A REVIEW ON WIRELESS POWER TRANSFER IN FREE SPACE AND CONDUCTING LOSSY MEDIA

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ABSTRACT

Recently, the interest in wireless power transfer (WPT) has significantly increased due to its attractive applications. The power transfer efficiency and communication range of most of the existing WPT systems are still limited, which is due to many technical challenges and regulation limitations. This requires more research and technical efforts to overcome the current limitations and make WPT systems much more efficient and widely used. This paper aims at reviewing recent advances and research progress in the area of WPT for the purposes of addressing current challenges and future research directions. To obtain these purposes, an introduction to WPT is provided. Also, main research themes of WPT in free space and lossy media are discussed. Additionally, the benefits of using split ring resonators WPT in conducting lossy media are investigated. This will be very helpful to boost WPT in lossy media and inspire more optimized structures for further improvement.

KEYWORDS

ICPT, MPT, PTE, UWICPT, WPT.

1. INTRODUCTION

Wireless power transfer (WPT) is a process of transferring electrical energy from transmitter to receiver ends without wires. It can be applied to power and charge different devices, such as mobile phones. Such applications will be very beneficial to increase the life time of devices and save their internal space which is mainly occupied by batteries. Additionally, WPT is green for the environment, as no batteries may be used [1]. The principle of WPT has been introduced since the days of Nikola Tesla and WPT has been adopted for commercial use for some small items, such as phones, toothbrushes and cochlear implants [2]-[4]. However, power transfer efficiency and range for most of commercial systems are still limited. Due to the promising applications of WPT in different media, research is ongoing to improve the efficiency and feasibility of WPT despite its challenges.

WPT techniques fall mainly into two categories: non-radiative and radiative techniques [2]. Most of research themes of all WPT types focus mainly on increasing power transfer efficiency and range. The research progress in the area of WPT has been reviewed in this paper. Compared to other related review papers, this paper elaborates the challenges of WPT in conducting lossy media, such as the human body. Further, it summarizes the work that has been conducted in the area of WPT to implantable and underwater devices. Additionally, it indicates the beneficial effect of using a layer inspired by split rings around antennas in a lossy medium on the WPT process. This paper is arranged as follows: First, an introduction to the principle and types of WPT is provided. Then, the research that has been conducted in the areas of inductive and microwave-based WPT in free space and lossy media (the human body and underwater devices) is reviewed and related challenges are summarized. Finally, the beneficial effect of using a layer inspired by split ring resonators on boosting WPT in lossy media is indicated and demonstrated by measurements.

2. TYPES AND PRINCIPLE OF OPERATION

The principle of operation and main characteristics of different types of WPT are discussed and summarized in this section.

2.1 Non-Radiative WPT

In non-radiative techniques, power is transferred by the following methods:

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2.1.1 Inductive Coupling Power Transfer (ICPT)

A typical inductive coupling system is shown in Figure 1. It is composed of transmitter and receiver coils (TC and RC, respectively) of self-inductances of L_{TX} and L_{RX} (H), respectively. The TC is connected to an AC source of V_s (V) voltage and R_s (Ω) internal resistance and the RC is connected to a load resistance R_L (Ω). A current $i_1(t) = I_1 \sin(\omega t)$ passing through the primary coil produces a magnetic field as explained by Ampere's law given in Equation (1). Most of this magnetic field links the secondary coil which induces a voltage and current as explained by Faraday's law given in Equation (2). Hence, power can be delivered to the load.

$$\oint \vec{H}.\overrightarrow{dL} = i\,. \tag{1}$$

$\vec{H}$ (A/m) is the magnetic field intensity and $\overrightarrow{dL}$ (m) is a differential length element along the closed path that encloses the current i (A) [5].

$$emf = -N\frac{d\Phi}{dt}\,. \tag{2}$$

emf (V) is the electromotive force (induced voltage), N is the number of turns of the secondary coil and Φ (Wb) is the magnetic flux [5].

The flux linkage between coils is proportional to the current $i_1(t)$and mutual inductance between coils (M); $\Phi = M\, i_1(t)$. Hence, the voltage at the receiver terminals $V_r(t)$ (V) can be expressed as [6]:

$$V_r(t) = M\frac{di_1(t)}{dt} \equiv M\,\omega I_1 \cos(\omega t)\,. \tag{3}$$

This technique offers the advantages of simplicity and safety. Also, energy is stored in the region between coils and no radiation will be lost to the surrounding area. Therefore, it has been widely used in different applications, such as charging medical implants. However, this technique has the shortcomings of short transmission range and sensitivity to misalignment between transmitter and receiver coils. Additionally, strong electromagnetic fields can be harmful to the human health. Therefore, it is important to evaluate the resonant system for WPT applications where humans are exposed to electromagnetic fields to ensure that the safety levels enacted by the European Union [7] are satisfied. If the distance between coils increases, the induced voltage at the receiver decreases. To increase the power transmission efficiency (PTE) over a longer distance, resonant circuits are used as will be discussed in the following section.

2.1.2 Magnetic Resonant Coupling (Electrodynamic Induction)

A typical magnetic resonant coupling system is shown in Figure 2. It is composed of transmitter and receiver coils and capacitors. For simplicity, the self-inductance for each coil is supposed to be (L (H)) and the capacitance of each capacitor is (C (F)). Maximum power transfer occurs at the resonant frequency to which the resonant circuits in the transmitter and receiver are tuned. If the distance between coils increases, the mutual coupling between coils decreases and thus $V_r(t)$ decreases accordingly (see Equation (4)). The frequency or TC current can be increased to compensate for any reduction in the induced voltage [6], [8]. However, the current in the transmitter coil is usually utilized to increase $V_r(t)$ as electromagnetic radiation and hence power dissipation around the system is possibly generated at very high frequency [6]. When a resonant frequency of $\omega_{res} = 1/\sqrt{LC}$ is approached, the currents in coils grow to the huge resonant currents $i_{1res}(t)$ and $i_{2res}(t)$ (A) at the transmitter and receiver coils, respectively. These currents produce a noticeable voltage at the receiver ($V_r(t)$) and hence enough power can be delivered to a proper load [6]:

$$V_r(t) = M\frac{di_{1res}(t)}{dt} + L\frac{di_{2res}(t)}{dt}\,. \tag{4}$$

Another effective parameter of the magnetic resonant power transfer system is the quality factor (Q-factor), which is a measure of the ratio between the energy stored by L and C and the energy loss rate (the loss is represented by R in the circuit) [9]. In general, resonators of high Q-factors are required for an efficient power transfer at small coupling levels and longer distance between the transmitter and receiver [10]. The main shortcoming of this technique is the difficulty to adjust the resonant frequency when charging multiple devices [11]. Also, at close ranges when the two resonant circuits are tightly coupled, the resonant frequency of the system is no longer constant, but "splits" into two resonant peaks, so the maximum power transfer no longer occurs at the original resonant frequency and the oscillator frequency must be tuned to the new resonance peak [12].

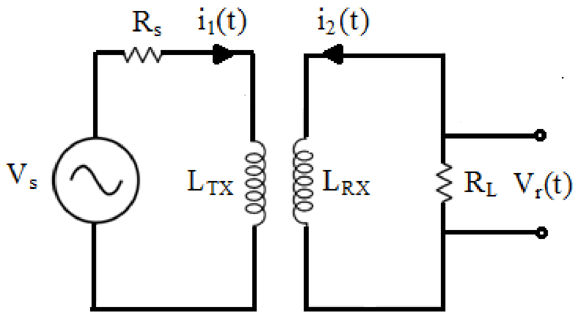


Figure 1. A typical inductive coupling system [6].

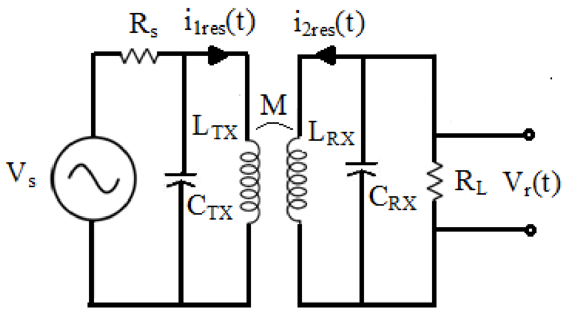


Figure 2. A typical magnetic resonant coupling system.

2.1.3 Capacitive Coupling (Electrostatic Induction)

In this technique, the transmitter and receiver electrodes form a capacitor as shown in Figure 3. An alternating voltage generated by the transmitter induces an alternating potential and current on the receiver plate by electrostatic induction [2]. It is worth indicating that this method will not be surveyed in this paper.

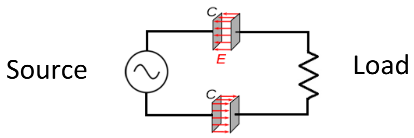


Figure 3. Capacitive coupling.

To overcome the limitations of non-radiative WPT and provide longer transmission ranges, power is transmitted using radiative techniques via microwaves or visible light.

2.2 Radiative WPT

2.2.1 Microwave Power Transfer (MPT)

For the case of power transfer via microwaves, a transmitting antenna emits electromagnetic waves to a receiving antenna which is connected to a rectifier in the rectenna as shown in Figure 4. The rectifier converts the ac power to dc power. An ideal diode for rectenna application with a small turn-on voltage or zero-bias is preferable, as well as with large reverse breakdown voltage and low capacitance. It should also have a high power handling capacity [13]. A matching circuit is used to match the antenna to the rectifier circuit. A filter is usually used before rectification to ensure that the incoming RF signal is operating at the desired frequency for the rectifier and prevent re-radiation of higher-order harmonics produced by the non-linear I-V characteristics of the rectifying diode. It will also reject out-of-band interference signals. The post-rectification filter is used to extract the dc component and reflect the rest of the frequencies back to the rectifier [14].

The conversion efficiency η of the whole system is the ratio between the DC output power at the receiver end $P_{out,DC}$ (W) and the input AC power $P_{in,AC}$ (W) at the receiver front [1]:

$$\eta = \frac{P_{out,DC}}{P_{in,AC}}. \quad (5)$$

$P_{out,DC}$ (W) delivered to the load resistance R_L (Ω) can be calculated using:

$$P_{out,DC} = \left(\frac{V^2{}_{out,DC}}{R_L}\right). \quad (6)$$

$P_{in,AC}$ (W) is mainly defined by the incident power density P_d (W/m^2) and effective area of the receiving antenna A_{eff} (m^2) [15]:

$$P_{in,AC} = (P_d)(A_{eff}) = \left(\frac{P_t G_t}{4\pi d^2}\right)\left(\frac{\lambda^2 G_r}{4\pi}\right) = \frac{P_t G_t G_r}{(4\pi d/\lambda)^2}\ ; \tag{7}$$

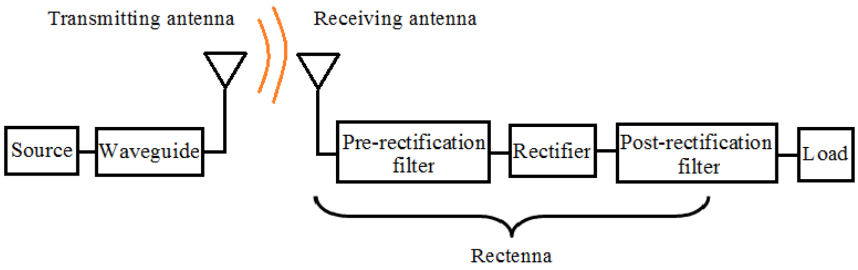


Figure 4. A typical microwave power transfer (MPT) system.

where P_t (W) is the transmitted power, G_t and G_r are gain of the transmitting and receiving antennas, respectively, λ (m) is the free space wavelength and d (m) is the distance. This equation shows that antennas of larger gain are capable of radiating and receiving larger power [16].

This technique has the advantage of transferring power over longer ranges than those for non-radiative techniques. Also, the rectenna lifetime is unlimited, as it does not need replacement (unlike batteries). However, the RF/microwave power is reduced from the transmitter through attenuation, mainly due to free-space path loss. Moreover, line of sight (LOS) transmission and small rectenna size are required [17]-[18].

2.2.2 Laser-Based WPT

In this case, power can be transmitted by a laser beam [19]-[20]. In comparison with MPT, laser systems offer larger improvement capacities and potentially much smaller systems [19]. However, laser radiation is hazardous and the conversion between electricity and light is limited. It is worth indicating that reviewing and investigating this technique is beyond the focus of this paper.

2.3 Main Characteristics and Applications of WPT in Conducting Media

WPT has many beneficial applications in lossy media, such as powering and charging implantable and undersea water devices [21]-[22]. For implantable applications, WPT can be achieved using: 1) primary coil on the skin and secondary coil beneath it (inductive coupling), or 2) two lightly coupled coils; one on the skin and another one deeply implanted inside the human body (magnetic resonant coupling), or 3) far field power transfer from a transmitter outside the human body (via microwaves). Power can be also transferred to an ingestible capsule that rotates while taking pictures of the digestive tract for the applications of wireless capsule endoscopy (WCE). WPT for these applications will be very beneficial to increase the lifetime of the device and save surgeries that are usually used to replace or charge the battery. For underwater wireless sensors, there is a variety of important applications. They are used to monitor environmental or physical phenomena, such as temperature, humidity, …etc. and to spread data through a sensor network to a shore access point [23]-[24]. There are also applications where the receiver is placed around the lossy medium, such as wearable sensors [25]. The review of WPT for wearable devices is beyond the focus of this paper.

The conducting medium is lossy and most of the power is absorbed inside it. Most of lossy media, such as the human body and sea water, are nonmagnetic and do not present magnetic losses ($\mu_r = 1, \mu''_r = 0$). Hence, the magnetic field is not dissipated in the region close to the source. The electric near field couples with the lossy medium and causes power loss due to absorption.

The absorbed power (P_{abs}) increases with the magnitude of the electric near field intensity ($|E|$) [26]:

$$P_{abs} = \frac{\omega}{2} \iiint \varepsilon_0 \varepsilon''_r |E|^2 dV; \tag{8}$$

where ω (rad/s) is the angular frequency, ε_0 (F/m) is the free space permittivity and ε_r'' is related to the imaginary part of the tissue permittivity which accounts for the electric losses of the medium [26]-[27].

$$\varepsilon = \varepsilon_0(\varepsilon'_r - j\varepsilon''_r). \tag{9}$$

Conductivity and permittivity of these lossy media are frequency -and temperature- dependent. The main challenge in all these applications is to mitigate the negative effect of the lossy medium on the power transfer system as much as possible. Requirements of the inductive coupling WPT for implantable applications in the lossy human body can be summarized as follows:

1. Small coil dimensions that fit into the available space inside the small implantable device.
2. Large inductance and quality factor Q over the frequency range of interest given the limited available space and size. This represents a challenge as an implantable coil of small size has usually a small inductance [28].
3. Robust performance with the other internal components of the implant (the performance should not be altered with the overall device package).
4. Robustness against misalignments.
5. Satisfaction of safety limitations.

Some of these requirements are contradictory as indicated in point 2. Thus, design parameters should be carefully adjusted to obtain the largest possible inductive coupling for a compact size. The probability of misalignment to happen is high for this case because of the changing and time-variant human body environment. For the case of underwater sea applications, size and safety requirements are less restricted. For the case of MPT for implants, antennas of magnetic type, such as loop antennas are preferred, because non-magnetic lossy media do not present magnetic losses. It is very important to satisfy the safety limitations of the specific absorption rate (SAR) and current density in order not to heat up the human body tissues [29]-[30]. The SAR can be calculated using Equation (10); where σ (S/m) and ρ (kg/m^3) are the tissue conductivity and mass density, respectively, and $|E|$ is the magnitude of electric near field intensity. Excessive received power may cause overheating of the receiver coil, but according to the Japan Society of Medical Electronics and Biological Engineering (JSMEBE), temperatures below 42.5 °C are safe for the tissues surrounding the RC [31].

$$SAR = \frac{\sigma |E|^2}{\rho}. \tag{10}$$

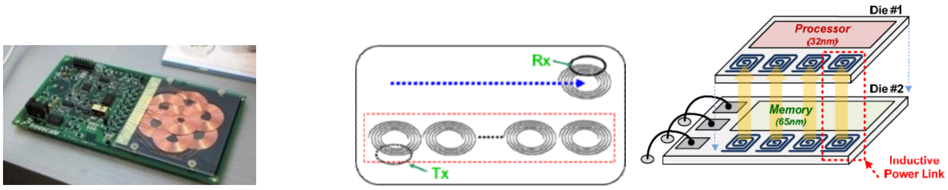
3. RESEARCH PROGRESS AND CHALLENGES

In this section, the main contributions and challenges in the area of WPT are reviewed.

3.1 Inductive WPT

3.1.1 In Free Space

Many WPT systems based on inductive coupling were presented in literature for both of low (mill watts) and high power (multiple kilowatts) applications, such as charging mobile phones and powering electric vehicles, respectively [32]-[33]. A PTE of more than 75% was obtained for these systems at a distance of less than 10 cm between the transmit and receive coils [34]. A mobile phone charger was developed in [32] at 1.2 MHz. For this system, an output DC voltage of 3.79 V was obtained at the load when the distance between the TC and RC was 5 cm. An inductive coupling system was also proposed in [35] for a radio frequency identification (RFID) system. However, PTE decreases with distance and when misalignment happens. Moreover, the receiver mobility is very restricted. Research has been directed to overcome these shortcomings as summarized in Table 1.



(a) (b) (c)

Figure 5. Proposed designs of multiple coils and resonators in: (a) [36], (b) [37] and (c) [38].

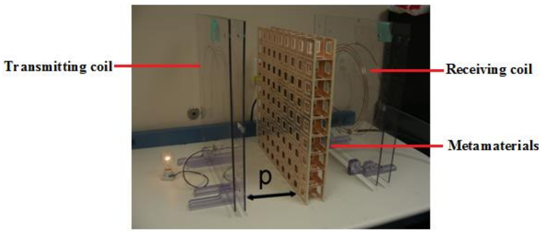


Figure 6. The proposed metamaterial in [40].

Based on the review above, it can be concluded that future investigations may be directed to:

1. Investigate the effect of using multiple metamaterial slabs and different metamaterial structures to obtain further improvement of WPT.
2. Design flexible coils that reduce the weight and size of the ICPT system and investigate the effect of the flexible structure on the coil parameters and performance.

3.1.2 In a Conducting Medium

Research on inductive power transfer in the lossy human body and underwater devices is reviewed in this section.

3.1.2.1 Underwater Applications

Underwater inductive coupling power transfer (UWICPT) system with resonant circuits has been shown to be a good candidate for charging underwater devices and vehicles. Such a system was presented in [49] for autonomous underwater vehicle docking applications. Figure 7 shows the installation of the coils in an AUV docking system. The output power was up to 45 W and the efficiency was up to 84%. A circuit and a finite element analysis (FEA) simulation model were developed to study the system power losses to increase the system efficiency. The electrical characterization of coupled electromagnetic coils in saltwater for an undersea WPT system was presented in [50]. It was indicated that the electrical properties of coils and their mutual coupling were almost identical whether in air or in saltwater at frequencies below 100 kHz, but different above 100 kHz, as seawater becomes much more effective. An underwater WPT system was realized in [51] for high power applications to recharge underwater vehicles. It was demonstrated that 3 kilowatts of power could be transferred over 15 cm with a high efficiency of around 80%.

All of these systems have validated ICPT for underwater applications. However, further research should be conducted to:

1. Increase the power transfer efficiency of WPT over longer ranges.
2. Generalize the effect of overall losses of the WPT system on its output power and efficiency.
3. Investigate the effect of packaging and realization of the ICPT system on the PTE.
4. Investigate and quantify the detrimental effect of seawater on the resistance of the coils and their coupling performance.

3.1.2.2 Implantable Applications

In this review, implantable applications are divided into two categories: WCE and implantable applications other than WCE.

3.1.2.2.1 WCE Applications

Magnetic resonant WPT is mainly used for this case, as the distance between TC and RC is relatively long. Low power levels are usually required to power or charge wireless capsules.

Table 1. A summary of main design approaches for inductive WPT in free space in literature.

Facility of improvement: Multiple coils. See Figure 5.		
Ref. and proposed approach	[36]	Multiple overlapped transmitter coils
Achievements	Mitigation of misalignment. Multiple receiver coils can be powered at the same time.	
Shortcomings	Increase of design size and complexity as a control IC is used to detect which coil is the best for WPT.	
Ref. and proposed approach	[37]	Array of coils of similar resonant frequency
Achievements	Increase of mobility range of the receiver. Increase of power transfer range. Multiple receiver coils can be powered at the same time. PTE of around 85% at f= 25 MHz for 10 resonant loops.	
Shortcomings	Increase of design size and complexity.	
Ref. and proposed approach	[38]	Planar spiral coils are designed using a 0.13μm CMOS process and vertically stacked.
Achievements	Increase of the amount of the transferred power which depends on the coil's diameter and distance between coils. PTE of 52% for a power transfer density of 49 mW/mm^2.	
Shortcomings	Increase of design size.	
Facility of improvement: Metamaterials. See Figure 6.		
Ref. and proposed approach	[39]	An NIM slab used between two resonators
Achievements	Improvement of magnetic coupling and hence power transfer efficiency due to enhancement of the evanescent wave coupling. PTE of around 50% at f= 10 MHz.	
Shortcomings	Complicated to design and fabricate, because both of ε and μ are required to be negative. Large loss, as it responses to both of electric and magnetic fields.	
Ref. and proposed approach	[40], [41]	A single negative ($\mu = -1$) metamaterial slab between resonators.
Achievements	Increases PTE with smaller losses and complexity in comparison with those of the NIM slab. [40] PTE of 50% at f= 27.12 MHz which is 42% larger than that when no metamaterial slab is used. [41] PTE of 18.2% at f= 26.65 MHz which is 61% larger than that when no metamaterial slab is used.	
Shortcomings	Larger losses than those when no slab is used.	
Facility of improvement: Techniques for mitigating frequency splitting.		
Ref. and proposed approach	[42], [43], [44], [45], [46]	Frequency tracking/ tuning techniques.
Achievements	The driving frequency of the ICPT link is maintained at an optimum value to ensure that the link is working at resonance and the output voltage is maximized. [42] PTE of over 70% for a range of 0-70 cm. [46] PTE of 15% at f= 4.5-5.5 MHz.	
Shortcomings	Additional space and power consumption are introduced because a series of complex control circuits -such as phase compensator phase-locked loop- is required.	
Ref. and proposed approach	[47], [48]	Anti-parallel resonant loops, Non-identical resonant coils (NIRCs)
Achievements	Offset of excess mutual inductance (magnetic over coupling) which is the reason of frequency splitting.	
Shortcomings	Further investigations on the system stability and impact of coil parameters on the overall system performance are required.	

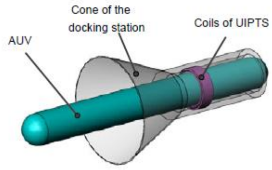


Figure 7. The UICPT system in [49].

However, the received power decreases for some orientations while the capsule is rotating in the digestive tract. To overcome these limitations, some approaches were presented as summarized in Table 2.

Table 2. Approaches to overcome ICPT limitations for WCE applications presented in literature.

Ref.	**The approach**	**The benefit**
[52]	3D orthogonal RC	The receiver delivers more than 300 mW at any orientation.
[53]	A hollow-cylinder-like 3D RC	Improves space utilization in comparison with typical 3D RC. An output power ranging from 206 mW to 1130 mW was obtained which powered the capsule robot successfully.
[54], [55]	Utilization of a ferrite core	Increases the magnetic field intensity and the received power at the RC. A ferrite core of large magnetic permeability and small loss factor is used for larger improvement. Reduces the size of the RC. 330 mW was received by the capsule.
[56]	A pair of double-layer TC solenoids	Produces a larger magnetic field intensity and PTE in comparison with that for a single solenoid and pair of solenoids.
[57]	Segmented TC solenoids	Improve the efficiency of the WPT system in comparison with non-segmented solenoids.
[58]	Helmholtz TC	Provides a much more uniform magnetic field within the inner region in comparison with that for the solenoid and reduces the risk of unnecessary exposure in the patient's body.

It is obvious that solutions of a ferrite core and 3D RC increase the capsule weight and profile. Moreover, the biocompatibility of the ferrite core should be validated. The detuning effect differs in different human bodies and becomes very large in close proximity to the fat layer [59]. No food and drink should be taken for around 10 hours before the investigation and 2-4 hours after swallowing the capsule [60], which means that the digestive tract will be filled up mostly with air for this case. Most of the existing software packages consider a digestive tract that is filled up with food of much larger permittivity than that for air, such as in [61]. This requires an accurate body model of the digestive tract when filled up with air (a model of an effective permittivity between air and tissues of the digestive tract). Therefore, an accurate in vitro test (inside a human body phantom) is very important and should be conducted. Based on this review of ICPT for WCE, it can be also concluded that further investigations on the SAR and safety limitations should be provided. More practical designs of light weight and small profile are also still needed.

3.1.2.2.2 Other Implantable Applications

For implantable (low power) applications other than WCE, magnetic resonant coupling is mainly used to transfer power to implants such as pacemakers. Examples can be found in [62]-[63]. In [64], a WPT system of resonant four coils was presented. The power transfer efficiency of the resonant four coils was shown to be much higher than that of two coils. An approximate output voltage of 3.3 V and a current of 10 mA were obtained at a distance of 2 cm. In addition, it was possible to obtain power larger than 100 mW when the distance was decreased, which can meet the power requirements of most reported biomedical implant consumption, such as artificial retina, intraocular pressure, and neural recording system. Printed coils for magnetic resonant coupling were designed in [26], [65]. In [65], a procedure to design the geometries of a pair of lithographically planar printed spiral coils was presented. This procedure optimized the mutual inductance and quality factor of printed coils in a way that the PTE was maximized. A flexible coil design was also presented in [66]. The transmitter and receiver coils were realized by inkjet printing. Wireless power transfer efficiencies of 55% and 35% at 13.56 MHz were obtained for the air and water (for testing purposes) surrounding environments, respectively. The printed and flexible designs help in providing more conformity and reducing the device size, weight and profile. However, further studies are still needed to: characterize the effect of the lossy human body on the design parameters and performance of printed or flexible coils, derive formulae of the design parameters for different structures of printed or flexible coils and evaluate the performance of flexible coils when they get bent.

3.2 Microwave-Based Systems

3.2.1 In Free Space

Research in this area has been mainly focused on optimizing the design of the receiving antenna and rectifier circuit. For the rectifier circuit, different rectifier diodes were used. Examples can be found in [67] and [68], where (HSMS-8101) and (HSMS2860) Schottky diodes were used, respectively because of their high speed and low voltage drop. A novel wide dynamic range and high-efficiency rectifier was proposed in [69]. The proposed rectifier consisted of two rectifying circuits in parallel, an asymmetrical output impedance power divider which adaptively divided the RF input signal to the rectifying circuits according to a signal power level and a DC combiner. More than 27 dB dynamic range with an RF-DC conversion efficiency of higher than 50% was obtained. A maximum conversion efficiency of 76.8% at 2.45 GHz was obtained at an input power of 5dBm. In [70], metasurfaces composed of different types of resonators were used instead of antennas in the rectenna, as they were found to be more efficient than classical antennas in energy harvesting. However, no in-depth study has been provided to explain the overall benefits of metasurfaces for the WPT process in general (not for harvesting purposes only). Antenna optimization techniques proposed in literature are summarized in Table 3. Metamaterials and metamaterial-based structures are found to be very advantageous for ICPT. Therefore, it is important to investigate them for MPT in depth.

3.2.2 In a Lossy Medium

For implantable rectennas, different types of antenna were designed and presented as summarized in Table 4. It is worth indicating that the comparison between different implantable rectennas can be considered accurate only if the properties of the medium of implantation is the same for all of them. Magnetic type antennas, such as loop antennas, are popular for this type of application, because they are of smaller SAR and larger radiation efficiency and gain. PIFAs have the advantages of small size and low profile in addition to relatively small electric near field and SAR. 0.433 GHz is mainly exploited for the applications of implantable rectennas, because it enables size reduction of the rectenna system in comparison with that at lower frequencies. At the same time, the human body loss around this frequency is smaller than that at higher frequencies. For the rectifier design, it is preferred to facilitate low turn-on voltage and very low leakage current. Different rectifier designs in literature are summarized in Table 4.

It is very important to evaluate and validate the implantable rectenna performance with the overall package which may alter the overall antenna performance. This has been done in some research studies such as in [93]. However, further deep related investigations are still needed. Based on this survey of proposed designs in literature, future research should be focused on:

1. Introducing new techniques and designs that further increase the magnetic field or decrease the electric field in close proximity to the implantable antenna, in order to boost the power received at the rectenna.
2. Introducing new techniques to maintain matching (of the receiving antenna and between the receiving antenna and rectifier) in the time-variant human body.
3. Investigating the effect of the implantable device packaging on the WPT process.
4. Validating the WPT system by both of in-vitro and in-vivo tests.

5. Evaluating the WPT system using actual design parameters (load resistance, available diodes, …etc.) for actual implantable chips in the market.
6. Characterizing the WPT channel of the human body in different areas of implantation for different implantable applications.
7. Investigating metamaterials or structures inspired by metamaterials for MPT in lossy media. The benefits of these structures will be indicated in the following section.

Table 3. A summary of antenna optimization techniques for MPT in literature.

<table>
<tr><th>Technique</th><th>Ref.</th><th colspan="2">Structure/ Achievements</th></tr>
<tr><td>Increasing the antenna gain</td><td>[71]</td><td colspan="2">Artificial magnetic conductor (AMC) with a λ/2 dipole antenna/3.529 dB enhancement in gain.</td></tr>
<tr><td rowspan="4">Antenna miniaturization</td><td>[72]</td><td colspan="2">Wide slot antenna/Size reduction of 60% with a measured RF to-DC conversion efficiency of 75%.</td></tr>
<tr><td>[73]</td><td colspan="2">A fractal structure/A maximum efficiency of 57% at an input power level of 20 dBm.</td></tr>
<tr><td>[74]</td><td colspan="2">A slot of cross shape slot etched on a square aperture patch antenna/ A patch size reduction of 32.5%. RF-to-DC conversion efficiencies were 15.7% and 42.1% for input power levels of -20 dBm and -10dBm, respectively at 2.45 GHz.</td></tr>
<tr><td>[75]</td><td colspan="2">Square patch with interconnection of four corner patches alternating with four strips and a fifth central patch/A size reduction of 60%.</td></tr>
<tr><td rowspan="2">Direct matching between the antenna and rectifier</td><td>[67]</td><td>Folded dipole antenna</td><td rowspan="2">Saves the space of the matching circuit and simplifies the rectenna.

RF/DC power conversion efficiencies were 49.7% and 72.9% at 0.868 and 2.45 GHz in [76] and [67], respectively.</td></tr>
<tr><td>[76]</td><td>Yagi-Uda</td></tr>
<tr><td rowspan="2">Increasing the bandwidth</td><td>[67]</td><td colspan="2">Folded dipole antenna</td></tr>
<tr><td>[77]</td><td colspan="2">A dual-polarized wideband rectenna with a cross-dipole/A maximum conversion efficiency of 57% was obtained at 1.7 GHz and over 20% over the frequency range from 1.6 to 2.5 GHz for an input power density smaller than 200 $\mu C/m^2$.</td></tr>
<tr><td>Antenna array and Multiple-Input, Multiple-Output (MIMO) elements</td><td>[78]
[79]
[80]</td><td colspan="2">The output voltage increases with the number of array elements.</td></tr>
<tr><td>Circular polarization</td><td>[81]
[82]</td><td colspan="2">[81] Truncated patch, [82] two crossed slots introduced to the ground of a patch antenna and coupled on a microstrip feed line/Overcomes the limitations of rectenna orientation.</td></tr>
<tr><td rowspan="4">Harmonic rejection</td><td>[83]</td><td>An optimized length of the feeding line and defect ground structure (DGS) of a microstrip rectenna are used to reject the second and third harmonics with a maximum conversion efficiency of 74%.</td><td rowspan="4">The insertion loss and rectenna size can be minimized when no low pass filter is used.</td></tr>
<tr><td>[84]</td><td>DGS is applied near to the coaxially fed location of a microstrip antenna/20 dB suppression at the 2^{nd} and 3^{rd} harmonic frequencies.</td></tr>
<tr><td>[85]</td><td>Harmonics were suppressed with the aid of a spur-line that is inserted between the feed and short line of Planar Inverted-F Antenna (PIFA).</td></tr>
<tr><td>[86]</td><td>A single slot on a ground conductor of a CPW-fed circular slot antenna is utilized for the suppression.</td></tr>
</table>

Table 4. A summary of proposed antennas for implantable rectennas in literature.

Ref.	Antenna type	f (GHz)	Dimensions (mm)	Tissue of implantation	The rectifier	Output voltage (V) or power (W)
[87]	Printed dipole	1.2	14×14	------------	Full-wave rectifier	3 V
[88]	Loop	0.433	30×15	Muscle	----------------	--------
[18]	PIFA	0.915	10×12.5×1.5	Six-Layer rat head model	Couple of Schottky barrier diodes	--------
[89]	Folded helical	0.433	9.5×23	Muscle	------------	--------
[90]	Multilayer PIFA	0.433	10×10	------------	------------	--------
[91]	Slot PIFA	0.433	19×30×1.6	Multilayer (muscle, skin, fat)	-------------	--------
[92]	Slot antenna	0.915	------------	Chicken breast tissue	Full-wave cross-coupled bridge rectifier	1 V / 50 μW DC
[93]	Meandered antenna with feeding loop	2.45	18×11×8.5	------------	A bridge rectifier (Avago HSMS-2828)	2.6 V/ 250 μW

4. Preliminary Investigations on Using Split Rings to Maximize the Power Received by Rectennas in Lossy Media

In this section, it is demonstrated that a layer inspired by split ring resonators (SRR) around a receiving antenna at the rectenna front inside a lossy conducting medium can improve the power received by this antenna. This has been indicated by the increase of the transmission coefficient between an external antenna in free space and the receiving antenna in the conducting lossy medium when the SRR-based layer is used. In general, the power received by an antenna at the rectenna front inside a conducting lossy medium can be increased if:

1. The antenna gain in the conducting medium (G_{con}) increases. This can be obtained by increasing the magnitude of the magnetic field |H| (A/m):

$$G_{con} = \frac{4\pi\sqrt{(\omega\mu/2\sigma)}\,(|H|de^{(d/\delta)})^2}{R_r(i_i)^2}\ ; \tag{11}$$

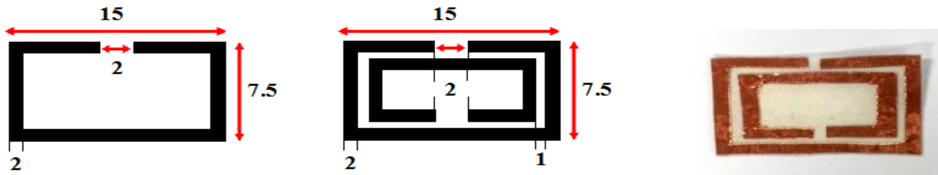
where d (m) is the distance at which |H| is taken or measured, δ (m) is the skin depth, R_r (Ω) is the radiation resistance and i_i (A) is the input current [94].

2. The power loss due to power absorption decreases. This can be obtained if the electric near field intensity around the antenna decreases as explained in some previous sections of this paper.

Both of magnetic and electric fields around the antenna can be controlled by metamaterials or structures inspired by metamaterials (which may not lead to the same properties of metamaterials) [95-97]. Therefore, a layer inspired by split-ring-resonators is designed and used around a loop antenna inside a lossy medium. The antenna and layer structures are shown in Figure 8. The antenna and layer are optimized using CST Microwave studio [61] in a model of a lossy conducting medium to work for the 2.45 GHz Industrial, Scientific and Medical (ISM) band for S11< -10 dB. The lossy medium is simulated with a conductivity of 1.74 S/m and a permittivity of around 52, which resemble the dielectric properties of the human muscle at 2.45 GHz [26]. It is worth indicating that this section aims to show the advantages of using SRR layer for WPT in lossy media and not to optimize the design for maximum power transfer.

The power transfer from an external meandered loop antenna to the proposed antenna with and without the SRR-based layer inside the conducting lossy model is set at a distance of 0.5 m and the transmission coefficient is simulated at this distance at a frequency of 2.45 GHz. The simulated antenna gain and transmission coefficient are found to be larger by 2.7 dB when the SRR-based layer is used. This is because the SRR-based layer served to increase the magnetic near field by 20% and reduce the electric near field by 40% in comparison with the case when no SRR layer is used. This increases the power at the rectenna front as discussed above.

A phantom of lossy medium was prepared by adding salt and sugar to water to control its conductivity and permittivity, respectively. Salt and sugar were added gradually until an effective permittivity of around 52 and a conductivity of 1.74 S/m were obtained and measured using Agilent 85070E Dielectric Probe [98].



(a) (b) (c)

Figure 8. A layout structure of the: (a) antenna (b) SRR-based layer (c) fabricated SRR-based layer; units in (mm).

The antenna (with and without the SRR layer) is wrapped around a cylinder and fed by a coaxial cable that is isolated from the lossy medium to provide accurate measurement results. The measurement setup is shown in Figure 9. The simulated and measured reflection coefficients are shown in Figure 10. The transmission coefficient between the antenna inside the lossy phantom and the external loop antenna at 0.5 m and 2.45 GHz was measured. 2.5 dB increase in the transmission coefficient and gain is measured which is in good agreement with the simulated results.

5. Conclusions

WPT has many beneficial applications in different media and thus has gained a wide interest. The development of efficient WPT systems require great and comprehensive efforts to overcome the current limitations and challenges of WPT. Different techniques and approaches were proposed to boost WPT in different media which have been discussed in this paper. There are, however, still many unsolved issues and challenges to solve and overcome.

While the option of multiple coils (overlapped, in linear array, stacked in parallel) has helped in increasing the power transfer range, mobility of the receiver coil and number of powered receivers in the ICPT system, it increases the system weight, size and profile. This might be not optimum for most of the recent wireless communication devices which are preferred to be small in size and light in weight. A good way to overcome the limitations of some of the multiple coil designs is to use printed or flexible coils. Therefore, further investigations on the effect of the flexible coil structure on the coil parameters and overall performance are needed. The bending effect of the flexible coil on the ICPT should be also studied. This also applies to ICPT for implantable applications, where printed or flexible coils are much more practical. For underwater applications, the option of using larger and multiple coils is viable as size and weight restrictions are less. However, coil parameters underwater should be derived for this case. Most of the proposed designs were tested in free space, which does not guarantee the actual validation of them underwater. The overall losses should be also quantified for such systems. Frequency splitting elimination techniques, such as using non-identical coils and frequency tracking techniques, increase the ICPT system complexity and consumed power and require further investigations regarding the system stability and optimized parameters.

Metamaterials have been used to increase the power transfer efficiency of ICPT systems. However, rigid structures between coils were mostly utilized. Future designs may utilize metamaterial-based coils which can yield the same performance without adding extra layers. Coils based on flexible metamaterials could be also utilized.

Figure 9. Measurement setup.

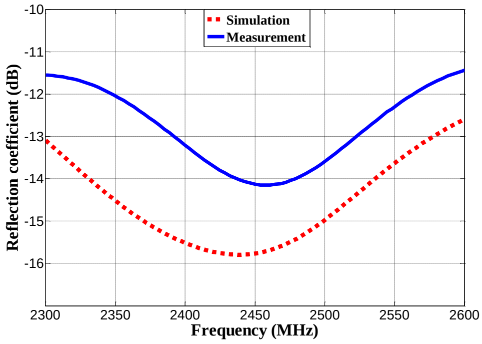


Figure 10. Simulated and measured reflection coefficients of a loop antenna with SRR-based layer for the 2.45 GHz ISM band.

Table 5. The simulated transmission coefficient (dB) and realized gain (dBi) of the receiving antenna in a conducting lossy medium with and without the SRR based layer.

	Transmission coefficient (dB)	**Realized gain (dBi)**
With SRR	-40	-27
Without SRR	-42.7	-29.7

For MPT, different rectenna designs were proposed. In general, miniaturized rectennas of wide or broad bandwidth are required for efficient and stable MPT. For applications where power limitations are not very restricted, rectennas based on MIMO and antenna arrays should be further investigated and designed. For the rectifier circuit, smart designs are still needed. In both of the human body and underwater media, the MPT channel should be carefully characterized which is very challenging considering that the human body and sea water are time-variant and their characteristics are affected by many factors such as the temperature. New functionalities of split rings for MPT in lossy media have been indicated in this paper. It has been shown that structures inspired by SRR can increase the received power at the front edge (input) of the rectenna in a lossy conducting medium (by 2.5 dB or larger for the case discussed in this paper). Further designs inspired by metamaterials or split rings to boost MPT especially in lossy media could be a hot research area for future investigations.

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ملخص البحث:

ازداد في الآونة الأخيرة الاهتمام بالنقل اللاسلكي للقدرة بشكل ملحوظ، نظراً لتطبيقاته الجذابة. والجدير بالذكر أن فعالية نقل القدرة ومدى الاتصال لغالبية أنظمة النقل اللاسلكي للقدرة لا يزالان محدودين، وذلك بسبب العديد من التحديات التقنية والتحديات المتعلقة بالتنظيم. وهذا يتطلب المزيد من البحث والجهود التقنية للتغلب على التحديات الراهنة وجعل أنظمة النقل اللاسلكي للقدرة أكبر فعالية وأوسع استخداماً.

تهدف هذه الورقة إلى مراجعة أوجه التقدم الأخيرة وتُقدم البحث في مجال النقل اللاسلكي للقدرة لأغراض التصدي للتحديات الراهنة وتحديد اتجاهات البحث المستقبلي. ولتحقيق هذه الأغراض، تقدم هذه الورقة مدخلاً إلى النقل اللاسلكي للقدرة. هذا إضافة إلى مناقشة القضايا البحثية الرئيسية المرتبطة بالنقل اللاسلكي للقدرة في الفضاء الحر وفي الأوساط التي يحدث فيها فقد للقدرة. من ناحية أخرى، يجري استقصاء فوائد استخدام دارات الرنين منفصلة الحلقات في النقل اللاسلكي للقدرة في الأوساط الموصلة التي يحدث فيها فقْد للقدرة. وهذا من شأنه أن يساعد كثيراً في تعزيز النقل اللاسلكي للقدرة في الأوساط التي يحدث فيها فقْد للقدرة، وأن يكون مصدر إلهام للحصول على بِنىً أقرب إلى المثالية من أجل مزيدٍ من التحسين.