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Wake-Up Radio's Quality of Service adjustment by leveraging RF Energy Harvesting

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Abstract—Wake-up radios (WuRx) are ultra-low power devices designed to continuously listen to the channel for an incoming message and activate the main node when necessary. The ultra-low power consumption of such devices opens the door to their powering only by exploiting Radio-Frequency (RF) energy. This paper presents the integration of an RF harvester in a WuRx and addresses the goal of optimizing WuRx quality of service based on the available harvested energy. Indeed, the harvested energy depends on the RF received power and the WuRx consumed energy must be adapted to the available energy. Therefore, the number of incoming messages processed by the embedded WuRx microcontroller is adjusted based on battery status, optimizing power utilization and ensuring WuRx sustainability. Using both energy modeling and experimental measurements, we show that the RF harvester is capable of maintaining WuRx operation with input power levels as low as -18 dBm.

Index Terms—Ultra-low-power, wake-up radio, radio frequency harvester, wireless power transfer (WPT), power management.

I. INTRODUCTION

In the context of an increasing deployment of the Internet of Things (IoT), the long-term operation of connected devices is often limited by their batteries, which typically serve as the primary power source. The use of Wake-up Radio receivers (WuRx), driving the IoT on-demand, reduces the required energy since, most of the time, the main node is in a deep sleep state [1]. Furthermore, making the WuRx independent of the main battery will enhance the sustainability of connected devices [2].

With the advancement of Ultra-Low Power (ULP) consumption electronic devices, ULP WuRx are now available. For example, ULP WuRx described in [3], [4], and [5] achieve power consumption levels in the order of nW. Powering such devices with the energy harvested from low levels of the Radio Frequency (RF) field is a promising solution currently being investigated [6]. Fig. 1 illustrates the targeted IoT device, composed of an IoT node triggered by a wake-up interrupt send by the WuRx once a specific signal, called Wake-up Signal, is correctly received. An RF harvester circuit powers the WuRx with a regulated Direct Current (DC) voltage, either from the RF power being harvested or from the RF energy stored from the surplus RF power not being used by the WuRx, as described in [7].

However, the RF power levels typically expected at the input of an RF harvesting circuit can be low and fluctuating. The energy consumed by the WuRx must be therefore adapted

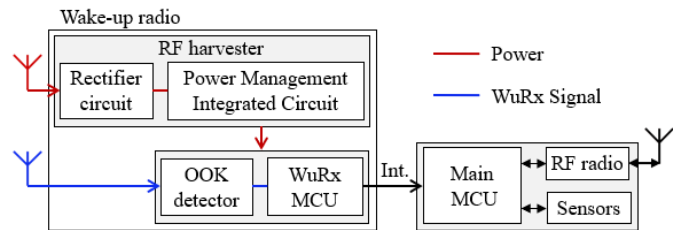


Fig. 1. Architecture of the IoT device embedding a WuRx powered by RF energy.

to the available harvested energy. The WuRx in [5] achieves a power consumption of 152 nW when no data is received, and this consumption can exceed $100 \mu\text{W}$ when processing the address. To ensure the sustainability of the WuRx, the number of processed addresses must be adapted based on the available harvested RF energy. This task is performed by an energy manager embedded in the WuRx microcontroller (MCU) firmware.

In the context of energy harvesting-based IoT, several energy managers algorithms have been reported in the literature, which are implemented in the main MCU of the IoT node for quality of service (QoS) optimization [8] [9] [10]. QoS can be defined as the frequency of IoT sensing measurements or the activation of the IoT radio interface. In the present paper, the QoS adjustment is implemented in the WuRx and is defined as the ratio of processed addresses among all the received ones. The proposed adjustment incurs very low computational overhead, making it suitable for resource-constrained systems like the WuRx. To the best of the authors knowledge, this is a novel strategy that additionally leverages RF harvesting energy.

II. RF ENERGY POWERED WAKE-UP RADIO

The scenario proposed in this work involves powering an ULP WuRx using RF energy harvested from the environment or a dedicated RF power source. An RF harvester, designed to be efficient over a wide power level range [7], is utilized in conjunction with the ULP WuRx proposed in [11]. The harvester antenna is solely dedicated to harvest RF energy, while the WuRx antenna is employed to receive information.

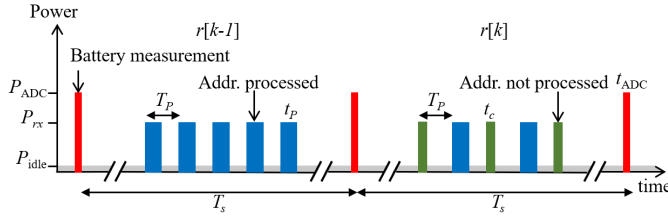


Fig. 2. Dynamic adjustment of the ratio of processed addresses within the received signals.

A. Wake-up radio

The WuRx, designed to process addresses, primarily consists of an On-Off Keying (OOK) detector and an ULP MCU. Signal reception triggers the activation of the WuRx MCU, thereby reducing power consumption during idle periods, as described in [11]. Battery measurement capabilities are added to the WuRx. A voltage divider is employed to reduce the battery voltage to the ADC range, which has a voltage reference of 1.8 V. Two transistors acting as switches are used between the voltage divider ground and WuRx ADC input. The switches are open when not measuring the battery, thus preventing current leakage. QoS and energy consumption is adjusted as illustrated in Fig. 2. The WuRx briefly measures its dedicated battery state of charge E_S although this step is power-intensive. This measurement is performed after a certain number of received signals that defines a time slot duration T_S . Within a time slot k , the QoS is defined as the ratio of address processing events N_{addr} within the received signals N_{rx} :

$$r[k] = \frac{N_{\text{addr}}}{N_{rx}}. \quad (1)$$

For simplicity, it is assumed that signals are received at a packet rate of $\lambda_P = 1/T_P$ packet/s.

The average power consumption of the WuRx per slot $\overline{P_S}$ for the operating mode depicted in Fig. 2 is modeled as:

$$\begin{aligned} \overline{P_S}[k] = & r[k]\lambda_P t_P \overline{P_{rx}} + (1 - r[k])\lambda_P t_c \overline{P_{rx}} \\ & + [1 - r[k]]\lambda_P t_P - (1 - r[k])\lambda_P t_c P_{\text{idle}}, \end{aligned} \quad (2)$$

where t_P is the duration of an address packet, $\overline{P_{rx}}$ is the average power consumption of the WuRx when processing a signal, t_c is the duration when a received signal is not processed and P_{idle} is the power consumption of the WuRx when no signals are received at its antenna. Although the activation of the ADC is power-intensive, it is not included in $\overline{P_S}$, since it occurs only once per slot for a short duration.

B. RF harvester

The wide power range RF harvester designed in [7] is employed. It consists of a RF rectifier circuit and a Power Management Integrated Circuit (PMIC). The former converts the RF power into DC voltage, which is then regulated by the PMIC. The RF harvester is capable of maintaining the operation of the WuRx with input RF power levels P_{in} as low as -20 dBm when the WuRx does not process any addresses. When higher power levels are available, the RF harvester

efficiently stores into a battery the energy not being used by the WuRx. The PMIC is a commercial BQ25570 from Texas Instruments, chosen for its low quiescent power P_L , which must be considered along with $\overline{P_S}$ to adjust the WuRx QoS.

III. WAKE-UP RADIO QUALITY OF SERVICE ADJUSTMENT

Despite the ultra-low power consumption of the WuRx, adjusting its energy consumption is necessary due to time-varying RF power levels expected at the input of a RF harvester. To be considered viable, the dynamic adjustment mechanism must add negligible power consumption relative to the inherent WuRx power consumption. To achieve the sustainability of the WuRx, the Energy Neutral Operation (ENO) strategy is considered and consists in spending only the energy harvested in the last slot period $E_H[k-1]$. It is implemented by:

$$E_H[k-1] = E_S[k] - E_S[k-1] + E_C[k-1], \quad (3)$$

where $E_S[k]$ is the energy state of the battery at the beginning of time slot k and $E_C[k-1]$ is the energy consumed by the system during the last slot, expressed by:

$$E_C[k-1] = \overline{P_S}[k-1]T_S + P_L T_S, \quad (4)$$

Since ENO is considered, $E_H[k-1]$ must be equal to $E_C[k]$. Thus, $\overline{P_S}[k]$ can be expressed as:

$$\overline{P_S}[k] = \frac{E_H[k-1] - P_L T_S}{T_S}. \quad (5)$$

By combining (2) and (5) and isolating $r[k]$, the next slot ratio leading to a power consumption equal to the harvested power during the last period can be obtained:

$$r[k] = \frac{\frac{E_H[k-1] - P_L T_S}{T_S} - \lambda_P t_c (\overline{P_{rx}} - P_{\text{idle}}) - P_{\text{idle}}}{\lambda_P (t_P - t_c) (\overline{P_{rx}} - P_{\text{idle}})}, \quad (6)$$

with $r[k]$ bounded to $[0, 1]$ and set to 0 when it falls below a safety threshold higher than the minimum energy E_{MIN} required by the WuRx during a slot. This strategy implies few computational overhead and only $E_S[k-1]$ and $r[k-1]$ must be saved in memory.

IV. EXPERIMENTAL EVALUATION

A. Microbenchmarking the hardware

First, in order to estimate the performance of the proposed strategy, both the WuRx and the RF harvester characteristics are microbenchmarked in order to feed the model and equations aforementioned with realistic values, achieving a hybrid modeling.

Addresses are transmitted using OOK modulation at a data rate of 1 kbps. Each address packet consists of 11 bits, with 8 bits coding the address and 3 bits used as a preamble, as described in [11]. Fig. 3(a) shows the measured power consumption profile of the WuRx. The peak in power consumption is due to the activation of the Analog-to-Digital Converter (ADC) of the WuRx MCU, which occurs only during battery state-of-charge measurements. To reduce $\overline{P_{rx}}$ during bit reception, the WuRx MCU is set to sleep mode

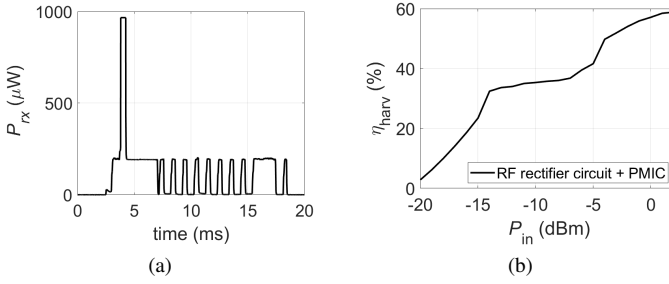


Fig. 3. (a) Power consumption profile of the WuRx when processing an address and measuring the battery and (b) total efficiency of the RF harvester circuit including the RF rectifier circuit and PMIC.

TABLE I
MEASURED WAKE-UP RADIO PARAMETERS

t_P	t_c	$\overline{P_{rx}}$	P_{idle}	t_{ADC}	P_{ADC}
13 ms	1 ms	150 μ W	250 nW	400 μ s	1 mW

periodically, which explains the valleys in the current profile shown in Fig. 3(a). The measured parameters of WuRx are summarized in Table I.

Regarding the RF harvester, the measured RF-to-DC conversion efficiencies, η_{rect} , are taken into account, along with the PMIC efficiencies, η_{PMIC} , provided by the manufacturer. Fig. 3(b) shows the total efficiency η_{harv} of the RF harvester as a function of the input RF power P_{in} . P_L is measured to be around 2 μ W. These values are used in the simulations presented in the next subsection.

B. QoS adjustment simulations

Fig. 4 shows $r[k]$ as a function of P_{in} for different λ_P to achieve ENO. λ_P is bounded to [1, 76] packet/s. There is not a substantial difference among the values lower than $\lambda_P = 1$ packet/s. Moreover, $\lambda_P = 76$ packet/s is the maximal packet rate for $t_P = 13$ ms. For the maximal data rate, it can be observed that adjusting $r[k]$ can lead to an ENO over a decade of input RF power levels, increasing $r[k]$ starting at -15 dBm. Regarding low input powers which is usually the case in RF harvesting scenarios, for $\lambda_P = 1$ packet/s, $r[k]$ starts increasing at -18 dBm and reaches its upper limit at -16 dBm.

When considering a Wireless Power Transfer (WPT) scenario, power is transmitted following a duty-cycled source with $D_{src} \in [0, 1]$ the duty-cycle setting. Fig. 5 shows $r[k]$ as function of the input power for different D_{src} when $\lambda_P = 1$ packet/s. For $D_{src} = 0.25$, to achieve ENO, $r[k]$ starts increasing at -15 dBm. This analysis allows the setting of D_{src} to be used according to the allowed RF power levels that can be transmitted and the expected λ_P in a determined environment.

Finally, the proposed QoS adjustment is tested with a variable RF power level at the input of the RF harvester with the following parameters: $\lambda_P = 1$ packet/s, $V_{MIN} = 2.3$ V and $V_{MAX} = 4.2$ V. A 100 μ F ceramic capacitor is considered as storage element which requires a time of charge of 50 s

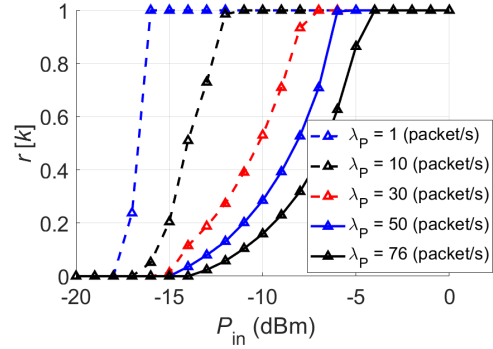


Fig. 4. $r[k]$ as function of the input RF power P_{in} for several packet rates.

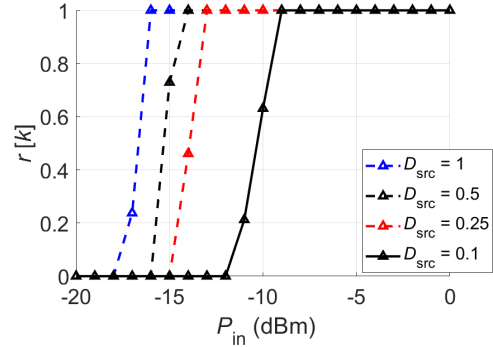


Fig. 5. $r[k]$ as function of the input RF power P_{in} for different duty-cycles of a dedicated RF power source ($\lambda_P = 1$ packet/s).

to charge the capacitor from V_{MIN} to V_{MAX} when a P_{in} of -14 dBm is available and η_{harv} is considered. D_{src} is fixed to 0.25 which implies a non-transmitting duration of 150 s. For this capacitor, the discharge time is 138 s when $r = 1$ implying the QoS must be adapted to keep the WuRx sustainable. T_S is set to 2 times the power source period, i.e. 400 s. Fig. 6 shows both the received RF power and the adjustment of $r[k]$ over time. Due to the safety threshold, the WuRx never entered into a dead state, demonstrating the capabilities of our proposed QoS adjustment.

C. Measurements

The proper operation of the WuRx with QoS adjustment based on the RF harvested energy is verified with measure-

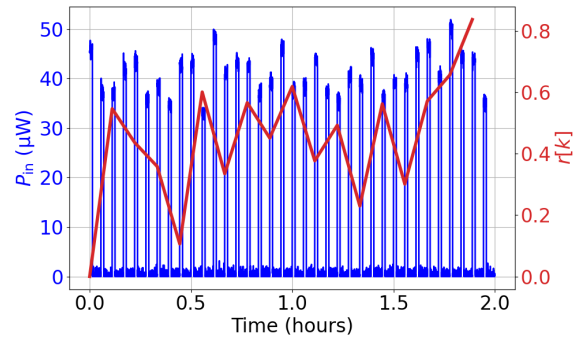


Fig. 6. $r[k]$ as function of the input RF power for achieving ENO for different duty cycles of a dedicated RF power source ($\lambda_P = 1$ packet/s).

ments. The RF harvester is fed with an 888.7 MHz continuous wave signal using a vector signal generator N5182A. The RF harvester power supplies the WuRx with a regulated voltage of 1.8 V. A STM32L0 Discovery kit is used to transmit address packets. A CX3300A waveform analyzer is used to measure the current profile of the WuRx. Fig. 7 presents the measurement setup.

To observe two slots as well as the duration of received signals, λ_P is fixed to 30 packets/s, and T_S is defined by the reception of 10 packets. Fig. 8 shows the WuRx current profile over two slots. When receiving a P_{in} of -9.3 dBm, $r[k]$ equals to 0.5 and a minimum P_{in} of -6.5 dBm is required to set $r[k]$ to 1. In simulation, the input powers required for these $r[k]$ are -10 dBm and -7 dBm, respectively. Differences may be explained by η_{PMIC} interpolations and P_{ADC} being neglected. Because the waveform analyzer was set to a range of $200 \mu\text{A}$, in Fig. 8, the peak of current corresponding to the ADC activation is limited to $270 \mu\text{A}$. The next available range setting is 2 mA , making it impossible to measure currents in the order of μA . However, this peak was measured with an Oti Ace power source to be around 1 mW as reported in Table I.

V. CONCLUSIONS AND FUTURE WORK

The integration of an RF harvester with a Wake-up Radio (WuRx) demonstrates the potential for optimizing ultra-low power consumption for continuous listening devices. This study addressed the challenge of balancing WuRx quality of service with the available harvested energy. The approach involves adjusting the number of processed packets with respect to the incoming signals, thereby adjusting power utilization and ensuring the sustainability of WuRx operations. Verification through both energy modeling and experimental measurements confirmed that the WuRx can adjust its quality of service based on available energy, underlining the viability of RF energy harvesting as a sustainable power source for

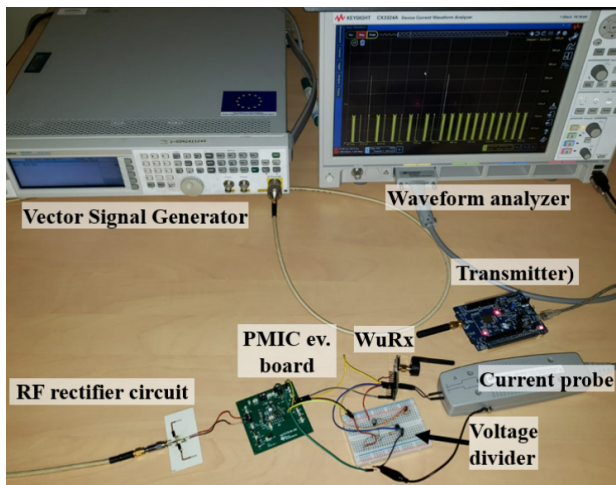


Fig. 7. Setup for measuring the QoS adjustment of the WuRx in function of the RF power levels at the input of the RF harvester circuit.

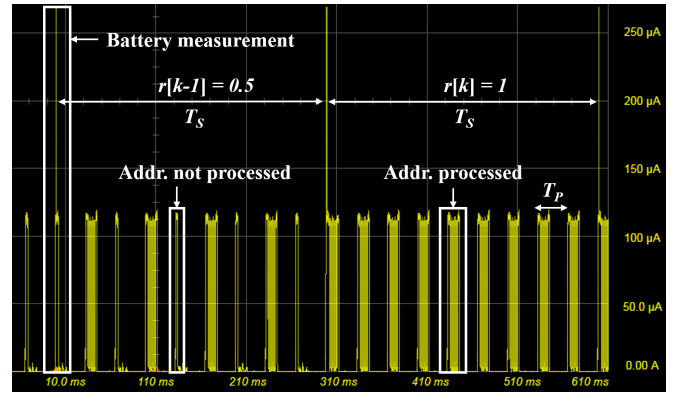


Fig. 8. Measured QoS adjustment for the following parameters: $\lambda_P = 30$ packet/s, $D_{src} = 1$ and P_{in} is varied from -15 dBm to -5 dBm.

WuRx, down to -18 dBm. Future work will focus on integrating the various circuits into a single and compact board.

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