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Implementation and Measurement of Spectrum Sensing for Cognitive Radio Networks Based on LoRa and GNU Radio

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Abstract

In wireless communication, efficient spectrum usage is an issue that has been an attractive research area for many technologies. Recently new technologies innovations allow compact radios to transmit with power efficient communication over very long distances. For example, Low-Power Wide Area Networks (LPWANs) are an attractive emerging platform to connect the Internet-of-Things (IoT). Especially, LoRa is one of LPWAN technologies and considered as an infrastructure solution for IoT. End-devices use LoRa protocol across a single wireless hop to communicate to gateway(s) connected to the internet which acts as a bridge and relays message between these LoRa end-devices to a central network server. The use of the (ISM) spectrum sharing for such long-range networking motivates us to implement spectrum sensing testbed for cognitive radio network based on LoRa and GNU radio. In cognitive radio (CR), secondary users (SUs) are able to sense and use this information to opportunistically access the licensed spectrum band in absence of the primary users (PUs). In general, PUs have not been very receptive of the idea of opportunistic spectrum sharing. That is, CR will harmfully interfere with operations of PUs. Subsequently, there is a need for experimenting with different techniques in a real system. In this paper, we implemented spectrum sensing for cognitive radio networks based on LoRa and GNU Radio, and further analyzed corresponding performances of the implemented systems. The implementation is done using Microchip LoRa evolution kits, USRPs, and GNU radio.

Keywords: *IoT, LoRa, Cognitive Radio, Spectrum Sensing, USRP, GNU Radio*

1. Introduction

The evolving field of wireless communication has been increasing rapidly in data transmission due to rising of the wireless services, devices, and applications. Regarding such context, the resource for supporting the demand is seriously lacked. Although the technical level of wireless communication has improved considerably, the spectrum sharing problem remains so far, an essential obstacle. In the coming decades the usages of wireless data communication will deteriorate due to an explosive growth of Internet of Things (IoTs) for the future development of wireless communication technologies. Meanwhile spectrum allocation

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policy in which government agencies assign static spectrum to licensed users (called as primary users (PU), leads to inefficient utilization of a large amount licensed spectrum.

Due to under-utilization of radio spectrum, cognitive radio (CR) has been announced as a promising technology to resolve spectrum scarcity issues in wireless communication system [1]. In this approach, the secondary user (SUs), proceeds for detecting the unoccupied PUs channel or remains silence according to the decision of availability of spectrum holes and should vacate when PUs begin its operations [2]. Several methods using spectrum sensing techniques have been developed to detect the spectrum holes within the interesting frequency band [3, 4, 5, 6].

In this paper, we focus specially on the emerging LoRa technology, which represents a critical example of wireless technology working with high density devices and the performance of energy detection-based spectrum sensing algorithm in real environment. The aim of this paper is to implement a real-time LoRa network and a CR system by using LoRa technology mix with narrowband. Since the LoRa and LPWANs technology are new, they have not received much of attention from academic researcher. Using LoRa technology with SDR platform such as USRP allows us to implement easily a testbed of real-time network traffic similar to the one that can be used by real IoT application such as sensor monitoring and for spectrum sensing in cognitive radio. The major contributions of this paper are as following: At first, in the paper we provide a short overview of the LoRa technology, describe the outdoor setup, show the detailed measurements results by observing the data traffic between the gateway, devices and the thing network (TTN) cloud; (ii) implement a CR system using USRP based spectrum sensing and evaluate the sensing performance of energy detection (ED) in real time, by computing the sensing parameters such as sensing threshold, probability of detection and false alarm. Our main objective is to combine a cognitive capability using SDR approach [7] with LoRa-WAN technology. This combined capability will allow the network to make a smart decision on spectrum sharing.

The remainder of the paper is organized as follows. System model of LoRa network and spectrum sensing technique are presented in Section II. In Section III, we provide implementation for spectrum sensing for cognitive radio networks based on LoRa and GNU radio. In Section IV, we discuss and analyze measurements of the implemented system. Finally, in Section V, we draw conclusions of the paper.

2. System Model

The structure of the system model is deployed in a star topology, in which a gateway relay messages between end-devices and a central network server. The system is composed of end devices , one gateway , server, database, user web application and USRP device. For the end devices a Microchip RN2903 LoRa Motes is used attached with internal temperature and humidity sensor. The wireless communication takes advantage of the LoRa physical layer characteristics, allowing a single-hop link between the end device and the gateways. Nodes are capable of bidirectional communication, and there is support for multicast addressing groups to make efficient use of spectrum during tasks such as Firmware Over-The-Air. A Microchip Gateway is used, which is connected to the network server via standard IP connection and act as a transparent bridge, simply converting RF packets to IP packets and vice versa and offers MQTT API. For the server, the data are provided by The Thing Network (TTN) and for the database, Cayenne application is used both are members of LoRa Alliance. The gateway receives data from the end devices and forward it to the TTN server cloud which transfer the data to the application server. Then data Is integrated to the cayenne application and saved in database that users can see the live stored data. While in the other hand, an Ettus Research NI USRP-2900, GNU Radio, and python with NumPy and SciPy formed the basis of receiving signal and decoding platform based on Linux OS. The LoRaWAN network and whole system of spectrum sensing with USRP is shown in Figure 1.

2.1. Overview of LORA-WAN

In this section we briefly describe the LoRa-WAN network architecture and MAC/PHY protocols. The specification of LoRa-WAN is a Low Power Wide Area (LPWA) networking protocol designed to wireless connect battery operated ‘things’ to the internet in regional, national, or global networks, and targets key

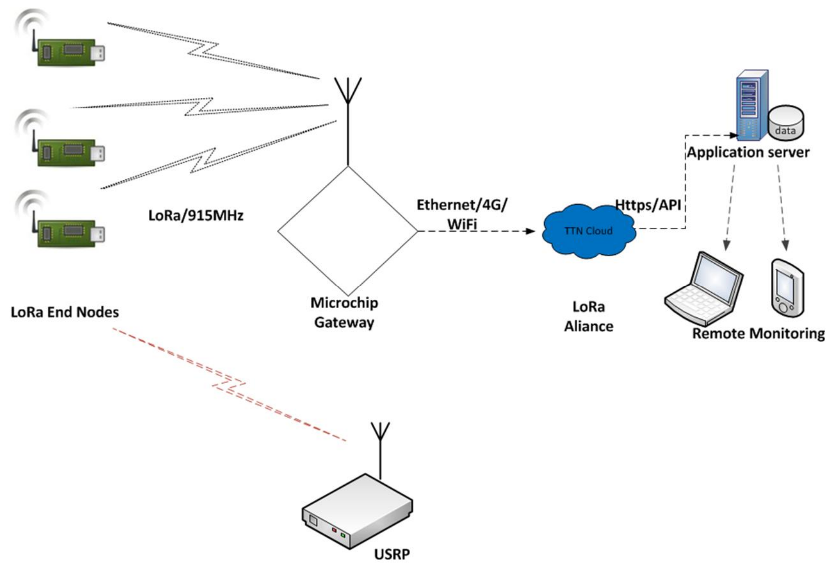

Figure 1. Structure of LoRa and GNU radio-based spectrum sensing.

Internet of Things (IoT) requirements such as bidirectional communication, end-to end security, mobility and localization-services. The protocol is built on the top of the LoRa PHY technology where a PHY layer is patented by Semtech^{TM} that works on ISM bands of 868 MHz with 3 default channels in Europe and 915 MHz in US with a limited duty cycle allowed to each device [8, 9]. A typical LoRa-WAN network as shown in Figure 1 consists of end devices, multiple gateways which forward the packets coming from the wireless medium to a backhaul interface, and a logically centralized server which analyzes information collected by all the devices and optimizes the network configuration. The end devices are not associated to a particular gateway to have access to the network. The gateway serves simply as a link layer and forward all the packets received from end-nodes to the network server. Same packets can also be forwarded by multiple gateways and the central server is responsible to detect the duplicate packets and choosing the appropriate gateway to transmit downlink packets. The LoRa-WAN gateways are equipped with multiple transceivers to receive simultaneously on multiple frequency channels which are configurable, while the end devices can dynamically select one transmission channel, among a set of available ones, at each transmission attempt. The LoRa-WAN MAC provides an open source MAC layer that is based on a simple Aloha protocol, in order to minimize the complexity and the energy consumption of the devices. The end nodes do not perform carrier sense, moreover they listen to the medium for receiving packets only in specific time windows after uplink transmission. The MAC layer consists of three classes: i) Class A: allows for bi-directional communications whereby each end-devices after the transmission of a packet, open two receive windows to get an acknowledgement (ACK), then they stay in idle mode until the next transmission; ii) Class B:

end-devices have more receive windows synchronized with beacon provided by the gateway allows the server to know when the end-devices are listening; iii) Class C: end-devices continuously stay in reception mode which makes them unsuitable for battery powered operation.

2.2. Spectrum Sensing of CRNs Using LoRa

The main duty of spectrum sensing is to obtain awareness of the spectrum usage of licensed Primary Users (PUs) in the specified frequency band. Secondary users (SUs) can decide whether there are spectral holes available or not based on the information provided by Spectrum Sensing operation. Energy detection (ED) is a non-coherent method that detects the PU signal based on the sensed energy [10]. Through ED method, we measure the energy of available radio resource and compare it against a predefined threshold level. If the energy measured is below the threshold level, then spectrum is marked as available otherwise it considered as occupied when the energy level is above the threshold. ED method does not need any requirement on a prior knowledge of PU signal. It only relies on the energy received in the band, if PU is absent then ED measure only the noise, otherwise it measures the signal plus noise energy in presence of PU. The absence or presence of PU in the environment can be defined through two binary hypotheses: H_0 and H_1. The received signal $y(i)$ at SU can be expressed as [11]

$$y(i) = \begin{cases} n(i) & H_0 \\ h(i)s(i) + n(i) & H_1 \end{cases} \tag{1}$$

where $y(i)$ is the complex signal observed by the sensing receiver (SU), $h(i)$ is the amplitude gain of the channel, $s(i)$ is the transmitted PU signal, and $n(i)$ is additive white Gaussian noise (AWGN). Under hypothesis H_0 PU is considered absent, and the received signal sample $y(i)$, contains only noise. On the contrary, the received signal under hypothesis H_1 consists of the transmitted signal after channel $h(i)$ together with the noise. The spectrum sensing operation consists to decide between the two binary hypotheses based on observing the received signal. The presence of PU can be detected only by calculating the amount of received power by considering the frequency band and compare it to a set of thresholds. The test static for ED which will make decision on the occupancy of the PU can be formulated as

$$T_y = \frac{1}{N}\sum_{i=0}^{N-1} |y(i)|^2 \tag{2}$$

where N represents the number of samples. Under each hypothesis (H_0 or H_1), the test static T_y can be modeled by the Gaussian distribution as following[8]:

$$T_y|_{H_0} \sim \xi\left(\sigma_n^2, \frac{\sigma_n^4}{N}\right) \tag{3}$$

,

$$T_y|_{H_1} \sim \xi\left(\sigma_X^2 + \sigma_n^2, \frac{(\sigma_X^2+\sigma_n^2)^2}{N}\right) \tag{4}$$

where σ_X^2 and σ_n^2 denote the variance of the transmitted signal and the variance of AWGN respectively. The corresponding probability of detection and false alarm can be given as

$$P_{f_a} = Pr\left(T_y > \lambda|_{H_0}\right) = Q\left(\frac{\lambda-\sigma_n^2}{\sigma_n^2/\sqrt{N}}\right) \tag{5}$$

,

$$P_{f_D} = Pr\left(T_y > \lambda|_{H_1}\right) = Q\left(\frac{\lambda-\sigma_n^2(1+\gamma)}{\sigma_n^2(1+\gamma_s)/\sqrt{N}}\right) \tag{6}$$

where *Q(.)* denotes the Gaussian Q-function and λ is the predefined sensing threshold.

3. Experiments and Results

3.1. Experimental System Setup

In this section, we will give the details of setup implementation for testing LoRa-WAN network and spectrum sensing for cognitive radio networks. In this experiment, different components were used that are necessary to test and provide coverage for IoT applications and for the performance evaluation of spectrum sharing using GNU platform. This test includes communication and collecting data from IoT devices by connecting them to the internet. In order to characterize the transmission range of a LoRa device, we have performed measurements of received power at increasing distances. Three microchip LoRa mote RN2903 end devices with temperature and humidity sensor, one microchip LoRa Gateway Core, and one USRP device were used during the experiment, to make LoRa-WAN network in 915 MHz bandwidth as shown in Figure 1. The measurement area can be divided into short range and long-range areas. The short range consists of two Libelium's Microchip LoRa-WAN module ported to Arduino and Raspberry Pi respectively. The first node maned "lora_uno1" is deployed on the roof of Audio Visual Education Building with a distance of 380 m from the gateway and the second node named "raspi_gate" is located inside the Multimedia Communication System Lab (MCSL) 3th floor of electrical engineering building. For the long range, a 915 MHz RN2903 LoRa Mote named "loraRnmote" is used with a distance longer than 2km. As a standalone battery-powered node, this Mote provides convenient platform to quickly demonstrate long-capabilities of the modem [12], as well as verify the inter-operability when connecting to LoRa-WAN gateway and infrastructure. We do the measurements for the three end-nodes by placing the gateway in different positions as shown in the map in Figure 2. For testing the spectrum sensing based LoRa-WAN network, we used the Universal Software Radio Peripheral (USRP) NI-2900 considered as a SU to receive the signal of LoRa end-devices which are considered as a PU. USRP is a flexible low-cost and high-quality platform that is designed for implementation of SDR for a wide range, developed by Matt Ettus [13]. The main role of USRP is to convert the digital base-band signal coming from the computer to analog signal in the RF band. All the software processing were realized in the open source GNU radio environment [15] which has the libraries for various modulation schemes, error-correcting codes and scheduling together for manipulating the USRP board and a graphical programing environment to allow the implementation of spectrum sensing technique. The signal process was realized in the graphical tool called GNU radio companion (GRC), where the hole system is built from blocks. A schematic diagram and the dedicated photographs of the hardware components assembled for outdoor setup at the University of Ulsan are shown in Figures 3 and 4, respectively. Table 1 shows the description of the gateway board.

Table 1. Specification of Microchip LoRa Gateway.

Model	Microchip LoRa Gateway version 0.12
Frequency	915 MHz

TX-Power	14 dBm
Rx Sensitivity	-146 dBm
Antenna	RFA-09-C55-U-B70-2
Distance	>15 Km

3.2 Network Parameters

In our measurement, two test-cases are considered as following and the operating frequency of 903 MHz is used in both cases.

1. Case - Test 1

In the case, we make a simple setup of LoRa by considering typical parameters values which were able to generate traffic really similar to one that can be used in practical applications. Spread spectrum is used as a modulation scheme. The initial and main parameters are as follow: center frequency, 902.3 MHz (8 channels enabled); spreading factor 10 and 8; coding rate 4/5; bandwidth 125 kHz; packet payload 21 bytes and 23 bytes.

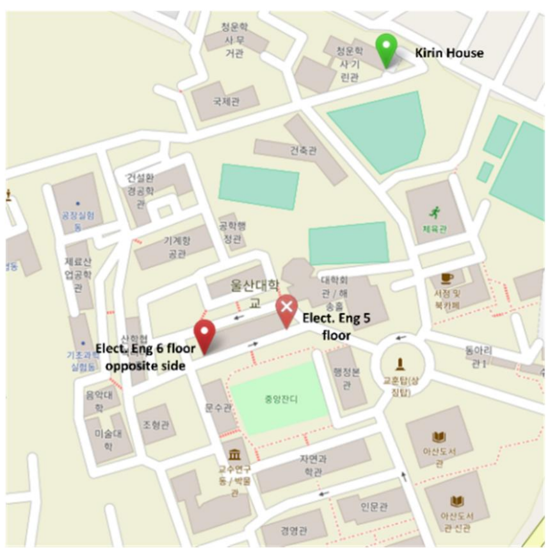

Figure 2. Map of gateways.

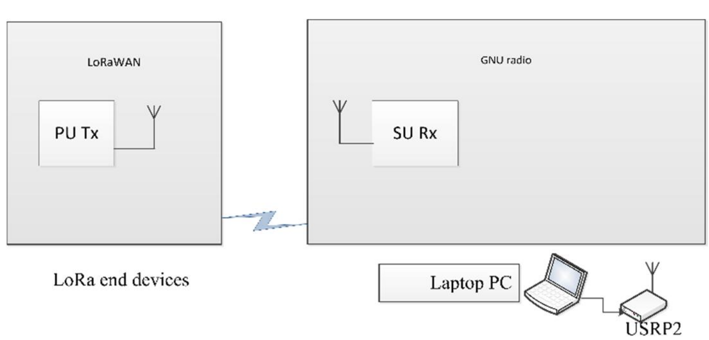

Figure 3. Schematic diagram of the implemented spectrum sensing system.

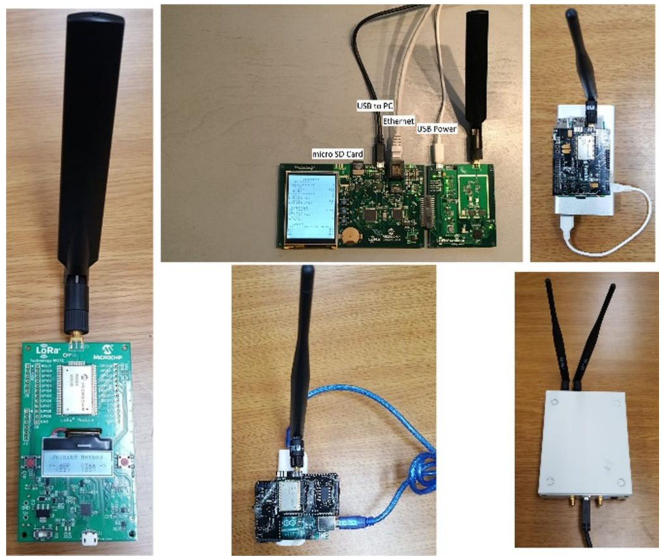

Figure 4. Hardware setup environment.

Data rate varies by spreading factor and the bandwidth. The performance measurements of LoRa are supposed to give us the insight of the quality of service (QoS) that the LoRa-WAN network can provide by giving us statistical data for different configurations of the network. To evaluate the QoS basic metrics, such as the Packet Error Rate (PER), the Received Signal Strength Indicator (RSSI) and the Signal to Noise Ratio (SNR) were considered. We focus our testing on the uplink communication as this is the common case for IoT. The packets flowing into LoRa-WAN network are received and sent by the LoRa gateway. Figure 5 shows some example of LoRa meta data.

Metadata


```
{
  "time": "2018-07-31T13:01:32.164984427Z",
  "frequency": 902.5,
  "modulation": "LORA",
  "data_rate": "SF10BW125",
  "coding_rate": "4/5",
  "gateways": [
    {
      "gtw_id": "eui-1123456788765432",
      "timestamp": 1425868132,
      "time": "",
      "channel": 1,
      "rssi": -109,
      "snr": 1.5
    }
  ],
  "latitude": 35.54414,
  "longitude": 129.25963,
  "location_source": "registry"
}
```


Estimated Airtime

247.808 ms

Figure 5. A sample of the spectrum sensing data received at LoRa gateway.

Figure 6. RSSI of received packets at the gateway located at the 6th floor of Department of Electrical and Electronic Engineering at the University of Ulsan as the sensing node moves from the gateway.

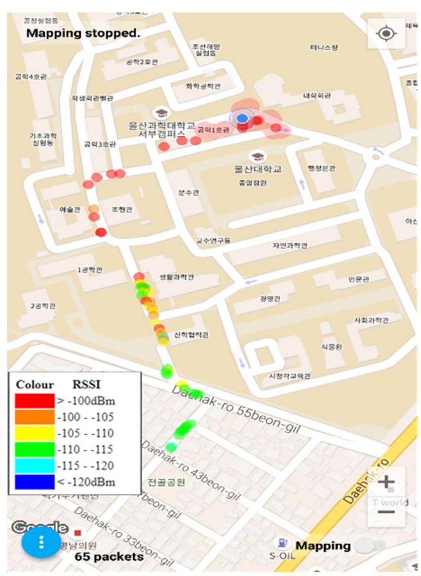

Figure 7. RSSI of received packets at the gateway located at the 5th floor of Department of Electrical and Electronic Engineering at the University of Ulsan as the sensing node moves from the gateway.

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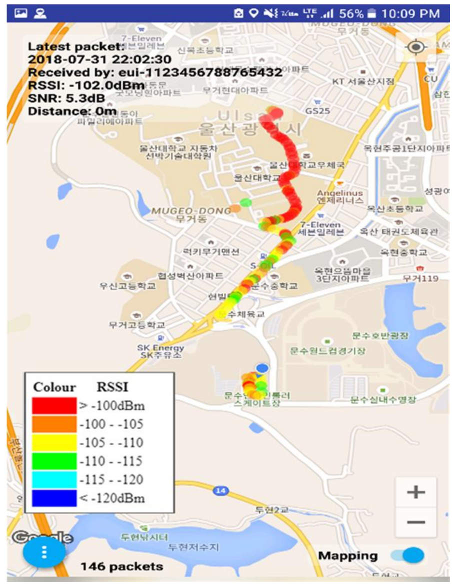

Figure 8. RSSI of received packets at the gateway located at the Kirin House at the University of Ulsan as the sensing nodes moves from the gateway.

From Figure 6, 7 and 8, it is observed that the results of packets received by the gateway which were periodically sent by the three IoT nodes and also the radio parameters such as SNR and RSSI. Both was using the spreading factor (SF) 10, 8 and 7. Each point represents one packet, as received by the gateway for the three given end devices. The color of each point represents the RSSI of the packets. From the LCD of the gateway we can observe that 445 packets were sent during the hole measurement. Out of that, the gateway placed in “Elect.Eng 5 floor” received only 65 packets and the gateway placed on “Elect.Eng 6 floor ” received 101 packets respectively. This is due the fact of the high building around, that make the connection loss, our gateway was not located in the highest building. while the gateway placed in highest building on the roof of “Kirin House” that is around 2 km away from the farthest point, received 146 packets. We observe that the RSSI received by the gateway during the whole measurements in different positions goes rarely in range between -89 and -115 dBm. Note that when the elevation profile is high between the gateway and the measurement points, the reception is very good. While, when the elevation profile between gateway and the measurements points is not high that might block the reception and the connection is much worse due the presence of the buildings around.

2. Case - Test 2

In this case we perform our test by using GNU radio platform to develop the spectrum sensing algorithm for CR. We used the LoRa end-devices to generate signal and considered as PUs (Tx), whereas the USRP device based on Linux OS connecting with the personal laptop, was used for spectrum sensing purposes and acted as SU (Rx) to capture and decode the signal of LoRa end devices. We used and modify the open source gr-lora out of tree module written by github user rpp0 [14, 15]. From the GRC we build the flowgraph to receive the signal of the LoRa end devices. We create a variable called $capture\_freq$ and set the frequency to 902.3 MHz which is supported by LoRa-WAN, and we set a variable $sample\_rate$ to 1 MHz. Data from the RF spectrum are collected by the $USRP\ Source$ block which center frequency was set at 902.3 MHz. Afterwards, the signal goes through $LoRa\ Receiver$ block which main function is to detect, capture and receive the LoRa signals. This block receives different input parameters from the user, such as low and highest frequencies of the band to be sensed, the number of samples, bandwidths considered for performing the magnitude analysis of the sensed signal, SF8 and 10 like the same configuration in the LoRa-WAN network. Then the data is stored into a data file which can be used in MATLAB to estimate the performance of energy detection. A schematic diagram of the SU receiver is shown in Figure 9.

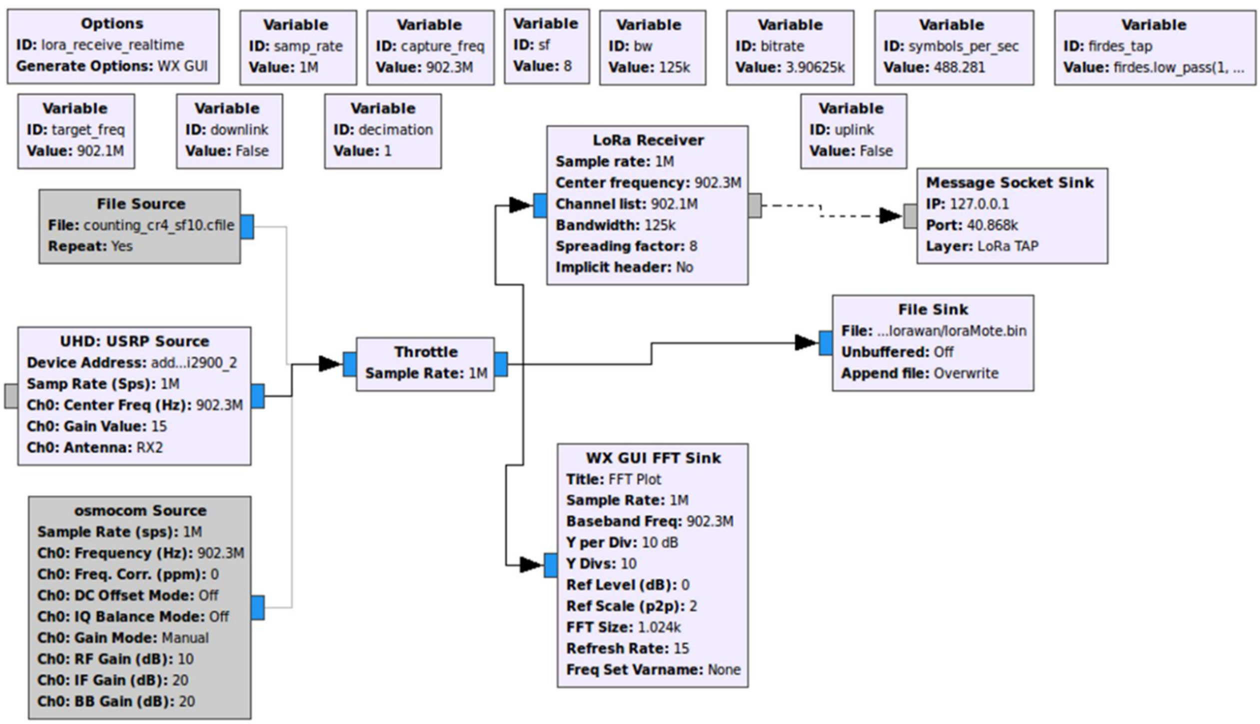

Figure 9. Flowgraph of SU receiver with 902.3 MHz with SF=8 and CR= 4/5.

In this experiment, we can observe the sensing information as shown in Figure 10 when no signal is transmitted by the PU (LoRa end devices) and Figure 11 shows the signal received by SU when end devices (PU) utilizes the channel

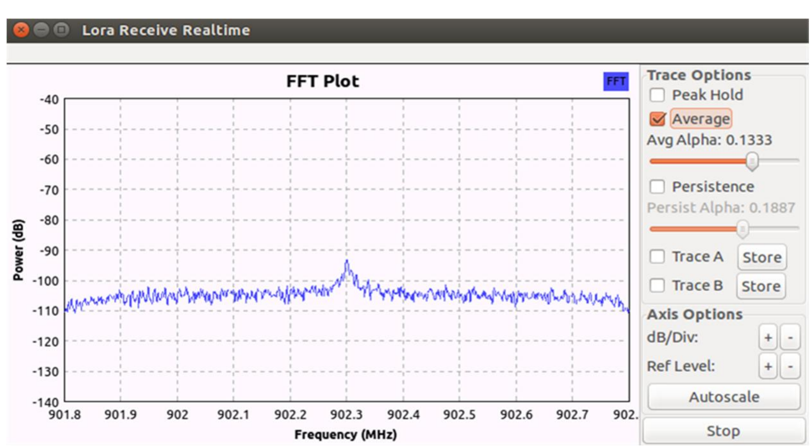

Figure 10. Received signal when PU is absent at center frequency fc= 902.3MHz.

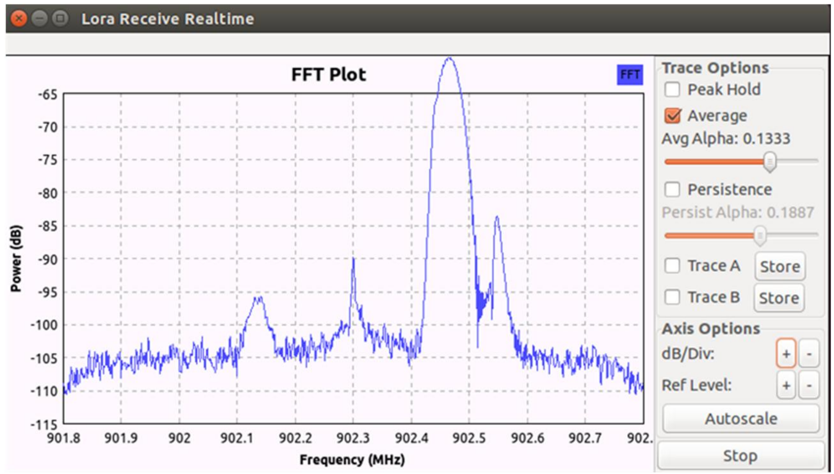

Figure 11. Received signal when the signal of PU is present at center frequency fc=902.3 MHz.

In GRC, we can observe received signals based on the *FFT sink* block during the transmission. One we can observe that tree channels were activated at 902.1, 902.4, and 902.5 MHz, when the three devices (PU) transmit packets. All the end- devices used for transmitting were set at same center frequency 902.3 MHz, and eight channels (0-7),were enabled. In LoRa-WAN the nodes were set to listen in eight channels and they can change channel automatically when the channel is being used by another device.

4. Performance Analysis

In this section, we present the results of the measurements for the two cases. First, we show the results for test case 1. In Table 2, we summarize the measurement results for payload length 23 bytes and 21 bytes in terms of RSSI and SNR. Figure 12 shows the measurements of the RSSI and SNR for different distances. We can observe how the RSSI decreases as the distances increases. The annotations on each point represents the number of packets received both successful and unsuccessful. Figure 13 shows the probabilities of false alarm and detection according to the SNR while Figure 14 shows the ROC curve of probability of detection and probability of false alarm. These figures show that experimental and theoretical results are almost similar.

Table 2. Summary of measurements

Measurement Points	SF	RSSI (dBm) mean value	RSSI standard deviation	SNR(dB) mean value	SNR standard deviation
Elect.Eng.5 floor	SF10 SF8	-111.39 -99.33	3.60 1.68	0.82 1.61	1.82 2.61
Elect. Eng. 6 floor	SF10 SF8 SF7	-108.49 -112.06 -117.36	0.50 0.93 0.68	3.71 -2.69 -.1.8	2.66 2.30 3.18
Kirin House	SF10 SF8 SF7	-113.35 -112.15 -110.16	0.48 0.84 0.83	-5.27 -4.80 -2.87	0.72 1.19 3.12

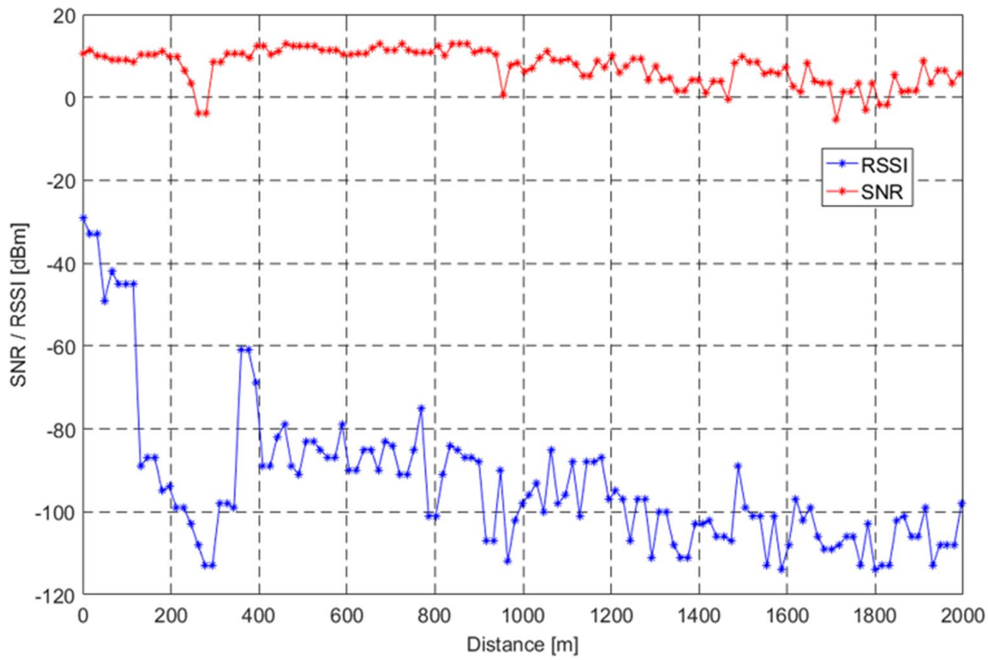

Figure 12. Measurement of RSSI and SNR values with payload length 21 bytes at the place taken away 2 km from the LoRa gateway.

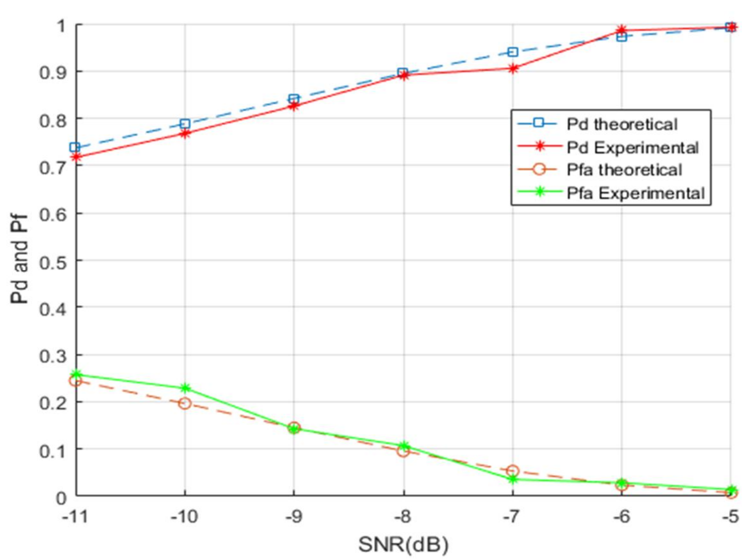

Figure 13. Probability of detection and false alarm according to the received SNR.

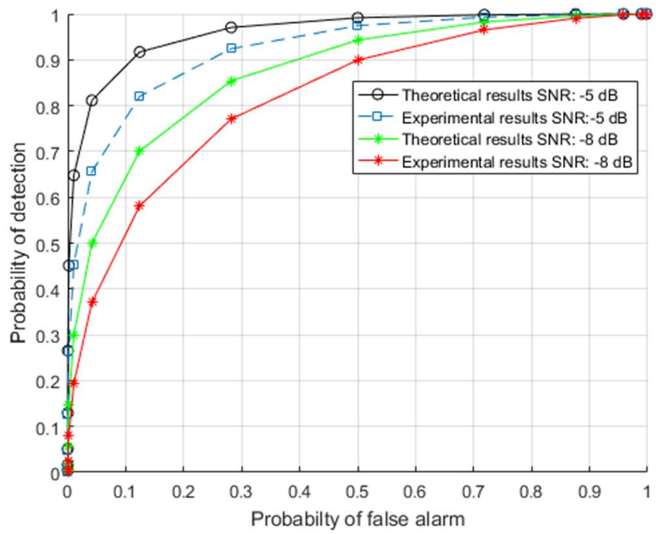

Figure 14. ROC curve for probability of false alarm and detection when SNR =-5 or -8 dB.

5. Conclusion and Future work

In the paper, we showed the implementation results of a real LoRa network based on LoRa-WAN technology mix with narrowband to implement spectrum sensing technique for CR. Our implementation was divided into two cases. At first, we designed the overall construction of the LoRa system using available commercial hardware and open-source software Microchip kit, and we analyzed measurements. After that, we implemented spectrum sensing with energy detection using USRP and GNU platform. From the results, it was shown that LoRa technology can offer an excellent outdoor coverage in urban area. In addition, it is shown that a single gateway can serve several devices sending few bytes of data per day. Furthermore, two performance metrics for spectrum sensing were measured in real time: the probability of detection and false alarm

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