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RF-Based Energy Transfer Through Packets: Still a Dream? or a Dream Come True?

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ABSTRACT Limitations in battery capacity has held back the active development of novel applications for the Internet of Things (IoT) or have caused embedded systems researchers to design a number of ‘‘go-around’’ schemes, which sacrifice various system performance metrics for energy efficiency. However, with the concept of simultaneous wireless information and power transfer (SWIPT), many researchers accept it as a potential technology that can be the basis of designing various next-generation low-power embedded computing systems. This work presents an experimental validation on RF-based SWIPT techniques. Specifically, using the Powercast P2110 Powerharvester Receiver, we evaluate its potential of being applied to various low-power embedded applications. We analyze the performance of these commercially available energy harvesting RF receivers in packet-based networks to show that energy harvesting in such cases are only possible with packets of long lengths in practical environments. Furthermore, we experimentally show that despite carrying energy, external noise factors on the wireless channel can deteriorate the RF-based energy harvesting performance due to high voltage amplitude fluctuations. Based on such observations, we present a set of system-level suggestions for future SWIPT-based system development.

INDEX TERMS Wireless power transfer, SWIFT, packet-based wireless networks.

I. INTRODUCTION

In designing low-power embedded systems for various applications in different environments, minimizing the energy usage on the resource-limited computing platforms has been a long-time challenge for system designers. As a result, the low-power embedded systems research community has introduced a number of schemes for conserving the energy on resource-limited wireless platforms [1], [2]. Given that the radio module is the dominant power consumer in most low-power platforms [3], minimizing the radio's idle listening durations has been a major research issue to resolve [2]. In addition to these ‘‘energy-saving’’ approaches, another direction of research was in designing systems that ‘‘harvest’’ energy from external sources (e.g., sunlight, wind, etc.). For outdoor deployments, utilizing the available external energy sources is considered to be a typical system design approach.

In addition to natural resource-based energy harvesting, researchers in the wireless communications community have introduced an interesting topic of transferring power resources ‘‘over-the-air’’ using the radio frequency (RF) signals that are used to transmit data packets. The concept of Simultaneous Wireless Information and Power Transfer (SWIPT) and RF-based energy harvesting utilizes the fact that RF signals themselves are a form of energy in the air. Compared to harvesting energy from other external sources, such as solar, thermal or wind, RF is more ubiquitously accessible in a wireless network environment and is less impacted by uncontrollable environmental factors such as weather and geographical conditions; thus, can provide the system with a more consistent form of energy source.

In SWIPT-based networks, a subset of nodes exchange data using the RF signals, while other nodes, which overhear these signals, collect RF signal-based energy using a capacitor and a charging circuit. Of course, ideally with resource division mechanisms, such as a power splitter [4] or a time switch [5], a single node can use a subset of the input signal for energy harvesting and the rest for information decoding. With an acceptable level of energy transfer efficiency, low-power wireless embedded systems can utilize this additional power-resource to worry less about their limited power budgets. A majority of previous research in the SWIPT domain

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present theoretical foundations on how SWIPT can benefit wireless systems and how resource division should occur for achieving efficient network performance. Systems designed based on SWIPT can be highly suitable for enabling the Industry 4.0 concept [6], by attaching multiple sensors for monitoring the status of various manufacturing equipment attached wirelessly to a data collection gateway [7]. In such deployments, SWIPT can allow the sensors to be (potentially) batteryless by gathering energy collected from the RF signals from the gateway.

With increasing interest in SWIPT and its attractiveness, commercial chip vendors, such as Powercast, released a number of hardware module implementations for experimentally validating SWIPT technologies [8]. In this work, we take an experimental approach in validating the effectiveness of SWIPT-based system designs using such Commercial-Off-The-Shelf (COTS) devices. Specifically, this work targets to validate one of the major assumptions that many theoretical SWIPT-related work take as granted: the assumption of continuous transmissions on the wireless medium. Most theoretical work and practical implementations in SWIPT research until now make the assumption that the transmitter node, which transmits the RF-based energy, continuously transmits signals for the receiver to capture energy from.

However, most current day wireless systems operate based on packet-based data transmissions rather than continuous signal-encoded data transmissions. Performing packet-based transmissions indicate that there are *idle times* in between multiple packet transmissions. On an energy harvesting perspective, these idle durations force the energy harvesting module's capacitor to deplete its stored energy. In a typical packet-based wireless network, system-level factors such as the packet transmission duration and the inter-packet interval can impact the RF-based energy transfer performance. Furthermore, the strength of the incoming packet signals can also be a critical factor that determines the energy harvesting efficiency of the system. Nevertheless, still, the question of how much these varying factors can potentially impact the energy harvesting performance, still remains open.

Using a COTS RF energy harvesting module (e.g., Powercast P2110 Powerharvester Receiver [8]), we empirically measure the impact of packet-based networks on its SWIPT and RF energy harvesting performance. Given that the Powercast P2110 module collects energy for sub-GHz RF signals, we use the Texas Instruments CC1200 sub-GHz transceiver as the packet transmission device (c.f., Fig. 1). Using such an experiment configuration, we confirm the effectiveness of RF-based energy transfer under various networking configurations as a way to provide guidelines for future system development and also to validate the practical feasibility of applying SWIPT technology in wireless systems. Our results quantify the impact of the data rate, packet size, packet transmission interval, and received signal strength on the RF energy harvesting efficiency. Especially, we show that the packet transmission interval, when dense enough, achieves a super-linear energy harvesting efficiency improvement performance. Furthermore, we also show that external interference or noise factors, although being a form of RF energy itself, affect the energy harvesting performance negatively due to the disrupted signal inputs to the RF-to-DC harvesting module. Based on these results, we organize a set of suggestions for future deployments that target to exploit RF-based energy harvesting for low-power embedded network system design.

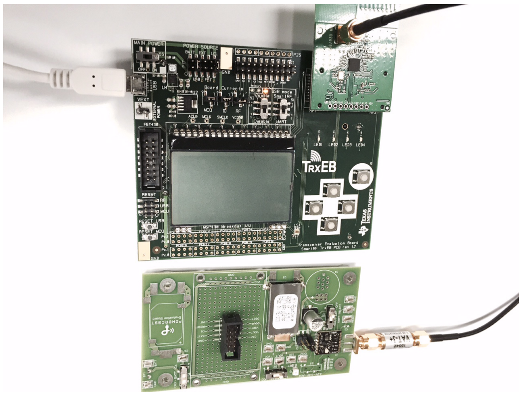


FIGURE 1. Our experimental setting with a Powercast P2110 Powerharvester Receiver for RF-based energy gathering and a Texas Instruments CC1200 Sub-GHz Transceiver as the packet transmission node. We vary the packet transmission and link characteristics to examine the efficiency of RF-based energy harvesting under various packet-based networking scenarios.

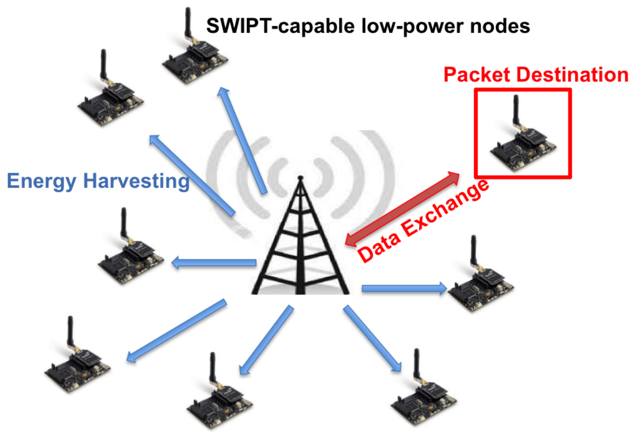
We summarize the contributions of this work in threefold.

- We identify a major assumption made by most SWIPT or RF-based energy harvesting-related previous work and discuss the importance of considering the packet-based networking paradigm in evaluating RF energy harvesting performance.
- Using a set of experiments, we provide empirical results on the impact of various network system-level parameters on RF-based energy harvesting efficiency.
- We provide practical suggestions on the consideration points for system designers that plan to apply SWIPT technologies to their low-power embedded platforms.

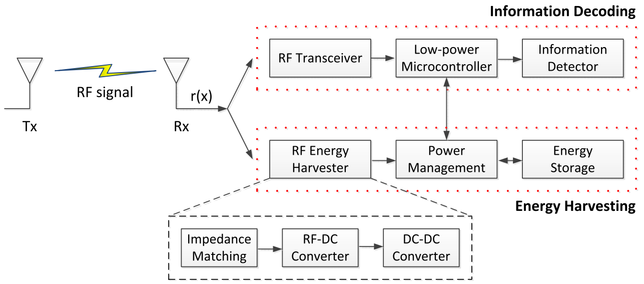
The remainder of this paper is structured as follows. Using Section II, we introduce the SWIPT concept and discuss the need for considering packet-based networks. We examine the impact of packet-based networks and how various networking parameters impact the RF energy harvesting efficiency in Section III and provide suggestions for future system designers in Section IV. We summarize some related previous work in the SWIPT and RF-based energy harvesting domain in Section V and Section VI provides an overall summary of our work.

II. SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER AND THEIR RESEARCH LIMITATIONS

SWIPT, Simultaneous Wireless Information and Power Transfer, is a technology for enabling energy harvesting and information transmission using the same RF signal in the wireless medium. Considering typical scenarios, SWIPT



(a) SWIPT overview



(b) Energy charging and data decoding sequence in SWIPT

FIGURE 2. **Conceptual diagram of SWIPT (top) and an illustration of SWIPT operations at the receiver (bottom).**

holds the potential to benefit various low-power applications, in which many power budget-limited nodes operate with a high-power transmitting base-station node. As we illustrate in Figure 2(a), data is typically transmitted to a single node in the network. Therefore, all other nodes that overhear this omni-directional RF transmission can capture the energy of the RF signals and store the energy in a local power storage unit (e.g., capacitor, re-chargeable battery). The data decoding device, or the destination node, can also determine what amount of the incoming RF signals will be spent for data decoding so that it can split the remaining proportion for harvesting and storing.

On a hardware perspective, supporting SWIPT requires an additional hardware module to typical platforms which combine a microcontroller (MCU) with a low-power radio [3]. Specifically, for supporting energy harvesting, an additional module for splitting (or dividing) incoming RF signals and a hardware unit for RF-to-DC conversion is required. We provide an illustration of this add-on hardware architecture in Figure 2(b). As we can see here, in an ideal configuration for SWIPT, RF signals are divided into two streams at the receiver: one for information decoding and the other for energy harvesting. We present details on the roles of each hardware module below.

- RF transceiver module for exchanging RF signals.
- Low-power MCU for processing information and application software management.
- Information detector for decoding raw RF signals into useful data.

In additional to these traditional mote-level components, SWIPT-based systems introduce additional modules for energy harvesting as the following.

- RF energy harvester for harvesting energy from RF signals, consisting of an impedance matching circuit, a RF-to-DC converter, and a DC-to-DC converter. Here, the impedance matching circuit maximizes the transferred power at the antenna, the RF-to-DC converter transforms the AC RF signals into DC voltage, and the DC-to-DC converter amplifies the DC voltage level from the RF-to-DC conversion unit to allow ultra-low voltage operations.
- Power management unit (e.g., splitting unit) for determining whether the RF should be used for information decoding or energy harvesting. This unit also determines the rate for energy splitting between the two operations.
- Energy storage module for storing the harvested energy (e.g., capacitor, battery etc.).

With such hardware assumptions, research work on SWIPT has been active in various system aspects. Examples include SWIPT configurations for point-to-point links [4], [5], [9], multi-user systems [10]–[12], multi-antenna systems [13]–[16], relay systems [17]–[19], and cognitive radio networks [20], [21].

While these previous work demonstrate how SWIPT technology can be used in various low-power wireless systems, they hold two major drawbacks. First, many of these work base their findings using simulations, which only partially reflect how SWIPT systems will perform in reality. Second, they mostly assume that RF signals are transmitted ‘‘continuously’’ at the transmitter. This second assumption allows the receiver to consistently maintain a full capacitor to provide its processing and radio units with enough power for continuous operations, making it easier to model mathematically. However, in reality, most wireless systems are designed around packet-based networks, which introduce discontinuous and sparse network traffic. This leads to the need for a detailed study on the conditions in which SWIPT systems are practically effective. Specifically, using real experiments in the next section, we try to answer a simple yet essential question in realizing SWIPT-based systems. ‘‘How often and how long should packet transmissions occupy the wireless medium for effective SWIPT operations to take place?’’

III. PERFORMANCE OF SWIPT SYSTEMS

With the problem statement above, this work targets to provide an experimental observation on the impact of packet-based networks (i.e., wireless networks with non-continuous traffic) on the RF-based energy harvesting performance within SWIPT systems. The goal of this work is not in proposing a new algorithm or mechanism for SWIPT systems, but rather its contributions are in sharing the current status of RF-based energy harvesting in a more realistic experimental environment.

A. EXPERIMENTAL ENVIRONMENT

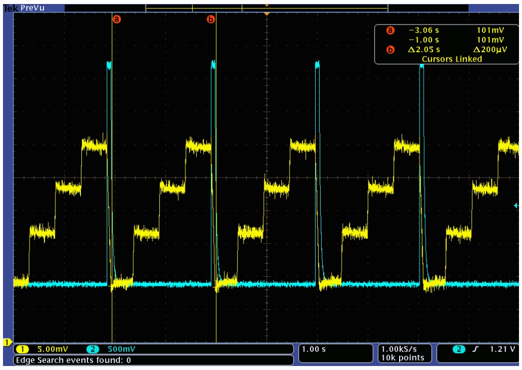
For our experiments, we set up an experimental environment consisting of a transmitter node and two types of receiver nodes. The transmitter sends periodic packets at different inter-packet intervals (IPIs), while one receiver tries to capture power from these RF signals. We also position a second receiver near by to confirm that information delivery takes place properly by receiving and decoding *data* instead of *energy*. For the transmitter and the data receiving node, we use the CC1200-DK platform, which provides a transmission power of up to 14 dBm and a receiving sensitivity of -100 dBm in the sub-GHz (e.g., 900 MHz) range [22]. As the energy harvesting unit, while ideally an energy harvesting module should be integrated to the transceiver directly, for testing purposes, we use the Powercast P2110 platform. The P2110 module is equipped with a 915 MHz-centered RF-based energy harvesting module along with two capacitors of different sizes [8]. Among the two capacitors, our work utilizes the smaller 1000μF capacitor, which has a dissipation factor, *tan* δ, of 0.3. We note that there are a number of the state-of-the-art products in RF energy harvesting, such that E-PEAS (AEM30940, AEM40940), RF Diagnostics (RFD102A), Energous (DA2210, DA2223), Ossia (Cota solutions), and Powercast (P2110, P1110). In our experiments, we select Powercast P2110 Powerharvester Receiver due to its high reliability in RF energy harvesting performance and compatibility with Texas Instruments CC1200 sub-GHz transceiver.

With these three node platforms, we configure the transmitter to send packets of various sizes at different IPIs as unicast packets to the data reception module. Note that the data receiving platform *only* focuses on collecting data and the P2110 module *only* collects energy from the incoming (omnidirectional) RF signals. Ideally, in a system where the energy harvesting module is integrated into the data transceiver as part of a SWIPT implementation, there will be a power splitting (e.g., resource dividing) module that determines whether or not the RF signal should be used for information decoding or energy harvesting (or what percent should be used for each case). In this work, we assume a scenario in which the two receivers each split the incoming RF signal fully towards data reception and energy harvesting, respectively.

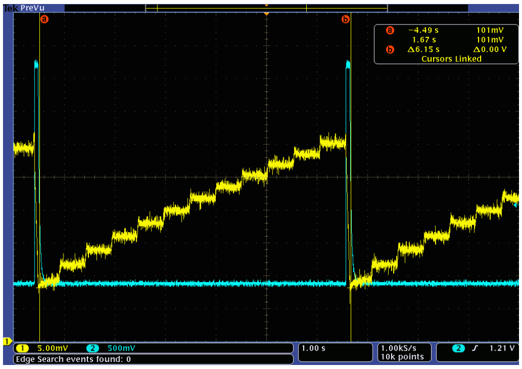
B. EMPIRICAL VALIDATION OF RF-BASED ENERGY HARVESTING

With the experimental configurations above, we now present empirical results collected on the performance of RF-based energy harvesting for realizing SWIPT-oriented systems in packet-based wireless networks.

Using Figure 3 we capture, and illustrate the operations occurring on the Powercast P2110 module in terms of the power harvesting performance and periodic voltage supply using the collected power from RF signals for two different input RF signal power levels (e.g., RSSI). Notice from the yellow traces, where we plot the charge level of the P2110's 1000μF capacitor, that as packets are received, the voltage level of the capacitor increases similar to a step function. With higher input power, each packet reception leads to a steeper increase, while a lower input power results in slower increase in charge levels. As a result, as the blue line plot shows, which represents the supply voltage for the output power from the P2110 module when connected to a 10K Ω resistor, the capacitor outputs its aggregated voltage once it reaches a target charge level. Furthermore, the interval of (periodic) power output occurrences change with respect to the charging efficiency (e.g., input RF power levels). If we were to have a significantly low RSSI at the receiver, the energy charge activity will not be able to keep up with the natural energy dissipation of the capacitor. Therefore, the power charging cannot occur properly. In such cases, a low-power platform and its capacitor will not be able to gather sufficient amount of energy for the radio and sensing modules to utilize.



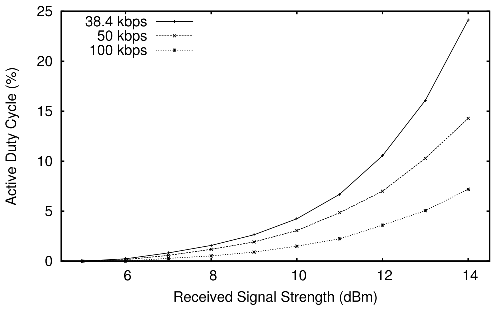
(a) 12 dBm Power Input



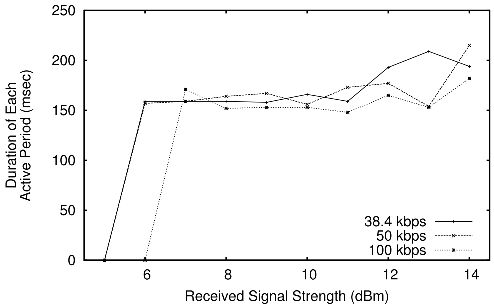
(b) 9dBm Power Input

FIGURE 3. On-board capacitor charge level traces illustrated over time with periodic packet receptions in yellow and power output supplied by the charged capacitor illustrated in blue. Higher input RF-signal strength leads to a steeper increase for each packet reception: allowing for a faster capacitor charge cycle.

To understand the impact of the input signal strength level on RF-based energy harvesting efficiency, and gain a perspective on the minimum level of signal strength that provides effective energy harvesting, we first present results on the RF-based energy harvesting performance with varying received signal strength at the energy harvesting unit. Here, we test for a periodic traffic pattern with an inter-packet interval (IPI) of 500 msec and configure the size of each packet



(a) Active Duty Cycle



(b) Active Duration

FIGURE 4. Active duty-cycles in which the Powercast P2111 provides 3.3V output for 10K Ω load with varying received signal strength levels along with durations for each active period. An input RF signal strength of 12 dBm with 38.4 kbps data rate provides enough energy to actively power the platform for 10% of the time, in which each duration lasts for ∼200 msec.

to be 100 bytes transmitted with varying data rates between 38.4-100 kbps. This traffic pattern leads to a channel occupancy duration of ∼8-20 msec every 500 msec. We note that the results that follow will further examine the impact of different networking factors such as varying IPI, packet sizes, and external noise, while this result focuses on the input received signal strength at the power harvesting platform in an ideal channel environment (e.g., no external noise).

Figure 4 plots the ratio of active power supply durations (e.g., `active duty-cycle`) computed as the percentage of the current supply duration, in which the platform was able to provide a steady current at 3.3 V using the energy gathered at the capacitor in Figure 4(a) (e.g., percentage of the blue duration in Figure 3 over the duration the capacitor needs to charge itself), and the actual time duration of each of these power supply periods in Figure 4(b). As the blue traces in Figure 3 suggests, the capacitor on the Powercast P2110 platform only outputs power when reaching a given voltage level. Therefore, these plots show how the power supply periods take place with energy harvesting. We can see from Figure 4 that with an input signal strength of ∼12 dBm, the platform is capable of providing a steady power for ∼10% of the operational periods and each of these (semi-periodic) power supply durations continue for ∼200 msec. Note that while the operational period stays fairly stable, the changes in the number of packets needed to charge the capacitor will heavily impact the active duty-cycle performance. We also emphasize that since a slower data rate will require the packet transmissions to take longer, more energy can be collected on the RF-based energy harvesting module's perspective. In other words, unlike in typical wireless communication systems, a lower data rate can benefit the system-level effectiveness of RF-based energy harvesting. This will naturally lead to a tradeoff between the communication efficiency and energy harvesting efficiency, which the system designers can utilize with respect to the objective of the wireless network.

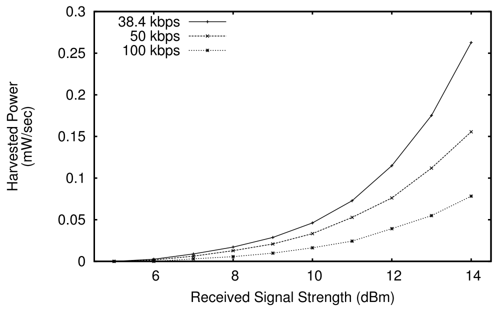
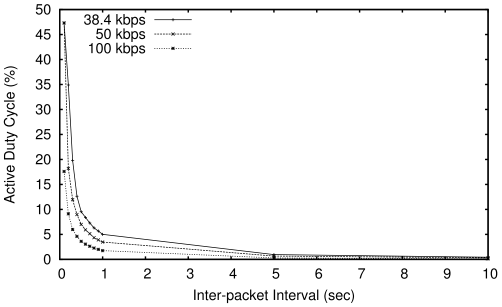


FIGURE 5. Per-second current supply at 3.3V for varying received signal strengths. At 12 dBm input power and a IPI of 500 msec, the energy harvesting platform collects enough energy to power a low-power mote platform for one second every eight minutes.

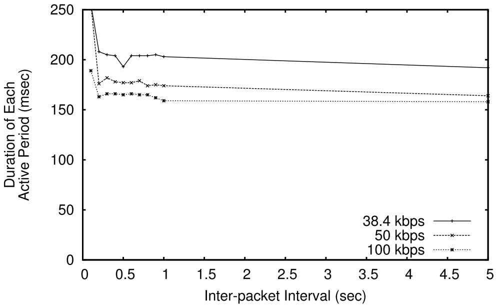
Furthermore, in Figure 5 we provide results on the empirically measured "per-second supply power" or the "aggregate per-second harvested power" for the energy gathering platform. We compute this by aggregating the amount of energy generated within the active power supply duration in Figure 4(b). Here we can observe a trend indicating that for regions with high-power input RF signals, the power gathering efficiency increases super-linearly. Given that a low-power embedded platform, such as the widely used TelosB platform [3], uses ∼60 mW in active mode (including its microcontroller and radio operations), ∼8 minutes of power gathering at 12 dBm (with an IPI of 500 msec and a data rate of 38.4 kbps) can allow a low-power platform to operate for one second. On more powerful platforms, such as the Egs platform using IEEE 802.15.4 and the ARM Cortex M3 microcontroller [23], we can compute an estimated operation time of ∼379 msec using this saved power. We note that these values are based on the reported energy usage values of each platform. In reality, the actual operation time that these platforms will experience can depend on the actual workload and platform design. This number suggests that the RF-based energy harvesting offers sufficient enough time to perform a simple sensor-sampling operation and transmit the collected data.

We note that the absolute performance values presented in this paper are specific to the Powercast P2110 module, which provides a lower-bound of -12 dBm for energy harvesting with a 1000μF capacitor. These absolute values can change with different energy-harvesting hardware configurations. Nevertheless, we believe that the results here can provide performance trend guidelines for other RF-based energy harvesting modules sharing similar characteristics.

Next, we fix the RF input signal power to 12 dBm and vary the IPI of packet transmissions, which will naturally vary the channel's occupancy durations (i.e., "how long is the wireless



(a) Active Duty Cycle



(b) Active Duration

FIGURE 6. **Active duty-cycles in which the Powercast P2111 provides 3.3V output for 10K Ω load with varying inter-packet intervals along with durations for each active period. With frequent packet transmissions (i.e., low IPIs), the energy harvesting performance increases "super-linearly".**

channel occupied?"). By changing the packet transmission intervals, we target to differentiate the energy harvesting module's chances of energy harvesting. Furthermore, for the three data rates tested previously, we configure a fixed packet size of 100 bytes.

Figure 6 plots the active duty-cycle and the duration of each active period for this experiment. We can see from Figure 6(a) that while the trend of the active duty-cycle stays linear up to IPI = 400 msec, with IPI<400 msec, the performance trend evolves to be "super-linear" with respect to decreasing IPI. The main reason behind this performance is in the fact that the frequent "step-like" increase in the capacitor's voltage charge at a low IPI allows little time for the capacitor to naturally dissipate its power in the idle durations (c.f., Fig. 3). Therefore, a more frequent charge due to a lower IPI allows a more effective charging performance to occur. Nevertheless, as Figure 6(b) shows, the duration of each power supply cycle stays fairly stable. Surprisingly, with an IPI of 125 msec at 38.4 kbps, our energy harvesting platform allows for an active duration of ∼250 msec with an active duty-cycle of ∼48%.

We then plot the empirically measured per-second supply power on the energy harvesting platform for varying IPIs in Figure 7. The results here similarly follow the active duty-cycle trend (c.f., Fig. 6(a)) due to similar reasons as detailed above. The fact that the amount of harvested power increases super-linearly at small IPIs suggests that a frequent charge activity from packet receptions can allow the energy harvesting to operate more effectively.

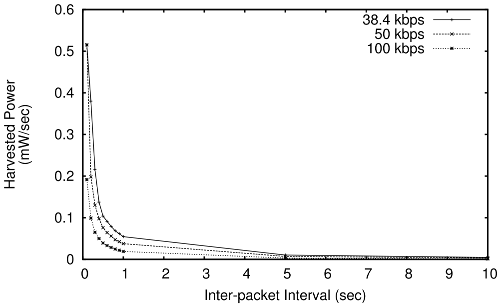
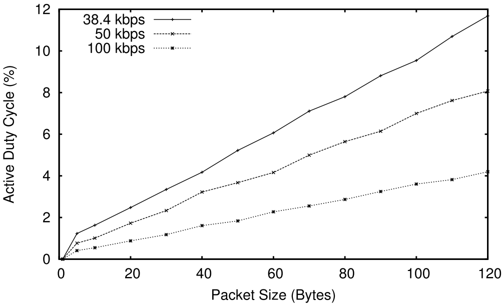
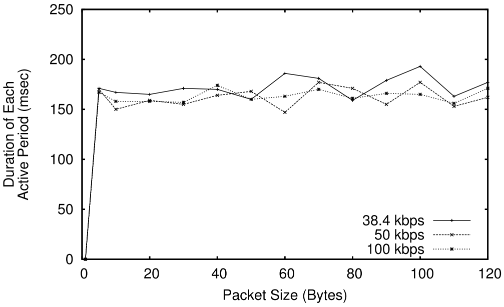


FIGURE 7. **Per-second current supply at 3.3V for varying inter-packet intervals. Similar to the active duty-cycle performance, the per-second current supply performance increases super-linearly with decreasing IPI in the low regions.**



(a) Active Duty Cycle



(b) Active Duration

FIGURE 8. **Active duty-cycles in which the Powercast P2111 provides 3.3V output for 10K Ω load with varying packet sizes along with durations for each active period. Increased packet sizes provide more time to perform RF-based energy harvesting and offer a higher active duty-cycle.**

Using Figures 8 and 9, we plot the active duty-cycle, per active period duration, and the per-second current supply, respectively, for varying packet sizes. Here, we fix the received signal strength to 12 dBm and the IPI to 500 msec. Given that increased packet sizes provide more time to collect energy for each packet transmission, the active duty-cycle and current supply levels increase linearly with this increasing duration.

When comparing these results with the results from varying IPIs (c.f., Figs. 6(a) and 7), we can notice that despite the packet size and IPI both increasing the channel utilization, which increases the energy harvesting durations, for RF-based energy harvesting, the IPI has a heavier impact. This behavior becomes prominent in the low IPI ranges by charging the capacitor more frequently by suppressing the capacitors energy dissipation; thus, increasing the active duty-cycle and current supply levels super-linearly.

Lastly, we examine the impact of energy harvesting with external interference. Wireless systems, especially those

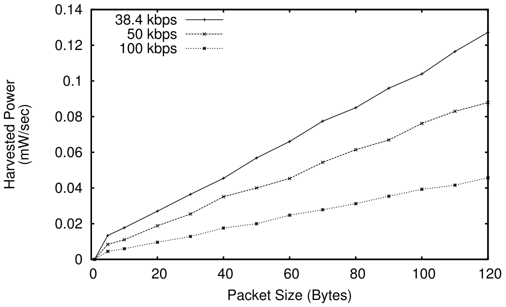


FIGURE 9. Per-second current supply at 3.3V for varying packet sizes. Increasing packet sizes linearly improves the current supply performance.

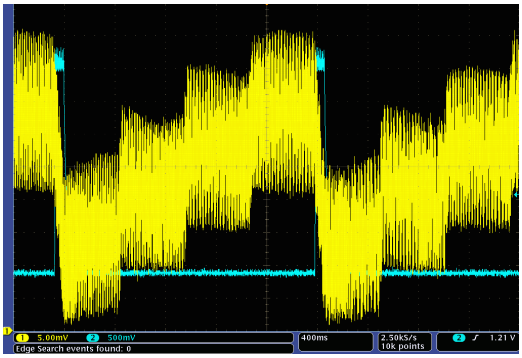


FIGURE 10. Voltage traces captured at the capacitor for cases with the external interferer. By introducing external interference RF signals, the input voltage towards the capacitor significantly fluctuates.

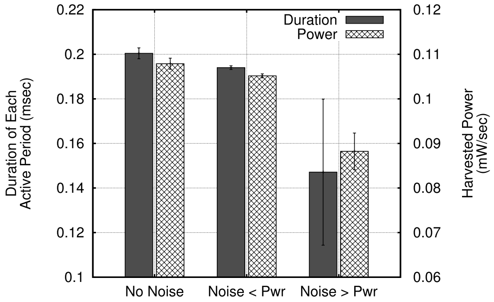


FIGURE 11. Duration of each active period and the harvested power for RF-based energy harvesting under different external channel configurations. Lines denote the standard deviation performance. The introduction of interference factors disturb the incoming RF signal patterns to reduce the RF-to-DC effectiveness and decrease RF-based energy harvesting efficiency.

operating on the ISM bands, are prone to facing external RF interference. Therefore, it is important to be cautious of how external interference will impact the overall system's performance and its objectives. For data communications, we already know through many decades of wireless systems research that external RF factors can harm the incoming quality of signals by distorting their original waveforms. However, for RF-based energy harvesting it is easy to believe that, external interference, since it is a form of wireless energy itself, can be "harvested" at the energy harvesting unit. To confirm such hypothesis, we designed an experimentation environment where we introduce an additional device generating unexpected external interference within the same frequency-band. We connect this third device to the original wired connection. We show the resulting capacitor voltage patterns after adding this additional interferer in Figure 10. Note that here, we set the signal strength of the interferer to be higher than the originally transmitted RF packet. When compared with the traces in Figure 3, we can see that the interferer introduces a highly fluctuating amplitude of voltage to the packet-reception originated voltage input to the capacitor.

With this, we plot duration of each active period along with the per-second harvested power in Figure 11. We can see here that with interference levels that are slightly lower than the transmitted signal (i.e., 12 dBm for the original signal and ∼9 dBm as the input power for the interference signal), our system faces a slightly shorter active duration period and lower harvested power supply levels. Furthermore, with the interferer generating signals at a power much higher than the strength of the received signal from the transmitter (i.e., 12 dBm for the original signal and ∼18 dBm as the input power for the interference signal), we see a ∼26% reduction in the active duration and ∼23% loss in the supply power. This result is somewhat unexpected given that interference RF is also a form of RF energy and the RF-based energy harvesting module should be able to capture this as well. We explain this using how the RF signals are translated into collectible energy. Given that the RF-to-DC unit (or a rectifier) uses the *absolute* amplitude of the incoming RF sinewaves to generate a stable DC, with distorted waveforms, where the amplitude of the positive and negative waves highly differ, the resulting absolute value of the amplitudes will fluctuate; thus, lead to an unstable DC being generated as input to the capacitor. Such unstable DC current input reduces the efficiency of energy collection at the capacitor, which results in lower energy harvesting effectiveness. This suggests that if the incoming signal is disrupted due to external interference factors, the performance of a RF-based energy harvesting unit may not perform at its optimal.

IV. SUGGESTIONS FOR FUTURE SYSTEM DESIGNS

Based on our empirical results and our experimental experience, we now present a set of practical suggestions for system designers that target to deploy RF-based energy harvesting and SWIPT technologies as part of their low-power wireless systems.

- **SWIPT is Not (yet) Ready:** Our results show that harvesting energy from RF signals is, in reality, possible; possible enough to potentially power and recharge low-power wireless embedded platforms in applications with minimal sensing/reporting requirements. However, such effectiveness was only possible with a high reception signal strength at the energy harvesting unit (e.g., >10 dBm). Nevertheless, practically achieving a stable received signal strength of >10 dBm is not possible in most wireless application scenarios. For systems that operate on limited energy sources, this high reception power is even harder to achieve. This is, therefore, a major engineering limitation that holds back the applicability of RF-based energy harvesting in various domains. Despite the fact that they may not be able to be applied right away, we still argue that the findings in this work can benefit future research in two major directions. First, installing a high-power transmitting gateway to form mini-clusters of many single-hop networks can help assist smaller-sized, resource-limited devices (surrounding the gateway node) to capture energy at high levels. With such smaller-sized ''cells'', the overall network architecture can be abstracted to multiple single-hop sectors, in which a high-power gateway interacts with multiple energy-harvesting nodes to form a multi-tier network topology. Second, given that these RF-energy harvesting limitations are an effect of the energy collection module (e.g., P2110), as technology improves, the energy harvesting efficiency holds the potential to further increase. Even in such cases, the question of how RF-based energy harvesting technologies will perform with (sparse) packet-based networks will remain a question. We believe that the findings from this work can act as a guideline in designing systems under such circumstances by simply scaling down the results related to the reception signal strength.

- **Channel Utilization Requirements:** The results from this work also suggest that there should be a substantial amount of traffic on the wireless medium for the radio to effectively pick up wireless RF energy for harvesting. Quantitatively, the data rate, packet size, and the packet transmission interval impact this channel utilization performance. With a lower data rate (or a longer packet size), the transmitter will spend more time sending packets, but at the same time, allow for the energy-harvesting nodes to collect energy for longer durations. Similarly, with more frequent packet transmissions, the energy harvesting unit will have more opportunities to charge its capacitor. We also noticed that the impact of inter-packet intervals (i.e., transmission frequency) had an heavier impact on the energy harvesting performance than the data rate and packet size factors, given that it decreases the idle times, in which the capacitor naturally dissipates its stored energy. Nevertheless, for most low-power applications, the packet transmission frequency is an application-level requirement that is not easily controlled at the system design phase. This means that in many cases it makes less sense to design a system with a frequent transmission interval just for the sake of charging a low-power node. Instead, system designers can apply heterogeneous data rate networks, where downlink packets (e.g., from a high-power gateway node to low-power energy-harvesting nodes) are sent using a lower data rate to maximize the harvesting duration, while uplink packets (e.g., from the low-power nodes to the gateway) are sent using a higher data rate to minimize the radio operation time on the resource-limited nodes. For various industrial applications, in which multiple sensors are connected to a manufacturing equipment to transfer data to a gateway, this single-hop, asynchronous transmission power-based wireless system can be a suitable design choice.
- **Capacitor Design Considerations:** The performance of the capacitor takes on a critical role in RF-based energy harvesting systems, especially for packet-based networks. Given a network traffic pattern of an application, it is important that a suitable capacitor is selected in the hardware design phase so that the natural energy dissipation speed of the capacitor's energy does not exceed the expected input power via RF-reception. In some sense, this can be planned in advance. Using an estimated channel utilization value (with respect to the data rate, packet size, and transmission frequency), combined with an expected connection topology (e.g., estimated received signal strength for each packet), system designers can plan the expected amount of energy input per time instance and configure an appropriate capacitor to meet their application-level design goals.

V. RELATED WORK

We now position our work among existing literature in the domains of energy harvesting and SWIPT technology on wireless sensor networks (WSNs).

Research on energy harvesting using various energy sources, such as vibration, light, thermal and solar energy, have been investigated steadily as a way to operate wireless sensor nodes without battery limitations [24]–[26]. Recently, in accordance with the characteristics of WSNs packet transmissions, which emit electromagnetic radiation, RF energy harvesting is gaining interest as a potential solution for enabling self-powered low-power platforms. In RF energy harvesting, a variety of research areas has been investigated, including the antenna design for miniaturization and high gain [27], [28], matching circuits for the high efficiency of energy conversion [29], rectifier designs for high sensitivity [30], [31], and the feasibility itself of achieving RF energy harvesting [32]–[38]. In particular, the performance of RF energy harvesting was theoretically analyzed by the random arrival model of RF energy source, e.g., a stochastic geometry approach, in [34]. [35], and its feasibility was also experimentally evaluated in large-scale networks [36]–[38].

With the hope that RF energy harvesting will successfully take-off over the next few years, many researchers also examined the potential of simultaneously transferring energy *as well* as information using the RF signals, SWIPT. As initial research, simple operation rules and implementation architectures at receiver for enabling SWIPT were researched intensively in point-to-point link-based systems. For example, opportunistic time switching [5] and dynamic power splitting [4] methods at the receiver were proposed to resolve various trade-offs between information transfer and energy harvesting under a finite amount of resources. Furthermore, two types of practical receiver architectures, separated and integrated information and energy receivers, have also been designed and evaluated by Zhou *et al.* [9].

To target system-level optimization, SWIPT-related research expands to multi-user systems, where researchers investigate the diversity of resource allocation algorithms for optimizing system performances. In order to maximize system throughput while guaranteeing a target energy harvesting level, power allocation schemes with time switching and power splitting were proposed in multi-user OFDM systems [12]. Similarly, researchers also looked into various power control schemes for various configurations such as single- or multi-user, downlink/uplink, and variable/fixed coding rates [10].

While these previous work provide a first-hand intuition in designing SWIPT-based systems, single antenna systems hold limitations in ensuring reliable system performance. This led to the research in multi-antenna systems. As examples, Shi et al. tried to minimize the transmission power at the base-station node using multiple antennas and beamforming vectors with mobile stations [14]. For maximizing achievable rate under the constraint of energy harvesting, Zhao et al. presented solutions to the joint optimization of antenna selection and the transmit covariance matrix [16]. In addition, the performance limits of multi-antenna SWIPT systems for separated and co-located receivers were evaluated by Zhang and Ho [15]. Similarly, Park and Clerckx performed research in identifying the achievable rate-to-energy tradeoff region in a two-user MIMO interference channel [13].

In addition to single-hop systems, research on multi-hop relay systems has also received attention in the SWIPT research domain as a way to further increase the network scalability. Here, various research issues exist in domains such as relay protocols and operation rules for energy harvesting networks. Nasir et al. proposed a pair of relaying protocols: time switching-based relay and power splitting-based relay systems [19]. Furthermore, Krikidis et al. introduced a simple greedy switching policy on time switching-based receivers [18], and in [17] the authors investigated in proposing a low-complexity antenna switching scheme between decoding and rectifying RF power in MIMO relay channels for efficient SWIPT operations.

More recently, cognitive radios are also gaining attention as a potential system architecture for SWIPT given that secondary users can continuously harvest energy occurring from the primary user's RF signals. To achieve such advantages, research on cognitive radio-based SWIPT systems mostly has focused on the evaluation of system performances with respect to the interaction between primary and secondary user systems. Lee et al. showed analysis on the secondary systems' performance, in which the secondary transmitter can harvest ambient RF power from nearby active primary transmitters while opportunistically accessing the unlicensed spectrum [20]. In addition to this, the work by Zheng et al. investigate into improving the spectral efficiency using joint information and energy cooperation between primary and secondary systems [21].

Finally, we acknowledge recent experimental work relevant to our research. In [39], the authors implemented a testbed for a multi-antenna wireless-powered sensor network (WPSN) to evaluate energy beamforming and duty cycle control algorithm to charge a single node. Furthermore, a beam-splitting beamforming was proposed to charge multiple nodes simultaneously by splitting energy beams [40]. In [41], the authors proposed a distributed wireless power transfer system, in which a number of power beacons equipped with multi-antenna transmit RF power with frequency and phase synchronization to charge IoT nodes.

An alternative approach for implementing batteryless systems is applying RF backscattering techniques [42]. These devices are used to reflect well known signals (e.g., TV signals or WiFi signals) to send messages to a distant receiver. While sharing the same philosophy of potentially enabling batteryless platforms for data exchange, energy harvesting techniques such as the ones used in SWIPT systems are designed to collect and store energy at higher scales than backscattering systems and can potentially be applied on more powerful platforms given proper capacitor-battery configurations.

VI. SUMMARY

SWIPT and its RF-based energy harvesting features hold the potential to alleviate low-power wireless systems from the long-lasting and limitation of operating under strictly limited energy budgets. Such attractiveness led to active research in this research domain. Until now, a majority of previous work in RF-based energy transfer has been centered around theoretical bounds; therefore, making a number of critical assumptions that cannot properly reflect reality. Among these assumptions, one critical assumption made by most previous work is the continuity of signal transmissions when capturing energy from RF-signals. This work starts with the observation that this, in most cases, is not true. Rather, most wireless systems are designed as "packet-based" networks. This means that the wireless medium will frequently, or mostly, be idle, while actively carrying traffic for only a small subset of the entire time-duration. Naturally, such idle duration between packet transmissions will give heavy impact to the overall energy harvesting performance. Using experimental evaluations with the Powercast P2110 energy harvesting platform, we show that impact is indeed true. Specifically, with low-channel utilization, even with a high enough input power, we noticed that, using our experimental settings, RF-based energy harvesting can result in a very low harvesting efficiency. Nevertheless, we also show that frequent packet transmissions and longer packet sizes can improve this efficiency super-linearly and linearly, respectively, by minimizing the duration in which the capacitor faces natural dissipation. Furthermore, we show that the impact of external interference, although also being a form of energy itself, can harm the RF-based energy harvesting efficiency by disrupting the waveforms of the incoming signals. These results, while performed in a controlled environment, suggest that RF-based energy harvesting in packet-based wireless networks can be possible, not at the moment, but possibly soon with further engineering improvements. We use these experiences to share guidelines with future system developers on how SWIPT can be designed for low-power wireless network systems. Overall, we see this work as one of the first and essential steps in realizing SWIPT systems for packet-based networks, a widely used networking paradigm.

REFERENCES

[1] N. Burri, P. Von Rickenbach, and R. Wattenhofer, "Dozer: Ultra-low power data gathering in sensor networks," in *Proc. 6th IPSN Conf.*, 2007, pp. 450–459.

[2] D. Moss, J. Hui, and K. Klues, "Low power listening," in *Proc. TinyOS TEP*, vol. 105, 2007, p. 24.

[3] Moteiv Corporation. *Tmote Sky*. Accessed: Nov. 11, 2019. [Online]. Available: https://www.advanticsys.com/

[4] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information and power transfer: A dynamic power splitting approach," *IEEE Trans. Commun.*, vol. 61, no. 9, pp. 3990–4001, Sep. 2013.

[5] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information transfer with opportunistic energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 12, no. 1, pp. 288–300, Jan. 2013.

[6] German Federal Ministry of Education and Research. *Project of the Future: Industry 4.0*. Accessed: Nov. 11, 2019. [Online]. Available: https://www.bmbf.de/en/index.html

[7] R. Adler, P. Buonadonna, J. Chhabra, M. Flanigan, L. Krishnamurthy, N. Kushalnagar, L. Nachman, and M. Yarvis, "Design and deployment of industrial sensor networks: Experiences from the north sea and a semiconductor plant," in *Proc. ACM Sensys*, Nov. 2005, p. 17.

[8] Powercast Co. (2010). *P2110 915 MHz RF Powerharvester*. [Online]. Available: http://www.powercastco.com/PDF/P2110-datasheet.pdf

[9] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4754–4767, Nov. 2013.

[10] K. Huang and E. Larsson, "Simultaneous information and power transfer for broadband wireless systems," *IEEE Trans. Signal Process.*, vol. 61, no. 23, pp. 5972–5986, Dec. 2013.

[11] D. W. K. Ng, E. S. Lo, and R. Schober, "Wireless information and power transfer: Energy efficiency optimization in OFDMA systems," *IEEE Trans. Wireless Commun.*, vol. 12, no. 12, pp. 6352–6370, Dec. 2013.

[12] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer in multiuser OFDM systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 2282–2294, Apr. 2014.

[13] J. Park and B. Clerckx, "Joint wireless information and energy transfer in a two-user MIMO interference channel," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 4210–4221, Aug. 2013.

[14] Q. Shi, L. Liu, W. Xu, and R. Zhang, "Joint transmit beamforming and receive power splitting for MISO SWIPT systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3269–3280, Jun. 2014.

[15] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[16] S. Zhao, Q. Li, Q. Zhang, and J. Qin, "Antenna selection for simultaneous wireless information and power transfer in MIMO systems," *IEEE Commun. Lett.*, vol. 18, no. 5, pp. 789–792, May 2014.

[17] I. Krikidis, S. Sasaki, S. Timotheou, and Z. Ding, "A low complexity antenna switching for joint wireless information and energy transfer in MIMO relay channels," *IEEE Trans. Commun.*, vol. 62, no. 5, pp. 1577–1587, May 2014.

[18] I. Krikidis, S. Timotheou, and S. Sasaki, "RF energy transfer for cooperative networks: Data relaying or energy harvesting?" *IEEE Commun. Lett.*, vol. 16, no. 11, pp. 1772–1775, Nov. 2012.

[19] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3622–3636, Jul. 2013.

[20] S. Lee, R. Zhang, and K. Huang, "Opportunistic wireless energy harvesting in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 9, pp. 4788–4799, Sep. 2013.

[21] G. Zheng, Z. Ho, E. A. Jorswieck, and B. Ottersten, "Information and energy cooperation in cognitive radio networks," *IEEE Trans. Signal Process.*, vol. 62, no. 9, pp. 2290–2303, May 2014.

[22] Texas Instruments. (2013). *CC1200 Low-Power, High-Performance RF Transceiver*. [Online]. Available: http://www.ti.com/lit/ds/symlink/cc1200.pdf

[23] J. Ko, K. Klues, C. Richter, W. Hofer, B. Kusy, M. Bruenig, T. Schmid, Q. Wang, P. Dutta, and A. Terzis, "Low power or high performance? A tradeoff whose time has come (and nearly gone)," in *Wireless Sensor Networks*, G. P. Picco and W. Heinzelman, Eds. Berlin, Germany: Springer, 2012, pp. 98–114.

[24] D. Dondi, A. Bertacchini, D. Brunelli, L. Larcher, and L. Benini, "Modeling and optimization of a solar energy harvester system for self-powered wireless sensor networks," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2759–2766, Jul. 2008.

[25] A. Khaligh, P. Zeng, and C. Zheng, "Kinetic energy harvesting using piezoelectric and electromagnetic technologies—State of the art," *IEEE Trans. Ind. Electron.*, vol. 57, no. 3, pp. 850–860, Mar. 2010.

[26] Y. K. Tan and S. K. Panda, "Energy harvesting from hybrid indoor ambient light and thermal energy sources for enhanced performance of wireless sensor nodes," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4424–4435, Sep. 2011.

[27] Z. Zakaria, N. A. Zainuddin, M. N. Husain, M. Z. Abidin, A. Aziz, M. A. Mutalib, and A. R. Othman, "Current developments of RF energy harvesting system for wireless sensor networks," *Adv. Inf. Sci. Service Sci.*, vol. 5, no. 11, pp. 328–338, Jun. 2013.

[28] J. M. Barcak and H. P. Partal, "Efficient RF energy harvesting by using multiband microstrip antenna arrays with multistage rectifiers," in *Proc. IEEE Subthreshold Microelectron. Conf. (SubVT)*, Oct. 2012, pp. 1–3.

[29] S. Agrawal, S. Pandey, J. Singh, and P. N. Kondekar, "An efficient RF energy harvester with tuned matching circuit," in *VLSI Design Test* (Communications in Computer and Information Science), vol. 382. Springer, 2013, pp. 138–145.

[30] A. Richelli, S. Comensoli, and Z. M. Kovács-Vajna, "A DC/DC boosting technique and power management for ultralow-voltage energy harvesting applications," *IEEE Trans. Power Electron.*, vol. 59, no. 6, pp. 2701–2708, Jun. 2012.

[31] Y. Wu, J.-P. Linnartz, H. Gao, M. K. Matters-Kammerer, and P. Baltus, "Modeling of RF energy scavenging for batteryless wireless sensors with low input power," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 527–531.

[32] T. Le, K. Mayaram, and T. Fiez, "Efficient far-field radio frequency energy harvesting for passively powered sensor networks," *IEEE J. Solid-State Circuits*, vol. 43, no. 5, pp. 1287–1302, May 2008.

[33] R. J. M. Vullers, R. van Schaijk, I. Doms, C. van Hoof, and R. Mertens, "Micropower energy harvesting," *Solid-State Electron.*, vol. 53, no. 7, pp. 684–693, 2009.

[34] I. Flint, X. Lu, N. Privault, D. Niyato, and P. Wang, "Performance analysis of ambient RF energy harvesting: A stochastic geometry approach," in *Proc. IEEE Global Commun. Conf.*, Dec. 2014, pp. 1448–1453.

[35] W. Liu, X. Zhou, S. Durrani, H. Mehrpouyan, and S. D. Blostein, "Energy harvesting wireless sensor networks: Delay analysis considering energy costs of sensing and transmission," *IEEE Trans. Wireless Commun.*, vol. 15, no. 7, pp. 4635–4650, Jul. 2016.

[36] M. Pinuela, P. D. Mitcheson, and S. Lucyszyn, "Ambient RF energy harvesting in urban and semi-urban environments," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 7, pp. 2715–2726, Jul. 2013.

[37] T. B. Lim, N. M. Lee, and B. K. Poh, "Feasibility study on ambient rf energy harvesting for wireless sensor network," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Dec. 2013, pp. 1–3.

[38] S. Kim, R. Vyas, J. Bito, K. Niotaki, A. Collado, A. Georgiadis, and M. M. Tentzeris, "Ambient RF energy-harvesting technologies for self-sustainable standalone wireless sensor platforms," *Proc. IEEE*, vol. 102, no. 11, pp. 1649–1666, Nov. 2014.

[39] K. W. Choi, L. Ginting, P. A. Rosyady, A. A. Aziz, and D. I. Kim, "Wireless-powered sensor networks: How to realize," *IEEE Trans. Wireless Commun.*, vol. 16, no. 1, pp. 221–234, Jan. 2017.

[40] K. W. Choi, P. A. Rosyady, L. Ginting, A. A. Aziz, D. Setiawan, and D. I. Kim, "Theory and experiment for wireless-powered sensor networks: How to keep sensors alive," *IEEE Trans. Wireless Commun.*, vol. 17, no. 1, pp. 430–444, Jan. 2018.

[41] K. W. Choi, A. A. Aziz, D. Setiawan, N. M. Tran, L. Ginting, and D. I. Kim, "Distributed wireless power transfer system for Internet of Things devices," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2657–2671, Aug. 2018.

[42] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient backscatter: Wireless communication out of thin air," in *Proc. ACM SIGCOMM Conf. SIGCOMM*. New York, NY, USA: ACM, 2013, pp. 39–50.

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