E-Textile RF Energy Harvesting and Storage using Organic-Electrolyte Carbon-Based Supercapacitors

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Abstract—Wearable radio frequency (RF) energy harvesting is highly dependent on the distance from the source and human-caused RF shadowing. Therefore, energy storage devices integrated with rectennas are of paramount importance to overcome this intermittency. In this paper, the use of carbon-based e-textile supercapacitors for storing the RF-DC converted power for powering body area networks nodes is investigated. A voltage doubler sub-1 GHz flexible rectifier, whose peak power conversion efficiency (PCE) approaches 80% is coupled to a two-cell 15.5 mF textile-based supercapacitor operating up to 4 V DC. Owing to the rectifier’s low optimum load resistance and high DC Voltage output, the average charging PCE of the rectifier-supercapacitor module reaches 31% for a 9.5 dBm input. Time-varying s-parameter measurements are performed to compare the time-averaged matching as opposed to instantaneous measurements using a resistive load, where the textile supercapacitor exhibits a similar response to a commercial supercapacitor. Finally, the RF-charged textile supercapacitor is demonstrated, for the first time, powering a microcontroller and Bluetooth transmitter with an average power consumption of 350 µW for up to 102 s, following 40 s of charging at 9.5 dBm, demonstrating its suitability for RF-powered body area networks applications.

Index Terms—Antenna, rectifier, rectenna, supercapacitor, wireless power transmission

I. INTRODUCTION

Radio Frequency (RF)-powered body area networks (BANs) have attracted significant research interest, with several textile-based rectenna implementations based on a variety of materials and targeting different frequency bands [1]–[4]. Compared to other forms of energy harvesting, RF energy harvesting rectennas, and more generally RF passives, can be implemented using standard low-cost conductors on most substrates without the need for specific materials [5]. For instance, multi-port RF energy harvesting and communication antennas have been realized using conventional 3D printed substrates [6] as well as all-fabric antennas [7].

Despite their high efficiency, low cost, and ease of construction, wearable RF energy harvesting rectennas suffer from a high intermittency due to the mobility of the user, and body-induced shadowing. It was previously found that, when considering the average angular gain of a wearable rectenna, the harvested power could drop by at least 50% [8]. As a result, the integration of a wearable rectenna with a textile supercapacitor was proposed to overcome the transient nature of microwave power transmission to wearables [1].

Compared to previous implementations where rectennas were integrated with capacitors [9], supercapacitors [10], or batteries [11], the e-textile module in [1] achieved the highest average wireless charging power conversion efficiency (PCE) of up to 37%. While this highlights the feasibility of high-efficiency RF harvesting and storage using e-textile materials, at least three supercapacitor cells were required to reach a voltage level around 3 V, which falls below the 3.3 V threshold of several commercial devices, as well as below the maximum voltage output of voltage-multiplying rectifiers which can surpass 8 V [1]. Therefore, there is a need for improved textile-based supercapacitors, compatible with the voltage operation range of typical BAN nodes and with the output of state-of-the-art rectennas [1].

In this paper, the integration of an organic-electrolyte carbon-based e-textile supercapacitor [12] with a sub-1 GHz rectifier is investigated. Using an improved electrolyte over our previous rectenna-supercapacitor module [1], the proposed module requires fewer supercapacitor cells to reach the operational voltage of a real sensor node. In Section II, the design and characterization of the rectifier and supercapacitor are presented. We then demonstrate the integrated module and characterize it using time-varying s-parameters, in Section III, before demonstrating it, for the first time, powering a real wireless sensor node load.

II. E-TEXTILE RECTIFIER AND SUPERCAPACITOR

A. Rectifier Design and Characterization

The rectifier used in this work is a coplanar waveguide (CPW) single-stage voltage doubler based on the Infineon BAT15-04R diode, whose breakdown voltage of 4 V enables up to 8 V DC output and a high peak PCE around 10 dBm [1]. The rectifier is matched using a single 22 nH lumped inductor. Fig. 1 shows the schematic of the full system, including the inductive-matched CPW voltage doubler rectifier.

The rectifier was characterized using a Vector Network Analyzer (VNA) as a continuous wave (CW) generator to characterize its DC output, PCE, and reflection coefficient (S11). In Fig 2(a), it can be observed that the rectifier achieves a peak PCE of 80% from a 10 dBm input. Due to the relatively
Following the curing process, a 1 M organic gel electrolyte was produced by dissolving 1.63 g of tetrathyrammonium tetrafluoroborate and 0.187 g of polyacrylamide in 7.5 ml of dimethyl sulfoxide. The supercapacitors were then submerged in the electrolyte before being placed in a vacuum of 25 mbar for 30 minutes to improve the wetting of the electrodes and to remove any trapped air. Fig. 3 shows a photograph of the two-cell textile supercapacitor (a), and a scanning electron microscopy (SEM) cross-section of the individual cell (b).

III. INTEGRATED MODULE CHARACTERIZATION

The time-averaged power conversion efficiency of the rectifier-supercapacitor module is given by

\[
PCE_{\text{Average}} = \frac{CV^2}{2} \times \frac{1}{t} \times \frac{1}{P_{\text{RF}}},
\]

where \( C \) is the capacitance of the two-cell textile supercapacitor, characterized to be 15.5 mF at a charge/discharge current density of 0.5 mA cm\(^{-2}\), \( V \) is the measured DC potential, \( t \) is the charging period, and \( P_{\text{RF}} \) is the input power [14].

Based on the 4 V turn-on voltage of the system, it was found that a minimum of 4.5 dBm RF input is required. Based on the measured charging time, \( PCE_{\text{Average}} \) was calculated using (1) at 4.5 and 9.5 dBm to be 29.5 and 31%, respectively. The lower average charging efficiency than the instantaneous PCE, in Fig. 2(a), was widely reported [1], [9], [14], and is attributed to the \( S_{11} \) time variation, introduced by the varying charging current of the supercapacitor [1]. A VNA was used to measure the time-varying s-parameter of both the proposed textile supercapacitor and a commercial supercapacitor. The measured response in Fig. 4 demonstrates that while the \( S_{11} \) for the optimal load is under –30 dB, the capacitor’s charging current varies the observed \( S_{11} \). Nevertheless, the omission of a standalone power management circuit along with the designed rectifier result in a higher charging efficiency than previous systems utilizing DC-DC converters [9], [11].

As shown in Fig. 1, the textile-based rectifier and supercapacitor are used to intermittently power an example BAN node. The cold-start circuit is based on two XC61C voltage monitors and a latch switch MOSFET. This creates a hysteresis switching loop enabling the supercapacitor to discharge through the load for \( 1.6 < V_C < 4.1 \) V. The load is based on a Texas Instruments CC2640R2F system-on-chip (SoC), comprising a 48 MHz Arm Cortex-M3 microcontroller.
The proposed textile-based supercapacitor was then demonstrated for the first time directly powering a wireless Bluetooth sensor node, from a minimum input of 4 dBm, and for up to 102 s from 39 s of charging at 9.5 dBm. Based on the measured results, rectennas integrated with supercapacitors are highly suitable for powering BAN nodes.

### References


