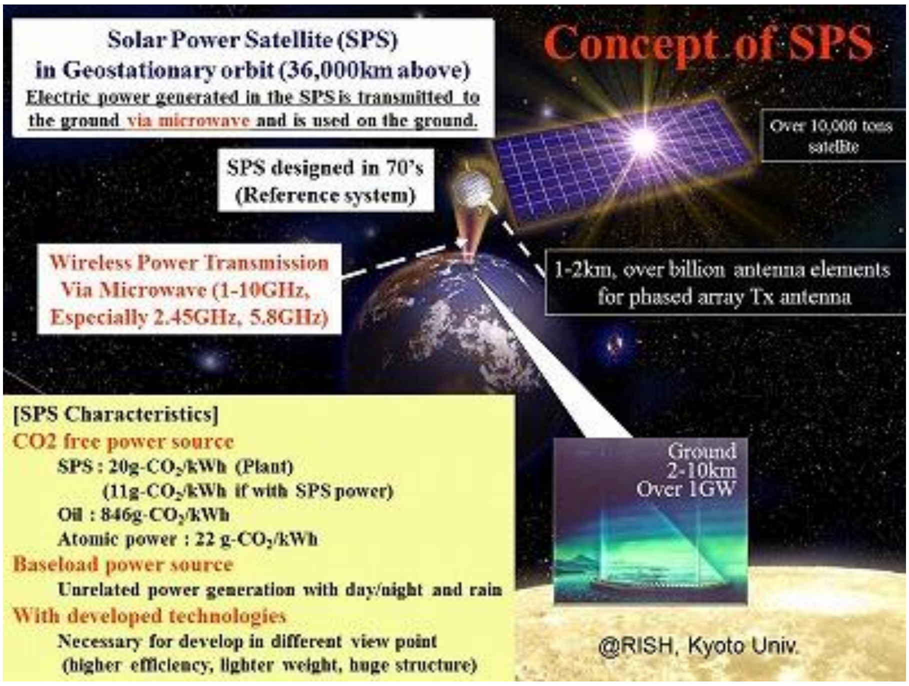
2.9 Solar power satellite (App ID: c4)

Hugest application of the WPT via radio frequency beam is a solar power satellite (SPS) [SPS 07]. The SPS is designed as a huge solar power satellite in geostationary orbit, 36,000 km above the Earth's surface (Fig. 2.9.1), where there is no cloud cover and no night throughout the year. The generated power in the SPS is transmitted to the ground via microwave. Because of the theoretically calculated, large antenna size required to achieve high beam efficiency to a far distant target like the SPS, approximately 2 km size antennas at 5.8 GHz are required for the SPS but it is not impossible. Microwave energy is not absorbed by air, cloud, and rain; therefore, it is possible to obtain approximately ten times the solar power, a stable and CO2-free energy source, from the SPS using MPT technology than that from terrestrial solar sources.

In the MPT system of the SPS, a large phased array with a high efficiency must be employed. The phased array is necessary for steering a power beam to a small rectenna target on the ground within a tolerance of 0.0005 degree; although, the transmitting antenna of the SPS will always move and fluctuate. The power beam must be generated and transmitted without much loss for economic reasons.

FIGURE 2.9.1

Image of solar power satellite



[SPS 07] Report of the URSI Inter-Commission Working Group on SPS, URSI, 2007, available at URL: http://www.ursi.org/files/WhitePapers/WPSPS-ReportMin.pdf

3 Technologies employed in WPT applications

In a WPT system via radio frequency beam, antennas are used to transmit and to receive radio wave. The transmitting and receiving antenna are not electromagnetically coupled. So number of transmitters and receivers are free from circuit parameters of transmitters and receivers. Main theory of the WPT via radio frequency beam is based on Friis' transmission Formula. The radio wave which transmits wireless power does not need modulation like a wireless communication system.

The WPT via radio frequency beam is classified as follows (Fig. 3.1 and Table 3.1);

a) Wide beam to multi-users at short range

b) WPT in closed area

c) Narrow beam to single user at short/long range.

FIGURE 3.1

WPT via radio frequency beam technologies

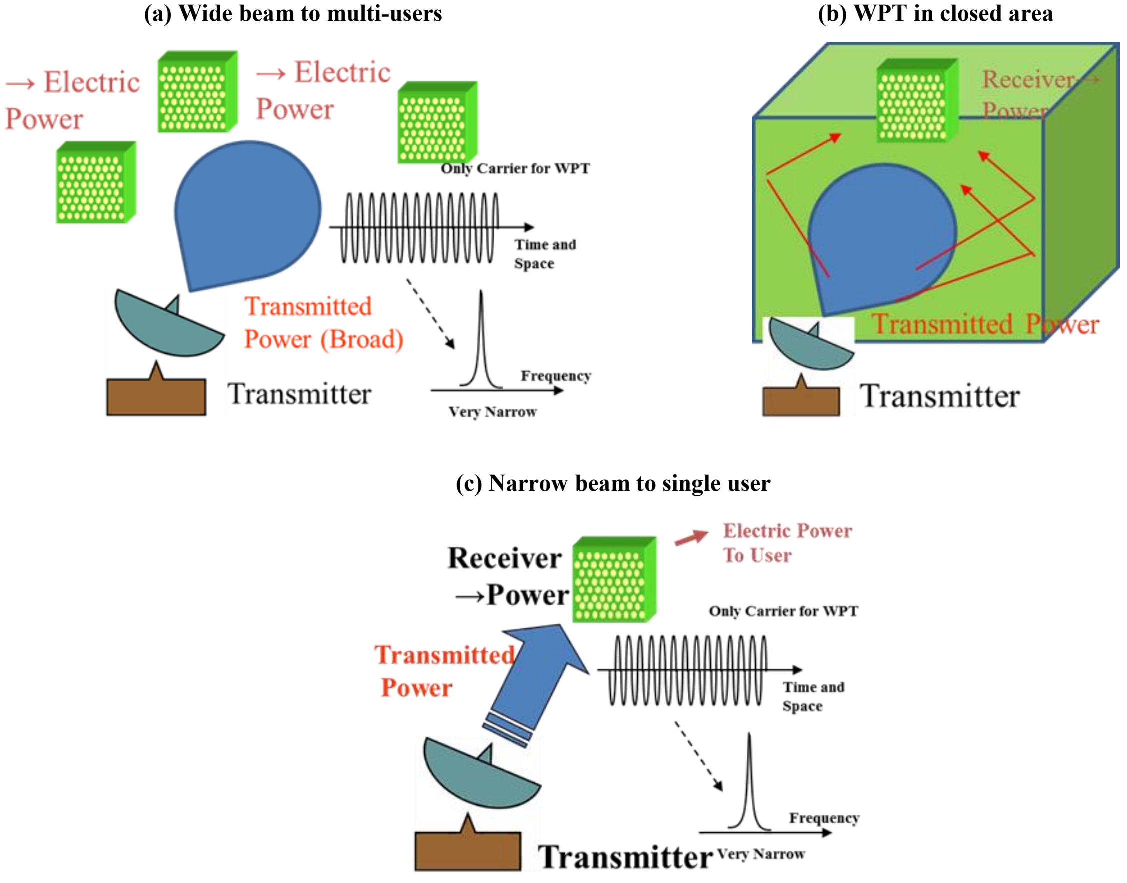


TABLE 3.1

Classification of WPT applications

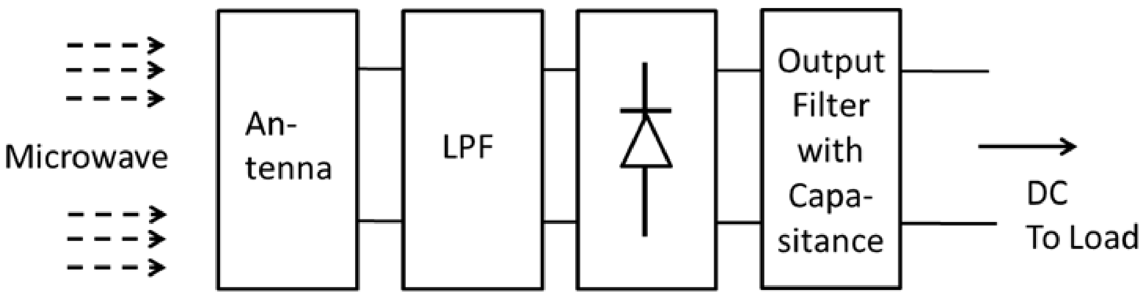
ID	Application	a) Wide beam to multi-users at short range	b) WPT in closed area	c) Narrow beam to single user at short/long range
a1	Wireless powered sensor network	○		
a2	Wireless charger of mobile devices	○		
b1	Wireless power transfer sheet		○	
b2	MPT in a pipe		○	
b3	Microwave buildings		○	
c1	WPT to moving/flying target			○
c2	Point-to-point WPT			○
c3	Wireless charging for electric vehicles			○
c4	SPS			○

In the narrow beam WPT and in the WPT in closed area, it is possible to suppress unexpected radiation in spacing with antenna technology. Phased array antenna, which can control beam direction and beam form with phase and amplitude controlled plural antennas, are sometimes used in the narrow beam WPT. The phase array antennas were developed for WPT and WPT field experiments were carried out [SHI 13].

The radio wave itself is an electric power. The only difference between the radio wave and the electricity is the frequency. MHz-GHz radio wave is used for the WPT via radio frequency beam, the wireless communications, and remote sensing. DC or 50/60 Hz (commercial power frequency) is used as the electricity. So frequency conversion from the radio frequency to DC/commercial power frequency is only required in the WPT, including not only the WPT via radio frequency beam but also an inductive WPT and a resonance coupling WPT. Rectenna, antenna with rectifying circuit with diodes, is used as a receiver and rectifier in the WPT via radio frequency beam (Fig. 3.2). RF-DC conversion efficiency of developed rectenna was approximately 90% at 2.45 GHz [BRO 80] [FUR 13] and 80% at 5.8 GHz [MCS 97]. The rectenna can be applied for all WPT via radio frequency beam, for example, at UHF [SAM 09], X-band [EPP 00], K-band [TAK 13], and W-band [WEI 14].

FIGURE 3.2

Rectenna, rectifying antenna



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4 Organizations expected to contribute to WPT's standardization

Although no standardization organization for WPT for radio waves exists, some organizations to promote the WPT are expected to contribute WPT's standardization.

4.1 Europe

WiPE (Wireless Power Transmission for Sustainable Electronics) [W13]

[W13] http://www.cost-ic1301.org/

COST has been an intergovernmental framework for European Co‑operation in the field of Scientific and Technical Research since its creation in 1971. Its goal is to strengthen the competitiveness of Europe's scientific and technical research for peaceful purposes.

The COST Action aims to address efficient WPT circuits, systems and strategies specially tailored for battery‑less systems. Battery‑free sensors, passive RFID, near field communications (NFC) are all closely related concepts that make use of WPT and energy harvesting systems to remotely power up mobile devices or to remotely charge batteries, contributing to develop and foster the Internet of Things (IoT) evolution.

In this context, this COST Action aims at bringing together RF circuit and system designers with different backgrounds to: 1) provide enhanced circuit and subsystem solutions to increase the efficiency in WPT; and 2) investigate the use of novel materials and technologies that allow minimizing cost and maximizing integration of the electronics with the environment and with the targeted applications.

The COST Action expected benefits include the creation of a wide network of experts both from academia and industry that can address the existing and upcoming challenges in WPT scenarios in an interdisciplinary manner paving the way for the future generations of WPT solutions and the associated regulation.

COST is an ideal framework towards joining efforts at an international level and establishing Europe as a leading scientific and industrial community in the field of WPT.

WiPE Management Committee includes 27 European countries at this time with more than 100 entities participation in regular meetings and workshops. WiPE also organizes a yearly PhD schools on WPT.

WiPE has five research workgroups (WGs). These are:

WG1. Far-field WPT systems

WG2. Near-field WPT systems

WG3. Novel materials and technologies

WG4. Applications (space, health, agriculture, automotive systems, home appliances)

WG5. Regulation and Society Impact

4.2 Japan

4.2.1 WiPoT (Wireless power transfer consortium for practical applications) [WI]

[WI] http://www.wipot.jp/english/

The objectives of the consortium are: 1) matching new ideas and solutions to society's needs regarding WPT technologies, particularly with regards to MPT, and 2) accelerating the development of practical applications of WPT. To achieve these objectives, the WiPoT shares information about not only technology, but also standardization, safety, and user needs. The consortium also advertises WPT technologies, including MPT, throughout the world. The consortium was established in 2013 and has 29 company members, 38 university members, and 3 institute members as of May, 2016.

The consortium considers that microwave power transmission can be base technology of all wireless power transmission and has the following working groups:

WG1: Wide Beam and Low Power Applications

WG2: Narrow Beam and high Power Applications

WG3: WPT in Closed Area

WG4: Commercialization

WG5: Standardization

4.2.2 BWF (Broadband wireless forum) [BWF]

[BWF] http://bwf-yrp.net/english/

The Forum shall aim at contributing to sound advancement of new radio use systems and services to promote early commercialization and international development of the systems and services using new radio communication technologies. To achieve these aims, the Forum conducts R&D, investigation, information collection, liaison and coordination with related organizations, and dissemination activities, etc., on new radio communication technologies. Its members are 128 bodies As of 11 January 2013.

Its activities are:

(1) R&D on new radio communication technologies utilizing test beds

(2) Investigation on new radio communication technologies

(3) Collection, exchange, and provision of information on new radio communication technologies

(4) Liaison and coordination with organizations related to new radio communication technologies

(5) Dissemination and awareness raising of new radio communication technologies

(6) Other activities necessary for the achievement of the Forum's aim

Technology Application Subcommittee has Wireless Power Transmission Working Group.

The Sub Group-5 in WPT-Working Group of BWF is taking responsibility for drafting WPT using microwave technical standards utilizing the ARIB (Association of Radio Industries and Businesses) drafting protocols. A draft standard developed by BWF will be sent to ARIB for approval.

4.3 Other international organizations

IEEE MTT (Microwave Theory and Technique) Society currently promotes the Wireless Energy or Power Transmission and conversion technologies, using either near-field or far-field techniques, for either fixed or mobile access platforms. For the purpose, they established Technical Committee 26 named Wireless Energy Transfer and Conversion in MTTS in 2011 [TC26]. Wireless energy harvesting from radio-frequency (RF) sources is also part of the interest of this committee. In the international microwave symposium (IMS), they conduct student design competitions every year since 2012. 15 teams from 12 countries joined the competition in IMS2014. The TC26 has been organizing an international conference named Wireless Power Transfer Conference (WPTc) since 2013, which started as a workshop in 2011 and was repeated in 2012. Number of the paper submission to this conference is over 170 in 2015.

URSI (International Union of Radio Science) is composed of 10 commissions. URSI organized the inter commission working group (ICWG) on SPS, which is one of MPT applications, and published the white paper on SPS in 2007 with the cooperation of all the commissions including those which cover SPS systems, radio technologies as well as MPT, electromagnetic interference, radio astronomy, and safety issues. URSI general assemblies (GA) which are held every three years have sessions on SPS and/or WPT since 2002 to 2014 (latest). A general lecture of RF energy harvesting and WPT was held in 2014 URSI GA.

[TC26] IEEE MTTS TC-26 http://www.mtt-archives.org/~mtt26/

5 Status of spectrum for WPT via radio frequency beam

One of expected frequency band for the WPT is ISM (Industrial, Scientific, and Medical) band. Since WPT signals do not carry intelligence in the form of signs, signals, nor pictures, they may not be considered as a conventional radiocommunication service.

The 902-928 MHz ISM band (in Region 2 only) is generally unsuitable except for short range WPT applications such as wireless powered sensor networks and UPS. The 2.4-2.5 GHz ISM band and 5.725-5.875 GHz ISM band were used for WPT experiments and are expected for narrow beam WPT applications. The 2.4-2.5 GHz ISM band is more desirable than higher frequency bands because propagation impairments are smaller. For those applications where transmission failure due to rain, etc. can be backed-up by for example having standby, alternate energy systems or adequate energy storage, the 5.725-5.875 GHz ISM band is desirable due to the reduction in aperture sizes.

Annex 1 of Recommendation ITU-R SM.1056 notes power transfer as a future application of ISM. However, Radio Regulations pertaining to ISM imply that the definition and designation of frequency bands for ISM may not have been done with wireless power transmission in mind.

6 Summary

This Report contains possible applications of WPT via radio frequency beam, technologies employed in those applications and candidate frequency bands.

Wireless powered sensor network, wireless charger of mobile devices, WPT sheet, MPT in a pipe, microwave buildings, WPT to moving/flying target, point-to-point WPT, wireless charging for electric vehicles and SPS are studied for applications of WPT via radio frequency beam. WPT technologies using wide beam to multi-users at short range, WPT technologies in closed area and WPT technologies using narrow beam to single user at short/long range are being studied and developed.

WPT technologies using wide beam to multi-users at short range have been studied in the 2.45 GHz, 5.8 GHz and 900 MHz bands. Wireless powered sensor network and wireless charger of mobile devices are studied under these technologies.

WPT technologies in closed area have been studied in the 2.45 GHz and 5.8 GHz bands. WPT sheet, MPT in a pipe and microwave buildings are studied under these technologies.

WPT technologies using narrow beam to single user at short/long range have been studied in the 2.45 GHz and 5.8 GHz bands. WPT to moving/flying target, point-to-point WPT, wireless charging for electric vehicles and solar power satellite are studied under these technologies.

Based on this Report, further studies for the impact between such WPT systems above and existing other systems, and safety aspects such as human exposure to electromagnetic fields are necessary in order to realize these applications.