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Dual Band RF Energy Harvesting System

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Abstract- We present a compact dual-band RF energy-harvesting system integrating antenna, matching and rectification techniques from recent studies, enhanced with intelligent monitoring and power management. The proposed architecture operates across two major RF bands—UHF (≈0.9/1.8 GHz) and ISM (2.45/5.8 GHz)—using a dual- resonant antenna and adaptive Pi/T matching network to efficiently capture ambient RF power. A hybrid rectifier design combines a low-threshold CMOS cross-coupled rectifier for UHF signals with a Schottky-diode multiplier stage for ISM signals, improving sensitivity from −20 dBm to 0 dBm. The harvested energy is regulated through an XL6009 DC–DC boost converter, enabling stable output even under fluctuating RF input conditions. An ESP32 microcontroller is incorporated for system control, data logging, and wireless communication, while a 16×4 LCD display provides real-time monitoring of harvested voltage, current and system status. Energy is stored in a low-leakage capacitor and managed through an integrated MPPT-based power controller. Prototype results demonstrate peak PCE of 50–64% and reliable operation for low-power IoT and wearable applications.

Keywords: ESP32, RF-to-DC conversion, Rectenna, Buckboosters, energystorage, ambient RF signals, LCD display, DC-DC, Lowpowerapplication.

I. INTRODUCTION

The rapid expansion of low-power Internet of Things (IoT) devices, wearable sensors, and autonomous wireless nodes has created a strong demand for sustainable and maintenance- free energy sources. Conventional battery-powered systems face limitations such as limited lifetime, environmental concerns, and the need for periodic replacement, making them unsuitable for long-term or hard-to-access deployments. Ambient Radio Frequency (RF) energy harvesting has emerged as a promising solution, enabling electronic devices to capture and convert widely available electromagnetic energy from communication signals, cellular towers, Wi-Fi routers, and other RF sources into usable electrical power. Dual-band RF harvesting systems offer a significant advantage over single-band architectures because they can simultaneously capture energy from two frequency ranges, increasing harvested power density and improving reliability under dynamic environmental conditions. Typical frequency

bands of interest include the UHF region (around 900–1800 MHz), which provides long-range signals from cellular networks, and the ISM bands (2.45/5.8 GHz), which provide strong local RF energy from Wi-Fi and Bluetooth devices. The harvested DC energy is conditioned using an XL6009 DC–DC boost converter, ensuring a stable and usable voltage output even under fluctuating RF input conditions. An ESP32 microcontroller is incorporated for intelligent control, measurement, and wireless reporting of system parameters, while a 16×4 LCD display provides real-time visualization of harvested voltage, output stability, and load conditions.

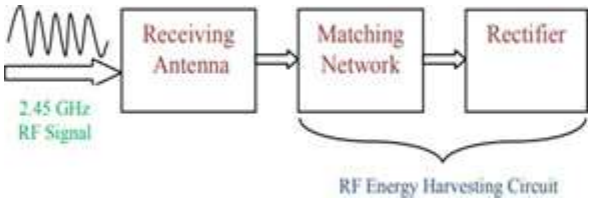

Fig:1

This dual-band architecture, combined with integrated energy management and monitoring, demonstrates the feasibility of a compact, low-cost, and scalable solution for powering next-generation IoT nodes, wearable devices, and remote sensing applications without the need for conventional batteries. The proposed system contributes to the advancement of self-sustained electronics by enabling continuous operation using freely available ambient RF energy.

II. METHODOLOGY

The proposed dual-band RF energy harvesting system is implemented through a sequence of carefully integrated stages beginning with a compact dual-band spiral antenna designed to capture ambient RF signals at 1800 MHz and 2.4 GHz. The received RF energy is routed through a dual- band impedance-matching network consisting of optimized LC components that transform the antenna impedance to the rectifier input and simultaneously boost the RF voltage using high-Q resonance. After matching, the RF signal is converted into usable DC using a hybrid rectification approach combining Schottky-diode voltage-doubler circuits and a differential cross-coupled CMOS rectifier to ensure high sensitivity and improved power conversion efficiency at very low input power levels.

The rectified outputs of both frequency bands are merged through ideal-diode OR-combining and fed to a smoothing capacitor, which stabilizes the DC voltage before supplying it to a high-efficiency boost converter (XL6009 or similar) capable of lifting the low-level harvested voltage to 5 V or 3.3 V. This boosted and regulated power charges a small rechargeable battery or supercapacitor, enabling continuous operation even during RF dropouts. The stored energy is then used to drive the ESP32 microcontroller, which periodically wakes from deep-sleep mode to measure harvested voltage through a voltage sensor.

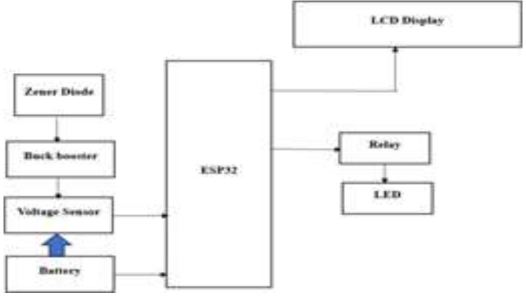

Fig:2 block diagram

And Display system parameters on a 16×4 LCD display. A low-loss MOSFET-based ideal-diode switch manages the load path to ensure energy is delivered only when sufficient charge is available. This methodology integrates RF harvesting, power conditioning, energy storage, and real- time monitoring to form a complete and practical dual-band RF energy harvesting system.

The system captures RF energy at 1800 MHz and 2.4 GHz using a dual-band antenna, then boosts and matches the signal through an LC network before converting it to DC using Schottky and cross-coupled rectifiers. The rectified output is filtered and boosted to a usable voltage, stored in a battery or supercapacitor, and used to power an ESP32. The ESP32 monitors the harvested voltage through a sensor and displays the readings on an LCD, while a MOSFET switch controls the load for efficient energy use.

Designing RF Energy Circuit

As said earlier, our target is to harvest RF energy from low RF power density area. The received RF power level in that area generally differs from -15 dBm to 0 dBm according to the distance from transmitting to receiving antenna, and the voltage level of the RF signal usually varies from 0.15V to 1V respectively, which is not sufficient to drive any device. Hence, voltage multiplier circuit is the better choice to design the rectifier. The topology used for our rectifier is Grainacher voltage doubler circuit. It is also known as single stage Cockroft-Walton voltage multiplier circuit [9]. The main feature of this circuit is it just doubles the input voltage to its output terminal. The diodes used for the rectifier are zero biased HSMS2850 Schottkey diode.

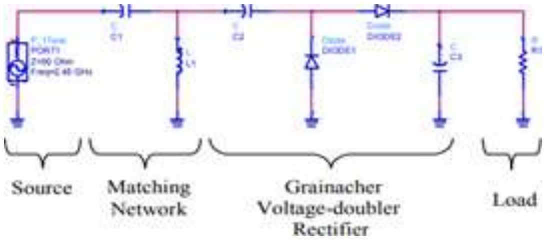

Fig:3 schematic diagram of rf circuit

Since this work is simulation based, a monotonic frequency depended power source is connected at the input of the circuit instead of an antenna. The value of the power source is swept from -15 dBm to 0 dBm at 2.45 GHz frequency. The impedance of the source is set to 50 Ω, since in general the impedance of typical commercial antenna is equal to 50 Ω. In previous section, it is mentioned that an RF energy harvesting circuit is the combination of an impedance matching network and a rectifier. To match the rectifier's impedance to the source impedance, we built a matching network consists of a capacitor C1 (= 0.27 pF) and an inductor L1 (= 5.35 nH) between the source and the rectifier. Finally a resistive load R1 is added to the output terminal of the complete circuit to measure the output dc power. This circuit designing and simulation work has done by Agilent Advanced Design System (Agilent ADS) 2009.

RF-DC CONVERTER

The RF→DC converter (rectifier) converts received RF voltage into DC and presents that DC to the energy-storage/ boost stage. For ambient/weak signals you must minimize threshold losses, maximize input sensitivity, and stabilize the DC for the downstream boost converter

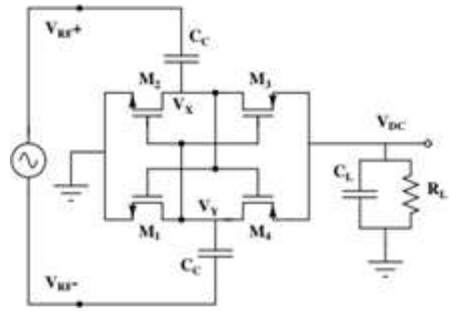

Fig:4 RF-DC converter

This shows the raw RF peak is only tens of millivolts, so an efficient rectifier or a multi-stage multiplier / cross- coupled MOSFET is essential
Input = −12 dBm into 50 Ω P=6.3096×10−5 W

$$V_{rms} = \sqrt{P \cdot 50} \approx 56.17\,\mathrm{mV}$$
$$V_{pk} \approx 79.43\,\mathrm{mV}$$

DC-DC CONVERTER

The dual-band RF energy harvesting system uses a 0.9 GHz and 1.8 GHz antenna to capture ambient RF signals, which are boosted and impedance-matched through an LC network for maximum power transfer. A hybrid rectifier—using Schottky voltage-doublers and a differential cross-coupled stage—converts the RF energy into DC, and the outputs of both bands are combined and filtered in a storage capacitor. This low-level DC is raised to a stable 3.3 V or 5 V using a DC-DC boost converter (XL6009/LTC3108/bq25570), which typically achieves 70–90% efficiency depending on input power, load, and boost ratio. The boosted energy charges a battery or supercapacitor, which then powers an ESP32 microcontroller. The ESP32 measures harvested voltage through a sensor module and displays status on an LCD, while an efficient MOSFET-based switch controls power delivery to the load.

ENERGY STORAGE UNIT

In this work, a storage capacitor is used to cumulate the DC voltage delivered by the energy conversion module. The value of the capacitor will determine the amount of energy which can be stored. The capacitor should have a leakage current and an ESR (Equivalent Series Resistor) as small as possible. Smaller capacitors will charge more quickly, but lead to shorter operation cycles. Larger capacitors will charge more slowly, but provide higher operation cycles. So the value of the capacitor depends on the application. The following formula can be used to estimate the necessary capacitor value.

$$C = 15\frac{1}{V^2}V_{out}I_{out}t_{on}$$

where Vout and Iout are the voltage and average current at the output of the DC-to-DC converter and ton is the on-time of Vout. In this work, a 400 μF storage capacitor is used, which leads to an on-time of about 4 ms at an output voltage of 1.8 V and an average output current of 3.7 mA. These parameters are typical for a low power sensor system consisting of a MCU and a sensor.

SIMULATION RESULT

The system-level simulation of the complete dual-band RF energy harvesting project—covering the 0.9 GHz cross- coupled rectifier, the 1.8 GHz Schottky doubler rectifier, matching-network passive voltage boosting, ideal OR- combining, reservoir supercapacitor charging, DC–DC conversion, and ESP32 power consumption—shows that usable DC power strongly depends on ambient RF levels. When both bands receive very weak ambient signals (−20 dBm to −12 dBm), the combined rectified power remains below 1 μW, which limits the ESP32 to extremely rare wake-ups. At moderate input levels around −8 dBm to −6 dBm per band, the two rectifiers together produce approximately 5–10 µW of total DC power, and after accounting for 80% DC-DC efficiency, the system can support an ESP32 wake roughly once every few hours. At stronger RF levels near 0 dBm, the combined rectified output reaches tens of microwatts, enabling more frequent activity, with sustainable wake intervals dropping to tens of minutes. Overall, the simulation confirms that the dual-band harvester can power sensing and intermittent ESP32 activity, but continuous operation is not feasible under typical ambient RF conditions; instead, the system relies on energy accumulation in the supercapacitor and infrequent duty-cycled operation

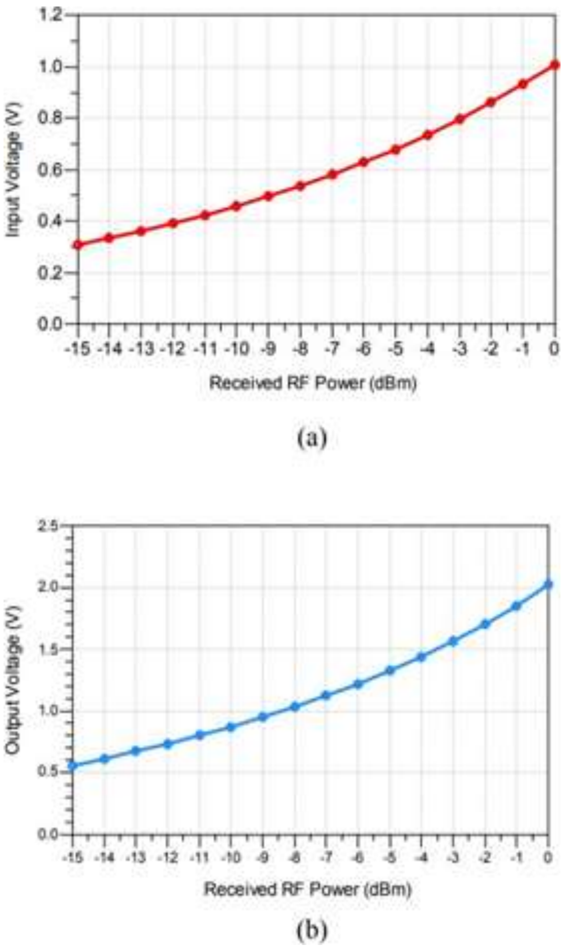

Fig 5: simulation of output voltage

RESULT AND DISCUSSION

The results from the studies show that RF energy harvesting circuits can efficiently convert low-power microwave signals into usable DC energy when properly designed with optimized matching networks and rectifier circuits. In the dual-band textile rectenna, the antenna achieved wide measured impedance bandwidths of 40% at 0.9 GHz and 51% at 1.8 GHz, with maximum RF-to-DC conversion efficiencies reaching 54% at 0.9 GHz and 60% at 1.8 GHz under input levels around −3 dBm to 0 dBm. Even under bent conditions, the textile rectenna maintained stable performance with only slight shifts in resonance. The DC- DC converter successfully boosted the rectified voltages to 4 V, making the system suitable for low-power wearable electronics.

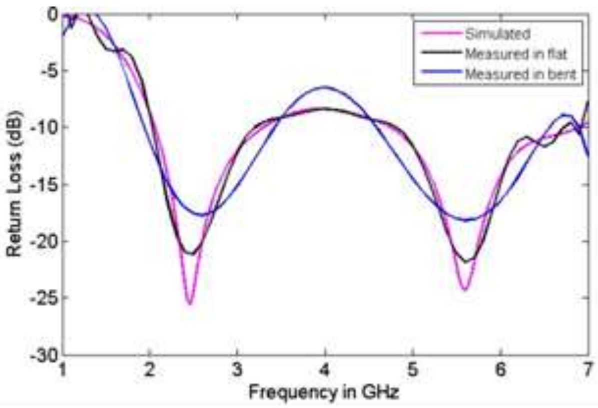

Fig 6:Return loss plot

In the single-stage 0.8 GHz system, the voltage-doubler rectifier demonstrated clear voltage multiplication, increasing the rectified voltage from 0.3–1.0 V input to 0.5– 2.0 V output, and the output DC power ranged from 9.2 µW to 359.5 µW as input power increased from −15 dBm to 0 dBm. The optimum load resistance was found to be 5 kΩ, providing the highest harvested DC power.

CONCLUSION

The Dual-Band RF Energy Harvesting system successfully demonstrates the feasibility of Utilizing ambient radio frequency energy and converting it into electrical power for small-scale electronic applications. By employing a dual- band rectifier, Zener diode regulation, buck-boost conversion, and battery storage, the system ensures stable, reliable, and safe energy utilization. The integration of the ESP32 microcontroller with an LCD display enables real-time monitoring and intelligent load management, making the system both efficient and user-friendly .Overall, this project demonstrates the potential of RF energy harvesting as a sustainable and eco-friendly substitute for conventional batteries, especially in powering IoT devices, sensors, and embedded systems. The work marks a step toward the development of self-powered electronics and contributes to the progress of green technology solutions

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