A Novel System for Long Range Wireless Power Transmission

Statement of Problem

Energy consumption is rising, due to population growth and newer power-hungry technologies, leading to a need for new clean green energy. Traditionally, power transmission has heavily relied on wired infrastructure. However, building wired infrastructure is expensive, when delivering from new sources over long distances OR even from new sources through older buildings (ex, solar panels in apartments). Wireless power transmission (WPT) systems could solve this dilemma, but face limitations, like high energy loss over medium-long range distance and costly materials.

This project seeks to overcome these challenges by developing a Novel Wireless Power Transmission (WPT) system. First, a novel WPT system was designed to translate energy into phase aligned and collimated 2.4GHz radio waves, so the energy could be beamed wirelessly. Second, High Frequency Simulation Software (HFSS) was used to validate the novel WPT design. Third, a full WPT prototype was built as a proof-of-concept to ensure the WPT system works in real world conditions.

Introduction

Energy usage per capita is rapidly increasing, due to population growth and new energy hungry technologies. Consequently, new clean energy sources and new methods of energy delivery are needed. In delivering energy, wired infrastructure is expensive to build due to high labor/material costs (ex, 1 power transmission tower every ½ kilometer). Alternatively, Wireless Power Transmission (WPT) could deliver power with convenience and lower costs. Current WPT technology is limited to extremely short distances. Wireless power transmission over medium-long range distances is a prerequisite to utilize newer clean energy, like using solar panels on apartments or using wind farms from long distances to cities. This project develops foundational techniques to build the technology for Wireless Power Transmission for these applications.

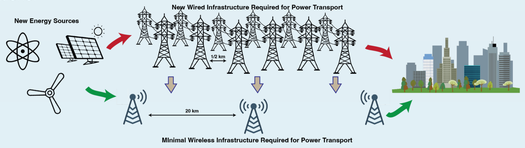


Figure 1. Usage Model for Wireless Power Transmission

Current WPT systems work well for very short distances (about 4 cm) via induction charging but not for long distances. Induction transmission over long distances is impossible due to increasing size of magnetic coils needed and decreasing efficiency of power transfer. One solution is to utilize radiofrequency (RF) electromagnetic (EM) waves instead.

RF EM waves to transmit energy is a new research field, with mixed outcomes because: 1) Poor transmission efficiency (ex, very high frequencies like 60GHz), and 2) Expensive due to high material usage at long wavelengths (ex, lower frequencies like 400MHz).

The WPT system designed in this project to transmit power wirelessly is novel : a) uses 2.4gHz RF EM waves to wirelessly transmit energy b) uses a Phased Array Transmitter to narrow and concentrate the wireless RF power beam, c) uses a newly designed Fresnel lenses for RF EM waves which phase aligns and collimates the radio waves in a specific direction. This WPT can allow for efficient wireless power transmission at a low cost.

The Phased Array Transmitter is an array of power amplifiers and antennas. Key advantages of Phased Arrays are narrowing/directing the beam and increasing the power gain transmission by N^2 instead of N. Phased arrays work by using multiple antennas, where each antenna sends out EM waves with different phase shifts. Through constructive interference, these waves combine to produce high gain in a specific direction, while destructive interference reduces unwanted EM waves in other locations. The Radiated power and Directivity (Half-power Beam width) are based on number of antennas, N, wavelength, λ, and distance between array elements, d, and antenna gain, G, as seen in these equations:

$$P_{radiated} = \frac{1}{r^2}\frac{G\lambda^2}{4\pi}N^2 P_{in} \qquad \text{Eq. 1}$$

$$HPBW\ \theta_B \sim \frac{0.886\lambda}{Ndcos\theta} \qquad \text{Eq. 2}$$

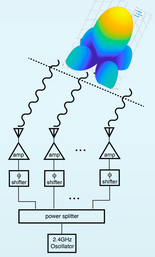


Figure 2. Phased Array Dynamics

Fresnel Lenses, originally designed to magnify and collimate light, are best known in lighthouses. A Fresnel lens replaces the curved surface of a conventional optical lens with a series of angular concentric rings, angling the light rays' path so that they collimate.

(a) (b)

Figure 3. (a) Curved Lens profile reduced to Fresnel Lens. (b) Front view of Fresnel Lens

Figure 4. EM waves propagating through 2 Fresnel Lenses

The newly designed Fresnel lens is created to beam 2.4GHz radio waves with a wavelength of 12.5cm, rather than light at 500nm. Unlike light, to collimate RF waves requires phase alignment of the RF waves. To phase align and collimate the RF waves, the novel Fresnel lens consists of concentric ring, each with different dielectrics and angles. For dielectric constants, the dielectric of a material, ε_R, changes the propagation speed of the EM wave relative to free space and also changes the angle of propagation (Snell's Law):

$$v_{\varepsilon R} = \frac{c}{\sqrt{\varepsilon_R}} \qquad \lambda_{\varepsilon R} = \frac{v_{\varepsilon R}}{f} \qquad \text{Eq. 3}$$

$$\text{Snell's Law: } \frac{sin\theta_1}{sin\theta_2} = \frac{v_1}{v_2} = \sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \qquad \text{Eq. 4}$$

To phase align the EM waves, the new Fresnel lens has different dielectrics in each concentric ring, with the central area having a high dielectric (to slow down the wave) while peripheral rings have lower and lower dielectrics (so a wave which traveled a longer distance to the periphery can catch up and phase align with the central EM wave). To achieve different dielectrics, each concentric ring uses differing density of lattice structures, so the effective dielectric is equivalent to the ratio of the material used divided by the total area in the lattice. Further, the now phase aligned EM waves are then collimated by angular grooves specific to each concentric ring of the Fresnel lens. With these angles, the phase aligned waves which were radiating as a cone are now collimated as they pass through the Fresnel lens.

Methodology

- To design the Transmitter (TX) and Antenna Phased Array, original programs written in MATLAB and then simulated for gain and directivity in Ansoft HFSS (High Frequency Structure Simulator), an EM simulator. (Fig 9)
  - The antenna was designed with representation for substrate, ground, and feedline that was built directly in HFSS
  - HFSS simulations done for single antenna and for an array of 9 elements looking at gain and directivity in both far-field and near-field conditions. (Figs.11-22)
- To design the novel RF Fresnel Lens, the lenses were created in Excel and Autodesk Fusion, simulated in HFSS, and then printed with a 3D printer.
  - A novel low profile Fresnel lens was designed in Excel based on focal length of 30cm and HPBW of 30deg for 2.4GHz EM propagation. (Figs. 6-8)
    - Full lens has a radius of 10cm with each ring having a width of 1cm.
    - Width of lens is 1cm + various low profile heights of the angles
    - Each concentric ring designed with: 1. different dielectrics to equalize propagation delay resulting in phase alignment and 2. different angles to provide correct angle refraction
  - Final design in Excel was then re-created in Autodesk Fusion to generate STEM file for HFSS simulation and STL file for 3D printing
- Simulation of the TX antennas and the Fresnel lens conducted in HFSS to determine the phase alignment and collimating properties of the WPT system for 2.4GHz EM waves.
  - Power estimates were determined based on near-field simulations
  - Electric field propagation was determined based on far-field simulations
  - Propagation at various distances were simulated to validate collimation of EM waves
- Prototype was built for WPT system (Fig. 5)
  - Solar panels were used for energy source to power the Antenna Array
  - Original Printed Circuit Boards were designed (schematic and layout) in Altium software for both the TX Phase Array Board and the Antenna Array Board (Fig. 9)
  - The PCBs were printed by Advanced Circuit Board and populated with surface mount (SMT) components, provided by Mini-circuits
  - ABS Material with a EM dielectric of 5 at RF 2.4GHz, procured from Avient Technologies
  - The Fresnel Lenses were printed on a Raise 3D Printer, supported by Magnetika Corp
  - Rectenna was designed to be built with copper tape on FR4 material with SMT components for antenna matching and rectifying electric waves to power a light bulb or store power in a super capacitor.
- Measurements using spectrum analyzer at various distances from the TX and Antenna Array were taken to determine the power transmission capability and efficiency of the WPT system

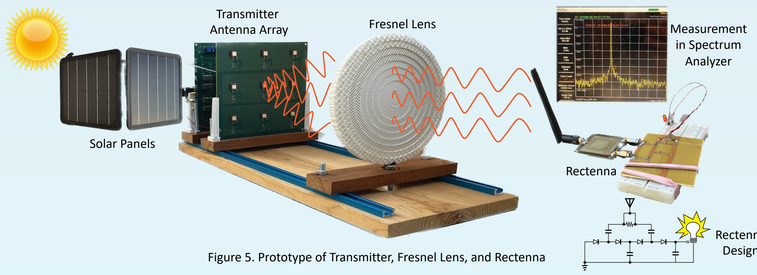


Figure 5. Prototype of Transmitter, Fresnel Lens, and Rectenna

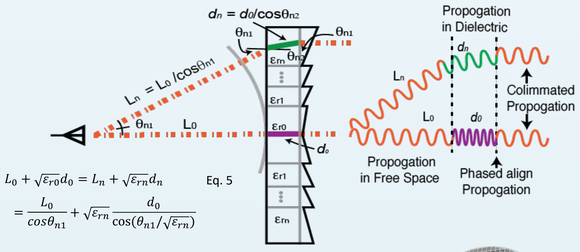
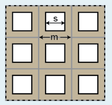


Figure 6. Fresnel Lens design methodology



$$\varepsilon_r = (\varepsilon_{rmax} - 1)\frac{(m^2 - s^2)}{m^2} + 1 \qquad \text{Eq. 6}$$

$$\varepsilon_{rmax} = 5$$

Figure 7. Lattice structure for the Fresnel Lens and equation used for design

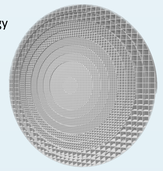


Figure 8. Fresnel Len designed in Fusion 360

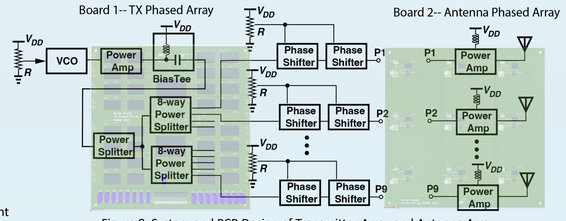


Figure 9. System and PCB Design of Transmitter Array and Antenna Array

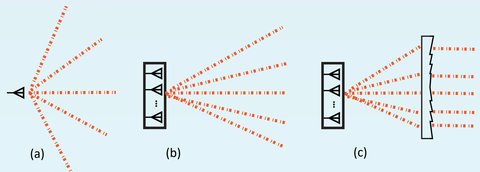


Figure 10. EM propagation from (a) single antenna transmitter, (b) phased array transmitter, (c) phased array transmitter with Fresnel lens

Electromagnetic (EM) Simulation Data for Wireless Power Transmission System

Simulations for Single Patch Antenna at 2.4 GHz

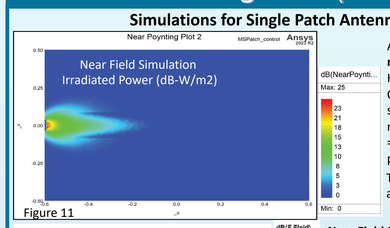


Figure 11

A **single antenna model** is built in HFSS using a Copper (Cu) substrate, Dielectric material like FR4 (ε_r = 3.8), and patch pattern in Cu.

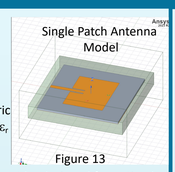


Figure 13

The patch shape must be designed for optimal antenna radiance at the frequency of 2.4Ghz

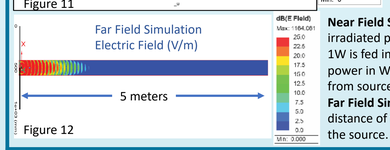


Figure 12

Near Field Simulations determine the irradiated power from the antenna if 1W is fed into the source. No or **0W** power in Watts is visible at 0.5m away from source.

Far Field Simulations determines the distance of the E field radiated from the source. Max distance is 1.2m.

Single Antenna Without Lens		
Distance (m)	E Field (dB)	E Field (V/m)
1	8.5	7.0795
2	0	0
3	0	0
4	0	0
5	0	0
Max Distance	1.2 m	

Simulations for Single Patch Antenna and Fresnel Lens at 2.4 GHz

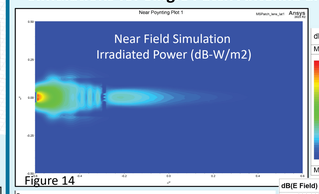


Figure 14

A **single antenna plus Fresnel lens** is simulated in HFSS using an imported model of the Fresnel lens designed in Auto-desk. The Geometry and dielectric materials are modeled in HFSS.

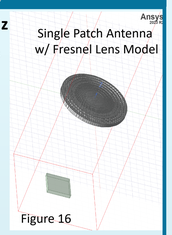


Figure 16

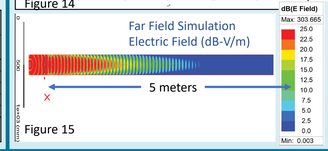


Figure 15

Near Field Simulations show the irradiated power from the antenna extends further with Fresnel lens and **0.3W** is calculated at 0.5m.

Far Field Simulations Also show an increase in the distance the E field is radiated from the source.

Single Antenna With Fresnel Lens		
Distance (m)	E Field (dB)	E Field (V/m)
1	23.5	223.87
2	18	63.096
3	9	7.9433
4	0	
5	0	
Max Distance	3.5 m	

Simulations for Patch Antenna Array (9 Element) at 2.4 GHz

An **antenna array model** is built in HFSS using the baseline single antenna and creating a 3X3 array with the single patch array. Each patch antenna is placed 6.5cm away from the other antenna so they are $\lambda/2$ apart from each other for a 2.4GHz signal.

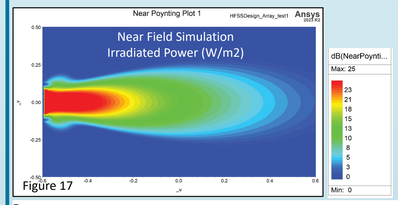


Figure 17

Near Field Simulations determine the irradiated power from the antenna if 1W was fed into each source (9X) and phase is aligned boresight. **16W** is calculated at 0.5m from source.

Far Field Simulations Phased Array also shows increased distance for field as seen in table as well.

3X3 Phased Array Without Lens		
Distance (m)	E Field (dB)	E Field (V/m)
2	37	5011.9
4	28.5	707.95
6	12.5	17.783
8	4.5	2.8184
10	0	
Max Distance	8.5 m	

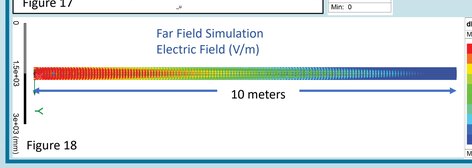


Figure 18

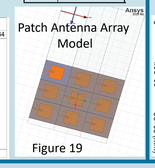


Figure 19

Simulations for Patch Antenna Array (9 Element) and Fresnel Lens at 2.4 GHz

An **antenna array plus Fresnel lens** is also modelled and simulated in HFSS. The phased array help narrow the Half Power Beam width of 9 source array and the Fresnel Lens helps further collimate the signal for transmission at further distance.

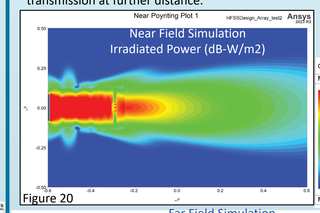


Figure 20

Near Field Simulations shows higher power radiation when Fresnel lens is added to simulation 30cm away. **56W** is calculated at 0.5m from source.

Far Field Simulations show Fresnel Lens phase aligns and collimates the E field so that it can travel beyond 10m. HFSS simulation limitation for field measurements is 10m.

3X3 Phased Array With Fresnel Lens		
Distance (m)	E Field (dB)	E Field (V/m)
2	40	10000
4	38.5	7079.5
6	37	5011.9
8	35.5	3548.1
10	35	3162.3
Max Distance	>10 m	

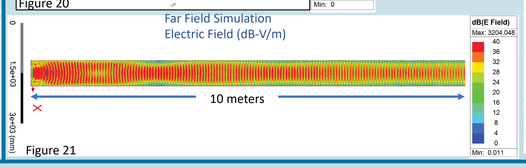


Figure 21

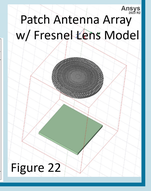


Figure 22

Results from the Prototype

The prototype is built with a PCB that includes the transmitter, a second PCB that includes the Power Amplifier and Antenna array, an EM Fresnel lens designed for a focal length of 30nm, and a track base stand to provide support for the PCBs and Fresnel Lenses. The Power Amplifiers for the Antenna Array are powered by a Solar Panel to generate EM waves with an initial energy usage of 100mA X 5V or 0.5 W per antenna.

Four conditions are measured at distances up to 5 meters with intervals of 1/3 meter. First, a single antenna versus the single antenna with a Fresnel Lens are compared. Absolute power is measured with a spectrum analyzer. Fig. 23 displays the power (dBm) for the Single antenna system with and with out the Fresnel Lens.

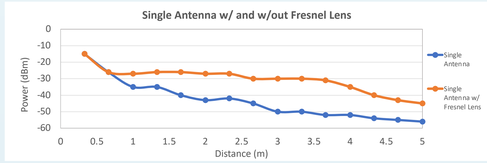


Figure 23: Single Antenna Power vs Distance (based on Spectrum Analyzer)

The power (dBm) for the Phased array WPTS with and without the Fresnel Lens is then compared against a baseline from the single antenna (Fig 24)

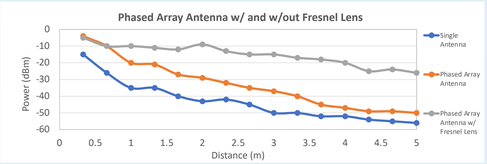


Figure 24: Phase Array Antenna Power vs Distance (based on Spectrum Analyzer)

Conclusion

This research shows the newly designed EM Fresnel Lenses combined with Phased Arrays can create a WPTS which wirelessly beams energy through radiofrequency EM waves. The prototype validates the proof of concept.

To calculate total power, Poynting Vectors are the magnitude and direction of energy in an electromagnetic wave. The total power is calculated as follows

$$Total\ Power\ (W) = \iint_{x,y} (Poynting\ Vector\ \left(\frac{W}{m^2}\right))dxdy$$

Simulation data in HFSS for the four Antenna and Lens models, calculating energy at 0.5m and 1m via Poynting Vectors, show:

- Power Transmission from the Phased Array is considerably larger than the single antenna
- The newly designed Fresnel lens for EM waves improves the distance the power can travel wirelessly, compared to either the single Antenna or the Phased array.

Distance (m)	0.5	1
Single Antenna w/out Lens (dBW)	-5	-5
Single Antenna w/ Fresnel Lens (dBW)	0	-5
Phased Array w/out Lens (dBW)	12	0
Phased Array w/ Fresnel Lens (dBW)	17.5	8

Table 1: Power based on Simulation for 0.5m and 1.0m

Prototype results, based on measurements, show:

- The Phased Array can improve the WPTS power transmission by up to 16 dB for a 9-element array
- Addition of the newly designed EM Fresnel Lens improves wireless power transmission by another 10-15 dB through collimation of EM waves
- By collimating the EM waves, the new Fresnel Lens increases the distance and efficiency of power transmission.
  - Longer range (distance) with new Fresnel Lens: >1.5X for the single antenna and >2X for the Phase array WPTS for any given power.
  - Greater efficiency with new Fresnel lens: energy transmitted at any given distance up to 15X for the single antenna and up to 50X for the phased array.

Distance (m)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Single Antenna Efficiency	100.0%	47.4%	15.8%	15.0%	3.2%	2.6%	2.0%	1.1%	0.8%
Single Antenna w/ Fresnel Lens Eff	100.0%	79.4%	79.4%	59.6%	39.8%	35.7%	12.6%	3.0%	1.3%
Single Antenna Improvement in Efficiency	**1.0**	**1.9**	**5.0**	**4.0**	**12.6**	**14.2**	**6.3**	**2.6**	**1.6**
Phased Array Antenna Efficiency	100.0%	49.7%	12.6%	4.7%	2.0%	0.7%	0.2%	0.1%	0.1%
Ph Array Antenna w/ Fresnel Lens Eff	100.0%	71.3%	63.1%	40.9%	31.6%	17.9%	10.0%	3.6%	2.5%
Ph Array Antenna Improvement in Efficiency	**1.0**	**2.1**	**5.0**	**9.0**	**15.8**	**35.0**	**50.1**	**28.4**	**25.1**

Table 2: Power Efficiency and the improvements in Efficiency with the Fresnel Lens

Future Work

The Prototype Fresnel Lens developed here is optimized to collimate in 1 direction, which does not take advantage of beam steering offered by Phased arrays. Future work will redesign Fresnel Lenses into Fresnel Spheres to collimate in several directions, so the EM beam can be directed in different directions.

Fig 25: Reshape Fresnel Lens into Sphere power

This work to design transmitters and lens for optimal collimation is the foundational technology for enabling new technology to harvest new energy resources, both terrestrial and extraterrestrial. When the power transmission problem can be solved, solar energy directly from the sun in space can serve as a new clean energy source for the entire planet to use, day and night.

Credit: Mark Garlick/Science Photo Library

Fig 26: Image of Solar power captured in Space

Additional study in the safety of the EM Beams at various power levels need to be further investigated as well, though 2.4Ghz EM currently is widely used.

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