LoRa Communications in Wireless Sensor Network for Radioactive Sources Monitoring System

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Abstract

Using LoRa, a low-power long-distance communication technology, for wireless sensor networks (WSNs) that have limited coverage range can extend to kilometers, much longer than other technologies such as Zigbee, WiFi, WiSUN, while maintaining the sensor node's energy consumption at a relatively low level. In this paper, the authors present the architecture of wireless sensor network systems used to monitor radiation sources. The system consists of sensor nodes integrated with radioactive sensors and linked together to form a radioactive network monitoring system. The LORA is used to transmit data between sensor nodes and sink. Also in this paper, authors propose to use the MAC multi-access protocol specifically designed for communication between nodes in the radiation control system, ensuring reliable transmission requirements and advantages of energy consumption for communication function. Experimental implementation results show that the system can work well with transmission range of up to 2 km in urban environments.

Keywords: radioactive sources monitoring, MAC, LoRa communications, wireless sensor network.

1. Introduction

Radioactive material out of the regulatory control are radioactive sources, nuclear materials, nuclear equipments that are lost, appropriated, abandoned, illegally transferred, undeclared [1]. The 2004 Code of Conduct on the Safety and Security of Radioactive Sources [2] requires countries to set up mechanisms to restore radioactive sources that out of regulatory control (Target number 5 of the Code). Under the general principles of the Code, each country must have a technical system to control the stolen, abandoned radioactive sources as well as to eliminate or minimize the consequences caused by these sources of radiation [3][4].

In spite of the management of the usage of radioactive sources, they are still frequently using in the world, increasing the risk of radiation exposure for the population and the environment as well as the impact on the socio-economic development. The majority of known stolen sources are sources which used in radiography, sources from isotopes, and sources in industrial irradiation. Lost radioactive sources are usually sealed sources, manufactured in the form of bars, metal ball and their metal containers. Therefore, when the radioactive sources is lost, it usually being sold to the scrap metal recycling facilities for recycling [3], [5], [6]. In order to detect and treat such radioactive sources, an IoT system is required. According to some reference models for IoT, the communications in IoT as well as the communications in wireless sensor networks (WSNs) requires a significant expansion in the number of connected devices. In response to this demand, sensor nodes is technically required low cost, low power consumption, and have the ability to connect through wireless communication technologies with appropriate transmission distance [7]–[9].

Popular communication technologies such as Bluetooth and WiFi are being used on a daily basis by many devices like smartphones, laptops, and tablets with high bandwidth but with a very shot communication distance and high power consumption have proved to be unsuitable for IoT or WSN systems. Some other communication technologies such as Zigbee [10] have low power consumption but the transmission distance is still limited. LoRa Technology (Long Range) [11] addresses the weaknesses of these above technologies with a theoretical straight line of sight transmission distance up to 20 km in non-urban environment and from 2 km to 5 km in urban environment. LoRa has the maximum bandwidth of only 50 Kbps, but it is suitable for IoT applications which do not require high bandwidth. LoRa's power consumption is quite low (36 mA at maximum output power with Semtech Module SX1272) [12]. In addition to LoRa long distance communication and low power consumption advantages, we found that this is a technology that

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satisfies the requirements of the Radioactive sources monitoring system.

In this study, the authors implement the LoRa technology, namely LoRa SX1278 (Semtech) chip to design and manufacture a low power consumption communication module integrated with the wireless sensor devices. The authors also propose a startopology communication model which requires multiple access in the radio sources. Therefore, we propose a MAC-based multiple access protocol applying the LoRa physical layer modulation technology based on the ALOHA multiple access protocol. Later we deployed the hardware system integrating the protocol that we have proposed and evaluated the stability, packet loss rate, and radio resource utilization.

2. LoRa Technology

LoRa is an ISM band wireless communication technology. LoRa modulation uses Spectrum Spread Chirp technique which is a small subset of DSSS (Direct Sequence Spread Spectrum). This modulation technique help to increase the link budget as well as impove the network interface resistance [10]. LoRa has three options of broadbands such as 125 KHz, 250 KHz, 500 KHz. This feature allows to increase the ability of resisting channel noise, long term relative frequency, Doppler effect and fading. Extending a narrowband signal based on a wider band reduces the use of spectrum. However, end devices use and/or orthogonal sequences with different channels resulting in higher overall system capacity.

Recently, various of research work has been published in the topic of LoRa technology, ranging from the fundamentals of LoRa modulation scheme and technical comparison of LoRa with other wireless technologies [10], to evaluation and investigation of LoRaWAN, the proposal of LoRa Alliance about the architecture and operation of LoRa-based networks [13],[14]. LoRaWAN has proposed different operation scheme for LoRa-based end devices/ sensor nodes. The author of the work [15] has proposed a mathematical model and simulation evaluation for estimating the collision and packet loss of LoRaWAN network in different scenarios of IoT applications.

In the following sections, we present three main features that define the distinction of the LoRa modulation technique.

2.1. Spreading Factor

Because the LoRa modulation technique is based on the Chirp spectral spreading modulation technique in which the spreading factor, ranging from SF7 to SF12, is an essential parameter. Selecting the SF creates a trade-off between the transmission distance and the data rate. If large SF is selected, the transmission distance will be long but the data rate is lower.

2.2. Bandwidth

LoRa uses three bandwidth values: 125 KHz, 250 KHz, 500 KHz. The receiver will send the data that has been chipped as the same rate as the bandwidth of the system. For example, if the system has a bandwidth of 500 KHz, the chip rate is 500 Kcps. Table 1 illustrates the relationship between data rate, spreading factor and receiver sensitivity.

Table 1. Relationship between DR, SF, and receiver sensitivity.

DR	SF	Bit Rate (kbps)	Sensitivity (dBm)
DR0	12	0.25	-137
DR1	11	0.44	-135
DR2	10	0.98	-133
DR3	9	1.7	-130
DR4	8	3.1	-129
DR5	7	5.4	-124

2.3. Coding Rate

LoRa supports FEC (Forward Error Correction) at receiver side as well as increases the sensitivity of the receiver [10]. The Coding Rate (CR) has an integer value from 0 to 4, with CR = 0 mean no FEC. With different CR values, the number of bits added is different and therefore the data rate is different. Adding FEC improves the error correction but reduces the data rate transmission.

3. Radiation Source Monitoring System

3.1. Radiation monitoring system architecture

The monitoring system of out-of-control radioactive sources includes the following modules (Fig. 1):

- Sensing and Data Processing subsystem: includes sensors for measuring radioactivity and other environment physical parameters, like temperature, humidity, etc.
- Communication subsystem: includes the communication modules on monitoring devices and gateway which all build up a star-topology wireless sensor network. Monitoring devices deliver data to the gateway through the LoRa radio and the gateway transfers the data to the data server by 2,5G/3G or WiFi.
- Storage subsystem: responsible for data collection and storage (data server), data processing.

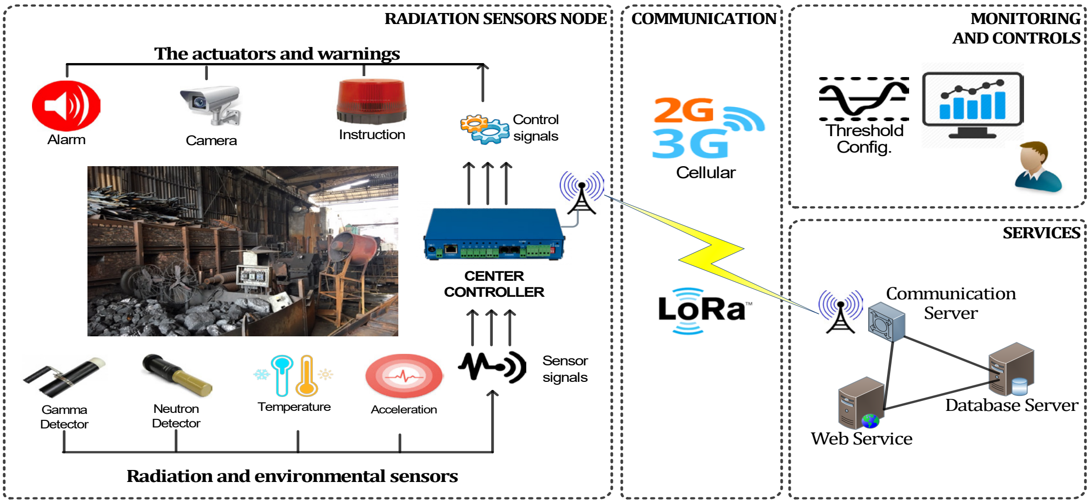


Fig. 1. The radioactive sources monitoring system.

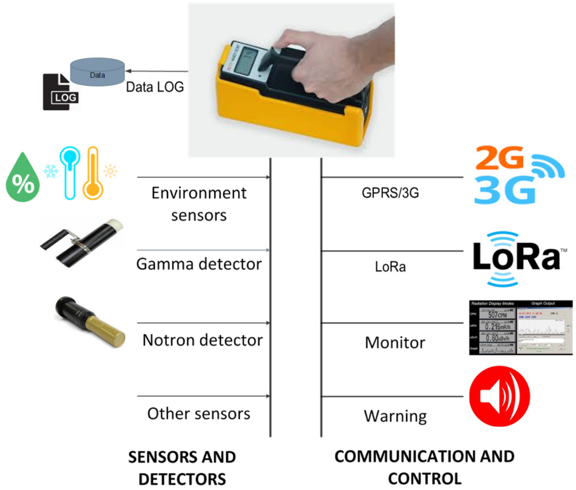


Fig. 2. The radioactive sources monitoring system function and architecture.

- Monitoring and controlling subsystem: responsible for displaying visually the monitoring data on the mobile application and web application. Users can configure the system, e.g. setup monitoring period, warning thresholds, ect.

3.2. Monitoring Node Architecture

The functional elements of a monitor node are shown in Fig.2. The node is equipped with specialized sensors that measure gamma radiation, neutrons, and other environment physical parameters. The sensed data is transferred to the central control unit for data processing, analyzing, and packaging to be sent to LoRa communication module. The LoRa SX1278 Chip is selected.

3.3. Gateway Architecture

In addition to the LoRa module, the gateway is integrated with GSM LEON G100 module. Data message received at the gateway will be processed and then forwarded to the server through the this module. Besides, the gateway is responsible to authenticate the joining requests from nodes and to synchronize the monitoring nodes regularly.

3.4. Communication Protocols

The network of monitoring nodes is configured in star topology due to the long range capability of LoRa technology. The monitor nodes will send the data to the common gateway, the data collection node. The gateway will aggregate data from the monitoring nodes and then forward to the server via the 2,5G/3G mobile communications.

The overall objectives of the system is to ensure the real-time monitoring requirements while maintaining low energy consumption at monitoring nodes. Therefore, the communication sessions of monitor nodes need to be well-controlled to minimize collision probability for reliable and low latency data transmissions. Besides, the procedure of authentication and node association into the network should be designed. In the following part, we describe in detail the design of communication procedure in the monitoring devices and the gateway.

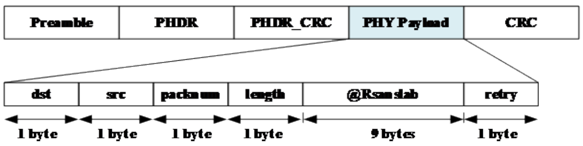
3.4.1. Message Formats

In this section, we discuss message structure of the proposed protocol which includes multiple different messages (Illustrated in Fig. 3(a), Fig. 3(b) and Fig. 3(c):

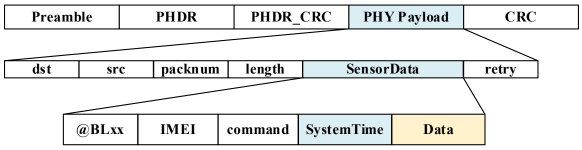
- *Joining Network Request message (msgJoinReq)*: is generated by monitoring nodes, and sent to the Gateway to request to participation into the network before transmitting data message.

- *Joining Network Response message (msgJoinRes)*: is created by gateway to response to the Joining Network Request.

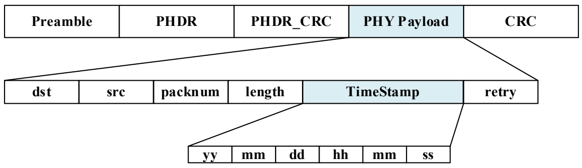
- *Data message (msgData)*: contains sensing data which sent from monitoring nodes to the gateway.
- *Time Synchronization message (msgTimeSyn)*: is utilized to synchronize system time which sent from nodes.
- *Time synchronization Response Message (msgTimeSynRes)*: is generated by the Gateway to response to the msgTimeSyn.
- *ACK Message (msgACK*): is generated by the Gateway to acknowledge the data reception.



(a)



(b)



(c)

Fig. 3. (a) Joining Network Message Format. (b) Data message Format. (c) Time-synchronized message Format

3.4.2. Random Multiple Access Protocol

We apply a multiple access protocol based on the Aloha scheme. When a node need to transmit a data message, the node will proceed to send that message on the radio channel immediately, and then wait for the ACK message in an approximate round-trip time (RTT). RTT depends on the propagation time of the message on the radio channel, and processing time at the monitoring node and the gateway. In the case of not receiving ACK, the node will re-transmit the message. The waiting time before the retransmission is setup equal to several times of RTT. The protocol is illustrated in Algorithm **1**.

Algorithm 1 Multiple Access Protocol

function SENDALOHABASED(*addr*, *message*)
    $K \leftarrow 0$ // set backoff to zero
    $state \leftarrow sendData(addr.message)$
    wait ACK with RTT (s) time
    if $state == success$ **then**
        if $(checkACK( ) == true$ **then**
            success
            $sleep( )$ until new message
        else
            $K++$
            if $K > K_{max}$ **then**
                abort
            else
                $n \leftarrow 0; 2^k - 1$
                wait $n \times RTT$ with:
                    $RTT = 2 \times T_p + T_s$;
                    T_s: processing time at gateway;
                    T_p: propagation time
                goto step 2
            end if
        end if
    esle
        goto step 2
    end if
end function

Algorithm 2 Receiving and Processing Data

$pass \leftarrow$ authentification command
Gateway self-configure, setup parameters: DR, SF, BW
while 1 **do**
    $waitReceiveData( )$
    if Receive packet **then**
        $packet \leftarrow packet\_receive$
        if $packet$ is data message **then**
            $data \leftarrow packet.data$
            if correct authentification **then**
                if correct CRC **then**
                    push data to buffer and wait to forward
                    send ACK to src-node
                else
                    abort
                end if
            else
                abort
            end if
        else if $packet$ is joining network request **then**
            $ID \leftarrow packet.src$
            $authentification \leftarrow packet.data$
            $response \leftarrow thue$
            if $authentification \neq pass$ **then**
                $response \leftarrow false$
            end if
                send joining network response to node
        else
                abort message
        end if
    end if
end while

3.4.3. Gateway Packet Processing Algorithm

The procedure of message reception and processing at the gateway is illustrated in Algorithm **2**. After receiving a message, the gateway will first authenticate the received message whether the source address of the message is a member node or not. If the authentication fails, that message will be discarded. Otherwise, the gateway will proceed to classify and process the message according to the type of message as follows:

- Joining network request: the gateway performs validation checking and sends Joining Network Response message back to the source node.
- Data message: the gateway calculates the checksum, and correct errors. Then the data message is enqueued to wait for transferring to the server.
- Time Synchronization message: the gateway prepares the Time synchronized Response message with the system timing, and sends back to the request-node.
- In other cases, the message will be aborted.

3.3.4 Joining and Leaving Processing Algorithm

The Algorithm 3 describes the procedure for the node association into the network. After launching, the node will send Joining Network Request to the Gateway and wait for the Join Network Response. This process will be repeated until the node successfully joins the network. Then the node will switch into sensing data mode and proceed data transmission when there is the data received from the sensors.

4. Implementation

We have designed and manufactured the hardware of BKRAD- LoRa monitoring node and gateway and implement the proposed protocols in the firmware. The main-board of the monitoring node is shown in Fig. 4. The firmware in the monitoring node and the gateway, including main program and drivers to control the sensors, memory card, and the radio modules, is based on the real-time operating system.

Algorithm 3 Joining Network Procedure

procedure RequestJoinNetwork(*broadcastAdd, JoiningNetworkRequest*)
  repeat
    $state \leftarrow sendAlohaBased(JNR)$
    if $state! = 0$ **then**
      $delay(\,)$
    else
      $response \leftarrow packet\_receive.data$
      if response is not correct **then**
        $state \leftarrow 1$
      end if
    end if
  until $state! = 0$
end procedure

The firmware structure includes multiple tasks as follows:

- The LoRa task: is implemented in the monitor node, the task proceeds the proposed protocols, sends the data, and requests for synchronization (illustrated in algorithms 1, 3). In the gateway, this task has additional functions of processing messages received from nodes, and then enqueue data messages to wait for the Cellular task.
- Sensing task: only in the monitoring node. Nodes regularly check ports connecting to sensors to retrieve data sensed by radioactive sensor,. . .
- Log2SD task: to log system file to SD card.
- Updating system time task: to update and synchronize system time.
- System monitor and The Watchdog task: to export the system activity information to the debug interface so that developer and operators can monitor and control the operation of the system.
- Cellular task (only in the gateway): has main function of establishing and maintaining the connections with the server, and packs collected data into TCP/IP standard. Furthermore, this task also proceeds the commands and the SMS of the mobile devices to check the device's status, or configure and control the devices.

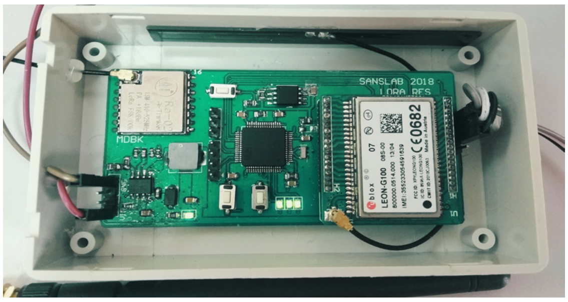


Fig. 4. Main-board of the radioactive sources monitoring device.

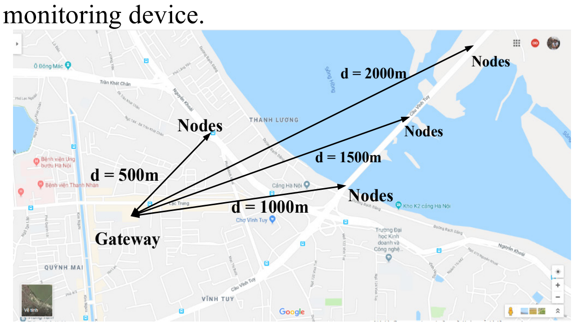


Fig. 5. The deployment of nodes in the 1st Scenario.

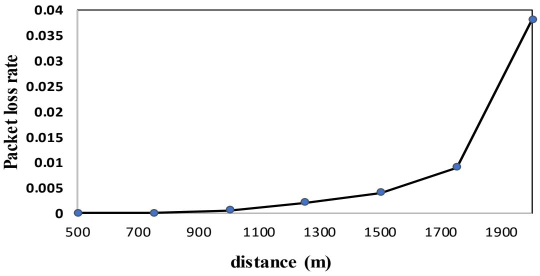


Fig. 6. Packet loss rate depends on the distance.

5. Experiment and Results

To evaluate the performance of the system in terms of the communication capability, we setup the following scenario and measure the packet loss ratio. Two monitoring nodes are deployed around the gateway in urban environment in Hanoi. The distance from a node to the gateway is varied from 500 m to 2000 m (illustrated in Fig. 5). The configuration parameters of node are as follow: BW = 125KHz, SF = 12, CR = 4/5, power = 14 dBm. The number of messages transmitted per node is 500 messages, of 100 bytes. Figure 6 demonstrates the measurement results of the test. The result shows that in the communication at the distance less than 2 km is reliable (the loss ratio is less than 4%).

6. Conclusion

In this work, we design and implement the monitoring system of radioactive sources using LoRa communication technology. To solve the problem of multiple access of nodes, we design and implement a multiple access protocol based on Aloha scheme. As a result, the system operates stable and the communication is reliable when transmission range is upto 2 km in urban environments. In subsequent studies, the research team will develop advanced functions based on AI and embedded the functions in the LORA sensor nodes to form an intelligent radiation sensor system.

Acknowledgments

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