Hybrid Wireless RF-Perovskite Photovoltaic Energy Harvester Design Consideration for Low-Power Internet of Things

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***Abstract*—The rapid growth of the Internet of Things (IoT) has led to increased demand for low-power energy harvesting solutions to power the vast number of interconnected devices. In this context, the combination of wireless radio frequency (RF) energy harvesting, and perovskite photovoltaic has emerged as a promising approach for efficient energy harvesting in low-power IoT applications. This paper presents a comprehensive analysis of the design considerations for a hybrid wireless RF-perovskite photovoltaic energy harvester tailored specifically for low-power IoT devices. For the first time, combined mathematical modelling of the system architecture is presented. The achieved efficiency of the combined system is 78% and this holds a great promise for next generation 5G/6G smart IoT passive electronics.**

***Index Terms*—5G, 6G, hybrid energy harvesting, IoTs, photovoltaic, RF, satellite-cellular.**

I. Introduction

Internet of Things (IoTs) devices are expected to create a world of meshed smart, seamlessly connected nodes in a decade's time. The end of 2013 saw approximately 7.7 billion active interconnected IoTs devices. This is estimated to reach about 25.4 billion in 2030, representing an 11% compound annual growth rate (CAGR). Short range technologies (including wireless sub-6 GHz 5G/Wi-Fi 6/6E/7) are tipped to account for about 68% connections in 2030. The current dominating cellular networks in public networks are forecast to increase by five times in 2019 to 6.0 billion IoTs connections in 2030 [1]. The private networks account for the remaining 9% connections in 2030. However, small smart electronic IoTs devices generally depend on batteries – that are frequently recharged and/or replaced within a maximum of five years in critical infrastructures. These occasion increasing high material and inefficient labour costs and dispensable environmental wastes. The quest to power satellite-cellular-IoT devices in a cost-effective, sustainable, reliable fashion cannot be overemphasised to enable a truly connected smart world. Hybrid multi-radio frequency and small form factor, cheap thin film solar cells (enhanced for a diffuse indoor light operation) offer a sustainable solution to this challenge [2], [3].

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This paper aims to provide an insight into the design considerations for wireless sub-6 GHz 5G/Wi-Fi 6/6E energy harvesters for low-power IoT devices. Section II describes the hybrid multi-RF-photovoltaic energy harvesting concept. Section III will go over the design and efficiency of rectification. Section IV will proceed through impedance matching and the final design. The outcome and conclusion will be discussed in the appropriate section.

II. Multi-RF-Photovoltaic Energy Harvesting

Wireless power transfer (WPT) technology has been in high demand in recent decades as the IoTs devices and passive home electronics have begun revolutionizing the way we interact with common objects. Hence, smart electronic devices communicate with one another and collect real-time data at edge, gateway and enterprise nodes of a hierarchical industry 4.0 system architecture. Specifically, EM-based radio frequency (RF) energy harvester technologies have the potential to power devices in remote area and eliminate the limitation of wire-based ultra-low powered IoTs devices and sensor nodes which directly restricts their capabilities for security surveillances, smart farming, and other related applications [4]. Although these technologies are unable to harvest enough power from the RF, their output can be improved using a voltage doubler. Energy harvesters enable a wide range of use-inspired applications across multiple industries, such as IoT sensors, wearable devices, and smart cities, by lowering energy usage, size of base stations, and power consumption, size of devices and carbon emission. One of the biggest obstacles in supporting the growth of the IoT ecosystem is the need for low-power devices that can operate for extended periods without requiring frequent battery replacements. Wireless sub-6 GHz 5G/Wi-Fi 6/6E energy harvesters have been developed as an option for this problem [5]. The design considerations for wireless sub-6 GHz 5G/Wi-Fi 6/6E energy harvesters for low-power IoT devices are crucial to ensure maximum efficiency, reliability, and performance. Perovskite solar cells can maintain high efficiencies under fairly low intensity or diffuse light. This positions them as the best candidates for both indoor and outdoor hybrid energy harvesting applications [6]. Hybrid multi-RF-photovoltaic energy harvesters hold a great promise for the emerging meshed satellite-cellular networks convergence ecosystem. This will enable integrated on-demand 5G/6G use cases and/or applications to be achieved seamlessly within an ubiquitous resilient energy-efficient network architecture.

III. HYBRID RF-PHOTOVOLTAIC SYSTEM MODEL DESIGN

During the night, the IoT device depends on the onboard storage batteries to maintain system functionalities; the power generation of the solar panels is 0 W while the IoT is unlit. This works for IoTs sensors with storage batteries. However, for completely passive smart electronic IoTs devices, this would amount to shutdown of the meshed IoTs network. Hence, the total energy reserve of the IoTs device is reduced per a 24-hour period due to the absence of the Sun's illumination during the night. To eliminate this problem, we propose a hybrid multi-RF-photovoltaic energy harvester to keep the IoTs devices operation anytime, anywhere [7], [8].

The total energy produced by the IoTs device's solar panels, E_o during a 24-hour operation is given by:

$$E_o = P_{sp}(\tau_o - t_e) \tag{1}$$

where P_{sp} is the solar panel's average sunlit power generation during the day.

The solar panels' sunlit power production capacity enables us to develop the electrical energy generation of IoTs devices during the day [3]. A two-power mode IoTs device has the following feasible power modes' power consumptions, viz:

- Power-storing, P_s; and
- Payload processing-overpower, P_p.

The total energy of the IoTs device during a 24-hour period for a two-power mode system is thus:

$$E_o = E_s + E_p \tag{2}$$

where E_s and E_p are the energy consumptions in the IoTs power-storing and IoTs device payload processing-overpower modes respectively. The IoTs device's operational time of the payload processing-overpower mode, t_p, is given by:

$$t_p = \tau_o - (t_s + t_e) \tag{3}$$

where t_s is the operational time of the IoTs device's power-storing mode; t_e the night-time of an IoTs device; and τ_o, the actual total operational time (maximum being 24 hours) of the IoTs device. Combining Eqs. (1) and (2) yields the operational time of the IoTs device's payload processing-overpower mode for a two-power mode system as:

$$t_p = \frac{E_o - P_s(\tau_o - t_e)}{P_p - P_s} \tag{4}$$

Equation (4) can be adapted to cater for multiple IoTs devices' power modes applications. For a N-power mode system, the feasible power consumptions are thus:

- Power-storing;
- Communication (downlink and uplink)-overpower, P_{du}, with a corresponding time, t_{du};
- Uplink-overpower, P_u, with a corresponding time, t_u;
- Payload processing-overpower; and
- Other overpower modes, Pn, with a corresponding time, tn, where n = 1, 2, ...

The energy budget balance for the operational IoTs device applications is derived as thus:

$$E_o = E_s + E_{du} + E_u + E_p + E_1 + E_2 + ... + +E_N \tag{5}$$

The corresponding operational time of the IoTts device's payload processing-overpower mode is obtained as:

$$t_p = \tau_o - (t_s + t_e + t_{du} + t_u + t_1 + t_2 + ... + t_N) \tag{6}$$

Hence, we derived the active service operational time of the IoTs device's payload processing-overpower mode, t_p, using Eqs. (5) and (6) as:

$$t_p = \frac{E_o - P_s(\tau_o - (t_s + t_e + t_{du} + t_u + t_1 + ... + t_N) - (P_1 t_1 + P_2 t_2 +}{P_p - P_s} \tag{7}$$

Equation (7) can be re-written thus:

$$t_p = \frac{E_o - P_s(\Sigma_{i=1}^{N-2} t_i + t_e - \tau_o) - (\Sigma_{i=1}^{N-2} P_i t_i)}{P_p - P_s} \tag{8}$$

where P_i and t_i represent the IoTs device's i_{th} power mode's power consumption and operational time respectively. Eq. (8) considers all the IoTs device's power modes except the power-storing and the payload processing-overpower mode. When calculating the operational time of a power mode other than the payload processing-overpower mode's, the latter is held constant and included in the summations while the power mode of interest is excluded. The different IoTs device's power modes' power consumptions and their corresponding operational times must be estimated to obtain the t_p for the IoTs use case and/or application. Moreover, estimates of the power consumptions of the power-storing mode and the power mode whose operational time is being calculated are needed as well.

To maximise the operational time of a hybrid power mode, Eq. (9) is adjusted to capture the maximised power mode. Given the power consumption of the maximised power mode, P_{max}, the corresponding maximised operational time, t_{max}, is obtained from Eq. (8) as:

$$t_{max} = \frac{E_o - P_s(\Sigma_{i=1}^{N-2} t_i + t_e - \tau_o) - (\Sigma_{i=1}^{N-2} P_i t_i)}{P_{max} - P_s} \tag{9}$$

Equation (9) enables the multi-objective optimisation of the IoTs device's use case and/or application design variables in a hybrid system design environment. Hence, the operational time of any smart IoT device's hybrid power mode can be optimally modelled for a cost-effective, sustainable and energy-efficient application. The multi-RF energy harvesting estimating relationship is derived with the assumption that the gains of the transmit and the receive antennas are non-reconfigurable and static.

Mathematically, this is given by thus:

$$P_{rT}(W) = \Sigma_0^n P_{rn}(W) = \Sigma_0^i P_{t_{ni}} G_{t_n} \left(\frac{\lambda_{ni}}{4(\pi)R_{n-m}}\right)^2 G_{t_m} \tag{10}$$

where the parameters for transmitter n and receiver m are defined as follows:

- R_{n-m} = Distance of the transmitter n from the receiver m in metres.
- G_{t_n} = Static gain of the antenna of transmitter n in dB.
- G_{t_m} = Static gain of the antenna of transmitter m in dB.
- P_{rn} = Power received from transmitter n in Watt.
- $P_{t_{ni}}$ = Power from frequency i of transmitter n in Watt.
- P_{rT} = Total Power received from all the transmitters in Watt.
- λ_{ni} = Wavelength of signal (frequency) i from transmitter n in metres.

IV. RESULTS AND DISCUSSION

RF Schottky diodes are high-frequency semiconductor devices widely used in microwave circuits, signal detection, and mixing. These diodes are ideal for RF applications due to their low forward voltage drop and fast switching speed. The rectifiers in Fig. 1 are designed and simulated on the ADS using the modelled SMS7630 diode and lumped capacitors of 470 pF. A single frequency power source (P_1Tone) component on the ADS library was used as input to the rectifier instead of the antenna, as the antenna file cannot be swept over different powers. The frequency is set at 2.4 GHz, the input power is swept from -25 to 20 dBm, and the output voltage is measured at the node voltage label (V_{out}). The rectifier sensitivity improved by adding a diode in series to the load resistance; as a result, the rectifier sensitivity lowered to -25 dBm.

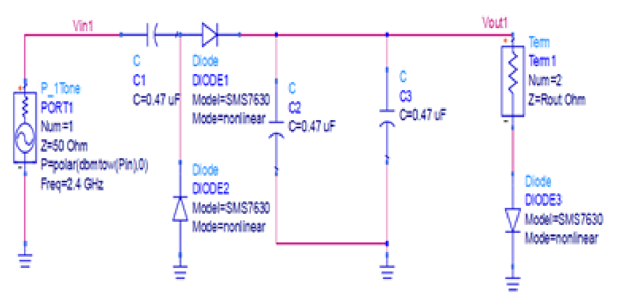

Fig. 1: The proposed rectifier circuit for the RF-EH circuit.

The output voltage of RF energy harvesting using a single antenna was insufficient as the input RF power is in µW. Therefore, the design was modified to a MIMO system where different antennae capture RF power from different or the same frequency. The power captured by each antenna is rectified using the same rectifier as in Fig. 1. The output of each rectifier is combined using the power combiner tool and then stored in the tank capacitor. The MIMO circuit harvests RF energy using six antennas and is designed and simulated on ADS. MIMO system improved the output voltage of the system and enhanced the overall efficiency of the RF energy harvester design. Fig. 2 shows the output voltage of the MIMO design

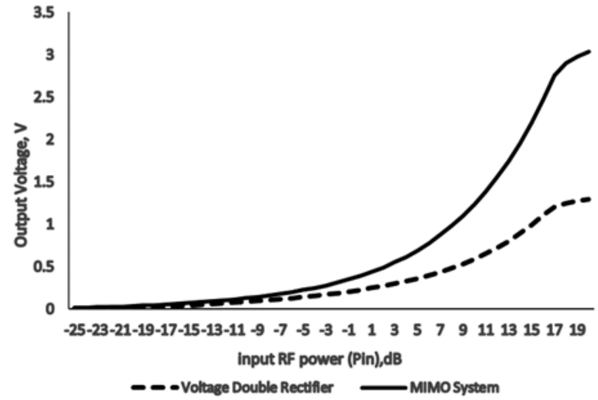

Fig. 2: Output voltage of the voltage doubler rectifier and the MIMO design

is greater than the single rectifier given in Fig. 1.

The efficiency of the RF energy harvesting circuit is improved when the MIMO design is used (Fig. 3). The overall efficiency of the MIMO design achieved is 78%, and an output voltage of 3.1 V was achieved.

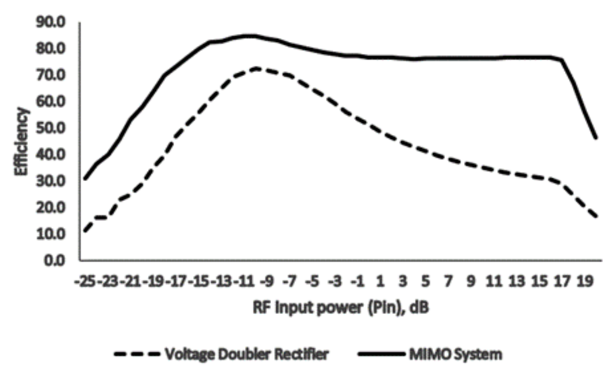

Fig. 3: Efficiency comparison of the voltage doubler rectifier and the MIMO design.

The table below (Table I) compares the designed RF energy harvester with existing literatures. It shows that the sensitivity and efficiency of the designed RF energy harvesting are much better than the conventional products.

V. CONCLUSION

The design considerations discussed in this paper provide valuable insights for the development of hybrid wireless RF-perovskite photovoltaic energy harvesters for low-power IoT applications. The integration of these technologies offers a promising pathway towards achieving sustainable and self-powered IoT systems. This paper presents a pioneering integration of mathematical modelling techniques to analyse the system architecture. Through our analysis, we have highlighted the individual strengths and limitations of RF energy harvesting and perovskite photovoltaic. By combining these technologies, we can harness their complementary characteristics and overcome their individual constraints, resulting

TABLE I: Comparison of RF energy harvester with existing literatures

Related Paper	Sensitivity (dBm)	Efficiency %	Output Power
[9]	-8.7	30	1 W
[10]	-14	16	3.2 W
[11]	-15	60	-
[12]	-10	18	50 mW
[13]	-	50	0.24 mW
[14]	-14.6	27	16 mW
This work	-25	78	14 mW

in improved energy harvesting efficiency for low-power IoT devices. The compatibility of perovskite photovoltaic with RF energy harvesting systems involves examining factors such as material properties, fabrication techniques, and device integration challenges. The reported multi-RF harvester sensitivity of -25 to 20 dBm will enable smart autonomous energy-efficient IoTs passive electronics in the next-generation of satellite-cellular 5G/6G networks.

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