A Novel System for Long Range Wireless Power Transmission

Statement of Problem

- Energy consumption growing exponentially but 1 in 10 worldwide lack access to energy (Fig. 1)
  - Population growth and new power-hungry technologies drive greater energy usage. Currently **180,000 TWh** of energy is used globally
- Wired infrastructure for energy transmission is costly and therefore limiting
  - Expensive: **~$5M per 100 kilometers**. Power tower needed **every 100 meters**
  - Limitations: older buildings need extensive re-wiring for more power transmission, new clean energy plants located next to cities (distant locations not feasible)
- Current Wireless EM Solutions: not adopted due to poor efficiency. Energy is lost as a function of distance (quadratic decay based on Friis's transmission equation)

Fig 1: Global Energy Usage over Time in years. Source: Energy Institute - Statistical Review of World Energy (2023), Smil (2017)

Proposed Solution

- Goal: Efficient wireless power transmission over distance, via beaming EM waves where energy stays near constant over distance
- My Original Wireless Power Transmission (WPT) System:
  - 2.4GHz EM waves to transmit power: selected as optimal mix of size + efficiency, while minimizing atmospheric impact
  - Components: Phased Array and original Fresnel Lens designed for EM transmission.
  - Efficiency: WPT phase aligns and collimates EM power waves, resulting in near constant power over distance.
- Wireless Cost: long range cost reduced 100x **(~$50K per 100 kilometers)** with towers using line-of-sight transmission ~**every 10,000 meters**. Medium range: minimal remodel costs

Fig 2: Power Transmission Systems

Fig 3: WPT Array and Lens Transmitter

Background Information

Current Wireless Power Transmission Systems

- Commercial WPT: based on induction charging. Works well over very short distances (<4cm) with efficiencies around ~80%
- RF Harvesting: for very low power, RF communication signals converted to power with IOT sensors. newly emerging field.
- EM based WPT: currently being researched for distances of 1-2 meters with published literature efficiencies of 20-35%
- Very Long Distance WPT: in experimental phase, such as Cal Tech's Solar Power MAPLE (Microwave Array for Power Transmission)
- My research: new methodology to improve efficiencies compared to current literature for EM based WPT, so can be used for medium distance (medical device implants, wireless charging across a room) and stepping stone towards long distance (clean energy power sources)

Phased Array Transmitter

- An array of power amplifiers and antennas used to narrow and direct an RF beam
- Key advantage: increases power gain transmission by N^2 instead of N.
- Each antenna sends out EM waves with different phase shifts. Through constructive interference, these waves combine to produce high gain in a specific direction following Euler's equations:

$$\mathbf{R}(\phi,\theta) = \sum_{n,m} e^{-j2\pi\left(\frac{d}{\lambda}\right)\cos\theta((m-1)\sin\phi+(n-1)\cos\phi)} \quad \text{(Eq 1)}$$

$$\mathbf{W}_{n,m}(\chi,\varphi) = e^{+j2\pi\left(\frac{d}{\lambda}\right)\cos\varphi((m-1)\sin\chi+(n-1)\cos\chi)} \quad \text{(Eq 2)}$$

$$W * \mathbf{R}(\phi,\theta) = \sum_{n,m} e^{+j2\pi\left(\frac{d}{\lambda}\right)\cos\varphi((m-1)\sin\chi+(n-1)\cos\chi)} * e^{-j2\pi\left(\frac{d}{\lambda}\right)\cos\theta((m-1)\sin\phi+(n-1)\cos\phi)} \quad \text{(Eq 3)}$$

Where R(ϕ, θ) is real space, W are phase shifts, (χ, φ) is the constant beam steer angle, λ is the wavelength, and d is the distance between array elements (Fig 4)

Friis Transmission Equations:

- Friis Equation for Transmission: determines radiated and received power based on the gain and power transmitted, wavelength of radiated power, and distance between the transmitter and receiver antenna. A wavelength, λ, is defined as speed of light, c, divided by the frequency, f.

$$P_{radiated} = \frac{G_{tx}P_{tx}}{4\pi r^2} \quad \text{(Eq 4)}$$

$$P_{rx} = \frac{G_{rx}P_{rad}\lambda^2}{4\pi} = \frac{G_{tx}G_{rx}P_{tx}\lambda^2}{(4\pi r)^2} \quad \text{(Eq 5)}$$

Fig 4: Phased array transmitter where d is the distance between antenna elements, and φ is the angle of the beam direction

- Power Transmission Efficiency: From Friis's equation, power received decreases with: 1) farther distance and 2) higher frequency (shorter wavelength) waves.
- Friis Equation with Phased Array: for N antennas, the Transmitter gain increases by N^2

$$P_{rx} = N^2\frac{G_{tx}G_{rx}P_{tx}\lambda^2}{(4\pi r)^2} \quad \text{(Eq 6)}$$

Fig 5: Wireless transmission between a transmitter(Tx) and receiver(Rx) where is the wavelength, c is the speed of light, and f is the frequency of the EM wave. Plot shows how power decays as function of distance.

Fig 6: Curved lens can reduce to Fresnel Lens with concentric Rings

Fig 7: Fresnel Lens collimates and magnifies light waves

Fresnel Lens:

- Designed by Fresnel for lighthouses: curved surface of conventional optical lens replaced with a series of angular concentric rings (Fig 6)
- Collimates and magnifies the light (Fig 7) with much less material than a standard optical lens
- Current EM Fresnel lens: designed for EM waves but limited to high frequency Ka–band and V-band millimeter (27-60 GHz). Lens for lower frequencies are expensive because of thicker lens and higher material cost, as lens thickness is equivalent to the wavelength of the EM wave.

Rationale to Design WPT System with Phased Array and EM Fresnel Lens at 2.4GHz :

- 2.4GHz (Microwave S-Band Frequency): Optimal EM frequency due to ideal mix of higher power efficiency, lower cost and minimal atmospheric loss. Lower frequencies costlier due to increased transmitter size. Higher frequencies are inefficient with more power loss.
- Phased Array: 1) narrows EM beam angle with gain and 2) can use smaller diameter/thinner Fresnel lens (half power beamwidth)
- Original EM Fresnel Lens: Vertically phase aligns and collimates EM waves into a focused EM beam, thereby maintaining power transmission over distance.

Design and Methodology

Design for Fresnel Lens:

- Lens Goal: efficient EM power transmission over distance due to 1) phased alignment of waves and 2) angling of waves into a collimated EM beam.
- Novel EM Lens: 1) Concentric Rings (unique design) 2) Concentric Angles (never reported for EM)
  - Concentric Rings: Phase aligns EM waves as they exit the Lens (Fig 8). Each ring has a different dielectric (Fig 9), determined by original formula (Eq 8). Desired dielectric obtained via lattice structure with differing densities (Fig 10)
  - Concentric Angles: to collimate waves as they exit lens, Snell's law (Eq 9) used to derive a unique angle for each ring (Eq 10 Fig 9)
- Lens size: 20cmX1.2cm determined by Phased Array Half-Power Beam Width (34°), focal distance (30cm), and dielectric constant of ABS material (ε_{rmax} = 5.0 at 2.4GHz)
- Design parameters (dielectric constant ε_r and angles θ_{n2}) optimized in Excel and then imported into Fusion360 to build 3-D model of Fresnel Lens
- Fresnel Lens 3-D printed in Raise3D Pro2 after experimenting with speed and temperature to precisely print correct lattice structure with varying dielectrics

Fig 9: Fresnel Len made of concentric rings and angles designed in Fusion 360

$$v_{\varepsilon R} = \frac{c}{\sqrt{\varepsilon_R}}, \lambda_{\varepsilon R} = \frac{v_{\varepsilon R}}{f} \quad \text{(Eq 7)}$$

Eq 7: Relation of frequency f, velocity $v_{\varepsilon R}$, and wavelength λ, with dielectric constant ε_R

$$L_0 + \sqrt{\varepsilon_{r0}}d_0 = L_n + \sqrt{\varepsilon_{rn}}d_n \quad \text{(Eq 8)}$$

$$= \frac{L_0}{\cos\theta_{n1}} + \sqrt{\varepsilon_{rn}}\frac{d_0}{\cos(\theta_{n1}/\sqrt{\varepsilon_{rn}})}$$

Eq 8: Equating phasor distance at each Fresnel ring to determine correct dielectric constant ε_R per ring

$$\textit{Snell's Law:}\ \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \quad \text{(Eq 9)}$$

$$h_x = L_0\frac{\sin\theta_{n1}}{\cos\theta_{n1}} + d_0\frac{\sin\theta_{n2}}{\cos\theta_{n2}},\ \theta_{n1} \cong \frac{\sqrt{\varepsilon_{rn}}\,h_x}{\sqrt{\varepsilon_{rn}}\,L_0 + d_0} \quad \text{(Eq 10)}$$

Eq 10: Relation of tangential angle θ_{n1} as function of height h, focal length L_0, and ring thickness d_0. Equations are iterated to get accurate tangential information for each curve of the angle ring

Fig 8: Fresnel Len design methodology to align phase and collimate EM waves at output of lens

$$\varepsilon_r = (\varepsilon_{rmax} - 1)\frac{(m^2 - s^2)}{m^2} + 1 \quad \text{(Eq 11)}$$

$$\varepsilon_{rmax} = 5$$

Eq 11: Equation to build lattice structure with the different dielectric using a material with single dielectric constant of ε_{rmax}. The lattice square side size is m (mm) and the spacing size is s (mm) shown in Fig 10.

		m	s
ε_{r0} =	4.36	2	0.8
ε_{r1} =	4.19	2	0.9
ε_{r2} =	3.79	2	1.1
ε_{r3} =	3.44	2	1.25
ε_{r4} =	3.04	2	1.4
ε_{r5} =	2.65	3	2.3
ε_{r6} =	2.22	6	2.5
ε_{r7} =	1.76	6	5.6
ε_{r8} =	1.39	8	7.6

Fig 10: Lattice structure for Fresnel Lens and table to generate dielectric constants for each Fresnel Ring

Design for Phased Array Transmitters:

- Phased Array Transmitter: narrows EM beam angle and adds gain
  - Voltage control oscillator creates 2.4GHz signal, amplifiers increase gain, power splitters split the signal to 9 separate paths, and antennas radiate power (Fig 11)
  - Phase shifters are used to change phase and align phases at output
- Components for Printed Circuit Board (PCB): selected based on frequency and gain
- PCB Design and Fabrication: using Altium software with RF techniques
- Phase alignment calibration: completed using Network Analyzer

Theoretical Calculations:

- Friis Equations for transmission used to determine predicted expected power as a function of distance

Simulation Method:

- Original Matlab code written to determine Phased Array Antenna gain
- Simulation of Antennas (Single Antenna & Phased Array) and EM Fresnel Lens conducted in an EM simulator, Ansys High Frequency System Simulator (HFSS), to determine the validity of phase alignment and collimating properties of the Fresnel Lens for focal distance of 30cm using 2.4GHz EM waves

Fig 11: The 2 boards used for the phased array transmitter split as (1) phased aligned frequency generation and (2) antenna array.

Fig 12: WPT Experimental Setup to measure power transmitted in various conditions of antenna, phased array, and Fresnel lens. Solar Panel is used as power source for antenna array

Experimental Method (Prototype):

- Measurements using spectrum analyzer at various distances from Single Antenna and Phased Array (with and without Fresnel lens) taken to determine the power transmission
- Rectenna used to determine RF to DC Power conversion at distance for WPT System

Data Analysis Method:

- Measurement data compared to theoretical expectation for power transmission
- Receiver antenna limitations are calibrated to determine true performance of WPT system in wireless channel

Fig 13: Circuit model of Rectenna

Fig 14: Spectrum Analyzer data of EM signal at 2.4GHz

Electromagnetic (EM) Simulation Data for Wireless Power Transmission System

HFSS Models for Patch Antenna, Phased Array, and Fresnel Lens

Fig 15: HFSS models for Single Patch Antenna and Antenna with Fresnel Lens

Single antenna model

- Built in HFSS using a Copper (Cu) substrate, Dielectric material like FR4 (ε_r = 3.8), and patch pattern in Cu.
- The patch shape must be designed for optimal antenna radiance at the frequency and validated using S11 plots

Single antenna plus Fresnel lens

- imported model of the Fresnel lens designed in Fusion 360. The Geometry and dielectric materials are modeled in HFSS

Fig 16: HFSS models for Phased Array Antenna and Phased Array with Fresnel Lens

Antenna phased array model

- 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 λ/2 apart from each other for a 2.4GHz signal.

Antenna phased array plus Fresnel lens

- Modelled and simulated in HFSS similar to the single antenna plus Fresnel lens .

HFSS Simulations

- EM Simulations validate gain from Fresnel Lens due to phase alignment and collimation
- Near Field Simulations: Phased array shows **18 dB** of gain similar to Matlab model. Addition of Fresnel Lens results in **5 dB** of gain at 0.5 meter and **8 dB** of gain at 1 meter. Results show Fresnel Lens provides increased gain as function of distance.
- Far Field Simulations: Fresnel lens gain increases with distance (Table 1). EM Fresnel lens + Phased Array show close to constant power over 10m. The relative data from the Far-Field simulations are aligned with measurements.

Fig 17: HFSS for Near-Field and Far-Field Simulation for the four different models

Matlab Simulations for Phased Array

- A matlab model was developed for the phased array to validate the gain, directivity, and half-power beamwidth
- Simulations for 9-element phased array shows gain of 18 dB and angle of beam 34° (Fig 18)
- This data validates the theoretical gain for phased array of 19 dB determined by N^2

Fig 18. Matlab Gain simulation of Phased Array

Table 1: Electric Field as function of distance from Far-Field simulations in dB versus meters

Distance (m)	Single Antenna E-Field (dB) w/ out Lens	Single Antenna E-Field (dB) w/ Lens	Phased Array E-Field (dB) w/ out Lens	Phased Array E-Field (dB) w/ Lens
1	18	23	36	40
2	10	18	30	38
3		14	28	37
4			24	37
5			22	36
6			20	36
7			16	36
8			11	34
9			8	34
10				33
Max Distance	**2m**	**3.5m**	**9m**	**>10m**

Results from Prototype

- Measurements: recorded 3x at each distance using a spectrum analyzer
- Single Antenna: power transmission follows Friis Transmission equation well up to 2 meters in distance (Fig 19)
- Phased Array Transmitter: **17dB** gain compared to a Single Antenna at 5 meters, **~50x power increase** (Fig 20)
  - Prototype Results match Simulations: Gain within 1dB of expected value of 18dB based on Matlab & HFSS sims
  - Gain validates Phase Array is calibrated correctly
  - Loss over distance similar for Phased Array as Single Antenna with measurements from dipole antenna receiver
- Antenna Correction Factor: beyond 2 meters, both Single Antenna and Phased Array display lower than expected results due to antenna loss, which is from partial field cancellation of dipole antenna. All antennas show some loss compared to predicted measurements over distance, requiring a correction factor.
  - Receiver antenna calibrated with 2 independent signals across measured distances to derive correction factor

$$\textit{Antenna Correction Factor}(d) = -0.36d^3 + 3.04d^2 - 3.81d + 0.6 \quad \text{(Eq 12)}$$

- Results of Antenna Correction Factor: mean measured values of both single antenna and phased array antenna are within the 3 standard deviations of expected values from Friis Transmission equation (Fig 21).

Fig 19: Single Antenna Measurement and Theoretical Data

Fig 20: Single Antenna and Phased Array Measurement

Fig 21: Single Antenna and Phased Array Measurement after Corrections

- EM Fresnel Lens Results:
  - Gain: Lens adds **12dB** of gain at 5m (**16x power increase**), for both Single Antenna or Phased Array (Fig 22, 23)
  - Collimated EM power beam: measured power is almost constant after 1.5m for Phased Array (Fig 23,24)
  - Far Field Simulations show similar trend lines to prototype results (Fig 23)

Fig 22: Single Antenna Measurement w/ and w/out Fresnel Lens

Fig 23: Phased Array Measurement w/ and w/out Fresnel Lens

Fig 24: Phased Array Measurement with Fresnel Ring and Angles

- Gain from Fresnel Lens: Concentric Rings component of the Fresnel Lens contribute 59% of total gain (phase alignment). Concentric Angles component contribute 41% of total gain (collimation of EM waves) (Fig 25)

Efficiency of WPT System (RF to DC power):

- Phased array data correlates with transmitted RF power of 8 dBm
- Rectenna output at 1.5 meter is 1.7 V and load current of 3 mA for the LED light
- $P_{TX\text{-}RF}$ to $P_{RX\text{-}DC}$ (RF to DC power) is measured at 81% efficiency

Fig 25: Gain measurements of Phased Array Fresnel, Ring, and Angle Lenses

Discussion

- A novel 2.4GHz WPT system is designed, simulated in Matlab and HFSS, built from scratch, and tested
- The novel WPT system demonstrates that a wireless power transmission channel with high efficiency can be developed with low loss over distance using a Phased Array and an original Fresnel Lens for EM designed from first principles
  - Phased Array shows over 17dB of gain (~50x power increase), where 18dB is theoretically possible
  - EM Fresnel Lens maintains power over several meters (from 1.5m to 5m). Fresnel lens gain increases with distance. At 5m, the gain is over 12dB (~16x power increase)
  - Concentric Rings portion of Original EM Fresnel Lens: uses a new methodology for 3D printing and provides ~60% of the total Gain
  - Concentric Angles portion of EM Fresnel Lens: has not been reported for EM Lens and provides ~40% of the total Gain
- The new Fresnel Lens provides over 12dB gain, a 16x increase compared to baseline. A similar gain would require a 4x larger Phased array. By reducing the number of Phased Array elements by ~ 75%, there is less thermal loss and reduced cost
- A matched charge rectifying Rectenna was designed from scratch to demonstrate the RF to DC power conversion
  - $P_{TX\text{-}RF}$ to $P_{RX\text{-}DC}$ is measured at **81% efficiency** (RF to DC power) for wireless power channel at 1.5m with current rectenna and up to 5m or more with improved receiver antenna
- My WPT system provides better power transmission efficiency at a lower cost, compared to current literature (Tb 2)

Current Literature Comparison

Reference	Frequency	Tx Power	Distance	Cost	Efficiency
Brown[1]	2.45 GHz	38 dBm	760 cm	$$$	51%
Gowda [3]	5.8 GHz	13 dBm	40 cm	$	33%
Yang [7]	5.8 GHz	25 dBm	100 cm	$$	47%
Hajimiri[5]	10 GHz	17 dBm	100 cm	$$	63%
Park [4]	5.8 GHz	6 dBm	50 cm	$	20%
Nusrat [8]	2.4 GHz	15 dBm	20 cm	$	19%
This work	**2.4 Ghz**	**8 dBm**	**150 cm**	**$**	**81%**

Table 2: Comparison of this work to past and existing WPT systems. The low cost ($) systems have simple antenna systems, the medium cost ($$) systems have expensive antenna systems, and the high cost system of the historical Brown design (3-meter diameter parabolic antenna) is extremely expensive

Use Cases: Short, Medium, and Long Range

Wireless charging of medical devices (limited life battery):

- Deep brain implants requiring 925mWH per 100 days. Using a system like the prototype, 13dBm (20mW) of power can fully charge the device over a 5-hour period while they sleep.

Fig 26: WPT for deep medical implants

Wireless charging in indoor and outside setting:

- Indoor Conference Room: Wireless charging of phones and laptops require 100W WPT system, which can be achieved by 32 element phased array with each element providing 20 dBm of power
- Electrics cars Charging: Requires 30kWH per 100 miles. A WPT system with a 128-element phased array with each element providing 30dBm (1W) of power can provide required power

Fig 27: WPT for charging electric vehicles

Transporting energy from power plants to inner city (long distance):

- To power 10,000 homes each using 10,000kWH annually, a system of 1024 array elements with 40dBm (10W) per element is required to transmit power from energy source to city receiver
- Solar power: Solar panels on satellites in low Earth orbit at ~200km (non-stop production). Good option to charge power stations around the world. Highly efficient, non-destructive terrestrial energy

Fig 28: WPT for indoor conference room

Fig 29: WPT for long-range solar transmission
Credit: Mark Garlick/ Science Photo Library