Wireless Power Transfer (WPT) Enabled IoT Sensors Based on Ultra-Thin Electrically Small Antennas

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***Abstract*-Wireless power transfer (WPT) enabled Internet-of-Things (IoT) temperature and light sensors based on two ultra-thin electrically small antennas are reported. Two distinctive wireless power capture capabilities are realized with metamaterial-inspired electrically small antennas. The near-field resonant parasitic (NFRP) element-based Egyptian Axe Dipole (EAD) antenna realizes an omnidirectional pattern. The Huygens dipole antenna, which combines a balanced pair of EAD and capacitively loaded loop (CLL) NFRP elements, realizes a unidirectional pattern. A sensor-augmented rectifier circuit is developed and seamlessly integrated with these antennas. Both of these systems are ultra-thin, being printed on a single piece of PCB substrate. The compact IoT temperature and light detection sensors were successfully implemented and tested. Since these high performance WPT-powered sensors are battery-free, they are very attractive for a variety of IoT applications.**

***Index Terms*—Electrically small antennas, Huygens antennas, Internet-of-Things (IoT), rectennas, sensors, wireless power transfer (WPT).**

I. Introduction

Wireless power transfer (WPT) enabled Internet-of-Things (IoT) applications are an emerging technology and recognized future trend that have arisen with the rapid development of 5G IoT ecosystems [1] – [3]. WPT-enabled IoT devices enjoy many advantages. These include being battery-free and, hence, environmentally-friendly. Moreover, they are capable of operating in remote places without manual maintenance [4]. Fig. 1 illustrates a potential application for smart agriculture and the farming industry. WPT-enabled IoT sensors will be distributed on farms, both in their fields and in their barns, to digitally monitor and manage plant growth and animal health. Rectennas, antennas integrated with rectifier circuits, are the most critical component in far-field WPT applications. Since the intent is to embed IoT devices into more compact and smaller platforms, it has become a major challenge to reduce the size, weight, and cost of rectenna systems.

Extensive research related to compact rectennas has been reported, including the typical examples in [5] – [10]. However, it remains difficult to simultaneously achieve an ultra-compact size, low cost, excellent wireless power capture capability, and high AC-to-DC conversion efficiency. Moreover, far-field WPT-enabled IoT sensors have not been a major applications focus until recently.

In this paper, two WPT-enabled temperature and light detection IoT sensors will be demonstrated. They are based on metamaterial-inspired electrically small antennas with distinct wireless power capture attributes. A temperature sensor augmented rectifier circuit is seamlessly integrated with an electrically small Egyptian axe dipole (EAD) antenna [11]. It features an omnidirectional wireless power capture capability. A light sensor augmented rectifier circuit is attached to a related Huygens dipole antenna (HDA) that is realized as a balanced combination of a pair of near-field resonant parasitic (NFRP) elements, an EAD and a capacitively loaded loop (CLL), driven by a simple dipole antenna [12], [13]. The HDA features a unidirectional wireless power capture capability. Both designs are low cost, ultra-thin and electrically small, i.e., with $ka < 1$, where k is the free-space wave number at the operating frequency and a is the radius of the smallest sphere enclosing the entire system. The impedances of both electrically small antennas are adjusted to be directly matched to the capacitive impedance of the rectifier circuit. This design distinction eliminates the lossy matching inductor found in the matching circuit found in standard rectennas and facilitates achieving the highest possible AC-to-DC conversion efficiency. Both WPT-enabled sensor systems have been built and tested. Experimental results successfully confirm that different levels of temperature and light illumination can be detected and that at a prescribed level, the rectenna provides the power for an acoustic alarm to sound.

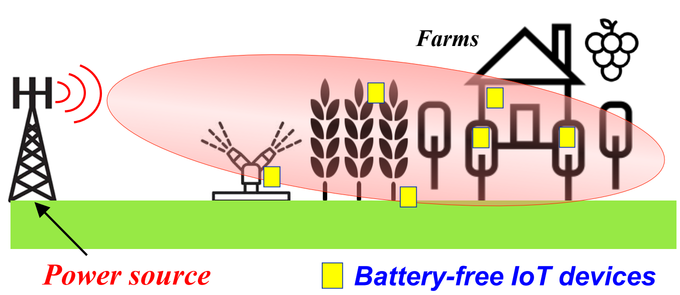
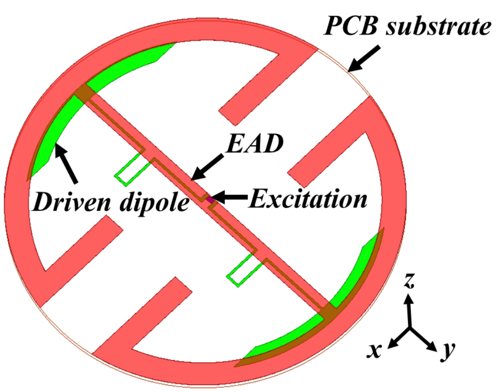


Fig. 1. Illustration of a WPT-enabled battery-free IoT sensor system for smart agriculture and farming applications.

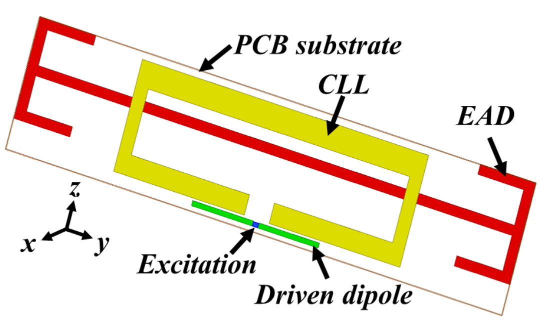
II. Designs and Operating Principles

A. Designs

The configurations of the omnidirectional and unidirectional electrically small antennas are shown in Fig. 2. Both antennas are designed for operation at 915 MHz frequency in the ISM (Industrial, Scientific, and Medical) band. Fig. 2(a) illustrates the Egyptian axe dipole (EAD) antenna. It is realized on a single piece of copper-clad 0.508 mm thick Rogers Duroid™ 5880 substrate, whose relative permittivity and loss tangent are 2.2 and 0.0009, respectively. The EAD radiator is printed on the top side of the substrate and the driven element is printed on its bottom side. Additional arms are attached to the basic EAD NFRP element at its four ends and meander elements are included in the driven dipole element to help facilitate nearly complete impedance matching. The arms provide additional capacitance; the meander elements provide additional inductance. A 0.47 *ka* value is achieved, which is 3.34 times smaller than a traditional half-wavelength dipole. The meander element can be adjusted to provide an inductive impedance that is directly matched to the capacitive rectifier circuit. The entire volume of the EAD antenna is: $\pi \times R^2 \times H = \pi \times 24.7^2 \times 0.508$ mm^3 ($\pi \times 0.075^2 \times 0.002\ \lambda_0^3$ at 915 MHz).



(a)



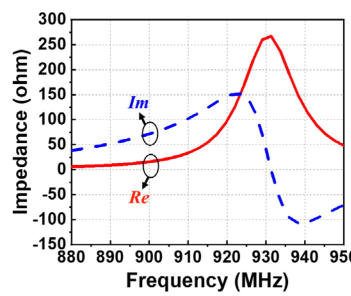
(b)

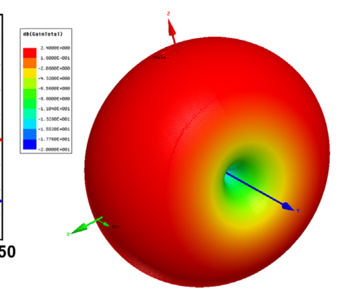
Fig. 2. Simulation models of the ultra-thin electrically small antennas. (a) Egyptian axe dipole (EAD) antenna. (b) Huygens dipole antenna that is formed as a balanced pair of EAD and CLL NFRP elements driven by a simple dipole element.

The configuration of the electrically small Huygens antenna is shown in Fig. 2(b). A capacitively loaded loop (CLL) NFRP element is organically combined with an EAD NFRP element. These NFRP elements create orthogonal and in-phased magnetic and electric dipoles, respectively. They are printed on opposite sides of the same Rogers Duroid™ 5880 substrate. A driven straight dipole element is etched on the same layer as the CLL element. The entire volume of the Huygens dipole antenna is: $L \times W \times H = 99.5 \times 26.5 \times 0.508$ mm^3 ($0.3 \times 0.08 \times 0.002\ \lambda_0^3$ at 915 MHz).

B. Operating principles

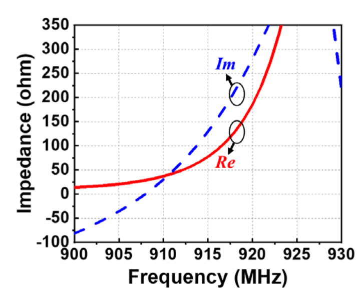
The realized gain pattern of the EAD antenna is quite similar as a single electric dipole, e.g., the figure 8-shaped omnidirectional pattern associated with a electric Hertzian dipole. The adjusted meander-augmented driven element of the EAD antenna successfully transforms its impedance at 915 MHz to an inductive value, 54 + j124 Ω, as shown in Fig. 3. On the other hand, the Huygens dipole antenna produces a unidirectional cardioid-shaped realized gain pattern as shown in Fig. 4. This operating mechanism has been verified in our previously reported papers in [12] – [16]. The desired inductive impedance for direct matching to the rectifier circuit is easily realized simply by adjusting the length of the short driven dipole. As shown in Fig. 4, an inductive impedance, 50 + j120 Ω, is obtained along with a symmetrical unidirectional realized gain pattern at 915 MHz.

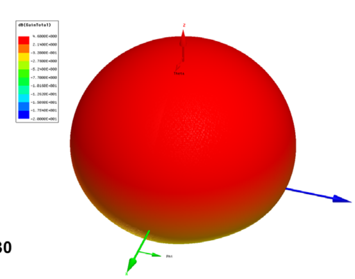




(a) (b)

Fig. 3. Performance characteristics of the electrically small EAD antenna. (a) Real and imaginary parts of its input impedance as functions of the source frequency. (b). Omnidirectional 3D realized gain pattern at 915 MHz.





(a) (b)

Fig. 4. Performance characteristics of the electrically small Huygens dipole antenna. a) Real and imaginary parts of its input impedance as functions of the source frequency. (b). Unidirectional 3D realized gain pattern at 915 MHz.

III. Integration of the IoT Sensor Systems with the Developed Electrically Small NFRP Antennas

To demonstrate the feasibility of realizing a WPT-enabled IoT sensor system based on the two ultra-thin electrically small antennas, one temperature sensor and one light detection sensor, have been successfully developed. Each system is realized by integrating a sensor-augmented rectifier circuit with them. The circuit is based on the full-wave rectifier design shown in Fig. 5(a). Two diodes D_1 and D_2 rectify the input AC wireless signal to the output DC power. Capacitors C_1 and C_2 serve as the input impedance matching circuit, and C_2 also acts as the power storage component in the negative cycle of the waveform. Capacitor C_3 works as a low-pass filter that smooths the output DC power. At the output side, an impedance-variable sensor is connected in series with a load resistor R_L. The PCB layout of this circuit is shown in Fig. 5(b). The total length of the rectifier is only 9 mm, 0.027 λ_0 at 915 MHz.

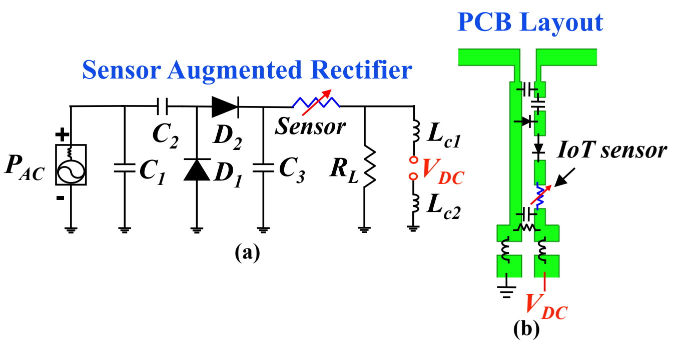


Fig. 5. WPT-enabled IoT sensor circuit. (a) Circuit model of the sensor-augmented rectifier. (b) PCB circuit layout of the rectifier.

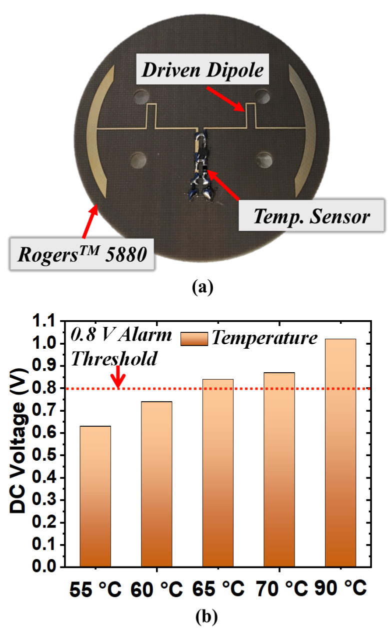


Fig. 6. Implementation of a WPT-enabled IoT temperature sensor based on the ultra-thin EAD antenna. (a) Fabricated prototype. (b) Output DC voltage values for different temperature levels.

A WPT-enabled temperature detection sensor with an omnidirectional wireless power capture capability was developed first. The system was measured with the far-field WPT measurement setup shown in [17]. It was realized by seamlessly integrating a thermistor-augmented rectifier circuit to the developed ultra-thin EAD antenna. The fabricated prototype is shown in Fig. 6 (a). The structure is compact and lightweight. The temperature sensor is a NTC (negative temperature coefficient) thermistor from TDK™. Its resistance as a function of the temperature can be found in [17]. Its resistance drops quickly when the ambient temperature goes up. As the impedance of the circuit drops, the output DC voltage goes up. To detect if the temperature exceeds a certain value, e.g., 65 ˚C, an acoustic siren was attached to the output port of the rectifier. The turn-on voltage of the siren is 0.8V. Thus, if the output voltage of the rectenna exceeds 0.8 V, the siren emits an acoustic signal. Fig. 6(b) presents the output DC voltage values under different temperature levels. It is seen that the voltage goes beyond 0.8 V if the temperature exceeds 65 ˚C. As a warning device, the acoustic siren will emit its sound at that temperature. Therefore, a WPT-enabled temperature detection sensor and alarm system facilitated by the developed EAD antenna-based rectenna was successfully realized.

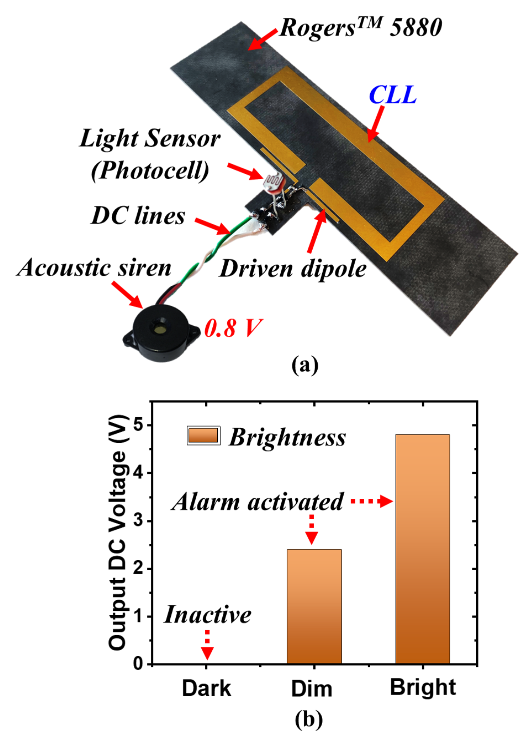


Fig. 7. Implementation of a WPT-enabled IoT light sensor based on the ultra-thin Huygens antenna. (a) Fabricated prototype. (b) Output DC voltage values under different illumination levels.

The related WPT-enabled light detection sensor with unidirectional wireless power capture capability was then demonstrated. It is realized by seamlessly integrating a photocell-augmented rectifier circuit with the developed Huygens antenna. The photocell is from Adafruit™; its resistance is almost infinite in a dark environment and is a low value, around 1.5K Ω, in a bright environment. When the photocell is integrated in series with the load resistor R_L, the output DC voltage becomes dependent on the illumination level of the ambient environment. For instance, the output voltage V_{DC} will be 0 V in a dark environment, but will increase rapidly when the illumination level rises.

The fabricated prototype of the battery-free light detection sensor is shown in Fig. 7(a). The entire structure is again compact and lightweight. The system was tested with the same measurement setup as was the EAD antenna-based temperature sensor. Fig. 7(b) shows the measured output DC voltage values and the associated status of the siren under dark, dim and bright light illumination levels. As expected, no output voltage was observed and, hence, the siren was silent when the sensor was in a dark environment. On the other hand, the output DC voltage rapidly went up to 2.4 V and 5.9 V, respectively, when the illumination level became dim and bright; and the siren emitted its sound. Therefore, a WPT-enabled light detection sensor and alarm system facilitated by the developed Huygens dipole antenna-based rectenna was successfully demonstrated.

IV. Conclusions

Two ultra-thin WPT-powered electrically small sensors and alarm systems were developed. An omnidirectional EAD antenna was augmented with a temperature sensitive rectifying circuit. A unidirectional Huygens dipole antenna was augmented with a light sensitive rectifying circuit. Prototypes of both WPT-enabled sensor systems were fabricated and tested. The results successfully demonstrated their desirable performance characteristics. Both are attractive examples of WPT-powered IoT devices.

As will be shown in our presentation, the measured and simulated values are in quite good agreement. Moreover, the fact that these electrically small rectenna-based sensor systems achieve nearly a 90% AC-to-DC conversion efficiency will be emphasized. A video of the light detection sensor system experiments will be presented.

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