An Ultra Low Power High Sensitivity Wake-Up Radio Receiver with Addressing Capability

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Abstract— **In power-limited wireless devices such as wireless sensor networks, wearable components, and Internet of Things devices energy efficiency is a critical concern. These devices are usually battery operated and have a radio transceiver that is typically their most power-hungry block. Wake-up radio schemes can be used to achieve a reasonable balance among energy consumption, range, data receiving capabilities and response time. In this paper, a high-sensitivity low power wake-up radio receiver (WUR) for wireless sensor networks is presented. The wake-up radio is comprised of a fully passive differential RF-to-DC converter that rectifies the incident RF signal, a low-power comparator and an ultra low power microcontroller to detects the envelope of the on-off keying (OOK) wake-up data used as address. We designed and implemented a novel low power tunable wake up radio with addressing capability, a minimal power consumption of only 196nW and a maximum sensitivity of -55dBm and minimal wake up time of 130µs without addressing and around 1,6ms with 2byte addressing at 10Kbit/s data rate. The flexibility of the solution makes the wake up radio suitable for both power constrained low range application (such as Body Area Network) or applications with long range needs. The wake up radio can work also at different frequencies and the addressing capability directly on board helps reduce false positives. Experimental on field results demonstrate the low power of the solution, the high sensitivity and the functionality.**

Keywords— nano-Watt Wake-Up Radio Receiver, Ultra Low Power, Wireless Sensor Networks, Power Optimization.

I. INTRODUCTION

Wireless sensor networks (WSN) have emerged recently as an effective technology for a wide range of applications, including smart homes and cities, agriculture, transportation, health and fitness, entertainment, structural health monitoring,[1]. As the sensor nodes which comprise the network operate with batteries, one of the most important challenge is extend the life time using both hardware and [i] software solution. Reducing the communication power consumption of the WSN sensors is significant, as the radio transceiver is one of the highest power consumers in WSN [2]. Optimizing the power consumption of the wireless transceiver can make the sensor smart as it decreases the overall power consumption of the complete WSN system and provides opportunities to add much more functionality. In components, incorporating the applicable criteria that follow. In addition, since the battery size is decisive in determining the size of battery-operated systems, low-power circuits could enable smaller batteries and lead to miniaturization required by many applications such as wearable WSN, medical Body Area Networks and implantable devices [3].

To achieve a reduction in the power consumption of communications, several techniques have been proposed [2]-[12][18]-[30]. All these techniques are trying to reduce or eliminate the wasted power due to the idle listening of the transceiver. The idle state is when the transceiver is listening to the channel to check for an incoming message. Unfortunately, a message can be received only if the radio is in its listening state and idle listening consumes significant power [2] hence a significant design effort is required to alleviate this energy waste.

Duty cycling is a method commonly used to reduce the energy consumption in idle mode. It consists of switching from listening mode to sleep mode, minimizing the transceiver's power consumption [2][4][12]. However, the power savings introduced by duty cycling have a cost. Since the radios cannot receive messages when they are switched off, the network reactivity is limited. Only when both the sender and receiver are awake, can communication be established, meaning the radios have to be synchronized. There are three types of synchronization according to three main schemes: synchronous, pseudo-asynchronous, or pure asynchronous communication schemes [5][10][16]. Duty cycling is, in general, a synchronous scheme, where the radio turns on and listens for any incoming messages for a fixed or adaptive time interval.

Asynchronous schemes are, by far, considered to be the most power efficient; and the most effective realization of asynchronous communication is by using a wake-up radio receiver [16][17][18]. This device, which continuously listens the transmission medium for a wakeup signal, can be coupled with a main transceiver, to be used only when a wake up signal is detected. If the wake up receiver has much lower power consumption than the main radio transceiver, then significant power savings can be achieved. An ultra-low power realization of the wake-up radio receiver can be achieved by reducing, or eliminating, idle listening [7].

A wake up receiver (WUR) must support a number of features in order to become effective [8]. First, the power consumption of the WUR has to be orders of magnitude less than that of the main transceiver in the receiving mode. In

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addition, features such as high sensitivity, robustness to interference, selectivity and latency are very important. Sensitivity is a commonly used the optimization goal, looking to match the sensitivity of the main transceiver but at much lower power. Sensitivity is directly related to the communication range: the higher the sensitivity (measured as the capability to sense the weakest signal in -dBm), the better the range. Unfortunately, improved receiver sensitivity usually translates to increased power consumption

In this work, we present a novel architecture for an ultra low power, low cost wakeup receiver, considering all of the previously mentioned constraints and specifications. More specifically, the contributions of this paper are as follows:

- The design and implementation of a frequency independent wake up radio using only one ultra-low power comparator and microcontroller as active components. The wake up radio consists of a minimal number of low cost, off-the-shelf components.
- Experimental validation of the proposed architecture with in field measurements of power, sensitivity, range, and addressing tunning the frequency at 868MHz.

The paper is organized as follows. Section II reviews the related work; Sections III and IV present the wake-up radio concept and its background. Section V presents the sub μW wake-up radio architecture. Finally Section VI presents the experimental results. Section VII concludes the paper.

II. RELATED WORK

In recent years, there has been a significant effort to reduce the power consumption in WSN using wake up radios, and several methods and techniques have been proposed.

Broadly speaking, Radio Frequency (RF) wake up systems can be classified into two groups: fully passive circuits, and semi or fully active circuits. The first group can work without any power supply, since the circuit can extract energy from the communication power, and use it to generate an interrupt. They are mostly realized using charge pump, Schottky diodes, CMOS or MOSFET topology. However, fully passive receivers can only detect activity on the communication channel, and are unable distinguish a wake up signal from other RF activity. Moreover, it is impossible to receive commands or data to select the proper node. This type of circuits also has a limited range when compared to many typical WSN applications. With a sensitivity of only around -30 dBm, these circuits require higher transmission power, or, where possible, a bigger antenna can be used to extend the range to tens of meters. Due to these limitations, they are usually more suitable for short range applications, where an addressing mechanism is not required. For example, they can be used in some implantable chips, body area networks, near field communication and RFID. Even though their features do not make them appealing for most WSN scenarios (e.g. long range, multi-hop, addressing), there are several relevant zero power building blocks present in a number of WUR architectures found in WSN. One example of such component blocks is the passive rectifier with interrupt, with many examples in recent years being presented in the literature [6] [19]-[22].

Although the zero power consumption feature is very appealing, the main focus of this work is achieving a long range (lower than -30dBm sensitivity). With an increased communication range, more WSN applications could benefit from using wake up radios and their power savings. For this reason the proposed approach makes use of a semi-active receiver.

The second group of RF wake up receivers is referred to as semi or fully active wake-up receivers. In the literature, the most common approaches are semi-active, where power is supplied to only a minimal part of the receiver's components. It is usual to realize this type of circuits using a Shottky envelope detector, MOSFET or ad-hoc ICs for the radio front end and, finally, a comparator to generate an interrupt. The works presented in [23], [24], [25] and [26] show similar architectures for ultra-low power WURs for WSN devices. They all drastically reduce the total network energy consumption by reducing the sensor node listening activities. All these solutions use Schottky diodes for envelope detectors and a comparator. Furthermore, these solutions use multi stage rectifiers instead of a single stage one. No information regarding their motivation given, nor is there much detail on the experimental methodology used to obtain the power and sensitivity measurements. In [27] a very interesting solution which has only 89nW power consumption is presented. This solution is similar to the previously mentioned solutions (using a rectifier and a comparator). They, however, use a custom CMOS rectifier to achieve a sensitivity of -41dBm. It should be noted that this sensitivity is lower and has a shorter range than the one achieved with our approach.

There are also fully active wake up receivers, which use active components both for the rectifier and the interrupt generator. In [28] a solution with a rectifier, high-band baseband amplifier and the wake up signal recognition is presented. They achieve a high sensitivity, -47.2dBm, similar to our wake up receiver. However, as is the case with fully active solutions, their power consumption (more than 6μW) is much higher than our solution. While one of the main goals of our wake up radio circuit is to achieve high sensitivity with sub-μW power consumption. The authors of [29] propose an architecture which uses a LNA and fully active solution to achieve a sensitivity of -89dBm. The use of an LNA allows this very high sensitivity. However, the resulting solution suffers from very high power consumption of a few mW, which offsets the main benefits of the wake up receiver.

The authors [5] have performed a thorough survey of several wake-up schemes and their advantages over the wake-on (duty cycling) schemes. It is shown that the wake-up radio presented in [21], when used without addressing has a clear power advantage when compared to other schemes. This is mainly due to its very low power consumption and low latency. However, an addressing mechanism can significantly reduce the power consumption during a network formation phase. If a wake up receiver is able to receive some command, the Media

Access Control (MAC) data communication protocol can be reduced for low power consumption. There are two ways of implementing the addressing mechanism: a) using a custom circuit; [29] b) using a generic MicroController Unit (MCU) [26]. How the addressing is implemented will have implications on the overall power budget and will influence the selectivity of the system. This confirms the importance of the addressing capability, which is included in our approach.

The approach proposed in this paper significantly improves the power consumption and sensitivity with respect to other state-of-the-art solutions. Furthermore, it offers guidelines and insights for designing wake up radio receivers with off-the-shelf components. To the best of the authors' knowledge, this is the first paper which takes into account all aspects of wake up radios, from the impedance matching, rectifier, and stages of rectifier, interrupt generator and matching to the addressing capabilities.

III. WAKE-UP RADIO CONCEPT

To make communication possible between two wireless nodes, the receiver node must be awake when the sender initiates the communication, a scheme which is referred as a rendez-vous [16]. The receiver having to be awake while it is not receiving any data, is one of the main contributing factors to the overall power consumption of wireless radio communications This is why research efforts attempt fundamentally to reduce or eliminate the power consumption of idle listening via a number of novel hardware (e.g. WUR), software (i.e. MAC and routing algorithm) and duty cycle optimization approaches [9][10]. Previous research highlighted that there are mainly three types of rendez-vous schemes:

a) **Pure synchronous:** The nodes' clocks are pre-synchronized so the wake-up time of each node is known in advance. This scheme requires recurrent time synchronization that consumes considerable energy. Moreover, the sensors wake up even if there is no packet to transmit or receive, causing idle listening or overhearing.

b) **Pseudo-asynchronous (or cycled receiver)**: Source nodes wake up and emit a preamble signal that indicates the intention of data transmission. The preamble time has to be set long enough to coincide with the wake-up schedule of the destination node (i.e. longer than its sleep time). In this scheme time synchronization is not required, but sensors follow a duty cycle and consume considerable energy with preamble signalling.

c) **Pure asynchronous**: The sensor nodes are in deep sleep mode and can be woken up by their neighbours on demand with very low-power wake-up receivers. Whenever a node intends to send a packet, it first wakes up the destination node with a wake up message and then sends the packet. Therefore, wake-up receivers are a solution to the redundant energy consumption caused by rendez-vous.

This paper is focused on the pure asynchronous typology and its implementation by using a separate wake-up receiver (WURx) to monitor the communication channel continuously, while the main radio is kept in the sleep mode all the time it is not needed (Figure 1).

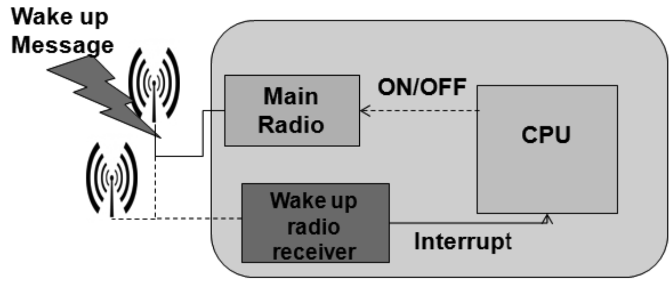


Figure 1 Generic block diagram of a wireless node with a separate wake up radio receiver.

When a node wants to communicate, it sends a wake-up signal which is detected from the WURx to allow the CPU to wake the main radio to start the communication Figure 2.

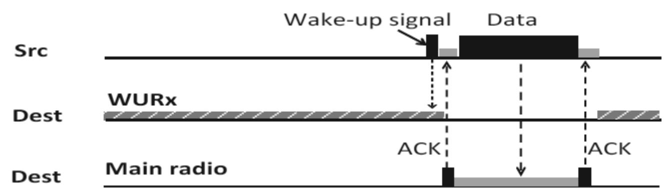


Figure 2 Pure Asynchronous communication scheme using a wake up radio.

The wake up message can contain, for example, the address of the destination node to wake up only the desired neighbour. This is an optional feature which depends on the design or the application requirements. The most important requirement of the wake up radio is to have very low power consumption, usually less than few μW or preferably few nano-watts. Such low power features allow the wake-up receiver to be continuously on, listening for the wake up signal while the main radio is switched off, achieving an overall power saving. Another important requirement of the wake up radio is the sensitivity which is typically measured in dBm. With greater sensitivity, the device is able to receive weaker signals, which means greater transmission distances can be supported. A typical sensitivity of wake up radio receiver is -30dB or higher (-50dB). This covers most communication ranges found in WSN for a transmission power which is limited to +10dBm or less in the ISM. It is important to increase the sensitivity without increasing the power consumption of the receiver; this is one of main challenges in designing the WURx. Finally, as Figure 1 shows, the radio wake up can use the main antenna, or use a second antenna. This depends on the frequency and the modulation used by the main radio transceiver. If the main transceiver is centred on the same frequency as the WUR and it supports the WUR modulation format, then a single antenna can be used. However, one must be aware that for this situation, the additional RF switch will have a negative impact on the link power budget due to some non-negligible losses. The design of the wake up radio requires careful consideration of design issues in RF, analogue electronics, and digital and system design to carefully evaluate the following trade-offs:

- wake-up range vs. energy consumption;
- wake-up range vs. delay;
- same-band vs. different-band wake-up radio;
- Addressing or without addressing.

Moreover, in [6] Gu and Stankovic, who can be considered pioneers of the wake up radio concept in wireless sensor networks, presented the following design goals for WURx which are still valid:

- Low power consumption;
- High sensitivity;
- Resistance to interference;
- Fast wake-up.

The following section presents design considerations of a wake-up receiver which takes into account the above mentioned trade-offs and goals and presents a real world implementation of a wake up receiver to evaluate the proposed approach.

IV. BACKGROUND

A. Frequency, sensitivity and antenna.

The selection of a proper operating frequency band for the wake up receiver is crucial since it will affect the overall size of the receiving antenna, the operating range of the system and the network matching, selection, availability of the required passive components, etc. To get an idea about how the frequency affects these features of the wake-up radio the Friis equation is used:

$$P_r = \frac{P_t * G_r * G_t * \lambda^2}{(4\pi)^2 * d^n} \qquad (1)$$

Where P_r is the power received from an antenna, P_t is the transmission power, G_r and G_t are the gains of the receiving and transmitting antenna respectively, d is the transmission distance, λ is the wavelength of the frequency used, and *n* is the path loss exponent. The P_r is usually expressed in dBm and the sensitivity of the receiving circuits is exactly the lower value of P_r at which the circuit can receive the wake-up message reliably. For example, circuits with -50dBm of sensitivity means that the circuit is capable to detect messages with P_r down to -50dBm. Thus, from (1) considering P_t +10dBm, G_r and G_t = 1dBi and frequency of 868 MHz, the max theoretically achievable distance is 34 meters. Again from (1) using same gains for the antenna, the same sensitivity of the circuits and the same transmission power, going down to 433 MHz it is possible to cover a maximum distance of 68 meters. The communication range becomes 125 meters for a frequency of 24 MHz, etc. It is clear how the frequency can affect the range of the wake up receiver and lower frequency leads to bigger range. However, decreasing of the frequency increases the antenna size. Equation (2) shows the relationship between the propagation speed (speed of light = 300 million meters/sec) and the frequency. So a full wavelength antenna for 24 MHz is around 12 meters and 3 meters for a quarter wavelength antenna, and only 3cm for a quarter wavelength antenna at 2.4 GHz.

$$Wavelenght = \frac{300}{Frequency\ in\ MHZ} \qquad (2)$$

Depending on the application scenario, it may be impossible to use a large size antenna (i.e. for a Body Area Network) so migration to a higher frequency has to be taken into consideration. If lower frequencies are part of the system specification, then one has to consider that antenna miniaturization for these frequencies may induce significant losses which are reflected in reduced communication range or higher transmission power. Moreover, the application scenarios often force the frequency at the same of the radio used in the network. In fact, in many applications to achieve low cost and small form factor the wake up signal has to be generated from the same the main radio. For instance in wireless sensor networks the most commonly used frequencies are 868 MHz and 2.4 GHz, commercial transceivers use this frequency. Hence, these frequencies are the most popular for the wake-up communications in WSNs; although examples using different frequencies can be found in [19]-[25] .

B. Modulation

The WURx can be considered to be a simple radio receiver with ultra-low power consumption, so it is important to have a very simple architecture. This design goal also imposes constraints on the modulation used for the wake-up radio. If the modulation used is highly complex (e.g. Phase shift keying (PSK), Quadrature Phase Shift Key (QPSK) and others) the wake up demodulation circuits will be more complex and will require more power consumption. The most popular modulation scheme used in wake up receivers is the On Off Keying (OOK) [5]. **OOK** denotes the simplest form of amplitude-shift keying (ASK) modulation that represents digital data as the presence or absence of a carrier wave, Figure 3. This modulation works as a Morse code where to transmit a digital signal, a carrier wave switched on and off, 1 and 0, respectively. This simple modulation allows a drastic simplification of the WUR circuitry and provides power reduction opportunities as will be presented in following subsections. In the rest of the paper we are assume OOK modulation is used.

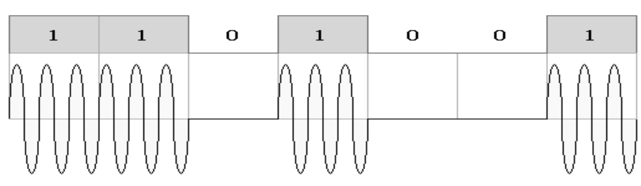
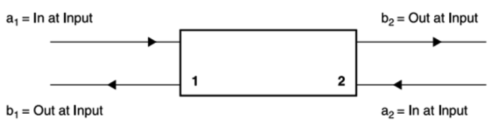


Figure 3 On Off Modulation. The signal is demodulated associating a 1 when there is a carrier frequency, 0 otherwise.

C. Impedance matching

The maximum of the available received power on the antenna (equation (1)) is transferred to the rest of the circuits when an impedance equals to the conjugate of impedance of the antenna noted is present from the antenna and the circuits. Since in general the impedance of the circuit is not equal to conjugate of the antenna impedance, a matching network circuit is required in between to achieve this important goal and not waste precious received power. The mismatch is a measure of the RF power that gets reflected when it reaches an RF component, and it is the ratio of reflected power to incident power [21]. There are various ways of specifying reflected power. The most common way of specifying mismatch is return loss expressed in dB. The other ones are SWR (*Standing wave ratio)* and reflection coefficient. S-parameters are another way of specifying return loss. Figure 4 defines S-parameters, it shows RF signal entering and exiting an RF component in both directions. If an RF signal is incident on the input side of the component, some of the signal is reflected and some is transmitted through the component. The ratio of the reflected electric field to the incident field is the reflection coefficient. The ratio of the transmitted electric field to the incident field is the transmission coefficient.



$S_{11} = \frac{b_1}{a_1}$ - Input Reflection Coefficient $\quad$ $S_{21} = \frac{b_2}{a_1}$ - Gain/Loss

$S_{12} = \frac{b_1}{a_2}$ – Isolation $\quad$ $S_{22} = \frac{b_2}{a_2}$ – Output Reflection Coefficient

Figure 4 Evaluation of S-parameters to evaluate the reflection.

The main goal of impedance matching is the reduction or elimination of reflected RF power which involves measuring the reflected power and calculating the matching network.

V. ULTRA LOW POWER WAKE UP RADIO

This section presents the design of the wake up radio receiver which uses only a comparator and an ultra low power microcontroller as active components. Figure 5 shows the whole architecture of the proposed wake up radio receiver where the energy harvester (solar or thermal) is an optional block, used to evaluate the self-sustainability of the solution but it is not part of this paper. The main goal is the design of a wake up receiver with high sensitivity (at least -35dBm), fast reactivity (less than 300μs), low power (less than 2μW) and with addressing capability on board.

Network Matching: As we mentioned in previous section the matching network is a very important block to transfer all the power received to the rest of the receiver's circuit. Using **Advanced Design System (ADS)** from Agilent and the model of the implemented circuit, an LC filter was found to be the best solution to match the impedance of Antenna and the rest of the circuit. Figure 6 shows the implemented LC circuits where the value of the inductor and capacitor were tuned directly on the PCB implemented at 868MHz transmission frequency. Although the proposed architecture can work with several transmission frequencies because is working with the envelope of the On Off Keying message, the matching network fixes the wake up radio for a specific frequency. As in this work we are presenting also experimental results on the field the selected frequency was 868MHz at all the circuits was optimized for this frequency.

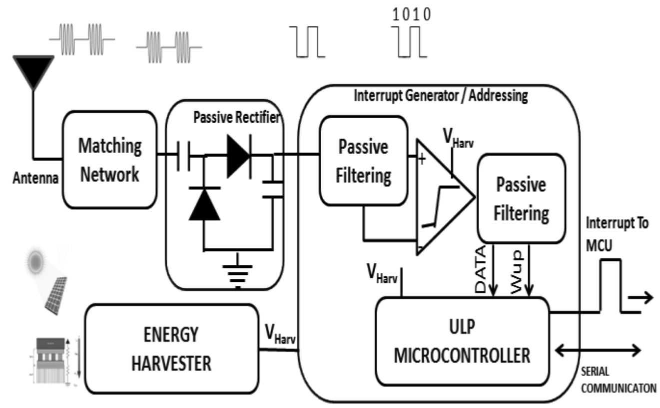


Figure 5 Nano power high sensitivity Wake up radio architecture

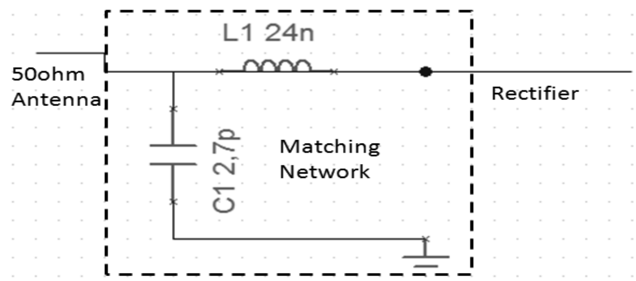


Figure 6 Matching Network Implemented.

Passive Rectifier: After the matching network, the AC signal is transferred to the rest of the circuit to be rectified and demodulated to reconstruct the data. One of main goals in designing the wake up receiver was the low power consumption and high sensitivity. For this reason a passive rectifier using a single stage rectifier with series diodes was implemented. The best diodes available in terms of sensitivity and radio frequency optimization are provided from Avago Technologies with the HSMS-285x and HSMS-282x respectively for frequencies below GHz and above 1 GHz. These diodes are optimized from incoming power of less than -20dBm and offer a sensitivity of -57dBm that makes these diodes the best solution on the market at the time the paper is written. The diodes are successfully used in several RF energy harvesting and wake up applications [32] which confirms the performance of these diodes in weak RF signal environments. The HSMS-285C [37]is used as the requirements are to cover frequency below 1GHz, however the same schematic we are presenting can be used for the frequencies above 1.5GHz.

Interrupt and Data Generator: Once the signal is rectified, the correct bit sequence of the sent message can be reconstructed. An ultra low power comparator is used to perform this task. We used an adaptive threshold mechanism using a simple RC circuit (R_1-C_4) connected on the negative input of the comparator while the positive input is directly connected to the signal from the voltage multiplier to allow the comparator effectively to detect both weak and strong signals.

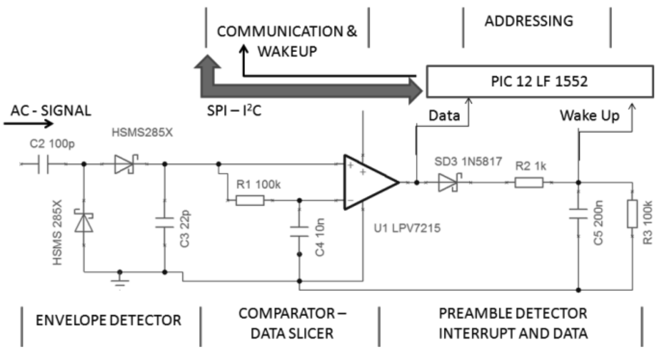


Figure 7

Three different comparators were used in the proposed paper in order to evaluate the trade-off between power and sensitivity. The TLV3691 from Texas Instruments was selected for its ultra low current consumption of only 75nA and acceptable value of offset voltage of around 2.2mV, the AS1976 from Austria Microsystems [35] was selected for the power consumption of 198nA and 1.7mV of voltage offset, finally the LPV7215 from TI was selected for the very low voltage offset of 0.4mV and the still low current consumption of 600nA. The input offset voltage of each selected comparators was measured using the method presented in [34]. The data shows the current consumption to be higher for comparators with a lower voltage offset. However, the voltage offset directly affects the sensitivity of the wake up radio as with lower voltage offset is possible to sense smaller signals.

After the comparator there is the preamble detector which generates the interrupt and the digital data. The RC filter (R3-C5) filters the interference which can generate by unwanted interrupts. To allow this filter to work properly a preamble is added to the beginning of the OOK signal with a specific length of only 2 bits. The preamble detector is responsible for generating a wake up interrupt signal for the on board microcontroller only when a preamble has been received.

Addressing: When the on board microcontroller is woken up, it can start to read the data from the data pin which is connected to the output of the comparator before the diode SD3. An ultra low power 8-bit microcontroller PIC12LF1552 from Microchip was selected for the ultra low current consumption (only 20nA in sleep mode), the small number of pins needed (only 8), the serial port (both I^2C and SPI) and the fast wake up time (around 130µs at 8MHz). The microcontroller can be programmed using the serial port with a specific address to generate the final wake up signal only if the first byte received is the correct address. Moreover the serial port can also be used to read the data received from the wake up radio to perform further processing or power management.

Output Connectivity: The connectivity to existing hardware there are a serial part which can be either SPI or I^2C as there are sharing the same pins. Moreover it is present the pin of wake up interrupt which has to be used to interrupt pin. The serial communication part is used to program the wake up radio with a specific address and to receive data. Both the serial communication and the interrupt pin are provided from the on board PIC microcontroller which is charge of all the communication.

VI. Experimental Results

This section presents an experimental evaluation carried out from a prototyped wake up radio receiver. The experimental results show the benefit of the propose wake up radio in terms of matching, power consumption, sensitivity and addressing capability. The developed prototype is shown in Figure 8 where it is possible to see the small form factor and the top of the attenuator used to carry out sensitivity power consumption.

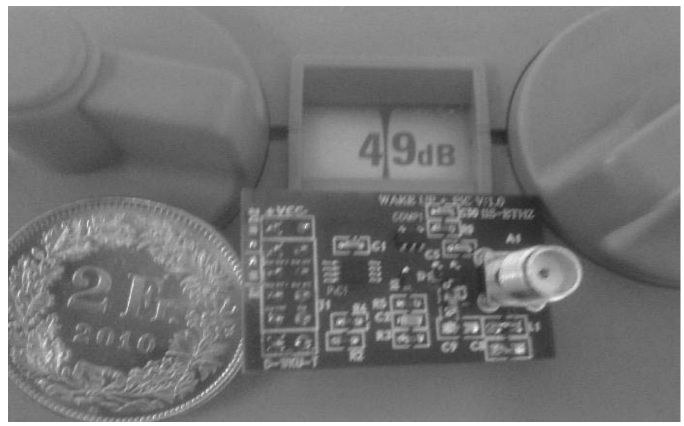


Figure 8 Wake up radio prototype on the attenuator used for the sensitivity measurements.

To test the functionality we set up the testbed shown in Figure 9. The test bed comprises of a transmitter, an attenuator to emulate the attenuation of the distance then reduce the power received from the wake up radio receiver and the wake up radio receiver prototyped. As transmitter we used the EM430F6137RF900 demoboard from Texas Instruments which has a CC430F6137 SoC with microcontroller and radio. This SoC can send OOK modulated message at 868MHz and through the programmer connected to the PC and RF Studio IDE from Texas Instrument it is possible to control all the parameters such as the data rate, the transmission power, and the message to send.

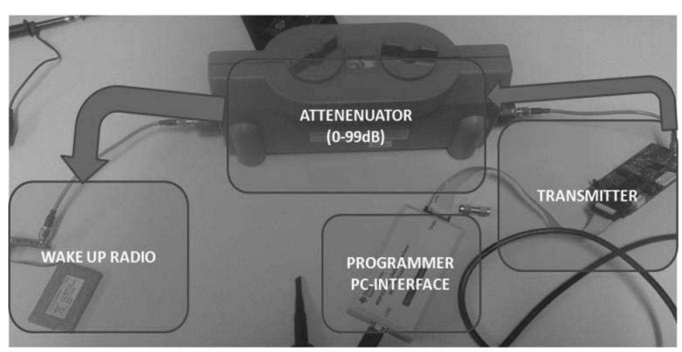


Figure 9 Test bed used to evaluate the performance of the proposed wake up radio.

The prototype was tested in the following conditions: OOK modulation, 868 MHz frequency, 10Kbit/second data rate, 2bits (0 and 1) start bits, 2byte message, and 0dBm transmission power on the transmitter. The prototype was tested with the three different comparators presented in the previous section and the first test was measuring the max sensitivity. To achieve this goal, the transmitter generates the 2 byte message 0xFF and 0xFF continuously and increasing the value of attenuation in the attenuator we checked in an oscilloscope until when the wake up radio was able to generate an interrupt. The second test was on the power consumption. In this case we measure the current supplied to the wake up radio using a shunt resistor of 100ohm. The evaluation of power was then done at 1.8V which is the lowest voltage level at which the wake up radio can work. The third test was empirical evaluation on the range. For this experiment we used a 3dBi antenna on the receiver and transmitter.

TABLE I. WAKE-UP RADIO PERFORMANCE FOR DIFFERENT COMPATORS.

WUR	Comp.	Power consumption [nW]	Sensitivity [dBm]	Range [m]
1	TLV 3691	196	-32	7
2	AS1976	426	-42	22
3	LPV7215	1276	-55	45

The addressing capability and the response time were tested implementing a firmware on the PIC microcontroller checking if the data were acquired correctly. Figure 10 shows the wave form of the wake up receiver in blue (top plot) and the sample time of the microcontroller in yellow (bottom plot). After the interrupt is generated the microcontroller starts to acquire the data when the wake up interrupt becomes low again. In this case a 16bit packet was sent and correctly received from the microcontroller. The 2bits are needed to guarantee the wake up of the microcontroller which was measured in around 130µs. The addressing time is linked to data rate of the received message. For 2 bytes address with 10Kbit/s data rate the addressing time is of 1.6ms.

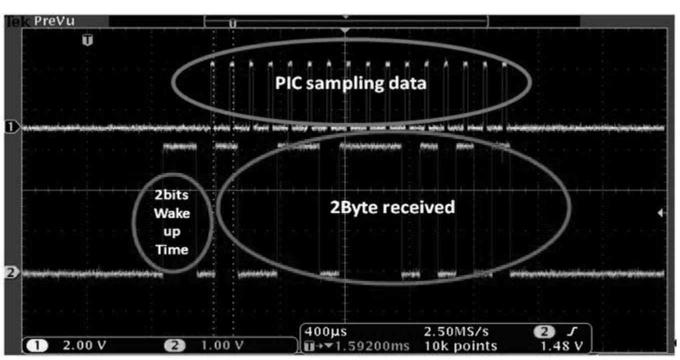


Figure 10 Wake up signal and data (down) generated from the wake up radio receiver, and sample period (up) of the microcontroller to acquire the data.

Other experimental results were performed on the matching network to evaluate with a network analyser the S11 parameter. Figure 11 shows the measured S11 using 2 different values of inductors and capacitors. The red line was measured with an inductor of 24nH and a capacitor of 2.7pF. This configuration has the best performance as the lower peak is exactly in 868MHz and the value of S_{11} = -20dB, but it is using non-standard inductor value (26nH) so the price of this component is higher. The second setup is a good compromise between price and performance as the peak is very close on 880MHz and at 868MHz we still have S_{11}= -15dB which is still a good result. In the previous experimental results we used the first configuration with L=26nH and C = 2.7pF.

VII. CONCLUSIONS

A nano power wake up radio receiver with high sensitivity and addressing capability was designed and implemented with off the shelf components. The paper presents circuit topologies and methodologies for matching the impedance, passive rectifier design, nano low power interrupt generator, addressing. The implementation of a nano-watt radio wake-up that generates interrupt and receives data has been presented in details across three different setups to achieve either low power or high sensitivity. As many applications require addressing capabilities, the proposed approach has a nano-power microcontroller directly on board to read the demodulated data and check the address before to wake up the main node and main radio. For this reason the wake up radio receiver proposed can significantly reduce power consumption of power constrain devices using a radio transceiver. Experimental results indicate that the proposed wake up radio outperforms the state-of-the-art with a significant increment in sensitivity and decrease in power consumption. It showed that the proposed wake up receiver can consume only less than 200 nW and achieve a -55dBm sensitivity in the higher power consumption version. Moreover the developed prototype evaluations in a real test bed confirm the benefit approach and high communication range achieved.

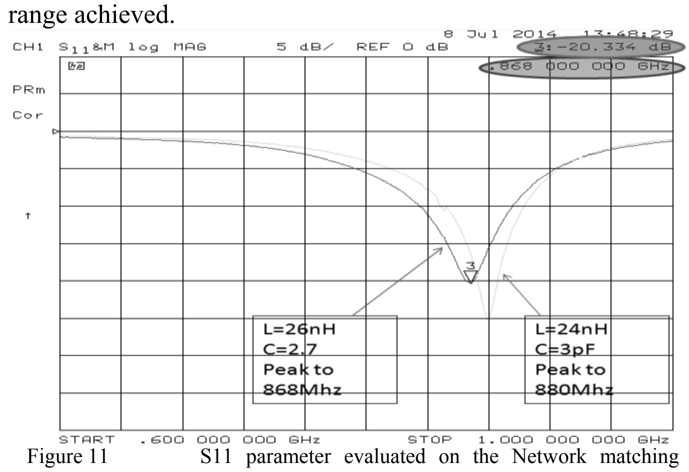


Figure 11 S11 parameter evaluated on the Network matching from 2 different LC values. It shows as the network matching is also really sensible to small differences of values.

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