
Design and Implementation of a Wake-Up Radio Architecture for Wireless Sensor Networks

PANAGIOTIS SKRIMPONIS
SUPERVISOR: ATHANASIOS KORAKIS



Department of Electrical and Computer Engineering
UNIVERSITY OF THESSALY

A dissertation submitted to the University of Thessaly
in accordance with the requirements of the degree of
MASTER OF SCIENCE in the Faculty of Engineering.

OCTOBER 2018

Σχεδίαση και Υλοποίηση μιας Wake-Up Radio Αρχιτεκτονικής για Ασύρματα Δίκτυα Αισθητήρων

ΠΑΝΑΓΙΩΤΗΣ ΣΚΡΙΜΠΙΟΝΗΣ
ΕΠΙΒΛΕΠΩΝ: ΑΘΑΝΑΣΙΟΣ ΚΟΡΑΚΗΣ



Τμήμα Ηλεκτρολόγων Μηχανικών και Μηχανικών
Υπολογιστών
ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ

Η παρούσα διπλωματική κατατέθηκε στο Πανεπιστήμιο
Θεσσαλίας στα πλαίσια της απόκτησης του ΜΕΤΑΠΤΥΧΙ-
ΑΚΟΥ ΔΙΠΛΩΜΑΤΟΣ στη σχολή των Μηχανικών.

ΟΚΤΩΒΡΙΟΣ 2018

ABSTRACT

Typical wireless sensor network applications follow duty-cycle mechanisms, yielding important energy savings by reducing the power consumption of idle listening. However, this approach still dictates predefined cycles of active operation, which in some application scenarios is meaningless. Extended lifetime can be achieved by asynchronously awakening sensor network's nodes only when truly required. In this work we present NITOS wake-up receiver that can be employed by typical sensor nodes to provide asynchronous wake-ups and substantially reduce their energy expenditure. Our wake-up circuit operates in the 868 MHz band and is activated by LoRa frames using OOK modulation. The developed system supports selective awakenings with the aid of a low-power microcontroller dedicated to sample the acquired signal and identify the wake-up address.

ΠΕΡΙΛΗΨΗ

Ταντικείμενο της παρούσας μεταπτυχιακής διατριβής αποτελεί η ανάπτυξη μιας πλατφόρμας που στοχεύει στη μείωση της κατανάλωση ενέργειας σε κόμβους από ασύρματα δίκτυα αισθητήρων. Συνήθως οι κόμβοι στα ασύρματα δίκτυα αισθητήρων για να πετύχουν μια συνολική χαμηλή κατανάλωση ενέργειας, χρησιμοποιούν έναν μηχανισμό γνωστό και ως duty-cycle. Σύμφωνα με αυτό το μηχανισμό οι κόμβοι έχουν συγκεκριμένες περιόδους λειτουργίας, ενώ στον υπόλοιπο χρόνο “κοιμούνται”, με αποτέλεσμα να πέφτει σε χαμηλά επίπεδα την κατανάλωση ενέργειας. Παρά την αποτελεσματικότητα της μεθόδου, οι περιορισμοί που θέτει λόγω της περιοδικότητας στη λειτουργία του συστήματος καθιστά δύσκολο το να βρει εφαρμογή σε πολλές περιπτώσεις. Το NITOS Wake-Up κύκλωμα που υλοποιήσαμε μπορεί να χρησιμοποιηθεί σε συνηθισμένους ασύρματους κόμβους αισθητήρων δίνοντας τους τη δυνατότητα ασύγχρονων “ξυπνημάτων” και όχι με βάση κάποιου ρολογιού. Το κύκλωμα μας λειτουργεί στα 868MHz και μπορεί να ενεργοποιηθεί από LoRa μηνύματα, τα οποία χρησιμοποιούν τη διαμόρφωση OOK.

DEDICATION AND ACKNOWLEDGEMENTS

The work of this thesis has been one of the most significant academic challenge I have faced so far. Without the support, patience and guidance of the people around me this thesis would not have been completed.

First of all, my enormous debt of gratitude goes to my thesis advisor and mentor *Professor Thanasis Korakis*. I am thankful for his knowledge and his belief in me, which provided the required support to overcome the initial problems encountered and keep working with passion. Throughout the period of my studies, he was there for me to actively support and guide me toward taking the best possible decisions.

Especially, I would like to thank my friends, for supporting me every day. I totally believe that great achievements require friends to celebrate, and throughout my lifetime I was always trying to meet new people and make new friends. I am deeply grateful to all of the people in the *NITLab* research laboratory and specifically to my colleagues *Yannis, Polychronis and Giannis* for their aid and guidance during the development of this master thesis.

Most importantly, I would like to thank my parents and my sister for their support all of these years. There are no words that can express my gratitude and appreciation for all they have done for me. Without their patience and support, I would not have been able to finish my thesis. The least I can do in recognition is to dedicate this thesis to them.

To my parents and my sister.

AUTHOR'S DECLARATION

I, PANAGIOTIS SKRIMPONIS, declare that the work in this dissertation titled as "DESIGN AND IMPLEMENTATION OF A WAKE-UP RADIO ARCHITECTURE FOR WIRELESS SENSOR NETWORKS", was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: DATE:

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INTRODUCTION

The unprecedented growth of Wireless Sensor Networks (WSNs) has revolutionized the way we interact with the physical context, improving our everyday life in several aspects. Several WSN applications require increased life-duration, while battery replacement is an impractical or sometimes an infeasible task. A typical principle that deals with the excessive energy consumption is duty-cycling. Duty-cycling, suggests that sensor nodes enter into a low-power mode (sleep state), where they turn off all the electronics except of a clock circuit dedicated to provide a wake-up interrupt, in order to save as much energy as possible during their inactive periods. Although substantially reducing the energy expenditure, this technique implies several limitations and drawbacks. For example, idle-listening is reduced considerably, but still remains present, since duty-cycle defines fixed intervals of active operation. However, a wide range of sensing application scenarios are event-based and do not require fixed wake-ups that only account for energy wastage. Moreover, this approach fails to serve time-critical applications that require immediate response towards sensing an abrupt event.

1.1 Wireless Sensor Networks

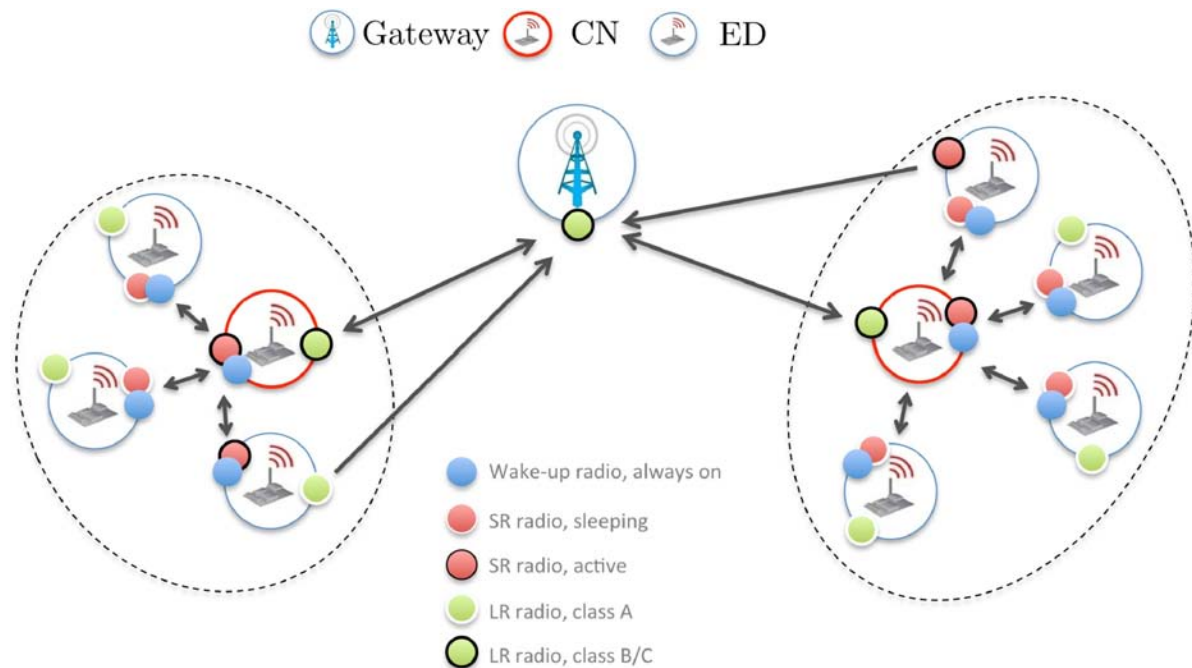


FIGURE 1.1. Wireless Sensor Network Architecture

Wireless Sensor Networks (WSNs) are considered as the key components of the emerging Internet-of-Things (IoT). In this type of networks, sensor nodes are spatially distributed in an certain area like home, office, city, industry, etc, while the collected measurements are stored in a centralized server. Based on the measurements and the state of the environment or object, the nodes use the actuators in order to act respectively. Usually WSN nodes are small devices with very low power consumption capable of being able to run on a battery for years. Several WSN applications require increased life-duration, while battery replacement is an impractical or an infeasible task. When multiple sensors and actuators are used together they form a wireless sensor and actuator network (WSAN). Based on the measurements and the state of the environment or object, the nodes use the actuators in order to act respectively.

The WSN node usually consist of the following core elements:

- **MCU** – A low power microcontroller unit (MCU) that communicates with the sensors to collect the measurements and send them over the radio.
- **Radio** – A transceiver to communicate with the gateway or the other nodes depending on the topology of the network. The typical wireless communication schemes are radio frequency (RF), optical communication, infrared (IR) and near field communication (NFC).
- **Power** – A Power source like batteries which are either rechargeable or non-rechargeable. Current sensor nodes are able to renew their energy from solar sources, temperature differences and vibration.
- **Sensors** – Sensors are devices that monitor and record the physical conditions of the environment and other objects. The most common environmental measurements are temperature, humidity, luminosity, barometric pressure, human presence, and noise levels.
- **Actuators** – Actuators perform actions in order to change the state and affect the environment or an object in some way. Some examples of the most common actuators are buzzers, motors or servos.

1.1.1 History of Wireless Sensor Networks

The initial development of WSNs was motivated by the army in order to collect information about the enemy, efficiently monitor the battlefield, and detect possible attacks. Also some government agencies and organizations contributed, in their own persons of interest.

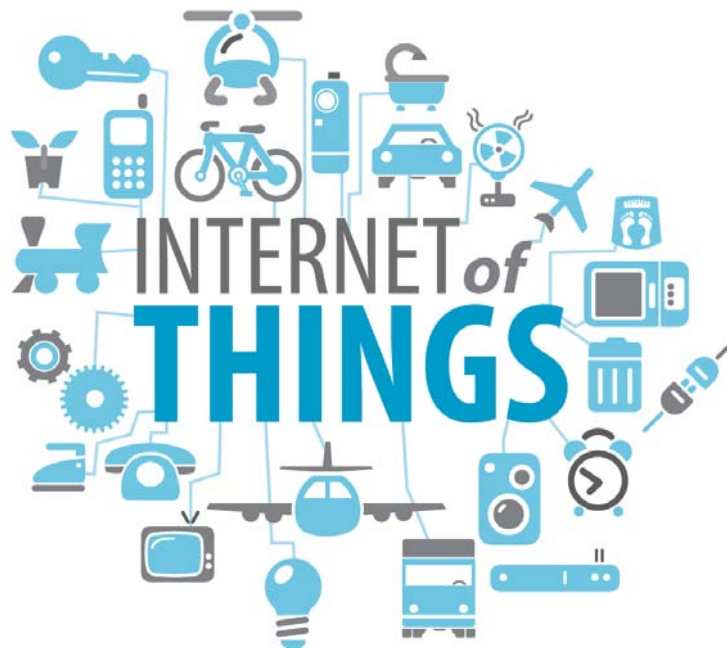
Research on WSNs dates back to the 1980s when the United States Defense Advanced Research Projects Agency (DARPA) started the distributed sensor networks (DSNs) program for the US military, although the technology was not quite ready yet. Especially, the sensors were quite large (i.e. the size of a shoe box and bigger), thereby reducing the total of potential applications.

Recent progress in microcomputing and networking technology have led in a significant shift in WSN research. The sensor nodes have been much smaller in size (i.e. from

that of a pack of cards to dust particle) and much cheaper in price, and thus many new civilian applications of sensor networks such as environment monitoring, vehicular sensor network and body sensor networks have emerged.

Today, industrial automation is one of the most important areas of WSN applications. According to ON World, wireless devices to be installed in industrial fields will increase by 553% between 2011 and 2016 when there will be 24 million wireless-enabled sensors and actuators, or sensing points, deployed worldwide. Among these, 39% will be used for new applications that are only possible with wireless sensor networking. By 2014, the number of WSN devices will account for 15% of the entire industrial measurement and control equipment sensing points, and 33% by 2016. In today's market, three-fourths of the industrial WSN income comes from the process industry with the oil and power industry being the fastest growing ones.

1.2 Internet of Things



The core concept of IoT is that everyday objects can be equipped with sensing, networking and processing capabilities that will allow them to communicate with other devices or services over the internet. For instance, attaching technology to everyday devices like home appliances, televisions, lights, smoke detectors, etc. and connect them on the

internet provides promises to support ubiquitous computing and context-awareness among devices.

The revolution of Ambient Intelligence is about to happen, where all of the above technologies will be embedded in our homes, offices, and transportation systems. The systems will be able to respond to human presence, actions, decisions, and adapt to individual needs which will improve their quality of experience.

The IoT represents the evolution of the existing technologies and network topologies, in terms of number and kind of devices across the internet. According to the Gartner [4] it's projected that by 2020, 20.4 billion things will be utilized around the globe.

1.3 Wake-Up Radio

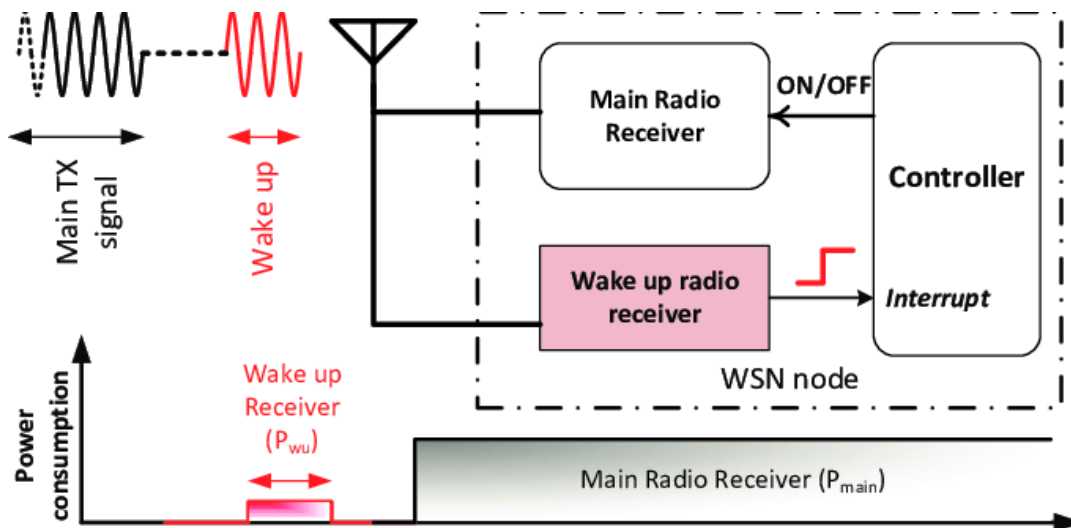


FIGURE 1.2. Wake-Up Radio Architecture Concept

All the above, motivate the development of wake-up radios to allow asynchronous awakenings, towards eliminating duty-cycle constraints. Several works have proposed novel schemes exploiting wake-up radios, that use external nodes to propagate wake-up frames to targeted nodes. By adopting such a technique idle listening is eliminated and the targeted nodes are only awakened where truly required. In this work we adopted a similar scheme and developed an ancillary radio module dedicated to provide an interrupt signal to the host sensor node, in order to awake it to perform a measurement cycle. Bellow we

list the key requirements and considerations for developing such a Wake-Up Receiver circuit.

1.3.1 Extremely low-power profile

The wake-up circuit should remain active during the entire lifetime of a sensor network in order to acquire Wake-Up Packets intended to awake the under consideration node. This suggests that the circuit must be of low-power consumption in order to extend the lifespan of the network. It is likely that the sensor nodes are deployed in a crowded context which implies that several communication systems may operate within the sensor network range and possibly in the same frequency zone. Apparently, the receiver may process a vast number of undesired packets. We aim at maintaining a low-power profile even when processing interfering/unwanted packets that trigger our receiver. Finally it is critical that the receiver circuit manages the operation of the sensor node, ideally by entirely turning off its electronics to consume zero power.

1.3.2 WuRx Sensitivity / Communication range

One crucial challenge when designing the WuRx is to attain as low sensitivity at the receiver side as possible while retaining ultra-low power consumption profile. The sensitivity of the the WuRx is defined as the minimum received power strength at which the receiver is able to correctly interpret an acquired WuP at an acceptable packet error rate (i.e. less than 5% of PER). Apparently, the WuRx sensitivity directly affects the achievable communication range. According to the Friis equation there is an upper communication range bound determined by the sensitivity of the WuRx the frequency used, the transmission power and the gains of the antennas used by both the receiver and the transmitter. Unlike typical RF communication systems that utilize active components, Wake-Up Radios employ passive or semi-passive approaches to reduce their power consumption, which comes at the price of reduced sensitivity.

1.3.3 Selective awakenings

In such network schemes it is crucial to support selective awakenings, avoiding to awake nodes that are not interested in communications or to perform a sensing cycle, which will inevitably lead to energy wastage. Every WuRx must integrate a logic entity to reliably interpret the incoming WuP and determine whether it has to awake or not. For

instance, a sensor network may consist of different type of sensors, or sensors which in fact introduces new challenges for the design of such features.

1.4 Related Work

In this section we are going to present the state of art of Long Range (LR) communication schemes that have recently emerged in the industry[7]. Furthermore, we are going to discuss about Ultra Low Power (ULP) Wake-Up Receivers (WuRx) technologies.

1.4.1 Long-Range Communications

Long-Range communication schemes can be grouped according to the spectrum use, i.e. (Ultra) Narrow Band ((U)NB) techniques, which aim to minimize the bandwidth to reduce the probability of interference, or spread spectrum schemes, which take advantage of spectral diversity.

The physical layer developed and patent by the french company SigFox achieves UNB by broadcasting binary data using BPSK modulation at very low bitrate (100 bps), on a much larger band, typically 192 kHz in the 868 MHz or 915MHz band. Frequency hopping inside the band is supported to improve reliability, and medium access is done using a modified Aloha scheme, where node access to the channel randomly both in time and frequency domain.

Another NB physical layer is proposed by Weightless, an organization which aims to provide wireless standards for internet of things networks. Multiple standards, targeting different use cases, are proposed. The Weightless-N standard, based on DBPSK modulation, is unidirectional and allows a range of 5 km. Similarly to SigFox, frequency hopping is used to counteract interference and fading. The Weightless-P standard is based on the Weightless-N standard, but enables bidirectional communication and acknowledgement. It uses FDMA and TDMA to scale to a large number of devices, but reduces the range to 2 km in urban environment. The last proposed standard, Weightless-W is not NB, but is a spread spectrum scheme. It operates in TV white space spectrum, and uses variable modulation modes coupled with spreading codes, to enable 5 km range and bidirectional communication.

The scheme proposed by Ingenu differs from the other long-range communication methods in that it operates in the 2.4 GHz ISM band. It is a spread spectrum technique, called

Random Phase Multiple Access (RPMA), that enables a range of 10 km, using a typical channel bandwidth of 1 MHz. Both uplink and downlink transmission are allowed, and performed in a half-duplex way with a downlink period of 2 s, followed by an uplink period of 2s. The spreading factor is dynamically adapted based on the received power.

Another spread spectrum technique for long-range communication was patented by Cycléo, and is based on Chirp Spread Spectrum (CSS). Named LoRa, this physical layer operates in the 868 MHz or 915 MHz ISM bands, and enables a range up to a few tens of kilometers. In the LoRa network architecture [5], all WSN nodes communicate directly with the gateway, which serves as a bridge between the nodes and a network server. The gateway is always active listening to the channel, while three types of classes are defined for end- devices: A, B and C. Class A is the lowest power consuming class, as nodes only leave the sleep state to send their data. Each uplink transmission is followed by two short downlink receive windows. Class B devices open additional receive windows at scheduled time in addition to class A receive windows, and time synchronized beacons from the gateway are used to allow the gateway to know when devices are listening. Finally, class C devices are continuously listening, except when they are transmitting. Therefore, using the LoRaTM network architecture, a trade-off must be made between latency and energy consumption for downlink communications.

1.4.2 Ultra Low Power Wake-Up Receivers

ULP WuRx designs present in the literature can be classified in two categories: passive circuits, which are exclusively powered by the energy of the received signal, and drain no energy from the node power supply, and active circuits, which require a supply power to operate.

Fully passive WuRx are attractive as they do not require a power supply to operate. However, they are characterized by a very low typical sensitivity of 25 dBm, which allows a range of a few centimeters [15]. Due to this limitation, the majority of ULP WuRx architectures used in WSNs are active, although their power consumption stays in the range of few micro-watts. With such a small power envelope, the sensitivities of these ULP WURx are typically in the range of 50–55 dBm, which allows a range of 20–30 m with 3 dBi gain antennas [21]. In this work, the state-of-art ULP WuRx presented in [21] is used, which achieves a sensitivity of 55 dBm and embeds an ULP MCU. The network protocols must take advantage of ULP WURx to fully exploit these emerging circuits,

and therefore a handful of MAC protocols leveraging ULP WuRx were proposed in the recent years [16],[12]. The benefits of using these new devices compared to traditional approaches, in terms of energy efficiency and latency, were shown in previous works [23],[13].

The authors in [25] propose the OpenMote+ platform, targeting industrial applications, combining three communication modules: one for LR (kilometers-range) communication, one for hundreds of meters communication, and one for contact-based communication. In this work, different radios are used as independent wireless communication, while we propose a collaborative combination of two technologies. In addition, we also propose to use WuRx to eliminate idle listening and perform purely asynchronous communication for SR communications. In [22] a platform that incorporates both energy harvesting and wake-up radio has been presented. In the proposed work, we extend this concept by adding long- range communication and using the wake-up radio also for low-power energy management. Furthermore, in [14] the authors have presented a preliminary study of the benefits of using a system with short-long range radio using a collaborative protocol with LoRaTM and WuRx, showing that using WuRx can both decrease latency and increase energy efficiency. In our work, the long-short range concept is significantly extended using the WuRx as power manager to further increase the energy efficiency and platform has been designed including also EH and sensors to evaluate the benefits of the proposed approach with experimental results. Finally, the authors in [20] present a platform that allows the building of an heterogeneous long-short range network architecture to reduce the latency and reduce the power consumption in listening phase at only 4.6W.

SYSTEM IMPLEMENTATION

The developed prototype receiver consists of low-cost off-the-shelf electronics and a low-power micro-controller. The schematic diagram of the receiver is illustrated in Fig. 2.1, while the actual board in Fig. 2.2. For the wake-up receiver a matching network, a passive rectifier and a comparator to generate interrupts were used. Moreover, a low-power micro-controller is responsible for processing the received signal and identifying the acquired address to verify whether it should wake the host node. To awake the network's nodes we utilize LoRa radio transceivers, by modulating the propagated information using *On-Off Keying (OOK)* modulation. Briefly, *OOK* scheme is the simplest form of amplitude-shift keying modulation, which defines that the presence of a carrier for a specific duration represents a binary one, while its absence for the same duration represents a binary zero. In the next sub-sections we analyze each different stage of our developed Wake-Up Receiver along with the considerations taken during the development.

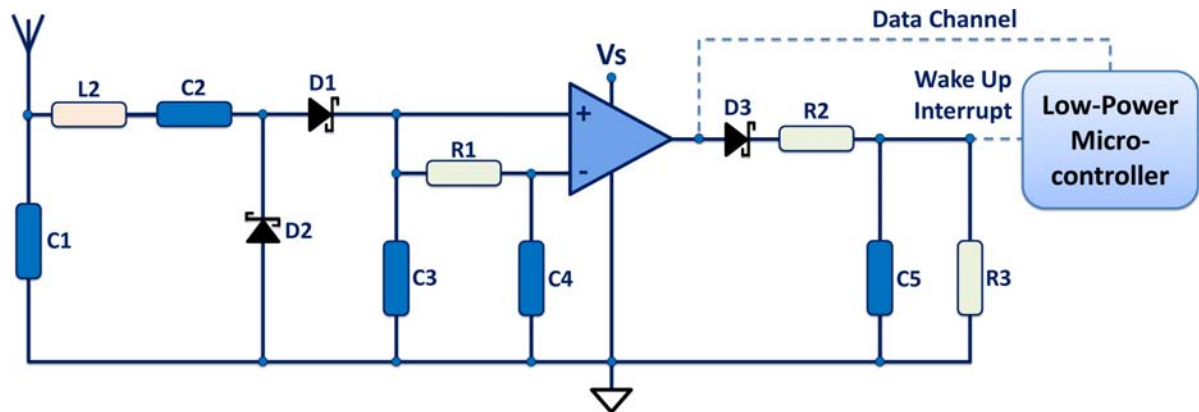


FIGURE 2.1. NITOS Wake-Up Radio Receiver Circuit

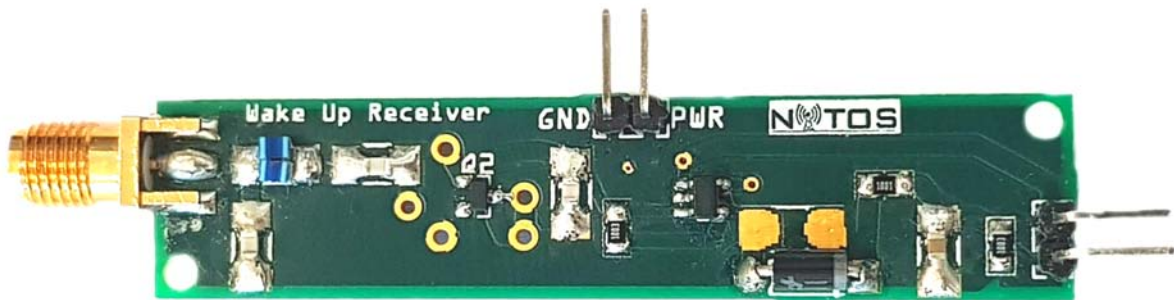


FIGURE 2.2. NITOS Wake-Up Radio Receiver Board

2.1 Matching Network

The matching network [2] is a block of prime importance when designing the receiver's signal propagation path. Firstly, it transfers all the power received from the antenna to the rest of the receiver's circuit, thus it must supply a stable impedance match to the 50Ω input source. According to the maximum power-transfer theorem, in order to obtain the maximum amount of power from an external source, the impedance of the load must equal the impedance of the source as viewed from its output terminals. Secondly, the network provides a narrow RF filter to remove out-of-band noise and interfering signals

The most straightforward matching-network topology is called the L network. This

refers to eight different L-shaped circuits composed of two capacitors, two inductors, or one capacitor and one inductor. The following figure shows the eight L-network configurations:

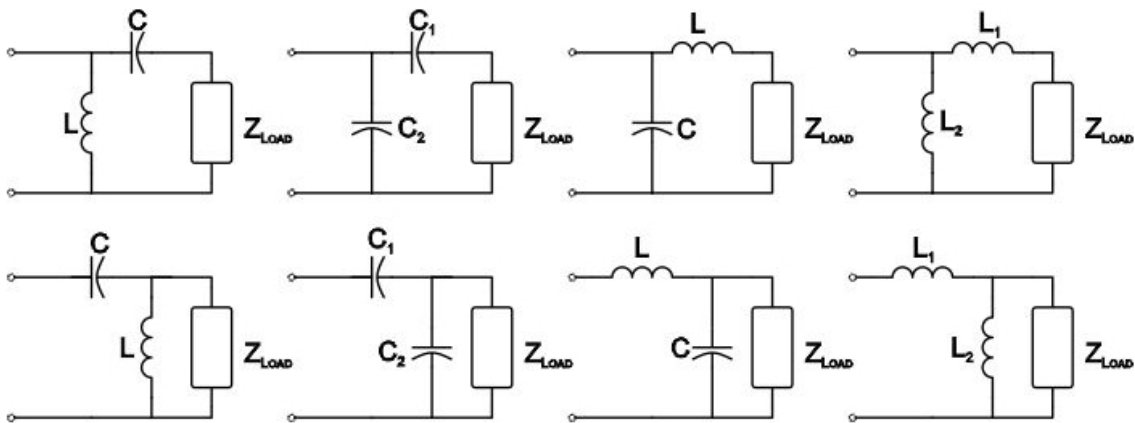


FIGURE 2.3. L-shaped Matching Network

The L network is simple and effective, but it is not suitable for wideband applications. We also have to keep in mind that inductors and capacitors exhibit seriously nonideal behavior at high frequencies, and thus the behavior of the L network will be less predictable as frequencies climb into the gigahertz range.

It is certainly valuable to understand the concepts involved in manually calculating matching-network values based on the source and load impedances, though this is more of an academic or intellectual exercise in an age when calculator tools can readily accomplish this task. We won't go through a calculation example here, but we will use a simulation to explore the effects of a matching network.

The developed matching network guarantees maximum power transfer between the antenna and the rest of the circuit by supplying a stable impedance match to the input source. It consists of an LC filter, whose inductor and capacitor values are dimensioned based on the transmission frequency. In this work, the receiver is optimized to work in the 868MHz transmission frequency. The output of the matching network is an RF signal.

2.2 Envelope Detector

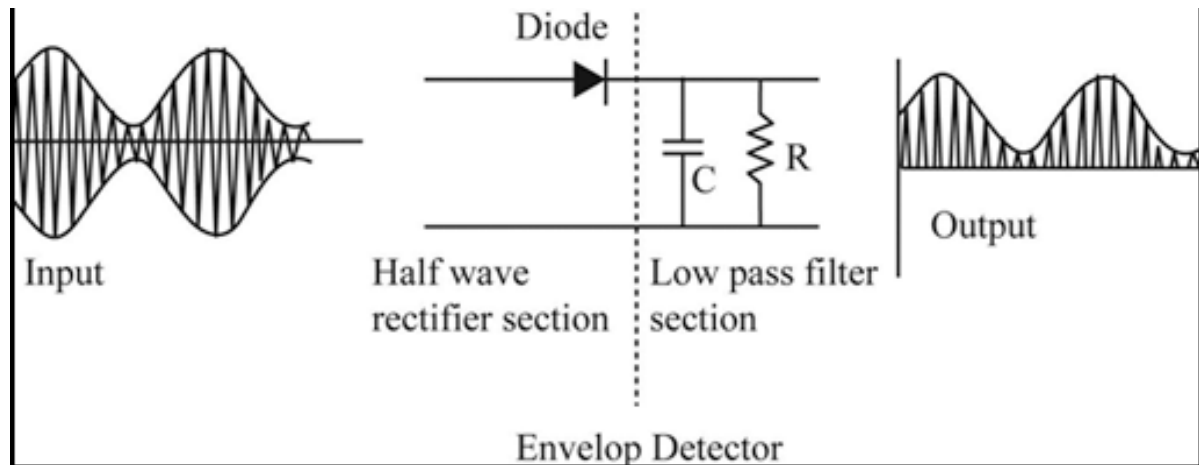


FIGURE 2.4. Envelope Detector

The second block is a passive demodulation circuit that allows to recover the information content from the modulated signal. As our design uses *OOK* modulation, the demodulation circuit consists of a passive envelope detector[1] that discards the frequency and phase content of the RF signal and only detects its amplitude. In our prototype implementation, we used a single-stage half-wave rectifier with series diodes. We selected the HSMS-285C[3] diodes from Avago Technologies, which are optimized for sub-GHz frequencies, and offer a sensitivity of -57dBm.

In an AM radio signal, the carrier signal carries the message and the message is contained in the envelope of the the AM modulated signal. So to extract the information we're interested in, we can use a circuit called an envelope detector, whose output is the envelope of the the input AM waveform.

It turns out that it is quite easy to convert the positive envelope into a normal signal. We start with a peak detector, which is just a diode followed by a capacitor. The diode conducts when the input signal is at least 0.7 V above the voltage on the capacitor, and otherwise it acts like an open circuit. Thus, the capacitor maintains the peak voltage: if the current input voltage is lower than the capacitor voltage, the capacitor voltage doesn't decrease because the reverse-biased diode prevents discharge.

2.3 Comparator

Once the signal is rectified, the bits of the received wake-up sequence are reconstructed by using an ultra-low power comparator. To perform this task, we used an adaptive threshold mechanism that keeps the V_{pin} of the comparator at half of the input signal level. With this approach, we use the energy from the antenna, rather than a voltage divider, for generating the threshold, thus reducing the static power consumption of the circuit. The adaptive mechanism is designed based on a simple RC circuit (R1-C4 in 2.1) that is connected to the negative input of the comparator. The positive input of the comparator is directly connected to the signal from the envelope detector. The voltage offset of the comparator affects the overall sensitivity of the wake-up radio: With a lower voltage offset it is possible to sense smaller signals. However, comparators with lower voltage offset generally have higher current consumption. In order to create our prototype, we evaluated several of the state-of-art comparators. After careful consideration and experimentation we selected the LPV7215 comparator from Texas Instruments [9], which features a very low voltage offset of 0.3mV and a reasonable energy consumption of 580nA. The comparison table of state-of-art comparators can be found below.

Comparators	Type	I _q	V _{offset}	Input Bias	CMRR
TLV3691	Analog Comparators	75 nA	3 mV	80 pA	
TLV3501	Analog Comparators	3.2 mA	1 mV	2 pA	70 dB
TLV3501	Analog Comparators	3.2 mA	1 mV	2 pA	70 dB
TLV7031/41	Nanopower Comparator/push-pull	335 nA	100 uV	2 pA	73 dB
LPV7215	Analog Comparator/push-pull	580 nA	300 uV	-40 fA	88dB
TSX393IYDT	dual CMOS voltage comparators	5 uA	100 uV	1 pA	73 dB
LTC1540	Nanopower Comparator	300 nA	<12mV	10 fA	60us
MAX919	Nanopower Comparator	350 nA	1 mV	150 fA	
MAX4000	Nanopower Comparator	900 nA	100uV@1.7V	1 nA	
MAX9644	Nanopower Comparator	400 nA	?	60 fA s	
TS881	Nanopower Comparator push-pull	260nA	< 1 mV	1 pA	

2.4 Ultra Low-Power Micro-Controller

The Texas Instruments MSP430 family of ultra-low-power micro-controllers [10] consist of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five software-selectable low-power modes is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 μ s.

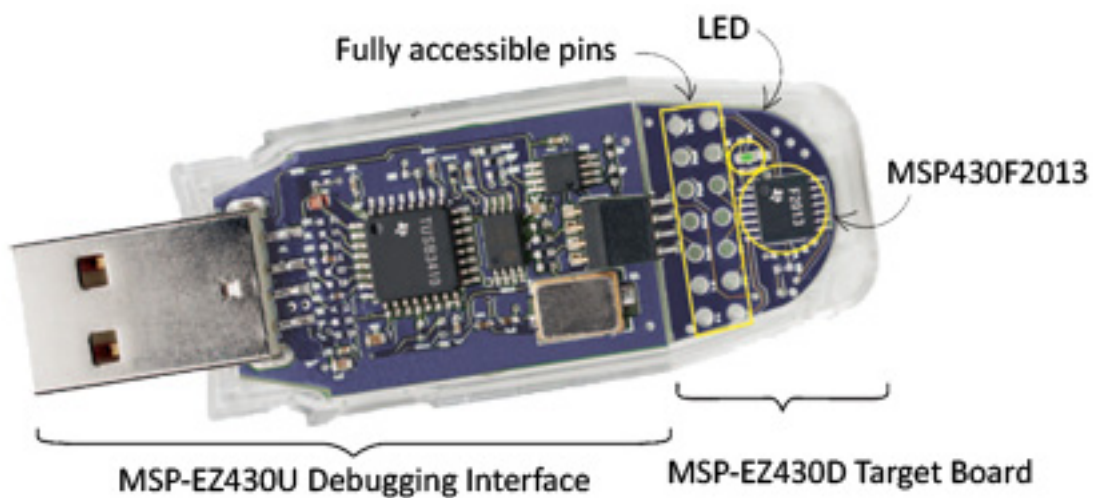


FIGURE 2.5. MSP-EZ430F2013 Mote

The Micro-controller Unit (MCU) is the processing core of the wireless node. Moreover, it receives a wake-up interrupt, which then starts reading data from the pin connected to the output of the comparator. In our implementation we decided to use MSP430F201x series of MCU[11]. We selected the specific MCU for the following characteristics:

Low Supply Voltage Range	1.8 V to 3.6 V
Active Mode Power Consumption	220 μ A at 1 MHz, 2.2 V
Standby Mode Power Consumption	0.5 μ A
Off Mode (RAM Retention) Power Consumption	0.1 μ A

The software consists of three main elements: the main routine, the address matching, and the interrupt service routine.

2.5 NITOS WuRx Prototype

In this work we have developed a prototype WuRx 2.6, that uses On-Off Keying (OOK) modulation and operates in the band of 868 MHz, engaging sub-GHz transceivers to achieve long-range distances. We employ an one-stage envelope detector to convert the RF signal into DC and an ultra low-power comparator to digitize the acquired pulses. In the next section we present the Related work, while in section 3 we describe the development of the wake-up radio module along with the implementation details. Section 4 demonstrates the evaluation of the developed receiver and section 6 summarizes our work. In this work, we propose to combine the LoRa communication scheme, able to achieve kilometer-range communication, with ultra low power wake-up receivers, which enable short-range distant wake up of the nodes with no significant power consumption increase, and low downlink latency.

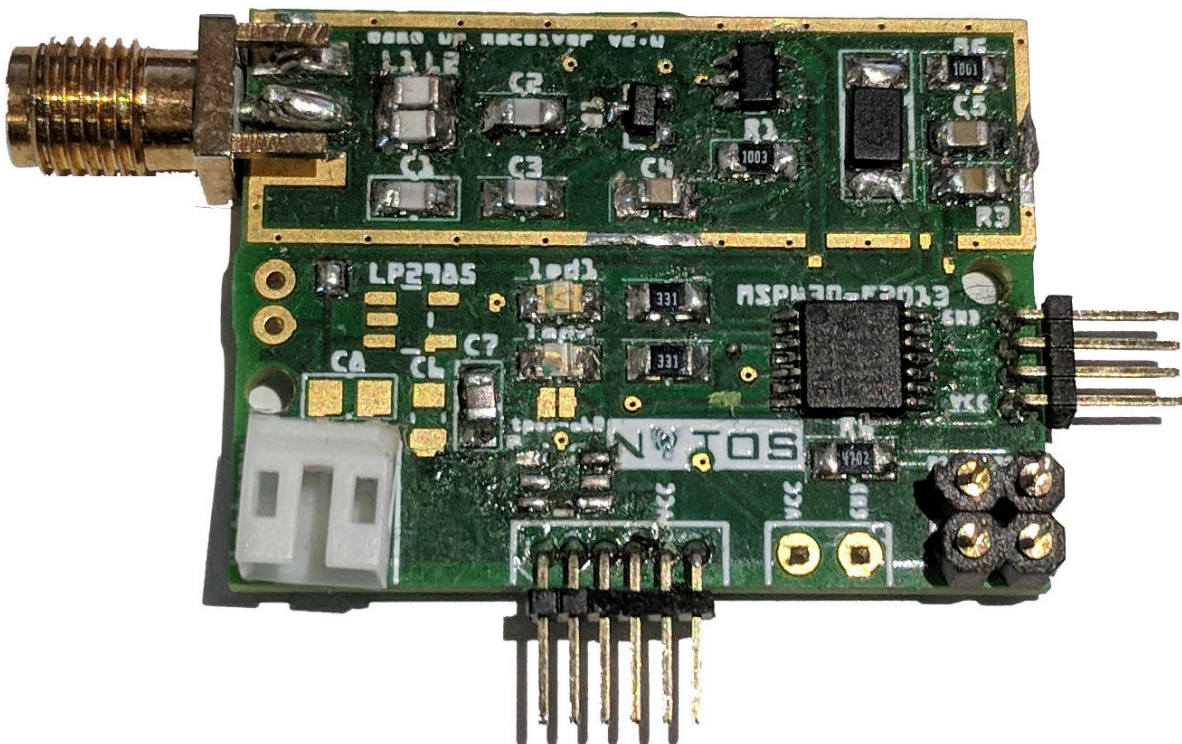


FIGURE 2.6. WuRx with MCU prototype

2.6 System Evaluation

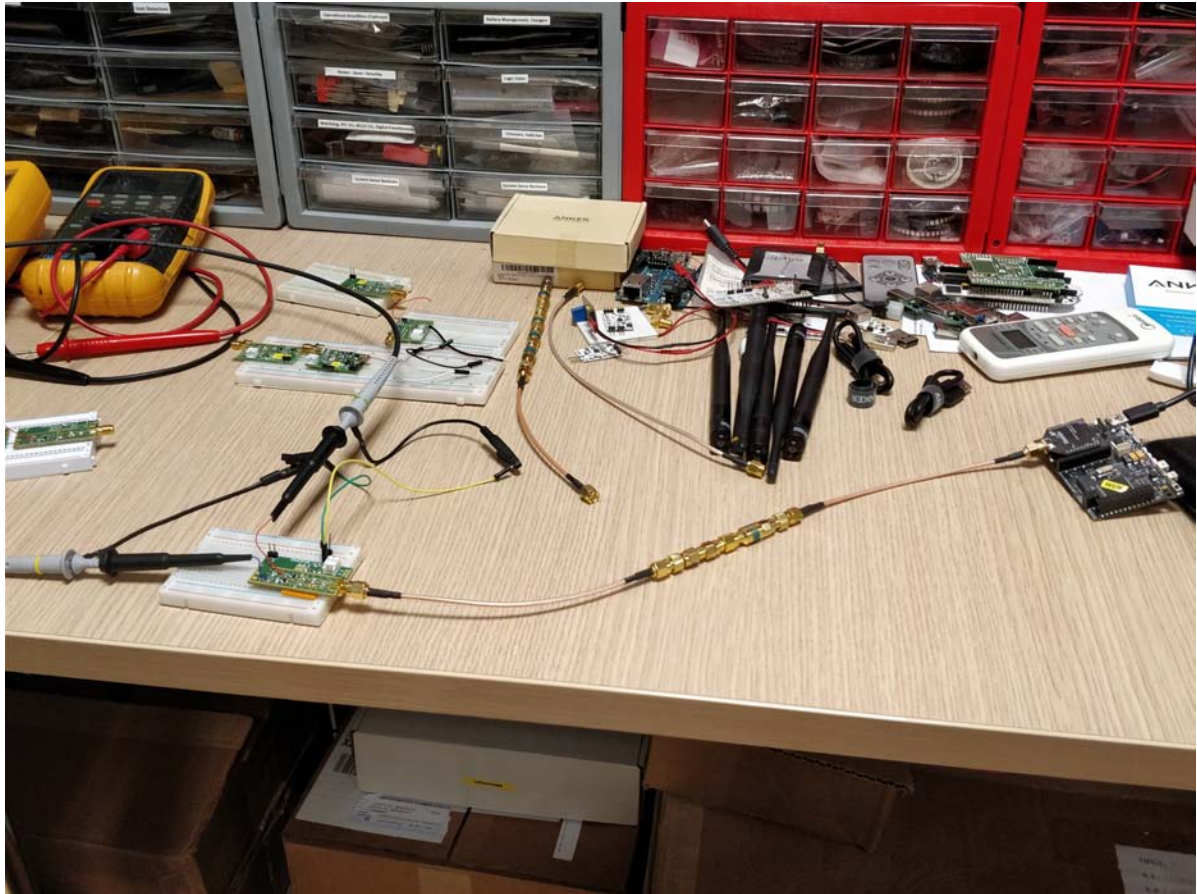


FIGURE 2.7. System Evaluation Setup

On the receiver side, the matching network consists of a capacitor and an inductor element that together form an LC filter used to reject undesired transmissions. In essence, the filter is designed to tolerate signals in the band of 868 MHz. Then, a passive rectifier in the topology of an envelope detector is formed with the aid of two Schottky diodes, used to discard the high frequency signals and to deliver the modulated *OOK* signal. Of course, a low-power comparator is used to aid the extraction of the received signal. The obtained signal is then provided to an auxiliary micro-controller that is responsible for checking for the matching address. More specifically, we employed the MSP430F2013 MCU that is constantly configured in the deep-sleep mode LPM4 (Low-Power Mode 4). When a signal is received by the circuit, an interrupt is generated that awakens the low-power micro-controller, in order to process the signal and determine

whether the modulated address refers to it. In case of address matching the low-power MCU awakens the host node. Notably, the utilized MSP430 features ultra-fast wake-up time, which ensures fast alternation to a working state to process the acquired signal.

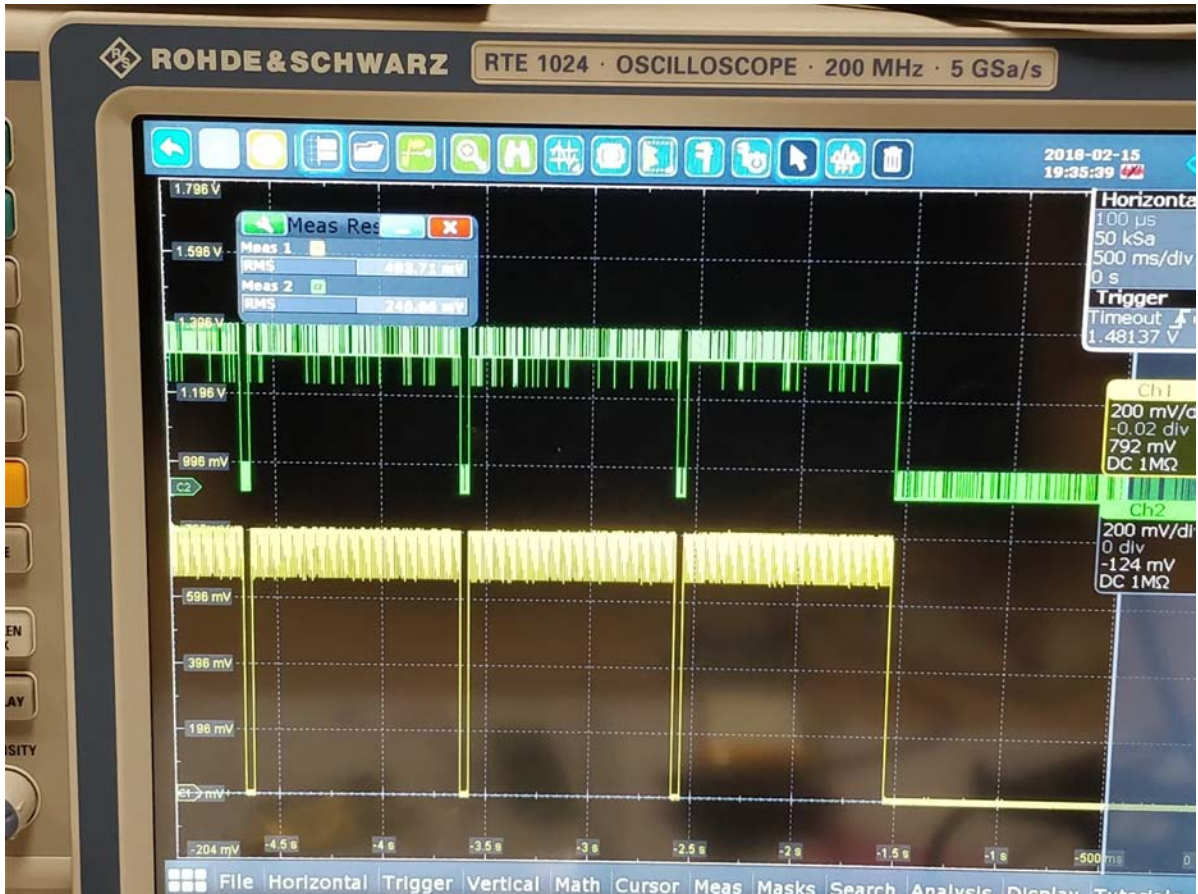


FIGURE 2.8. Observed signal using an Oscilloscope

To awake the network's nodes we use LoRa [7], which is a low-power ultra-long range IoT technology. More specifically, we use the SX1276 transceivers and custom-made sensor nodes, developed in-lab to send the wake-up packets. As described, the wake-up packet is modulated using *OOK* modulation, which in essence means that we transmit a carrier to represent binary one, or we suspend the transmission to represent binary zero. Of course, the signal is modulated at a fixed transmission rate, known to the receiver, so that it can extract the information by the received signal. Notably, the modulated packet contains two chunks of information, the *network id* and the *address* of the targeted node. This way, the wake-up circuit, ensures firstly that the packet belongs to its wake-up

network and secondly whether the address refers to it. Of course, sensor nodes, can support more than one wake-up addresses, so that we can awaken a set of nodes at the same time. An instance of the received signal is illustrated in Fig. 2.9, as obtained by the wake-up circuit. The received signal contains the *network id* and the *address*, which is the $0xA5$ and $0x06$ respectively, but depicted inversely. Naturally, this wake-up packet was intended to awake node *number 6*. It is worth noting that the wake-up signal begins with an artificial delay (*WuD*) to allow the activation of the MSP430, prior to the reception of the modulated information.

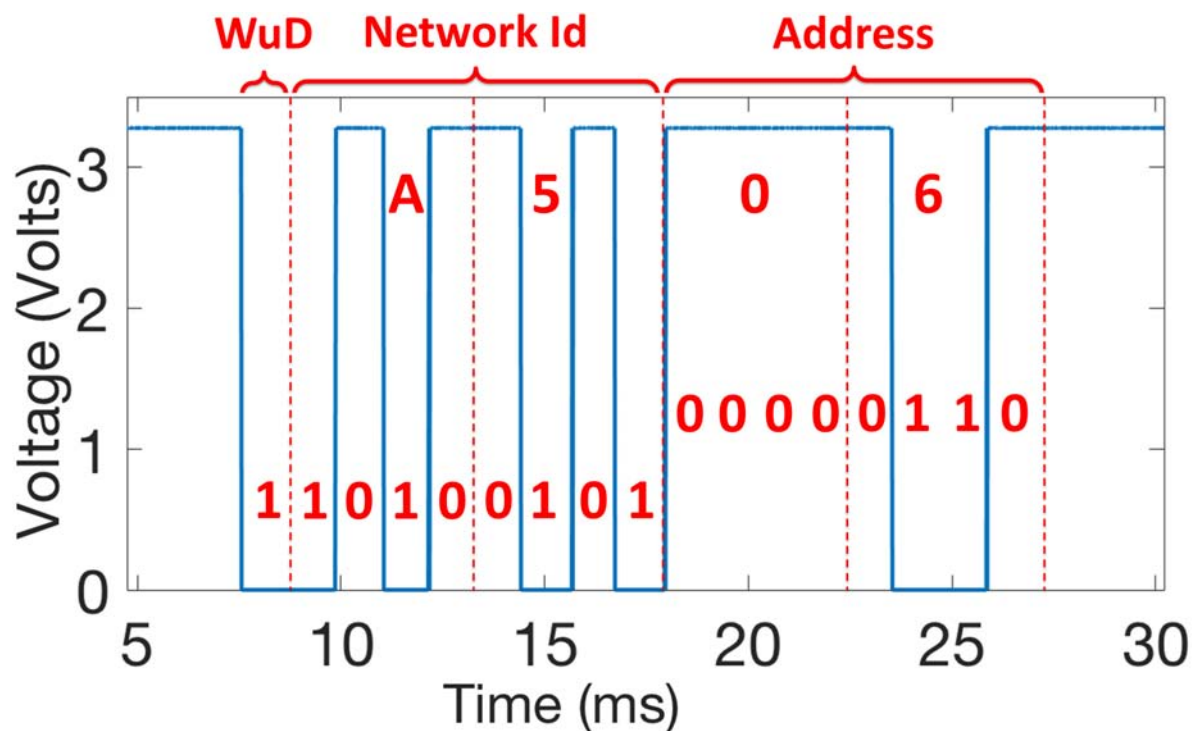


FIGURE 2.9. Obtained Wake-Up Signal

Finally, we characterize our implementation in terms of power consumption by using our high-end power consumption monitoring tools developed in [19], [17]. The total consumption when idle is roughly as low as 700 nA, very close to the consumption of [24] that features 650 nA in the same state. Notably, the consumption when processing a received packet is just 1.8 μ A, since the MSP430 is switched to the LPM3 and not in its typically active state. This plays significant role in the depletion of the battery, especially in a network with many wake-up packets being transmitted or other active

transmissions in this band that activate the MSP430.

2.7 Demonstration

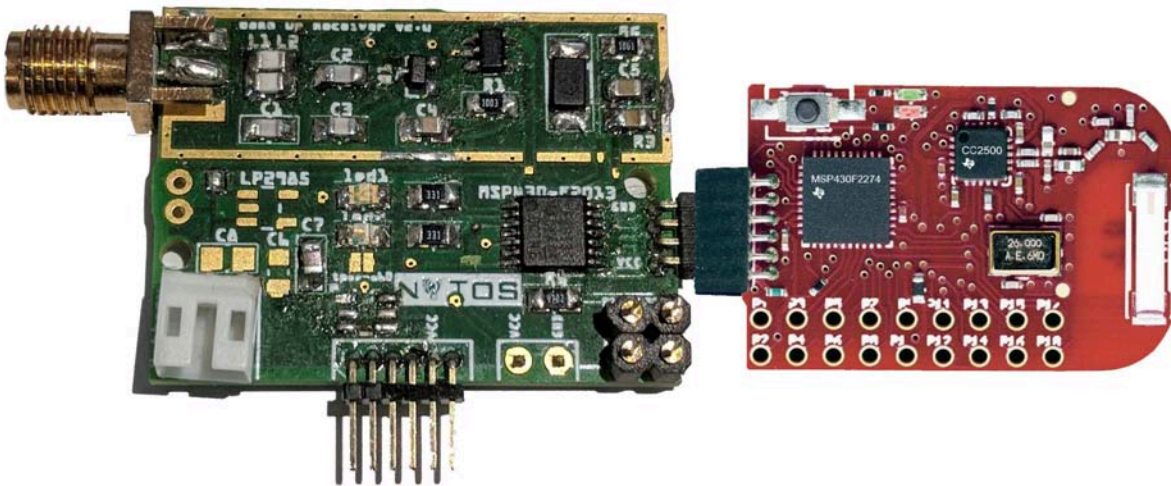


FIGURE 2.10. NITOS Demo – Receiver

To demonstrate the performance of our system we use a set of wake-up receivers attached to a state-of-the-art sensing platform, the eZ430-RF2500 [8] (Figure 2.10). We propagate wake-up requests by an neighboring node (Figure 2.11) to selectively awake the first node and the second one afterwards. Of course, the developed system features a broadcast address, in order to wake-up all the networks nodes or a set of them, towards serve complicated scenarios such as packet forwarding. During the demonstration, the nodes will be configured to sleep and they will be activated when receiving a wake-up packet. An LED will indicate their activation and a neighboring node operating as receiver will obtain their transmitted packets.



FIGURE 2.11. NITOS Demo – Transmitter

CONCLUSION AND FUTURE WORK

In this work we presented the NITOS wake-up receiver, attached to off-the-shelf sensor devices to provide asynchronous awakenings. This paper presents a novel network architecture exploiting radio diversity by combining LoRa and wake-up receivers. Using LoRa, a trade-off between latency and power consumption for packet transmission from the gateway to the nodes must be made. Our implementation drains roughly **700 nA** when idle and just **1.8 μ A** when receiving and processing a wake-up request. The main advantage of the proposed scheme is the utilization of LoRa transmitters to allow for long-range distances.

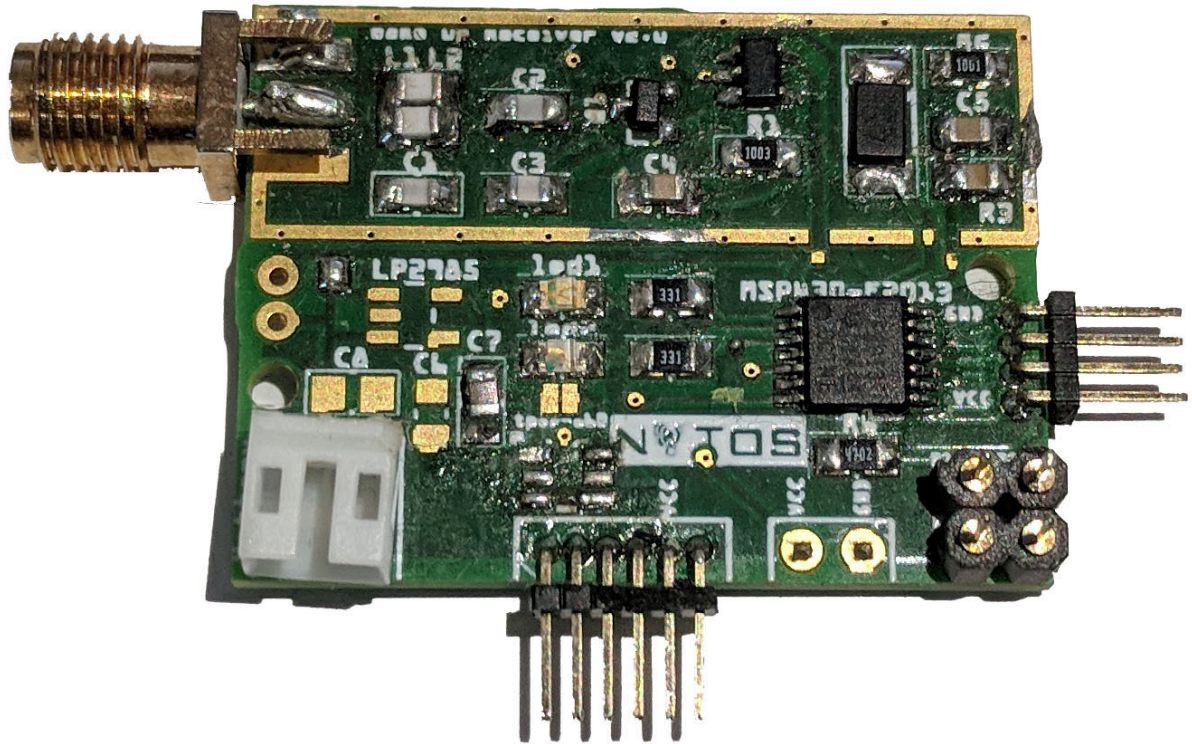


FIGURE 3.1. NITOS WuRx with MCU prototype

The long-short range architecture is validated with experimental measurements. A dedicated platform that embeds both LoRa and wake-up receiver technologies has been prototyped for the experiments. Experimental and analytical comparison showed the benefits of the proposed scheme, as it removes the trade-off between power consumption and latency.

3.1 Future Work

Our future plans include experiments in different distance ranges and under varying wake-up transmission rate. Furthermore, in order to increase the distance range of our circuit, thus increasing the sensitivity of the receiver, more research needs to be done on the multistage envelope detector 3.2.

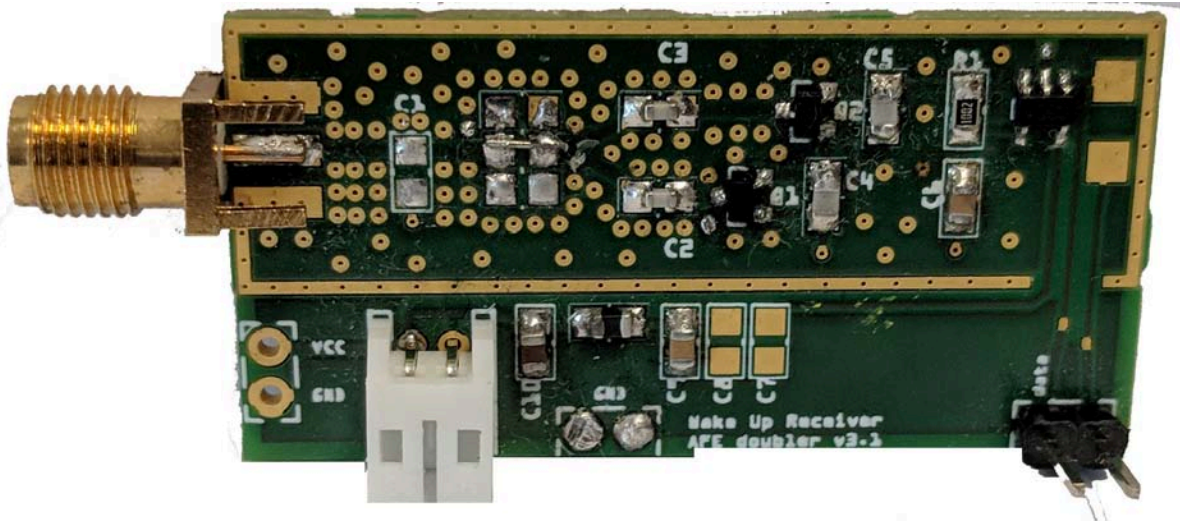


FIGURE 3.2. NITOS WuRx Analog Front-end with 2-stage envelop detector

Another concept we need to do more extensive research on the values of L-C of the matching filter. To this purpose we created an Analog Front End with variable inductor and variable capacitor 3.3.

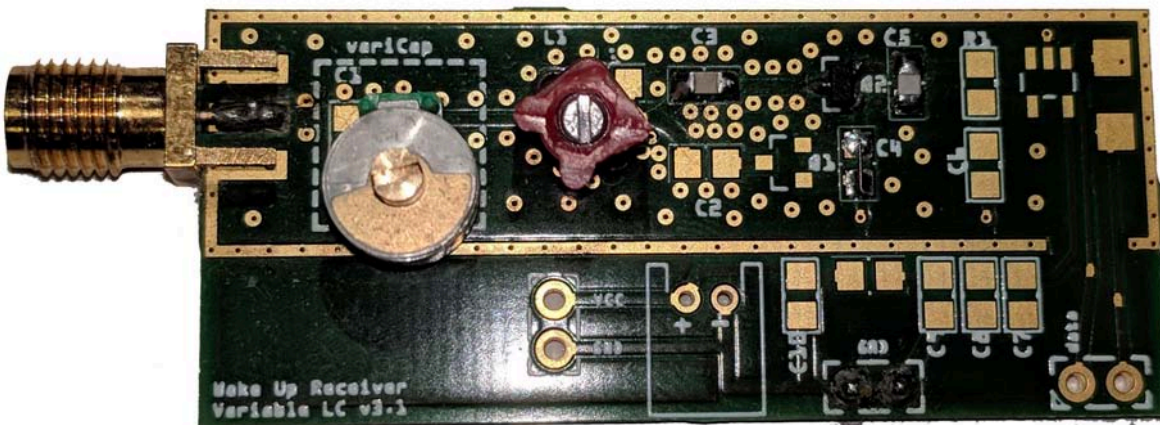


FIGURE 3.3. NITOS WuRx Analog Front-end with variable matching filter

Furthermore, we need to investigate more transmitter nodes than Waspote with LoRa. A cheaper solution we tested is Feather. In the following image you can observe Adafruit's Feather 868MHz Transmitter attached with attenuators in order to measure the sensitivity of the AFE.



FIGURE 3.4. Adafruit's Feather with Attenuators

Finally, more research needs to be done with the use of active components. Active components may increase the power consumption, but they increase the circuit sensitivity. To this aim we developed the following prototype 3.5

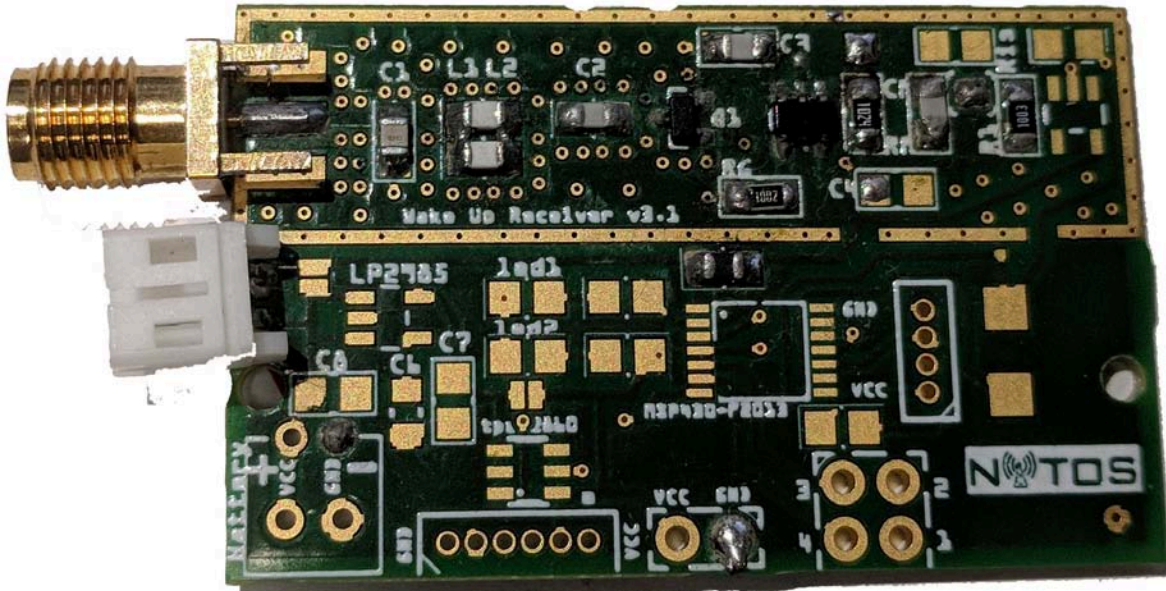


FIGURE 3.5. NITOS WuRx with Op-Amp

3.2 Acknowledgements

The research leading to these results has received funding from the European Union's Horizon 2020 ICT CAPS initiative under grant agreement no. 687983 (MAZI Project) [6]. This work is also published with the title "Demo: Enabling Asynchronous Awakenings in Wireless Sensor Networks Towards Removing Duty-Cycle Barriers", WiNTECH '17 [18]

BIBLIOGRAPHY

- [1] *All about Circuits | Envelope Detector.*
<https://www.allaboutcircuits.com/textbook/radio-frequency-analysis-design/radio-frequency-demodulation/how-to-demodulate-an-am-waveform/>.
- [2] *All about Circuits | Matching Networks.*
<https://www.allaboutcircuits.com/textbook/radio-frequency-analysis-design/selected-topics/understanding-matching-networks/>.
- [3] *Avago HSMS-285x Series.*
<http://www.efo.ru/components/avago/catalog/files/pdf/5989-4022EN.pdf>.
- [4] *Gartner.*
<https://www.gartner.com/en/newsroom/press-releases/2017-02-07-gartner-says-8-billion-connected-things-will-be-in-use-in-2017-up-31>
- [5] *LoRaWAN Specification v1.0, Lora Alliance, Inc. 2400 Camino Ramon, Suite 375 San Ramon, CA 94583 (2015), 2015, LoRa Alliance, Technical Report.*
- [6] *MAZI Project.*
<http://www.mazizone.eu/>.
- [7] *Semtech | LoRa Family | Wireless & RF ICs for ISM Band Applications.*
<http://www.semtech.com/wireless-rf/lora.html>.
- [8] *Texas Instruments eZ430-RF2500.*
<http://www.ti.com/lit/ug/slau227f/slau227f.pdf>.
- [9] *Texas Instruments LPV7215.*
<http://www.ti.com/lit/ds/symlink/lpv7215.pdf>.

BIBLIOGRAPHY

- [10] *Texas Instruments MSP430 Family*.
<http://www.ti.com/microcontrollers/msp430-ultra-low-power-mcus/overview.html>.
- [11] *Texas Instruments MSP430F201x*.
<http://www.ti.com/lit/ds/symlink/msp430f2013-ep.pdf>.
- [12] F. A. AOUDIA, M. GAUTIER, AND O. BERDER, *Opwum: Opportunistic mac protocol leveraging wake-up receivers in wsns.*, *J. Sensors*, 2016 (2016), pp. 6263719:1–6263719:9.
- [13] F. A. AOUDIA, M. MAGNO, M. GAUTIER, O. BERDER, AND L. BENINI, *Analytical and experimental evaluation of wake-up receivers based protocols.*, in *GLOBE-COM*, IEEE, 2016, pp. 1–7.
- [14] —, *A low latency and energy efficient communication architecture for heterogeneous long-short range communication.*, in *DSD*, P. Kitsos, ed., IEEE Computer Society, 2016, pp. 200–206.
- [15] H. BA, I. DEMIRKOL, AND W. B. HEINZELMAN, *Passive wake-up radios: From devices to applications.*, *Ad Hoc Networks*, 11 (2013), pp. 2605–2621.
- [16] F. Z. DJIROUN AND D. DJENOURI, *Mac protocols with wake-up radio for wireless sensor networks: A review.*, *IEEE Communications Surveys and Tutorials*, 19 (2017), pp. 587–618.
- [17] G. KAZDARIDIS, S. KERANIDIS, P. SYMEONODIS, P. DIAS, P. GONÇALVES, B. LOUREIRO, P. GJANCI, AND C. PETRIOLI, *Everun - enabling power consumption monitoring in underwater networking platforms*, in *Proc. of WiNTECH '17*.
- [18] G. KAZDARIDIS, P. SKRIMPONIS, I. ZOGRAPHOPOULOS, P. SYMEONIDIS, T. KORAKIS, AND L. TASSIULAS, *Demo: Enabling asynchronous awakenings in wireless sensor networks towards removing duty-cycle barriers*, in *Proceedings of the 11th Workshop on Wireless Network Testbeds, Experimental Evaluation & Characterization, WiNTECH '17*, New York, NY, USA, 2017, ACM, pp. 95–96.
- [19] S. KERANIDIS, G. KAZDARIDIS, V. PASSAS, T. KORAKIS, I. KOUTSOPOULOS, AND L. TASSIULAS, *Online energy consumption monitoring of wireless testbed infrastructure through the nitos emf framework*, in *Proc. of WiNTECH '13*.

- [20] M. MAGNO, F. A. AODIA, M. GAUTIER, O. BERDER, AND L. BENINI, *Wulora: An energy efficient iot end-node for energy harvesting and heterogeneous communication.*, in DATE, D. Atienza and G. D. Natale, eds., IEEE, 2017, pp. 1528–1533.
- [21] M. MAGNO, V. JELICIC, B. SRBINOVSKI, V. BILAS, E. M. POPOVICI, AND L. BENINI, *Design, implementation, and performance evaluation of a flexible low-latency nanowatt wake-up radio receiver.*, IEEE Trans. Industrial Informatics, 12 (2016), pp. 633–644.
- [22] M. MAGNO, S. J. MARINKOVIC, D. BRUNELLI, E. M. POPOVICI, B. O'FLYNN, AND L. BENINI, *Smart power unit with ultra low power radio trigger capabilities for wireless sensor networks.*, in DATE, W. Rosenstiel and L. Thiele, eds., IEEE, 2012, pp. 75–80.
- [23] J. OLLER, I. DEMIRKOL, J. CASADEMONT, J. PARADELLS, G. U. GAMM, AND L. M. REINDL, *Has time come to switch from duty-cycled mac protocols to wake-up radio for wireless sensor networks?*, IEEE/ACM Trans. Netw., 24 (2016), pp. 674–687.
- [24] D. SPENZA, M. MAGNO, S. BASAGNI, L. BENINI, M. PAOLI, AND C. PETRIOLI, *Beyond duty cycling: Wake-up radio with selective awakenings for long-lived wireless sensing systems*, in Proc. of IEEE INFOCOM '15.
- [25] P. TUSET-PEIRÓ, X. VILAJOSANA, AND T. WATTEYNE, *Openmote+: a range-agile multi-radio mote.*, in EWSN, K. Römer, K. Langendoen, and T. Voigt, eds., Junction Publishing, Canada / ACM, 2016, pp. 333–334.

