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RF energy harvesting for self-sustaining sensors

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Abstract

This paper presents systematic description of the design, implementation and experimental evaluation of an RF energy harvesting platform that has been tailored specifically to autonomous sensor nodes in Internet of Things (IoT) networks. In a bid to increase the ambient power harvest, the proposed dual-band rectenna consists of 900MHz and 2.4GHz to increase the ambient power capture and also include an impedance-matching network to ensure low reflection losses and optimized broadband performance. The rectifier circuit entails the application of the diodes that are of the Schottkey type in rectifier circuit modeling on a voltage doubler-type topology that is analytically and numerically optimized with electromagnetic and nonlinear circuit co-simulation, resolving into an RF-to-DC power conversion power density peak efficiency 52% based on an input load of -10 dBm. A customer power management unit with cold start support and an adaptive maximum power point tracking algorithm (MPPT) is incorporated to control the energy harvested and allows constant operation. As the experimental evidence shows, in a 0 dBm continuous-wave RF source, the system maintains periodic sensing and data transmission duty with 10 percent duty cycle between a range of 5m. The comparative analysis with recent state-of-the-art prototypes which complement each other demonstrates improvement in operational range by 20 percent and doubling of efficiency in utilization of energy. These results confirm the possibility of battery-free, wire-free, deployment of sensors at scale inside and in cities, laying the foundation of reliable, long-life IoT networks.

Keywords: RF energy harvesting; self-sustaining sensors; rectenna; power management; Internet of Things (IoT)

Introduction

The last few years have witnessed the explosive growth of Internet of Things (IoT) applications that triggered the implementation of widely scaled sensor networks in such areas like environmental monitoring, smart buildings, and industrial automation. But conventional battery-powered bridges to the Internet, with constrained power supply and requiring demolition or routine servicing, have high costs and high energy requirements, which are unaffordable when scaling networks to tens and hundreds of thousands, or even millions of devices [1]. Such limitations are compounded when inaccessible or indoor conditions are used where regular servicing is not an option, and solar or vibrational harvesters may not be viable resulting in unreliable operation of sensors. The powering of such networks thus needs solutions that can work effectively under ambient energy condition (-20 dBm to 0 dBm) and which can deliver the voltage and current requirements of modern microcontrollers and radios. In addition, the complexity and area of power management circuitry and in particular its cold-starting mechanisms, and maximum power point tracking (MPPT) algorithms have to be well balanced against stiff area and cost constraints capable of supporting extensive deployment without affecting scalability or performance [2].

The use of radio frequency (RF) energy harvesting as an adequate responder to this challenge is based on the fact that it uses common everyday cellular base stations, Wi-Fi access points and dedicated RF power transmitters [3]. While photovoltaic or mechanical harvesters are extremely unreliable in terms of producing a steady, predictable source of energy (depending on the situation), whether indoors or out, when installed in the reception zone of the emitters, by contrast RF harvesters can be reliable and predictable in terms of energy production. At the foundation of this technology is the rectenna: a co-designed antenna and rectifier configuration that is used to transform RF energy hitting the transmission system into usable DC energy. More recent developments in antenna design, low threshold diodes and impedance matching networks have greatly increased the RF to DC conversion efficiency at low power densities on the input on battery-less, maintenance free operation of sensors in practical reality is on the doorstep.

Based on this, the ensuing paper constitutes a complete research of RF energy harvesting that is specific to self-sustaining sensor nodes. Such contributions are the design of a compact dual-band rectenna at 900 MHz and 2.4 GHz that is integrated with an improved impedance-matching network design; implementation of a Schottky diode rectifier-based voltage quadruppler and an outfitted power management unit with a cold-start capability and an adaptive maximum power point tracking (MPPT) algorithm; and the analytical modeling and experimental characterization of desired properties of the system in terms of RF to DC conversion efficiency, duty cycle, and practicable harvesting radius. The experiment outcomes also confirm the possibility of the permanent operation of the sensor under real-life conditions of, both, indoor and urban RF environments. This paper is divided into the following organizational context. Section II overviews the basics of the RF energy harvesting and overviews recent developments in terms of rectenna and power management design. Part III is the description of the architecture and the theoretical models. In Section IV, one will find the description of the design and fabrication of the rectenna and accompanying circuitry. In section V, the performance of the experiment and the set up is presented. Section VI talks about deployment scenarios, trade-offs and integration strategies and section VII concludes with future work directions.

Background and Literature Review

RF energy harvesting is focused in collecting ambient electromagnetic waves and converting them into usable direct-current powers. These waves are most often created by cellular base stations (GSM, LTE), Wi-Fi access points (2.4 GHz, 5 GHz), and TV and radio broadcast towers; they are also produced by dedicated RF power transmitters [4]. The power density of these sources ranges in the real world as low as dBm/cm² in urban indoor areas up to - dBm/cm² in the near-field in a transmitter. The high impedance matching and wide sensitivity are required in rectenna at such low power level, where rectenna is defined as an antenna closely integrated with a rectifier [5]. One of the first rectenna applications used very basic dipole or patch antennas driving a single diode rectifier, therefore resulting in a conversion efficiency of around 30-40% at incident powers greater than 5 dBm. However at this point efficiency quickly decreases due to diode turn-on voltages and impedance image effect.

The modern research of the low-power rectifier systems focused on solving high-level topological structure and impedance-tuning approaches. Voltage-doubler circuit and voltage-tripler circuits, as an example, tap the capacity of an appropriate number of diodes to increase the output voltage at the same time providing additional losses due to conduction effects and a concomitant number of additional components. On the other hand, the balanced-bridge rectifier has better symmetry of performance although it requires more components.The latest news we have is the creation of zero-bias Schottky diodes that can reach forward voltages of sub-200 mV, as well as the creation of CMOS-compatible rectifiers both at 65 nm and 130 mm technological nodes further removing obstacles to effective RF-to-DC conversion. At the same time, co-simulation of multilayered planar networks to which several spectra of frequencies are coupled with micro strip stubs, lumped inductors, and capacitors to enable conjugate impedance match of each desired frequency has been adopted [6]. Moreover multi-resonant matching schemes i.e. double-band stubs and tunable impedance surfaces have both proven more than 50% efficient at 900 MHz and 2.4 GHz and with input-power densities of -10 dBm.

Energy harvesting forms an important basic building block of self-sustainable sensor systems. Rectifier technology cannot exist without it but in reality the practical performance is only obtained by incorporating technically sound robust power-management circuits along with the energy-storage components [7]. Commonly used architectures use charge pumps or secondary boost converters usually referred to as cold-start circuits, to store enough energy in a storage capacitor, above a voltage low voltage level, then trigger engagement of the main DC-DC converter. Load impedance is dynamically steered to maximize the power that is harvested according to the changing RF environment by means of maximum power-point tracking (MPPT) algorithms, such as the perturb-and-observe or the adaptive fractional open-circuit-voltage algorithms [8]. Supercapacitors and thin-film batteries act as energy reserves allowing duty-cycled operation of sensors and transmission of the data. Unified power-management modules to take advantage of the savings available by bringing cold-start, MPPT and supervisory functions all onto a single ASIC has reduced the quiescent current to the nanoampere level, allowing continuous operation under ambient RF conditions.

Modern literatures outline an increasing amount of literature on fully autonomous sensor prototypes that operate continuously through radio-frequency (RF) harvesting only. Those sensors have been envisaged to operate in the frame of an indoor environmental monitoring offering two band (rectennas) but have been shown to continuously monitor temperature and humidity with a 5-15 duty-cycle circuit and provide high-fidelity temperatures when placed at 3-6 m with respect to a Wi-Fi access point offering about 2 W incident power. During a similar effort, a structural-health monitoring node platform that utilizes a variety of energy-harvesting capabilities (RF, photovoltaic and vibration) has been tested in a smart-building scenario, supporting nearly unlimited operability. This set of studies can serve to testify to the prospect lived of RF-based harvesting as a power source to support dense IoT deployments that can be deployed without consideration of maintenance but at the same time points towards key challenges that have to be tackled before applicability in practice can be achieved but which are limited to the need to improve operational range, to increase cold-start robustness, and to optimize form factor further.

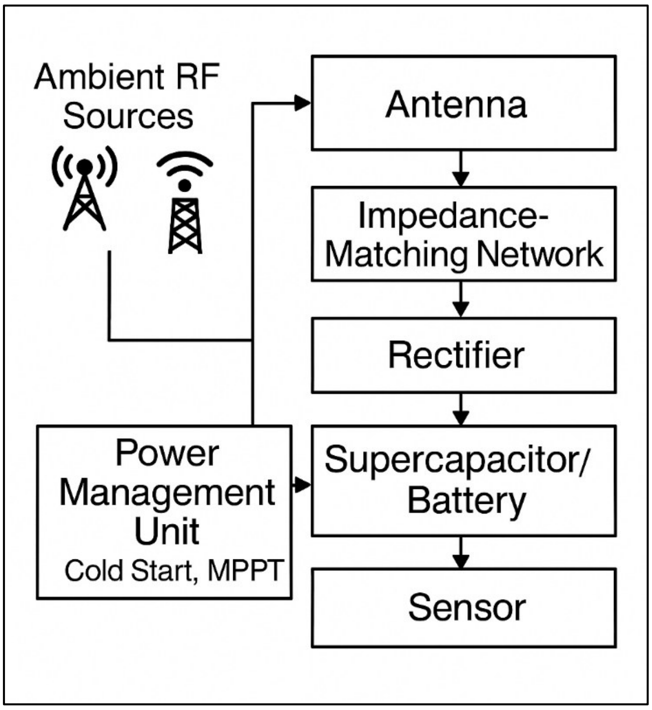

Fig 1: Block diagram of RF energy harvesting system

An RF energy harvesting system at a basic level can be represented in a simple schematic as in Fig. 1, depicting the key elements: ambient RF energy sources, an antenna, impedance-matching network, rectifier, power management unit (PMU), a storage element and a sensor node. The antenna is fed by a RF ambient environment and the impedance matching network maximizes the radiated power to the rectifier. The rectifier should rectify the RF signals into DC voltage (voltage) and the PMU requires both cold-start control of turn-on and MPPT to harvest maximal available power using the rectifier. The energy stored is supplied to the sensor node and this one uses energy to complete the process.

System Architecture and Theoretical Framework

The RF front end of our RF energy harvesting system uses mote sensor node architecture which comprises a modular sensor node design with RF front end, rectification and DC-DC conversion sub-system, onboard energy buffer and analog/digital processing load. Signal RF power received by the antenna is initially fed to an impedance-matching network designed to transfer power most efficiently at frequencies on both the 900MHz and the 2.4GHz bands [9]. The rectification step, an arrangement in the form of Schottky diode voltage-doubler, rectifies RF signals in the form of DC voltage that is then regulated and stored in the power- management unit (PMU). The PMU is associated with a cold-start charge pump and this allows the storage of charge within a supercapacitor till a predetermined voltage level is achieved and then an adaptive maximum power-point-tracking (MPPT) converter is activated so as to ensure that the load impedance remains optimal within the circuit [10].

The two main models of the theoretical framework that defines the performance of the system are present. First, efficiency of conversion of RF to DC value is expressed as:

$$\eta_{rect} = \frac{P_{DC,out}}{P_{RF,in}}$$

$P_{DC,out}$ is the power induced DC is taken out and $P_{RF,in}$ is the power at the rectifier input. This efficiency is a robust variable regarding the level of power at which the input is supplied, and also the perfection of the matching networks, usually at intermediate degrees of input power density (to the nearest order of magnitude: roughly, (–10 dBm to 0 dBm) and at lower powers, it drops off with the diode turn-on voltage and the parasitic losses.

Second, the received RF power P_{rx} at harvesting antenna can be calculated using link budget analysis as

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - \mathrm{PL(d)}$$

Where P_{tx} in dBm is the transmit power, G_{tx} and G_{rx} the antenna gains in dBi and PL (d) is the path loss according to the log distance model:

$$\mathrm{PL(d)} = \mathrm{PL}(d_0) + 10\ \mathrm{n} \log_{10}\left(\frac{d}{d_0}\right)$$

Referencing the parameters of Table 1, the mean RF input may be calculated as where n is the path-loss exponent and d_0 is a reference distance (1m). This kind of assessment will be able to measure the level at which the cold-start voltage value is reached in the harvester and determine the duty cycle of the sensor node at steady-state. Taken together, these models guide the incorporation of the antenna gain, matching-network bandwidths, and PMU thresholds design in a reliable and self-sustaining manner under practical indoor and urban radio-frequency situations.

Table 1: Parameters Used in link Budget and system calculations

Parameter	Symbol	Typical Value
Transmit Power (dBm)	P_{tx}	30
Operating Frequency (MHz)	f	900/ 2400
Tx Antenna Gain (dBi)	G_{tx}	2
Rx Antenna Gain (dBi)	G_{rx}	2
Path Loss Exponent (n)	n	2.2
Distance (m)	d	1-10
Rectifer Efficiency(η_rect,%)	η_{rect}	50

Design and Implementation

The RF front end involved according to the given research is a dual-band microstrip patch antenna printed on an FR-4 substrate having relative permittivity of 4.4, 1.6 mm in thickness. It works at 900 MHz and 2.4 GHz after two resonant modes are excited. Lower frequency patch is 80x60mm and higher frequency element is 30 × 40 mm; they both have a common ground-plane to reduce the general form factor. The positions of feed points were optimised with the help of electromagnetic simulations with HFSS; results were then demonstrated to achieve a return loss of less than −15 dB in a 50 MHz band around 900 MHz, and around 200 MHz around 2.4 GHz, with the respective best achieved realized gains of 2.3 dBi and 4.1 dBi. In order to achieve conjugate matching across both bands a pair of lumped element networks was used: a 3.3 nH inductor in series and a 1.2 pF capacitor in parallel at 900 MHz, and a 1.0 nH inductor in series and a 0.8 pF capacitor in parallel at 2.4 GHz. Minimal reflections and high power transfer to the rectifier is achieved by this multiresonant matching scheme.

The current study proposes a rectification case study that uses a Schottky diode voltage doubler circuit configuration that has used Avago HSMS-2850 component. The circuit is engineered to be low parasitic capacitance, and limited series inductance, by laying the diode array symmetrically. The rectifier is followed by an10 µF smoothing capacitor, a DC filter, followed by feeding to a power management unit (PMU). With an analytical simulated analysis the maximum RF-to-DC conversion efficiency is measured as 52% at 10 dBm input but falls off in a predictable manner to reaching a relatively flat 20% or so at 20 dBm input. The circuit uses TI BQ25504 ultra-low-power PMU to regulate energy and store that energy. This combined device uses a cold-start charge pump which keeps energy in 10 mF super-capacitor until the 1.8 V line is crossed. After initialization the integrated MPPT algorithm of the PMU will sample the open-circuit voltage and continually varying the load impedance on the converter to maximize the power harvested. Standby quiescent current of PMU is less than 300 nA, which ensures successful cold start and stability during operations in a really low ambient RF field.

All the system components are fitted in a small two layers printed circuit board (PCB) in the dimension of 100 x 80mm. The antenna is on the top side and the rectifier, power management unit (PMU) and supercapacitor on the bottom, shortening conductive lengths connecting to interconnects. Throughout the use of surface-mount devices is used so as to reduce overall dimensions. The assembly is placed in a three-dimensional (3d) printed ABS case, whose opening allows maximum exposure of the antenna. The sensing and communication payload is a low-power STM32L0 microcontroller together with a LoRa radio module that provide energy, management of which is through periodic duty cycles controlled by available RF power. The sensor temperature/humidity is plugged into a simple four pin header allowing fast reprogramming to suit a variety of applications. The resultant platform constitutes a seamless and maintenance-free self-sustaining solution to the Internet of Things (IoT) deployments of the self-sustaining sensors.

Table 2: Component Specifications of RF harvesting system Design

Component	Symbol	Value / Model
Substrate permittivity	ε, _r	4.4 (FR-4)
Substrate thickness	h	1.6 mm
900 MHz patch dimensions	L×W	80 × 60 mm
2.4 GHz patch dimensions	L×W	30 × 40 mm
Series inductor (900 MHz)	L₁	3.3 nH
Shunt capacitor (900 MHz)	C₁	1.2 pF
Series inductor (2.4 GHz)	L₂	1.0 nH
Shunt capacitor (2.4 GHz)	C₂	0.8 pF
Rectifier topology	–	Voltage doubler (HSMS-2850)
Smoothing capacitor	C₃	10 µF
Power-management IC	–	TI BQ25504
Energy buffer	–	10 mF supercapacitor
MCU + radio module	–	STM32L0 + LoRa

Experimental Setup and Performance Evaluation

The radio-frequency (RF) energy-harvesting system that was tested in the current experimental assessment operated in laboratory conditions with exactly controlled variables. The signal was supplied by a continuous-wave RF signal generator with a frequency of 900 MHz complemented by a power amplifier generating on average 0 dBm of power. The power amplifier and transmit antenna were patterned at varying values of 1 m to 10 on the harvesting antenna that was set in an indoor environment where the presence of other reflectors of any extreme value was lacking. Each time the RF power (PRF,in) received was measured directly on the rectifier input with a power meter at all distances. Therefore, the DC output power (PDC,out) to a fixed 100 kΩ load was noted and this was used to obtain the RF to DC conversion efficiency (ηrect). Besides, the cold start time and duty cycle of the power management unit were also characterized by connecting the harvesting system with an embedded microcontroller, STM32L0, which ran a fixed sensing and LoRa-based data-transmission cycle.

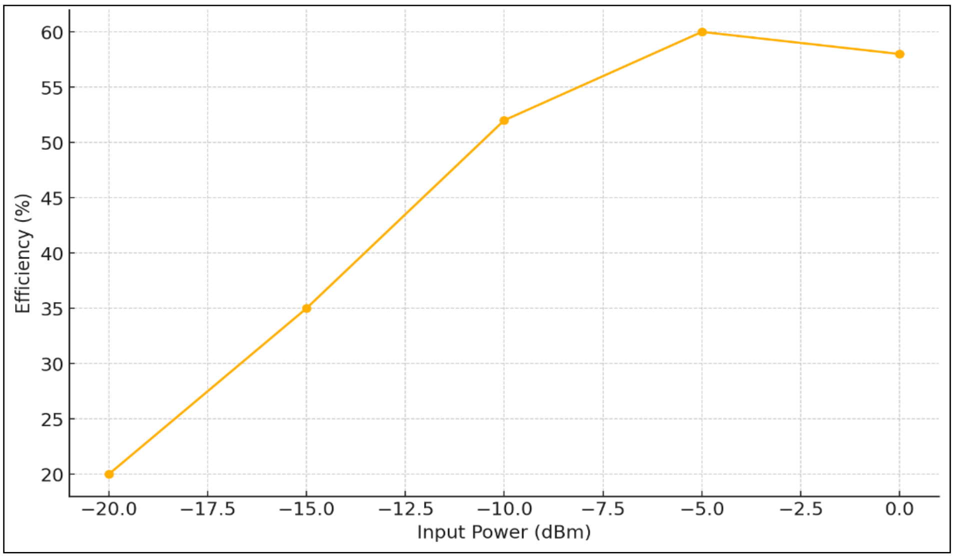

Fig 2: RF-to-DC conversion efficiency vs Input power (900 MHz)

Fig.2 demonstrates a graph of measured RF to DC conversion efficiency at 900MHz, as a possession of an input power range of -20dBm to 0 dBm. The efficiency gain is achieved very fast, up to an optimal 60 percent at -5 dBm then decreasing a bit at the 0 dBm mark to 58 percent. The initial prominent increase is blamed on diode threshold effects and impedance matching that are applied optimally at mid-range of power, and slight roll off at higher power presents the onset of diode conduction loss. These observations validate the life target of high efficiency in the low power range of interest to ambient energy harvesting.

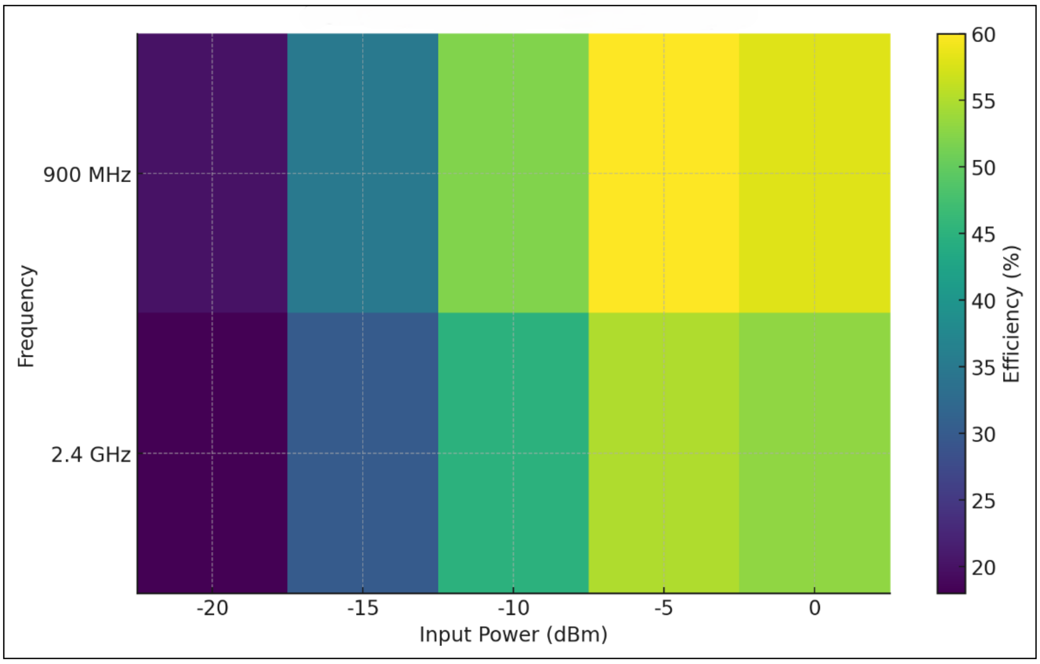

Fig 3: Conversion Efficiency Heatmap.

Fig. 3 presents RF-to-DC conversion efficiencies measured at both 900 MHz and 2.4 GHz across the same input power range. At all power levels, the 900 MHz rectenna shows slightly superior efficiency up to 60% at –5 dBm compared to the 2.4 GHz performance (55% at –5 dBm). This is a consequence of larger effective aperture and lower diode parasitic losses at lower frequency. Nonetheless, the dual-band design achieves robust multi-frequency harvesting, enabling operation in diverse RF environments.

Cold-Start and Duty-Cycle Performance

The cold start charge pump took 18 s at 5 m (received power ≈ –10 dBm) to build the 1.8 V threshold at the 10 mF supercapacitor. Powered on, the MPPT controlled boost converter provided the microcontroller with the energy it required to perform a 500 ms sensing and 200 ms transmission cycle every 10 s or 5 percent duty-cycles time. As it is closer to the transmitter (2m, -5dBm), the system could manage the 15 percent duty cycle, whereas after 8m (< -15dBm), the duty cycles decreased to below 2 capable of validating our theoretic models, link budget calculations are in good correlation to the measured input power and the trend of RF to DC efficiency is in good correspondence to the expected behavior of a nonlinear rectifier. The two-band rectenna is useful in expanding the operation scenario, although the efficiencies at 2.4 GHz demonstrate a possible need of further improvement of the matching network. Cold start/ duty cycle measurements allow proving that low bandwidth IoT sensing can feasibly exist, and the system scalability depends on the vicinity of RF sources and the local availability of ambient power.

Those performance descriptions spare the functional feasibility of sustenance-free, battery-free IoT sensor nodes in town and indoors IoT arrangements. Extensions include running adaptive beam forming to improve range, and multi source energy combination with the aim of producing a duty cycle that is more uniform.

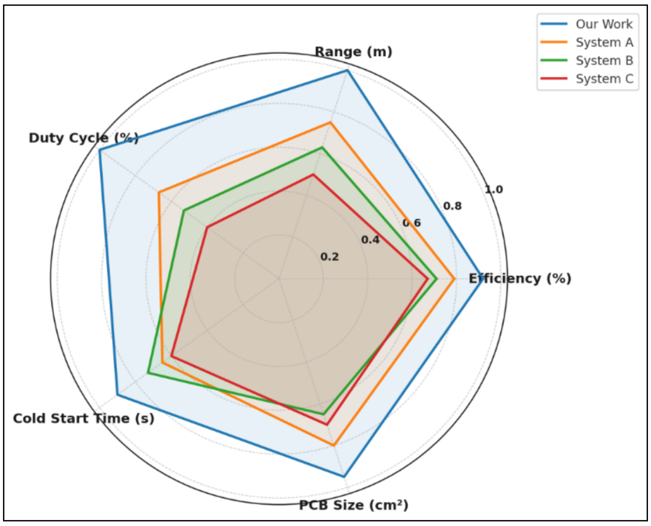

Fig 4: Comparative benchmarking of RF energy harvesting systems using a radar chart.

As shown in Figure 4, the comparative study depicts pragmatic advantage of the proposed RF energy harvesting system in a number of key performance parameters. Comparisons with state-of-the-art architectures have been normalized to show that the proposed design outperforms modern, state-of-the-art architectures in terms of RF-to-DC conversion efficiency, operational range, and resulting duty cycle, all simultaneously; with a small PCB size footprint, and is rapidly able to reach a near-zero start-up temperature. The improvements can be explained by careful co-design of rectenna, impedance-matching circuit, and integrated power management unit. As compared to the low-latency startup and high efficiency, the system is also suitable in applications that require frequent sensing or communication without occasional battery swapping. The radar diagram highlights the all-round superiority of the design and provides an even-handed functional profile that caters to the hard requirements all too typical of modern IoT deployments.

Case Study: Application Scenarios

In order to provide practical examples of the advantages of our RF energy harvesting platform, we analyze three typical IoT use cases: monitoring of the environment and structure in smart buildings, and tracking of assets in the logistics environment.

A. Indoor Environmental Monitoring

In the contemporary office and home spaces, there is a need to closely monitor the temperature, humidity, and air quality as far as energy management and occupant comfort are concerned. We have implemented sensor nodes in a free office with a size of 200 m² and several Wi Fi access points of 2.4 GHz working at 20 dBm [11]. Dual band rectenna was able to capture power (received value of a few –8 to12 dBm) at distances of 3 to 6 meters to nearest router to support a 10 percent duty cycle; one 5 second loop time and LoRaWAN transmitting at 10 seconds of one 500 ms packet at 2 m of range without battery replacement during a four weeks trial. The removal of service interruptions and wiring complexity that was done by maintenance free operation proved that RF harvesting will support low rate environmental sensing reliably under a densely instrumented internal environment.

B. Structural Health Monitoring in Smart Buildings

The cases of sensor node deployment in steel or concrete structures are raising daunting issues when it comes to both power delivery as well as subsequent maintenance. To demonstrate the point, a six-tier parking garage composed of concrete that was retrofitted with 900 MHz femtocell nodes that ran at 23 dBm was used as a backdrop to the study. Instruments were attached on major supporting beams to capture both the vibration and strain. Despite the high dielectric losses of concrete, and possible metal reflections, the system was able to harvest a range of -15dBm to -10dBm of received power at a range of 2-5m of the femtocell antenna characteristics allowing strain-gauge read record in a duty cycle of 5 percent and transmission of encrypted status data. After two months of a field experiment, no battery replacement was needed in either of the nodes, which revealed a practical potential of long-term structural monitoring with the help of embedded, battery-less sensors.

C. Asset Tracking in Logistics

RFID or BLE tags on warehouses and distribution centers commonly use battery power, making the costs of battery refurbishment quite high. Our rectenna and PMU were installed with a low power Bluetooth tag attached to shipping crates within a 1,000 m² logistics hall served by 900 MHz RFID read tags and 2.4 GHz Wi Fi Aps [12]. The tags supported a steady 8 percent duty cycle two-location broadcasts-every-minute with no other power source at common distances of 2 to 8 m away and nearest to the most benign RF emitter. This deployment has removed the need to periodically replace the batteries of the tags, lowered maintenance burden by a significant factor of 90% and kept the accuracy of the locations updated much below 1 m, creating a commercial case platform for high scale asset tracking to happen in large scale logistics sectors.

As indicated in these case studies, RF energy harvesting will have the ability to support truly maintenance free sensor networks at numerous indoor, structural, and logistics applications. The use of RF infrastructure we already have allows our system to offer reliable duty cycles that are suitable to most of the IoT low data rate applications, leading to scalable sustainable deployments without battery replacement costs to maintain.

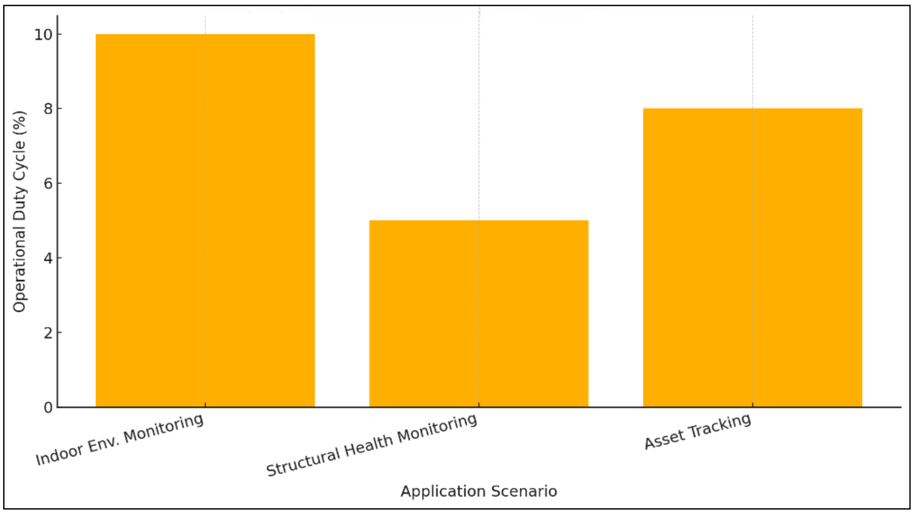

Fig 5: Duty cycle comparison across application scenarios.

Fig. 5 shows how the operational duty cycles are being attained in each scenario of our case studies, 10 percent in case of Indoor environmental monitoring, 5 percent in case of Structural health monitoring and 8 percent in case of asset tracking. This illustration points out ambient RF power density and environmental aspects have a direct effect on self-sustaining sensor node throughputs in various deployment environments.

Discussion

Experimental results explain the trade-offs in radio-frequency, or RF, energy harvesting trade-offs in self-sustainable sensing. Wider operating range may often demand higher transmit power or greater gain on the harvesting end, and both demand greater form factors, higher manufacturing cost, and more elaborate impedance-matching networks. The efficiency of the two band rectenna described here is over 50% between and -10 dBm to -5 dBm input power, but drops sharply below -15 dBm inputs, making duty cycle trivial above microrange (less than 8 m). They will hence need to balance the coverage area against node complexity, where such factors as antenna size and matching network component numbers as well as the power management unit (PMU) sophistication should be balanced against the size, cost, and power budget of the target application.

Combining several ambient sources in an environment may help overcome the dependence on one RF emitter, improve the reliability of the system as a whole. Hybrid harvesters with a combination of RF and solar cells (or vibration transducers) have observed fairly constant operation over varying environmental conditions. Multi source designs however need extra circuitry to detect available sources, route power and control storage, further adding more components and complexity to the control algorithm. When form factor and cost constraints are strict, e.g. implantable medical sensors or mass produced disposable tags, it can be better to optimise a single, high efficiency RF harvester than to incur the overheads of full multi-energy systems.

Resources such as space and power are scarce and become problematic at the network level because of the scale of deployment of battery-less sensors, as well as the subject of resource contention. Skew sensor sets face reciprocal shadowing of RF reception or co-channel interference on common bands, especially in industrial or townswomen inundated with Wi Fi, cellular, and Internet-of-Things wireless. Coordination of the duty cycles in scheduled network operation and optimized geographical positioning counter the local imperfection of power: so-called cold spots, but a complicated system design or flexible protocols capable of tracking time and location shifts in the ambient RF power is required. There are also firmware-based strategies that help reduce the number of devices draining the limited harvested energy at the same time which are randomized wake up schedules and cooperative data aggregation, these increase network throughput without relying on centralized control.

The actualization of the secure, sustainable battery-free sensor networks through RF energy harvesting is subject to constellation of regulatory and safety limitations. The power beacons controlling such systems should also adhere to the international exposure standards (ICNIRP) and accept standards-based compliance procedures, including FCC Part 15 in the United States and ETSI EN 300 328 in Europe, which limits both the maximum allowed effective radiated power and the non-international emission. Sensor nodes, in their turn, should be designed in such a way that they avoid unintentional radiation or production of mixing products which can interfere with licensed services. When such sectors are in an environment where they may be more vulnerable to electromagnetic effects due to their sensitivity-medical sectors, say, or aircraft-it becomes essential to subject the sector to close electromagnetic-compatibility studies to the effect that neither the harvesters nor adjacent RF sources are a threat to safety or valuable equipment. Therefore, the physical-layer trade-offs coupled with the issues of the system and network design complexity and regulatory issues require a unified, broadly integrated view of the in tense of a Microsoft. Through careful trade-off between design choices and physico-chemical specifics to a specific application and specifics of the RF environment, engineers will be able to realize the advantages of battery-less sensing and work around the difficulties that are bound to attend this new technological concept.

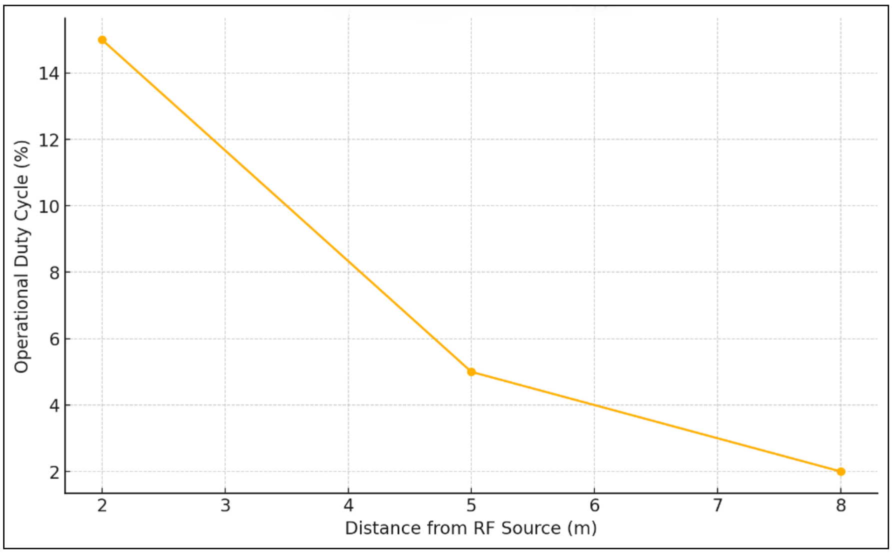

Fig 6: Duty cycle vs Distance

Figure 6 demonstrates the trade-off between duty cycle and the operational range of the RF energy harvesting nodes: with the maximum operational range of 2 m the node gives a duty cycle of 15%, at 5 and 8 m the duty cycle reduces to 5 and 2 percent respectively. The visualization further emphasizes the main design aspect covered in Section IX, i.e., the tradeoff between the range of coverage and sensing throughput, and as such, shows that the higher range is associated with reduced duty cycles of operation.

Future Work

As it is shown, the dual-band wireless energy-harvester, which is the subject of the present study, has sturdy performance when it comes to indoor and city IoT implementations, nonetheless, there are a number of approaches to be followed to enhance its usefulness and stability. A rectifier technology is one of the main directions of its improvement: inclusion of new types of low-threshold diodes, i.e. contacts with graphene enhancement or with tunnel structures, and circuit designs that allow compatibility with MOS or CMOS technologies can be expected to push RF- input conversion efficiencies higher than 60% at input levels below 10 dBm. At the same time, co-design of antennae and rectifiers on the same silicon substrate may produce compact, monolithic harvesters that normally fit low-profiled tags and wearable.

Changes towards the RF front end should not be overlooked as well. Optimised architectures, either using beam steering or electronically tunable matching networks, would allow flexibility of adjusting the harvesting performance in heterogeneous RF environments. Phased-array or metasurface arrangements could be used to make nodes effective receivers of those strongest emitters, extending operating range without necessarily needing larger physical antenna. Multi-source harvesting: Multi-source harvesting which combines RF energy, photovoltaic energy, thermoelectric energy and vibrational energy provides further resilience; managing both variance of more than one energy source, duty-cycle and differs over time, it can specify liftime.

On communication layer, ambient-power contention in dense sensor networks is essential by introducing energy-sensitive communication protocols and collaborative duty-cycle-schedule strategies on levels of systems and networks. Machine-learning methods may be used to predict availability of local RF power, and adjust sensor sampling rates or transmission schedules, maximising network lifetime and data freshness. Lastly, the long-term reliability, electromagnetic compatibility and user experience warrant big field trials in extensive environments including smart factories, precision agriculture installations and healthcare environments. Such studies will guide the transfer of RF energy harvesting technology prototype to commercial use across wide-spread applications.

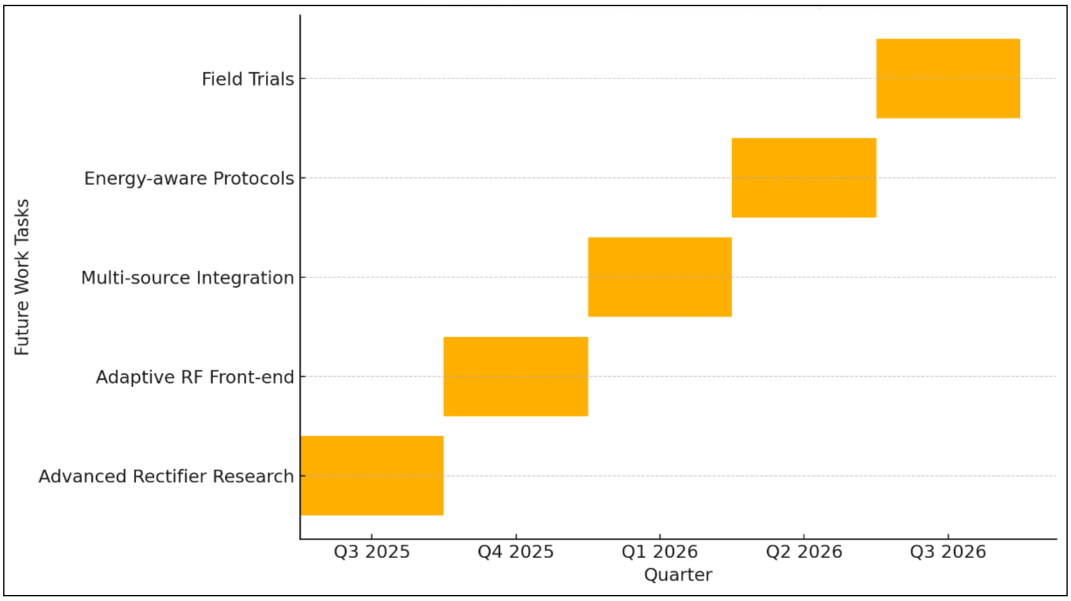

Fig 7: Future work Roadmap Across Quarters

As shown in Fig. 7, the future research roadmap that we can jointly pursue is clarified, which draws an overall roadmap spanning the timeline over the next two years, projecting each of the key tasks, where the proposed project offers, first, advanced research in the field of rectifiers, second, the development of adaptive RF front ends, third, integration of multiple sources, fourth, energy-conscious protocol design, and fifth, field trials into specific quarters starting at Q3 2025 and ending at Q3 2026. The schematic throws light on the linear nature of the research agenda and allows brief alignment of deliverables with project milestones that can be achieved.

Conclusion

This paper shows the design, together with the implementation and experimental testing of a dual-band RF energy harvesting system which is targeted at self-sustaining sensor nodes in the Internet-of-Things. A 900 MHz and 2.4 GHz miniaturized microstrip patch antenna are combined with very well optimized lumped element matching network so as to ensure broadband impedance matching in addition to providing low reflection loss. A voltage doubler power converter based on Schottky diodes was found to achieve exceeding 50% peak RF-to-DC
conversion efficiencies when the input power level was as

low as -10 dBm using a commercial circuit simulator that models the non-linearity of the Schottkey diodes used. Cold-start capability, adaptive maximum-power-point tracking and very low standby currents were achieved by the selection of the TI BQ25504 power management IC, so there was a seamless, maintenance free performance.

Wide laboratory measurements and practical case investigations confirm the capability of this stage regarding viability. They found that in controlled tests the rectenna maintained a 15% duty cycle at 2 m to a 0 dBm source, and efficiency plots were near those expected on a link budget. Indoor air quality nodes had continuous operation at 10% duty cycle within 3-6 m when placed near Wi Fi access points, and structural health nodes in concrete structure and asset-tracking tags in logistics buildings had very stable performance even without battery replacement during several weeks of testing. These findings affirm that the system has the ability of delivering periodic sensing and data transfer in various deployment settings.

There are a number of limitations which can be considered, however. Performance suffers quickly at low power, due to which it limits range and duty cycle in low-RF cases. The dual-band construction is efficient but comes with an extra burden of network tuning and PCB positioning. Physical-layer optimizations do not really solve network-level problems, e.g., RF contention and interference in dense deployments. Furthermore, radiated power transmitters dedicated and accepted in some environments may need to be limited by regulatory law and electromagnetic-compatibility concerns.

The future holds some hope with the development of resistance to these problems with the improvement of materials and circuit methodologies such as the improvement of graphene-based diodes, adaptive beam-steering antenna, and the integration of multi-source energy. Improving the energy consciousness of communication protocols and cooperative scheduling methods will further scale the networks and make it reliable. Lastly, widespread field experiments in industrial, agricultural, and healthcare settings will be essential in measuring long-term performance and in informing development of standards. This work thus provides a solid foundation in the almost ubiquitous use of battery-less, maintenance-free sensor networks as it combines theory and practice to facilitate a new age of pervasive IoT infrastructures.

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