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Safety of Wireless Power Transfer

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ABSTRACT Wireless power transfer (WPT) systems are developed to provide electric power either directly or via battery charging. The optimism on WPT technology is driven by the ubiquity of cellphones, laptops, and mobile communication devices. Aside from not having to plug in a cellphone or laptop, WPT battery charging offers the potential for mobile devices to get electrical power the same way they get data through harvesting ambient electromagnetic radiation. The dream is a truly wireless mobility scenario with tether-free electric power for cellphones, laptops, appliances, and transportation systems. Beyond wireless communication, the electromagnetic power required for large-scale commercial WPT implementation is substantial. A key facet of the system design and research should include consideration of health effects and safety of radiofrequency electromagnetic radiation.

INDEX TERMS Buses, battery charging, capacitive coupling, cars, cellphone, laptop, drones, electric power, energy harvesting, far field, inductive coils, microwave power transfer, near field, radiative field, solar power, space power satellite, transportation systems.

I. INTRODUCTION

Interest in wirelessly providing needed electrical energy to power electronic devices and systems has reemerged in recent years. The enthusiasm that surrounds wireless power transfer (WPT) is clearly driven by the ubiquity of cell phones, laptops, and other wireless mobile communication devices. Aside from not having to plug in the mobile phone or laptop, a fascinating cause for the interest in battery charging through WPT comes from the potential for mobile communication devices to get their electric power the same way they get their data through harvesting ambient radio frequency (RF) electromagnetic radiation. The dream is a truly wireless mobility scenario with completely tether-free electric power supply for mobile phones, laptops, electronic and electrical appliances, and various transportation systems.

The promise of WPT - transmission of electric power from one point to another without wires, using the so-called Tesla coils - was first proposed, and successfully tested by Nikolas Tesla shortly before the turn of the last century [1], [2]. Indeed, over the intervening years, WPT systems have been developed for point-to-point transmission of electric power over long distances using microwave beams [3], [4]. Furthermore, the concept of WPT from solar-power satellites (SPS), envisioning the generation of electric power by solar energy in space for use on earth via microwave power transmission [5], [6], represents a realistic option for islands or locations with limited land space [7], [8]. At present, near-field, close-range inductive-coupling WPT has been widely commercialized in such applications as battery charging for mobile phones, household items, drones, and electrically powered vehicles [9], [10]. The potential and promise have only partially been fulfilled as the limitations of precise positioning and less than ideal charging speeds have become more acute as fast charging of mobile phones has become more important to the consumer.

The broad concept of magnetic resonance has been proposed to overcome the limitations. Recently, resonance-coil coupling was applied to demonstrate the transfer of 60 watts of power with 40% efficiency over 2 meters [11]. The incentives for this work are that it could open the door to transmitting enough energy to power electronic devices efficiently over a range such as a room without knowing exactly where the target receivers are in relation to the transmitter. The challenge is to fill spaces such as an office with the RF field levels necessary to provide useful amounts of power even over more than a few meters and not encountering human health and safety issues [12].

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This paper will provide discussions on the human safety implications of above-mentioned WPT technologies and applications and will highlight the exciting research opportunities for advances in architecture and technology that may evolve with energy harvesting across long distances using RF radiation schemes. The goal is to reach the potential for mobile communication devices to get their electric power the same way they get their data through harvesting ambient RF electromagnetic radiation. The dream is realization of a safe, truly wireless mobility scenario with completely tether-free electric power supply for mobile phones, laptops, and other electronic devices.

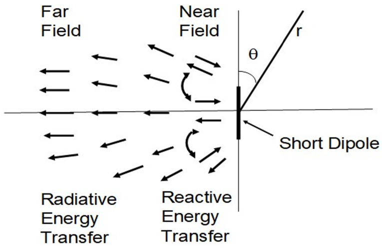

FIGURE 1. The flow of electromagnetic energy in the near- and far-zone from a short linear antenna (dipole) where the arrows represent the direction of energy flow at successive instants in time.

II. ENABLING ELECTROMAGNETIC LAWS

The laws of electromagnetics specify that the spatial distribution of fields from an RF source is directional and varies with distance from the antenna. The distance criterion commonly used to distinguish the reactive near or radiative far zone is that the phase variation of the field from the antenna does not exceed λ/16 [13]. This boundary often occurs at a distance of

$$R = 2D^2/\lambda \qquad (1)$$

where D is the largest dimension of the source antenna.

The near zone can be divided into two regions: the reactive region and the radiative region. The space surrounding the antenna, at points close to the antenna, in which the reactive component predominates is known as the reactive region. The precise extent of the regions varies for different antennas. For most antennas, the transition point between reactive and radiative regions occurs from 0.2 to 0.4 D^2/λ [14], where the reactive and radiative components are equal. In the radiative region, the region closer than $2D^2/\lambda$, the radiated power varies with distance from the antenna. Note that at 100 GHz, the wavelength is 3 mm, and the reactive induction zone is negligible. However, at 10 MHz the wavelength is about 30 m. Therefore, the corresponding induction field could encamp typical offices with workers in it for near-field WPT and communication devices using this frequency.

Invoking the Poynting vector shows that the induction fields represent energy that is stored in the electric or magnetic field during one-quarter of a cycle and is returned to the antenna during the next one-quarter of a cycle without a net or average outward flow [15]. In the near zone, the energy exchange is largely reactive. The energy transfer characteristics are illustrated in Fig. 1 where the arrows represent the direction of energy flow at successive instants in time. Power density in the near zone is not as uniquely defined as in the far zone, since the electric and magnetic fields vary from point to point. Furthermore, the angular distribution depends on the distance from the antenna. It is necessary to individually determine the power density at all points. In the radiative near-field region close to $2D^2/\lambda$, a circulating leakage component (an evanescent component) can also radiate power that varies with distance from the source.

In the near zone, the spatially varying electric and magnetic fields and their maxima and minima do not occur at the same point in space. Also, the electric field is shifted by 90° in time (in phase quadrature) from the magnetic field, as in a standing wave, where the electromagnetic energy is transferred periodically between the source and its field and is cycled back and forth between its electric and magnetic components. Thus, the electric and magnetic fields in the near zone may be treated as two independent fields. Indeed, the transfer of electromagnetic energy in the near zone may be conveniently realized using separate electric and magnetic field generating schemes such as shown in Fig. 2 using capacitive plates and inductive coil systems.

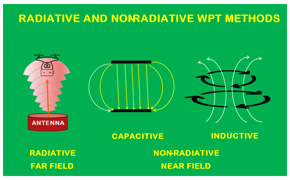

FIGURE 2. Schematic representation of radiative and non-radiative WPT technologies.

Instead of using axially aligned inductive coils, the outgoing radiating component (evanescent component) from the near field of an inductive coil may be received through RF resonance-coil coupling by off-setting the second or receiving coil and the use of smart frequency tuning for enhanced efficiency.

At points far from the source antenna, in the far zone, the electric and magnetic field components are uniquely defined. The wave impedance in the far zone is defined by the ratio of electric field to magnetic field, which is the same as the intrinsic impedance of the medium. Also, both the electric and magnetic fields are in time phase and are perpendicular to each other. Thus, the electric and magnetic fields in the far zone are related in the same fashion as in a plane wave.

In general, the far-field description of any antenna will involve seven physical parameters, regardless of how complex the antenna structure may assume. They include the antenna current, antenna size or length expressed in wavelengths, distance away from the antenna, intrinsic impedance of the medium, phase factor, and the pattern factor specifying the field variation with angle. For the case of a linear dipole antenna (8,9), the electric field, E_θ, may be written as

$$E_\theta = \frac{1}{2} I \frac{l_1 - \frac{1}{\lambda}\eta j}{r} e^{j(\omega t - \beta r)} sin\theta \tag{2}$$

where I is the antenna current, $\frac{l}{\lambda}$ is the antenna length expressed in wavelength, $\frac{1}{r}$ is the distance factor, η is the intrinsic impedance of the medium, $je^{j(\omega t - \beta r)}$ is the phase factor, and $sin\theta$ is the pattern factor specifying the angular field variation. Furthermore, the Poynting vector gives the direction and quantity of energy flow [16]. As shown in Fig. 1, energy flow in the far zone is outgoing in the axial or radial direction. The electromagnetic energy is radiated into space, and the term radiation zone is synonymous with far field. As in a plane wave, the electric and magnetic fields are outgoing waves with plane wave fronts; the field strengths decrease inversely with distance and the fields are reflected and refracted by material surfaces and are enhanced by standing-wave formation.

Typical features of far- and near-field WPT methods and technologies are given in Table 1. Antennas are used exclusively for the radiative operations using a wide spectrum of frequencies at high power or low power to reach receivers remotely at medium and long range. The non-radiative near-field resonance coil coupling approach can remotely cover the medium range using frequencies up to one GHz at relatively low power. The near-field coaxial induction coils are viable for a wider set of frequencies compared to capacitive plate systems with comparable power ratings, but both are restricted to short-range power transfer scenarios.

III. ELECTROMAGNETIC FIELDS FROM WPT SYSTEMS

WPT has been a hot research topic for the past decade. Near-field inductive-coupling WPT has been widely commercialized and are commonly found in many battery-charging applications for mobile phones, internet-of-things (IoT's) gadgets, and items for personal care [8]. WPT techniques are popular developments for electric cars and buses. They are gradually substituting for wired approaches for charging unmanned aerial vehicles (UAVs) used for agriculture, surveillance, and healthcare purposes [9]. Far-field WPT using RF-microwave radiation is expected to follow soon. Energy harvesting from ambient RF fields has also been demonstrated. Typically reported RF field levels for some of these are briefly described below. It will be followed by an examination of these field levels with respect to human health and safety.

TABLE 1. Typical Features of WPT Method and Technology.

Type	Far Field (Radiative)	Near Field (Non-Radiative)		
Method/ Technology	Antennas	Capacitive Plates	Inductive Coils (Coaxial Coils)	Resonance Coupling (Off-Set Coils)
Frequency	kHz - GHz	kHz - MHz	Hz - MHz	kHz – GHz
Power Capacity	High/Low	High/Low	High/Low	Low
Transfer Range	Medium/Long	Short	Short	Medium
Efficiency	50 - 90%	85%	85%	30 - 80%
Cited References	[3, 4, 5, 12]	[17]	[6, 15]	[7, 14, 15]

A. WPT FROM SOLAR-POWER SATELLITES

The concept of WPT from solar-power satellites was envisioned in the 1970's for generation of electric power by solar energy in space and for use on earth via microwave beam transfer [5]–[7]. The SPS-WPT in this case clearly takes place in the radiative far field. Currently, it is being explored as a source of clean energy or for remote installations [18]–[20]. For example, an SPS-WPT system would involve placing a constellation of solar power satellites in geostationary Earth orbits. Each satellite would provide between 1 and 6 GW of power to the ground, using a 2.45 or 5.8-GHz microwave beam (see Table 2). The power-receiving antenna (rectenna) on the ground would be a structure measuring 1.0 to 3.5 km in diameter. The higher (5.8 GHz) frequency becomes a viable option since it has a similar atmospheric transparency. Although, in principle, the higher frequency would allow a reduced size for the transmitting and receiving antennas, as can be seen from the table, some designs have opted for larger transmitting antennas and smaller rectenna sites with a larger power density on the ground to conserve land use (which is not essential if the rectenna site is on the sea).

Table 2 shows that at the center of the microwave beam, where power densities would be maximum, the proposed power densities range from 230 to 1800 Wm $^{-2}$ above the rectenna. At 2.45 GHz, the power density is projected to be 1.0 Wm^{-2} at the perimeter of the rectenna. Beyond the perimeter of the rectenna site or 15 km, the side lobe peaks would be less than 0.1 Wm^{-2}. These values are below the currently promulgated ICNIRP guidelines and IEEE standards of 10 Wm^{-2} [21]–[23]. The danger of loss of control of highly focused beams may be minimized by tightly tuned phased array techniques and by automatic beam defocusing to disperse the power in the event it occurs. Defocusing would degrade the beam toward a more isotropic radiation pattern, which would give rise to even lower power density on the ground. Near the center of the microwave beam, power densities would be extremely high. Except for maintenance personnel, human exposure would normally not be allowed at this location. In the case of occupationally required presence, protective measures such as glasses, gloves, and garments could be used to reduce the exposure to a permissible level.

TABLE 2. Microwave parameters proposed for WPT from solar power satellites.

System Design	NASA*	JAXA*	JAXA*
Frequency	2.45 GHz	5.8 GHz	5.8 GHz
Total transmitted power	6.72 GW	1.3 GW	1.3 GW
Maximum power density in beam	22,000 Wm^{-2}	630 Wm^{-2}	1,140 Wm^{-2}
Minimum power density	2,200 Wm^{-2}	63 Wm^{-2}	114 Wm^{-2}
Power/element	185 W	0.95 W	1.7 W
Antenna elements	97 million	3,450 million	1,950 million
Transmit antenna size	1.0 km dia	2.6 km dia	1.93 km dia
Amplitude taper	10dB Gaussian	10dB Gaussian	10dB Gaussian
Rectenna size	1.0 km dia	2.0 km dia	2.45 km dia
Power density above rectenna	230 Wm^{-2}	1,800 Wm^{-2}	1,000 Wm^{-2}
Power density at rectenna perimeter	0.1 Wm^{-2}	1.0 Wm^{-2}	1.0 Wm^{-2}
Power density at 15 km away from rectenna	0.1 Wm^{-2}	0.1 Wm^{-2}	0.1 Wm^{-2}

*National Aerospace Administration (NASA) **Japan Aerospace Exploration Agency (JAXA)

B. INDUCTIVE WPT TECHNOLOGY

Since Panasonic's commercialization of the inductive battery charger in the 1980's, near-field inductive energy transfer has become the most widely used WPT technology. Its applications have proliferated to include wireless sensors, watches, mobile phones, aerial drones, and electric vehicles including cars, buses, and trains along with material transport systems in warehouses and cleanrooms with cars being the most prevalent of electric vehicles. Note that currently most near-field inductive WPT for charging mobile phones permits power profiles from 5 to 15 W by industry agreed-upon protocols.

TABLE 3. Measured magnetic fields from electric shuttle bus with WPT at 20 kHz with shielding for stray magnetic field emissions.

Measurement Location	Magnetic Field	ICNIRP Guidelines (3kHz – 10 MHz)	IEEE Standards (3.35 kHz – 5 MHz)
Driver's side, between wheels	2.3 – 7.2 μT	27 μT	205 μT
Door side, between wheels	7.2 – 7.5 μT	27 μT	205 μT
Inside bus at floor level over coils	4.1 μT	27 μT	205 μT
Inside bus at 3ft above floor over coils	0.41 μT	27 μT	205 μT
Inside bus at 6 ft above floor over coils	0.21 μT	27 μT	205 μT
Ambient background	0.13 μT		

A recent review of reported magnetic fields distributions within or outside the vehicle at several distances and including misalignment conditions [24] suggested that in none of the investigations described in the quoted publications [25]–[31], the measured magnetic or electric fields during charging exceeded either the ICNIRP or IEEE exposure limits when proper shielding is involved. As an example, Table 3 gives a list of measured magnetic fields from electric shuttle bus with WPT at 20 kHz with shielding for stray magnetic field emissions [32], [33]. Note that all the measured magnetic fields during charging process were about a quarter or lower than the ICNIRP limits and were more than 27 times below the more lenient IEEE exposure standards. However, some computer simulations (verified by physical measurements) showed that a typical WPT system at 85 kHz delivering 10 kW of power for passenger electric vehicles can produce a magnetic field strength of 49 A/m around the WPT system mounted on the center-back of the car, delivering 10 kW of electric power [30], which clearly exceeds the ICNIRP exposure guideline of 21 A/m but is well below the 163 A/m allowed by IEEE.

C. ENERGY HARVESTING FROM AMBIENT RF FIELDS

A fascinating rationale for the interest in battery charging through WPT comes from the potential for mobile communication devices to get their electric power the same way they get their data through harvesting ambient RF electromagnetic radiation. A principal challenge of energy harvesting is the amount of power available from ambient RF radiation. The first steps in realizing the dream of a truly wireless mobility scenario with completely tether-free electric power supply were reported in 2017. A prototype battery-free mobile phone harvesting 3.5 μW of power was demonstrated by using a combination of analog and digital circuit architectures and a high-efficiency rectenna [34], [35]. The prototype mobile phone was able to place voice calls by harvesting RF power at a distance of 9.4 m from the laboratory base station.

It is significant to note that at present, the maximum allowable power consumption is 125 to 250 mW for mobile phones, which are about 5 orders of magnitude higher than the prototype's power consumption. It is conceivable that future developments would enable mobile phone operations with data transmission via enough energy harvesting without any concern for RF health and safety. Moreover, the minuscule 3.5 μW of power consumption suggests that the high levels of currently allowable 125 to 250 mW RF powers for mobile phones may become unnecessary in the future. Low-power wireless devices may be able to constantly transmit or receive data and voice calls over long distances via energy harvesting without batteries. Of course, it remains imperative to be vigilant so that the enabling ambient RF radiation will not reach such high levels that would make itself a source for health and safety concerns.

CONCLUSION

WPT systems are being deployed to provide needed electric power either directly or via battery-charging services using a very wide RF spectrum. It has been shown that existing and proposed WPT systems can operate within currently promulgated RF exposure limits, except for a few isolated cases during battery-charging maneuvers associated with electric cars such as during battery-charging. A truly wireless mobility scenario with completely tether-free electric power supply for mobile phones, laptops, electric appliances, and various modes of transportation systems is sustainable. An exciting prospect is the development of low-power, battery-free wireless devices to enable real-time transmission and reception of data and to make voice calls over long distances via energy harvesting. Further progress in this regard would enable mobile phone operations via energy harvesting with minimal concern of RF health and safety.

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