Dynamic and Efficient RF Lens for Wireless Power Transfer over Long Distances

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Abstract—**Through the past few years, there has been a dramatic increase in the number of small electronic devices available on the market. All those devices need to be powered by some means, usually facilitated through use of a cord plugged into the device. Users, however, may want to use their device without being restricted by a cord. Wireless power makes it possible to charge without needing to plug a device in. In addition, allowing users to move their device away from the charging apparatus allows for a better user experience. Radio frequency lensing was explored to deliver power at a distance to be harvested by a device.**

Index Terms—**RF Lensing**

I. Introduction

THROUGH the use of radio frequencies, humans are able to do everything from listening to music and streaming videos to using Wi-Fi to connect to a server and perform scientific calculations. To use the array of devices that allow people to communicate and be productive wirelessly, each device must have a battery or other power source that must be charged by some means. In almost all cases, this currently means devices must be plugged into an outlet in the wall, severely limiting their mobility.

To be able to charge wirelessly is therefore necessary to create a device that is truly able to operate without any wires. This report details one such approach: Radio Frequency (RF) Lensing.

II. Background and Motivation

Wireless charging is certainly not a new idea. Many systems are currently deployed to charge devices wirelessly. However, they require the device to be co-located with the charging apparatus since the systems employ induction or magnetic resonance. Using these methods requires a set of two coils, one on the charging station and one in the device, to induce current from the charging station in the device. The main difference between the two approaches is the addition of an LC resonant circuit to increase efficiencies in magnetic resonance charging. In both cases, the charging is only effective when the device is very close to the charging station.

By contrast, RF Lensing is designed to deliver power at a distance. The motivation for efficient power transfer through radiative means emerges from the focusing action of a lens. Using an optical lens, it is possible to focus light on a single point in space. Using an array of radiating RF sources with controllable phase gradient, it is possible to make the radiated signals constructively interfere at the focus point. Having control over the phase gradient, it is possible to dynamically change the focus point to follow a device around a room.

III. Approach

Simulations were conducted to determine the feasibility of this approach. A 4x4 square grid phased array antenna was placed in 3D space operating at 915 MHz and with each element being dipole for simulation purposes, spaced at a distance of $d = \frac{\lambda}{2}$ to reduce the power of side lobes, where λ is the wavelength, approximately 0.16 m at 915 MHz. The phases are adjusted to satisfy (1).

$$\Delta\phi = \beta \times (d_i - d_1) \tag{1}$$

In the above equation, $\Delta\phi$ is the added phase, β is the wavenumber, and $d_i - d_1$ is the difference in the distance from emitter *i* to the receiver and the distance from emitter *1* to the receiver.

Simulations were run with various distances from the array to the receiver as well as various angles. Doing these simulations, over 50% efficiency was seen at a distance of 1 m from the antenna array. The beam was also steerable to various angles and distances, increasing power delivery at various locations it was pointed towards.

Based on simulation results, an array at 915 MHz with controllable phase gradient was built, as well as a receiver to rectify the received RF power. On the transmitter side, a 183 MHz common RF source was selected with a voltage controlled oscillator (VCO). Individual printed circuit boards (PCBs) were created for each element in the array. On each board, the 183 MHz signal is shifted by a Phase Locked Loop (PLL), which is controllable to 1.3 mUI, or approximately 0.468 degrees. This signal is then put through a second PLL to create a 915 MHz signal that contains the phase shift from the 183 MHz signal. Since the frequency is multiplied by a factor of 5, the phase shift is also multiplied accordingly, leading to approximately 2.43 degrees of control over the output phase. This 915 MHz is amplified by a power amplifier (PA) that has

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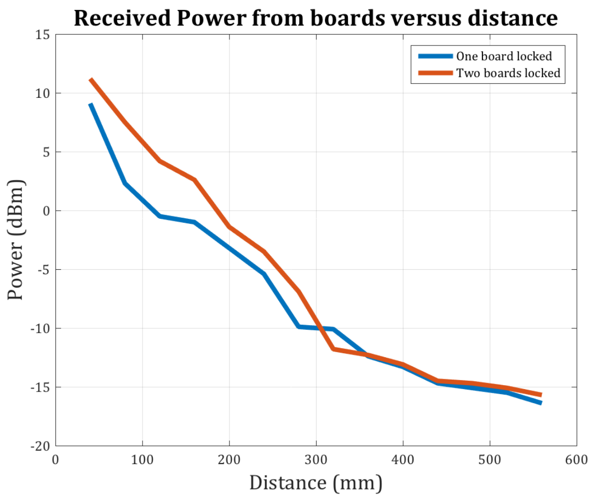

Fig. 1. Power received from two boards versus distance.

a maximum output power of 34.5 dBm. Based on the datasheets of the components that make up the previous stages, approximately 30 dBm is available. The amplified signal is then delivered to an antenna to be radiated out.

Digital control for all components was implemented using a Raspberry Pi using Python to interface with each component.

IV. Experimental Results

After the PCBs were created, multiple tests were run to characterize each individual component of the system. The input voltage to the VCO was tuned using a potentiometer connected to a 5V source. The frequency had a slope of approximately 20 MHz/V, and the power of each harmonic decreased by roughly 10 dB from the harmonic before it. The delay from the output of the first PLL was measured to be roughly 0.4183 degrees with an r^2 value of 0.9936. The second PLL delay was measured to be 2.1500 degrees with an r^2 value of 0.9963. The output from the second PLL was around 8 dB smaller than the datasheet specified (-2 dBm), which led to less power delivered to the PA than designed. With this lower power, he PA was only able to deliver around 11 dBm to the antenna. The antenna selected was a patch antenna with a nominal center at 915 MHz with right hand circular polarization (RHCP).

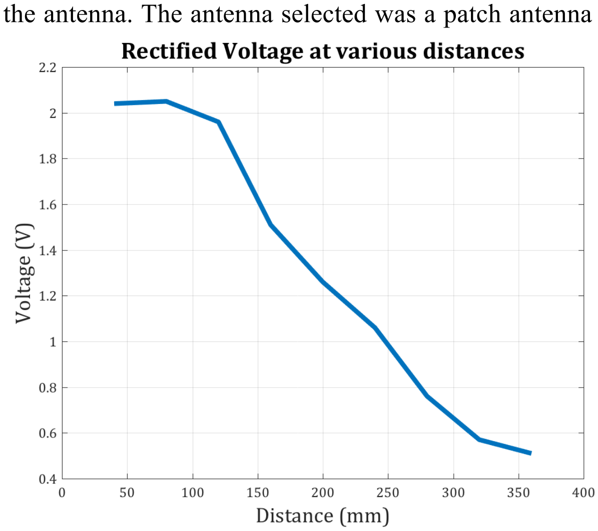

Fig. 2. Rectified Voltage versus distance from transmitter array.

To measure received power, a small board was made with a patch antenna connected to an SMA connector. Received power was measured in one and two emitter board configurations. Beyond two boards, there was difficulty in getting all the PLLs to lock due to reflection increasing the power of harmonics. Results for received power versus distance is show in Fig. 1. Using control, phases were adjusted to find the highest output power level.

A small rectifier PCB was developed using a diode bridge to rectify it followed by a buck/boost converter to output a 5 V signal that is routed to a USB connector. The pre-rectifier output voltage is shown in Fig. 2.

V. Conclusions and Future Work

Through this work, a system that can deliver power at a distance was demonstrated. The power received was impacted by the phase difference on the transmitters and larger powers can be seen with increasing numbers of boards.

There are several routes to build upon this work and make a commercially viable wireless power system. Delivering more power to the first PLL would be the first step to get more boards to lock. This could be followed by increasing the power to the antenna with another PA. The PCB design should be revisited to ensure that the signals on the board are not impacted by board design. Adding automated control, possibly by a feedback loop through a separate wireless channel, would be another improvement that could be made.

After graduating from Princeton University, I started working at Lockheed Martin in Moorestown, NJ, where I am a member of the Engineering Leadership Development Program. I plan on pursuing a Masters degree in Embedded Systems in the future. I would like to sincerely thank the IEEE Microwave Theory and Techniques Society for their support of this research and the ability to attend the IMS 2016. The conference was a wonderful opportunity to see what problems are being researched as well as to interact with leading minds in the industry. The MTT-S Scholarship program has furthered my interests in designing complex electrical systems and has encouraged my decision to pursue opportunities in communications and systems. I look forward to working on ever more complex systems in his career and as a hobby.

References

[1] K. Sengupta and S.A. Hajimiri. Smart rf lensing: e cient, dynamic and mobile wireless power transfer, June 26 2014. URL https://www.google.com/patents/ US20140175893. US Patent App. 14/078,489.

[2] Lawrence Berkeley National Laboratory. Standby power summary table, 2016. URL http://standby.lbl.gov/summary-table.html.

[3] Brian Barrett. Wireless charging is still a mess, but it won't be forever. Wired, 15 November 2015.

[4] Constantine A. Balanis, editor. Modern Antenna Handbook. John Wiley & Sons, Inc., 2008. Chapter 11.

[5] V. Marian, B. Allard, C. Vollaire, and J. Verdier. Strategy for microwave energy harvesting from ambient eld or a feeding source. IEEE Transactions on Power Electronics, 27(11):4481–4491, Nov 2012. ISSN 0885-8993. doi: 10.1109/TPEL. 2012.2185249.