RF Energy Harvester-based Wake-up Receiver

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***Abstract*—Wake-up receivers (WuRxs) can improve the lifetime of a wireless sensor network by reducing energy consumption from undesirable idle listening. The amplitude level of the incoming RF signal is used by a WuRx to generate an interrupt and wake up the radio of a sleeping sensor node. Existing passive WuRx designs are generally based on RFID tags that incur high cost and complexity. Thus, there is a need for cost-effective and low-complexity WuRxs suited for both long-range and directed wake-ups. In this work, we present a WuRx design using an RF energy harvesting circuit (RFHC). Experimental results show that our RFHC-based WuRx can provide a wake-up range sensitivity around 4 cm/mW at low transmit RF powers (< 20 mW), which scales to a long wake-up range at high powers. Our design also obtains accurate selective wake-ups. We finally present simulation-based studies for optimizing the design of RFHCs that enhance decoding efficiency with improved rise and fall times.**

I. INTRODUCTION

A wireless sensor network (WSN) typically consists of tiny nodes that sense the surrounding phenomenon and communicate their sensed information to a base station. Due to their small form-factor, these nodes have batteries with limited energy. Once this energy is depleted, the nodes become dead [1]. As data communication accounts for major energy drain for the node, one way to extend the lifetime of nodes is by judicious use of the radio on period. In this regard, energy-efficient medium access control (MAC) protocols aid the node in transmitting optimally, thereby reducing collisions and re-transmissions. In addition, MAC protocols put the node in sleep mode most of time as energy consumption is at least an order of magnitude less in the sleep state compared to the active state. Using this alternate active and deep-sleep cycles extends the node lifetime substantially. However, in such duty-cycle-based protocols, the node suffers from idle listening and overhearing [2].

Both idle listening and overhearing can be alleviated with the help of an additional hardware component, a wake-up receiver (WuRx). A WuRx allows a node to switch off its radio and stay in sleep mode unless it needs to sample the sensor, thereby prolonging the sensor node's life. The WuRx wakes the node on-demand when it receives a wake-up signal from a wake-up transmitter (WuTx). This WuRx can be either active – using the energy of the node to receive a wake-up signal, or passive – deriving the energy from the wake-up signal. The wake-up technique can be classified as range-based wake-up (RW) – where all the nodes that receive the wake-up signal wake-up, and directed wake-up (DW) – when a node wakes up on an ID match [2]. In this paper, we show that our proposed WuRx can perform both RW and DW.

Energy harvesting is a solution that has the potential to provide perpetual node operation. The sensor node harvests the energy whenever available and stores this energy into a rechargeable battery or a super-capacitor. Unlike other harvesting techniques that depend on spatio-temporal factors, radio frequency (RF) energy harvesting has an advantage that it does not require contact with the source transmitting RF energy and also a dedicated source could be used to provide quality of service (QoS) when needed [3]. It was shown in [4] that cooperative RF energy harvesting can provide significant energy gains in both sparse and dense WSN deployments. An RF harvesting circuit (RFHC) that converts the input RF power to DC energy can be attached to a sensor node to support continuous operation. However, an RFHC introduces another antenna in addition to the antennae for data communication and WuRx. In this work, aiming at more compact node, we use an RFHC itself as a WuRx, thus reducing the components of the node without compromising the functionality.

The rest of the paper is organized as follows. In Section II we present the related research work. Section III introduces our prototype of an RFHC based WuRx (RFHC-WuRx), where we experimentally demonstrate its range performance. The accuracy of DW is demonstrated through experiments and simulations in Section IV. Section V concludes the paper.

II. RELATED RESEARCH

Most of the current state-of-the-art techniques on passive WuRxs rely either on an RFID–based approach or simulation studies. Nonetheless, there exist few non-RFID-based WuRx implementations which use simple circuits. Gu et al. [5] first introduced a passive WuRx as a radio triggered circuit that is capable of performing RW. Using SPICE simulations, they showed that their design could provide a wake-up range of 30 meters with a 55 msec delay. Furthermore, they proposed a circuit that performs DW with the help of multiple transceivers operating at different frequencies. A node wakes up only when it receives a particular set of frequencies. Ba et al. [6] demonstrated a passive WuRx designed using a passive RFID tag – Intel wireless identification and sensing platform (WISP) that could provide a range of up to 4 meters. They showed that their WuRx could provide both RW and DW. Later, Chen et al. [7] showed an increase in the wake-up range by a WISP based design with the help of an RFHC [8]. In addition, the authors presented a novel passive WuRx using a reset circuit and an RFHC [8], termed as REACH mote [7]. This design could provide a range of up to 6 meters using an RFID reader or a Powercast transmitter [9]. However, this does not selectively wake up a sensor, i.e., it is unable to perform a

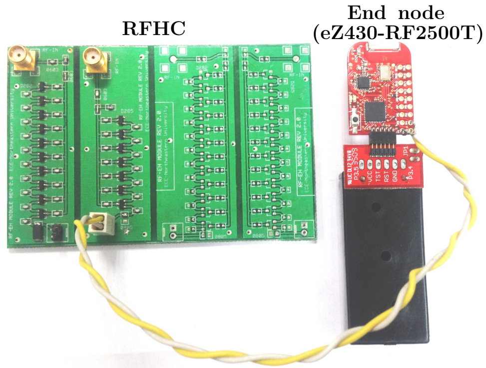


Fig. 1: Prototype of our RFHC-WuRx enabled sensor node.

DW. Recently, Donno et al. [10] designed a long-range passive WuRx providing DW by using an additional DC-DC converter. Although their design provides a wake-up range of 11 meters, the presence of DC-DC converters significantly increases the hardware cost. In contrast, in this work, we propose a WuRx design based on RFHC that is capable of providing both RW and DW, without using any additional hardware.

III. Range-based Wakeup

The prototype of our proposed RFHC-WuRx enabled wireless sensor node, shown in Fig. 1, consists of an RFHC connected to the interrupt pin of the micro-controller (μC). Unlike in the typical use of RFHC as an RF-DC transducer, we utilize it as a WuRx. A 7-stage RFHC designed to operate at extremely low input RF power [8] is used. We have used a Texas Instruments (TI) eZ430-RF2500T as a sensor node, which contains a TI MSP430F2274 ultra-low power μC and a CC2500 transceiver that operates at 2.4 GHz. From now onwards, we use the term *end node* for the sensor node that is connected to the RFHC.

Within the safe operation limits of the μC, the DC output voltage of an RFHC can be categorised as LOW and HIGH corresponding to the μC's low and high logic levels, respectively. The input RF power to the RFHC (such as a wakeup signal) causes its output voltage to go from LOW to HIGH after a minimum threshold RF power P_{th}. This transition from LOW to HIGH behaves as a positive edge trigger, which interrupts the sleeping mote's μC to go into the active state.

A. Experiments to characterize wake-up range

In order to experimentally find the achievable wake-up range at different input RF powers, we program the mote to stay in the deep-sleep mode. Upon receiving a wake-up trigger, the node enters the active state to send the wake-up sequence number to the access point connected to the laptop. The sequence of operation states is shown in Fig. 2. Experiments are carried out with the Agilent N9310A RF source operating at 915 MHz and the prototype shown in Fig. 1 placed inline. Further, we use Powercast 6 dBi antennae [9] at both the RF source and the RFHC-WuRx enabled sensor node.

B. Observations

As the maximum transmit power of the RF source is just +13 dBm (= 20 mW), experiments were limited to this

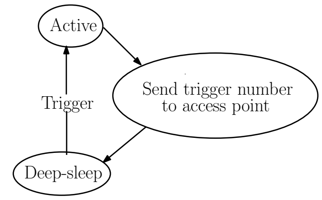


Fig. 2: Range-based wake-up state diagram.

low-range transmit powers. The effect of transmit power of the RF source on wake-up range is shown in Fig. 3. The solid line shows the maximum wake-up range that can be achieved at different RF transmit power levels. We observe that a maximum range of 116 cm could be achieved for 20 mW transmit power of the RF source in our case. Using polynomial fitting in MATLAB, we observe that the maximum wake-up range indeed exhibits a linear behaviour at this low power regime, providing a range sensitivity of 4 cm/mW. Although extrapolation gives the wake-up range obtained for higher RF powers, the actual range would be much lower. However, the wake-up range attained by our design at high RF transmit power is the same as that of REACH mote [7]. We confirmed this by finding the maximum range provided by the REACH mote (Tmote sky replaced with eZ430-RF2500) at low RF transmit power levels. The wake-up performance exhibited by the REACH mote is identical to the characteristic shown in Fig. 3 for our design. Moreover, as the proposed design eliminates the reset circuit used by REACH mote, our approach has reduced hardware requirements and thereby it is cost-efficient.

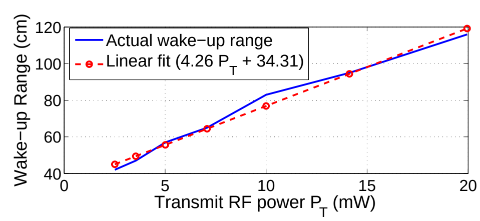


Fig. 3: Effect of transmit power on WuRx range.

IV. Directed Wakeup

RFHC-WuRx can also be used for selectively waking up a sleeping sensor node. The idea behind this possibility stems from the fact that the output of an RFHC transitions from LOW-to-HIGH upon the arrival of an RF signal, and it goes from HIGH-to-LOW shortly after removal of the RF signal. A modulated RF signal can be sent by a WuTx, following which, a node's μC can interpret the target node ID from the knowledge of such LOW-to-HIGH transitions or *interrupts* arrived with-in a fixed time. This can be explained with the help of the timing diagram shown in Fig. 4.

As an example, we assume that the RFHC-WuRx enabled sensor node is in the deep-sleep state and the target node ID to be decoded is 101. The duration of each bit is T sec. A WuTx sends this ID using Return-to-Zero (RZ) encoding and ON-OFF Keying (OOK) modulation. In addition, a 1-bit preamble ('1') is added to the ID. This choice of modulation, encoding, and preamble follows from the facts mentioned below.

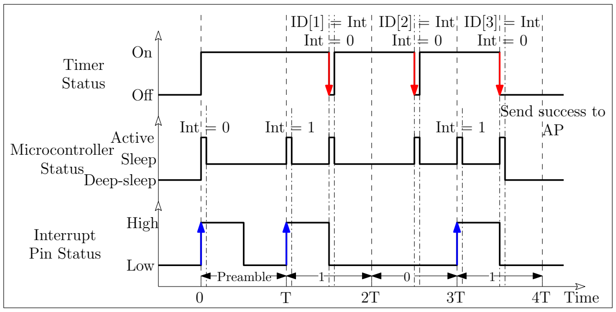


Fig. 4: Directed wake-up timing diagram for ID = 101.

- OOK modulation has an advantage of being simple, i.e., an output signal is present for a '1' bit and no signal for a '0' bit. This output signal for a '1' bit produces an interruption at the μC's interrupt pin, while, a '0' bit generates no interrupt.
- RZ encoding helps in detection of consecutive '1' bits, as the signal is low for some fraction of the bit duration.
- With a 1-bit preamble ('1'), even a binary code that starts with a '0' bit can be successfully decoded.

Reception and decoding of the node ID using a DW follows the steps given below:

1) The preamble causes the μC to go from deep-sleep to active state.
2) In the active state, the μC starts a timer to fire after $1.5T$ sec and goes to sleep.
3) Meanwhile, the first bit of the target node ID ('1'), makes the μC transit from sleep to active state.
4) The μC notes down the arrival of a '1' by changing the Int flag from 0 to 1 and then switches to sleep.
5) Expiry of the timer generates an internal interrupt, which changes the μC state from sleep to active.
6) Now, the μC copies the Int flag status to an ID buffer, clears the Int flag, sets the timer to fire after time T and then goes to sleep.
7) Hereafter, the decoding procedure continues the same way as just described for the first bit in step 3. The only difference is that the '0' bit does not produce an interrupt, as no RF signal is transmitted.
8) As the ID length is known, after receiving the last bit of the target node ID, the μC stops the timer.
9) If the decoded ID matches the target node ID, the node turns on its transmitter to send a success packet.
10) Later, it goes to the deep-sleep mode.

A. Implementation of RFHC based directed wake-up

We consider a delay-tolerant WSN scenario mentioned in [3] where a mobile ubiquitous LAN extension (MULE) collects data from static field sensor nodes. The block diagram in Fig. 5 illustrates the components of the MULE as well as that of the static sensor nodes. The RZ waveform generator is used to encode the node ID. An RF source that is capable of performing OOK modulation is chosen to send the DW signal to the sensor node. On ID match, the target node sends a packet to the access point.

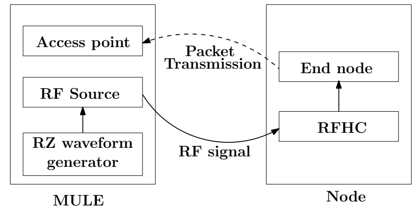


Fig. 5: Block diagram for a directed wakeup.

Experiments have been performed to determine the decoding accuracy with varying bit duration. The specifications for all the components used are listed in Table I.

The field node is programmed with a 5-bit node ID = 11111. In addition, it is programmed to stay in the deep-sleep state the arrival of a wake-up signal, and on ID match, it sends a packet to the access point, which is logged on to the laptop.

For every bit-duration value that we considered, the RZ wave form generator sends the '11111' encoded waveform to the RF source. The RF source modulates this waveform using OOK modulation and transmits the RF signal, i.e., the DW signal, to the RFHC-WuRx enabled end node. After proper ID coding and on match with its programmed ID, the end node sends a success packet to the access point.

TABLE I: System Specifications

S.No.	Device	Specifications
1	Access point	eZ430-RF2500T + eZ430-RF USB connected to laptop
2	End node	eZ430-RF2500T supported by 2 AAA batteries
3	RF source	Agilent N9310A RF Signal Generator transmitting at 915 MHz
4	RZ waveform generator	Agilent 33220A Arbitrary waveform generator
5	RFHC	7-Stage voltage multiplier matched to 915 MHz [8]

B. Experimental results

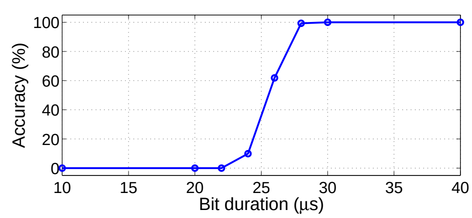
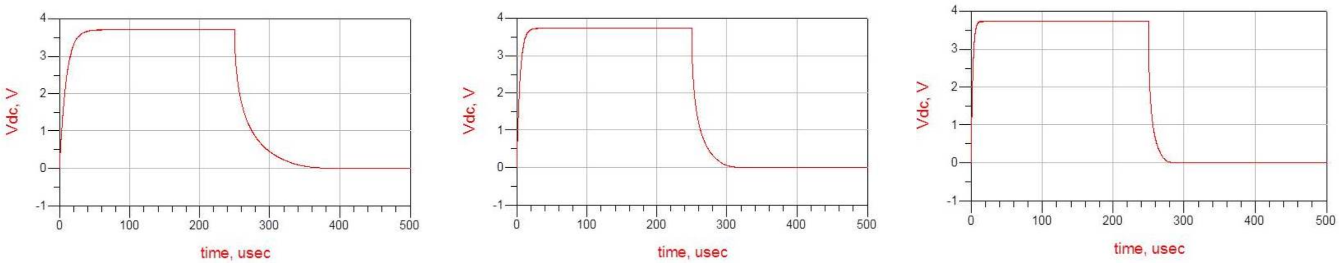


Fig. 6: Decoding accuracy versus bit duration.

The RZ waveform generator is programmed to send 10^4 DW signals for each bit-duration. Successive wake-up signals are transmitted after a short interval so as to allow the end node to send back a packet to the access point. Fig. 6 shows the accuracy for various values of bit-duration. It can be seen that, a 5-bit directed WuC transmitted with a bit rate of $<$ 33.33 kbps can be decoded with 100% accuracy. This bit rate is higher than some of the state-of-the-art WuRxs, such as [11], which provides a bit-rate of 0.5 to 8 kbps.



(a) stage capacitance = 36 pF. (b) stage capacitance = 18 pF. (c) stage capacitance = 9 pF.

Fig. 7: Effect of stage capacitance on rise and fall times. Vdc is the harvested DC voltage.

C. Simulation Studies

A commercial RFHC, such as Powercast P1110 [9] can also be used for DW. But, the presence of a capacitor in the output stage results in a very high discharge time, which is on the order of a few seconds. Such RFHCs lead to high energy consumption when used for a DW. This is due to the fact that, the μC remains in the sleep state, where its timer is switched on for the entire duration of the ID decoding process. Reduction in the rise and fall times of the bit leads to low bit-duration. Due to this, the time taken by the μC to decode the ID is shorter. Thus, energy savings are achieved as the μC can go to the deep-sleep state earlier.

We study the rise and fall times from the response of an RFHC to an RF signal for a limited duration using transient analysis simulation conducted with the Agilent advanced design system (ADS). Simulations are performed to find the effect of stage capacitance on rise and fall times. An RFHC is subjected to an RF signal for 250 μsec. It can be observed from Fig. 7, that the rise time is smaller compared to the fall time for all three values of stage capacitance. Table II shows the rise and fall times obtained for different stage capacitances.

TABLE II: Effect of stage capacitance

S.No.	Stage Capacitance (pF)	Rise Time (μsec)	Fall Time (μsec)
1	36	19.83	55.4
2	18	9.908	27.6
3	9	4.979	14.0

It may be noted that the authors of [8] have developed an RFHC using 36 pF stage capacitors, which we have used in our experiments. The minimum bit duration can be improved by using a 9 pF capacitor, which provides much lower rise and fall times as mentioned in Table II. Compared to the 36 pF stage capacitors used in [8], our choice of 9 pF stage capacitor exhibits 74.89% and 74.72% lesser rise and fall times, respectively. With the reduction in the rise and fall times, the accuracy of DW can be increased for bit-duration less than 30 μsec, which was not possible earlier (Fig.6). In addition, as the energy consumed in DW is proportional to the time for decoding, reduced bit-duration resulting from the reduction in rise and fall times offers significant energy savings.

V. Conclusion

We propose a novel RF energy harvester-based WuRx for WSNs. Our proposed prototype can be used for both RW and DW. Experimental implementation of RW at low transmit power levels provide insights on its high range sensitivity. In addition, the accuracy of DW for varying bit-duration has been demonstrated through hardware experiments. Finally, using ADS simulations we show that the optimal redesigning of an RFHC can lead to high RF energy harvesting efficiency as well as high data rate in DW.

Acknowledgments

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