Charging and Wake-up of IoT Devices using Harvested RF Energy with Near-Zero Power Consumption

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***Abstract*—Sixth generation (6G) wireless systems are envisioned to support ubiquitous connection of a massive number of battery-powered Internet-of-Things (IoT) devices. Radio frequency (RF) energy harvesting and wake-up radio have been extensively considered as standalone technologies to extend the battery lifetime of IoT devices. In this article, we present a general framework for designing efficient combined RF energy harvesting and wake-up circuits to further reduce the energy consumption of IoT devices and allow them to operate nearly self-sustainably. Specifically, we propose two address detector designs: a dual-power-mode pulse width detector (PWD) and a multi-power-mode pulse width modulation (PWM) detector that can be integrated in combined architectures with a single shared antenna and rectifier. Furthermore, we validate the practicality of the presented framework by testing sample designs under real operational conditions. Finally, we conclude the article by introducing future research directions for realizing large IoT networks with combined RF energy harvesting and wake-up radio.**

***Index Terms*—6G wireless systems, IoT devices, energy harvesting, wake-up radio, RF circuit design.**

I. INTRODUCTION

THe sixth generation (6G) of wireless systems is expected to enable sustainable societies with smart infrastructure, through Internet-of-Things (IoT) deployments with near-zero power consumption [1]. This vision is constrained by the limited battery lifespan of wireless IoT devices and the difficulty to replace the batteries of the devices in hard-to-reach areas. Radio frequency (RF) energy harvesting and wake-up radio offer effective solutions to wirelessly power IoT devices and reduce their overall energy consumption [2], [3]. The IoT devices can then recharge their energy storage unit using a passive harvesting system, such as an antenna with a well matched rectifier. With RF wake-up radio, the device can also enter an ultra-low power sleep mode and only wake up when it receives a special RF wake-up signal from an external transmitter [3]. This allows the device to shutdown its main components for energy consumption reduction except for the auxiliary wake-up circuit that monitors the reception of the wake-up signal. Unlike RF energy harvesting circuits, the wake-up receiver must contain a digital address decoding unit. Towards this end, effective ultra-low power, noise-immune address detectors need to be designed to improve the energy efficiency of wake-up receivers [4].

While RF energy harvesting and wake-up radio have been mostly considered as two standalone solutions to improve the performance of IoT networks [2], [3], combining these two techniques together brings great benefits in further decreasing the energy consumption and enabling fully passive IoT devices that can operate nearly self-sustainably. The main advantage of combining RF energy harvesting and wake-up stems from the fact that the device does not require a separate battery to be functional. Instead, it can harvest energy from ambient RF signals while remaining in sleep mode then use the harvested energy when it switches to active mode. Numerous challenges persist when combining RF energy harvesting and wake-up together for IoT devices, including increased noise at the device front-end, reduced harvester efficiency due to varying input power and load, in addition to the address detector's sensitivity and energy consumption requirements.

In this article, we present a general framework for designing and implementing combined RF energy harvesting and wake-up circuits with different address detector design options. Unlike previous work concerned with circuit design and fabrication under specific constraints [5], we describe the general architecture and the main components needed in combined schemes in addition to the technical challenges that should be addressed. We further present the design of a dual-power-mode pulse width detector (PWD) circuit and a multi-power-mode pulse width modulation (PWM) detector and compare their performance in terms of current consumption. In addition, we demonstrate the efficiency and practicality of the described framework with sample performance analysis to extract practical insights and we compare it with standalone RF energy harvesting and wake-up solutions. We conclude the article with proposed future research directions.

II. ARCHITECTURE OF COMBINED RF ENERGY HARVESTING AND WAKE-UP SYSTEMS

A fundamental component in RF energy harvesting and wake-up receivers is the rectifying circuit that converts the received RF energy into DC voltage [6]. Relying on a shared rectifier for the combined system is crucial in order to reduce the complexity of the RF front-end. Systems that combine RF energy harvesting and wake-up can employ one rectifier for both tasks, as shown in the general framework presented in Fig. 1. This architecture has the advantage of eliminating the need for active components such as mixers or oscillators for down conversion.

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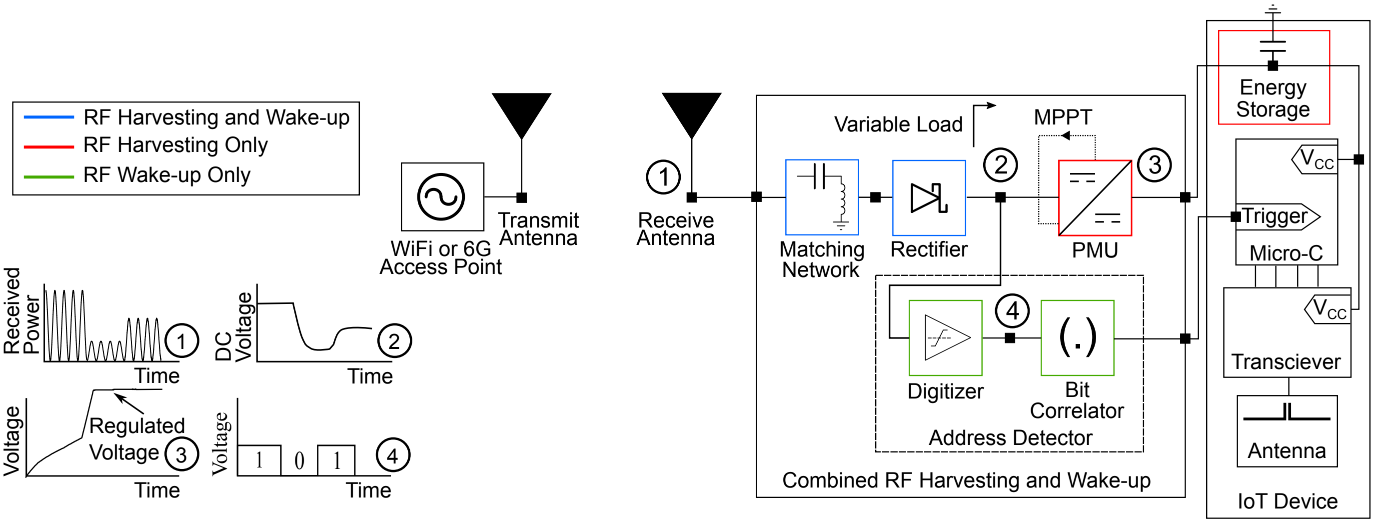

Fig. 1. A framework architecture that combines RF energy harvesting and wake-up by sharing a single antenna and rectifier for both tasks. Signal ① shows a variable received signal power at the receive antenna. Signal ② shows the rectifier's DC output voltage which follows the peak of the signal at the input. Signal ③ shows the regulated voltage at the output of the PMU. Signal ④ shows the digitized wake-up signal containing the IoT device's address.

An unmodulated charging signal or a modulated wake-up signal is received from the transmitter and delivered to the rectifier. The received signal power may vary depending on the channel conditions or the selected modulation scheme. The DC voltage collected at the rectifier's output is a function of the received signal power and the rectifier's efficiency as well as its non-linear response. Therefore, a power management unit (PMU) is required to boost and regulate the DC voltage into the energy storage. The PMU's input resistance is variable because it typically includes a buck or boost converter and may feature maximal power point tracking (MPPT). An input voltage exceeding the PMU's sensitivity is required to initiate the PMU's operation.

To enable the RF wake-up functionality, the amplitude of the DC voltage at the rectifier's output can be modulated to deliver a wake-up signal. An address detector containing active electronics to digitize the signal and a bit correlator to match the bit pattern to a pre-configured address constitute the RF wake-up path. A simple modulation scheme such as on-off-keying (OOK) simplifies the design of the address detector, which can be powered through a dedicated energy source or through a shared battery with the IoT device. The address detector generates an interrupt signal to activate the main components of the IoT device upon the reception of a specific wake-up address. We coin term "near-zero power consumption" as a reference to the long-term behavior of energy consumption and is a characteristic of perpetual operation. To accomplish near-zero power consumption, an IoT device with sleep and active power modes must: 1) Avoid excess operation in active mode by relying on targeted wake-up and 2) Leverage RF energy harvesting to replenish its energy storage.

III. TECHNICAL CHALLENGES

Several challenges arise from utilizing a combined architecture, which are divided into the following three categories.

1) Optimized Charging and Wake-up Signals:

Typical wireless transmitters generate intermittent signals with limited power delivery capability, which impacts the rectifier's output voltage in combined RF energy harvesting and wake-up architectures. Therefore, there is a need to maximize the transmitter's activity during charging operations, with the ability to modulate the transmission with a wake-up signal to perform combined RF energy harvesting and wake-up. In contention-based wireless systems, only two devices can communicate at a given time when the channel is sensed to be idle. Nevertheless, the transmitter may occupy the channel for a long period to charge a storage capacitor or transmit a wake-up signal at a low bit rate. Consequently, the performance of other devices in the network can be negatively impacted due to the increased medium occupation. Therefore, minimizing the impact of charging and wake-up transmissions on the network performance remains a key challenge to address.

2) Efficient Rectifier Designs:

The rectifier in combined architectures must exhibit a high power conversion efficiency to harvest energy and a quick response to demodulate the wake-up signal. The rectifier receives variable input power, and it sees a constantly changing load impedance represented by the varying input impedance of the PMU (due to the MPPT function) and the various power states of the address detector as well as the IoT device. Therefore, a versatile rectifier design with agnostic power and load characteristics is required to enhance the charging performance. On the other hand, utilizing the rectifier as a demodulator for wake-up applications dictates that the rectifier's output DC voltage responds quickly to variations in the received signal power. The rectifier's swift response is an essential parameter because it determines the wake-up signal's maximum possible data rate. It is shown that the responsiveness of the rectifier depends on the architecture of the rectifying element and the number of stages when using a voltage multiplier [7].

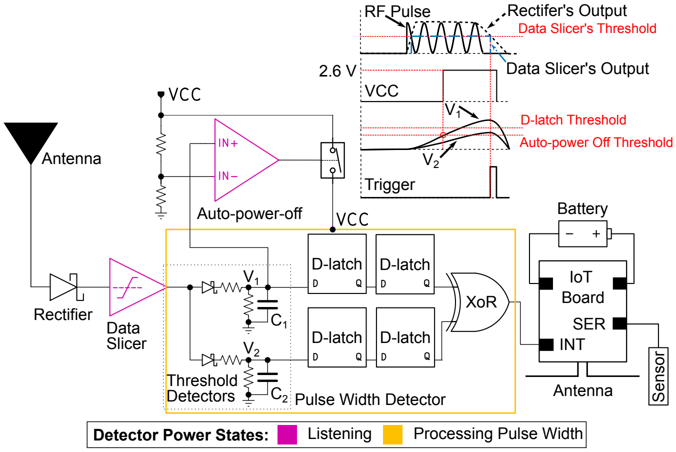

Fig. 2. Architecture of dual-power-mode PWD. The top timing diagram highlights the discrepancy between the width of the received RF pulse and the digital pulse generated by the data slicer.

3) Reliable Address Detector Designs: The address detector and the PMU are both connected to the rectifier's output in combined system architectures. This negatively impacts the operation of the address detector because it may receive a strong noise signal during charging tasks. Therefore, it is crucial to enhance the address detector's noise immunity to avoid jamming and false wake-up of the IoT device. On the other hand, the address detector contains active components to perform analog-to-digital conversion, demodulation, and correlation of the wake-up signal. Therefore, the current consumption of the address detector must be reduced during charging tasks or when listening to the wake-up signal. Carefully devising the addressing scheme can augment the address detector's noise immunity and reduce its average current consumption. Furthermore, innovative techniques are required to differentiate between charging and wake-up operations, which allows for complete shutdown of the energy consuming components of the address detector during the charging phase.

IV. ADDRESS DETECTOR DESIGNS FOR COMBINED RF ENERGY HARVESTING AND WAKE-UP

By considering the challenges introduced in Section III, we present a general framework for designing combined RF energy harvesting and wake-up circuits. We focus mainly on the design of powerful address detectors that can process wake-up signals with minimal energy consumption and are immune to the noise caused by the charging phase. The developed methodology builds on our extensive experience in the design, implementation, and prototyping of energy harvesting and wake-up circuits. Detailed description of the proposed architectures at the circuit level can be found in previous work [5], [8].

A. Design of Pulse Width Detector (PWD) Circuit

Before combining RF wake-up and charging, it is useful to discuss the attainable modulation schemes to devise a wake-up signal in the combined system. The rectifier cannot detect phase- and frequency-modulated wake-up signals [3]. Nevertheless, it can operate as an envelope detector to demodulate amplitude shift keying (ASK)-modulated wake-up signals.

A sample design can be achieved by considering a wake-up signal that comprises a single RF pulse with a distinct width, where the width of this pulse determines the address of the IoT device. The data slicer converts the rectifier's output into a digital pulse, as shown in Fig. 2. The data slicer is configured with a threshold that determines the sensitivity of the system, and it represents a high impedance load for the rectifier with a very small input current. The D-latch networks store the voltage levels as 0 or 1 bits, and the XoR gate compares the two bits and generates a trigger only if the received pulse width is within a specific range. The rise and fall time of the rectifier's output voltage causes an error in detecting the true width of the RF pulse. This detector design can be hardware-programmed to detect different pulse widths by adjusting the time constant of the threshold detectors. An auto-power off timer detects the rising edge that initiates the wake-up signal to generate a control signal and deliver common collector voltage (VCC) to the PWD.

The main drawback of this scheme when compared to OOK- or PWM-modulated bits is the limited scalability when adding more IoT devices in the network. This requires extra addresses with larger pulse widths. As such, increasing the addresses' pool requires further hardware changes in the PWD circuit, which is not practically feasible. Furthermore, the wake-up delay in the circuit is equal to the pulse width because the entire pulse must be received by the PWD before performing the XoR operation. The PWD can therefore be considered as a baseline approach for designing low energy address detectors for combined RF energy harvesting and wake-up and must be further optimized to realize simultaneous charging and wake-up, especially in time and energy constrained massive IoT deployments.

B. Combining RF Wake-up and Charging using PWD

Combining charging with RF wake-up can be achieved by leveraging the idle periods of the PWD that separate consecutive wake-up signals. To do so, a PMU must be integrated at the rectifier's output, in parallel with the PWD. The PMU's input resistance is independent of the RF frequency [9], however it is a function of several factors, such as the input and output voltage, the switching frequency and the duty cycle of the buck/boost converter. We can define the sensitivity of the charging component as the PMU's minimum threshold to charge the battery of the IoT device to the steady state.

Although the suggested architecture can realize simultaneous charging and wake-up, the main disadvantage is that the D-latch network and XoR gate of the PWD remain powered ON during charging. Moreover, there is a disparity between the sensitivity of the wake-up and charging components, which encourages further work on using adaptive transmit power when performing charging and wake-up. Another interesting research direction is to use mobile transmitters such as unmanned aerial vehicles (UAVs) to minimize the mismatch between the charging and wake-up ranges. Our preliminary

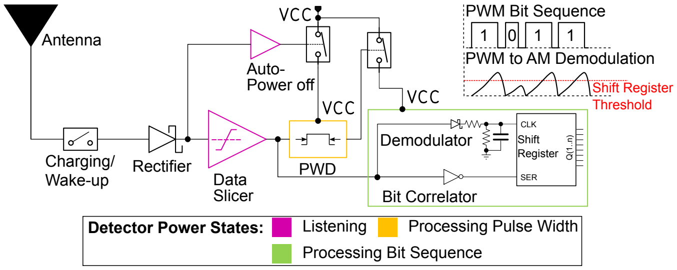

Fig. 3. Multi-power-mode PWM detector's hardware showing the components needed to process the wake-up signal.

work validated that UAVs can wirelessly charge a capacitor with a value in the order of a few hundred μF [10]; however, it remains a challenge to charge larger batteries.

C. Design of Multi-power-mode PWM Detector Circuit

To scale up the addressing scheme beyond detecting a pulse width, a multi-power-mode pulse width modulation (PWM) address detector is designed to perform sequential activation while processing the wake-up signal. A general architecture of the multi-power-mode PWM detector is shown in Fig. 3, and it is based on the PWD discussed previously. The PWD acts as a preamble detector that receives an RF pulse and informs the PWM detector that a PWM-modulated bit pattern will follow. Therefore, the bit correlator of the PWM detector is only activated for a short period to process the bit pattern, and the current consumption reaches the maximum value.

The PWM detector features a scalable addressing scheme because the wake-up signal is composed of the combination of the pulse width and bit pattern. The bit correlator comprises a passive PWM-to-AM demodulator at the shift register's serial input, and an inverter to extract the clock's rising edge from the PWM-modulated bits to further reduce the energy consumption. The PWM detector also examines the data slicer's output voltage to detect an unmodulated charging signal and disconnect power from the PWM detector during charging tasks. Therefore, the PWM detector activates the minimal needed components for listening, pulse width detection, and PWM demodulation and correlation. This approach limits the average current consumption because the bit correlator contributes the most to the overall current consumption. On the other hand, the current consumption is minimized during charging because the power is disconnected. In this setup, the charging/wake-up switch is active to monitor the unmodulated charging signal. The unmodulated charging signal is transmitted for a limited period that is sufficient to charge the device's energy storage.

V. EXPERIMENTAL DEMONSTRATION

Based on an appropriate hardware implementation and following the methodology described in Section IV-A, a sample PWD circuit is designed [11]. The PWD current consumption was shown to decrease from 3.16 μA during the reception of a wake-up signal to 160 nA in the listening state. To highlight the advantage of the proposed design, the PWD is connected to a commercial agricultural sensor as shown in Fig. 4.A, and the unit is programmed to shutdown the transceiver and switch to sleep mode. Consequently, the board's current consumption decreases from a few hundred milliamps to a few hundred microamps, and the board's lifetime extends from around 10 hours to more than six months. A Wi-Fi router was positioned at 3 meters away from the sensor, and it was used to generate the wake-up signal by transmitting an RF burst at a power level of 7 dBm and a frequency of 2.4 GHz. The RF burst contains 100 to 140 packets with fixed inter-frame spacing which causes the PWD to trigger the IoT device.

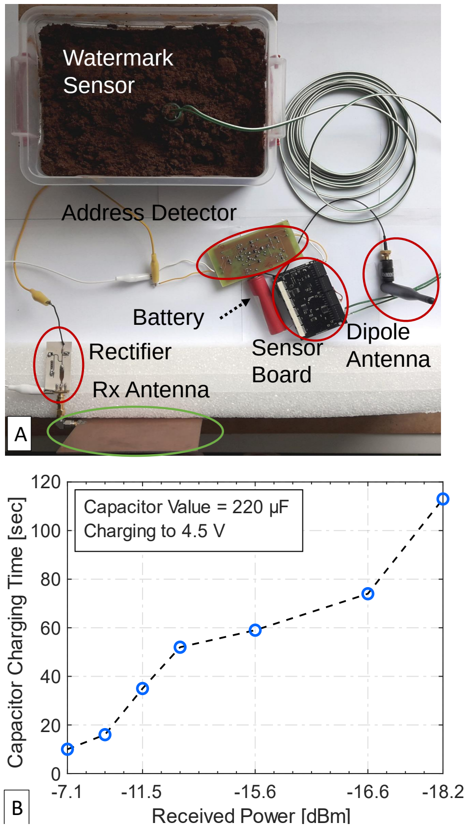

Fig. 4. A) Experimental setup of the PWD to trigger an agricultural sensor and measure soil moisture [11]. B) The capacitor's charging time in a combined RF wake-up and charging system as a function of the received power.

Beyond just the PWD, Fig. 4.B shows the time required to charge a 220 μF capacitor as a function of the input power in a sample combined architecture design following the general framework described in Section IV-B. We choose this capacitor value because it is common for various IoT applications. The transmitting power is set to 10 dBm, and the transmitter and receiver are equipped with antennas with a gain of 12 dB. Each data point in Fig. 4.B represents the time required to charge the capacitor from an empty state to 4.5 V. The PMU fails to reach the steady state voltage when the input power is decreased below the sensitivity of the charging system (−18.2 dBm) as a result of increasing the distance from 0.2 to 1.2 meters. On the other hand, the sensitivity of the wake-up component is −40 dBm because it uses active digital logic to process the signal. This experiment shows that the time required to charge an energy storage element (up to a few minutes) is much larger than the time required to deliver a pulsed wake-up signal (a few milliseconds or less). Therefore,

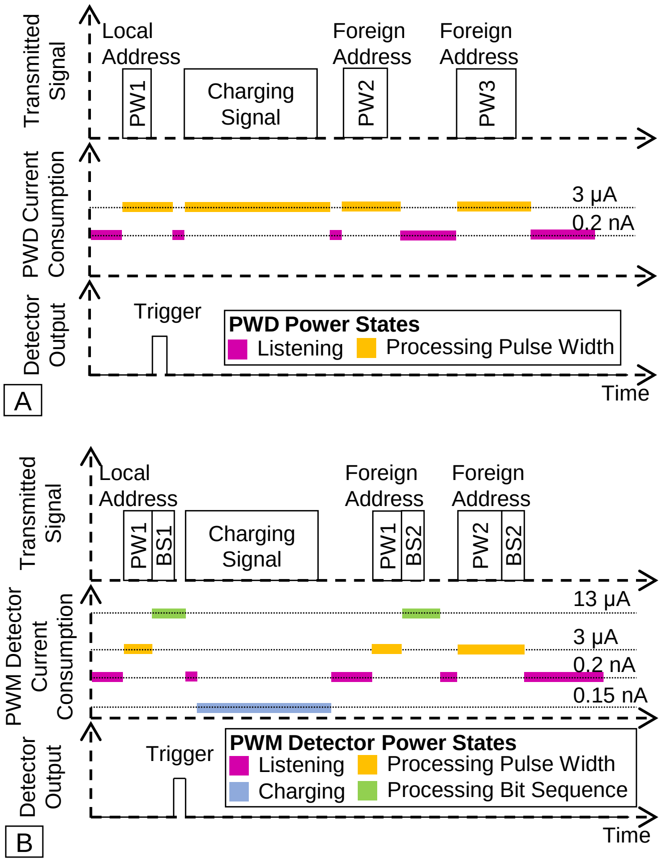

Fig. 5. Current consumption of the PWD and PWM detectors in a test scenario that includes an unmodulated charging signal for a limited period and several modulated wake-up signals.

it is crucial to consider minimizing the current consumption of the address detector during charging. This further validates the importance of the multi-power-mode PWM design described in Section IV-C.

VI. Comparison of PWD and PWM Detectors

A common practice in address detector design for wake-up receivers is to focus on reducing the maximum current consumption during the processing of the wake-up signal. In fact, the maximum current consumption is often considered as the most crucial figure-of-merit when comparing the performance of wake-up receivers [3]. A question that arises when designing a multi-power-mode address detector is whether we should take the maximum current consumption as the figure-of-merit, and if not, how do we assess the current consumption savings that we achieve through hardware design. To answer this question, we may consider the current consumption profile of the PWD and the PWM detector circuits in a test scenario where the two circuits receive a wake-up signal containing a local address and two wake-up signals that contain foreign addresses, in addition to an unmodulated charging signal.

The test scenario is shown in Fig. 5. The transmitter relies on a dedicated energy source and can either generate a time-limited unmodulated charging signal, modulated wake-up signal, or seize transmission. We may think of the two detectors as operating in a power state machine where the default state is the listening state. The PWD shifts from the listening to the processing pulse width state upon the reception of the wake-up signals (PW1, PW2 and PW3) and it generates a trigger when the local address (PW1) is received. The PWD also remains in the processing pulse width state when an unmodulated charging signal is received. On the other hand, the PWM detector sequentially activates the hardware to process the local address, which is composed of a pulse width and a bit sequence (PW1 BS1) and generates a trigger. The PWM address detector also reaches the maximum current consumption when a foreign address that begins with the same pulse width (PW1 BS2) is received, and it switches to the charging state with minimal current consumption during the reception of the unmodulated charging signal.

The PWD achieves a significantly smaller maximum current consumption when compared to the PWM detector. However, in the test scenario, where switching between charging and wake-up occurs, the PWM detector may achieve a lower average current consumption due to the switching to the charging state with minimal current consumption. The results in Fig. 4.B show that the time to charge a capacitor could exceed a minute, and the PWM detector's current consumption is minimal during this period. Although the PWM detector's maximum current consumption is relatively high, this is incurred only in short bursts (few milliseconds) when the local pulse width (PW1) is detected, indicating the start of a bit sequence. Still, in an application where charging is infrequent, and there is a need to address a limited number of IoT devices, a PWD design may be better than a PWM design with a lower average current consumption.

To sum up, the PWM detector achieves higher bursts of maximum current consumption, and a smaller average current consumption due to switching to the charging state for extended duration. The bursts period is reduced by sequential activation and powering the bit correlator only when the local address pulse width is received. The PWM detector is therefore suitable for applications where random switching occurs between charging and wake-up. By comparing the current consumption profile of the two detectors, the average current consumption is an appropriate figure-of-merit to consider when the detector is switching between several power states, and it is important to consider how the address detector's power state machine responds to long periods of charging.

VII. Combined Vs Standalone RF Energy Harvesting and Wake-up

To highlight the benefits of combined RF energy harvesting and wake-up, the total current consumption of a commercial IoT device [12] that implements the combined architecture with the use of the multi-power mode PWM-detector discussed in Section IV-C is compared with the cases when wake-up and energy harvesting are considered separately. The considered IoT sensor has a current consumption of 0.2 μA in sleep mode and 23 μA in active mode. The current consumption results are shown in Fig. 6. The harvesting-only scheme does not implement any RF wake-up mechanism. Instead, a rectifier and a power management unit are introduced to harvest RF signals when possible to extend the battery power supply of the IoT device. In addition, the IoT device is cycled between sleep and active modes, which may result in excess wake-up events, extended delays and further energy consumption.

In the wake-up only case, a conventional two-power mode address detector is added to the IoT device. To ensure a realistic comparison, an embodiment of the PWM detector is considered with conventional listening (0.2 nA) and processing (13 µA) modes. When an RF signal is received, the address detector switches to the processing state and cannot differentiate between charging, local address and foreign addresses. During the processing state, the total current consumption is dominated by that of the address detector consuming 13 µA. The wake-up only scheme eliminates the excess wake-ups incurred in the harvesting-only scheme. However, it raises the total current consumption outside the active period of the IoT device. The unnecessary current consumption occurs whenever a charging signal or foreign address is received.

In the combined scheme, the front-end circuit includes the multi-power-mode PWM detector. The PWM detector distinguishes between the charging signals and wake-up signals with foreign addresses once received, and unlike the conventional two-mode detector, it remains in the listening state with minimal energy consumption. When a charging signal is received, the PWM detector detects it and starts charging the battery of the IoT device. When the correct address is received, the PWM detector switches to the processing bit sequence state and raises its current consumption to 13 µA. By comparing the proposed structure with the traditional schemes, we can notice that further energy savings are achieved across all windows, including charging, processing a local address, and processing foreign addresses. This is mainly due to the ability of the proposed architecture to differentiate between charging and wake-up as well as between local and foreign addresses. Thus, only needed components are activated and the total energy consumption and latency are reduced. Furthermore, frequent battery charging/replacement is no longer required. As a result, the IoT device can reach near-zero power consumption with high responsiveness and self-sustainable operation.

VIII. CONCLUSION AND FUTURE DIRECTIONS

In this article, we presented the challenges of implementing combined RF energy harvesting and wake-up where a single rectifier is used for RF-DC power conversion and demodulation. We introduced a general design framework with two design architectures, namely, the PWD and the PWM detectors to enable the combined architecture and overcome the encountered challenges. The PWM detector includes the PWD in its hardware and it extends its capability by adding a bit correlator and a wake-up/charging mode switch. We further validated the practicality of the proposed methodology by testing prototype designs under practical operational conditions and comparing them with traditional RF wake-up only and energy harvesting only schemes. We outline below additional future research directions.

1) Advanced Hardware Designs: To further reduce the energy consumption of IoT devices and enhance the efficiency of energy transfer in combined systems, optimized signal structures must be designed to maximize the efficiency of the implemented hardware. For instance, adaptive signal generation can be applied at the transmitter's side to change the number, size, and inter-frame spacing of transmitted packets according to network conditions. This action aims to optimize the power delivery efficiency and minimize wake-up delay. On the other side, a power- and load-agnostic rectifier design is required at the receiver's side to overcome fluctuations in input power and variations in load impedance. Employing the rectifier for wake-up also necessitates a fast rectifier response to support the demodulation of wake-up signals at a high bit rate. Decoupling the address detector during charging tasks is essential to reduce its current consumption and false wake-up probability. On addition, jamming avoidance at the address detector is an essential factor to handle in highly dense networks where the device shuts down wake-up signal processing during charging tasks.

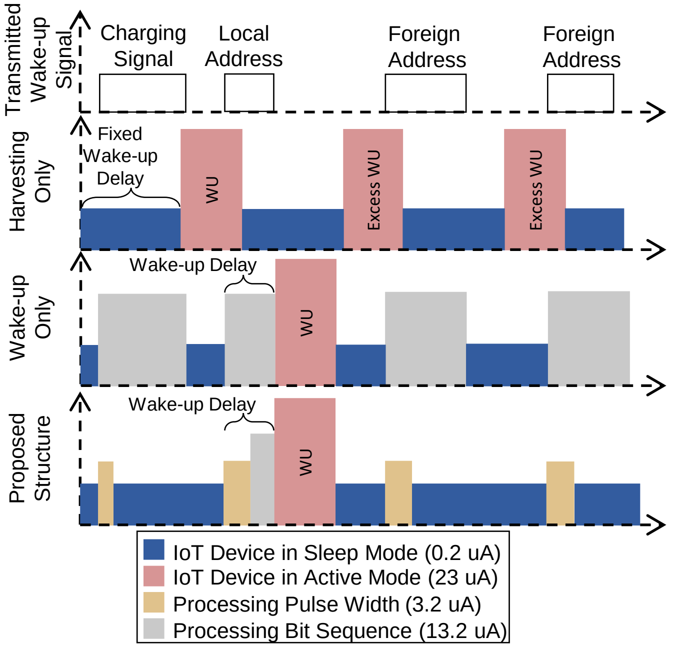

Fig. 6. A comparison of the total current consumption between a harvesting only system, wake-up only system, and a system implementing combined RF energy harvesting and wake-up.

2) UAV-enabled Combined RF Energy Harvesting and Wake-up: In addition to the hardware-related enhancements, UAVs can be effectively used to enable combined RF energy harvesting and wake-up of IoT devices in remote and hard-to-reach areas [10]. The use of UAVs can reduce the gap between the charging range and wake-up range since a UAV can easily relocate to get closer to the IoT device for charging tasks and remain distant during wake-up tasks. Several research works have addressed the use of UAVs for data collection from IoT devices and for wireless energy transfer purposes [13], however, UAV-enabled combined RF energy harvesting and wake-up is still a new research direction with plenty of open problems that need to be addressed. For instance, the

UAV's trajectory and height should be optimized to enable combined charging and wake-up. This must be achieved while maximizing the power received by individual IoT devices and while minimizing the energy consumption of both the UAV and IoT devices. The flight trajectory can also be optimized based on the design objectives (RF energy harvesting only, RF wake-up only, or mixed flight) while accounting for the size, weight and power constraints of the UAV.

3) Integration in B5G/6G networks: Although 3GPP and IEEE 802.11 have introduced RF wake-up in their recent standardization efforts [14], [15] to extend the lifespan of battery-powered IoT devices, many challenges still persist especially in terms of integration with existing transceiver designs and alignment with the control-plane and data-plane protocol stack. Advanced technologies in B5G/6G systems such as ultra-massive MIMO, multi-user energy beamforming, and reconfigurable intelligent surfaces can be exploited to enhance the efficiency of the proposed combined RF harvesting and wake-up architecture. These technologies allow for the smart reconfiguration of the propagation medium and for focusing the transmitted RF energy in narrow beams toward the IoT devices. This requires, however, efficient channel estimation techniques to acquire the channel state information and optimize the beamforming accordingly, which is quite challenging with battery-limited IoT devices.

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