

Cut the Cord: Wireless Power Transfer, its Applications, and its limits

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Abstract:

The transfer of power from source to receiver is a technology that has existed for over a century. Wireless power transfer (WPT) has been made feasible in recent years due to advances in technology and better implementations of transfer techniques, such as Microwave Power Transfer (MPT). The MPT system works by converting power to microwaves through a microwave generator and then transmitting that power through free space where it is received and converted back to power at a special device called a rectenna. The applications of MPT are numerous, not only to change the way existing technologies work, but also as theoretical constructs for future constructs. While the benefits are great, there are many limitations and drawbacks of MPT, necessitating the discussion of possible alternative methods for WPT. The transfer of power wirelessly has the potential to completely disrupt and revolutionize existing and future technologies.

Keywords:

Wireless Power Transfer, Microwave Power Transfer, Rectenna, Solar Power Satellites, Highly Resonant Wireless Power Transfer.

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1. Introduction

The transfer of energy from a source to a receiver has traditionally necessitated the use of a physical connection. Indeed, electrical grids and power outlets span nearly the entire globe and deliver power to billions of people worldwide. Recently, there has been much interest into the area of wireless power transfer (WPT), that is, the transmission of power without the need for a physical connection [[WikiWP](#)]. Research into WPT, however, is nothing new, as experiments in the field took place as far back as Nikola Tesla in the early 20th century [[Brown84](#)].

The aim of this paper is to provide an overview of WPT, with a focus on the radiative approach to wireless power; that is, transmitting power using the electromagnetic spectrum. In particular, this paper details the transfer of power over the microwave band, called microwave power transfer or microwave power transmission (MPT). Other approaches to WPT include magnetic field resonance and capacitance, and are mentioned in this paper for completeness as alternative methods for WPT.

Section 2 of this paper provides an overview of the fundamentals of wireless power, detailing MPT and how it works. Section 3 outlines and highlights some key and interesting applications of wireless power. Section 4 poses some limitations, drawbacks, and potential safety concerns of MPT, as well as some of the alternative methods for WPT, which are discussed in this paper but not described in detail.

WPT is an extremely useful technology that has numerous applications and benefits. Cell phones, laptops and other mobile devices could function without ever having to be plugged in, cars could drive on highways burning no fossil fuels; wireless power even has the potential to solve much of the renewable energy issues we face.

2. Fundamentals of Wireless Power Transfer: Microwave Power Transfer

Transfer of power via microwaves has long been the focus of study and experimentation [[Brown84](#)]. In the early 1900s, Nikola Tesla experimented with transmission of power wirelessly, through microwaves. His work, however, was largely left unimplemented, as his experiments were vastly ahead of their time and the technology did not yet exist to make WPT via microwaves feasible [[Brown84](#)]. Advances in wireless technologies since Tesla, however, have made possible that which was not in the early 20th century [[Wu13](#)]. Described in this section are the details of those technologies behind MPT as a mechanism for WPT.

2.1 Overview of the system

As mentioned above, MPT as a mechanism for WPT is the central focus of this paper. MPT is defined as the transfer of power through space by means of microwaves. In particular, a MPT system converts direct current (DC) power to microwaves, transmits that microwave radiation to a target, and the target converts the microwave radiation back to DC power [[Brown84](#), [Reddy13](#)]. Figure 1 below depicts a block diagram of the MPT system. First the microwaves are generated by the microwave generator. This radiation then passes through the Coax-Waveguide Adapted, which in turn passes through the waveguide circulator, a device that reduces the radiation to exposure from outside power. Finally the radiation passes through the tuner and directional coupler device, which separates the signal according to signal propagation direction. The radiation is then transmitted over the air through antennae, where it is received by the antenna at the rectenna, at which the microwave radiation passes through a low pass filter, then a matching network, then a rectifier as it is converted to DC power [[Reddy13](#)]. The details of the relevant steps are described in the sections to follow.

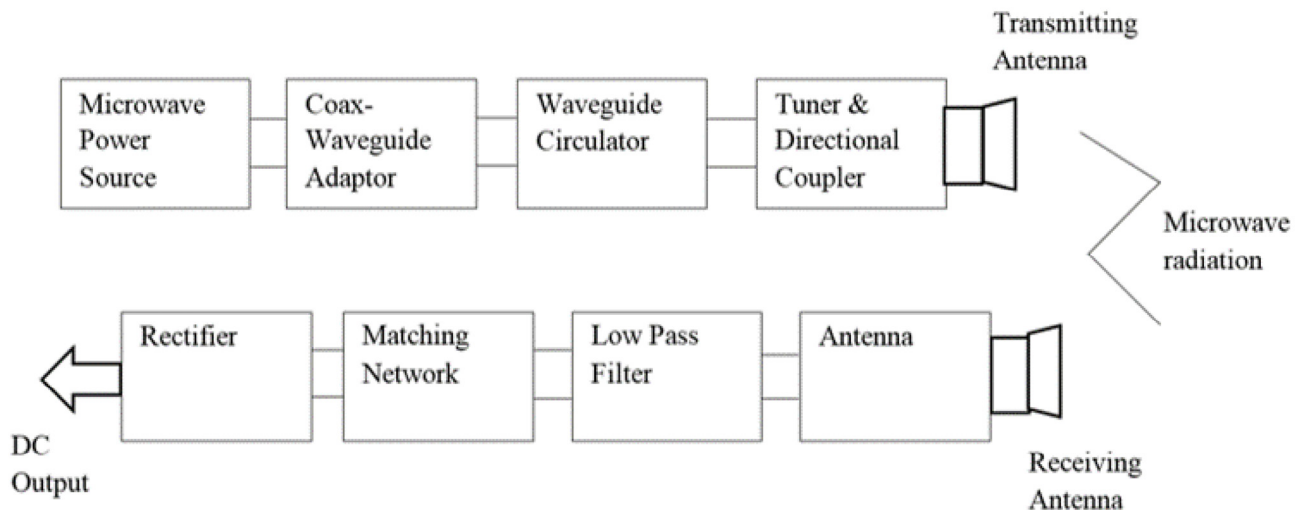


Figure 1: Block Diagram of MPT [Adapted from [Reddy13](#) & [Ojha13](#)]

2.2 Transmission: Microwave Generator

Several devices, known as Microwave Vacuum Tubes, are used to transmit microwaves through space; these devices include magnetron, klystron, and the Travelling Wave Tube among others, with the magnetron being the device used the most often [[Reddy13](#)]. The magnetron device generates microwaves by passing electrons through a magnetic field [[WikiMagnetron](#)]. These microwaves are then transmitted via antenna into space.

The exact frequency at which microwave radiation is transmitted through space to achieve maximum efficiency has been an area of great deal of research. Frequencies often used within the microwave range are 2.45 GHz, 5.8 GHz, 8.5 GHz, 10 GHz and 35 GHz [[Reddy13](#)]. Experimental results have demonstrated that 2.45 GHz is the most efficient frequency to transmit microwaves, as the power capacitance achieved at that frequency is higher than the frequencies listed above [[Huang13](#), [Reddy13](#)]. Figure 2 below shows that the lowest measured loss (solid line) occurs when transmitting at a frequency of 2.45 GHz. Table 1 shows efficiency percentages achieved using different frequencies.

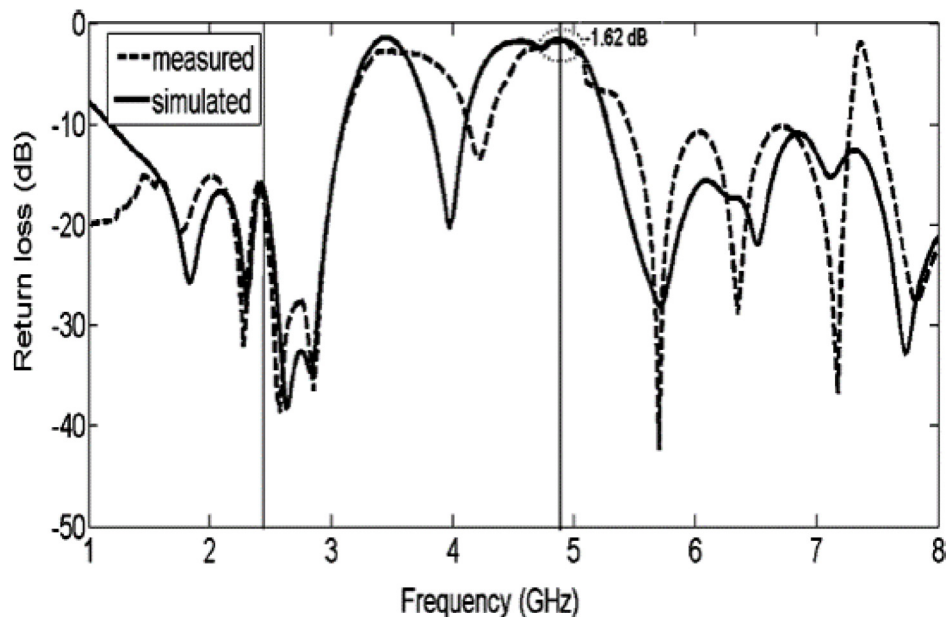


Figure 2: Graph of power loss based on frequency [[Harouni11](#)].

Table 1: Table of measured and calculated efficiencies of different frequencies [Adapted from [Reddy13](#)].

Frequency (GHz)	Measured Efficiency (%)	Calculated Efficiency (%)
2.45	92.5	90.5
5.8	82	78.3
8.51	62.5	66.2

Some studies have demonstrated efficiency values, defined as the amount of power retained after being converted from microwaves, of upwards of 85 - 90% have been achieved using a 2.45 GHz frequency [[Reddy13](#)]. More details of efficiency of transfer are described in the section to follow.

The transmission of microwaves is vital to the wireless power system, however the efficiency is dictated to a large degree by the reception of those microwaves, and conversion back to DC at the receiving end of the system. The reception and conversion is described in the next section.

2.3 Reception: The Rectenna

Once DC is converted to microwaves and transmitted into space, a system that requires power needs to receive and convert microwaves back to DC. The device used for this reception and conversion is called a rectenna. The rectenna device was created by W.C. Brown in his groundbreaking work in WPT in the 1960s [[Brown84](#), [WikiRectenna](#)]. The term is derived from the fact that a rectenna is comprised of an antenna coupled with a rectifying circuit [[Huang13](#)]. It has been determined through experimentation that the 2.45 GHz frequency, as mentioned above, achieves the greatest efficiency for the rectenna [[Harouni11](#)].

In particular, microwave radiation is received by the antenna component of the rectenna, passes through a low pass filter as well as a matching filter (devices which are in place to ensure that the impedance of the incident signal matches that of the rectifier to follow), through diodes that only allow electrons to flow in one direction, and is then converted to DC by means of a rectifying circuit [[Reddy13](#), [Ojha13](#)]. While the finer details of the mechanisms of the individual components are outside the scope of this paper, it is important to note that the materials used to create the rectenna have large implications with respect to the efficiency achieved by the rectenna, as shown in Table 2.

Table 2: Efficiency of rectenna using different materials [Adapted from [Reddy13](#)].

Type of Rectenna	Operating Frequency (GHz)	Measured Peak Conversion Efficiency (%)
Printed Dipole	2.45	85
Circular Patch	2.45	81
Printed dual rhombic	5.6	78
Square Patch	8.51	66

As shown, the dipole antenna system achieves the maximum efficiency for conversion to DC from received microwave radiation [[Huang13](#), [Reddy13](#)]. Efficiency is quantified by the ratio of DC output power after conversion to the received frequency power of the antenna as shown below in Equation 1.

$$\eta = \frac{\text{DC Output Power}}{\text{incident RF Power}}$$

Equation 1: Rectenna Total Efficiency Equation [[Ojha13](#)].

In sum, the rectenna at the target captures microwave radiation from the generator through the antenna, the microwaves pass through filters and diodes, and then to the rectifying circuit which transfers DC power to the target system [[Choudhary11](#)].

2.4 Putting the pieces together

MPT depends on the system of a microwave generator and rectenna to transmit power from source to target. Systems attempting to wield MPT to transfer power wirelessly can thus use the described configuration. Importantly, the system is quite scalable. Large microwave generators can be constructed to transmit a greater amount of microwaves over space, and, as shown in Figure 3 below, rectenna units can be arranged in an array to capture as much of the transmitted microwave radiation as possible to be converted to DC.

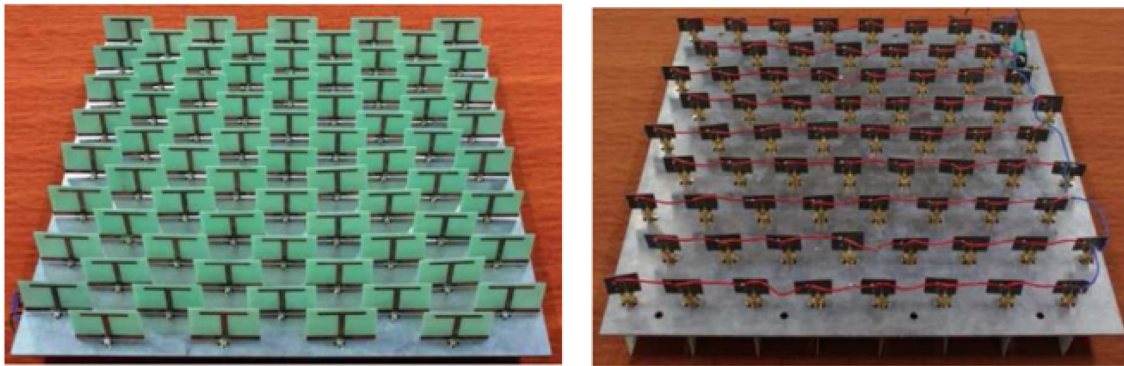


Figure 3: Front and back picture of array of rectenna [[Huang13](#)]

MPT has several exciting applications, both for existing technologies and for theoretical systems still being researched.

3. Applications of WPT

Several applications of wireless power transfer are apparent and obvious. Firstly, WPT could eliminate traditional charging systems in place today. Instead of plugging in a mobile phone or laptop via power cord to charge the battery, wireless power can be harnessed and implemented in a home such that a laptop and phone charge continuously and wirelessly without the need for plugging anything in. Higher level applications include charging of electric vehicles (EVs). As EVs become more and more prevalent on the roads, the feasibility of driving such a vehicle can be maximized via stationary, and even mobile, WPT systems. Future and theoretical applications include a potential solution to renewable energy for the planet, by means of satellites collecting sunlight and sending power back to earth through MPT. Applications of WPT are described in this section.

3.1 Electronic portable devices

Cell phones, laptops, tablets, even smart watches are found all over the globe and are owned and used by billions of people. What these devices all have in common is the need to recharge their internal battery so that the device can be used while mobile. Such is the paradox of portable devices: they provide convenience by running off internal power so they can be used anywhere, but always must return to be tethered to a power cord in order to charge.

WPT has the potential to disrupt and revolutionize the traditional portable device, not only by making mobile devices more convenient by eliminating the need for a physical power supply, but also safer (power cords carry risk of shock and can cause fires), as well as a reduced cost for consumers [[Kesler13](#)]. Research has even been done into multi-hop WPT systems, wherein a generator transmits power wirelessly to targets, which can then in turn become sources for other targets, and transfer power wirelessly to those targets. Thus, a network of WPT can be created to support several devices [[Rault13](#)].

3.2 Electric Vehicles

As concern over global warming and greenhouse gas emissions grows across the globe, the prevalence of electric vehicles has also increased. One of the drawbacks of electric vehicles is their battery. Electric vehicles currently need to be plugged in to recharge their internal batteries, and take many hours to do so [Shwartz12]. However, many envision that in the near future, one need only park her car in a pre-determined spot in her driveway and the car will charge wirelessly and automatically [Kesler13]. Thus a great deal of research has been done into WPT, specifically through the MPT mechanism, and how it can be used for the charging of electric vehicles.

The case study we will use for MPT charging of electric vehicles, specifically a system for charging electric trucks. As shown in Figure 4 an electric truck has a rectenna on its roof, and an MPT system can be created such that when an electric truck parks beneath the microwave transmitter, the rectenna converts the microwave radiation to DC to charge the vehicle.

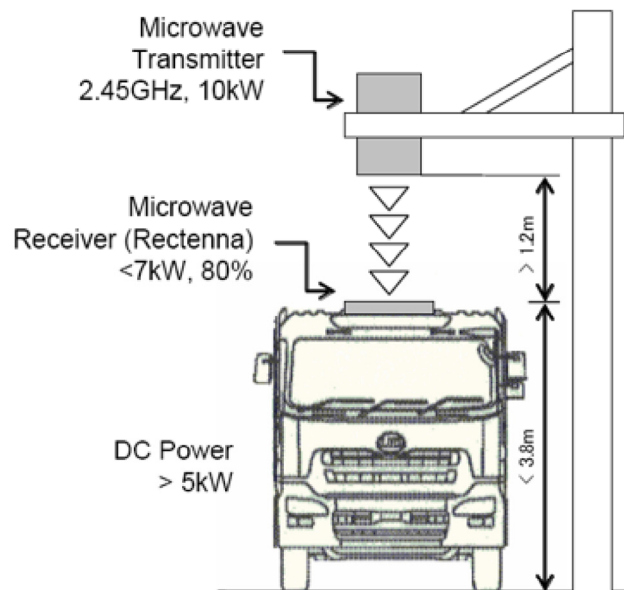


Figure 4: MPT charging of electric vehicle [Shinohara13]

In particular, the transmitter emits 10kW power through microwaves at 2.45 GHz, and the rectenna converts those microwaves with an efficiency of greater than 80%, yielding more than 7kW to the electric vehicle. Accounting for other losses through the charging of the system, the battery is able to receive more than 5kW power. The figure depicts a practical application of MPT. Importantly, the MPT system depicted has a high density with respect to the forming of the beam, and since the beam is highly focused, thus it does not create a large area of microwave radiation which could potentially be unsafe for human exposure [Shinohara13].

3.3 Theoretical applications: Aerial Vehicles and Solar Power Satellites

While portable device and vehicle charging are applications that could be implemented in the near future, some other theoretical applications have been posited for further research and development.

One such application is the Stationary High Altitude Relay Platform (SHARP) [Choudhary11]. The SHARP system consists of an unmanned airplane that flies at an altitude of approximately 13 miles above the earth, constantly circling the earth in a 2 kilometer diameter. The SHARP airplane would then be used as a communications relay. Here, the SHARP airplane has a large rectenna behind the wings, allowing for power to be transmitted to it from the earth, and thus is able to stay in the air for long periods of time, potentially months [Choudhary11]. A picture of the aircraft is shown in Figure 5.



Figure 5: SHARP airplane [[Choudhary11](#)]

Another exciting and future application of MPT is that of the Solar Power Satellites (SPS) system. Carbon dioxide (CO₂) emissions from burning fossil fuels have become a point of great concern with respect to global warming. Additionally, fossil fuels are a nonrenewable energy source, and by some estimates fossil fuels could be completely consumed in 100 to 150 years [[Sasaki13](#)]. Thus the need for clean, safe, and abundant renewable energy has been a topic of much debate and recent study. Current renewable energy systems have many drawbacks; solar cells are constrained by the weather, most significantly by cloud cover and lack of sunlight during the night. Wind turbines are contingent upon weather as well, and do not function when no wind is present. Nuclear power plants produce toxic waste and have the potential to cause great disasters in the event of a nuclear meltdown.

The SPS, on the other hand is a different system entirely, with the collection of solar power unconstrained by environmental factors. In the SPS system, a satellite is fixed in a geostationary orbit above the earth. This satellite collects solar energy and, using the MPT mechanism, beams the energy back down to the earth via microwaves where it is received and converted to power at a rectenna of a size of approximately 2 km² and then transfers that energy to existing power grids [[Sasaki13](#)]. A satellite above the earth is superior to ground based solar power harvesting because it is unaffected by the weather and is unconstrained by lack of sunlight during night hours, and thus can collect solar energy continuously. Even after accounting for loss during conversion of power to and from microwaves, the SPS system is still able to deliver more power than ground based solar panels. For example, solar radiation has been measured on the ground in Tokyo, Japan as approximately 140 W/m², whereas a satellite in space can collect solar energy that is measured as 1400 W/m² [[Sasaki13](#)].

The SHARP and SPS systems are both practical implementations of WPT via the MPT mechanism. Indeed, both systems are simply MPT systems, just scaled to a larger size. They consist of a microwave generator that converts power to microwaves and sends those microwaves to a target rectenna that converts the microwaves back to DC power to be used by the target system.

As exciting and potentially beneficial as MPT can be, there are many potential drawbacks that need to be mentioned and considered.

4. Limitations, Drawbacks, Safety Concerns, and other approaches.

The center and base of this paper has been wireless power transfer via the electromagnetic spectrum, the microwave band in particular. Indeed, the aim has been to demonstrate the numerous benefits of applications of MPT systems. However, MPT has some drawbacks and limitations and even potential risks associated with it. Thus, alternate methods for WPT have been proposed and researched. While the central focus of this paper has been on WPT by means of MPT, these alternate methods are discussed briefly for completeness as part of the overview of WPT.

4.1 Limitations and drawbacks of MPT

MPT hinges upon microwaves being transmitted through the media of open space from source to target. While efficiency of conversion of power to and from microwaves has been discussed above, one of the variables of transfer through the use of microwaves is the media through which it travels. Thus, the ability to efficiently transfer microwaves through open space is dependent on whether or not a clear line of sight exists between source and target. Factors such as weather and physical objects can obstruct the line of sight between source and target and can inhibit the transfer of power via microwave [Karalis07]. Additionally, as discussed in the case study of the charging of the electric vehicle above, beamforming and focusing the microwave radiation is vitally important for an efficient WPT system [Shinohara13]. It follows, therefore, that the transfer of power from a source to a moving object, especially at longer distances, would be extremely difficult to do so with a highly directional antenna, and would be inefficient to the point of impracticality with an omnidirectional antenna.

Therefore, systems wherein a target or source or both are in motion are not ideal for WPT by means of MPT.

4.2 Safety Concerns

One of the major limitations of MPT, and WPT in general, is the concern of its safety, especially with respect to human exposure to microwave radiation. Indeed, the transference of microwave radiation through free space is a major design consideration in MPT systems. In the charging of the EV example given above and depicted in Figure 4, a great deal of effort was made to ensure that the magnetic beam formed by the system was concentrated on the antenna, thus creating a guard area outside of which the power level was low enough for human exposure [Shinohara13]. A graphical example is depicted below in Figure 6.

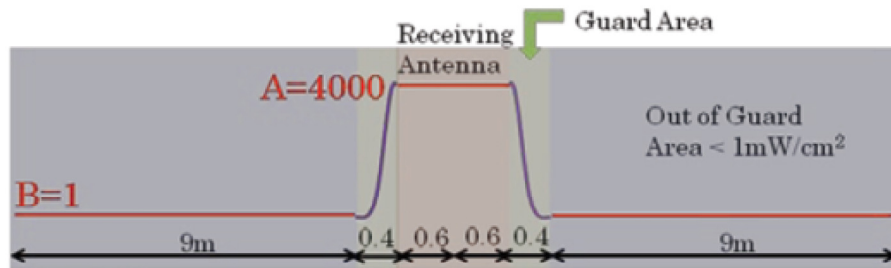


Figure 6: Depiction of microwave transmission and guard areas of MPT [Shinohara13]

The precision with which an MPT system must be implemented, therefore, is extremely important. This limits the use of an MPT system of high energy to very controlled environments, making difficult its use in the power transfer to moving vehicles.

With these considerations in mind, some alternate mechanisms for WPT have been proposed.

4.3 Alternate method for WPT

Approaches other than MPT have been identified as viable mechanisms for WPT. One such method is called highly resonant wireless power transfer, or HR-WPT [Kesler13]. HR-WPT relies on magnetic resonance to transfer power wirelessly from a source to a target.

The details of the system are outside of the scope of this paper, but the applications and benefits of HR-WPT, especially with regard to how HR-WPT can overcome some of the limitations of MPT, are of note. Take, for example, the limitations of MPT in the moving source and/or receiver system. Beamforming to focus microwave radiation from a source to a receiver, when one or both are in motion, is difficult to do efficiently and safely. Tangentially, MPT requires a line of sight in order to transfer energy via magnetic radiation successfully. The HR-WPT system can address both of these limitations successfully. Since magnetic resonance does not require line of sight, the transfer of power from source to target is uninhibited by weather or obstructing objects [Karalis07]. Many studies have shown that HR-WPT can be optimized to be more efficient than MPT [Yuan10].

Thus, the HR-WPT has been shown to be effective for applications of WPT in systems with a mobile target. For example, magnetic coils could be placed beneath the pavement of a highway, constantly charging cars as they drive [Lee13]. Each of these coils contains a magnetic field that couples with the receiver in a particular way to transfer power wirelessly [Kim10]. In Figure 7 below, a working model is shown, with a mobile vehicle travelling over a track inlaid with magnetic transmitters, powering the vehicle as it moves.

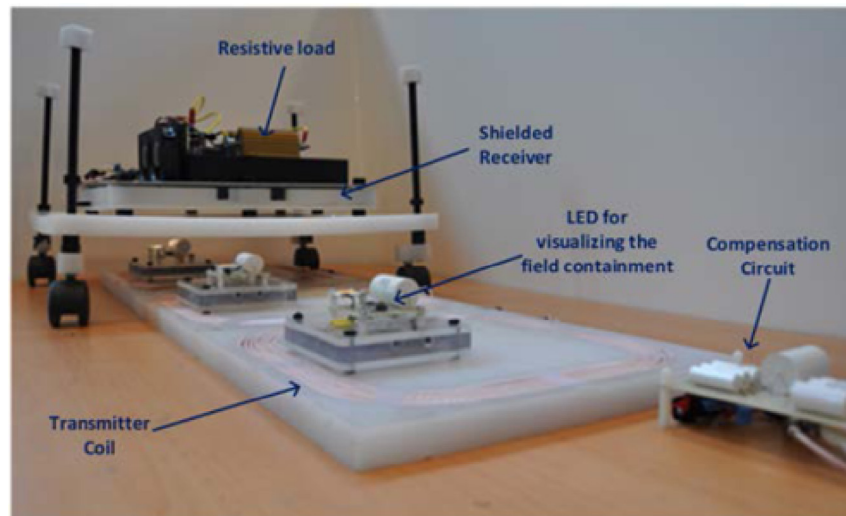


Figure 7: Vehicle moving over track and receiving power through HR-WPT [Lee13]

HR-WPT has also been devised as a powering mechanism for unmanned aerial vehicles (UAVs) [Griffin12]. In this study, the UAV acts as the source itself, with the researchers positing a system of sensors that need to be charged by the UAV periodically, as in underwater sensors that collect data and surface every so often to be charged [Griffin12].

Finally, HR-WPT has been demonstrated to be safe. In contrast to microwave radiation being transmitted in free space, magnetic resonance field levels of the HR-WPT system are kept below the established level for safe human exposure, and match existing technologies such as cellphones and Bluetooth [Kesler13].

In summary, HR-WPT is an alternative mechanism for WPT that addresses some of the limitations and concerns of the MPT system.

5. Conclusion

The focus of this paper has been an overview of the MPT mechanism for WPT, and its aim has been to highlight the many benefits and applications of MPT. The discussion began by describing and defining the fundamental aspects of the MPT system. This was followed by a look at the many applications of MPT to wirelessly transfer power from a source to a target, both in practical and near future applications and in theoretical applications for the future. The limitations and potential safety concerns were also pointed out, and the mechanism of HR-WPT was described as an alternate method for WPT. WPT has the potential to completely disrupt the way that mobile devices, from cellphones and laptops to cars and aerial vehicles, operate and obtain energy. The future of energy is the untethering of devices from a power cord to realize the freedom of mobile technologies.

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Appendix A - List of Acronyms

WPT Wireless Power Transfer
MPT Microwave Power Transfer
DC Direct Current
EV Electric Vehicle
SPS Solar Power Satellites
CO₂ Carbon Dioxide
UAV Unmanned Aerial Vehicle
HR-WPT Highly Resonant Wireless Power Transfer

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