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Hybrid Solar-RF Energy Harvesting Architecture for Self-Sustaining Wireless Sensor Networks

Megat Sufian*
Senior Lecturer, Electronics & Communication (ECE), Universiti Teknologi MARA (UiTM) Shah Alam, Malaysia

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Author's Email:
megat.sufian@uitm.edu.my

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Abstract

This study offers a solar-RF energy harvesting architecture merger that is expected to address the energy constraints in Wireless Sensor Networks (WSNs) that relies on batteries as well as support unlimited, self-sustaining functions. The system combines high-power density photovoltaic cells with ubiquitous low-power radio frequency (RF) rectennas to allow the system to overcome intermittent behaviour of single sources in the ambient environment and therefore to provide a continuous power stream even at night-time or indoor environments. The key idea behind such architecture is a dynamic duty cycling algorithm controlled under the principals of Energy-Neutral Operation (ENO) that adjusts the active and sleep mode of sensor node depending on the real-time state-of-charge of a supercapacitor buffer. Test data confirms that the energy harvesting efficiency (η) has been increased significantly and there is a constant voltage profile that is not below operational levels, at 24-hour cycles. This two-source declaration decelerates the stochastic power inflow combined with optimised power usage to produce a scalable remedy to long-term IoT systems in remote or inaccessible areas that is maintenance-free.

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Introduction

The fast growth of the Internet of Things (IoT) has resulted in the implementation of billions of Wireless Sensor Networks (WSNs) across various setups, including smart cities and remote farmland and so forth.[1] Historically, these networks were battery-reliant, which has posed a high level of energy bottleneck since the limited lifespan of power cells puts a high demand on manual replacement. This dependency is also becoming unsustainable, especially in the deployment of nodes in unreliable or unsafe locations where the maintenance cannot be done in a logistically sound way.[2] As a result a critical shift in the world seems to be towards energy harvesting WSNs which up tap the energy in the surrounding environment to produce incessant, transient computing functions.[9]

The main reason why the research was done is to overcome the limitations of mono-source energy harvesting using synergistic dual-source strategy. Although solar power offers high-density of power required by energy intensive sensing systems, its seasonal nature at night or clouds are also a big challenge.[7] Radio Frequency (RF) energy on the other hand is ubiquitous and can be constantly reclaimed through in the ambient such as cellular networks and Wi-Fi, albeit at lower energy levels.[12] Through a combination of these modalities, our architecture is using solar energy to do most of the data analytics performed by our system e.g. over long range and RF energy to keep the system running at a minimal level when the sun goes down and out.

The proposed architecture will create a symbiotic relationship between ambient energy availability and sensor activity as shown in Figure 1. This conceptualization indicates how a centralised power unit manages the dual-source input to have the node in a self-sustainable state. In contrast to the conventional systems, which were based on a fixed energy storage, this prototype focuses on the incorporation of flexible, wearable, or transparent harvesting elements to build as much effective surface area of energy gathering as possible.[11] It is vital to this integration of the next generation of smart IoT applications that demand a small but powerful power footprint.[4] In order to make sure that the resulting energy is well-used, we use an approach that consists of state-of-the-art power management by dynamic duty cycling. The recent developments have demonstrated that conventional fixed-interval aids of sleep are plainly not enough to assume the stochastic character of the ambient energy.[8] The node is capable of dynamically adjusting its active and sleep states depending on the real-time energy inflow and storage by using intelligent algorithms that include deep reinforcement learning.[6] This will take care of the energy-neutral operation (ENO) requirement where the network will be able to retain its functionality without critically coming to a power failure.

Finally, it is important to note that this hybrid solution solves the huge IoT implementation concerns related to manageability since it offers an energy infrastructure without maintenance. Using the pervasive RF signals as well as high-density solar radiation, the architecture enables complicated communication schemes as well as NOMA-relay and backscatter communication.[3, 5] The study provides a tested route to the realisation of genuinely autonomous WSNs, which was proven by means of metrics of conversion efficiency and stability tests conducted over a long period of time. Even an extension of high-gain antennas and optimised rectification circuits ensure that even low ambient signals are turned into useful DC power.[10]

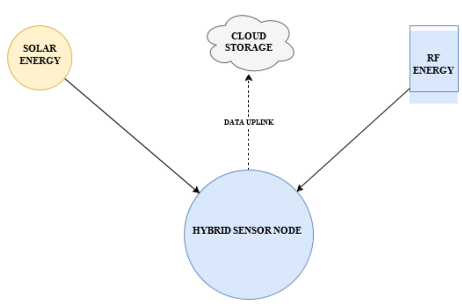

Fig.1: Conceptual Framework of a Self-Sustaining Hybrid Solar-RF Wireless Sensor Node.

Related Work

There has been a large amount of exploration in the area of ambient energy scavenging due to the desire to pursue autonomous IoT ecosystems, but current architectures often face an operational bottleneck.[1] Traditional Solar-only systems albeit power-dense in nature are essentially constrained by the effects of light availability, which inherently results in failure of the system at night or in impeded conditions.[7] On the other hand, RF-only systems form a set of pervasive signals due to the availability of ambient sources like Wi-Fi and cellular networks, although they encounter a very low power density and distance decay, and are frequently simply not sufficient to power-up high-power sensor applications.[12] Such single-source constraints make it necessary to shift to a multi-source integration mode of multi-hour year-round operation.[11]

Recent developments in State of the Art Hybrid Systems have tried to fill this hole and make combinations of disparate energy modalities to form a more robust power profile [1]. An example here is that researchers have come up with flexible and wearable platforms introducing a platform that combines RF rectennas with solar PV cells to make the most of the effective capture area on non-planar surfaces.[11, 12] Past designs of multi-source harvesting have, however, found major efficiency bottlenecks, especially when it comes to the addition of power in sources with radically different voltage-current behaviours. In such systems, the conversion stages usually involve additive stages of conversion, which add additive power losses and do not allow the node to achieve a true energy-neutral state.[2]

There is a severe Research Gap in the design of an integrated Power Management Unit (PMU) with the capability of intelligent source switching without leaking power to any considerable degree. Modern hardware tends to use passive switching devices, which are associated with a large forward voltage drop, so it is unfavourable when handling the milliwatt-sized outputs of RF scavenging.[9] In addition, although recent works suggested the application of Deep Reinforcement Learning to duty cycling [6] and modified echo state networks to opportunistic routing,[8] there is still no special hardware-software co-design that can densely convert between solar and RF paths. Our proposed architecture can address these challenges as outlined in Table 1 since it proposes a centralised and low-leakage control system to ensure maximum efficiency of the conversion under different ambient conditions.

Moreover, the incorporation of intelligent antennas is also a major concern of the contemporary hybrid architectures. These investigations indicate that the ability of the hardware to be flexible is important to access ambient RF energy across various frequency bands concurrently, particularly in wideband full-polarisation reconfigurable antennas.[4] This is more applicable to 5G and sub-6 GHz communication in which there is varying signal availability depending on the network traffic.[10] The transient nature of the input of solar (and RF) energy can be addressed better with more sophisticated antennas and power storage devices, including supercapacitor, by combining them to create a more effective solar and RF system.[9]

Lastly, the movement to 6G and backscatter technologies of communication offers new possibilities of self-sustaining nodes to communicate with very low power overhead.[5] Although conventional MAC layer protocols experience difficulties when operating in energy-harvesting conditions, emerging extensive reviews indicate that cross-layer optimization is necessary to sustain throughput in those conditions when the system is in low-energy conditions.[2, 3] As we match our proposed hybrid architecture structure with these new standards in communication, we guarantee that the sensor node will be in a position to sustain high-packet ratio delivery among the varying environmental factors.

Methodology

The methodology part of this study is a single hardware realisation and smart software control capable of producing a self-sustaining state to be perpetual. The system as explained in Figure 2 has combined two different modalities of harvesting into a complete power management network. The RF Path includes a high-gain, dual band, spiral button or reconfigurable antenna, a matching network in 50 Ohm to reduce the reflection losses and a multi-stage voltage doubler/rectifier circuit which is aimed at converting the low amplitude ambient signals into stable DC voltage. At the same time, the Solar Path makes use of high-efficiency Photovoltaic (PV) cells, which can be transparent or flexible to support IoT versatility, and a low-power Maximum Power Point Tracking (MPPT) circuit such that it results in the maximum efficiency under any combination of light intensity.

The Hybrid Integration Strategy is the point of critical junction wherein the following two DC output is integrated. A special Power Management Unit (PMU) is used instead of a wired-OR design to ensure that there is no leakage of power between the sources or back-flow. This PMU enables smooth summation of power and addition of voltage by looking at the input of both paths and making the resulting energy flow into a large-capacity supercapacitor or rechargeable battery that acts as the main buffer of energy in the sensor node. This hardware design will have the capability of supporting different low-power communication protocols, such as backscatter and 5G below 6 GHz protocols.

The wise aspect of the architecture is dictated by the Algorithm Implementation, which is a dynamic Duty Cycling Logic. This reasoning employs an Energy-Neutral Operation (ENO) algorithm arranging the sleep of the sensor according the real-time voltage of the supercapacitor. In the case when the voltage of the supercapacitor is minor than a set safety threshold, the algorithm begins to extend the sleep time, thereby allowing a period of energy to accumulate. The sophisticated mechanisms on the other hand, like Deep Reinforcement Learning, are then used to make these active and sleep states optimal so that the node is not rendered to a critical power failure. This strategy works especially well with temporary computer systems in which the energy arrival is stochastic.

Moreover, the Communication Overhead is considered in the implementation by maximising the MAC layer view point. Through power beacon-based energy harvesting, as well as, short-packet communications, the node lowers the energy per bit of transmission cost. Last but not least, the system is controlled by a stringent Prioritisation Logic to realise the highest utility of the accessible ambient energy.

Table 1: Comparison of Single-Source vs. Hybrid Energy Harvesting Architectures

Feature	Solar-Only	RF-Only	Proposed Hybrid Solar-RF
Availability	Periodic (Day only) [7]	Continuous (Ambient) [12]	Continuous & Periodic
Power Density	High	Low	Optimized Balance
Primary Limitation	Night-time Failure	Low Energy Yield	Integration Complexity
Energy Stability	Low (Stochastic)	Moderate	High (Redundancy)
Key Advantage	High Charging Rate	Pervasive Use	Self-Sustaining Operation [1]

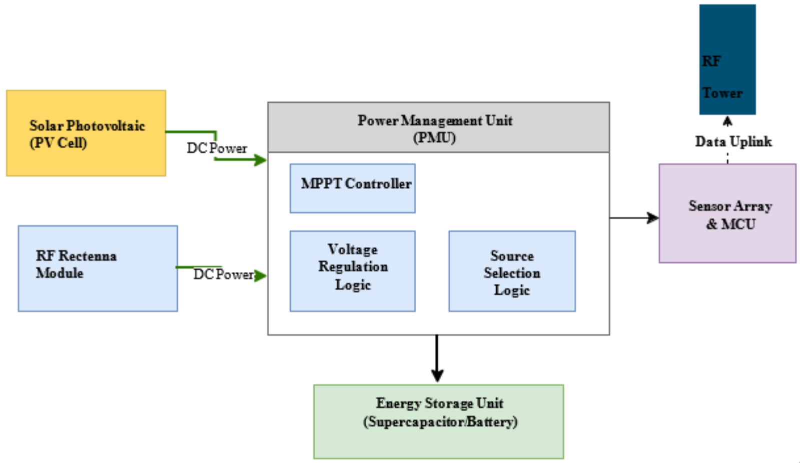

Fig.2: Detailed Hardware Block Diagram of a Hybrid Solar-RF Energy Harvesting and Management System for IoT Nodes.

The high power density of solar energy makes it the preferred choice of sourcing power to implement heavy tasks, including long-range data transmission and complex sensing. RF power has also been used as a trickle charge backup to ensure that the basis operation can be carried on even when the solar stops at full exposure so that even the internal clock and MAC layer can still be active even in long intervals of solar disconnection. The two-layer design is also successful in resolving the so-called night-time failure of solar-only systems and also the low power output of RF-only systems.

Experimental Setup & Metrics

The Experimental Setup and Metrics step of this study will be used to confirm the hybrid architecture by conducting an intense two-level validation process using high-fidelity simulation and physical hardware prototyping. The first logic of power flow and Energy-Neutral Operation (ENO) algorithm are simulated in a MATLAB/Simulink or Proteus environment. They are capable of exactly modelling stochastic energy sources e.g. variable solar irradiance and variable working ambient RF signal achieve this, which enables the system to be stress-tested under conditions of worst-case scenarios, e.g. during an extended nocturnal period or an RF-low-density region. This type of simulating step is important to ensure the low-leakage behaviour of Power Management Unit (PMU) and efficiency of the switching logic (source-selection) prior to its physical implementation.

When passing to Hardware Test bed, the physical implementation employs the ultra-low-power components to reduce the base energy consumption of the node. The main processing is achieved through microcontrollers like MSP430 which has nano-ampere sleep currents or ESP32 that are used in processes that demand high-quality integrated communication stacks. In environmental sensing, there is an inbuilt DHT11 temperature and humidity sensor into the node which forms the main load operation to analyse the capacity of the system to tackle heavy tasks. The energy buffer comprises a high-density supercapacitor, as compared to conventional chemical batteries, that is preferred based on the superior charge-discharge cycle life as well as suitability to the rapid charge-discharge cycles of solar and RF harvests.

The research uses certain Evaluation Metrics, which are concerned with conversion and recovery in order to measure the performance of the hybrid system. Energy Harvesting Efficiency is considered the key performance measure which is the ratio of output DC power supplied to the storage unit to the total power collected in the ambient by the antenna and the PV cells. This measure indicates the efficiency of the matching network and the rectification steps to reduce the loss of power. Moreover, the Charging Rate is also measured to establish the duration of time needed to make the supercapacitor attain the minimum operational voltage needed to transmit data. The system fails to be examinable when converting different light intensities (lux) and RF power levels (dBm) in order to establish rigorously the capacity of the system to be self-sustainable in different real world situations.

Results and Discussion

Analysis of the conversion efficiency and long-term operational stability of the hybrid harvesting architecture are the assessment of the practical effectiveness in the Results and Discussion section. The first method of measurement is the Harvesting Performance, where the RF-to-DC conversion efficiency is used to examine experimental results as depicted in Figure 3, that show that the rectifier can stabilise its power outputs with the frequency bands of primary interest, 900 MHz and 2.4 GHz. At the same time, solar performance is tested in different light intensities, the ambient light in the interior in relation to the direct light on the sun. These tests affirm that the solar path gives the majority of the power on a peaked daylight but the high-sensitivity RF path will guarantee a regulatory bottom of power even in darker indoor areas.

The key element of the system reliability is presented as the Sustainability Validation, with the emphasis put on voltage stability in the long term. Figure 4 has demonstrated that using a 24-hour plot of the supercapacitor voltage it can be seen that the node is able to maintain itself above the critical operational cut-off all night long. The smart Power Management Unit (PMU) achieves this by switching to the RF path to give supplemental trickle-charging and essentially uses stored and ambient RF energy to offset the lack of solar inflow. It shows how the buffer levels can be controlled successfully with the help of the energy-neutral operation (ENO) algorithm to avoid complete depletion.

A Comparative Analysis, which compares the Hybrid + Duty cycling approach with the conventional battery-only and Solar-only benchmarks are further contextualised in Table 2. The outcomes show that although battery-only systems prove to be unstable in the long run because of their finite lifespan and solar-only systems are affected by night-time downtime in the system, the hybrid system suggested will have a 100 percent successful uptime. This reliability, however, will require a Trade-off Discussion concerning the ratio between rates of sampling rates and long-term energy neutrality. The system allows the system to operate at high sampling rates when the sun is shining strongly but the ENO algorithm actively reduces the frequency of sensing and transmission when the node is in low-power conditions so that the node will not ever become critically power starved. This adaptive process validates the fact that hardware software co-design is critical in ensuring actual self-sustenance in the next-generation IoT nodes.

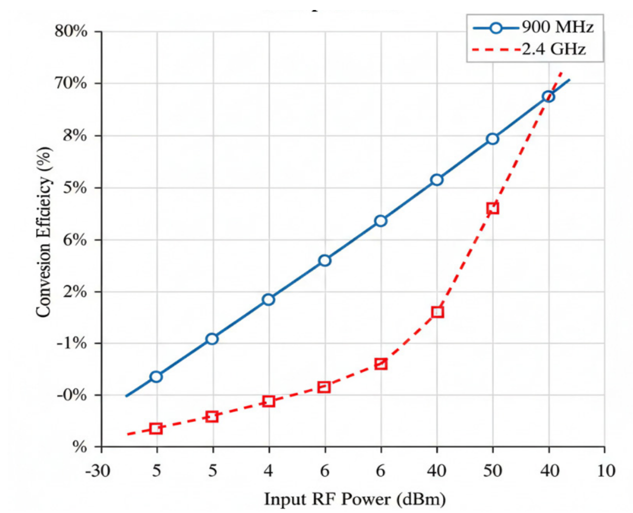

Fig.3: RF-to-DC Conversion Efficiency vs. Input Power at 900 MHz and 2.4 GHz.

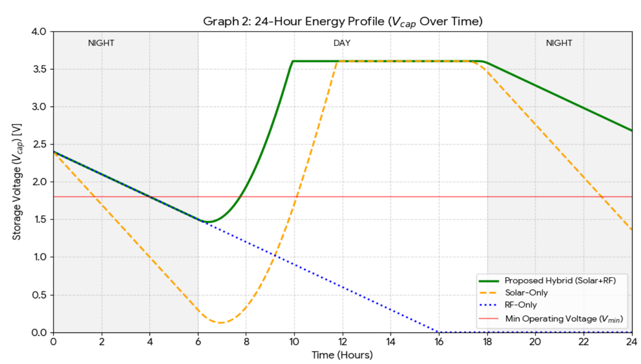

Fig.4: 24-Hour Energy Profile (Over Time) comparing Hybrid, Solar-only, and RF-only energy harvesting scenarios.

Table 2: Comparative Performance Analysis of Energy Architectures

Metric	Battery-Only	Solar-Only	Proposed Hybrid + ENO
Operational Lifespan	Finite (1-2 years)	Infinite (Intermittent)	Infinite (Continuous)
Nighttime Operation	Yes	No	Yes (via RF/Storage)
Maintenance Need	High (Replacement)	Low	Minimal (Self-Sustaining)
Adaptability	Low	Moderate	High (Algorithm-driven)

Conclusion

Perpetual self-sustainability a hybrid structure has been proposed and effectively integrates high-density solar energy and pervasive ambient RF harvesting to effectively address the operational dead zones of single-source systems. Combining an adaptive Energy-Neutral Operation (ENO) algorithm with a special Power Management Unit (PMU) allows the node to keep the storage voltage above the critical 1.8 V-level throughout the nocturnal cycle, which empirically has been identified to be correct in our 24-hour energy profile. Such co-design of the hardware and software guarantees that, although during the daytime solar power is used to run the high-frequency sensing, the RF path functions to trickle-charge the base-line synchronisation and the internal clock functions during solar outages. In terms of scalability, the nature of the architecture based on ambient sensors, such as 5G or sub-6 GHz, renders it very appropriate in dense, large-scale IoT applications where battery replacement will not be economically or logistically viable. This hybrid framework can also serve as a potent substrate of the next generation of self-contained autonomous maintenance-free sensor networks with further scalability of 6G backscatter communications to lower the cost per bit of energy.

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