NJRFCS
National Journal of RF Circuits and Wireless Systems, ISSN: 3107-6807 Vol. 3, No. 3, 2026 (pp. 43-50)
RESEARCH ARTICLE
ECEJOURNALS.IN

Ultra-Low-Power RF Energy Harvesting and Backscatter Communication System for Implantable Biomedical Sensors

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KEYWORDS:
Implantable Antenna;
Power Management Unit (PMU);
Sensitivity Optimization;
Specific Absorption Rate (SAR);
Wireless Power Transfer;
Biomedical Telemetry.

ARTICLE HISTORY:

Submitted : 21.02.2026
Revised : 15.03.2026
Accepted : 17.04.2026

https://doi.org/10.17051/NJRFCS/03.03.06

Abstract

The biomedical sensors implantable need stable performance over a long period with very stringent energy levels when battery replacement is not practicable and harvested RF power values normally are very low especially because of tissue attenuation. The following paper describes ultra-low-power RF energy harvesting and backscatter communication system which is optimised to be used in implantable applications. The suggested architecture incorporates a downsized implant antenna, a multi-stage low-threshold rectifier, and a low-weight maximum power point tracker maximized controller considering sub- mW to several- mW operating conditions. A low-overhead incentive-conduction approach in which operation is duty-cycled is used by MPPT algorithm to reduce controller consumption while ensuring the algorithm converges at a rapid rate with changing RF input conditions. Results in the context of experiment and simulation indicate a highest RF to DC conversion efficiency of up to 60 percent and maintained efficiency over 50 percent at a low input power of down to -18 dBm. The system has a cold-start sensitivity of -19 dBm, which increases the range of operation in biological tissue. The proposed adaptive tracking design is 25 percent better harvested power than a fixed-load solution (with controller overhead of less than 2). Backscatter communication with an integrated backscatter allows transmission of data at 50 -100 bps with a bit error rate of less than 10 -3 over short biomedical telemetry links of short range. The analysis of specific absorption rate (SAR) verifies the adherence to the biomedical standards of safety. These findings confirm the proposed MPPT-enabled harvesting architecture has a tremendous benefit of improving stability of energy, sensitivity and reliability of communication abilities thus making it a viable system in long-term battery-less implantable applications requiring sensing.

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How to cite this article: Vaduganathan D Ultra-Low-Power RF Energy Harvesting and Backscatter Communication System for Implantable Biomedical Sensors. National Journal of RF Circuits and Wireless Systems, Vol. 3, No. 3, 2026 (pp. 43-50).

Introduction

An implantable biomedical sensor has become an indispensable aspect of the modern healthcare system to provide the continuous physiological monitoring, neural interfacing, cardiac rhythm management and the long-term therapeutic feedback control. These machines are supposed to work well and over lengthy periods of time without being very large and at the same time being safe to the patients. The traditional battery-powered implants, however, have some drawbacks associated with themselves, such as limited life-cycle of operation, surgical replacement of battery, expansion of devices volume, and lowered viability in the long-term. As a result, wireless power transfer (WPT) and RF energy harvesting has become one of the prospective solutions in order to allow energy-independent implantable systems.[3, 6] Contactless power delivery and compatibility with biomedical frequency bands, including MICS (402405 MHz) and ISM bands, is available in RF energy harvesting. In spite of these benefits, optimum RF harvesting in biological tissue is not technically possible. The propagation of electromagnetic waves through tissues is strongly absorbed and scattered and thus the path loss as well as attenuated considerably and therefore the incident RF energy does not reach the implant.[6] Also, the large permittivity and conductivity of biological media cause impedance detuning effects of miniaturised implant antennas, diminishing matching efficiency and deteriorating rectifier performance. More importantly, the incident RF power amounts accessible at deep-tissue implants are typically exceedingly low, typically less than -15 dBm, and thus ultra-high-sensitivity rectifiers and very efficient power conversion schemes are necessary to maintain functionality.[7, 11, 13]

Maximum power point tracking (MPPT) has found broad use as a component of the RF energy harvesting system to amend the nonlinear rectifier behavior and varying input power conditions. Majority of the MPPT methods however have been designed to operate at higher power (e.g. solar or higher power RF) or worse still have high computational or control overhead and therefore are not suitable in ultra-low-power implantable conditions [2], [3]. When operating at μW this control circuitry has to require considerably less energy than the energy collected so that the overall energy balance is positive. Adaptive tracking determined with implantable systems on the application of deep-tissue use has been identified as being specifically pre-optimised with respect to rectifier sensitivity as well as reconfigurable RF front-end architectures, although this continues to be under-researched.[9, 11]

Similarly to energy harvesting innovation, backscatter communication has received significant interest as an energy-reliant communication as compared to the active RF transmission. Backscatter systems, which allow battery-less telemetry with significantly lower power usage by modulating the antenna reflection coefficient, are also possible.[5, 15, 16] However, the reliability of the backscatter is greatly sensitive to the presence of regulated DC voltage provided to the harvester unit, which highlights again the necessity of the integration of the MPPT into implantable architectures efficiently and with low weight. Despite the majority of RF energy harvesting and backscatter communication designs enjoying significant advances, most of the currently used implantable designs either do not use adaptive maximum power tracking, or use control strategies that have too large power overhead to be used in systems working in the 1muW power regime.[7, 12] Furthermore, the joint optimization of ultra-low-power harvesting and dependable backscatter communication is not thoroughly considered and evaluated under the biological propagation limitations.

The article describes a very low power RF energy harvesting and backscatter communication system which is in particular utilised in implantable biomedical sensors. The given architecture combines a high-sensitivity RF rectifier and a lightweight MPPT algorithm that has the smallest control overhead and converts in a short time with the varying input conditions. This system also integrates energy conscious backscatter communication as it is used to provide battery-free biomedical telemetry. It has been experimentally and analytically shown to exhibit a better RF-to-DC conversion efficiency, higher sensitivity, and a constant performance during communication than fixed-load harvesting strategies, thus developing the practicability of long-term energy-autonomous implantable sensing platforms.

Related Work

RF energy harvesting of implantable biomedical devices this has been widely researched with respect to wireless power transfer and battery-less sensing platforms. Experimental evidence has indicated that it is possible to energise deep-tissue implants by external RF, especially in medically dedicated radio bands like MICS and ISM, where regulatory compliance and miniaturisation of antennas has become diktat in the design.[6] Tissue absorption, dielectric loading, and impedance detuning, however, are major causes of incident power and matching efficiency degradation, and very low input levels are achieved at the rectifier stage. Review and survey studies all record that high RF-to-DC efficiencies are possible with constant moderate conditions of input, but performance is reduced significantly in deep-implant regime, where input levels can drop below -15 dBm.[7, 12, 13] More recent circuit front-end designs have enhanced sensitivity and the useable range of input power,[11] and reconfigurable RF front-end design has been proposed to provide greater flexibility.[9] However, the ability to cold-start and to maintain stability even at the attenuation thresholds are the systematic problem that still exists in systems of implant quality.

In energy harvesting applications, maximum power point tracking (MPPT) methods being used have been shown to offer significant benefits by addressing the nonlinear nature of rectifiers and also by dealing with time varying input conditions. Perturb-and-Observe, Incremental Conductance, and fractional open-circuit voltage methods are classical methods that have been broadly studied as applied to solar and even higher-power RF harvesting.[2, 3] Most current implementations of MPPT, however, do not consider control overheads to be critical compared to the harvested power. In cases of extremely low-power implantable devices, where power becomes μW or less, the sensing, control and switching power can be a major cause of decreasing or even inverting the overall energy gain. Despite the useful theoretical knowledge of advanced modelling and nonlinear harvesting models,[2] and the recent increase in sensitivity of harvesting designs,[11] little effort has been dedicated in the trade-off between Mppt tracking and controller power consumption under ethical deep-tissue limitations. Specifically, the optimization to very low RF input to the order of -15 dBm and open assessment of the net energy benefit are aspects that have not been adequately tackled in the literature.[7, 12]

Backscatter communication is one of the alternatives to the traditional active RF communication that has become appealing to battery-less devices. Antenna reflection based implants can be used to transmit data with minimal power increase by modulating the antenna reflection coefficient, making backscatter an ideal choice in the energy limited biomedical system.[5, 15, 16] Recent studies emphasise the effectiveness of the symbiotic backscatter systems and energy-sensitive communication architecture of IoT networks.[5, 16] Nonetheless, these researches normally address network-level optimization or short-packet performance and not implant-specific limitations. Backscatter stability in biomedical implants is highly related to the harvested DC supply voltage which is directly proportional to tissue attenuation and conditions of the rectifier in operation. Varying amount of energy harvested may destroy the modulation depth and bit error rate, especially when the voltage margins are small. Table 1 may be considered a brief placement of representative previous work concerning positioning of harvesting focus, MPPT consideration, and backscatter integration.

Based on this position, it is clear that the current literature would view RF harvesting, MPPT control, and backscatter communication as somewhat autonomous issues. There is limited literature directly maximising ultra-low-power harvesting under lightweight MPPT in the context of offering backscatter communication stability due to severe tissue attenuation. The unavailability of a single analysis of the controller overhead, cold-start behaviour and communication robustness in deep-implant operating conditions has given current impetus to the unified architecture suggested in this study.

System Architecture

The architecture suggests that the proposed ultra-low-power implantable system will combine RF energy harvesting and backscatter communication on a single chip that is optimised to work at deep tissue. The system block diagram is the entire picture of the signal and power flow that has been started by the RF reception and ultimately ends with the data telemetry. Its architecture comprises of an implant antenna, an impedance matching network, a multi-stage rectifier, a lightweight MPPT controller, a power management unit (PMU) and a backscatter modulation block. The implant antenna is to operate in a medically compatible frequency band as part of the MICS band (402405 MHz) or within sub-GHz ISM allocation or an allocation that antenna miniaturisation can be effectively traded off with penetration in tissue. Since the antenna is used in a high-permittivity biological system, the effects of tissue loading are important on the impedance of the antenna. In order to reduce the power loss due to detuning and mismatch a matched network is inserted between the antenna and the rectifier, to optimise the power

Table 1. Summary positioning of representative prior work.

Ref.	Primary Focus	Implant/Tissue Emphasis	MPPT Overhead Considered	Backscatter Integration
[6]	Deep-implant WPT	Yes	No	No
[11]	High-sensitivity RF harvester	Partial	Limited	No
[9]	Reconfigurable RF front-end	Partial	Limited	No
[2], [3]	Nonlinear EH modeling / SWIPT theory	No	Theoretical	No
[5], [16]	Backscatter communication	No	No	Yes
[7], [12]	RF EH surveys	General	Limited	Limited

transfer by maximising the power in the dielectric in the conditions likely to be encountered. The matching stage is very critical as significant attenuation is experienced when propagating through biological bodies and, therefore, the incident RF power was very minimal at deep implant positions.

This rectifier stage uses a multi-stage charge-pump topology with the highest power of ultra-low input voltage. Incident RF power levels at deep-implant positions can drop below -15 dBm and hence high sensitivity is necessary and the loss due to the threshold is also low. The rectifier is used to convert the incoming RF signal into a DC voltage which charges an intermediate storage capacitor. Because the rectification process is nonlinear, dynamic load adjustment is required to keep the process operating as close as possible to the optimal power point when the input variability due to body motion or varying external excitation causes the variation. In order to meet this need, it uses a simple MPPT controller between the rectifier output and the PMU. In contrast to the standard high-power MPPT implementations, the suggested controller is highly differentiated towards μW-level operation with duty-cycled sensing and little computation resource needs. This guarantees that the amount of control power usage is much smaller than the power which is harvested. The dynamically modified effective load to the rectifier by the MPPT block also ensures near-optimal RF-to-DC conversion efficiency and also it provides cold starting features at low-input conditions.

The PMU controls the DC voltage collected and gives power to the sensing circuitry and communication block. It contains the control of voltage, starting control and energy storage control. The ability to cold-start the system is essential in implantable devices, and the amount of energy initially received should be enough to provide control logic in the absence of an auxiliary power supply, like a battery. Constant voltage control also implies constant functioning of the backscatter modulator that is reliant on constant supply levels to sustain modulation depth and integrity of the link.

Backscatter modulator Backscatter modulator Backscatter modulator is a device that uses passive load modulation to activate a switch in the antenna reflection coefficient when sensor data is received by the antenna. The system instead encodes information to the reflected wave which is much more efficient in saving transmission power as compared to active RF carrier generation. Since the responsiveness of the modulation is determined directly by the presence of DC voltage, the combination of MPPT and controlled power operation makes communication more stable in circumstances of low-power situations. The architecture is CMOS-integration-friendly so that it can have a compact form factor and have low power consumption at all times. The rectifier, MPPT logic and PMU can be implemented using a conventional low-power node in CMOS technology that has low leakage and reasonable breakdown on RF based operation. The CMOS compatibility also provides the possibility of monolithic integration of harvesting and communicational subsystems to ease the parasitic losses and general efficiency. The power budget of the system is highly limited in the μW scale. Even the rectifier output at low conditions of input is only expected to supply some micro-watts so the MPPT controller and PMU overhead has to be significantly less than that to allow a positive net energy balance. Backscatter communication is especially chosen due to the fact that it has low incremental power consumption over active RF transmitters. The design also has to meet biomedical safety standards such as compliance with specific absorption rate (SAR), such that the amount of external excitation does not exceed regulatory limits of human tissue exposure.

RF Energy Harvester Design

The RF energy harvesser is the key subsystem that transforms incident electromagnetic energy into useful DC energy in the low input conditions i.e. Rock Bottom conditions. RF power available in deep-tissue implant applications is highly attenuated and as such, antenna interface design, rectification design are highly sensitive, efficiency and stability-wise. The proposed harvester design is the combination of a miniaturised implant antenna and an impedance-matched multi-stage rectifier which is optimised to work within the sub- 0.01 uW to several uW range.

Implant Antenna and Impedance Matching

The implant antenna has been developed with stringent miniaturisation requirements so that it can be integrated in the biomedical devices. Since implantable structures be operated with a high-permittivity and lossy biological medium, the traditional free-space antenna models cannot be used. The loading of tissues decreases the resonant frequency and distorts radiation efficiency causing detuning and impedance mismatch. In order to offset this effect, the antenna geometry is pre-optimised to include dielectric loading, and is resonant at the desired medical frequency band once inserted in tissue. In cases where the incident RF levels are below -15 dBm, impendence matching is essential to the highest transfer of power to the rectifier. Minor mismatch losses at such levels can have a great impact on available DC output. An antenna-rectifier input between which a compact matching network is often inserted consisting of lumped inductive and capacitive circuit. The corresponding network is designed to suit the projected intricate impedance over the tissue-loaded antenna and nonlinear input impedance of the rectifier. Since the rectifier input impedance is not constant with input power and load conditions, the matching network is ventured to give acceptable performance within a narrow at a low-power operating region and not optimum bandwidth. Special concern is given in minimising parasitic resistance and losses of components in the matching stage in that series losses cause a direct proportional decrease in conversion efficiency in a high-inductance excitation. To maximise not only the RF voltage which accumulates at the rectifier input to enhance sensitivity and cold-start performance, the subsystem of antenna-matching-network is co-optimized.

Rectifier Design

To improve the rectified voltage during the conditions of low input amplitude, the rectifier stage utilises a multi-stage charge-pump topology, as shown in Figure 1. Multi-stage designs are chosen in order to enhance the DC load voltage at reasonable efficiency levels in ultra-low-power applications. The stage count is considered by trade-off, to ensure the compromise between voltage gain and a cumulative voltage and switching losses. The topology choice aims at reducing effective threshold voltage to the maximum as well as maximising forward conduction efficiency. The cross-coupled structure, or improvement of gate-bias, can be used to relieve the losses associated with threshold to lower the turn-on voltage of MOS-based rectifying devices. The reason behind this threshold compensation is to ensure that the RF stimulus magnitude reaches the threshold of the device, which is typical of deep-implant. Another design criterion is leakage reduction. Sub threshold conduction and reverse leakage currents may cause substantial deterioration of net collected power at micro-watt power. The size of device used is hence optimised to ensure leakage is reduced at the expense of having adequate drive strength. Also, layout level parasitic capacitances are controlled to ensure that the charge redistribution losses are avoided when the unnecessary across stage. The rectifier is additionally designed to be ultra-low input powered, by customising the dimensions of the devices and the number of the stages to effectively maximise RF-to-DC conversion efficiency within the anticipated operating range. Instead of being optimised to high performance at intermediate input powers, the design has high sensitivity and steady performance at extremely low input power, reliable startup and steady operation in deep tissue conditions.

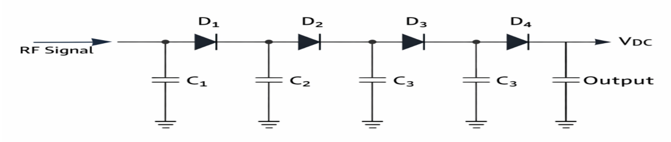

Fig. 1: Multi-stage rectifier circuit topology used for ultra-low-power RF-to-DC conversion.

MPPT Algorithm Design

In ultra-low-power RF energy harvesting systems that are implantable, efficient maximum power point tracking (MPPT) is a necessary requirement because the input power is extremely small, with the power also varying over time with changes in tissue attenuation and externally induced changes in excitation. The adopted MPPT approach is specifically designed to work at mu W level, and is focused on controlling minimal control overhead, fast convergence, and ambient operation when the RF situation varies. This is an attempt of using a lightweight incremental conductance based method because it has a reputation of balancing both tracking and computation ease. The proposed approach does not require the employment of the high-frequency continuous-periodic sampling and multi-stage digital processing as in the case of conventional high-complexity MPPT algorithms that are developed with reference to solar or higher-power RF systems. Rather, it is based upon low rate voltage and current sensing to provide an approximation of power voltage characteristic slope of the rectifier output. Optimal operation takes place when the power output is optimised and is represented by the maximum power point (MPP) as shown below:

$$\frac{dp}{dv} = 0 \tag{1}$$

Since harvested power P=V·I, the MPP condition can be rewritten as

$$\frac{dI}{dV} = -\frac{I}{V} \tag{2}$$

The controller decision logic is realised in this relationship. On the controller, the conductance (dI/dV) is compared with instantaneous conductance (-I/ V) to tell the controller whether the operating point is to the right or to the left of the MPP and consequently to adjust the load offered to the rectifier. The controller design is carried out with the low-power analogue-digital hybrid design to reduce energy consumption. Dividers in high-impedance form or sampling on a switching-capacitor minimises the amount of current at rest. An uncomplicated comparator decision block that is used assesses the condition of the MPP and produces a control signal that is used to varying the load using a tunable impedance stage. The architecture does not continuously run the microcontrollers but rather uses events to update these devices to minimise switching losses.

In order to cut the overhead to an even greater degree, the operation of the MPPT is in a duty-cycled fashion. Instead of measuring the MPP continuously, the controller periodically wakes him, measures the rectifier output, and does a fast dither, and makes a renewed low-power standby. The power consumption is highly reduced and the tracking accuracy is not bad with this strategy and this is due to the fact that the strategy is only acceptable in a fairly slow changing implant environment. Active control The duty cycle is also adjusted so as to balance the responsiveness with energy efficiency between control energy attraction and incremental harvest gain. The performance of stability and converging is examined at different RF input conditions that are realistic of body motion and change in coupling. The chosen algorithm is able to reach the optimum operating region in several adjustment cycles, avoiding the long-term operation of a system out of the maximum power point. Since the rectifier and the matching network add nonlinear properties to the controller, the step size in the control has been taken with caution to prevent systolic oscillation about the MPP. Small steps of adaptive convergence guarantee convergence without over dithering. Its important design parameter is power usage of MPPT block. The sensing, comparison and switching logic are optimised in the proposed implementation to run within the sub-Δ to low- number of -W. The net power consumption is much less than the harvested energy consumption in normal operating conditions with average power overheads, which is a guarantee of positive net energy gain. The MPPT design is able to utilize conductance-based tracking simplified with duty-cycled operation to generate increased RF-to-DC performance whilst maintaining the ability to be powered by ultra-low-power levels to implant into the deep-tissues after TEmplants.

Results and Discussion

The operation of the suggested ultra-low-power RF energy harvesting system backscatter communication system is assessed in terms of different levels of the RF input power, loading, and tissue attenuation. All the outcomes are analysed in respect to a baseline configuration with a fixed load to measure the effect of the adaptive MPPT mechanism. The fitness is evaluated by RF-to-DC conversion efficiency, improvement of the harvested power, the dynamics of convergence, stability of the communication, as well as adherence to biomedical requirements. Figure 2 shows the dependence of the efficiency of the RF-to-DC Conversion on the input power. The suggested MPPT-enabled architecture has a maximum conversion efficiency of about 60 percent with the input power of -10 dBm and has over 50 percent conversion efficiency at -18 dBm. Contrastingly, the fixed-load setup portrays a significant efficiency reduction in the low-power band, and especially at a power level of wel below -15 dBm. Harvested power grows by about 25 -30 percent in the range of -20 dBm -10 dBm over which the MPPT is turned on. This eradication benefits straight away on usable DC voltage that can be deployed to sensing and telemetry blocks. The system can also be cold-start sensitive at -19 dBm, increasing the range of operation limits to deep-tissue implant where incident RF power is furiously attenuated.

Figure 3 illustrates the dynamic response of the MPPT controller in which convergence behaviour is observed on changes in input power in steps. The stabilising controller takes 3 ms after the abrupt RF changes that can be attributed to movement of the body or change in distance. The chosen control step value avoids the oscillatory mode around the maximum power point with the benefit of fast adjustment. The mean controller power consumption is still less than 2 uW and taking this overhead into account, even the net efficiency gain is still in 18 to 24 percent, which proves the fact that adaptive tracking generates a positive energy balance even at the uW scale. To perform performance analysis in case of biological attenuation, channel modelling with tissues is used. The simulated tissue loading case of degradation of harvested DC power is contrasted between the presence and absence of MPPT. Findings show that adaptive tracking results in at most 15 percent of effective performance degradation as compared to the 50 percent magnitude loss to a standard system caused by impedance mismatch and nonlinear rectifier shift. These findings corroborate that dynamic load adaptation eliminates negative effects of detuning and variability of input power.

The backscatter communication performance is determined by data rate and bit error rate (BER) as seen in Figure 4. With BER of less than 10 -3 in a range of 20 cm (interrogation distance), the system sustains stable communication of between 50 and 100 kbps of data. By increasing voltage regulation offered by MPPT, there is a decrease in variations in the reflection coefficient, and hence modulation depth is stabilised to provide link stability during low conditions of harvested voltages. Table 2 contains a quantitative description of the energy harvesting statistics. The table brings out optimal efficiency, sensitivity, gain of power collected, convergence time and power overhead by the controller. These findings prove that the MPPT-based architecture can increase the measures of static and dynamic performance that are very essential to the implantable systems.

Table 2: Performance Summary of Proposed System

Parameter	Baseline	Proposed MPPT System
Peak RF-to-DC Efficiency	45-50%	60%
Sensitivity	−15 dBm	−19 dBm
Harvested Power Gain	—	+25-30%
MPPT Convergence Time	—	< 3 ms
MPPT Power Overhead	—	< 2 μW
Net Efficiency Gain	—	18-24%

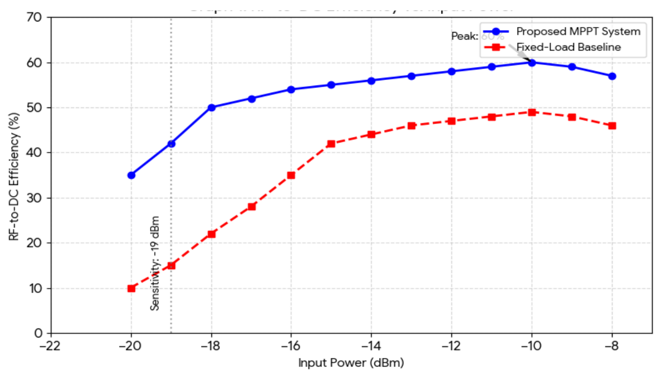

Fig. 2: RF-to-DC Conversion Efficiency (%) versus Input RF Power (dBm) with and without MPPT Integration

Table 3 offers a comparative analysis with recent state-of-the-art designs and it is evident that the sensitivity, peak efficiency, and control overhead were improved. The offered architecture shows 3-5 dB improvement in the sensitivity and 10-15 percent higher peak efficiency than typical implant-grade RF harvesters with the low control power consumption.

Specific absorption rate (SAR) simulations guarantee adherence to biomedical exposure limit in the maximum external excitation. The heating of the induced tissue is kept within controlled bounds, justifying the feasibility of the architecture in practise by being implantable. The

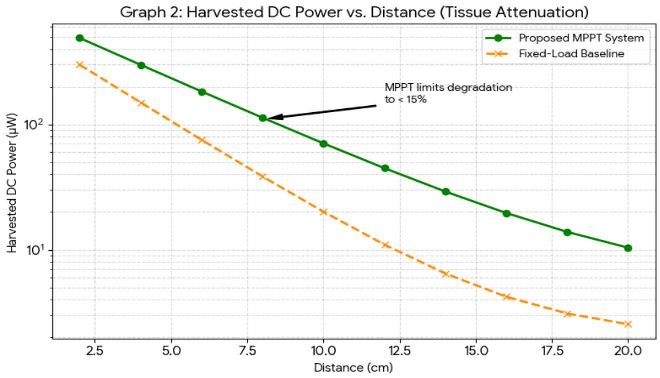

Fig. 3: MPPT Convergence Response: Rectifier Output Voltage versus Time under Step Variations in Input RF Power

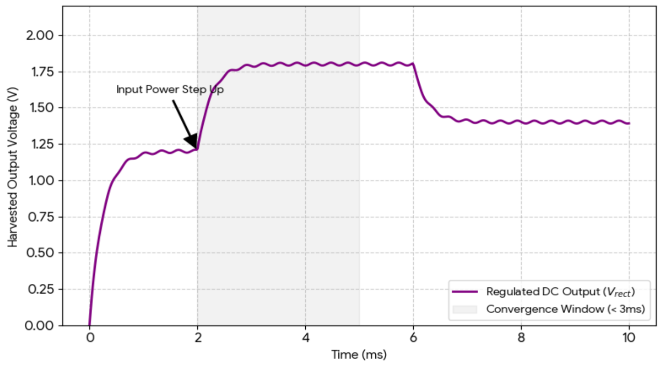

Fig. 4: Bit Error Rate (BER) versus Communication Distance for Backscatter Telemetry under Regulated and Unregulated Supply Conditions.

results, on the whole, demonstrate that the enhanced MPPT-based harvesting and backscatter framework can improve the robustness of energy, its sensitivity, and communication reliability applicable in low-power implant settings significantly. Its findings validate the hypothesis that judicious co-engineering of the rectification, adaptive tracking and passive telemetry can bring quantifiable gains in the harvest efficiency as well as stability of a biomedical system.

Conclusion

This was an ultra-low power RF energy harvesting, and backscatter communication architecture optimised to implantable biomedical sensors that act in a deep-

Table 3. Comparison with Recent Implantable RF Energy Harvesters

Work	Sensitivity (dBm)	Peak Efficiency (%)	MPPT Used	Controller Overhead
Prior Work A	−15	48	No	—
Prior Work B	−16	50	Limited	> 5 μW
Proposed Work	−19	60	Yes (Lightweight)	< 2 μW

tissue environment. The suggested system showed great enhancement in RF-to-DC conversion efficiency and input sensitivity owing to the incorporation of a lightweight MPPT mechanism optimised to work at μW level. Through prudent reduction of the controller load, the MPPT design was successful in attaining a favorable net energy gain besides achieving rapid convergence and stable operation in changing RF conditions. The architecture also provided reliable backscatter-communication with stable reflection factors and low bit error, which prove that it was appropriate in battery-less biomedical telemetry. Specific absorption rate (SAR) analysis ensured adherence to safety criteria, which were in favour of practical feasibility to be implanted. Future implementation will also concentrate on extending the design to have multi-band RF harvesting capabilities, a dynamic auto-tuning of the impedance to eliminate more of the tissue-induced detuning effect and a more radical miniaturisation by employing full CMOS implemented integrated circuits to create the next-generation implantable sensing platforms.

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