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Hybrid RF-Solar Energy Harvesting for IoT

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***Abstract*—This work studies hybrid radio frequency (RF)-solar energy harvesting, which stacks a layer of radio frequency energy harvester (RFEH) beneath a layer of solar panel, with a boost converter combining them. The aim is to minimize the size of the whole energy harvester, while acquiring a sufficient amount of energy for realizing net-zero energy Internet of Things (IoT). Driven by this, a novel patch antenna is designed and fabricated with a single-stage rectifier, forming a compact-sized RFEH (3.5cm by 5cm) with a gain of 5.6 dBi. To the best knowledge of the authors, this is the highest gain that has been achieved with a similar size of RFEH in the existing literature. A hybrid RF-solar energy harvester is built upon the newly designed RFEH and an off-the-shelf solar panel with a similar size (5cm by 5cm). Experimental results show that the hybrid energy harvester can reduce the charging time by up to about 60% in comparison to a stand-alone solar panel. The hybrid energy harvester spends less than 50s to fully charge a 0.01 F supercapacitor, which can store 125mJ and support an IoT device to operate at a low level of power consumption (∼1 mW) for 125s. This indicates that the hybrid energy harvester is capable of supporting such an IoT device to work continuously.**

***Index Terms*—Internet of Things (IoT), net-zero energy, energy harvesting, solar panel, radio frequency (RF)**

I. Introduction

There are over 30 billion Internet of Things (IoT) devices deployed nowadays, and it is projected that this number will double by 2025 [1]. One of the biggest challenges in realizing the vision of large-scale and distributive IoT systems lies in powering the IoT devices in a cost-effective way, as most of them currently use primary batteries which require regular replacement and hence burden the maintenance cost. This motivates the concept of net-zero energy IoT, which aims to power IoT devices purely through energy harvesting.

However, achieving the goal of net-zero energy IoT is challenging due to the requirement for compact size for IoT devices. This drives researchers to make efforts on investigating wireless power transfer (WPT) and back-scattered communication (BSC), such as [2], to address the issue in two key aspects: a) increasing energy harvesting capability and b) reducing power consumption. Alternative to the classic radio frequency (RF) techniques, visible light communication (VLC) is an emerging and energy-efficient wireless technique towards the sixth generation (6G) communications. VLC can be embedded into the existing light infrastructure, providing illumination and communication at the same time. Meanwhile, the solar panels, which are one of the most commonly used approaches for energy harvesting, can be used to harvest optical energy and receive optical signals simultaneously [3]. To further enhance the capability of energy harvesting, a hybrid scheme of RF-solar energy harvesting is reported in [4]. However, the design is for wearable IoT devices which have a dimension of 178cm by 40cm, while IoT sensors usually have a frontal area of 10s cm^2. For these IoT devices with a restricted size, the hybrid RF-solar energy harvesting becomes more challenging due to: a) the limited area of solar panel and thus the energy harvesting capability; and b) the compact design of RF antennas with highly efficient energy harvesting.

In this paper, a novel hybrid RF-solar energy harvester is developed to meet both the goal of net-zero energy and the requirement for compact size. Specifically, a new patch antenna of RF energy harvester (RFEH) is designed to pair with an off-the-shelf solar panel in a size of 5cm by 5cm. The design aim is to maximise the efficiency of RFEH while keeping its size in a level similar to that of the solar panel, in order to construct a compact-sized hybrid RF-solar energy harvester. Experiments are carried out to validate the performance of the proposed hybrid energy harvester. Results show the designed RFEH with a size of 3.5cm by 5cm can achieve a gain of 5.6 dBi, which is 1.2 dBi higher than the design with a similar size in [5]. Upon the new RFEH design, the hybrid energy harvester can reduce the charging time by up to about 60% in comparison to a stand-alone solar panel.

The remainder of this paper is organized as follows. The system models of RFEH and hybrid RF-solar energy harvester are given in Section II. The novel design of RFEH and hybrid energy harvester is proposed in Section III. Experimental setup and results are presented in Section IV. Finally, conclusions are drawn in Section V.

II. System model

A. RF Energy Harvester (RFEH)

The key components of RFEH include an antenna to collect the ambient electromagnetic waves and a rectifier to convert alternating current (AC) to direct current (DC). This is also referred to as a rectenna. An input impedance matching circuit is also needed to achieve maximum power transfer. In this paper, the design aim for the RFEH is two-fold: small size and high power conversion efficiency (PCE). PCE depends on the antenna gain, the power efficiency of the matching circuit, and the power efficiency of the rectifier. The power received by the antenna is governed by the Friis transmission formula, which is given by:

$$P_{\rm Rx} = \frac{P_{\rm Tx} G_{\rm Tx} G_{\rm Rx} \lambda^2}{(4\pi R)^2}, \tag{1}$$

where R is the distance between transmitter and receiver, P_{Tx} is the transmitted power, G_{TX} denotes the gain of the transmitter, and λ is the wavelength. These parameters are not adjustable for the RFEH system. In order to maximize P_{Rx}, we need to maximize G_{Rx}, which is the gain of the receiver, for a certain wavelength λ. In addition, the exact location of the transmitter source is unknown. Hence, the antenna should be as close to omnidirectional as possible, to avoid the need for beam pointing during deployment [6]. In this work, the microstrip patch antenna is considered, which is suitable for designs which require simplicity, omnidirectionality, and a broad bandwidth [7]. Other benefits of the patch antenna are: i) it can be readily fabricated on a printed circuit board (PCB); ii) it is compact, inexpensive, and light-weighted; and iii) linear and circular polarization can be achieved with it. The following formulas are used to design a patch antenna for a given dimension, with the width and the length denoted by W and L:

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_R}{2}}}, \tag{2}$$

and:

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{\text{eff}}}} - 0.824h\frac{(\varepsilon_{\text{eff}}+0.3)(\frac{W}{h}+0.264)}{((\varepsilon_{\text{eff}}-0.258)(\frac{W}{h}+0.8)}, \tag{3}$$

where c is the speed of light, f_0 is the resonant frequency of the antenna, h is the height of the substrate, ε_R is the value of the dielectric substrate, and ε_{eff} is the effective refractive index of the patch, which accounts for the fact that air and the substrate have different dielectric values. The parameter ε_{eff} can be expressed as follows:

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12(\frac{h}{W})}}\right]. \tag{4}$$

The rectifier converts the received RF power, which is an AC, to a DC output. The AC-DC conversion efficiency of the rectifier is given by:

$$\eta_{\text{AC-DC}} = \frac{P_{\text{DC}}}{P_{\text{Rx}}}, \tag{5}$$

where P_{DC} is the DC output power. Zero-bias Schottky diodes are commonly used in rectenna applications due to their high switching capacity and low turn-on voltage. In this work, SMS7630 Schottky diodes are used, as they can provide a high conversion efficiency at frequencies near 2.4 GHz [7]. For the matching network design, the equivalent impedance of the diodes can be found as follows:

$$Z_{\text{eq}} = (R_j||Z_{C_j}) + R_s, \tag{6}$$

where R_j is the junction resistance, Z_{C_j} is the junction capacitance and R_s is the serial resistance.

B. Hybrid RF-Solar Energy Harvester

Fig. 1 shows the schematic diagram of the hybrid RF-solar energy harvester. The system consists of three layers: i) a solar panel (SparkFun PRT-18723) on the top layer; ii) the rectenna and matching network on the middle layer; and iii) a DC-DC boost converter (Microchip MPC1640) and a supercapacitor for energy storage on the bottom layer. The energy stored in the supercapacitor is given by:

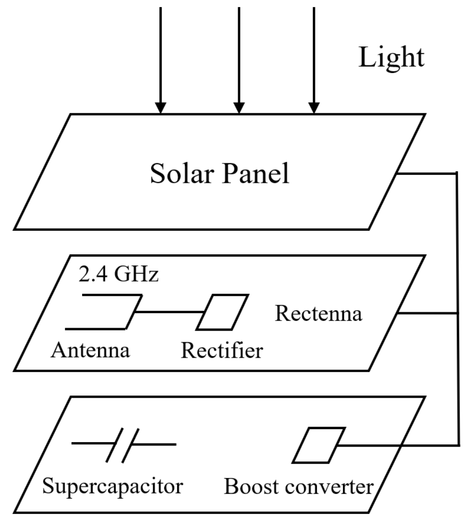

Fig. 1. Schematic diagram of hybrid RF-solar energy harvester.

$$E_{sc} = \frac{1}{2}CV_{sc}{}^2, \tag{7}$$

where C is the capacitance and V_{sc} is the voltage across the capacitor. The amount of stored energy needs to support both the active and sleep modes of operations for the IoT device throughout the day. However, the volumn of supercapacitor is not the larger the better. There exists a trade-off between the size of the supercapacitor and its charging speed, for a given voltage rating. The supercapacitor with a higher capacitance can store a larger amount of energy but it takes longer to become fully charged. The relationship between the charging time t and the capacitance C is expressed as follows:

$$V_{sc} = V_{\text{boost-output}}\left(1 - e^{-\frac{t}{RC}}\right), \tag{8}$$

where R is the output resistance of the boost converter and $V_{\text{boost-output}}$ is the output voltage of the boost converter.

III. Design of Hybrid RF-Solar Energy Harvester

A. Patch Antenna Design

A patch antenna that fits the 2.4-2.45 GHz Wi-Fi frequency band is designed and simulated on CST software, based on the formulas in Section II.A and along with physical tuning of various dimensions for optimisation. The main targets of this antenna design are compact size (to match the dimension of the selected solar panel) and high gain. Several factors that affect the performance of the microstrip antenna are investigated. First, increasing the thickness of the substrate increases both the radiated power and bandwidth, while decreasing the conduction loss. In other words, a higher substrate thickness renders a higher gain. However, if the substrate thickness exceeds 0.11λ then the antenna will stop resonating because of

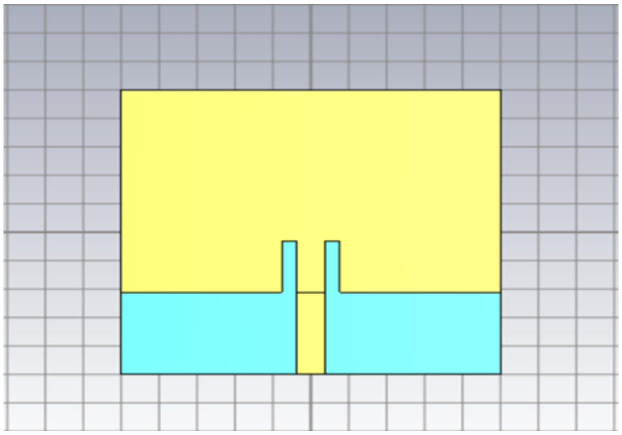

Fig. 2. Patch antenna structure in the CST software.

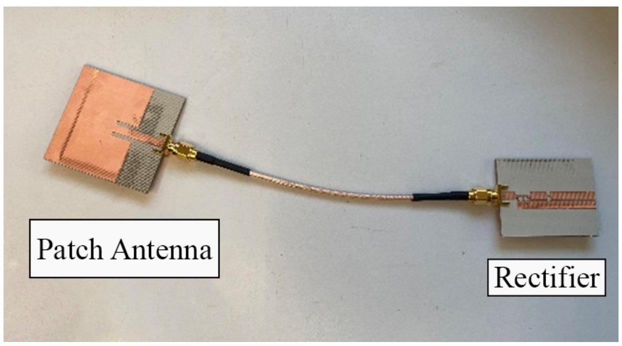

Fig. 3. PCBs of the designed patch antenna and rectifier.

inductive reactance [7]. In this work, the substrate is designed to have a height of 1.52mm and a dielectric value of $\varepsilon_R = 3$. Second, adding insets or slits to the patch can improve the gain performance [8]. It is found that a length of 35.5mm and width of 50mm is sufficient in obtaining the desired resonant frequency and bandwidth. The patch antenna with such a size can well fit beneath the chosen solar panel. Two symmetrical insets are then added to the patch to improve the S11 (reflection coefficient/return loss) parameters. Finally, a 50Ω feedline is added for matching the antenna to the rectifier. The layout of the patch antenna design is shown in Fig. 2.

LPKF ProtoMat C60 is used to print out the patch antenna, as shown in Fig. 3. A single-stage voltage-doubling rectifier and matching network are simulated, optimized and tested on AWR software. The rectifier should be able to operate for a range of input power as the strength of the ambient electromagnetic waves may vary with time. It is found that a 1000Ω load resistor gives optimality for different levels of input power, achieving up to 60% efficiency. Then the PCB of the rectifier is also produced using LPKF ProtoMat C60, as shown in Fig. 3. In this work, the antenna and the rectifier are printed out on two separate PCBs and connected via a 50Ω coaxial cable for purpose of test convenience. It is worth noting that they can be readily integrated on one PCB to construct a more compact design.

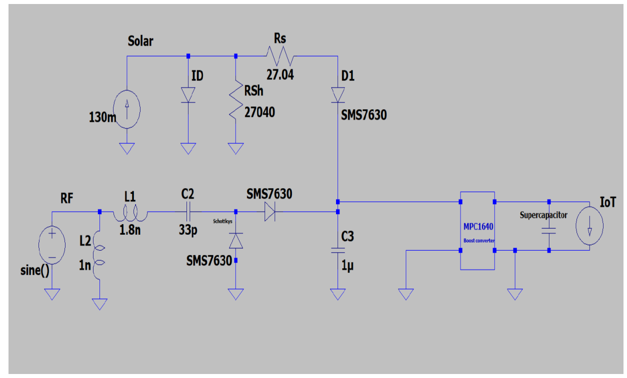

Fig. 4. Circuit design of hybrid RF-solar energy harvester.

TABLE I
EXPERIMENTAL TOOLS

Tools	Purpose
Rhode & Schwartz vector network analyser	Calibrate antenna performance
Rhode & Schwartz signal generator	Generate ambient RF signals
Extech light meter LT300	Measure light intensity

B. Hybrid RF-Solar Energy Harvester Design

A boost converter (Microchip MPC1640) is adopted to merge the two branches of RF energy harvesting and solar energy harvesting, outputting a voltage that is suitable for charging the energy storage unit (which is a supercapacitor in this case). Fig. 4 shows the equivalent circuit of the entire hybrid RF-sloar energy harvester in LTspice. The boost converter has a typical start-up voltage of 0.65V and an operating voltage of 0.35V. Using a resistor divider, the output voltage is adjustable over a 2.0V minimum to 5.5V maximum range. The output voltage of the boost converter is set to be regulated at 5V, since a higher V_{sc} provides a higher E_{sc} according to (7). This requires the supercapacitor to have a voltage rating of 5V or above.

IV. RESULTS

In this section, experiments are first carried out to evaluate the performance of the designed patch antenna, compared to several works in the existing literature. Then the performance of hybrid RF-solar energy harvester is validated with comparison to each harvester working stand-alone. The measurement tools used in the experiments are listed in Table I.

A. Patch Antenna

Table II compares the performance of the designed patch antenna with several existing works which harvest RF energy in a similar frequency band. As shown, the proposed patch antenna design achieves the highest antenna gain of 5.6 dBi, which is 1.24 dBi higher than the second highest [5]. Meanwhile, the surface area of the proposed patch antenna design is 35.5mm by 50mm, which is slightly smaller than the one in [5] (36mm by 53mm).

TABLE II
PERFORMANCE COMPARISON OF PATCH ANTENNAS

Ref.	Antenna frequency (GHz)	Max gain (dBi)	Antenna type	Patch size (mm)
[5]	2.36-2.49	4.36	Patch	36 × 53
[7]	2.35-2.45	2.7	Patch (strip)	35 × 2.5
[9]	2.3-2.45	1.9	Patch	60 × 60
[10]	2.39-2.49	2.14	Patch	37 × 31
This work	2.39-2.48	5.6	Patch	35.5 × 50

B. Hybrid RF-Solar Energy Harvesting

To guarantee a fair comparison, the ambient light is kept at 400 lux, which is a typical level of light intensity for indoor office scenarios. Two cases of RF input power are considered: i) -17dBm, where the patch antenna is placed 1m away from the Wi-Fi route which transmits at full power (i.e., 100mW); and ii) 5 dBm, where two patch antennas are placed 24cm apart with the signal generator used to generate RF signals. Three energy harvesting setups are tested: i) stand-alone solar panel; ii) solar panel combined with RFEH in Case 1, and this setup is referred to as hybrid harvester (Case 1); and iii) solar panel combined with RFEH in Case 2, and this setup is referred to as hybrid harvester (Case 2).

Fig. 5 presents the charging process for the above three setups with two volumes of supercapacitors, 0.01F and 0.1F. As can be seen, the hybrid harvester offers a faster charging speed than the stand-alone solar harvester. In the case of 0.01F, hybrid harvester (Case 2) can decrease the charge-up time by 58.2% compared with the solar panel alone. As for hybrid harvester (Case 1), the charge-up time is 4.3% less than the solar panel alone. When the supercapacitor increases from 0.01F to 0.1F, the saving of charge-up time becomes less pronounced. For hybrid harvester (Case 2), it reduces the charge-up time by only 23% in comparison to solar panel alone. This is because in the hybrid harvester, the output current of the boost converter reduces as the supercapacitor increases. According to the datasheet of MPC1640, the conversion efficiency is proportional to the output current when it is below 30mA, which exceeds the maximum combined DC current that can be generated by the hybrid harvester. Consequently, the conversion efficiency becomes lower for a larger supercapacitor, reducing the benefit of the hybrid harvester.

Fig. 6 shows the charge-up time as a function of different capacitance values of the supercapacitor, where hybrid harvester (Case 2) is compared with stand-alone solar panel. It is observed that for different supercapacitors, the hybrid RF-solar energy harvester can always outperform the stand-alone solar panel. However, as the supercapacitor increases, the gap of charge-up time between the two methods gradually reduces. The dominant factor for this trend is the conversion efficiency of the boost converter, as explained above.

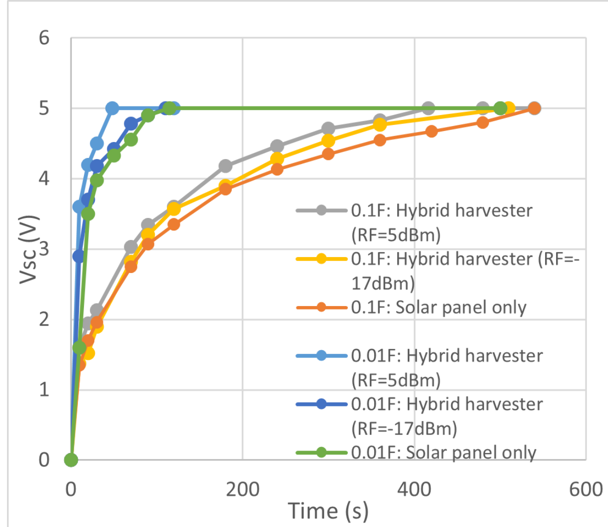

Fig. 5. Charging process of different harvester setups.

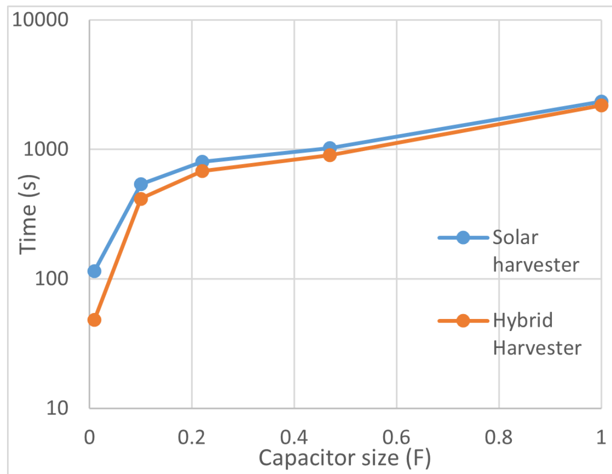

Fig. 6. Charge-up time vs the capacitance of supercapacitor.

V. CONCLUSION

In this paper A hybrid RF-solar energy harvester was developed for net-zero energy IoT. Specifically, a novel patch antenna was designed to achieve a high-gain RFEH, and a boost converter circuit was used to merge the branches of RF and solar energy harvesting. Results show that the proposed design of patch antenna can achieve a high gain of 5.6 dBi, with a compact size (3.5cm by 5cm) to suit practical IoT applications. Compared with stand-alone solar panel, the hybrid RF-solar energy harvester can save up to about 60% time to fully charge a supercapacitor. With a 0.01F supercapacitor, the hybrid energy harvester can charge 125mJ within 50s. This amount of energy can well support a low power consumption IoT device to operate at 1mW for 125s. This indicates that the hybrid energy harvester is capable of supporting such an IoT device to work continuously.

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