Design and implementation of wake-up radios for long-range wireless IoT devices

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Abstract

As the development within Internet of things IoT increases rapidly and the market starts to utilize its potential, an enormous effort is being made in both academia and industry to optimize solutions according to the market demands. The demands vary from case to case. Some applications might require relatively high data rate, long battery lifetime, low latency and long range/area coverage. The numerous use cases and demands for IoT resulted in various IoT technologies. In many IoT applications, especially Wireless IoT applications, energy-efficiency and battery lifetime are some of the most important performance metrics. The wireless access mechanisms used in current technologies utilize Duty-cycling (DC) to reduce power consumption. DC allows a node to turn the radio on and off in specific intervals in order to reduce power consumption.

These DC-MAC protocols suffer from overhearing, idle listening or unnecessary transmission of advertisement packets. The different protocols may also include long delay time caused by the inactive period in the MAC protocol. The recent research and development of Wake-up Radios (WuRs) addresses some of these problems. A WuR is a simple low power radio receiver which always listens to the channel to detect a Wake-up Call (WuC). A wake-up radio receiver (WuRx) is attached to the main radio which is always OFF, except when it is supposed to send data. The WuRx and the main radio (MR) are two parts of an IoT node. The use of WuRx eliminates the unnecessary power consumption caused by idle listening and reduce the overhearing consumption as well as the latency. Many articles have been published about WuRs. However, most of the current WuR solutions focus on short range applications. The objective of this thesis is to design a WuRx for long-range applications, implement a WuRx and evaluate the results and compare to existing technologies.

To reduce the power consumption in long-range IoT applications, a WuRx has been proposed, tested and evaluated. Performance of the proposed WuRx integrated with LoRaWAN node is compared to a LoRaWAN node without a WuRx. A DC-MAC protocol which is combined with a WuRx to reduce power is also investigated.

Preface

The thesis is a result of the research work carried out at the department of Information and Communication Technology (ICT), University of Agder (UiA), Grimstad, Norway, from August 2018 to May 2019. During my thesis my supervisors have been Linga Reddy Cenkermaddi and Magne Arild Haglund.

Production note: Latex has been adopted as the tool for writing this thesis, as well as the articles produced during the period. Altium has been used for PCB design, LTspice for simulations and Matlab for graph generations.

List of Publications

The author of this thesis is the first Author and the principle contributor of the three papers listed below. The first set of papers represents the main research achievements. The papers listed in the second set are complimentary to the main focus.

Papers included in thesis

Paper A: Anders Frøytlog , M . Arild Haglund, Linga Reddy Cenkeramaddi, Thomas Jordbru, R . Arne Kjellby and B. Beferull-Lozano, "Design and Implementation of a Long-Range Low-Power Wake-Up Radio for IoT Devices" (IEEE WF-IoT 19), Limerick, Ireland [Presented]

Paper B: Anders Frøytlog , M . Arild Haglund, Linga Reddy Cenkeramaddi,and B. Beferull-Lozano "Design and implementation of a long-range low-power wake-up radio and costomized DC-MAC protocol for LoRaWAN" [In progress]

Paper C: Anders Frøytlog and Linga Reddy Cenkeramaddi, "Design and Implementation of an Ultra-Low Power Wake-up Radio for Wireless IoT Devices" (IEEE ANTS 2018), Indore, India

Other Publications not included in Thesis

Paper: 3 Anders Frøytlog, Thomas Foss, Ole Bakker, Geir Jevne, M. Arild Haglund, Frank Y. Li, Joaquim Oller, and Geoffrey Ye Li, "Ultra-Low Power Wake-up Radio for 5G IoT," in IEEE Communications Magazine, vol. 57, no. 3, pp. 111-117, March 2019. doi: 10.1109/MCOM.2019.1701288

Paper 4: D. Ghose, A. Frøytlog, and F. Y. Li, "Enabling Early Sleeping and Early Data Transmission in Wake-up Radio-enabled IoT," *Computer Networks*, vol. 153, pp. 132-144, Apr. 2019.

Paper 5: Debasish Ghose, Anders Frøytlog, and Frank Y. Li, "Reducing Overhearing Energy in Wake-up Radio-enabled WPANs: Scheme and Performance" In Proc. International Conference on Communications (ICC 2018), Kansas City, USA.

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Glossary

3GPP Third Generation Partnership Project. 8

ABP Activation by personalization. 9

ACK Acknowledgement. 11

DC Duty-cycling. iii, 4, 5, 9

DC-MAC Duty-cycling Medium Access Control. iii, 5, 11

ICT Information and Communication Technology. v

IoT Internet of Things. iii, 3, 4, 7, 39

IP Internet Protocol. 9

LNA Low Noise Amplifier. 37

LoRa Long-Range. 5, 9

LoRaWAN Long-Range Wide Area Network. iii, 3, 4, 7–10, 40

MAC Medium Access Control. iii, 9

MCU Microcontroller. 12

MR Main Radio. iii, 11, 12

OTAA Over the air activation. 10

PCB Printed Circuit Board. v

S-MAC Sensor Medium Access Control. 11

TTN The Things Network. 5

UiA University of Agder. v

Wi-Fi Wireless Fidelity. 8

WSN Wireless Sensor Network. 5, 9, 39

WuC Wake-up Call. iii

WuR Wake-up Radio. iii, 4, 5, 7, 13, 39, 40

WuRx Wake-up Radio Receiver. iii, 4, 5, 12, 40

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X-MAC Short Preamble Medium Access Control. 5, 11

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Part I

Research Overview

Chapter 1

Introduction

1.1 Motivation

The development of IoT devices will rapidly increase within the next couple of years. It is expected that by 2020, there will be more than 50 billion devices connected to the Internet, and 1 trillion by 2022 [4]. All these devices need to be powered using either rechargeable or non-rechargeable batteries. Energy harvesting solutions were also explored to avoid the maintenance of the batteries. Power will become particularly critical when these IoT devices operate in the long-range, which is in the order of 10 km to 15 km.

Many applications demand such long-range IoT devices. Some of the long-range applications include environmental monitoring in large rural areas, agriculture and smart cities. The current most widely used low power solution for long-range applications is the long-range wide-area-network (LoRaWAN) standard. The energy performance of the various LoRaWAN devices are very well studied [2]. The study reveals a relatively high energy consumption resulting in a maximum operating period of 1 year using a 2400 mAh battery with a transmission interval of 5 minutes. This solution, like most wireless IoT systems, utilizes duty cycling to reduce the power consumption of the node.

Duty cycling (DC) nodes turn the internal radio ON and OFF with a certain interval to minimize power consumption and idle listening in the network. This introduces some limitations. In a DC controlled system, a node can only "wake-up" at certain intervals, thereby increasing the latency of the system. Additionally, the nodes need to have a process running continuously to make sure the radio initializes at given intervals, thereby increasing the "sleep" current. In addition, the radio on the node must be made complex enough to be able to modulate and demodulate the access mechanism associated with the system, which also increases the overall energy consumption. Both the energy consumption and the latency can be massively improved by deploying an on-demand wake-up radio (WuR) to these long-range IoT nodes.

1.2 Thesis Definition

The main objective is to design a low power wake-up radio for long range IoT devices to reduce power consumption. Implementation and testing in an IoT device and comparison of the performance to the existing solutions.

1.2.1 Thesis Goals

Goal 1: Design a low-power wake-up radio for long range communication.

Goal 2: Implementation and testing of the WuR design.

Goal 3: Evaluate the current low-power solutions for long range IoT applications.

Goal 4: Comparing the performance with the existing solutions.

1.3 Contributions

The contributions presented in this thesis are three-fold. Design and evaluation of a low-power WuRx, system design of LoRaWAN with attached

WuRx, and a customized DC-MAC protocol to further reduce power consumption. The major contributions are outlined as follows.

- Wake-up Radio design: A low-power WuRx has been designed and tested to accommodate the low-power solution for long-range IoT applications, particularly LoRaWAN.
- LoRaWAN: A system design consisting of a TTN server, Gateway, Wake-up Radio Transmitter (WuTx) and a LoRa node with an attached WuRx.
- DC-MAC protocol: A proposed variant of the X-MAC DC protocol, modified for WuRx-enabled Wireless sensor network (WSN) nodes. This will further reduce power consumption while maintaining the low latency advantages provided by the WuR.

1.4 Thesis Outline

The thesis consists of three major parts. Part one will give an introduction to the primary field of research, existing technologies and alternative solutions. Part two consists of the three published or submitted papers, which are listed previously. Part three will consist of a discussion of the findings, future work and a conclusion to the thesis.

Chapter 2

Background

This chapter will give an introduction to the Internet of Things (IoT) and the importance of energy-efficiency, as well as a description of how LoRaWAN operates. Then a brief description of some of the most used duty-cycling protocols and a description of how the MAC-layer functions with an attached WuR. Lastly, a general overview of how a wake-up radio enabled node operates.

2.1 IoT

The concept of internet of things mainly refers to the infrastructure in which "things" are connected to one another and/or the internet. In other words, the devices are objects with specific purposes. They can have virtual perceptions and be used for data collection or physical attributes such as door locks. The "things" must also have communication capability in order to be able to connect to the internet or a wireless sensor network. The development of IoT will play an important role in the digital transformation of both the private, public and industrial sector.
To provide connection to the internet, the IoT devices can be connected either by 3GPP or by a non-3GPP connection.

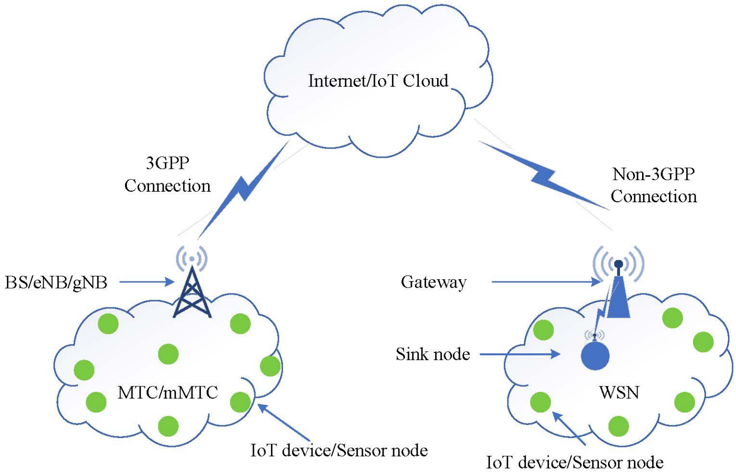

Figure 2.1: Overview of IoT connections

2.1.1 3GPP Connections

3GPP connection involves a device directly connected to a cellular tower, i.e., direct third generation partnership project (3GPP) connection. Some examples of 3GPP connections are 2G, 3G, 4G and 5G cellular connection. The development of 5G will be quite beneficial, especially for Machine type Communication. For example, if there is a problem with a car, the information from the car could be automatically sent to the manufacturer which can order spare parts or book an appointment with the mechanic.

2.1.2 Non-3GPP Connections

Non-3GPP is connections to the internet that do not involve cellular base station connection. This includes wireless fidelity (Wi-Fi) and systems where a gateway between the IoT devices and internet is necessary. LoRaWAN is such an example, where the nodes transmit packets to the gateway over LoRa and the gateway forwards the packet to a server. More on this in section 2.2.

2.1.3 Energy-efficiency

One of the most important requirements of wireless sensor nodes are the lifetime and the energy-efficiency of the sensor nodes. It is expected that a wireless sensor node has multiple years of lifetime, therefore the development of energy-saving solution is essential.

In traditional WSNs, multiple nodes are connected to a gateway, often referred to as a sink. The role of the nodes is to gather or collect data and send it to the gateway. These data transmissions are ordinarily done in a timer-driven manner. Where the nodes send data between given intervals. There are different ways of optimizing the energy-efficiency, but it's become a norm to adopt duty-cycling (DC) medium access control (MAC) mechanisms to reduce energy wastage.

2.2 LoRaWAN

The Long-Range Wide Area Network, is designed to wirelessly connect operated "things" to the internet over a long range.

2.2.1 Architecture

The architecture of LoRaWAN is a star-of-stars topology, where a gateway has multiple nodes and connection to a server over IP. A LoRaWAN gateway forwards all received LoRa traffic as IP-packets to the configured IP-address. An overview of the LoRaWAN architecture is shown in figure 2.2.

2.2.2 Data Transfer

Data communication between LoRa nodes and the server is end-to-end encrypted. This means that the gateway does not interfere with the content of the packet, it only forwards the data as an IP packet. Encryption between the end node and the server can be done in one of two ways. It can use Activation by personalization (ABP) which uses preconfigured keys to

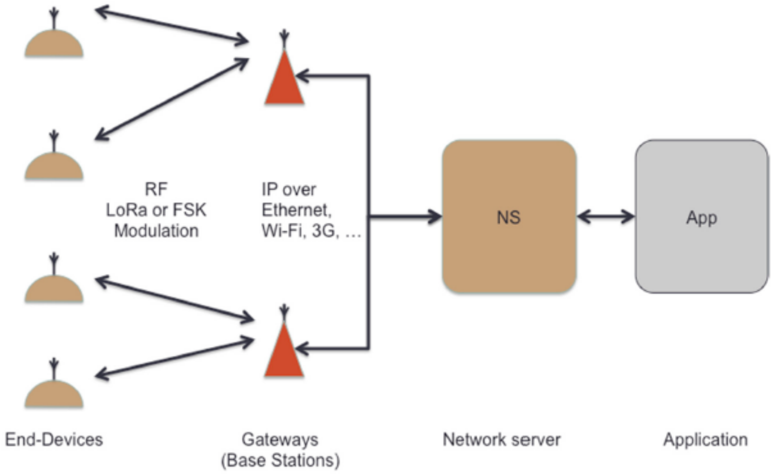

Figure 2.2: Overview of LoRaWAN [2]

encrypt the data to a specific application on the server side. It can also use Over the air activation (OTAA) which establishes session keys in a join procedure before data is sent. An overview of the different LoRaWAN layers is presented in fig 2.3.

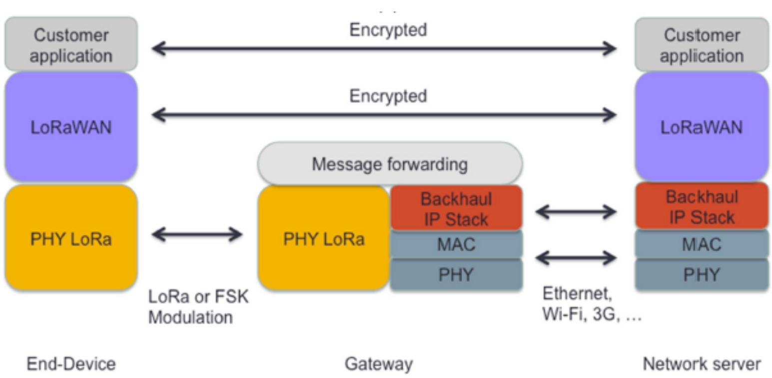

Figure 2.3: Overview of Layers in LoRaWAN [2]

2.3 Duty-Cycling Protocols

The most common way of optimizing energy-efficiency is by adopting duty-cycling protocols. These protocols reduce the time the radio is listening and transmitting packets on a given channel. By switching the radios ON and OFF with certain intervals reduces the overall power consumption. Although, DC also introduces latency and overhearing in the network, which again increases power consumption. These DC-MAC protocols can either be synchronous or asynchronous.

2.3.1 X-MAC

X-MAC was proposed in [1] and is one of the most popular DC-MAC protocols for asynchronous networks. On the transmitter side it uses short preamble packets containing the identity of a certain node. The preamble packets are sent in succession if it doesn't get an ACK from the receiver. The receiver sleeps for a certain interval and then samples the channels for preamble bursts. If a preamble is detected and the ID is correct then it transmits an acknowledgement (ACK) and data can be exchanged.

2.3.2 S-MAC

S-MAC was proposed in [6] and is a synchronous DC-MAC protocol. Time is partitioned into cycles of same length and includes an activation period and a sleep period. The active period is used for synchronization messages and data communication. This way every node in the network shares the same active and sleep schedule.

2.4 Wake-up Radio

Wake-up Radio is a on-demand solution to the sensor nodes. An external low-power radio is attached to the main radio (MR). This means that the MR can be off if there is no need for it to operate. In other words, the MR is off until the wake-up radio receives an address intended for that node.

2.4.1 General Structure

The Wake-up radio receiver (WuRx) provides a microcontroller (MCU) with an external interrupt and an address. The address is decoded by the MCU and validated. If the address matches with its own, it can turn on the main radio (MR) and start the communication. The general structure of a wake-up radio enabled node is shown in fig 2.4

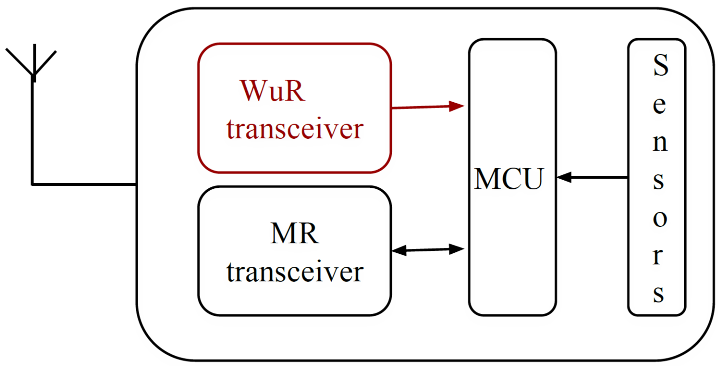

Figure 2.4: Wake-up radio enabled node

Chapter 3

State-of-the-art

3.1 Wake-up Radio

Previous implementations of WuRs have primarily focused on short range solutions with almost no current consumption. In paper 3, an extremely low power solution with very limited range was proposed. In paper 5, over-hearing in WuR enabled nodes were reduced by introducing a bit-by-bit scheme. Paper 4 combines the wake-up address with data. There are few implementations of long range solutions regarding wake-up radio. A survey of many wake-up radios were outlined in [5]. However, many of these solutions consist of simulations and/or missing documentation of practical implementation and measurements.

3.2 Advantages of Wake-up Radio

A thorough study of the energy consumption in WuR enabled networks and DC enabled networks were made in [7]. There it was found that the energy consumption in a WuR enabled network was excellent if the traffic load was light. However, when the traffic load increases, it gradually looses its advantages. It was also implied that due to the decrease in performance related to increased traffic load, long-distance WuR may not be beneficial.

Part II

Contributions

Paper A

Title:	Design and Implementation of a Long-Range Low-Power Wake-Up Radio for IoT Devices
Authors:	Anders Frøytlog , M . Arild Haglund, Linga Reddy Cenkeramaddi, Thomas Jordbru, R . Arne K jellby and B. Beferull-Lozano
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Conferance:	*IEEE WF-IoT 19, Limerick, Ireland [Presented]*
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Design and implementation of a long-range low-power wake-up radio for IoT devices

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***Abstract*—In this paper, we present the design and implementation of an on-demand wake-up radio (WuR) for long-range wireless IoT devices to reduce the power consumption, thereby increasing the life time of the devices. A custom narrow-band (NB) low noise amplifier is designed and implemented for WuR. The low-noise amplifier achieves a gain of 31 dB at 1 mA current consumption from a 6 V power supply. The WuR achieves a sensivity of -80 dBm by consuming just 1 mA, thereby optimizing the energy consumption of battery powered long-range IoT devices, hence reducing the power consumption and overall costs when deployed in large scale.**

I. Introduction

The development of IoT devices will rapidly increase within the next couple of years. It is expected that by 2020, there will be more than 50 billion devices connected to the Internet, and 1 trillion by 2022 [1]. All these devices need to be powered using either rechargeable or non-rechargeable batteries. Energy harvesting solutions were also explored to avoid the maintenance of the batteries [2]. Power will become particularly critical when these IoT devices operate in the long-range, which is in the order of 10 km to 15 km.

Many applications demand such long-range IoT devices. Some of the long-range applications include environmental monitoring in large rural areas, agriculture and smart cities. The current most widely used low power solution for long-range applications is the long-range wide-area-network (LoRaWAN) standard. The energy performance of the various LoRaWAN devices are very well studied [3]. The study reveals a relatively high energy consumption resulting in a maximum operating period of 1 year using a 2400 mAh battery with a transmission interval of 5 minutes. This solution, like most wireless IoT systems, utilizes duty cycling to reduce the power consumption of the node.

Duty cycling nodes turn the internal radio on and off with certain interval to minimize power consumption and idle listening in the network. This introduces some limitations. In a duty cycling controlled system, a node can only "wake-up" at certain intervals, increasing the latency of the system and the nodes need to have a process running continuously to make sure the radio initializes at given interval, thereby increasing the "sleep" current. In addition, the radio on the node must be made complex enough to be able to modulate and demodulate the access mechanism associated with the system, which also increases the overall energy consumption. Both the energy consumption and the latency can be massively improved by deploying an on-demand wake-up radio (WuR) to these long-range IoT nodes.

This article focuses on the low-power solution for the long-range IoT devices by employing an on-demand wake-up radio solution. The rest of the article will focus on the design and implementation of the wake-up radio, low-noise amplifier employed in the WuR, measurement results and finally conclusion.

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II. Design of a long-range low power Wake-up radio

A. Overview

An overview of the WuR is shown in Fig. 1. The WuR consists of five major parts, a matching network, a low noise amplifier, an envelope detector, a comparator and a preamble detector.

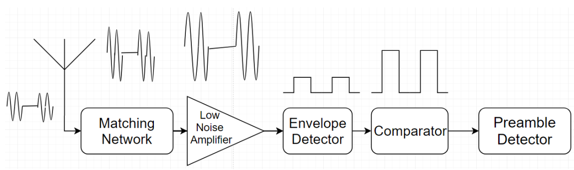

Fig. 1. Overview Of The Wake-Up Radio.

The Matching network provides proper impedance matching between the antenna and the amplifier at a given frequency. The low noise amplifier consists of a cascoded BJT amplifier using the 2SC3838k NPN transistors. A buffer stage is also included to match the impedance to the envelope detector, which provides the demodulation of the received signal. Following that, the comparator amplifies the demodulated signal such that a microcontroller (MCU) will be able to interpret it. The preamble detector provides an interrupt to MCU when the received signal has a certain length, which will account for some interference from the surroundings. The WuR is designed to demodulate an on-off keying (OOK) modulated signal at 433 MHz.

B. Circuit Design

The schematic shown in Fig. 2 is the entire wake-up radio with component values used in the design. All parts, a matching network, a low noise amplifier, an envelope detector, a comparator and a preamble detector can be observed in the design.

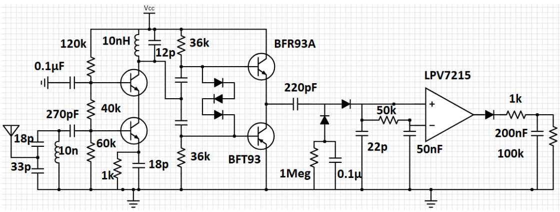

Fig. 2. WuR Circuit.

1) Matching Network: The matching network consists of two capacitors and one inductor which is tuned to a 50 Ω antenna. The Matching network provides appropriate impedance matching between the antenna and the low noise amplifier (LNA). Since the input impedance at the LNA will be greater than the output impedance at the antenna, there will be a voltage gain, given the fact that most of the input power is preserved. With the assumption that the power will be 100% preserved, the voltage at the LNA is given by equations 1 and 2.

$$P_{antenna} = P_{LNA} \tag{1}$$

$$\frac{V_{in}^2}{R_{antenna}} = \frac{V_{out}^2}{R_{LNA}} \tag{2}$$

In practice, some power will be reflected back to the antenna.

2) Low Noise Amplifier: The low noise amplifier is a cascoded BJT amplifier designed using the 2SC3838k NPN high-frequency transistors. The resistor values shown in Fig. 3 were chosen by optimizing the current consumption for maximum possible gain. The LC-filter connected to the collector of the top transistor in LNA is designed such that the peak gain will be at 433 MHz, which is the frequency used in the prototype. With an inductor value of 10 nH and a capacitor value at 12 pF, the cut-off frequency will be:

$$f_c = \frac{1}{2\pi\sqrt{10nH * 12pF}} = 459\ MHz \tag{3}$$

The resistor and the capacitor connected to the emitter of the bottom transistor provides the amplifier with a narrowband amplification. The amplifier consumes 1 mA, with a supply voltage of 6 V.

The buffer stage after the amplifier provides an impedance transformation from LNA to envelope detector. The output impedance of the amplifier is high, while the input impedance of the envelope detector is assumed to be lower. Therefore, a buffer stage is required. The diodes provide stable voltage biasing for the base of the PNP transistor. The current at the emitter is expected to be around 0.1 mA.

3) Envelope Detector: The envelope detector demodulates the received OOK signal. The diodes used in the envelope detector are the HSMS-285x. These diodes have been designed for use in small signal applications and frequencies of up to 4.0 GHz. The resistor and the capacitor connected to the anode at the diode provides stability in reference to RF-ground in addition to storing negative voltage.

4) Comparator: The comparator detects the pulses demodulated from the envelope detector and generates pulses that can be interpreted by a microcontroller. The comparator used in this design is an LPV7215 with a power consumption of only 580 nA and an offset voltage of +/- 0.3 mV. The Resistor and capacitor connected to the negative input will store some of the energy from the OOK signal in order to make sure the comparator goes negative when a '0' is received.

5) Preamble Detector: The preamble detector provides an interrupt signal or a wake-up signal to an MCU. For the preamble detector to provide this signal, the pulse from the comparator must be sufficiently large to charge the capacitor in the detector. This is done to prevent the MCU from false wake-ups caused by smaller signals.

III. Implementation

PCB layout plays a critical role in the hardware implantation of high frequency RF-circuits. FR-4 substrate which has a propagation velocity of about 2/3 of the speed of light, i.e. approximately $2 * 10^8$ m/s is used for this design. For a frequency of 433 MHz, the wavelength becomes $\lambda = \frac{v}{f} = \frac{2*10^8 m/s}{433MHz} = 43$ cm.
The path-length can be calculated as $\frac{\lambda}{40}$. This will result in 10-degree shift in the smith chart, which is in acceptable limits. This means that the high impedance connections in the RF-path must be less than $\frac{\lambda}{40} = 1.15$ cm.

In addition to the path-length, other considerations must be taken into account. Decoupling capacitors are added close to the LC circuit, on the collector of the BFR93 transistor and at the supply voltage of the comparator. Failing to add these will cause severe problems. Finally, the inductors must be placed appropriate to one another. Inductors create a magnetic field which can have a negative impact. These are placed 90-degrees facing each another, which will eliminate the problem of magnetic interference.

Fig. 3 shows the PCB-layout used in this prototype, where C10, C11 and C15 are all decoupling capacitors. The resistor

R7 is added to the layout to make it easier to view the S21 parameter from the buffer-stage. This is done before the diodes are soldered on to the circuit. This allows to make sure the gain is centered at the desired frequency.

A prototype of the LNA designed for WuR is shown in Fig. 4.

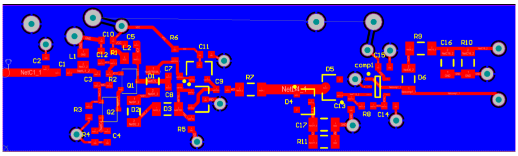

Fig. 3. PCB layout Of The Wake-Up Radio.

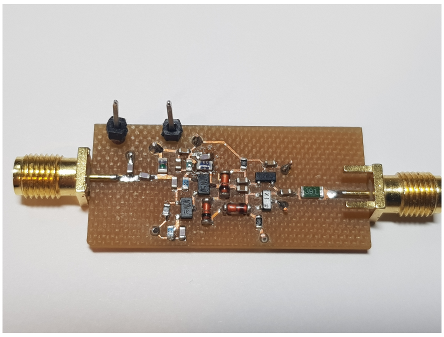

Fig. 4. Prototype of LNA

IV. Measurements and Results

A. Measurements of Reflection Coefficient

The reflection coefficient is measured by connecting the network analyzer to the input of the matching network.

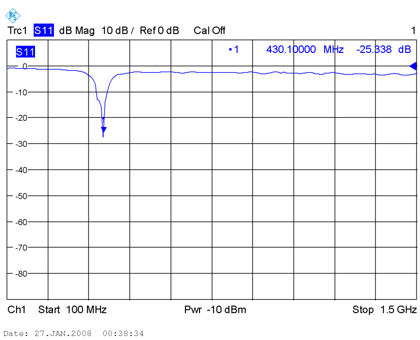

Fig. 5. Measurements of S11 parameter.

As can be observed from Fig. 5, the reflection coefficient is measured to be -25.33 dB. This results in the following reflection:

$$r = 10^{\frac{-25.33}{20}} = 0.0540 \tag{4}$$

$$Reflection = r^2 = 2.92 * 10^{-3} = 0.29\% \tag{5}$$

This means that 0.29% of the received signal will be reflected back to the antenna.

B. Low Noise Amplifier Measurements

1) Measurements of the S21 Parameter: Fig. 6 shows the measurement of S21 parameter of the prototyped LNA. As can be observed from this figure that it has a center frequency of 415 MHz. This can easily be adjusted by adding varactor diodes to the LC-circuit of the amplifier. This enables tuning of the center frequency of the LNA.

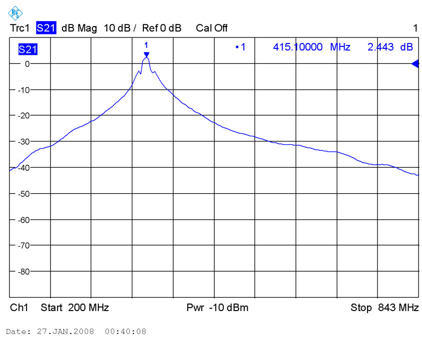

Fig. 6. Measurements of S21 parameter.

2) Gain Calculation: To measure the gain of the amplifier properly, gain is calculated by measuring the power after a given resistor and then compensate for the power loss through the resistor as shown in Fig. 7.

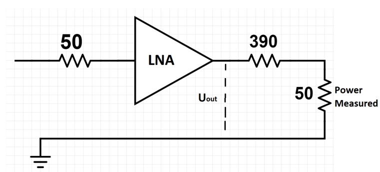

Fig. 7. Simplification of the amplifier.

The input power was set to -50 dBm and the measured power was -37.94 dBm. The power in mW is given by:

$$P_{in} = 10^{-\frac{50}{10}} = 1 * 10^{-5}\ mW \tag{6}$$

$$P_{measured} = 10^{-\frac{37.94}{10}} = 1.61 * 10^{-4}\ mW \tag{7}$$

From the measured power, resulted peak voltage of:

$$V_{rms} = \sqrt{1.61 * 10^{-4} * \frac{50}{10^3}} = 2.83\ mV \tag{8}$$

$$V_{peak} = \sqrt{2} * V_{rms} = 4\ mV \tag{9}$$

Voltage after the LNA becomes:

$$V_{out} = V_{peak} * \frac{50 + 390}{50} = 0.03527\ V \tag{10}$$

$$V_{outRMS} = \frac{V_{out}}{\sqrt{2}} = 0.025\ V \tag{11}$$

Output power from LNA in reference to a $50\,\Omega$ resistor can be calculated as:

$$P_{LNA} = V_{outRMS}^2 * \frac{10^3}{50} = 0.01244\ mW \tag{12}$$

The power gain will then be given by:

$$PowerGain = 10 * log(\frac{P_{LNA}}{P_{in}}) = 30.9\ dB \tag{13}$$

This means that the LNA achieves a gain of 30.9 dB with the input power of -50 dBm.

3) Linearity of the LNA: The linearity of the amplifier can be found by calculating the gain for multiple input power levels. Fig. 8 shows the gain versus RF input power.

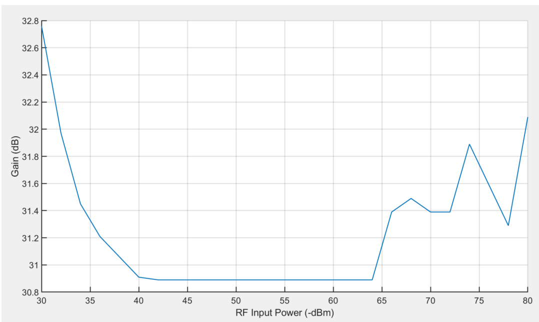

Fig. 8. Variation in Gain with different input power levels

As can be observed from the above figure, the gain varies from 30.9 dB to 32.8 dB when input power is varied from -30 dBm to -80 dBm.

4) Power Consumption: The current consumption measured to be 1 mA with a voltage source of 6 V, resulting in a power consumption of 6 mW.

C. Wake-up Radio

The wake-up Radio design presented in [4] achieves a sensitivity of -50 dBm with a power consumption of 1.7 μW. By introducing the LNA in the WuR design, a sensitivity of -80 dBm is achieved with a power consumption of:
6 mW + 1.7 $\mu W \approx$ 6 mW.

V. Discussion

Based on the measurements of the LNA, a gain of 30 dB is achieved at a current consumption of 1 mA from a 6 V power supply. With this LNA, a sensitivity of -80 dBm can be achieved. The achievable distance can be calculated with the following practical assumptions: A transmission power of +10 dBm, antenna gain of +10 dBi at a frequency of 433 MHz and a fading margin of 6 db (assuming free space). With these parameters, distance can be calculated as:

$$Power = 80 + 10 + 10 + 10 - 6\ dBm \tag{14}$$

$$Distance = 10^{\frac{Power}{20}} * \frac{\lambda}{(4 * \pi)} = 8.74\ km \tag{15}$$

Performance of this WuR is compared to the recently reported WuR solutions for long-range IoT devices [5] and [6]. As can be observed from Table 1, this WuR consumes only 6 mW compared to 30 mW in [5] and 27.3 mW in [6]. On the other hand, these designs achieve better sensitivity compared to the WuR proposed in this paper at the expense of high power consumption.

TABLE I
Comparison with previous work

Work	Sensitivity	Power Consumption
This work	-80	6 mW
[5]	-90	30 mW
[6]	-122	27.3 mW

VI. Conclusion

Design and implementation of a long-range low power solution for wake-up radio is presented by introducing an LNA. The Prototyped LNA consumes 1 mA from a 6 V power supply and achieves a gain of 31 dB. A sensitivity of -80 dBm can be achieved by including the LNA in WuR. A distance of 8.74 km is achieved with the introduction of this LNA.

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Paper B

Title:	Design and implementation of a long-range, low-power wake-up radio and costomized DC-MACprotocol for LoRaWAN
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Design and implementation of a long-range low-power wake-up radio and costomized DC-MAC protocol for LoRaWAN

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***Abstract*—In this paper, we present the design and implementation of a long-rage wake-up radio (WuR) and customized duty cycled (DC) MAC protocol for long-range wireless IoT applications. The WuRx achieves a sensivity of -65 dBm by consuming just 0.032mA, thereby optimizing the energy consumption of battery powered long-range IoT devices, hence reducing the power consumption and overall costs when deployed in large scale.**

I. Introduction

It is expected that by 2020, there will be more than 50 billion Internet-of-Things (IoT) devices connected to the Internet, and 1 trillion by 2022 [Ref]. All these devices are usually powered up using either rechargeable or non-rechargeable batteries which usually require maintenance. Practical ambient energy harvesting solutions are reported in the literature to avoid the maintenance of the batteries for IoT devices [5]. Even with embedded ambient energy harvesting solutions, powering up of these IoT devices will become particularly critical when they operate in the long-range, which is in the order of 10 km to 15 km.
Long-range (10 km to 15 km) IoT devices fits best to many practical IoT applications such as environmental monitoring in large rural areas, transportation sector, agriculture sector, smart cities and surveillance applications to name a few. The current most widely used low power solution for long-range applications is the long-range wide-area-network (LoRaWAN) standard. The energy performance of the LoRaWAN devices are very well studied and reported in the literature. It reveals relatively a high energy consumption for these IoT nodes resulting in a maximum operating time period of 1 year using a 2400 mAh battery with a transmission interval of 5 minutes [6]. All these low-power IoT devices mainly utilize duty cycling to reduce the power consumption of the node. Duty cycling turn the internal radio on and off with certain interval to minimize power consumption of the nodes and idle listening in the network. This introduces some limitations. In a duty cycling controlled system, a node can only "wake-up" at certain intervals, increasing the latency of the system. In addition, nodes need to have a process running continuously to make sure that the radio initializes at given interval, thereby increasing the "sleep" current. Apart from these, the radio of the node must be made complex enough to be able to modulate and demodulate the access mechanism associated with the system, which also increases the overall energy consumption. Both the energy consumption and the latency can be massively improved by deploying an on-demand wake-up radio (WuR) to these long-range IoT nodes.
This article focuses on the design and practical implementation of low-power solution for the long-range IoT devices by employing an on-demand wake-up radio. The article is organized into five sections. After introduction in section I, section II focuses on the design and implementation of the wake-up radio, and low-noise amplifier employed in the WuR. Measurement results are presented in section III, discussion in section IV and finally conclusion in section V.

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II. Design of a long-range low power Wake-up radio

A. Overview

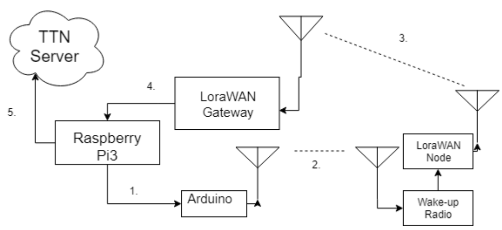

Fig. 1. Proposed system overview.

The system level design of the long-range wake-up radio is shown in Fig. 1. It consists of one raspberry pi, one Arduino, a wake-up radio and a set of LoRaWAN mote and gateway from Microchip. The raspberry pi serves as a switch between the LoRaWAN gateway and the internet (TTN server here) and a controller for the Arduino. The Arduino generates a wake-up call intended for the wake-up radio. The wake-up radio demodulates the incoming wake-up call and provides the demodulated address and an interrupt to the LoRaWAN node. The LoRaWAN node stays in sleep mode until it gets an interrupt from the WuR. When an interrupt signal is provided then the LoRa node will switch on and decode the address provided by the WuR. If the address is decoded successfully and if it matches then the LoRaWAN stack will be initialized and connect to the server through the gateway and sends the data.

B. Wake-up Radio

The schematic of the proposed wake-up radio design including component values is shown in Fig. 2. It consists of a matching network, a low noise amplifier (LNA), envelope detector, a comparator and a preamble detector. The design details are further elaborated in the following sections.

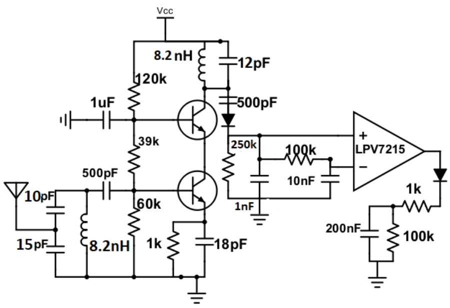

Fig. 2. Proposed WuR

1) Matching Network: The matching network provides impedance matching between the antenna and the LNA. This preserves the input power between the two loads. The values of the matching network are found using the smith chart (S11) of the LNA and then simulate the filter towards the measured input impedance. The smith chart of the LNA is shown in Fig. 3.

This shows an impedance of 10.8 -j53 ohm. This can be converted to a resistance value and a parallel capacitance.

$$Z = 10.9 - j53.4\Omega \quad (1)$$

$$Y = \frac{1}{Z} = 3.67 * 10^{-3} + j0.018 \quad (2)$$

From this the resistance and capacitance can be calculated.

$$R = \frac{1}{Re(Y)} = 272.511\Omega \quad (3)$$

$$C = \frac{im(Y)}{\omega 0} = 6.608 * 10^{-12}F \quad (4)$$

In other words, the input impedance of the LNA can be modeled as a resistance of 272.522Ω in parallel with 6.6 pF capacitor. From the simulations a proper matching can be achieved by using the values from the schematic in Fig. 2.

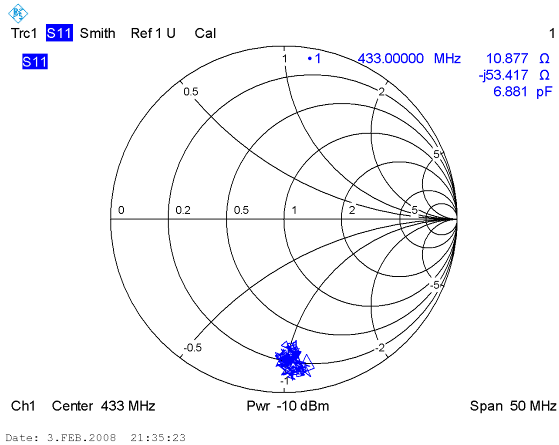

Fig. 3. Input impedance of LNA.

2) Low Noise Amplifier: The proposed LNA is a cascoded BJT amplifier using 2SC3838k high-frequency NPN transistors. The values of the resistors were found using simulations and optimizing the power consumption and gain. The LC-circuit connected to the collector of the top BJT provides the frequency adaptation for the gain of the amplifier.

3) Envelope Detector: The envelope detector demodulates the incoming address from RF-AC signal to DC representation. The envelope detector consists of a diode followed by a resistor in parallel with a capacitor. Previous implementations of wake-up radio utilize a second diode instead of a resistor [4], which causes a lot of shot-noise when combining it with an active high gain amplifier. A better solution would be a resistor instead. After the demodulation, the signal is passed on to the positive and negative input of a comparator. The positive input is directly from the envelope detector while the negative input passes through a low pass filter. This creates a sawtooth signal at the negative input, forcing the output of the comparator to go low when the positive input goes low. A simulation of the demodulation from the envelope detector is provided in Fig. 4.

4) Comparator: The comparator detects the envelope signal from the detector and amplifies the pulses so they can be interpreted by a microcontroller. The comparator used is a LPV7215 Micropower comparator from Texas Instruments (TI). It has an offset voltage of +/- 0.3mV, which means that the minimum amplitude the comparator can interpret is 0.3mv. It also means that the output of the comparator can have a positive initial value, in the case of an offset voltage of -0.3mV. This means that the output will be high if there is no input signal. This can be a problem if the address is of sufficient length with multiple repeating 0s. For this reason, Manchester coding is utilized to prevent repeating 0s from switching the output of the comparator high. For example, a 12-bit address of 110000010101 will have multiple repeating 0s. This potential

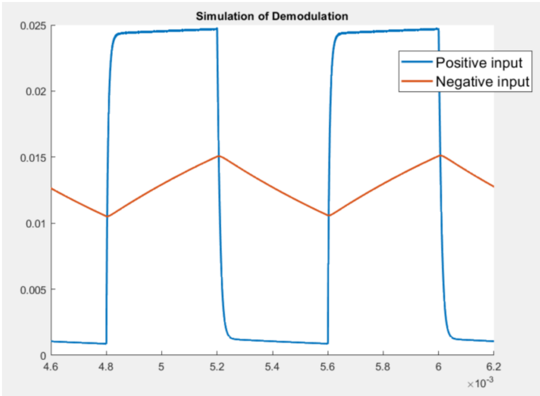

Fig. 4. Simulation of demodulation

problem is eliminated with Manchester coding as shown in Fig. 5.

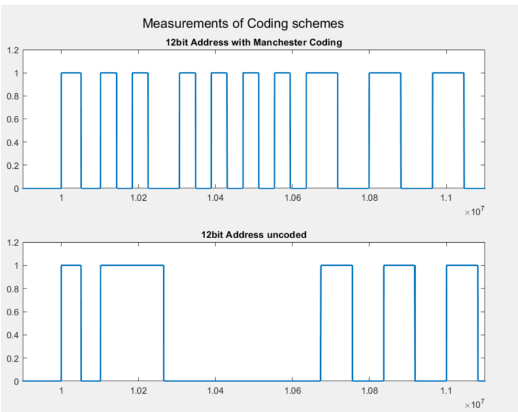

Fig. 5. Measured output from Arduino

Figure 5 shows the measured output of the Arduino with and without Manchester coding with an address of 110000010101.

5) Preamble Detector: The preamble detector is used for providing the MCU with an interrupt signal. The filter after the comparator will prevent short pulses from the surrounding environment waking up the MCU unnecessarily.

C. Wake-up transmission

The raspberry pi sends an address to an Arduino over serial communication. The Arduino uses Manchester coding to code the address. The wake-up call is sent with a bit rate of 1.25kbps. When using Manchester coding, the data rate will be half of the coded transmission, i.e 625bps. The transmitter is an AM-RT14-433P low cost AM hybrid transmitter module which has an output power of +12dbm. A directive antenna should also be used (for example a directive patch antenna with +10dBi).

D. LoRa mote

The LoRa mote is an RN2483 module with integrated microcontroller and radio transceiver from Microchip. A thorough study of the energy performance of the RN2483 has been done in [6], it is also well documented in the datasheet. The RN2483 detects the interrupt signal from the preamble detector and start a timer to sample the address. Thereafter, the module will decode the Manchester coded address and compare it with its own. If it matches, it will connect to the TTN server through the LoRaWAN gateway.

III. Measurements and Results

A. Measurements of Reflection Coefficient

The reflection coefficient (S11) is measured with a network analyzer connected to the input of the WuR.

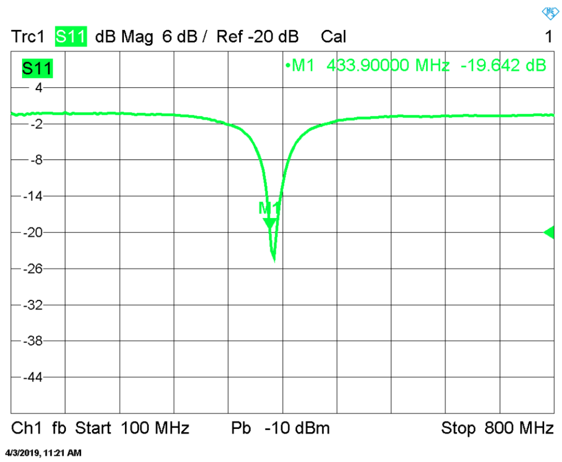

Fig. 6. Measurement of S11

A reflection coefficient of -19.6dB is achieved. The reflection in percentile can be calculated as:

$$r = 10^{\frac{-19.6}{20}} = 0.104 \tag{5}$$

$$Reflectedpower = r^2 = 10.9 * 10^{-3} = 1.09\% \tag{6}$$

This means that 1% of the received power will be reflected back to the antenna.

B. Low Noise Amplifier Measurements

1) Measurements of the S21 Parameter: S21 is the measured gain from port 1 to port 2 using a network analyzer. For accurate measurements, a simplified circuit is tested with only the matching network and the LNA.

From this figure, it can be observed that the center frequency is 433MHz and a gain of 23dB is achieved. The bandwidth is marked by the doted lines in Fig. 7, the lines intercept

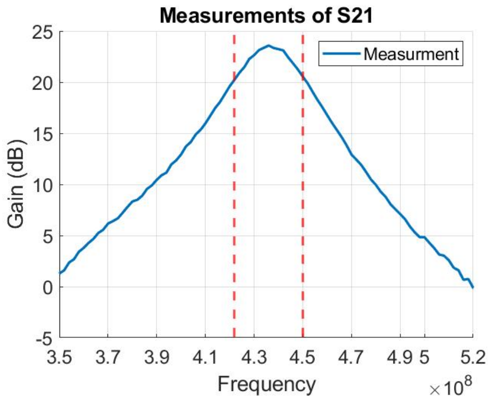

Fig. 7. Measurements of S21

the graph where the gain is -3dB of the maximum gain. The Lowest frequency is 422MHz and the highest limit is 450MHz. This gives a bandwidth of 28MHz.

C. Wake-up Radio Measurements

1) Sensitivity measurements: The sensitivity of the wake-up radio was measured by using an RF-generator with signal-generator as an external modulator. By measuring the output of the comparator, the sensitivity can be found by adjusting the input power from the RF-generator. The sensitivity was measured to be -65dBm.

D. Proposed MAC protocol

As shown, the proposed WuRx design consumes more energy than conventional WuRx designs. However, this power consumption can be optimized by adopting a duty-cycle (DC) MAC protocol for WuR enabled nodes. The DC MAC protocol will reduce power consumption by switching the WuRx on and off, while at the same time maintaining the low latency advantages. This can be achieved by increasing the size of the preamble signal and use it to detect the incoming wake-up call. To increase the possibility that the WuRx will detect the transmitted preamble, the size of the preamble should be larger than the sleep period. This is similar to the X-MAC scheme [3]. The X-MAC protocol is an asynchronous DC MAC protocol which uses a preamble mechanism to initiate data communication.

Strategies in X-MAC were adapted for the proposed WuRx design. The WuRx listens to the channel for a certain time less than the sleep period. If no preamble is detected, it will go back to sleep. When the WuRx detects a preamble, it will be ON to sample the address sent after the preamble. The preamble frame will be finished with the negative flank. When the negative flank is detected, the MCU will start the timer to sample the address. This will be done in a bit-by-bit manner [2] that is, whenever the MCU detects a wrong/incorrect bit, it will go to sleep for the rest of the address length in addition to the pre-defined sleep period. An illustration of the protocol is provided in fig 8

E. LoRa decoding

The RN2483 receives the preamble sent from the transmitter. When it detects the negative flank of the preamble then the timer will start. For each timer interrupt, it will sample the voltage on the pin from the output of the comparator and interpret it as high or low. If the module detects a wrong bit, it will stop the timer and go back to sleep. In other words, the decoding will be done in a bit-by-bit manner, presented in [2].

F. Power Consumption

The LNA uses a continuous current of 0.5mA with 6V power supply. The comparator consumes only 580nA with 3V supply. Hence, the total power consumption will be:

$$0.5mA * 6V + 580nA * 3V \approx 3mW \quad (7)$$

The total power consumption of the wake-up radio is: 3mW

However, if the DC-MAC protocol presented with a duty-cycling of 10 % is implemented then the energy consumption decreases drastically. With this module, the sleep current will be 0.0016mA, and the listening current will be the idle current of the module in addition to the WuRx. Idle current: 2.8mA + 0.5mA = 3.2mA. With a duty cycling of 10% and a period time of 100ms, charge can be calculated as:

$$Q_t = 90ms * 0.0016mA + 10ms * 3.2mA = 0.032mAs \quad (8)$$

The average current consumption over 1 second:

$$Current = \frac{0.032mAS}{1s} = 0.032mA \quad (9)$$

By adopting this MAC protocol, the current consumption reduces significantly from 0.5mA to 0.032mA.

IV. Discussion

With the integrated WuRx and the MAC-protocol new possibilities emerges for power optimization within LoRaWAN networks. For example, these technologies can be combined with the present solutions in order to obtain durable and reliant solutions. One possible situation where this might be suitable is a system where it is required to send a LoRa packet every hour and at the same time get on-demand sensor measurements if needed.

Due to the low power consumption of the system, it is well suited for energy harvesting solutions. In [5] a wireless sensor node with a 0.36W solar panel was implemented. The proposed wireless sensor node provided in this article combined with the energy-harvesting solutions in [5] will result in a long-distance wireless sensor solution with very long lifetime.

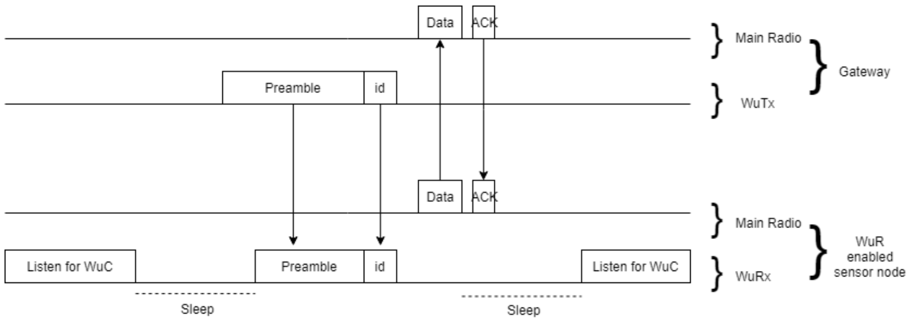

Fig. 8. Proposed DC-MAC for WuRx enabled node

V. Conclusion

This paper proposed a low-power wake-up radio designed for long distance IoT devices and a customized DC-protocol to reduce the power consumption further. The wake-up radio achieves a sensitivity of -65dBm and a current consumption of 0.5mA while the idle current consumption of the node is 2.8mA. Giving a total current consumption of 3.2mA. By introducing a customized DC-protocol, the average current consumption can be reduce to 0.032mA. This design can alongside an energy harvesting solution provide adequate lifetime of long distance IoT devices.

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Paper C

Title:	Design and Implementation of an Ultra-Low Power Wake-up Radio for Wireless IoT Devices
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Conferance:	*IEEE ANTS 2018, Indore, India*
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Design and Implementation of an Ultra-Low Power Wake-up Radio for Wireless IoT Devices

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***Abstract*—In this paper, we present the design and prototype implementation of an ultra-low power wake-up radio for wireless IoT devices. The prototyped wake-up radio consumes only 580nA from 3V power supply, covers distance range of up to 55 meters and achieves a sensitivity of -49.5dBm. This wakeup radio module can easily be integrated into wireless IoT devices and thereby reducing the overall power consumption of the battery powered and energy harvesting based devices. The prolonged life time of the devices can reduce the overall costs when deployed in large scale.**

Keywords—Ultra-low power wireless IoT devices, wake-up radio, and wireless embedded systems.

I. Introduction

Wireless internet of things (IoT) is transforming day to day life in many aspects and it is expected that there will be about 50 billion IoT connected devices by 2020 [1]. Most of these devices are either battery (both rechargeable and non-rechargeable) powered or based on energy harvesting from ambient sources [1]. Due to increased demand for wireless IoT devices, better solutions are required to save battery power to prolong the life time of these devices. Most of the wireless IoT nodes today utilize duty cycling. Duty cycling nodes provide a state of idle or parked but are on to sense if the master node wants to exchange data with it. This causes idle listening and overhearing in the network. If we consider a Bluetooth piconet, the slave or peripheral node will send out an announcement to connect with a master node [2]. The slave or peripheral node will "wake up" each cycle to check if the master node wants to talk. The point of this is to minimize the idle listening of the sensor nodes, but this does not eliminate idle listening.

To eliminate this problem, implementation of an on-demand wake-up radio is a viable solution as shown in Figure 1.

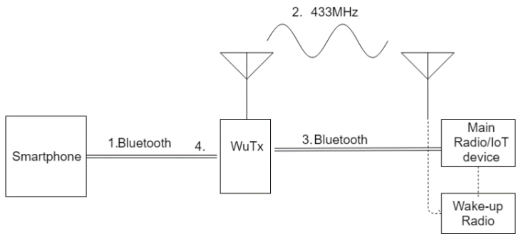

Fig. 1. Design of Wakeup radio.

The implementation of wake-up radios will provide much less power consumption to the network nodes as well as reduced response time. A wake-up radio provides a wake-up call to a sensor only when the user asks for it (on-demand). In this way the sensor only transmits data when it is required.

There are reported wakeup radio solutions based on simulation and hardware. Simulation based ones are not really of much use when it comes to practical implementation. Reported hardware-based ones are not very cost effective and not ultra-low powered [3-5]. These also do not achieve very good sensitivity that is needed for variety of wireless IoT technologies [3-5]. This article presents an ultra-low power wake-up radio based on hardware and it can easily be integrated into wireless IoT devices.

II. Design of ultra-low power wake-up radio

The Wake-up radio consists of 4 major parts as shown in Figure 2. It includes a matching filter, an envelope detector, a comparator and a preamble detector.

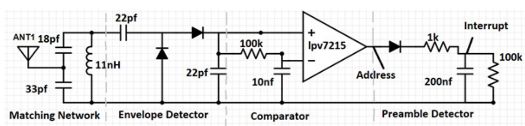

Fig. 2. Design of Wakeup radio.

The Matching filter provides appropriate matching to the received signal to preserve the received power and is tuned to a 50Ω antenna. The filter consists of two capacitors and one inductor. The filter is designed to have a narrow bandwidth in order to minimize the number of false wake ups. Since the impedance of the peak detector will be higher than the impedance of the antenna (50Ω), a voltage gain is included after the matching filter. Matching network is verified by using a network analyzer and measurements of S22 parameter as shown in Figure 3.

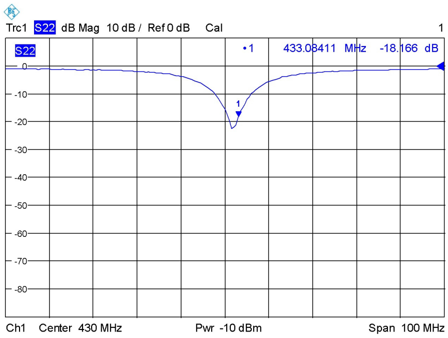

Fig. 3. Reflection measurement (Screenshot from network analyzer).

The percentage of the reflection of the received signal is:

$$r = 10^{-\frac{18.166}{20}} = 0.123 \quad (1)$$

$$\frac{P_r}{P_t} = \frac{\frac{(V^-)^2}{50}}{\frac{(V^+)^2}{50}} = \left(\frac{V^-}{V^+}\right)^2 = (r)^2 = 0.123^2 = 0.015 \quad (2)$$

With a reflection coefficient of -18.16dB, the matching filter will only reflect 1.5% of the received signal.

The envelope detector demodulates the envelope transmitted from the transmitter. The diode, HSMS-2850-TR1G is used to demodulate low power RF signal. Diodes with less leakage is essential in the design as it will reduce the voltage to the comparator.

The comparator detects the pulses from the envelope detector and generates pulses that can be interpreted by the microcontroller unit (MCU). The comparator used in this design is LPV7215 with a power consumption of 580nA and an offset voltage of +/- 0.3mV.

The preamble detector sends an interrupt signal to the MCU, telling it to wake up and start decoding the address. This is done to minimize false wake-ups from smaller and shorter signals. The achieved sensitivity of this design is -49.5dBm. This was measured by using an rf-generator and a signal generator as a modulator to mimic the signal transmitted from the transmitter. The sensitivity was found by measuring the lowest power level the wake-up radio was able to demodulate.

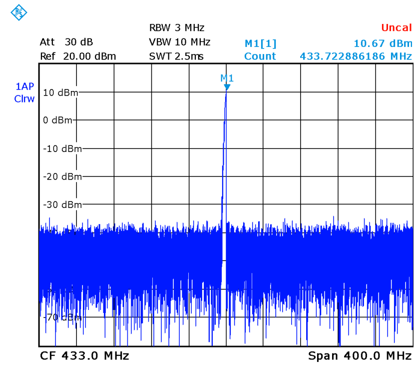

Fig. 4. Transmit power measurement (Screenshot from spectrum analyzer).

Figure 4 shows the transmission power and frequency from the transmitter. It was measured a signal strength of +10dBm at the transmitter.

With these results, theoretically a distance of 55 meters is achieved assuming 0dB antenna gain and no fading. TX = 10dBm, $RX_{sensitivity}$ = -49.5dBm, Ant_{gain} = 0dB.

We can calculate theoretical distance as follows:

$$\text{Distance} = 10^{TX - RX_{sensitivity} + (2*Ant_{gain})} * \frac{\lambda}{4*pi} = 55m \quad (3)$$

The reflection coefficient of the antennas is measured to be -2.6dB as shown in Figure 5. This will cause a reflection of 55% and reducing the signal drastically at both ends.

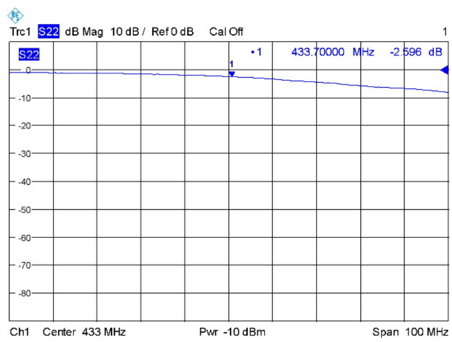

Fig. 5. Reflection measurement of antennas (Screenshot from network analyzer).

The gain was measured between two of these antennas with 10cm between them. This distance gives a fading of 5.17dB.

$$20 * \log\left(\frac{4*pi}{\lambda} * d\right) = 5.17\ dB \quad (4)$$

The measured signal strength between antennas was -15dBm as shown in Figure 6.

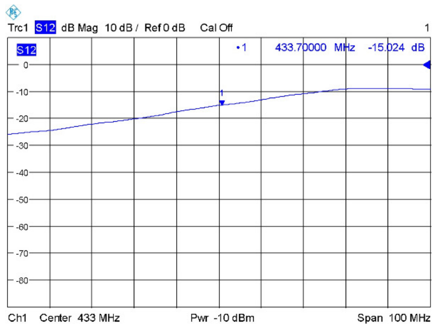

Fig. 6. Measured signal strength between two antennas.

The gain of these antennas at 433MHz will be:

$$\left(\frac{-15+5}{2}\right) = -5dBi \quad (5)$$

With the measured antenna gain of -5dBi, the theoretical distance that can be achieved is 17 meters.

TX = 10dBm, $RX_{sensitivity}$ = -49.5dBm, Ant_{gain} = -5dBi. The theoretical distance can be calculated as below:

$$\text{Distance} = 10^{TX-RX_{sensitivity}+(2*Ant_{gain})} * \frac{\lambda}{4*pi} = 17.43m \quad (6)$$

III. IMPLEMENTATION OF ULTRA-LOW POWER WAKE-UP RADIO

The complete system consists of three parts, a smartphone, a wake-up radio transmitter (WuTx) shown in Figure 7 and the sensor with the attached wake-up radio receiver (WuRx) shown in Figure 8. The smartphone is connected to WuTx through Bluetooth. Smartphone is used for sending the address to transmit and to receive the sensor data from WuTx. When the smartphone transmits the address, the WuTx will then generate a RF-representation of the address using OOK/ASK modulation. When the WuRx receive the address, it will demodulate the signal and sample the address in a bit-by-bit manner [6].

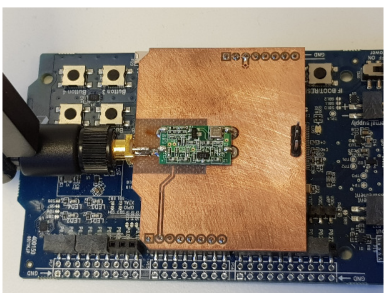

Fig. 7. Wakeup radio transmitter (WuTx).

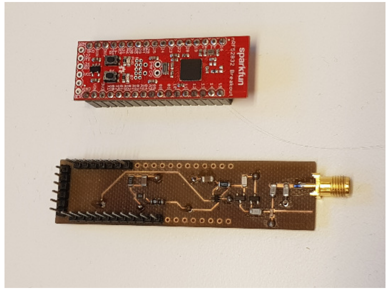

Fig. 8. Main radio (top) and wakeup radio receiver (bottom).

If the address matches with the address of the main radio then it will wake-up, enable a connection with the WuTx through Bluetooth and transmit the sensor data. The WuTx will then relay the sensor data to the smartphone for visual representation. Smartphone acts as a master towards the WuTx where as WuTx act as a master towards the WuRx.

Both the main radio and the WuTx use nRF52832 [7]. The WuTx uses also an external RF-transmitter to transmit the address over 433MHz. The smartphone uses the Nordic UART application for android [8]. The sensor is an integrated temperature sensor in the nRF52843.

IV. MEASUREMENT RESULTS

For the prototyped wake-up radio a theoretical distance of 55 meters and a current consumption of only 880nA was achieved with 0dB antenna gain. Antenna gain was measured to be -5dBi and this translates to a theoretical distance of 17 meters. Measured distance was 16 meters and very well matches with theoretical results.

The performance of the recently reported hardware-based wake-up radios for similar applications are shown in table 1. It can be clearly observed that proposed wake-up radio consumes only 1.7µW and achieves sensitivity of -49.5dBm.

TABLE I. PERFORMANCE COMPARISON

Ref.	Frequency (MHz)	Power Consumption (µW)	Sensitivity (dBm)
[3]	868	820	-51
[4]	869	13	-4.37
[5]	2400	1	-19
This work	433	1.7	-49.5

From the table, it can be observed that design reported in [5] consumes only 1µW but achieves sensitivity of only -19 dBm whereas this prototype achieves sensitivity of -49.5dBm. The various frequencies are included instead of distance. If we use the same transmission power and antennas, higher frequencies will have shorter distances than lower frequencies.

V. CONCLUSION

An ultra-low power wakeup radio enabled wireless IoT node was prototyped and tested. It achieves a sensitivity of -49.5 dBm and a distance of 55 meters with current consumption of only 580nA from a 3V power supply. It fits best for battery powered and energy harvesting based wireless IoT devices.

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[8] http://infocenter.nordicsemi.com/index.jsp?topic=%2Fcom.nordic.infocenter.rds%2Fdita%2Frds%2Fuart_app.html

Part III

Discussion and Conclusion

Chapter 4

Discussion

4.1 Paper: A

The envelope detector in this paper is not ideal. It was found that the diodes created a lot of shot-noise. Therefore, a better solution was implemented in paper B. The combination of the amplifier and the buffer-stage worked quite well, although it increases the overall current consumption. However, if higher sensitivity is required, this might be necessary.

4.2 Paper: B

There is greater potential regarding the sensitivity of the Wake-up radio. The AC-characteristics of the LNA changes when the detector is connected. This is because of the parasitic capacitance effect from the diode in the envelope detector. This has an impact on both the reflection coefficient and the gain. The way to fix this is to measure the input impedance of the envelope detector and compensate for that in the LC-circuit on the collector. Thereafter, the input impedance of the LNA should be measured and the matching circuit changed accordingly. Due to time issues this was not done but will be included in the final version of paper B. It is reasonable to expect that proper matching will lead to a sensitivity of around -72dBm.

The MAC-protocol proposed in this paper can also be used to make a synchronous version. This will alleviate even more of the traffic in the network, thereby increasing energy efficiency in the network. This can be done by using the proposed protocol to synchronize the network.

4.3 Antenna Design

An effort was made to design a patch-antenna according to the procedure in [3]. The results were not sufficient and due to the material cost no more attempts were made. Also, patch antenna design is not a new technology and could not have been considered as a contribution in this thesis.

Chapter 5

Conclusion and Future Work

This chapter is organized into three parts. Part one, summary of the thesis in overall. In the second part the contributions of the thesis work are highlighted. Finally, a few potential directions for future work are discussed.

5.1 Conclusion

The WuR is one of the key technologies that improve both the energy-efficiency and the lifetime of the of IoT WSN nodes. After a review of the state-of-the-art of the design and implementations of wake-up radio solutions, potential improvements were identified for this thesis work. Though some articles regarding long range wake-up radios have been published, and many lack practical implementation.

Chapter 1 describes the motivation and the goal of the thesis work and outlines how the thesis is structured. It also gives a brief overview of the contributions presented in papers A,B and C. Chapter 2 introduces the background of the research. Various technologies in IoT were discussed and laid out. A general introduction to IoT and the way devices connect to the internet, an overview of LoRaWAN and some of the configurations. Also, some of the popular MAC-protocols were described. Lastly, the general structure of WuRs were outlined. Chapter 3 describes the state-of-the-art solution presented in the literature.

5.2 Contribution

The main contribution of the thesis is the design and implementation of a WuRx for long range IoT devices such as LoRaWAN. The second contribution is the proposed system design of a LoRaWAN network with integrated WuR. Finally, the ultra-low power solution based on MAC-protocol in paper B to reduce the energy-consumption of the WuR enabled node significantly while maintaining the on-demand advantages of WuR.

5.3 Future Work

This thesis focuses mainly on the physical layer of the WuR design. However, a MAC-protocol has also been proposed to further reduce current consumption. This MAC-protocol could be added on top of the previous protocol in the cases where an on-demand response might be required. An implantation of such a system could extend the lifetime of long-range wireless sensor nodes drastically. It could also alleviate some of the traffic load caused by the WuTx.

Because of the low power-consumption, ambient energy-harvesting could be ideal to optimize the lifetime of the sensor nodes and to eliminate the maintenance. A solar panel implementation as suggested in [4] with a 0.38W panel would provide the sensor with more than enough power for entire life time of the devices.

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Appendices

A Links to Paper C, 3, 4 and 5

Paper C

Design and Implementation of an Ultra-Low Power Wake-up Radio for Wireless IoT Devices
https://ieeexplore.ieee.org/document/8710086

Paper 3

Ultra-Low PowerWake-up Radio for 5G IoT :
https://ieeexplore.ieee.org/document/8642801

Paper 4

Enabling Early Sleeping and Early Data Transmission in Wake-up Radio-enabled IoT :
https://www.sciencedirect.com/science/article/pii/S1389128618310107

Paper 5

Reducing Overhearing Energy in Wake-up Radio-enabled WPANs: Scheme and Performance :

https://ieeexplore.ieee.org/document/8422696

B Arduino Code

```
int out = 2;
String input = 0;
int address_Size = 0;
bool check = true;
int uncoded = 3;

// the setup routine runs once when you press reset:
void setup() {
  // initialize the digital pin as an output.
  pinMode(out, OUTPUT);
  pinMode(uncoded, OUTPUT);
  Serial.begin(9600);
}

// the loop routine runs over and over again forever:

bool inputCheck (String input) {
  check = true;
  Serial.print("Running Test \n");
  address_Size = input.length();

    for(int i = 0; i < address_Size; i++){
      char temp = input.charAt(i);
        if(temp != '1' && temp != '0'){
            check = false;
        }
    }
  return check;
}

void ManchesterCoding(String input){
  address_Size = 0;
  address_Size = input.length();

    digitalWrite(out, HIGH);
    digitalWrite(uncoded, HIGH);
    delay(1);
    digitalWrite(out, LOW);
    digitalWrite(uncoded, LOW);
    delay(1);


    for(int i = 0; i < address_Size; i++){
      char temp = input.charAt(i);
      if(temp == '1'){
```

```
        digitalWrite(uncoded, HIGH);
        digitalWrite(out, HIGH);
        delayMicroseconds(800);
        digitalWrite(out, LOW);
        delayMicroseconds(800);
      }
      else if(temp == '0'){
        digitalWrite(uncoded, LOW);
        digitalWrite(out, LOW);
        delayMicroseconds(800);
        digitalWrite(out, HIGH);
        delayMicroseconds(800);
      }

    }
    digitalWrite(uncoded, LOW);
    digitalWrite(out, LOW);
}


void loop() {
  if(Serial.available() > 0) {

    input = Serial.readString();
    Serial.print("I received: ");
    Serial.println(input);
    address_Size = input.length();
    Serial.println(address_Size);
    char temp = input.charAt(0);
    Serial.print(temp);
    check = inputCheck(input);

    if(!check){
      Serial.print("False input \n");
    }
    if (check){
      Serial.print("Correct input \n");
      ManchesterCoding(input);

    }
    check = true;
  }
}
```

C PCB Design

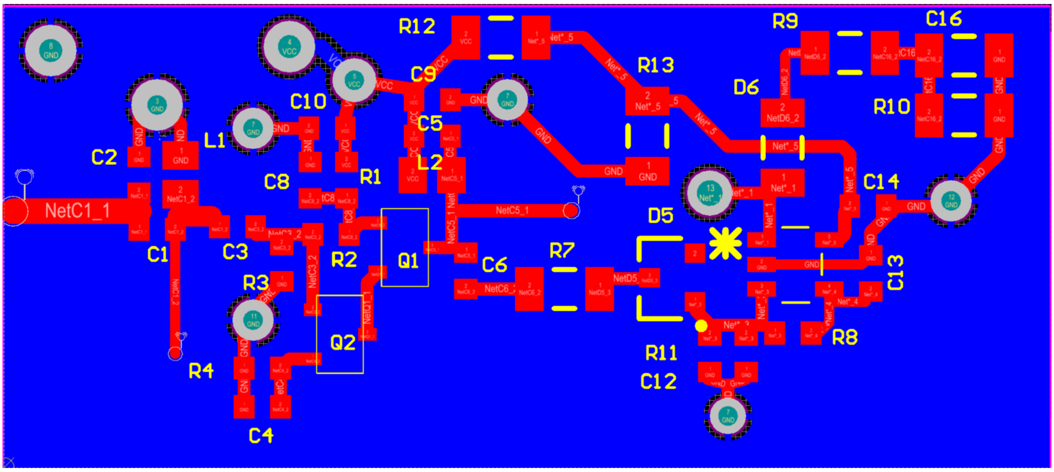

Figure 1: Top Layer of WuRx

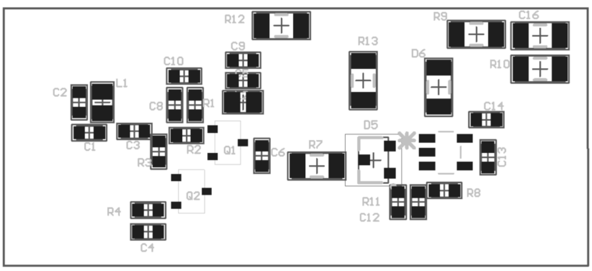

Figure 2: Drawfile of WuRx

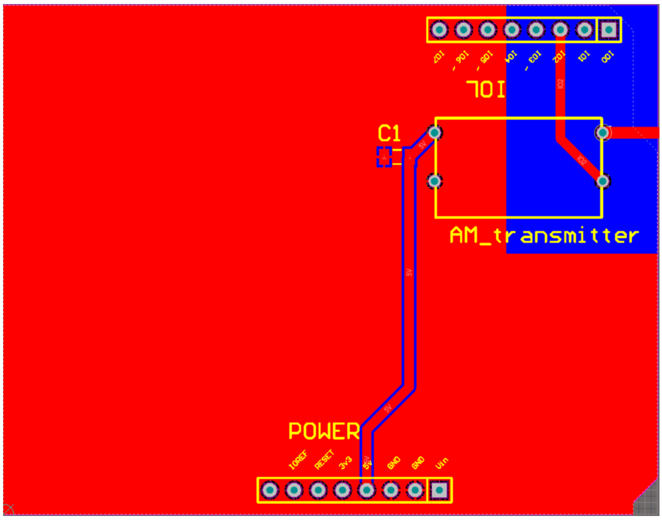

Figure 3: Top layer of WuTx

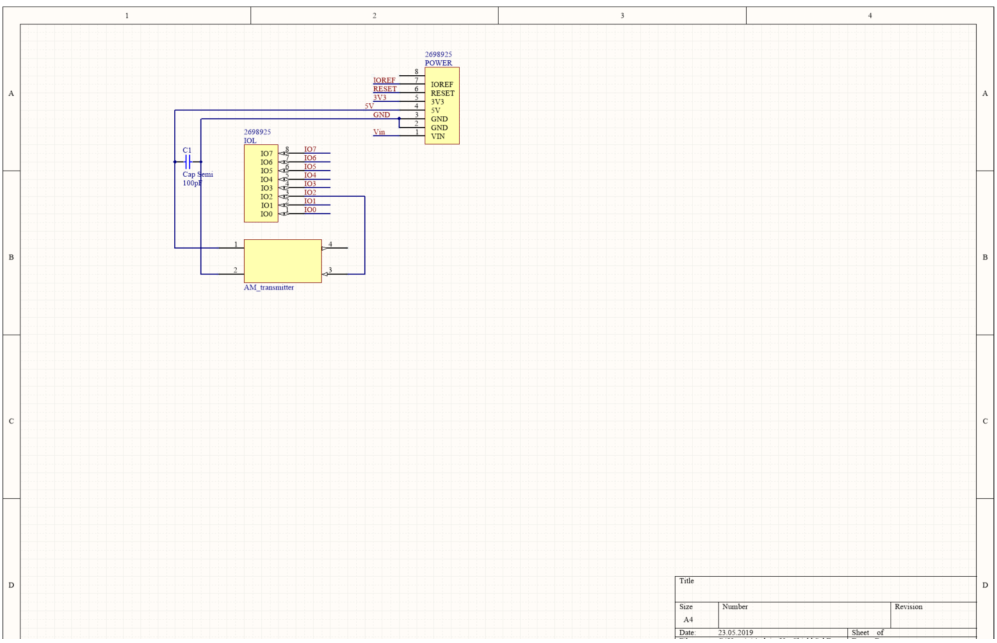

Figure 4: Schematic of WuTx

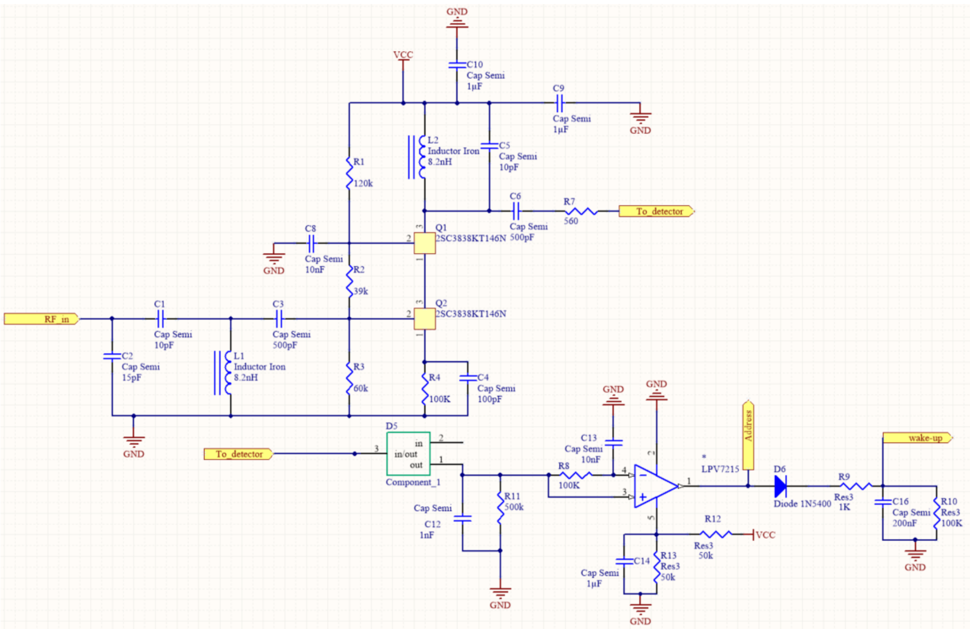

Figure 5: Schematic of WuRx

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