RFID-Enabled Energy Harvesting using Unidirectional Electrically-Small Rectenna Arrays

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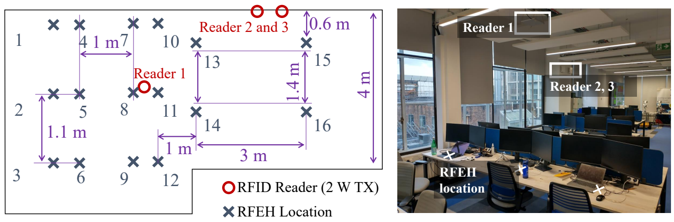
***Abstract*—RFID has been widely adopted in sensing applications based on passive tags. We present, for the first time, a practical room-scale demonstration of a wireless power grid based on 868 MHz UHF RFID, with 27 dBm radiated power. The proposed harvester is a state-of-the-art flexible rectenna surface based on serially-connected tightly-coupled electrically-small rectenna elements. Reflector-backing is proposed increasing the harvester's effective area by 3 dB with over two-fold increase in the harvested energy. The DC power harvesting pattern of the array are experimentally characterized showing an 18 dB front-to-back ratio. In a 40 m^2 room with a single reader and 3 antennas, a maximum energy of 5.3 mJ was harvested using the unidirectional array in a capacitor over a 1-minute charging period. The minimum energy yield of 0.5 mJ, sufficient for powering a Bluetooth beacon, evidences that, despite its intermittency, RFID packets can create an indoor RF grid.**

***Index Terms*—antennas, antenna arrays, rectennas, rectifiers, wireless power transfer (WPT).**

I. Introduction

Radio Frequency IDentification (RFID) based on the UHF Gen-2 RFID standard has been widely incorporated in sensing applications [1]. RFID sensing has the advantage of relying on a single low-cost RFID IC for providing the unique ID of the backscattered RF signal that is amplitude-modulated by the measurand. RFID sensing has been incorporated in various applications ranging from vital signs monitoring using textile antennas [2], supply chain security [3], [4], wireless ice detection [5], as well as loaded by sensors for on-body temperature sensing [6] or indoor light intensity monitoring [7].

Nevertheless, RFID sensors are typically limited to one measurand per IC, and lack the computational power for near- or in-sensor computing. To explain, while RFID ICs incorporate an RF energy harvesting rectifier to power the tag's baseband [8], only a µW-level power output is produced. Therefore, existing computational RFID prototypes incorporating discrete diodes have a short range of operation due to the low sensitivity of the voltage multipliers used in the RF to DC conversion [9]. Although electrically small energy harvesting rectennas have been widely explored [10], [11], [12], [13], their DC voltage output is limited due to the relatively small collection area from µW/cm^2 power densities. To generate a sufficient power and voltage output from a typical RFID interrogation packet over a range exceeding 3 m [9], a large-area RF energy harvester, optimized for a wide range of incident power densities, is required, to overcome the limited collection area of existing RFID tags.



(a) (b)

Fig. 1. Deployment environment of the RFID-powered energy harvesters: (a) room layout and dimensions; (b) photograph showing the reader antennas and desktop harvester locations.

In this paper, we propose a unidirectional broadside RF energy harvester based on a state-of-the-art rectenna array [14] and demonstrate in an indoor RFID-centred energy harvesting use-case. Following an RF power survey in an indoor multi-RFID reader environment (in Section II), the rectenna array is optimized through reflector-backing showing a gain and DC power output increase of up to 6 dB (in Section III). A measurement campaign demonstrates that despite the heavy duty-cycling of the RFID interrogation packets a sufficient energy level can be stored in a capacitor with over 4 V potential in more than 50% of the tested locations, demonstrating that indoor asset-tracking and occupancy monitoring RFID readers could simultaneously power active sensors (in Section IV).

II. Indoor RFID Sensing and Power Survey

The proposed RFID energy harvesting system is designed for an indoor office environment where 868 MHz RFID readers are deployed for asset-tracking and occupancy monitoring using passive tags. Three antennas connected to a single RFID reader are required to provide uniform coverage across the room enabling the sensing and tracking tags to be read successfully. Fig. 1 shows the layout and photograph of the room. Reader 1 is deployed at a height of 3 m whereas reader antennas 2 and 3 are at a 2.5 m height.

A spectrum analyzer connected to a standard half-wave dipole antenna was used to estimate the power density available in the room, from the RFID readers' emissions. The spectrum analyzer was configured to hold the peak measured values to evaluate the highest power level available during the RFID interrogation period. As the readers are installed at a height above the expected sensor's deployment location, a uniformly high power coverage can be achieved over the room, where it was previously shown that an optimal position

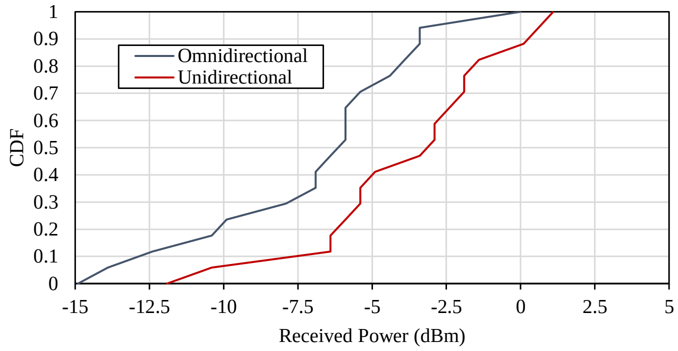


Fig. 2. CDF of the measured peak RF power using the spectrum analyzer across the positions shown in Fig. 1.

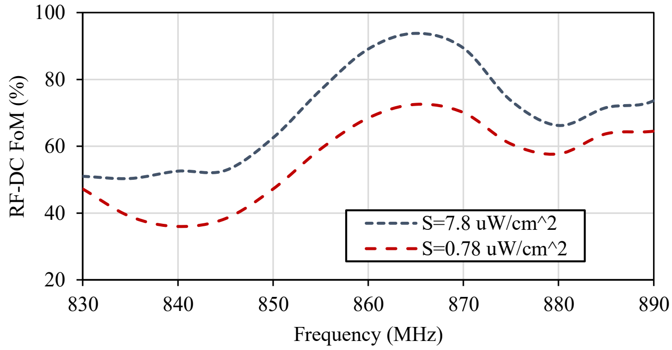


Fig. 3. Measured DC power output of the rectenna array around the EU RFID 868 MHz band for different power densities S.

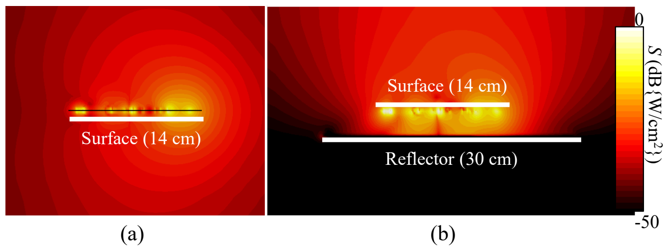


Fig. 4. CST-simulated power flow magnitude surrounding: (a) the omnidirectional array [14]; the reflector-backed array showing an increased collection array due to the higher gain.

of RF WPT transmitter is above the user [15]. The power was measured in the 16 positions shown in Fig. 1(a), at an approximate height of 1 m on the desktop. The measured power levels include the interference between the different readers as well as the multi-path reflections from the surrounding objects. Fig. 2 shows the cumulative distribution function (CDF) of the measured RF power level. The measurements were repeated twice, using an omnidirectional free-standing half-wave dipole and using a reflector-backed dipole, to illustrate the benefits of a more directional broadside harvesting pattern. The reflector was spaced by 3 cm from the antenna, representing around 0.1 λ at 868 MHz.

From Fig. 2, it can be seen that the mean received power can improve using the unidirectional receiver, owing to the overhead deployment of the readers. For the omnidirectional dipole, the mean received power is −7.1 dBm, whereas the mean increases to −3 dBm using the reflector-backed dipole. Moreover, the standard deviation is reduced by 0.5 dB, implying a more uniform RF energy harvesting performance. Therefore, the energy harvesting array is optimized to achieve a broadside harvesting pattern in the next section.

III. Unidirectional Array Characterization

The proposed unidirectional array is based on the rectenna surface proposed in [14]. The surface is backed using a flexible micro-meshed “e-textile” reflector with a sheet resistance under 50 mΩ/square. The RF to DC power harvesting Figure-of-Merit (FoM) is given by

$$\text{FoM} = \frac{P_{\text{DC}}}{S A_{\text{physical}}}, \tag{1}$$

where S is the incident power density, and A_{physical} is the array's physical; the FoM definition is widely used to evaluate the overall (antenna and rectifier) of energy harvesting surfaces [16], [17], [18].

Fig. 3 shows the DC power output of the array as a function of frequency. The DC output was measured at 1.2 m from a continuous wave (CW) generator across the optimum load impedance of 40 kΩ. From Fig. 3, it can be seen that the array maintains an FoM exceeding 90% for S=7.8 μW/cm^2; such power level can be expected at a 2-meter distance from a 2 W RFID reader.

The reflector-backed array was characterized over varying angles of incidence to evaluate its suitability for broadside energy harvesting. The array elements were first simulated in CST Microwave Studio, where the power distribution for the free-standing and reflector-backed arrays are shown in Fig. 4(a) and (b) respectively. Observing the power flow around the reflector backed array, in Fig. 4(b), it can be seen that effective collection area of the array increases in the broadside direction, which will enable it to capture more of the available power from the RFID readers, as in the power survey carried out using a standard dipole.

The far-field radiation patterns were then evaluated numerically (in CST Microwave Studio) and experimentally; the simulated patterns are shown in Fig. 5(a). Experimentally, the rectenna array was position at 2 m from a 0.5 W omnidirectional transmitter based on off-the-shelf parts and its DC power output was measured across a resistive load. The measurements were performed in an anechoic chamber as shown in Fig. 5, with the array rotated around its elevation plane in 30° increments.

A good agreement between the simulated RF gain and measured DC power patterns can be observed in Fig. 5(a). Compared to the free-standing array, measured in the same position in the anechoic chamber, the reflector-backing results in over 5 dB increase in the harvested power in the broadside direction, and an increase of over 24 dB to the front-to-back ration compared to the free-standing array. Therefore,

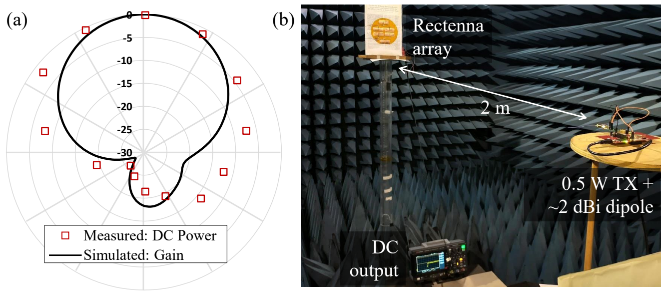


Fig. 5. Energy harvesting patterns of the unidirectional rectenna array: (a) measured normalized DC patterns and simulated gain patterns; (b) array measurement setup from a 0.5 W source.

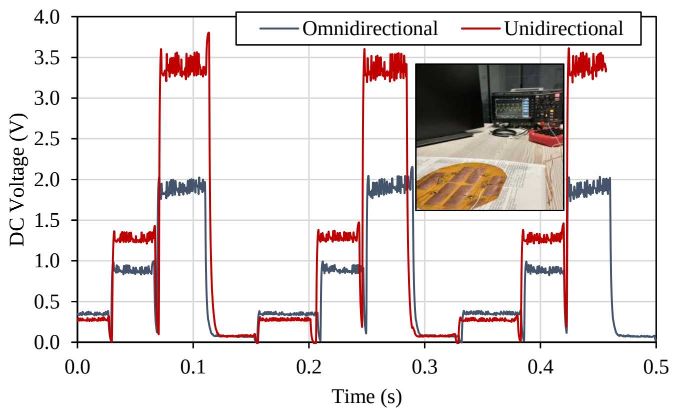


Fig. 6. Measured DC voltage across the optimal 40 kΩ for position 16 (from Fig. 1) for three consecutive RFID interrogations.

it is expected that the reflector-backed array could generate a higher DC power output in the RFID energy harvesting application.

IV. Wireless Powering Trials

The first step in evaluating the RFID-enabled energy harvesting is observing the DC power traces harvested from individual RFID interrogation events. The array was positioned in location 16 (from Fig. 1) and its DC output was connected to the optimum 40 kΩ load and observed using an oscilloscope. Fig. 6 shows the harvested voltage traces using the free-standing and unidirectional reflector-backed arrays; the inset shows a photograph of the measurement setup using the resistive load and the oscilloscope.

Firstly, the heavy duty-cycling of the RFID interrogation packets, mandated by the RFID standard, can be observed in Fig. 6, where the peak RF power level is transmitted for under 26.6% of each interrogation window. As expected from the RF power survey (Fig. 2) and the improved array gain (Fig. 5), the harvested DC power increases by three-fold, leading to a peak harvested power level of 306 µW. However, the intermittent nature of the packets implies that energy storage, in the form of a buffering capacitor, is required for powering wireless sensor nodes [14]. Fig. 7 shows the measured FoM of the array when connected directly to a capacitive load for varying incident S values.

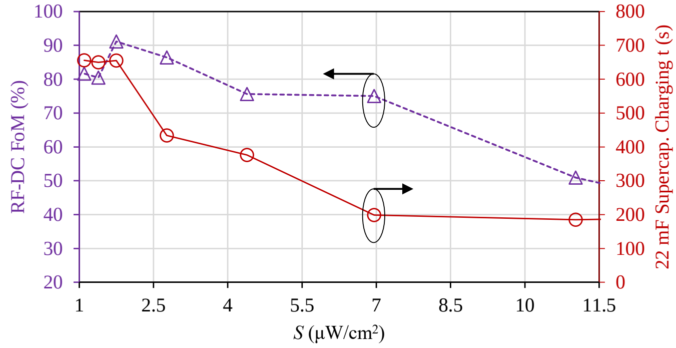


Fig. 7. Measured charging Figure of Merit (FoM) of a supercapacitor connected directly to the surface and the charging time to reach 3 V.

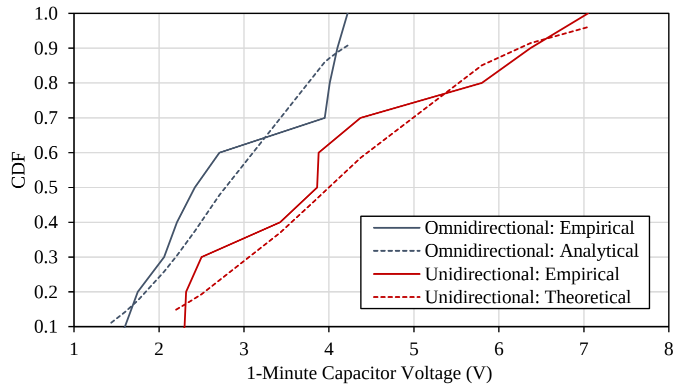


Fig. 8. CDF of the harvested voltage across the 220 µF capacitor for the different charging locations for the omnidirectional and unidirectional array.

For the capacitive load, the FoM was calculated using the net energy stored in the capacitor using

$$\mathrm{FoM_C} = \frac{CV^2}{2} \times \frac{1}{t_{\mathrm{charging}} P_{\mathrm{RF}}}, \quad (2)$$

with t_{charging} being the capacitor charging time, $P_{\mathrm{RF}} = SA_{\mathrm{physical}}$, and C and V being the capacitor's size and stored voltage, respectively [19]. This includes both the capacitor's leakage and impedance mismatch losses between the capacitor and the rectifier. The high FoM observed in Fig. 7 is in line with previous works where it was concluded that the omission of a DC-DC conversion stage in high-power (>0 dBm) can significantly increase the overall charging efficiency [19].

A 220 µF electrolytic capacitor is chosen as the energy storage unit, which is sufficient for powering a sensor node incorporating a Bluetooth Low Energy (BLE) transceiver and an Arm-based microcontroller [14]. Both the omnidirectional free-standing array and the unidirectional reflector-backed array were used to charge the capacitor in the positions shown in Fig. 1. The CDF of the measured DC voltage stored in the capacitor after one minute of charging is shown in Fig. 8 for both arrays.

From Fig. 8, it can be seen that the net energy stored in the capacitor (based on the stored voltage level) can be significantly improved using the unidirectional array. The mean energy stored using the unidirectional array is 1.8 mJ compared to a mean of 0.8 mJ for the omnidirectional array. While it was previously seen that the mean received power level only increases by 3 dB, a higher increase is expected in the harvested DC energy. This is attributed to the non-linearity of the rectennas, where the rectifiers achieve a higher RF to DC power conversion efficiency (PCE) at higher power densities. Therefore, an increase in the antenna's gain increases both the collected RF power and the RF to DC PCE, leading to a 2.25$\times$ increase in the harvested DC energy.

V. Conclusion

In this paper, a room-scale RFID-enabled UHF wireless power grid was proposed based on standard RFID readers and a state-of-the-art electrically-small six-element rectenna array. To maximize the harvested energy and increase the collection area of the surface, reflector-backing to achieve unidirectional harvesting patterns is proposed with the broadside harvested DC power patterns experimentally demonstrated. Despite the intermittent nature of the RFID interrogation packets, the use of an energy storage buffer does not impede achieving a high energy harvesting figure-of-merit, relative to the array's size. The indoor measurement campaign reveals that the proposed unidirectional array could generate at least 0.5 mJ in 1 minute of charging, with a peak DC energy output as high as 5.4 mJ, showing the feasibility of powering active computational sensor nodes using RFID power grids in dense indoor environments.

Acknowledgment

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