Chapter

Introductory Chapter: Wireless Power Transmission – An Overview

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1. Introduction

Wireless power transmission (WPT) refers to the process of transferring and harvesting electrical energy without the use of wires and cables. Although this technology has only started to gain traction in about a decade or two ago, the idea of realizing WPT is not new and can be dated back to the turn of the twentieth century, about 150 years ago. Inspired by the experimental observations reported independently by André-Marie Ampère, Michael Faraday, and Carl Friedrich Gauss, James Clerk Maxwell established the unified theory of electricity and magnetism and published his formulations in his textbook "A Treatise on Electricity and Magnetism" in 1873 [1]. These four sets of notable equations outline the fundamental principles of electromagnetism and have contributed significantly toward the development of technology based on electromagnetic fields and waves. In the late 1800, Heinrich Hertz conducted a series of experiments, which successfully verified the presence of electromagnetic waves theorized by Maxwell. In one of his experiments, Hertz showed the propagation of waves in air. In 1886 to 1889, Hertz proved that the electric and magnetic field vectors are perpendicular to each other and to the propagating direction [1]. The discoveries of these scientists have laid the cornerstone that sparked the exploration of wireless technology. Nikola Tesla was the first scientist to demonstrate experimentally the feasibility of transferring power wirelessly *via* inductive and capacitive couplings. In 1881, Tesla invented the Tesla coil, *viz.* a resonant transformer with the coils separated by air-gap, which could be used to generate low-current, high-voltage, and high-frequency electricity. By connecting the Tesla coil to a coupled oscillatory circuit with a spark gap driven by a low-frequency alternating-current (AC) or direct current (DC) source, he showed that light could be generated by the strong electric field when it was passing through a rarefied tube [2]. Tesla's continuous relentless study on this matter gave him the epiphany that the technology could one day be used to drive motors and switch lamps at considerable distance from the source. Following this discovery, Tesla gave a series of lectures and demonstrations on his wireless technology in 1892 and 1893 and among the gist of his lectures was his speculation of using wireless technology to transmit information and power. Wireless telecommunication and wireless power transmission are ubiquitous to mankind today; however, these concepts were flabbergasting when it was first suggested by Tesla more than a century ago. Tesla lit light bulbs across the stage when demonstrating before the American Institute of Electrical Engineers and at the 1893 Columbian Exposition in Chicago [3]. In 1899, he used a 108 V high-frequency power to wirelessly turn on Geissler tubes [4, 5]. He further showed in his Colorado Springs laboratory in 1899 to 1900 that his experimental setup was able to lit three incandescent lamps at a distance of about 30.5 m [3]. In March 1901, Tesla obtained $150,000 from J. P. Morgan to build the 57-m tall Wardenclyffe tower in Shoreham, New York. The Wardenclyffe tower was intended to be used as a power plant to transfer electrical energy through the ionosphere, over large distances. It was indeed unfortunate enough, though, the project ended in vain in 1905. Tesla had no choice but to abandon it when he failed to secure investments to support the Wardenclyffe tower project. Due to his bold idea on wireless power transmission at his time and his discovery on wireless communication, nevertheless, Nikola Tesla was regarded as the "Father of Wireless Technology" today [6].

The daily lives of mankind today are interwoven seamlessly with electrical and electronic (E&E) devices. Wherever we are and whatever we are doing, there are certainly E&E devices that we rely on. This is to say that E&E products have become an indispensable commodity to mankind. The variability of these E&E products is wide and may range from telecommunication gadgets such as cell phones, to living accessories such as toothbrushes and razors, to transports such as electric cars and scooters. It is to be noted that E&E devices could only operate with the supply of electrical power. One way to empower these devices is to tether them to the power grid. Although it is immaculately fine to do so, fettering an E&E device with wires actually restricts its portability and mobility, rendering it cumbersome to be used and limiting the distance of its usage. Take for instance, a vacuum cleaner or a phone that can only operate when it is connected to the source using wires. The functional distance of the device is significantly bounded by the effective length of the wire. The inconvenience caused by wires can be overcome if the devices are modified to operate wirelessly, using batteries. The advent of the wireless technology provides the flexibility for users to use the E&E devices remotely, without the worries of the limitation imposed by distance. Even so, however, a wireless device such as a cellular phone or an unmanned aerial vehicle (UAV) is, strictly speaking, not entirely "wireless" after all. Despite the prevailing advancement of wireless technology, there still comes a time where a wireless device has to be connected by wires to the power grid for battery recharging. An E&E device could only become completely portable and mobile when it is disentangled from this last cut of wires. To do so, the batteries attached to the device have to be facilitated with the function of being wirelessly charged. The hope to realize a fully wireless E&E device has prompted the scientific community to devote vigorous researches related to wireless power transmission [7]. This chapter presents a brief overview of different wireless power transmission (WPT) methods. Like a wireless telecommunication system, the energy radiated from a WPT system attenuates along with distance. To improve the effective distance of power transmission, parasitic wires can be integrated into the system. An elaboration of this method is described at the later part of the chapter.

2. Wireless power transmission mechanisms

Based on the separation distance d between the transmitting and receiving antennas, the mechanisms are employed to transfer power wirelessly bifurcate into those used in the (i) near- and (ii) far-field regions. As can be seen in **Figure 1**, when both the antennas are placed in close proximity, within the distance of a wavelength (λ), the WPT system is said to be operating in the near-field region. In this region, both reactive and radiative fields exist. Fields close to the transmitting antenna (i.e., $d \le \frac{\lambda}{2\pi} \approx 0.16\lambda$) are literally reactive and the phases between the

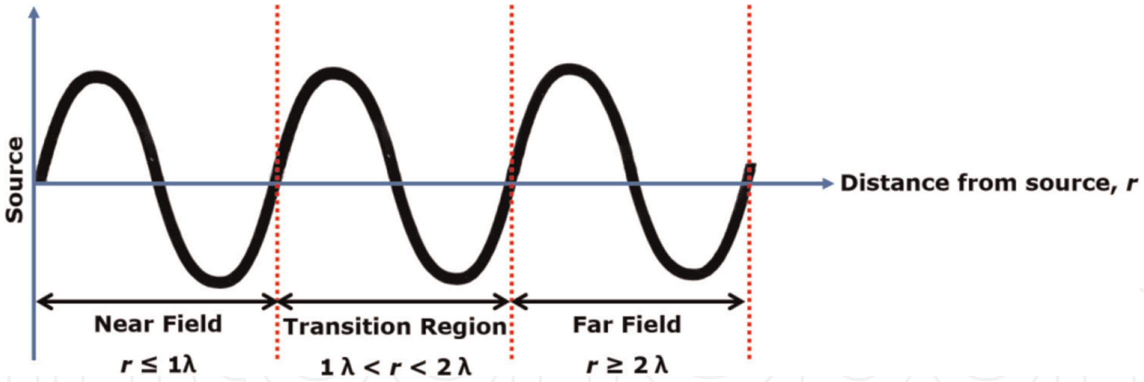

Figure 1.
Field regions for antenna size not more than 0.5λ.

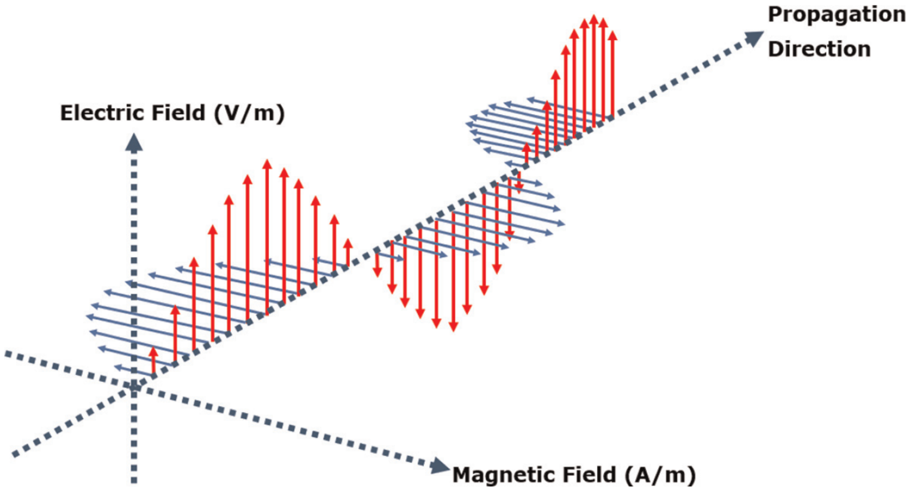

Figure 2.
Transverse electromagnetic wave.

electric and magnetic fields differ by 90°. In the reactive near field, the energy exchanges periodically between the reactive loads and the source, resulting in zero average power. At $\frac{\lambda}{2\pi} \leq d \leq \lambda$, and the fields start to radiate; but the intensity of the fields decays at a fast rate, which is inversely proportional to d^3 and, likewise, the power density is inversely proportional to d^6. When the distance between both antennas is at least two wavelengths (2λ) apart, the system is said to operate in the far field. Owing to propagation delay, the electric and magnetic fields are orthogonal, but in phase with each other in this region, both fields polarize perpendicularly to the direction of propagation. This type of wave is known as the transverse electromagnetic or TEM wave and is graphically depicted in **Figure 2** [8]. At the far-field region, the fields decay as $\frac{1}{d}$, which is relatively slower than the case of the radiative near field, while the power density decays as $\frac{1}{d^2}$. As can be seen in **Figure 1**, the transition zone lies between the near and far fields. Both near and far fields fade into each other here. Hence, the transition zone exhibits the characteristics of both fields in this region.

2.1 The near-field mechanism

The near-field mechanism transmits power wirelessly from the source to the load based on the inductive or capacitive coupling. In inductive or magnetic

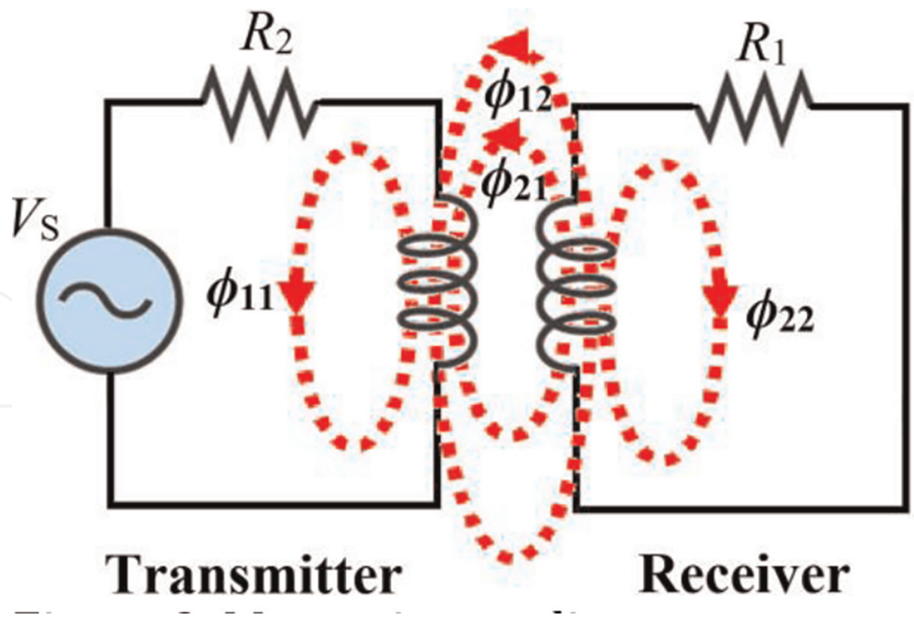

Figure 3.
Magnetic coupling.

coupling, power is generated at the load *via* the variation of magnetic flux. The operational concept of this type of energy transfer is rather similar to how a transformer works. **Figure 3** depicts the circuit schematic used for inductive coupling. As can be seen in figure, the AC source at the transmitter creates magnetic flux at the coils. The total magnetic flux can be classified into two parts—the individual flux induced in the transmitter and receiver coils and the flux induced by the transmitter coil that interlinks to the receiver coil, and *vice versa*. According to Faraday's law, when the magnetic flux density **B** varies with time t, voltage V is induced, that is, [8]

$$V = -\int_S \frac{\partial \mathbf{B}}{\partial t} \cdot dS \tag{1}$$

where S is an arbitrary surface in space. Hence, by virtue of this law, power is delivered from the transmitter source to the receiver load, without the physical need of connecting the transmitter and receiver circuits together [6]. When power is transferred from the primary coil to the secondary, a fraction of it tends to be lost in air. To minimize the loss, it is advisable to place the circuits at the same plane and at close proximity. The coupling between the coils can also be increased using wide and flat coils. Like the case of a transformer, the intensity of the magnetic field and current is directly proportional to the number of turns of the coil n. Hence, by increasing n, the efficiency of inductive coupling can be improved accordingly. Some of the available WPT systems that work based on the inductive coupling concept are rechargeable toothbrushes and razors.

Since the fields in this region are non-radiative in nature, the energy decays rapidly. The effective distance of the power transferred using the inductive coupling method is not more than the size of the antenna. To increase the effective distance, the transmitter and receiver circuits can be modified into resonant circuits. This type of WPT method is known as resonant inductive coupling (RIC). To enable power transmission, the primary and secondary coils have to resonate at the same frequency. The resonance frequency f_r can be determined using Eq. (2) below

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

where L is the inductance of the coil and C the capacitance in the circuits. By employing RIC, the effective distance can be extended by 10 times of that obtained by the conventional inductive coupling method. Charging pads for cell phones and other handheld devices are examples of WPT systems, which operate using RIC. Some implantable medical devices (IMDs), such as the implantable glucose sensors used mostly by diabetes patients and pacemakers for patients with irregular heart palpitations, are remotely charged using the RIC method as well.

The capacitive or electric coupling method makes use of the variation electric flux to generate power at the load. **Figure 4** illustrates the different types of circuit configurations used for capacitive coupling [9, 10]. Upon inspection on the figure, it can be observed that pairs of electrodes are commonly found in all configurations. The electrodes are usually made of metallic plates. With air sandwiched in between the plates, capacitors are formed. According to Maxwell, the time rate of change of electric flux density $\mathbf{D}$ leads to a displacement current I_D [11], that is,

$$I_D = \frac{\partial \mathbf{D}}{\partial t} \tag{3}$$

Hence, when the electric flux imposed on the coupled plate varies with time (due its connection to the oscillating voltage source), a displacement current is generated to deliver power from the transmitter to the receiver [12]. Since the plates act as capacitors, the efficiency of power transfer can be enhanced by increasing the area of the plates and reducing the intervening air gap. Some charging pads and IMDs also operate based on capacitive coupling. Like the case of its inductive counterpart, the effective distance of capacitive coupling is rather limited. Hence, resonant circuits can also be introduced into it to ameliorate its performance. **Figure 5** depicts the schematic of a resonant capacitive coupling circuit [13]. The transmitter circuit in the figure is supplied with a V_{in} source with an internal resistance of R_{in} embedded in it and the energy generated is to be transferred to the R_{load} resistor at the receiver circuit. The transmitter and the receiver circuits are capacitively coupled through capacitances C_3 and C_4. Capacitor C_1 and inductor L_1 are incorporated into the transmitter circuit to generate the resonance effect. Likewise, C_2 and L_2 serves the same purpose as C_1 and L_1 at the receiver circuit. The resistors R_1 and R_2 account for the losses experienced, respectively, by L_1 and L_2.

2.2 The far-field mechanism

To realize wireless power transmission in the far-field region, the energy carried by the electromagnetic waves has to be radiated from the transmitting antenna, propagates in air for a distance, and is finally coupled to the receiving antenna.

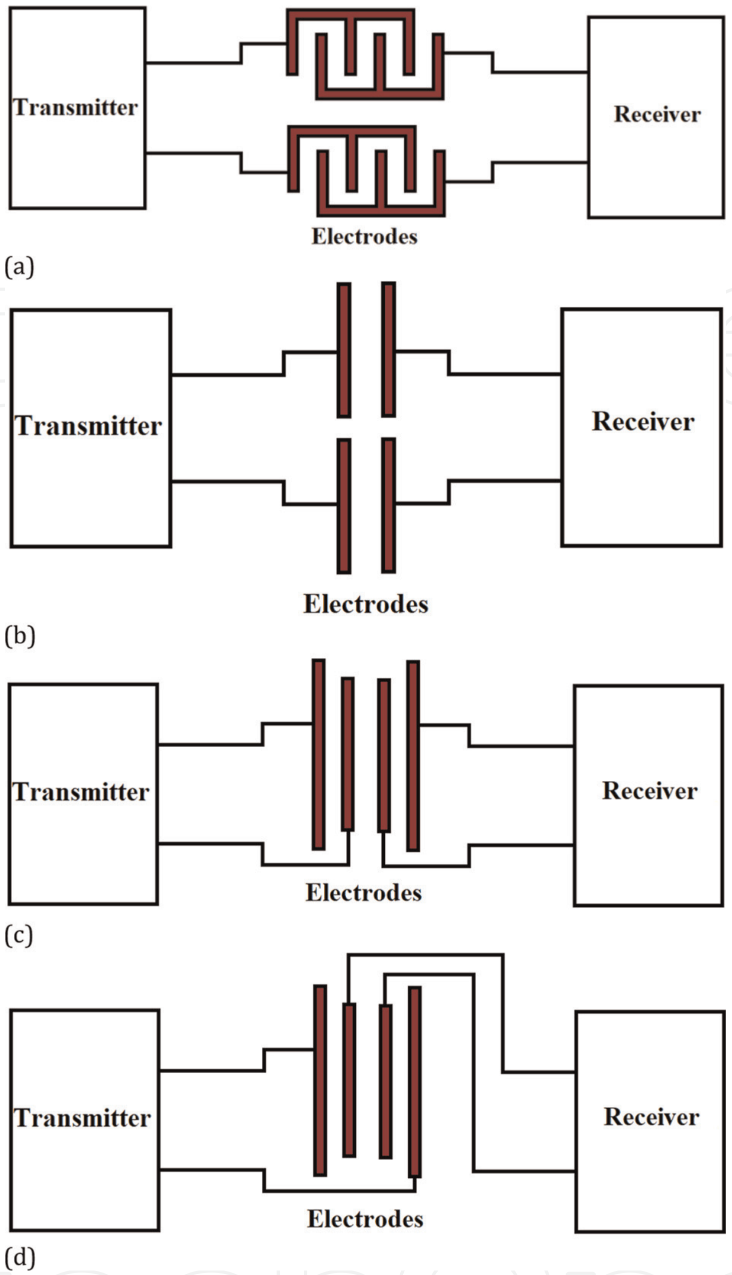

Figure 4.
Different types of capacitive coupling structures, that is, the (a) stack array structure, (b) the conventional two-plate structure, and the modified two-plate structures proposed by (c) Zhang et al. *[9] and, (d) Han* et al. *[10].*

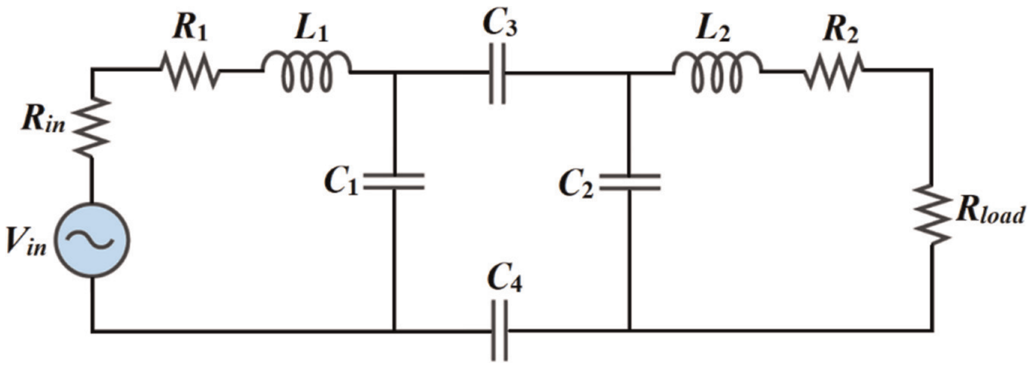

Figure 5.
Circuit model of a resonant capacitive coupling circuit.

For an electromagnetic wave to propagate, it has to satisfy Helmholtz's equation. Since air is lossy and homogeneous in nature and assuming that it is also source free, Helmholtz's equations for the electric **E** and magnetic **H** fields can be written as

$$\nabla^2\mathbf{E} + k^2\mathbf{E} = 0 \tag{4}$$

$$\nabla^2\mathbf{H} + k^2\mathbf{H} = 0 \tag{5}$$

where $k = \beta - j\alpha$ is the wavenumber in air and β and α are, respectively, the phase and attenuation constants, which, for a TEM wave, can be expressed as [14],

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right]} \tag{6}$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} + 1\right]} \tag{7}$$

where ω is the angular frequency, and σ, ε and μ are, respectively, the electrical conductivity, electrical permittivity, and magnetic permeability of air. It is worthwhile noting that air is usually assumed lossless in most textbooks because its conductivity is very small. In reality, however, the conductivity of air ranges from 3 to 8 fS/m, depending on the humidity of air [15]. The solutions of (4) and (5) represent waves propagating with a velocity of $\frac{1}{\sqrt{\mu\varepsilon}} \approx 3 \times 10^8 \mathrm{m/s}$.

The efficiency of wireless power transmission is essentially determined by the designs of the transmitting and receiving antennas. To ensure that the signal is effectively delivered by the transmitting antenna, the following performance indicators are used for design assessments [14]:

i. Radiation pattern

The radiation or antenna pattern is a graphical representation of the field intensity or power density in terms of spatial distribution, when the field radiated from the antenna.

ii. Radiation intensity

The radiation intensity refers to the power radiated by the antenna at a unit solid angle.

iii. Directive gain

The directive gain shows the concentration of the radiated power at a specific direction. It compares the radiation intensity in that direction with the average radiation intensity.

Since waves tend to diffract as they propagate, spill over loss is inevitable. To minimize such loss, high-directivity antennas capable of exhibiting radiation patterns in the shape of a pencil beam are preferred.

When collecting the power from the radiation, the effective area of the receiving antenna is to be optimized. The effective area dictates the ability of the receiving antenna in coupling energy scattered to it. The effective area A_e is given as

$$A_e = \frac{G_d \lambda^2}{4\pi} \tag{8}$$

where G_d denotes the directive gain. In 1946, the Danish-American engineer, Harald Trap Friis modified the effective area equation in (8) so as to relate the power received by the receiving antenna P_r from the transmitting antenna P_t at far field. The equation, which is more commonly called the Friis transmission formula these days, is mathematically described in (9) below,

$$P_r = G_{dr} G_{dt} \left(\frac{3 \times 10^8}{4\pi d f} \right)^2 P_t \tag{9}$$

where f is the operating frequency and G_{dr} and G_{dt} are, respectively, the directive gains of the receiving and transmitting antennas. Friis formula comes in handy when designing the receiving antenna since the relationship between both the transmitting and receiving antennas can be easily found, without the need to figuring out the effective area. Upon inspection of (9), it can also be observed that the received power P_r drops with the square of the signal frequency f. This is to say that, although signal with higher frequency has the advantages of carrying higher energy and that the size of the system that supports it can be greatly miniaturized, it suffers the drawback of high path loss. The loss is particularly conspicuous when the distance of energy transfer is far. Hence, for a system to transfer energy wirelessly to a reasonably long distance, Rosa et al. [16] recommended f = 900 MHz to be the best trade-off.

Since both the WPT and telecommunication systems radiate and collect electromagnetic signal, their theory of operations is rather similar. **Figure 6** depicts the block diagram of a general WPT system. As can be seen from the transmitter module, the AC source is first rectified to produce DC signal. The signal is then modulated to radio frequencies (RF) and emitted to air. The RF wave is harvested by the rectenna at the

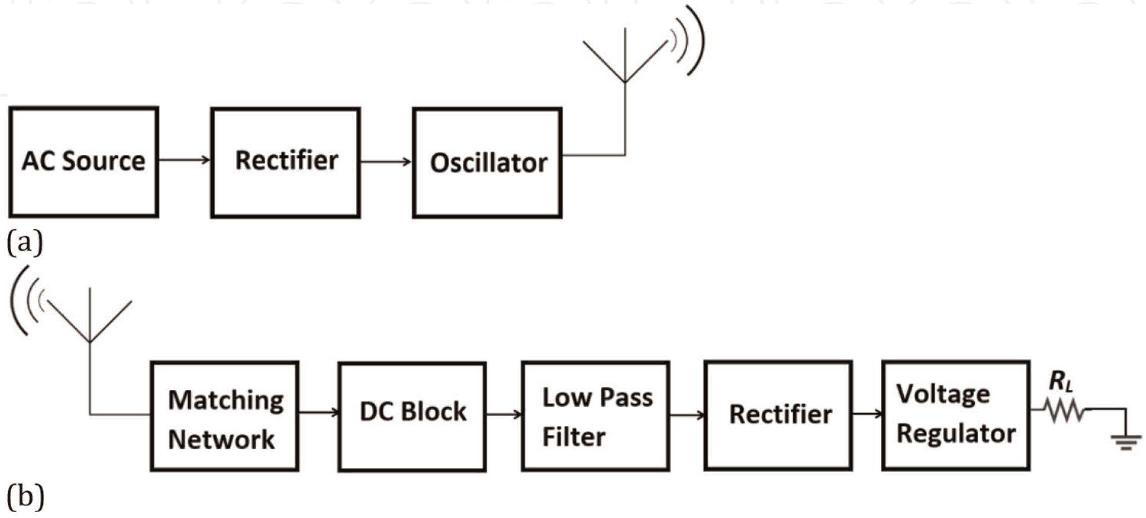

Figure 6.
Block diagrams for the (a) transmitter and (b) receiver circuits.

receiver. The rectenna constitutes the receiving antenna and a rectifier circuit, which is used to convert the RF signal into DC power. As can be seen in **Figure 6**, the output of the rectenna is connected to the load resistor. Upon coupling the incident RF signal to the receiving antenna, the energy is fed to a matching network such as an open-ended single stub tuner [17]. The purpose of the matching network is to provide impedance matching, so that wave reflections can be minimized [18]. A DC block is connected between the matching network and the rectifier circuit to filter any DC signal from passing to the rectifier circuit. The rectifier circuit constitutes nonlinear devices such as diodes. Various spectral components are produced at the output of the nonlinear devices, including the DC component, the AC fundamental frequency and its harmonics, and the intermodulation mixing products [19]. The low-pass filter connected in cascade with the rectifier circuit is used to filter the unwanted components, so that only the DC signal remains, and to recover the efficiency degradation caused by the junction capacitance of the diodes [17]. The last block before the DC signal reaches the load resistor R_L is the regulator, which can be easily constructed using a parallel-connected capacitor and Zener diode. The regulator suppresses the ripples so that a smoothened DC signal is received at the output.

3. Optimization using parasitic wires

As mentioned in the preceding section, the power density of the waves attenuates rapidly along with the propagation distance. This phenomenon is corroborated by the experimental findings by Kurs et al. in [20]. When sending a 9.9 MHz signal to remotely light up a light bulb, the researchers found that the efficiency of the RIC system dropped more than 50% at a distance above 2 m, which corresponds to about 0.066λ. The result will, of course, be worse for a nonresonant WPT system.

One way to improve the effective distance of wireless power transmission is to introduce parasitic wires into the system [7, 21, 22]. As shown in **Figure 7**, the parasitic wire, which could be in the form of circular or rectangular geometry, is inserted in between and along the same axis as the transmitting and receiving

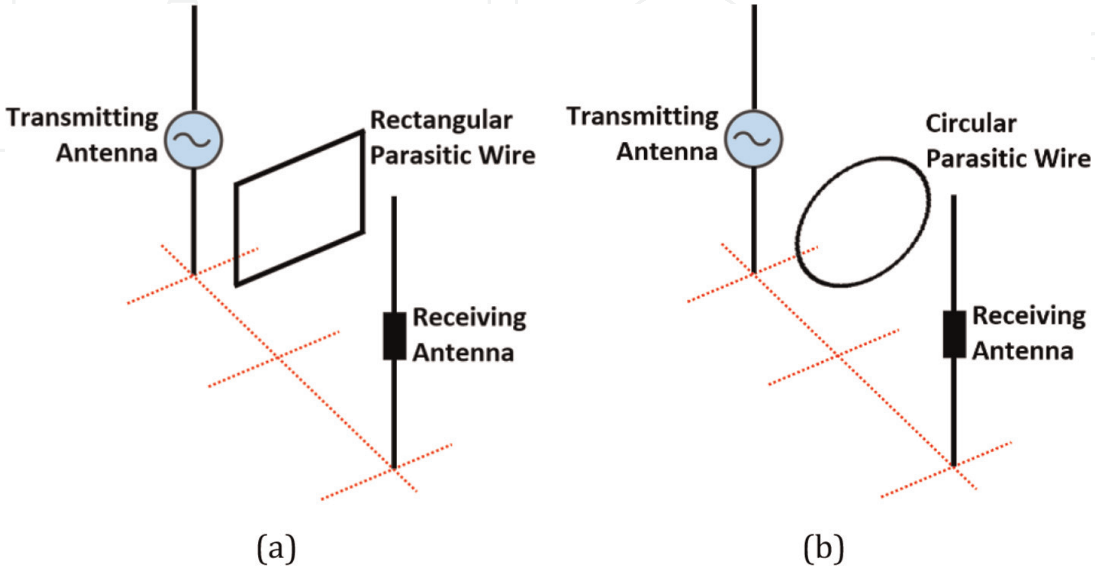

Figure 7.
A wireless power transmission system integrated with a (a) rectangular and a (b) circular parasitic wire.

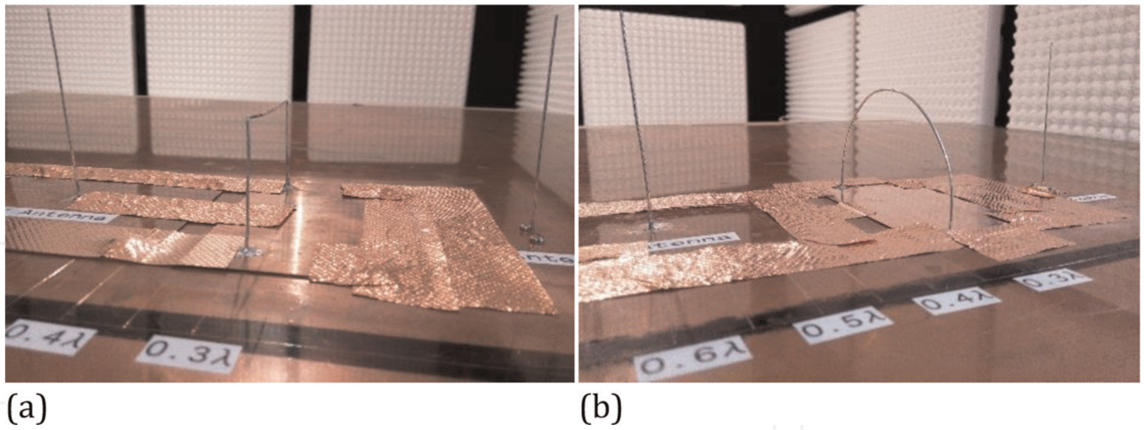

Figure 8.
Experimental setup of a wireless power transmission system integrated with a (a) rectangular and a (b) circular parasitic wire.

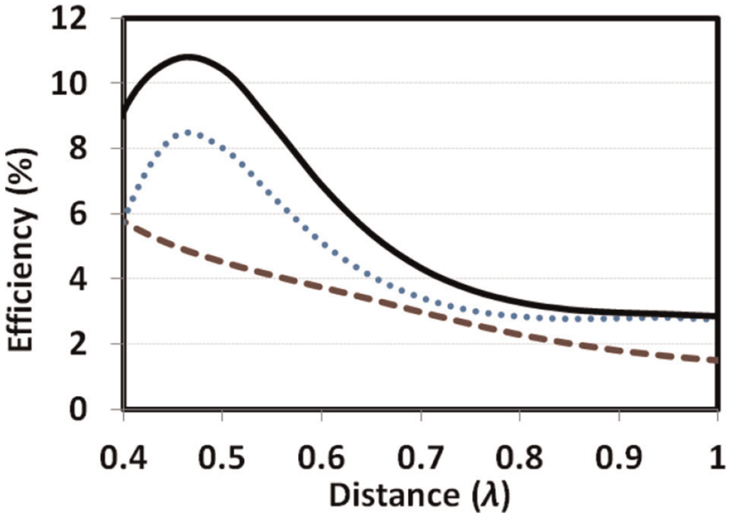

Figure 9.
The power efficiency of a conventional wireless power transmission system (dashed line) and those with a circular (dotted line) and square (solid line) parasitic wire.

antennas. Measurements were taken from the experimental setups based on the image of theory, as depicted in **Figure 8**. In the experiment, a 1 GHz signal was transferred between the 0.15-m transmitting and receiving antennas, with a square- or circle-shaped parasitic wire inserted between them. Despite having different geometries, both parasitic wires in the figures constitute an identical size of 0.3 m. The comparison between the efficiencies of the systems with and without the parasitic wires is given in **Figure 9** [7]. The efficiencies of the system with parasitic components, as seen in the figure, increase along with distance and reach their crests at approximately 0.45λ away from the transmitting antenna. The efficiencies subsequently decrease exponentially at distance beyond the crests. Even so, it can be observed that, the efficiencies of the systems with parasitic components are consistently higher than that without. This phenomenon can be attributed to the additional energy scattered from the parasitic wires. Besides the direct electromagnetic energy radiated from the transmitting antenna, the receiving antenna also collects the additional scattered energy. Unlike their conventional counterparts that suffer from path losses at the instant waves radiate from the antenna, the WPT systems with parasitic components is clearly more effective in conserving the energy carried by the waves.

4. Conclusion

In this chapter, a general overview of near- and far-field wireless power transmission (WPT) system is presented. By sparing the physical need of wire attachment, the WPT technology inculcates portability and mobility in E&E devices. Although both the near- and far-field mechanisms allow energy to be wirelessly transferred, their underlying principles differ. In the near-field mechanism, the electrical energy harvested at the load is generated from the variations of electric or magnetic fields at the intervening space between the transmitter and receiver. The far-field mechanism, on the other hand, exploits wave radiation to carry the energy. Nonetheless, the efficiency of both mechanisms deteriorates along with distance. The distance of effective power transmission can be extended if parasitic wires are integrated into the system.

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