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Research Article

Multihop Uplink Communication Approach Based on Layer Clustering in LoRa Networks for Emerging IoT Applications

Alain Bertrand Bomgni,[1,2] **Hafiz Munsub Ali**,[3] **Mohammed Shuaib**,[4,5] **and Yann Mtopi Chebu**[2]

[1]*University of South Dakota, Vermillion, SD, USA*
[2]*University of Dschang, Dschang, Cameroon*
[3]*Binghamton University, Vestal, NY, USA*
[4]*College of Computer Science and IT, Jazan University, Jazan, Saudi Arabia*
[5]*University Center for Research & Development (UCRD), Department of Computer Science and Engineering, Chandigarh University, Gharuan, Mohali 140413, Punjab, India*

Correspondence should be addressed to Alain Bertrand Bomgni; alain.bomgni@usd.edu

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LoRa technology is widely used in the Internet of things network applications. It enables low-volume data transmission via small wireless devices. The principle of LoRa networks (an LPWAN technology: Low Power Wide Area Network) is to transmit data by air from sensors with a short transmission range, about over ten kilometers. These sensors should not be powered by electricity, and batteries power them. Hospital visits are inevitable, but current advances in communication could reduce the burden on hospitals with remote (from home) treatments using these wireless sensors. Thus, using the LoRaWAN protocol could greatly facilitate patient diagnosis by transmitting data between doctors and patients in real time and with minimal energy consumption. The objective of this work is to set up a multihop IoT network containing a large number of sensors based on LoRa for uplink communication. This work evaluates the energy consumption and the packet delivery rate in the multihop IoT network. The simulation result shows that the proposed approach reduces power consumption by 50% and improves the packet delivery rate by 2% compared to the existing state of the art.

1. Introduction

The Internet of things (IoT) is experiencing considerable scientific expansion in several areas, facilitating the exchange of information between objects, hardware, and software resources [1–5]. Technological advancements in the field of IoT have enabled the development of a wide variety of applications such as precision agriculture (PA), smart city, asset tracking, health care, and many more [6, 7]. Most of these applications require long-range communications with characteristics such as low data rate, low deployment cost, low power consumption, and security management [8–11]. Thus, short range radio technologies are not very suitable for wide coverage applications. A wide range of data acquisition objects already participate in a broad spectrum of applications that significantly consider long-range communication with low power consumption to extend network life without human intervention [11]. Thus, these growing needs have led to the emergence of Low Power Wide Area Networks (LPWANs). LPWAN is a type of wireless communication that is positioned as a connectivity facilitator for IoT applications or for cellular networks. Indeed, cellular solutions have the advantage of offering long connectivity but are energy intensive [11, 12]. LPWAN technology has experienced considerable growth because it has a set of interesting features among which we can mention scalable deployment, high energy efficiency, low management, and operating costs. Indeed, LPWAN technology makes it possible to build networks made up of thousands of objects with a long range (several kilometers) [13]. Figure 1 [11]

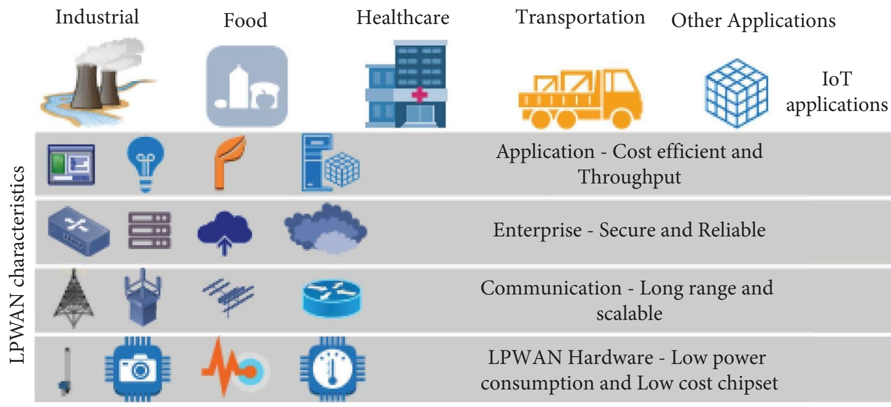

FIGURE 1: LPWAN characteristics make it an excellent choice for the IoT applications [11].

presents an architecture of LPWAN technology that facilitates the increase in the number of IoT applications. You can see a panoramic view of the functionalities at different layers as an added value for many applications. In the literature, there are several licensed and unlicensed LPWAN technologies, and among them, the most used solutions are LoRaWAN, Sigfox, and NB-IoT [11, 14].

LoRaWAN is an LPWAN-based communication solution that was designed to take advantage of a long-range, low-cost, and low-power hub-and-spoke network [15]. A LoRaWAN network consists of three essential components as follows: the terminals, the gateway, and then a link to the server, as shown in Figure 2. In addition, security (end-to-end encryption in the various communications) is an important element taken into account in LoRaWAN solutions. Such a LoRaWAN network consists of objects equipped with sensors or actuators that use the LoRa physical layer to exchange messages with the [16] gateway.

Remote health care and remote patient monitoring are concepts that have captured the attention of researchers in recent years [7]. Indeed, a smart home equipped with several objects capable of remotely monitoring one or more patients appears to be an interesting solution nowadays. Specifically, such technology can be an alternative for monitoring disabled people, quarantined people, and people with chronic illnesses. IoT provides an environment of objects connected to cloud-based applications and services, with different co-operation mechanisms, appropriate standardization, and advanced sensors with low-cost and low-power microprocessors [17, 18]. According to Figure 3, LoRaWAN is considered as one of the best IoT solutions based on the healthcare monitoring system due to its wide communication range and perfect interoperability between IoT sensors.

In this work, we have explained a multihop communication protocol over a large-scale area with LoRa devices while ensuring a deterministic and intelligent choice of the gateway which must redirect the information submitted by a device to guarantee, for example, a real-time information treatment by the server while minimizing the amount of energy.

This protocol takes place in two phases. A first phase consists of subdividing the networks into different layers and a second phase during which each device chooses the relay gateway for uplink communications.

We proposed a layered multihop clustering method for structuring large-scale networks. For this purpose, we supposed that the communications between two-end devices are reliable. The proposed algorithm tries to minimize the energy consumption spent during the formation of the layers. We obtained an acceptable packet delivery rate, and the number of messages sent is very low. Moreover, the proposed protocol is energy efficient extending by the way of IoT device battery life time, and it has a linear time complexity which is an asset for real-time IoT applications.

The rest of this paper is organized as follows: Section 2 presents a state of the art on some LoRa protocols, a mathematical formulation of the problem is presented in Section 3, our approach is presented in Section 4, the results of the experiments are presented in Section 5, and finally, the conclusion and some future works are presented in Section 6.

2. Review of the Literature

2.1. LoRa and LoRaWAN. Long Range (LoRa) is Semtech's spread spectrum modulation technique, a proprietary communication standard that enables long range, single-hop communications. With LoRa technology, it is possible to decode transmissions of up to 19.5 dB on a noise floor [21–23]. This technique allows the reception of a multiple number of messages on channels, an orthogonal separation between the signals. This offers an advantage in the management of the flow.

A characteristic of LoRa is that it offers an improvement of criteria such as SF (spreading factor), TP (transmission power), CR (coding rate), and BW (bandwidth) with a relation given by equation (1) [23–25].

$$R_b = \text{SF} \times \frac{\text{BW}}{2^{SF}} \times \text{CR}. \quad (1)$$

This technology is based on the ISM (industrial, scientific, and medical) bands, whose distribution of frequencies and regulations vary according to the region of the world. The two frequencies mainly used are 868 MHz in Europe and 915 MHz in North America. This physical layer relies on an alternative Spread Spectrum Modulation (SSM) called Chirp Spread Spectrum (CSS) which spreads the base signal over

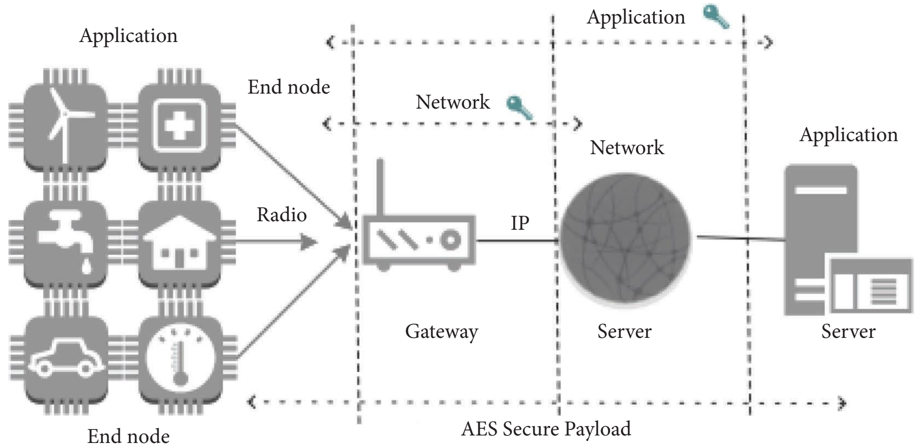

Figure 2: LoRaWAN network architecture [11].

Network topologies	Topology	Radio frequency	Range	Data rate	Energy Consomption
BLE	Ad hoc	2.4 GHz	10 m	1-2 Mb/s	Very Low
ZibBee	Mesh	868.3 MHz, 2.4 GHz	100 m	0.02-0.25 Mb/s	low
WIFI	Star	2.4 GHz	Less than 1 km	11 Mb/s - 10 Gb/s	High
SigFox	Star	Between 862 and 928 MHz	10 Km	100-600 b/s	Medium
LoraWan	Star or peer to peer	Between 860 and 1020 MHz	Less than 30 Km	Up to 50 Kb/s	Very Low

Figure 3: Comparison between different specifications of network technology [13, 19, 20].

a given frequency domain and increases mean bandwidth with the aim of increasing resistance to interference, reducing energy consumption, and integrating an error-correcting code. This type of modulation, widely used for radar applications in the past, is now necessary for low-speed communications. During a transmission, the spreading factor is adjustable and imposes a preliminary search to optimize the value according to various criteria. Indeed, starting from a fixed pass-band, a high SF directly implies an increase in the range and in the transmission delay T_s of a symbol expressed in seconds. The latter can be calculated using Formula (2). On the other hand, still in the case of a high SF, the communicating system sees its bit rate decreasing but has better reception sensitivity. Formula (1) presents the relationship between the final flow rate and the spreading factor [26].

$$T_s = \frac{2^{SF}}{\mathrm{BW}}. \tag{2}$$

In LoRa, there are several types of equipment among which we can mention the following: terminals, gateways, servers, application servers, and Join Server; a layout of a LoRa architecture is given by Figure 4.

LoRaWAN is a robust solution competing with other LPWANs by taking up the strengths of LoRa technology while having a strong influence on battery life, network load capacity, quality of service, and security. The LoRaWAN network is organized according to a star of stars topology. The communication proposed in this network is bi-directional while clearly favoring uplink transmissions towards the concentrators [15]. This organization, illustrated in Figure 4, is in fact composed of a multitude of concentrators which relay the information received from the nodes to a central server using a GSM or Ethernet protocol most of the time. The central server makes it possible to eliminate duplicates received by the various concentrators and manages the flow rates of the nodes in order to optimize the

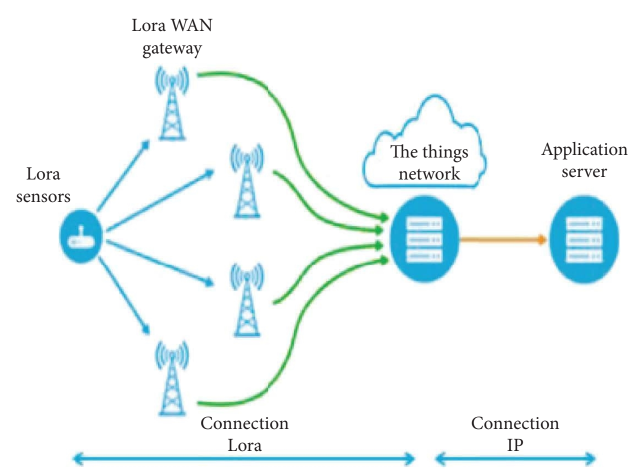

Figure 4: LoRaWAN technology [27].

capacity of the network and to extend the autonomy of the wireless devices.

2.2. Multihop Communications in LoRa Networks. In [22], the authors propose an algorithm which addresses three main criteria which are load balance in the network, reduction of the number of hops between the root, and a terminal and connectivity problem, using a faster throughput (higher SF) for connections for insertion of each node away from the root with the Topdown Breadth First-Search (TBFS) algorithm. This protocol uses long range communications for subtree formations, which requires a higher spreading factor and therefore additional energy consumption.

In [24], the author proposes new multihop clustering algorithm LoRaWAN networks. This approach is divided into two steps. The first one allows to form the layers, and the second one allows to choose the gateway for the communications to the root. For the layer formation, the protocol modifies the initial structure by adding elements of layer identifications by the gateways. The process is managed by the root which sends a broadcast with a hop count of 0 for the identification of the first layer. The answers of the elements of this layer allow him to make another diffusion for the identification of the following layer by passing by layer 0. Layer 1 sends an answer, and the process proceeds thus until obtaining all the layers. The selection is made from the RSSI of each gateway except for this one at a layer lower than a node. It has been compared to the method proposed in [28]. It also proposes an approach of multihop communication in LoRa and has LoRaWAN. This method thus allows a good communication between terminals over a long distance. However, the layer formation mechanism is very tedious when the number of layers is very high and would consume a lot of time and energy.

In [29], a protocol that maintains connectivity and coverage with the network using multihop communications is proposed. Evaluations are made on parameters such as the spreading factor and the packet reception rate. This protocol shows how in a smart city, the use of LoRa technology with multihop communications can save energy, ensure network coverage, and good connectivity. However, the use of the spread spectrum factor is still very high. This increases the energy consumption of the nodes.

In [30], it is proposed to use a simple relay device to increase the LoRaWAN coverage area for rural areas. The authors suggested deploying relay nodes by knowing the locations that are not covered by the gateway. The authors proposed a simple message forwarder and a synchronization mechanism. They showed that the energy consumption decreases with the addition of the relay node to deliver the packets. This method saves energy by minimizing retransmissions and increases the network connectivity rate. However, this protocol is only valid for a maximum of 2 hops. This does not allow for scalability.

In [31], the authors propose a transmission protocol (concurrent transmission) which proceeds by flooding the network for the design of multihop communications. The transmission of packets is done by transmitting identical packets in a synchronous manner, which increases the efficiency of the network by solving the problem of packet collisions. Although this protocol improves the efficiency of the multihop network and is robust against collisions, it results in a huge energy consumption due to the numerous identical messages broadcasted through the network.

3. Problem Formulation

We consider $\{gw_1, gw_2, \ldots, gw_g\}$ the set of gateways in the network, $\mathrm{DV} = \{dv_1, dv_2, \ldots, dv_d\}$ the set of LoRa terminals in the network that need to be dispersed in layers, and $C = \{c_1, c_2, \ldots, c_c\}$ the set of formed layers in the network. We seek to improve the operation of large-scale LPWANs by considering the multiobjective problem (energy-efficient formation of layers and intelligent selection of the best gateway). The selection of the best gateway is given by

$$dv_i = \left\{ g_j \in E_i | j = \arg\min_k \left(f\left(g_k, dv_i\right)\right)\right\}, \tag{3}$$

où.

(1) dv_i is the set of gateways determined as follows:

$$dv_i \| E_i \| = \sum_{i=1}^{i=g} Li,$$
$$L = \begin{cases} 1, & si\ d\left(dv_i\ g_k\right) \leq R\, \forall k \in \{1, 2, \ldots, g\}, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

(2) f is the objective function of each terminal in relation to a gateway.

This problem is formulated subject to the constraints as follows:

(1) Let $\text{alpha}_{i,j}$ be a binary value which indicates the admission of the device dv_i to the gateway g_j.

(2) $\sum_{k \in dv} \alpha_{k,j} = 1$.

(3) $\forall i, j \in GW,\ g_i \cap g_j = \varnothing$.

4. Multihop Uplink Communication Approach

In this section, we present an efficient approach to multiobjective routing in a LoRa network based on layer clustering. This approach is divided into two steps. The first one is to form layers, and the second one is to select the best gateway for routing data to the root.

4.1. Assumptions

(1) The nodes are randomly deployed on a square surface

(2) The transmission radio is the same for each equipment

(3) The gateways are deployed in a deterministic way to ensure the coverage of the deployment area

```
layer_id = ∞;
if id = = 0 then
   CREATE_DIS_MESSAGE (1, 0, 0, 0);
   BROADCAST (DIS);
end if
if DIS message then
   if DIS. L_ID ¡ layer_idthen
      gtwlayer_id = DIS.L_ID
      CREATE_DIA_MESSAGE (M_ID + 1, gtwlayer_id + 1, H_CNT + 1, ID);
      UNICAST (DIA);
      CREATE_DIS_MESSAGE (M_ID, gtwlayer_id, ID);
      BROADCAST (DIS);
      EXPIRER (timer);
      WAIT_UNTIL (timer);
      if EXPIRER (timer) then
         if Not DIA reception then
            CREATE_DIN_MESSAGE (id, layer_id, g);
            UNICAST (DIN)
         end if
      end if
   end if
end if
if DIN message then
   CREATE_DIN_MESSAGE (ID, gtwlayer_id, layer_id);
   UNICAST (DIN);
end if
```

Algorithm 1: Formation of the network layers.

4.2. Layer Formation. Each gateway has the following parameters for layer formation:

(1) id represents the identifier of the gateway
(2) layer_id is the layer number to which the gateway belongs
(3) *gwt* contains the id of its gateway to reach the root gateway

We define three types of messages for layer formation. A DIL (Discover Information Layer) and DIA (Discover Information Acceptance) which contain the fields L_{ID} for the layer number, H_{NT} is the number of hops from the root gateway, T_{NID} is the identifier of the node transmitting a DIA or DIL message, and finally, a gatewaylayer_id contains the identifier of the relaying gateway towards the root. A DIN (Direct Information Notification) message contains the fields ID for the identifier of the transmitting gateway, gatewaylayer_id contains the identifier of the relay gateway to the root, and layer contains the number of layers of the formed network.

The root gateway initiates the broadcast of a DIA message with the LID field set to 0 to indicate the start of the layering process. As soon as a DIS message is received, each gateway initiates a DIA message to indicate that the message has been received and initiates a DIS message again, this time with the LID number incremented by 1 and the hop number set to 1. It then sets a timer t and waits until the end of this time. If it has received another DIL message, it generates a DIL message and transmits it to its relay gateway.

Otherwise, it generates a DIL message and forwards it to its relay gateway and thus considers itself as the leaf node of the layered tree. The process repeats itself until layer $n-1$ receives DILs from layer n, transmits DILs to layer $n-2$, and so on until the DILs are distributed to the root. This will allow the root gateway to know the number of layers formed in the network. Algorithm 1 is executed by all the gateways for the formation of the network layers.

An illustration of this approach is presented in Figure 5. The root gateway in the center of the figure (purple color) illustrates the formation of the layers. The other gateways in green, red, and blue colors are Layer 1, Layer 2, and Layer 3 gateways, respectively.

4.3. Gateway Selection. This step consists of intelligently choosing a gateway in its layer to be able to route information to the root gateway. Once the layer formation is complete, each gateway will issue a broadcast message to tell each device which gateways in its layer, the upper and/or perhaps lower layer, where it can access. Each node will calculate its objective function to determine which gateway should be chosen to minimize energy consumption costs. Algorithm 2 is executed by all the end devices for the selected gateway.

$$f = w_1 \times \text{RSSI} + w_2 \times SF + w_3 \times \text{Layer\_id}, \quad (5)$$

where RSSI (Received Signal Strength Indication) is the received signal strength, SF (spreading factor) and Layer_id is the layer number of the gateway, and $w_1 + w_2 + w_3 = 1$.

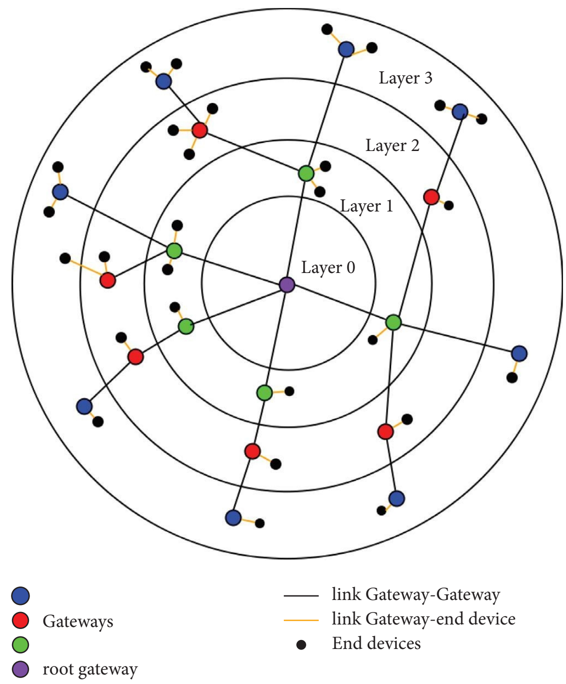

Figure 5: Example of layer formation.

$\forall$ node n in network;
  $\forall$ receive g_i Broadcast;
    Compute f_i for Gateway g_i with formula $w_1 \times \text{RSSI} + w_2 \times SF + w_3 \times \text{Layer\_id}$;
  Select max (f_i) and send it unicast_message;

Algorithm 2: Selection of gateway.

For each gateway message received, the device evaluates the objective function f. It will therefore choose among the gateways in its layer, the gateway with the largest value of f.

5. Results

The simulation is conducted on an i5 series processor with 4 GB of RAM using LoRaSim. LoRaSim is a discrete-event simulator based on SimPy for simulating collisions in LoRa networks and to analyse scalability. Their simulator and the model energy are described in [32].

The simulation parameters are listed in Figure 6.

Parameters	Value
Frequency	500 KHz
Initial Energy	5j
Bandwidth	125 KHz
Data Rate	250 bps
Spreading Factor	7
Coding Rate	4/5
Number of LoRaWAN Nodes	30-120
Number of Gateway	20-40
Number of Layers	1-20

Figure 6: Simulation parameters.

Figure 7 shows a comparison of the energy consumed by the RPL, Farooq, and LoRaWan protocols. We can observe that our protocol outperforms those of the others by consuming 50%, 70%, and 80% less than the Farooq protocols [24, 28] and LoRaWan.

We also bring an improvement in the packet delivery rate of 2% compared to [24] in Figure 8.

Figure 9 shows the number of messages sent for the layer formation process in the network. We see that compared to the Farooq protocol, the number of messages sent remains constant regardless of the number of layers formed in the network. This proves that the root gateway sends the same number of messages for the formation of the layers whatever the size of the network. So, it also proves that this protocol is suitable for large-scale networks.

Figure 10 shows the number of messages sent for the layer formation process in the network. We see that compared to the Farooq protocol, the number of messages sent remains constant regardless of the number of layers formed in the network. This proves that the intermediate gateways send the same number of messages for the formation of the layers whatever the size of the network. Therefore, the

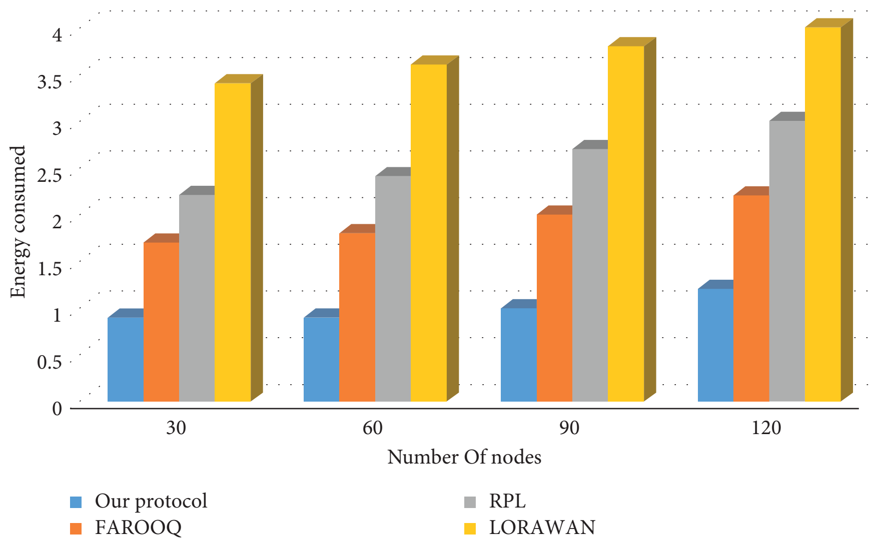

Figure 7: The comparison of energy consumption.

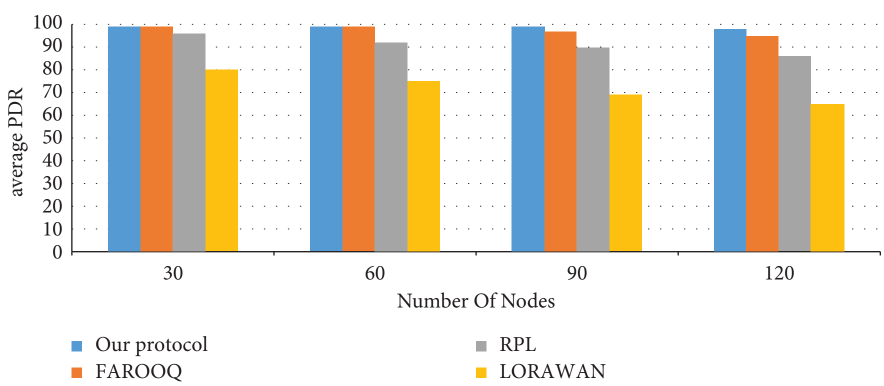

Figure 8: Mean packet delivery ratio (PDR).

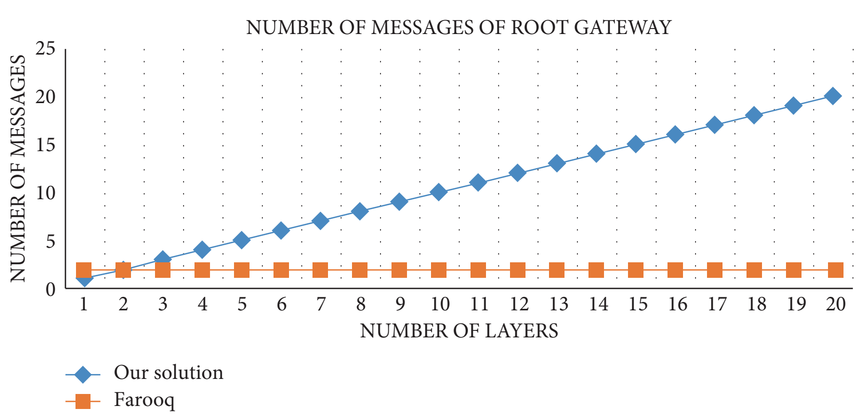

Figure 9: Number of messages sent by the root gateway.

scalability of the network has no impact on the messages sent by the intermediate gateways.

The protocol in the literature review sends too many messages in the case of the root gateway as well as in the case of the intermediate gateways, which indicates without a doubt that the energy consumption of this protocol is extremely high for the formation of layers in the network.

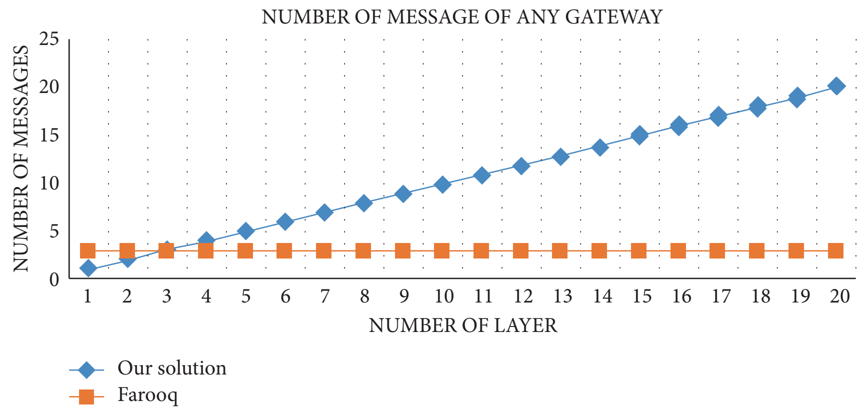

FIGURE 10: Number of messages sent by intermediate gateways.

6. Conclusion

In this article, we have proposed a low power system with LoRa technology. This system can be used to monitor the physiological parameters of a patient to determine his medical situation, in order to anticipate the aggravation of pathologies for patients and to reduce the time of hospitalization and cost, especially with the spread of the Covid pandemic. Our results showed very good efficiency in terms of system life, with autonomy gains multiplied by 2. Work is underway to improve the study surface.

Data Availability

No underlying data was collected or produced in this study.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent

Informed consent was obtained from all individual participants included in the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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