Production of dual-band embedded system capable of behaving as a node in a wireless sensor network

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Abstract *Recently, wireless sensor networks (WSNs) have been widely studied. They use the packets retransmission in order to save energy of the nodes and guarantee the packets delivery to the destination. WSNs can be one of the few technically viable solutions in locations without available telecommunications infrastructure. However, in urban environments, WSNs can be an alternative to avoid dependence on cellular networks for information sending. This article describes an embedded system with an ARM Cortex-M0+ based microcontroller, which incorporates two RF transceiver modules, based on the 433 MHz and 2.4 GHz ISM bands. The device was designed to behave as a node in a wireless sensor network. It communicates with the other nodes through these wireless technologies. In deciding the technology to be used to transmit data packets, an adapted algorithm was tested that operates strongly in the disposal of unnecessary retransmissions. Depending on the environmental, system and network conditions, the wireless technology to be used is selected and the information is retransmitted between the nodes always with two goals: to ensure the delivery of packets and to minimize power consumption.*

Keywords: *Embedded system, Wireless sensor networks, ISM dual-band*

1 Introduction

A wireless sensor network consists of a set of nodes capable of transmitting information via wireless communication links. It uses packet retransmission to save energy of the nodes and guarantee delivery of packets to the destination. One of WSN application areas occurs, in imperative or temporary occasion, when the fixed communications networks facilities are damaged or unavailable. Therefore, the WSN is indicated for not relying on any fixed network installation and its rapid self-organization characteristic [1].

One possible application for wireless sensor networks is on sale services with electronic points that have several sales outlets nearby and can function as repeaters. Thus, its activities would be independent or less dependent on cellular networks. Those companies that depend on the cellular network to carry out their commercial activities could use WSNs to reduce operating costs, conserve battery power of the transmitter equipments and have flexibility in transmission to ensure the delivery of information packets at the lowest cost and lowest delivery time possible.

A WSN could be applied, for example, in an automated bicycle rental system that can be found in large Brazilian cities. Each bike station would be a node that would communicate with the other stations to get the desired information to a server. Additionally it would be even possible to install electronic circuits of low power on the bicycles to use them as data retransmitter or even to share their GPS positions.

Various WSNs have been implemented using only one communication band. The ISM (industrial, scientific and medical) frequency band of 2.4 GHz has a large path loss per meter, higher consumption and low power of penetration in building materials and can be affected by weather, but has high data rate and uses smaller antennas. The ISM frequency band of 433 MHz has higher reception sensitivity, smaller path loss and lower consumption. However it is characterized by having low data rate, low quality hardware available and antennas tend to be larger [2].

To take advantage of the strengths and overcome limitations, some applications already use more than one RF communication band in the embedded system. A. Kim et al. [3] propose to implement a hybrid WSN that uses wireless communication technology based on the 2.4 GHz band and 400 MHz band. The study investigates the differences between two communication bands in the environment of a building. The article suggests the use of battery powered nodes with portable sensors and with low data rate, using a star topology to communicate with the coordinator node on the band of 400 MHz. The mesh topology is used for communication with a fast data rate between the coordinators nodes on the 2.4 GHz band.

This paper proposes an embedded system able to behave as a node of a WSN based on two technologies that use different RF ISM bands. Power usage determines the longevity and it influences the practical decisions of a sensor network, so the network nodes must have low power consumption. The transmission of information in sensor nodes spends more energy than the algorithms and calculations by the microcontroller [4]. So, in an attempt to reduce power consumption, first the node sends the data through the 433MHz RF module, which has shorter range but uses less power. If the node does not receive confirmation that the message was retransmitted, the 2.4 GHz RF module is used to resend the data. To ensure the delivery of packets to the base station and reduce unnecessary retransmissions an unified coordination-communication strategy protocol has been adapted and tested. [5].

The following sections of this article are organized as follows: Section 2 contains the hardware design of the embedded system. Section 3 displays the firmware development process and the tools used. Section 4 presents the implementation of the communication protocol and the tests performed. Finally, Section 5 presents the conclusion of the article and it discusses future work.

2 Hardware design

The hardware and firmware designs were inspired by the Freescale Freedom development platform [6]. This platform meets our requirements to use microcontrollers with ARM architecture and provide examples of hardware designs. It also is free (open source), allowing the development of the firmware with editing and compiling the project, recording the flash memory of the microcontroller and code debugging.

The Freedom Platform boards use microcontrollers of the Kinetis family [7]. They have 32-bit architecture with ARM core (Cortex-M0+, Cortex-M4 and Cortex-M7) and high performance with low power consumption. Each board has an OpenSDA system [8], a serial and debug adapter, which is a bridge of communication between a USB host device and the target microcontroller. The hardware design was developed in Altium Designer CAD tool [9].

2.1 Overview

The main elements of embedded system are: power supply unit, microcontroller unit, RF transceivers units and micro SD memory card. The system design is represented in block diagrams with their interconnections in Figure 1.

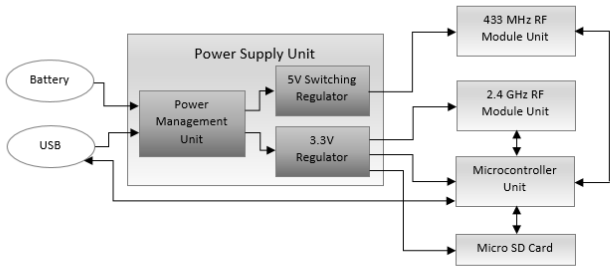

Figure 1: Block diagrams of the system.

2.2 Power supply unit

The main device of the power management unit is the BQ24075RGTT IC[10], a single Li-Ion cell battery charger that has a dynamic power path management function. The schematic with the IC is shown in Figure 2. The dynamic power path management powers the system while simultaneously and independently charging the battery. This feature reduces the number of charge and discharge cycles on the battery, allows for proper charge termination and enables the system to run with a defective or absent battery pack.

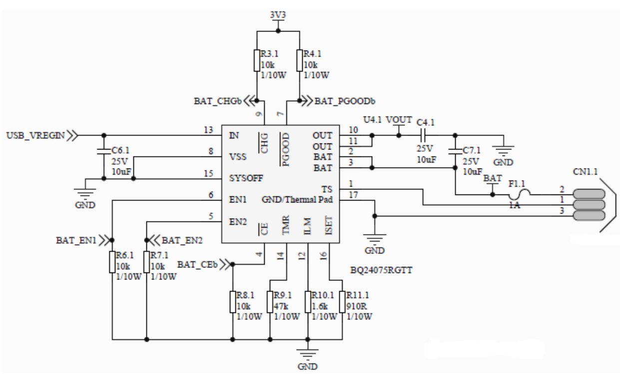

Figure 2: Circuit for charging Li-Ion battery and powering the system with the BQ24075RGTT IC.

The 5 V input voltage of the component (USB_VREGIN) is provided by the USB interface. When it is connected to the USB interface, the output voltage of the component, VOUT, is 4.4 V. When the component is disconnected VOUT assumes the battery voltage value. VOUT is the input voltage of the 3.3 V linear regulator and the 5 V switching regulator.

The component enables instant system turn-on when a USB power source is plugged in even with a totally discharged battery. The power path management architecture also lets the battery supplement the system current requirements when the USB power source cannot deliver the peak system currents.

The device respects the complex procedure to charge a Li-Ion battery. The process occurs in three phases: pre-charge phase, fast charge phase with constant current and stabilization phase with constant voltage. Figure 3 shows the complete battery charge cycle. In the pre-charge phase, the battery is charged with the current value equal to 10% of the fast charge current. Once the battery voltage reaches 3V, the battery will be charged with the constant current of fast charge. When the battery voltage reaches its final value of 4.2 V, it is loaded with this final voltage up to reach the full charge.

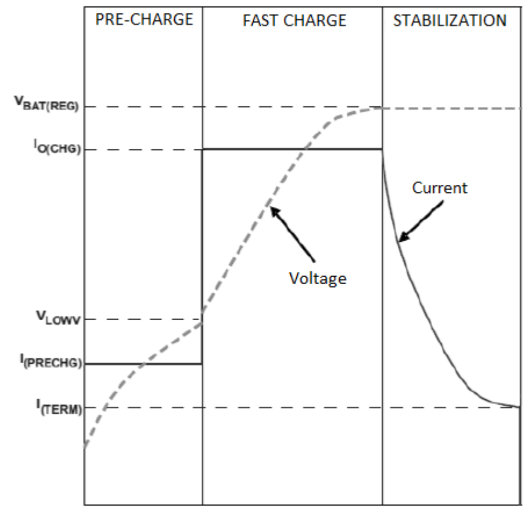

Figure 3: Charge cycle for 3.7V Li-Ion battery managed by the BQ24075RGTT IC.

There is also an internal control of the IC that monitors the temperature through a connection with a NTC thermistor. If the temperature monitored is above or below of the range between 0 ° C and 50 ° C, the charging is suspended. The maximum battery charging time and the value of the fast charge current is programmable using external resistors. The microcontroller determines the input current limit through a connection with the battery charger IC, using 2 digital pins.

To power the microcontroller [11], the 2.4 GHz RF unit [12], the micro SD card [13] and the LED RGB [14], the SPX3819M5-L-3-3/TR CI [15] was used, a 3.3 V linear regulator capable of supplying 500 mA of output current. To power the 433 MHz RF unit [16], the NCP1400ASN50T1G IC [17] was used, a step-up switching regulator, ensuring the voltage level of 5 V and a maximum current of 100 mA, even when the system is powered only by a 3.7 V Li-Ion battery.

2.3 Microcontroller unit

The parameters of the MKL25Z128VLK4 microcontroller relevant to the project are presented in Table 1.

In addition to the microcontroller, the circuits of the unit are: SWD debug interface, reset circuit and the oscillator circuit, with a 8 MHz Crystal. The maximum frequency of 48 MHz is used with the PLL aid of the microcontroller.

Parameter	Description
Core processor	ARM® Cortex®-M0+
Core size	32-Bit
Speed	48 MHz
Conectivity	I2C, LIN, SPI, UART/USART, USB OTG
Peripherals	Brown-out Detect/Reset, DMA, LVD, POR, PWM, WDT, RTC
Number of I/O	66
Program memory	128KB (128K x 8) FLASH
RAM size	16K x 8
Supply voltage	1,71 V ~ 3,6 V
Data converters	A/D 14x16b, D/A 1x12b

Table 1: Parameters of the MKL25Z128VLK4 microcontroller.

2.4 RF module units

Both modules were selected for respecting the criteria of low cost (under R$ 10.00 for each RF module, excluding the value and the soldering process of the antenna), buying availability in the Brazilian market and vast educational materials available online. The RF modules are docked in connectors of the printed circuit board of the embedded system design.

The 433 MHz RF unit is divided into 2 parts: the transmitter (with size of 30mm x 12mm) and receiver (with size of 20mm x 20mm) modules shown in Figure 4. Because of their lower cost, quarter-wave helical antennas are used in both modules. The parameters of the modules are given in Table 2.

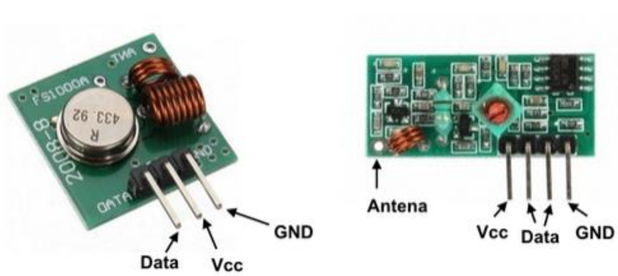

Figure 4: 433 MHz receiver and transmitter modules.

Resistors were used as a voltage divider to make the impedance matching between the receiver, MX-FS-03V model (powered with 5 V), and the microcontroller (powered with 3.3 V). The transmitter, MX-FS-03V model, is directly connected to the microcontroller as it is compatible with 3.3 V. The microcontroller receives and sends information through two GPIO pins (one input and one output pin).

The modules of the 433MHz RF unit do not have sleep mode. The microcontroller must continuously monitor the connecting pin with the receiver module to know if a message was received. To reduce power consumption, it is common to connect the transmitter module only when it is necessary to transmit information.

Parameter	Description
Frequency	433 MHz
Modulation	ASK
Data rate (max)	5 kbit/s
Range (max)	200 m
Current in receiver module	4 mA
Receiver sensitivity	- 105 dB
Power in transmitter module	10 mW
Supply voltage	3,5 V ~ 12 V

Table 2: Parameters of the 433 MHz RF modules.

The 2.4 GHz RF unit is formed by a board (with size of 40mm x 15mm) with the nRF24L01+ transceiver, from Nordic Semiconductor company, and external LNA antenna with a gain of 2 dBi. This module parameters are presented in Table 3.

The 2.4GHz RF module has sleep mode, important to reduce system power consumption. In order to receive messages it is necessary to be in receive mode. The IC has an interrupt pin that tells the microcontroller when a message was received (useful feature when it is essential to put the microcontroller in power-saving mode). To transmit messages it is required to be in transmit mode. The microcontroller must send commands to select the desired mode. It is only possible to assume one mode at a time. The communication between the 2.4 GHz RF module and the microcontroller is performed via an SPI interface.

Parameter	Description
Frequency	2,4 GHz
Modulation	GFSK
Data rate (max)	2 Mbit/s
Range (max)	1 km
Current in transmit mode	145 mA
Current in receive mode	45 mA

Current in sleep mode	4,3 uA
Receiver sensitivity	- 104 dBm
Supply voltage	1,9 V ~ 3,6 V

Table 3: Parameters of the 2.4 GHz RF module.

Figure 5: 2.4 GHz module with the nRF24L01 transceiver.

The nRF24L01+ IC uses the embedded baseband protocol engine (Enhanced ShockBurst [12]). This feature enables automatic packet assembly, shipping confirmation and automatic message retransmission. Making possible the implementation of low power and high performance systems with low cost microcontrollers [4].

2.5 Peripheral

All messages received and sent by the system are recorded in a txt log file, stored on a micro SD memory card. Details such as event time and which RF module was used are also recorded. The system also registers when there was a failure when sending a message. Communication between the micro SD card and the microcontroller is performed via an SPI interface.

The information stored on the micro SD card can be used to verify the efficiency of the chosen communication protocol and making future improvements possible. For a commercial application of the system, this feature can be turned off to save energy and reduce manufacturing costs.

The USB interface is the main source of system power. In addition, there is the possibility of connecting the system to a computer's USB port to view messages sent and received by the connected node in real-time. It is also possible to adjust the time of the connected node and send this information to synchronize the RTC peripheral of the microcontroller of the other nodes (via the RF modules).

The system also has a status indicator (a RGB LED) and a connector (allowing external access to a SPI interface, two UART interfaces, an I2C interface and a differential pair of the ADC module). Thus, the module can be connected to various sensors of different communication interfaces.

2.6 Printed circuit board

Three printed circuit boards with size of 50mm x 50mm were produced. The lower face of a board is shown in Figure 6 and the top surface in Figure 7.

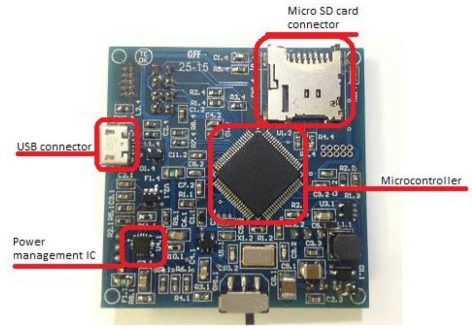

Figure 6: Lower face of the board.

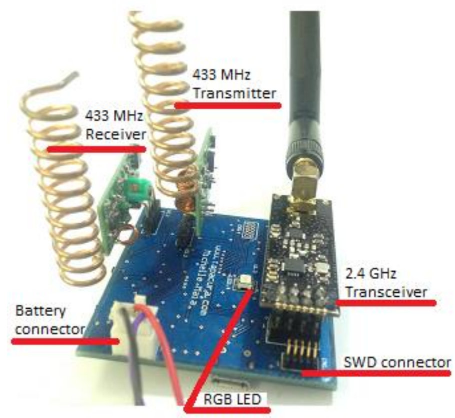

Figure 7: Top face of the board.

3 Firmware development process

Freescale offers firmware support with the development tool Kinetis Design Studio IDE [18]. The IDE is based on free, open source software including Eclipse, GNU Compiler Collection (GCC) and GNU Debugger (GDB). It enables editing, compiling and debugging with no code-size restrictions. It also has the Processor Expert plug-in [19], capable of creating the peripheral drivers of the microcontroller with a few mouse clicks. The project code was developed in the Kinetis platform with the C language. The C language was chosen because it is a structured and portable language and generates compact code.

The firmware code has been implemented with the support of the FreeRTOS real time operating system [20] to increase the control over the tasks performed by the microcontroller. The embedded system executes functions in real time that complete within a certain critical time limit. An error could result in absolute failure of the system [21]. The FreeRTOS is designed to be small and simple (between 4K and 9K bytes). The core kernel is contained in only 3 C files. The operating system provides methods for multiple tasks (with different priorities), semaphores, and timers in software. There are 4 memory allocation options.

In addition, the platform is open source, provides one solution for many different architectures and development tools and provides ample documentation.

4 Implementation of the communication protocol and tests

For the initial communication test, a network of sensors was assembled using three modules. The communication protocol for Unmanned Aerial Vehicles (UAVs) [5] was adopted with some modifications.

In this experiment, the contents of the packets were reduced because the maximum size of the packet sent by the 2.4 GHz RF module is 32 bytes. To keep the elements size, the message could be sent in 2 packets.

The packets sent contain GPS coordinates, but the developed system does not have GPS module. The performed test was made using simulated coordinates.

Each node was modeled with one role: a transmitter node, a repeater node and a base node. The communication protocol has 4 types of packets. The transmitter node was modeled to send TYPE I and TYPE II packets, shown in Table 4 and Table 5 respectively.

The TYPE I packet is sent to ask the status of the connection with the base. The fields ID, Type and Source UAV N° together uniquely identify the packet. The packet also contains simulated GPS coordinates.

ID	Type	Source UAV N°	Retrans UAV N°	Source UAV Lat	Source UAV Long	Retrans UAV Lat	Retrans UAV Long
6 bits	2 bits	8 bits	8 bits	32 bits	32 bits	32 bits	32 bits

Table 4: Type I packet format, it asks the status of the connection with the base.

Type II packet is sent to inform the base of a target detection. The fields with simulated GPS coordinates of a target are added to the packet.

ID	Type	Source UAV N°	Retrans UAV N°	Source UAV Lat	Source UAV Long	Re-trans UAV Lat	Re-trans UAV Long	Target Lat	Target Long
6 bits	2 bits	8 bits	8 bits	32 bits	32 bits	32 bits	32 bits	32 bits	32 bits

Table 5: Type II packet format, it informs target detection.

The transmitter node sends TYPE I or TYPE II packets, every 5 seconds, as shown in Figure 8. The test cycle is started using the 433 MHz module. Several messages are sent altering the simulated GPS location of the transmitter node. If the transmitter node does not receive the response from the base node in the time interval determined, it is considered disconnected from the network and adopts the 2.4 GHz module to send new message.

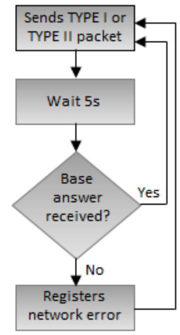

Figure 8: Flowchart of the transmitter node behavior.

The repeater node was modeled to only forward packets using the criteria of the flowchart shown in Figure 9 to decide whether to dispose or forward the packet. As the GPS coordinates are only simulated, the repeater node and the base node receive all the messages sent by the transmitter node. So the messages that would be out of communication radius are ignored by software. The communication radius (RCOM) of 1 km is considered for the 2.4 GHz module and RCOM equal to 200 m is considered for the 433 MHz module.

The first time the packet is received, the repeater node stacks it. Then, the distance test is performed. If the distance is greater than RCOM / 2 (half the radius of communication), the repeater forwards the packet immediately. If the distance is less than RCOM / 2, the node starts a 2 seconds counter. If a copy of the packet is received in this interval, the packet is not transmitted, but kept on the stack. If it does not receive a copy, the packet is forwarded. When the packet is forwarded the fields of N° and GPS coordinates from the repeater UAV are filled with the number that identifies the repeater node and its simulated GPS coordinates. The message is sent in the same frequency band that it was originally received.

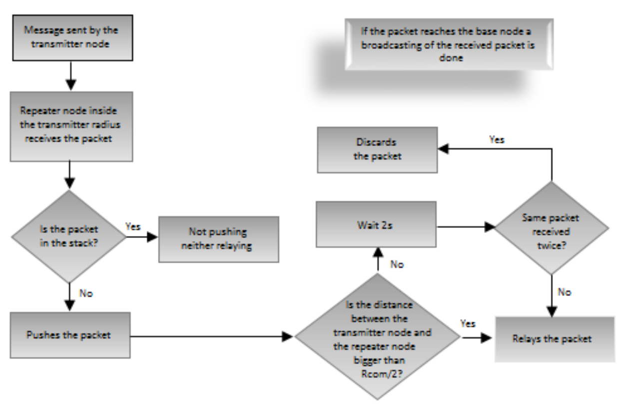

Figure 9: Flowchart of the repeater node behavior.

The base node was modeled sending TYPE III packet (Table 6), which is the response to the TYPE I packet, and

TYPE IV packet (Table 7), which is the response to the TYPE II packet. The message is always sent through the 2.4 GHz module and we consider that the base has enough power to reach all other nodes.

ID	Type	Source UAV N°	Source UAV Lat	Source UAV Long
6 bits	2 bits	8 bits	32 bits	32 bits

Table 6: Type III packet format, base response to the TYPE I packet.

ID	Type	Source UAV N°	Source UAV Lat	Source UAV Long	Target Lat	Target Long
6 bits	2 bits	8 bits	32 bits	32 bits	32 bits	32 bits

Table 7: Type IV packet format, base response to the TYPE II packet.

As described previously, all information sent and received by a node are stored in the micro SD memory card with the time of the event and communication module used. When the node is connected to the computer, this information can be viewed in real time via a USB CDC connection.

In order to get a real-time visualization of network behavior the RGB LED was also used. When a node sends information through 433 MHz module, the LED emits the yellow color. When receiving the information of the 433 MHz module, the LED emits the green color. The LED emits purple color when the node sends data through 2.4 GHz module. The LED emits the blue color when the node receives data of the 2.4 GHz module.

The experiment was filmed and can be viewed on the Internet [22].

5 Conclusion and future work

This article has proposed an embedded system with a robust power supply unit, microcontroller, 2 RF transceivers in the ISM bands of 433 MHz and 2.4 GHz and the memory card. The system was used to create a WSN and test the protocol which ensures delivery of packets to the base station and reduces unnecessary retransmissions.

The transmission tests between nodes of WSN have been successfully carried out in the 433 MHz band and in the 2.4 GHz band. We have recorded all the test data and it can be used for statistical analysis and future improvements.

We propose as future work: full implementation of the communication protocol; test the behavior of the network with the highest possible load; perform measure distance performance, power usage and packet delivery rate; add GPS module for actual location information.

The last proposed step is to add a GSM modem. The modem is only to be used in extreme cases, when a node is out of reach, the data can be sent over the cellular network.

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