Wireless power transmission and its applications for powering Drones

António Carvalho[1], Nuno Carvalho[1], Pedro Pinho[2], Ricardo Gonçalves[1]

[1]Instituto de Telecomunicações, Dep. de Electrónica, Telecomunicações e Informática, Universidade de Aveiro, Portugal
[2]Instituto de Telecomunicações, ISEL, Portugal

***Abstract*—Unmanned aerial vehicles or drones, as they are commonly referred to, suffer from a few drawbacks of which their short flight time can be underlined. For most commercial applications the maximum flight duration falls around a total of 15 minutes. In order to solve this limitation a microwave wireless power transmission system, working at 5.8 GHz, aimed at enabling drones to be charged in flight will be proposed and described in detail. The development of the antennas used, and corresponding rectifiers, will be thus discussed and suggestion for further work will be presented. With the architecture used it was possible to enable the drone to turn on and establish a link with its remote control by transmitting 32 dBm of power. The designed RF-DC converter did not reach its efficiency peak at the desired input power, still it presented a power overall efficiency of 70 % for 20 dBm of input power.**

***Keywords*—Microwave antenna array, Microstrip antennas, Rectennas, Unmanned Aerial Vehicles.**

I. INTRODUCTION

Unmanned Aerial Vehicles (UAV), commonly referred to as drones, are non-crewed aircrafts that can either be autonomous or remotely controlled. These devices have become massively used in the military, commercial and academic fields for several ingenious applications.

Several successful applications have arisen from the use of drones. These devices have been used to create a 3-D mapping of the Matterhorn, guide MIT students around campus and even to aid the American police in drug busts. Amazon has also recently announced they plan to create a UAV delivery service. However, this section will only present the research made specifically on wireless power transmission for drones.

A major drawback of these devices comes from their dependence of external power connections or batteries in order to function. These elements can lead to a rapid degradation of the hardware given that the pins connected to these devices get lax over time and can prevent proper battery charging after some use and also batteries have limited lifespans. It is thus necessary to make them able of being powered in a more effective and versatile way.

Lasermotive is the only company thus far to have presented a functional mean of wirelessly charging a drone at distance. It first got its financing after winning the NASA Centennial Challenges Power Beam challenge and their approach is based on a laser power beaming, where light is sent from the ground to the device and is then converted into useful electricity [1].

Another way of looking at wireless power transmission is seeing the drones not as receivers but as the power transmitters. Nebraska Intelligent MoBile Unmanned Systems Lab, from Nebraska-Lincoln University, have focused their efforts the other way around and have been developing a adaptive and autonomous energy management system that used drones to charge sensor networks via resonant inductive coupling [2]. This application can be very helpful, for example, for powering and transferring information with sensors in large or remote crop fields.

The University of Purdue as picked up on its part regarding the Wireless Power Helicopter and, in 2010, demonstrated a small model helicopter taking flight, powered by means of a flared horn antenna on the transmitter end and two dipole antennas on the receiver end. Also the research group from the University of Colorado is working now on a means of wirelessly powering a micro-drone in flight, enabling it to charge in confined environments and even charge several drones simultaneously, but there are still no publication on the matter.

In this article a wireless charging system will be proposed detailing the transmission, reception and power conversion architectures used. Section II presents a summary of the history of wireless power transfer, underlining some of the most relevant feats obtain so far. From that point forward, a full description of the proposed system and its elements is displayed, given that Section III regards the overall system while Sections IV and V show in more detail the current development of each section of the system.

The final section underlines the most relevant conclusions and obtained results.

II. HISTORY OF WIRELESS POWER TRANSMISSION

The idea of transferring electrical energy without the means of wires is not new. For the past century several scientists and engineers have thrived on the idea of building a truly wireless world by getting rid of the need for cables.

Nikola Tesla, probably the first and most frequently mentioned supporter of the concept of wireless power transmission, is said to be responsible for the first ideas and experiments on this field. This inventor, famous for his support of alternating currents, dreamt of wireless communications and power transfer and dedicated a considerable amount of effort to the development of these fields [3]. In 1893, Tesla was able to demonstrate the wireless illumination of phosphorescent lamps at the World's Columbian Exposition, Chicago, and between 1900 and 1917, he focused his efforts to the development of the Wardenclyffe tower, a tower that would work as an antenna for wireless transatlantic telephony and demonstrate the transmission of power through long distances without cables. Yet, given the difficulty to find further financial support for this project, the tower was demolished during the 1st World War [4].

Almost half a century later a noticeable feat was accomplished by an electrical engineer from the Raytheon Company. William C. Brown devised a somewhat entertaining experiment as proof of concept for his developments in rectifying antennas (*rectennas*) and succeeded in 1964 to fly a helicopter 15 meters in the air without use of an onboard power supply. Even though the helicopter required kilowatts of power to be transmitted in order for it to maintain flight this experiment proved the feasibility of microwave power transmission [5].

Already in the 21st century, several companies that are focusing their efforts on wireless power transmission systems have popped up. Of these, probably the most mediated would be WiTricity, a company that spun off from its homonymous Massachusetts Institute of Technology (MIT) project which was lead by Prof. Marin Soljačić. WiTricity is a company that manufactures devices for wireless energy transfer using "strong" inductive coupling and has already demonstrated a power unit powering simultaneously a television set and three cellphones at the TED Global Conference in Oxford, 2009.

Several major industry associations have been created in order to globally standardize wireless power transfer mechanisms. The first consortium to be established, back in 2008, was the Wireless Power Consortium. It includes already over 180 companies, industry leaders in the most various of fields, e.g. mobile phones, batteries and infrastructure [6] and has established their *Qi* norm, which defines interface for low power transfer (around 5 W), and is working on their standard for medium power (up to 120 W).

III. DESCRIPTION OF THE PROPOSED SYSTEM

The typical wireless power transfer system can be divided into two major sections, the power transmitter and the receiver. In the transmitter, high frequency waves are generated with enough power to comply with the specifications of the project and are then directed and radiated at the receiver. The receiver end must then capture and efficiently convert this power to direct current (DC) so that it might be provided to a given load. These core components are better observed in Figure 1.

The transmitter must be capable of generating and radiating power at microwave frequencies. The choice of generator, which is typically between a magnetron or solid-state source, will vary with desired frequency, efficiency, signal purity and power, which will have the major weight on the overall cost of this section [**?**]. The antenna, as described in [5], should present an extremely directive radiation pattern.

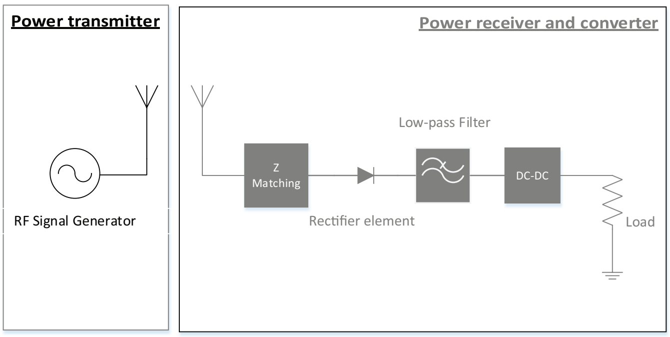

Fig. 1: Wireless power transfer system consisting of a transmitter and receiver section.

Fig. 2: Representation of a drone charging with resort to microwave power transmission.

The receiver's antenna on the other hand should be "non-directive" so that the target is able to capture power even when subjected to small movements. Following the antenna an impedance matching network is typically used to reduce mismatch losses between the antenna and the rectifier, this section might not be necessary if both the antenna and rectifier are designed to be already matched at the desired input power. Then comes the RF-DC converter and, if needed, a DC-DC converter to tune the output current or voltage's value. It should be noted that the power overall efficiency (POE) of the receiver is equal to the product of the independent efficiencies of each of its stages and thus to obtain maximum power conversion efficiency the number of stages needed must be minimum [7].

Schottky diodes are the most commonly used devices for high frequency rectifiers. These diodes present a much lower junction capacitance [8] and dropout voltage then common pn junction diodes. Their conductivity is mostly due to the majority-carriers (i.e. electrons), thus these diodes don't exhibit the effects of minority-carrier charge effect present in forward biased pn junctions, making it able of switching much faster between on and off [9], and much more appealing for high frequency applications. However, the input impedance of these diodes changes with the available power, making it somewhat difficult to precisely optimize the circuit given that with a moving target and antenna polarization mismatch there will be significant changes in the available power levels.

As in [10], the frequency chosen for this project was 5.8 GHz for it implies smaller components dimensions. This frequency is complaint with the Industrial, Scientific and Medical standards.

The load is of major importance for the receiver given that, for diode based rectifiers, it limits the conversion efficiency at higher input power levels [11]. For this project the load is a commercial HUBSAN X4 quadcopter.

Given the quadcopter acts as a variable load and that the power conversion efficiencies of RF-DC converter vary with the available input power and the load, several compromises will be taken when designing the RF-DC converter. A representation of the concept of wirelessly charging a drone is showed in Figure 2.

IV. TRANSMITTER

For this section only the antenna will be designed. The specifications of this project are therefore limited to the available power at 5.8 GHz which is 32 dBm.

The type of antenna chosen for both the transmitter and receiver was microstrip patch given they are simple to replicate and can easily be displayed in a planar array configuration in order to gain greater directivity. These antennas are conformable to planar or even nonplanar surfaces, are simple to manufacture with the same means of common printed-circuits and are versatile regarding their fundamental parameters [12].

First, a single patch element was designed and then simulated using the Microwave Studio from the CST suite. The dimensions of the patch were tuned so that it would present a return loss over 20 dB at the desired frequency and a bandwidth sufficiently wide to have some safeguard regarding the implementation tolerances the dielectric constant and printing tolerances. The substrate used was a 1.27 mm high Rogers RO3006 substrate with a design dielectric constant of 6.15 and a loss tangent of 0.002.

The patch was excited using an inset feed composed of a quarter-wave impedance transformer from inside the patch to a 50 Ω line were the connectors would be soldered and resulted in a simulated return loss of 21 dB at 5.8 GHz. This single element antenna presented a directivity of 7 dBi.

The single patch antenna presented measured a return loss of 22.5 dB at 5.7 GHz instead of the desired frequency and so for remainder of the design of the array the dielectric constant was considered to have a slightly higher value. The comparison between simulated and measured S_{11} is presented in Figure 3.

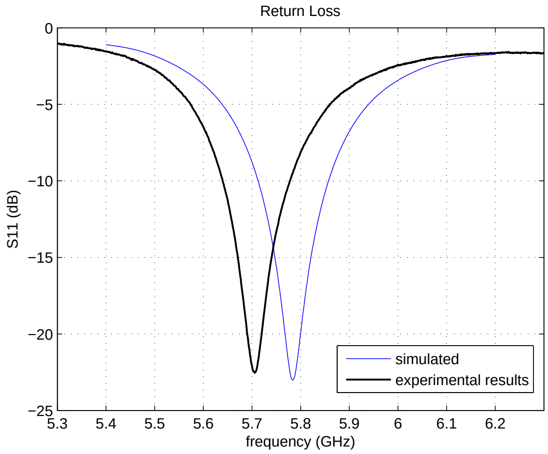

Fig. 3: Measured return loss of the patch compared with the simulated values.

After the dimensions of the patch were tuned to approximate the simulated and measured results, the array factor was derived with regards to distribution of the individual elements. For this case the array is symmetrical so that the antennas are excited with the same amplitude and phase, therefore only the spacing was optimized. A total of 16 elements were considered.

The feed network of the complete array is composed by quarter-wave impedance transformers and T-junction. The final design is presented in figure 4.

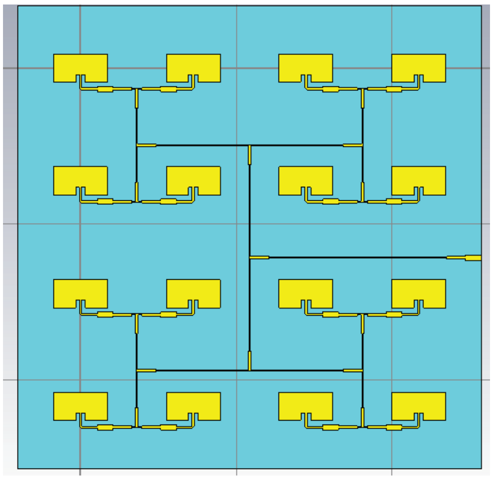

Fig. 4: Final array layout.

A directivity of 19.6 dBi for the main lobe was obtained through simulation, with a return loss is 18.19 dB at 5.8 GHz and a bandwidth of 130 MHz.

A return loss of 9.8 dB was measured at 5.8 GHz, being that its minimum value is presented at 5.864 GHz. Moreover, a gain of 16.8 dBi and 18 dBi were measured for the antenna array at 5.8 GHz and 5.864 GHz, respectively. The measured and simulated S_{11} and radiation pattern at 5.8 GHz are respectively presented in Figures 5 and 6.

The directivity of the radiation pattern was calculated using Kraus' formula [12] resulting in 20 dBi and this array can thus be considered as directive.

V. RECEIVER

A. Antennas

To verify the effects of polarization mismatch both a linearly and a right-hand circularly polarized patch antennas were designed. Both antennas were also design regarding a Rogers RO3006 substrate with a height of 1.27 mm. This dielectric of 6.15 is fairly high, given radiation is desired, but was used as a compromise to obtain smaller dimensions. The designs are presented in Figure 7.

For this case the antennas were designed with a coaxial feed so that the rectifier circuit could be added at the back o

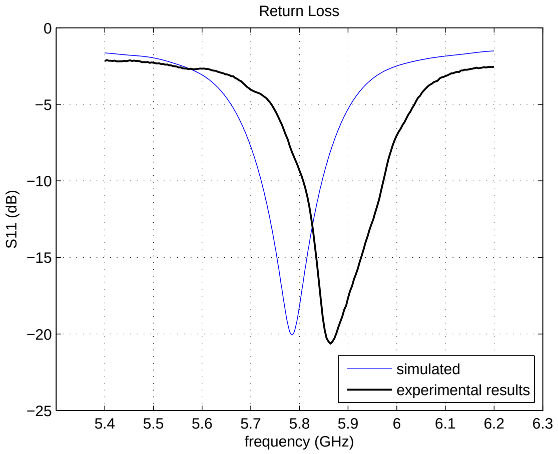

Fig. 5: Comparison between the measured and simulated S_{11} of the full array.

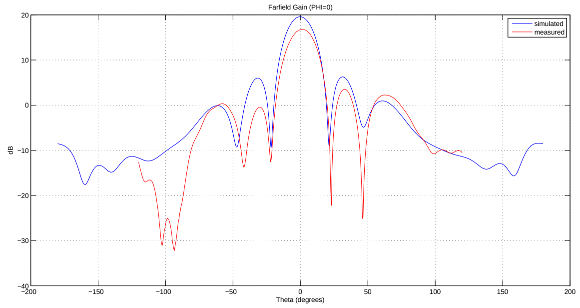

Fig. 6: Simulated and measured gain variation with theta of the 4x4 patch antenna array.

the antenna.

The simulated square patch presented a return loss of 42 dB at 5.8 GHz and a bandwidth of 162 MHz while the circularly polarized patch presented a return loss of 13 dB and an axial ratio of 0.35 dB. The S_{11} of the measured and simulated results for both antennas are presented in Figures 8 and 9.

The results shifted from the simulations for both antennas but still present themselves as acceptable at 5.8 GHz. These changes in frequency response can come from small shifts in the placement of the feed, given this implementation was done by hand, and parasitic effects from the solder, which was not considered during simulation.

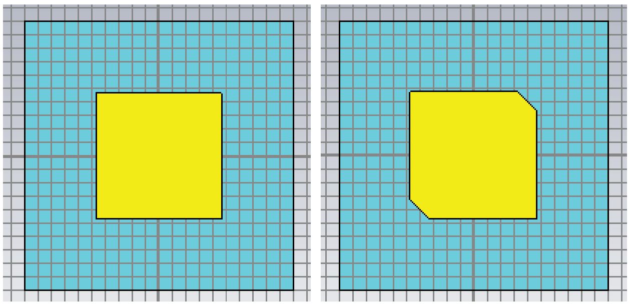

Fig. 7: Receiver antennas.

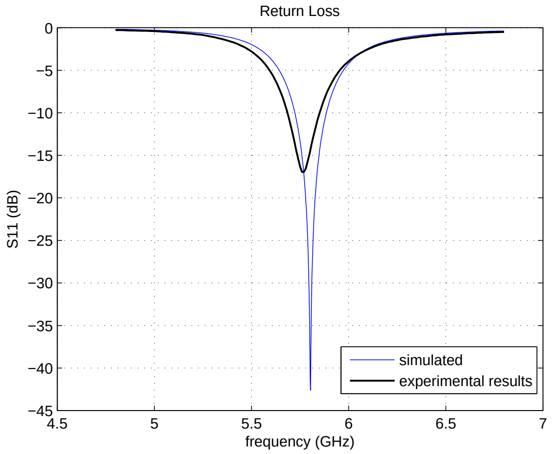

Fig. 8: Comparison between simulated and measured values for the linearly polarized square patch.

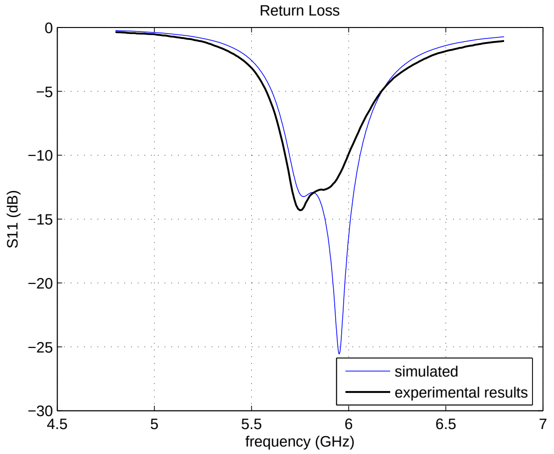

Fig. 9: Comparison between simulated and measured values for the right hand circularly polarized patch.

The linearly and circularly polarized antennas presented a return loss of 14.7 dB and 13.2 dB, respectively. The later presented a measured axial ratio under 2.4 dB for ± 30 degrees from mainbeam at 5.8 GHz making its polarization acceptable.

B. RF-DC

For the HUBSAN X4 to fly in ideal conditions it needs approximately 3.7 V and 1.8 A, which represent 6.66 W of power. However, the maximum power conversion is limited to an input power of $\frac{{V_{BR}}^2}{4R_L}$ [7] and that the maximum power conversion efficiency expected from a half-wave rectifier, with high powers at the input, will be around 50 % [10] given it is also limited by the diodes non-ideal behaviour. Given the available power is only 32 dBm and considering path, conversion and mismatch losses, it is predictable that the drone will not be able to fly depending solely on this system.

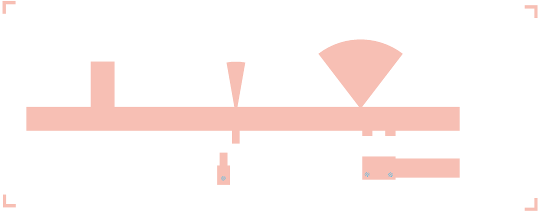

Fig. 10: Single shunt rectifier circuit layout.

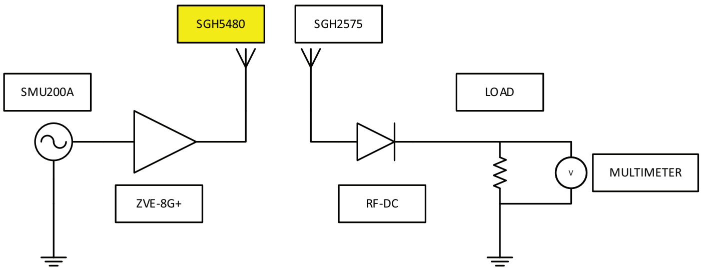

Fig. 11: Diagram of the experimental setup for the measuring of the output voltage of the RF-DC converter.

Considering that 32 dBm of received power would imply a peak-to-peak voltage of the sinusoidal signal, for a 50 Ω system, of 25.175 V the diodes chosen were the HSMS-2810 which present a minimum breakdown voltage, V_{BR}, of 20 V, a series resistance of 10 Ω and a maximum forward of 400 mV.

For the low pass filter following the diode a 100 pF capacitor was picked for it works as a short-circuit at 5.8 GHz and guarantees a RC time constant would be lower than the period of the RF wave. Given the drones behaves as a variable resistor, the considered load in the simulations is that which implies greater efficiency for the overall circuit.

A single shunt rectifier topology was thus designed and simulated using Advanced Design Systems, being that the lumped elements were tuned through Large Signal S-Parameters and Harmonic Balance simulations and the microstrip lines were optimized through Momentum Microwave simulation. Radial stubs were added to the circuit in order to attenuate the behaviour of power at undesirable frequencies. Also an impedance matching network was added to match the impedance of the antenna to the input impedance of the RF-DC converter that resulted in maximum power conversion efficiency at 32 dBm. The circuit layout is presented in Figure 10.

The circuit was measured using the experimental setup presented in Figure 11, where isolation between power amplifier and load is obtained using two references antennas. The antenna array designed previously was not used because it had suffered some damage to its connector due and was not operational at the time.

Even with such high gain antennas it was only possible to measure a maximum input power of 20.6 dBm and therefore, for the measured results, only efficiencies for input power of 0 do 20 dBm where considered.

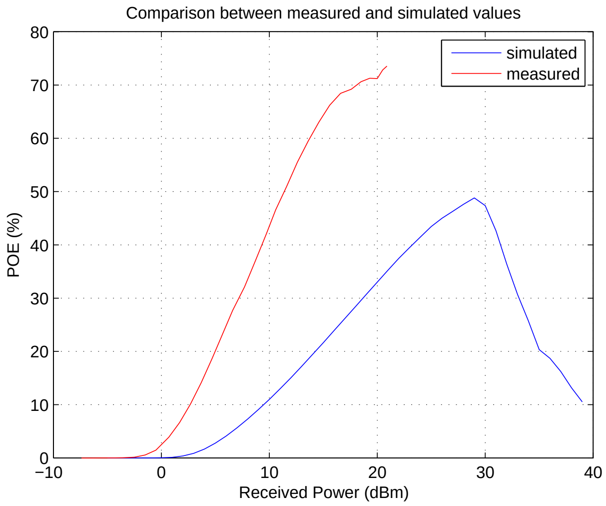

Fig. 12: Simulated versus measured POE of the Momentum simulated RF-DC Converter.

It can be observed in Figure 12 that the POE is reaching for its maximum value at input power level lower than that which was intended in the simulation. It is likely that this change in POE is either due to changes in the characteristic impedance of the lines, or due to shifts of the input impedance of the antennas which leads the matching circuit to reach 50 Ω at a lower input powers.

The efficiency at 20 dBm of input power is approximately 70 %, which is very close the the 75 % maximum found in the literature [13], and it is expected that at 30 dBm the circuit will have already passed the higher power threshold and will present low efficiencies.

VI. EXPERIMENTS WITH THE DRONE

Given that not enough power could be converted in receiver so that the drone could take flight the power amplifier was connected to the RF-DC converter, with a broadband DC-Block between them, to verify the response of the device. For this case the battery was removed and the drones was directly connected to the RF-DC converter.

It was verified that once connected to the RF-DC converter the drone was able to fully light its four LED's and establish a link with the remote control. However, at this point the LED's would start blinking as a sign of low battery (lack of current). No measurements were devised in order to gather information on how much power was being transmitted from the power amplifier to the RF-DC Converter.

VII. CONCLUSION

A 16 element antenna array with a gain of 16.8 dBi at 5.8 GHz has been developed with the intent of being used for wireless power transmission while two single patch antennas, with different radiation polarizations, were designed for the receiver end. Although its results shifted from the simulations, a single shunt RF-DC converter was designed, obtaining an efficiency of 70 % for an input power 20 dBm.

Overall, the several sections designed present potential in being further implemented in fully or temporarily charging an unmanned aerial vehicle, tackling its reduced autonomy.

ACKNOWLEDGMENT

We would like to acknowledge the financial Support of COST IC1301.

REFERENCES

[1] Brooke Boen. After the Challenge: LaserMotive. http://www.nasa.gov/offices/oct/stp/centennial_challenges/after_challenge/lasermotive.html, November 2012.

[2] B. Griffin and C. Detweiler. Resonant wireless power transfer to ground sensors from a uav. *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, 2012.

[3] Nikola Tesla. The transmission of electric energy without wires. *The thirteenth Anniversary Number of the Electrical World and Engineer*, 1904.

[4] Hugo Gernsback. U.S. Blows Up Tesla Radio Tower. *The Electrical Experimenter*, page 293, September 1917.

[5] William C. Brown. The microwave powered helicopter. *Journal of Microwave Power and Electromagnetic Energy*, 1(1):1–20, 1966.

[6] Wireless Power Consortium. http://www.wirelesspowerconsortium.com/about/.

[7] Christopher R. Valenta and Gregory D. Durgin. Harvesting wireless power. *IEEE Microwave Magazine*, 15(4):108–120, June 2014.

[8] R. Ludwig and P. Bretchko. *RF Circuit Design: Theory and Applications*. Prentice-Hall, Upper Saddle-River, N.J., 2000.

[9] Adel S. Sedra and Kenneth C. Smith. *Microelectronic circuits*. Oxford University Press, 2011.

[10] James O. McSpadden, Lu Fan, and Kai Chang. Design and experiments of a high-conversion-efficiency 5.8-ghz rectenna. *IEEE Transactions on Microwave Theory and Techniques*, 46(12):2053–2060, December 1998.

[11] Tae-Whan Yoo and Kai Chang. Theoretical and experimental development of 10 and 35 ghz rectennas. *IEEE Transactions on Microwave and Techniques*, 40(6):1259 – 1266, June 1992.

[12] Constantine A. Balanis. *Antenna Theory: Analysis and Design*. John Wiley & Sons, Inc., 2005.

[13] W. Tu, S. Hsu, and K. Chang. Compact 5.8-ghz rectenna using stepped-impedance dipole antenna. *IEEE Ante*, 6:282–284, June 2007.