A Franklin Array Antenna for Wireless Charging Applications

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Abstract — A Franklin array antenna is proposed in this work to be used for wireless charging applications. It is a fascinating idea to use radio waves as the power source for portable devices. However, due to the relative long wavelength, the power density of microwave radiation dilutes as it propagates. According to power budget analysis, at a distance of one meter, if transmitting and receiving antennas of moderate gains are used, only a few mW is available with a one watt transmitter. In order to enhance the available power level and increase the remote operation distance, larger antennas, which intercept more radiated power, can be employed. In this work, a rectenna made of a high gain Franklin array and RF-to-DC rectifier was developed. RF-to-DC power conversion efficiency was evaluated.

1. INTRODUCTION
As wireless communication technology evolves, more and more mobile devices are entering our everyday life. How, most “portable” gadgets still require charging via cables and adaptors from time to time. One can’t help but imagine how convenient it would be if those devices can be charged wirelessly to avoid tangled wires. In this work, we probe the wireless charging and powering issues using radio frequency.

The most well known and developed application for wireless power transmission is radio frequency identification (RFID) [1, 2], which usually employs a passive IC embedded antenna to receive the RF power emitted from the reader. RFID tags then scatter back modulated signals using the incoming RF energy. Wireless power transmission methods can be divided into three categories according to the operating range. They are near field, moderate range of magnetic resonance, and farfield. In this work, we focus on the scenario of powering up a device with a moderate power rating at a distance of a few meters, which falls into the farfield category. For example, a small LCD panel requires tens of µW. A well engineered wireless mouse operates with tens of mW.

The wireless charging and powering scheme is illustrated in Fig. 1. RF power is emitted from the transmitter via a directive antenna to provide a coverage area. Devices that require charging or powering may intercept the RF power via a receiving antenna when placed within the coverage area. RF signal is next rectified to DC power via RF diodes. Note the coverage area size and remote charging distance constitutes a trade-off. A proper transmitting antenna should be chosen according to the required operation range.

The RF power available to portable devices can be estimated via Friis transmission equation in (1)

\[
P_r = \frac{G_t G_r \left( \frac{\lambda}{4\pi R} \right)^2}{P_t}
\]  

(1)
Assuming the RF frequency is 2.4 GHz, then the wavelength is 0.125 m. If the transmitting and receiving antenna gains are 12 and 6 dBi, respectively, and the device is placed 1 m in front of the transmitter, the received power is only 6.23 mW when 1 W is emitted from the transmitter. Since the RF-to-DC rectification circuit is in general of poor efficiency with a low input RF power level, the converted DC power may be too small to operate the device.

According to the Friis transmission equation, there are a couple of measures to power up devices at a longer distance. For example, one can increase the transmitted power or improve the rectification efficiency. Directive antennas can also be used. In this work, we attempt to develop a high gain receiving antenna based on the Franklin array antenna configuration [3, 4]. This antenna increases the received power using its enlarged antenna aperture.

Development and performance verification of the high gain Franklin array antenna is presented in Section 2. In Section 3, the receiver assembly is tested with resistive and capacitive loads to examine its power conversion efficiency. A brief summary of this work is given at the end.

### 2. DEVELOPMENT OF A RECTENNA USING HIGH GAIN FRANKLIN ARRAY

In order to extend the operation distance of the rectenna module, which is a combination of rectification circuitry and antenna, the Franklin array configuration is used to increase the antenna aperture. The System diagram is shown in Fig. 2, which includes a RF transmitter and the rectenna module connected to either a discharge resistor or a super capacitor.

Figure 3 shows the geometry of the proposed stacked Franklin array antenna design, which contains 8 Franklin array elements and a total of 32 patch elements. Those elements are grouped into two set of perpendicular orientations. Each set rest on a 0.6 mm thick FR4 slab. The two slabs are glued together and placed on a metal ground plane with a spacing of 2.1 mm. The total height

![Figure 3: Stacked Franklin array antenna design.](image1)

![Figure 4: Prototype Franklin array antenna.](image2)

![Figure 5: Simulated and measured reflection coefficient spectra.](image3)

![Figure 6: Measured radiation pattern.](image4)
Table 1: Detail antenna design parameters (Unit: mm).

<table>
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<th>W</th>
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<th>h₁</th>
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<th>h₃</th>
<th>S₁</th>
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<td>3</td>
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Line1 160 Ω, Length = 15 mm, W₂ = 3.6 mm
Line2 228.5 Ω, Length = 19.2 mm, W₂ = 1.14 mm

Figure 7: Measured voltage and calculated power conversion efficiency of the rectenna with different resistive loads.

Figure 8: 1 F super capacitors used for rectenna efficiency evaluation.

of the antenna is 4.4 mm. Principle design parameters of the array are listed in Table 1.

The fabricated prototype Franklin array antenna is shown in Fig. 6. Simulated and measured reflection coefficient spectra are provided in Fig. 7. Multiple resonances are observed. However, the principle radiation mode occurs near 2.4 GHz and the bandwidth is approximately 20 MHz. The antenna’s radiation pattern was measured in a 3D nearfield anechoic chamber. Fig. 8 shows the concentrated beam, which is formed by 16 patch elements. The antenna gain is approximately 12 dBi.

3. POWER CONVERSION EFFICIENCY EVALUATION

The power delivered to the rectenna can be estimated from the aforementioned Friis transmission equation. In the following experiments, a transmitter of 30.6 dBm (1.148 W) is hooked up with a patch array antenna of 11 dBi to provide RF power. The rectenna is placed in front of the transmitter by either 1 or 1.5 m. The rectenna is connected to either a resistor or a capacitor to evaluate the power conversion efficiencies when used in powering and charging applications.

We first examine the power conversion efficiency of the rectenna by connecting to resistors of different values. Fig. 7(a) shows the measured DC voltage with resistors ranging from 100 to 1000 Ω. As expected, the converted DC voltage is proportional to the load resistance and is inversely proportional to the remote powering distance. The power conversion efficiency is defined in (2).
The RF power available to the rectenna, $P_r$, can be estimated by the Friis transmission equation in (1).

$$\eta(\%) = \frac{P_{DC}}{P_r} \times 100\% = \frac{V_{DC}^2}{R_L \cdot P_r} \times 100\%$$  \hspace{1cm} (2)

According to the calculated curves shown in Fig. 7(b), the power conversion efficiency is a function of the load resistance. Take the results of 1 m for example; optimal power conversion performance is achieved with a 510 $\Omega$ load. The power conversion efficiency in general ranges between 35% to 60%.

Next the load is changed to capacitors to evaluate the rectenna’s charging efficiency. Two super capacitors of 1 F are used. As shown in Fig. 8, one looks a disk while the other shapes like a cylinder. The efficiency is estimated by tracing the output DC voltage as time progresses. In (3), the denominator is difference in energy stored in the capacitor. The nominator is the RF work accumulated at the antenna.

$$\eta(\%) = \frac{0.5 \times \left[ CV(t_2)^2 - CV(t_1)^2 \right]}{P_r \times (t_2 - t_1)} \times 100\%$$  \hspace{1cm} (3)

Figure 9(a) records the DC voltage every ten seconds for the rectenna connected to the cylinder-like capacitor. The efficiency is calculated for each time slot. Therefore, the curves in Fig. 9(b) are somewhat volatile. In general, the efficiency varies from 35% to 65% when placed 1 m away from the transmitter. When the disk-like capacitor is connected, although the labeled capacitance...
is the same as the previous one, a better efficiency performance is achieved. As Fig. 10 shows, the voltage increases very quickly for the first 20 seconds. Afterward, the voltage rises with a steady pace. The calculated efficiency values range from 50% to 85%.

4. CONCLUSION
In this work, the wireless charging and powering issues are explored via the radio frequency technique. A high gain antenna is connected to the rectification circuit made of RF diodes to extend the wireless charging and powering distance. The main advantage of using a high gain antenna is that the enlarged antenna aperture not only increases the available power but also helps to improve the rectification efficiency. Measurement result shows the conversion efficiency can be as high as 65% at 1 m away from a 1 W transmitter. For capacitive loads, the charging efficiency can reach 85% at 1 meter, which is promising for wireless charging application.

REFERENCES