

Evaluation of A Mesh Network based on LoRa Technology

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Abstract—In the last decade, the Internet of Things (IoT) technologies have brought many applications in different fields. Many communication technologies have been developed to communicate everything to each other and the Internet. Besides, the long-range power-efficient wireless technologies have emerged, such as LoRa (Long Range), which enables transmission over long distances with low energy consumption and can work within p2p, star, or mesh topologies. In this paper, we analyze a model of a mesh network based on the LoRa technology. The model considers various parameters of nodes and communication channels in the network. Based on a simulation model on OMNET++, a series of computer experiments are performed to analyze the delivery latency and packet delivery ratio (PDR) in different cases. According to the analytical results, conclusions are drawn about the possibility of using a LoRa mesh network to expand the network coverage and integrate with other short-range networks.

Keyword—IoT, LoRa, mesh network, routing method, latency, packet delivery ratio

I. INTRODUCTION

NOWADAYS, info-telecommunication technology is one of the main infrastructures of any country or company. The advent of the Internet has helped change the approach to

information. The Internet brings information to users, communicates people to the other, human to machine, and machine to machine. This term is called the Internet of Things (IoT), where every device can communicate over the Internet, as described in [1], [2]. This leads to the expectation of the revolution of Industry 4.0.

The Internet of Things has been attracting many interests in both scientific and commercial fields [3]. Many IoT applications have been developed as Smart Devices, Smart Home, Smart City, Smart Factory. Besides, communication technologies also have contributed greatly to the development of IoT applications. Many technologies have been proposed to ensure the network's quality of connection while the number of connected devices does not stop increasing. Each technology has different characteristics such as data rate, transmission distance, power consumption. Based on those technologies, network models are considered for different requirements. Low Power Wide Area Network (LPWAN) is a networking group, which allows long-range transmission and requires small power consumption [4]. Among LPWANs, LoRa (Long Range) is a promising technology for IoT applications, which do not need high-speed data rate and require energy saving with long-range transmission [5], [6].

Using LoRa as the physical layer, the project LoRaWAN (Long Range Wide Area Network) has been developed widely with a large contribution by LoRa Alliance. In the LoRaWAN, the devices are managed by Gateway or Base Station. In this case, the star topology is used for constructing LoRa Networks. On the other hand, the mesh topology also is considered in different cases. In Wireless Sensor Networks (WSN), for instance, ZigBee, Z-Wave, Bluetooth Low Energy 5.0, devices are connected in the mesh topology, each device can be a router relaying the packet of the other devices to the destination [7], [8]. The highlight difference of LoRa respected to these technologies is the ability of long-range transmission. This advantage can help expand the network model without needing additional base stations.

Smart City is a typical IoT application, where many devices in the city are expected to communicate with each other and send data to the cloud server. For instance, a bus can inform the bus station directly about the destination time. The buses and bus stations communicate in the network and exchange information with each other. The decentralized or mesh topology is applied to manage such applications.

Moreover, the mesh topology also is used in networks such as VANET or FANET. In a search and rescue application, as

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can be seen in [9], [10], the UAVs (unmanned aerial vehicles) are connected to others in a mesh topology. So, the data are transmitted through several UAVs to the destination.

The mesh topology for the LoRa network is a solution to expand the number of connected nodes and the network coverage area. We propose a LoRa-based network model using the mesh topology for these goals in this paper. In this topology, the routing option is an important parameter to ensure the quality of service. While considering the network model, the optimal route selection is found between the nodes based on the link quality. Moreover, we consider the delivery latency in the influence of the load intensity and the number of relay nodes.

The rest of the paper is organized as follows: Section 2 gives an overview of LoRa technology and its related works. Section 3 presents a mesh network model based on LoRa technology and a simulation model to analyze the latency distribution and packet delivery ratio in the network. Obtained analytical results are presented in Section 4. And the conclusion is concluded in Section 5.

II. LoRa OVERVIEW

Semtech Corporation is one of the leaders developing wireless chipsets for IoT applications. Since when the company launched the first LoRa chipset, the LoRa technology has been attracting much interest in the development of IoT applications. In 2015, LoRa Alliance was established to develop and support the global network LoRaWAN. It is observed that LoRa has become a promising technology at the moment.

The key parameters used to configure the LoRa radio module are modulation method, frequency range, bandwidth (BW), spreading factor (SF), coding rate (CR), and transmission power [5], [6]. At the LoRa physical layer, a chirp spread spectrum (CSS) modulation method is used, providing an increased channel budget and better noise immunity. In the LoRa network, there are some options to choose the used bandwidth, such as 125, 250, and 500 kHz. The low bandwidths make LoRa resistant to channel noise, long-term relative frequency, Doppler effects, and fading.

Coding rate (CR). A forward error correction technique is used to increase reception sensitivity. The coding rate is denoted as k/n , where k represents useful information, the encoder generates n output bits, i.e. $n-k$ will be redundant bits. Redundancy allows the receiver to detect and correct errors in messages, as well as reduces data rate. There are coding rates such as 4/5, 4/6, 4/7, or 4/8 used in the LoRa network.

Spreading factor (SF). In the LoRa technology there are several spreading factors from 7 to 12 used to expand the transmitted bits. The SF parameter defines two values: the number of source bits that can be encoded for one symbol, and each symbol can contain 2^{SF} chips. With a higher spreading factor, the data rate is lower, and vice versa. Each symbol is spreading in the length of 2^{SF} chips, i.e. 2^{SF} chips are required to expand one symbol. The method of replacing one symbol with several elements of information shows the influence of the spreading factor on the transmission speed. Therefore, if the value of SF increases, then the data rate decreases.

Bandwidth (BW). There are different values such as 125, 250, or 500 kHz used to configure LoRa radio models. Data are propagated at a chip frequency equal to the throughput in chips per second. Hence, 125 kHz corresponds to a chip speed of 125 kilo-chips per second.

The combination of between SF, BW, and CR determines the data rate as (1):

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

$$\text{where } \begin{cases} SF = \{7, 8, 9, 10\}; \\ BW = \{125, 250, 500\}, \text{ kHz}; \\ CR = \{4/5, 4/6, 4/7, 4/8\}. \end{cases}$$

The high BW increases the DR, but it decreases the decoding sensitivity. The high SF increases the decoding sensitivity but decreases the DR. Therefore, with the low BW, and high SF, the decoding sensitivity and transmission distance are increased, but the DR will be decreased. Depending on the application requirements, this combination of parameters can be configured.

Studies on LoRa technology get much attention from the physical layer to the application deployment. In recent years, research and development based on LoRa have gained many prospects. In the context of Smart Cities, there are several LoRa-based applications, such as for waste management [11], water quality monitoring [12], or street lighting.

Since LoRa has high sensitivity, tracking, or positioning solutions were proposed in [13], [14]. It can be seen that the applicability of LoRa is used for many IoT applications. It is relevant to discover the other possibility of LoRa technology. Almost LoRa-based applications are deployed in cases required to transmit on long-distance and save energy consumption. According to different requirements, the parameters can be set up in the LoRa network.

Thus, to use the LoRa's advantages, a mesh topology model is analyzed for LoRa networks in the next sections.

III. ANALYTICAL MODEL

A. Network Model

In a mesh topology model, a network can be presented as a connected graph. For instance, as shown in Figure 1, the network includes device nodes and gateways connected in a graph. The device node can be either the end-device or relay node, via which the data are relayed. The data received by the relay node will be forwarded to the next node according to the optimal route to the destination.

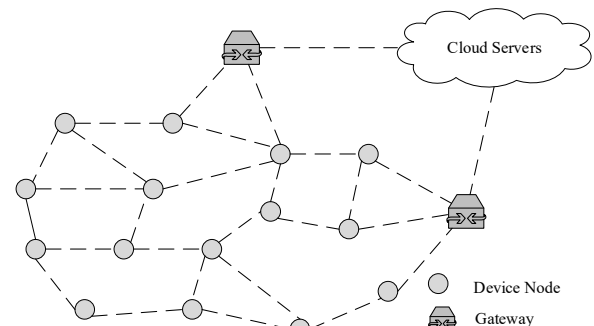


Figure 1. Network model

As shown in Figure 1, the mesh network model can be described by a Graph $G(V, E)$ with a set of Vertices – V , and a set of Edges – E . The set of vertices $V = \{v_i\}, i = 1 \dots n$, which represents the set of device nodes in the network. The set of edges $E = \{e_{ij}\}, j = 1 \dots n$, which represents the set of communication links between the nodes in the network. Each node has a maximum communication radius R ; the nodes can communicate with the others within this distance. If the coordinates of a node are described as (x_i, y_i) , the distance between 2 nodes i and j follows as:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (2)$$

Hence, there is a communication link between 2 nodes if the distance between them is less than R . It can be illustrated by the following: if $d_{ij} \leq R$; $\exists e_{ij}$ and $E = \{e_{ij}\}$ with $i, j = 1 \dots n$.

Each edge between vertices is weighted by a set of link costs $C = \{c_{ij}\}$ with $i, j = 1 \dots n$, which represents the possibility of data transmission between two nodes. A low link cost means that this link is more suitable to exchange information.

B. Route selection

In this case, the routing path is calculated to find the optimal route to the destination. The link cost is denoted by the parameter RSSI (Received Signal Strength Indication), which can be considered the signal strength between the transmitter and receiver. The link cost is represented as a dependent function of RSSI:

$$c_{ij} = f(RSSI_{ij}), |RSSI_{ij}| \leq \text{threshold and } i, j = 1 \dots n$$

The matrix $C = \{c_{ij}\}$ with $i, j = 1 \dots n, s$ contains the characteristics of all communication links of the network (weights of edges of the graph).

$$C = \begin{bmatrix} c_{1,1} & c_{1,2} & \dots & c_{1,n} & c_{1,s} \\ c_{2,1} & c_{2,2} & \dots & c_{2,n} & c_{2,s} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ c_{n,1} & c_{n,2} & \dots & c_{n,n} & c_{n,s} \end{bmatrix}$$

There is a set of possible paths $\Omega = P_{i,s} = \{P_1, P_2, \dots, P_k\}$ between a node i and a sink node in graph G .

Thus, the total link cost of the path from node i to the sink node – s (gateway) is defined as follows:

$$w_{i,s} = \sum_{j=1}^{|P_{i,s}|-1} c_{i,j+1} \quad (3)$$

The optimal route from node i to the sink node is computed as:

$$\text{Route}_{i,s} = \arg \min_{P_{i,s} \in \Omega} (w_{i,s}) \quad (4)$$

C. Queueing system

In the network, each node perceives and transmits data to the other. There are incoming packets and outgoing packets through the nodes. To evaluate the performance of this topology, we can assume that each node in the network is

represented as a queueing system, which serves the incoming and outgoing requests, as shown in Figure 2.

In Figure 2, the incoming traffic is denoted by mean arrival intensity – λ_i and is served by the node i with a mean service intensity – μ_i . There is an intensity of loading the system that is calculated by $\rho_i = \frac{\lambda_i}{\mu_i} (Erl)$. The load factor influences

serving time in the system, i.e. the delivery time will be influenced. By considering the queueing system, the network performance is evaluated to see the usage possibility in application deployment.

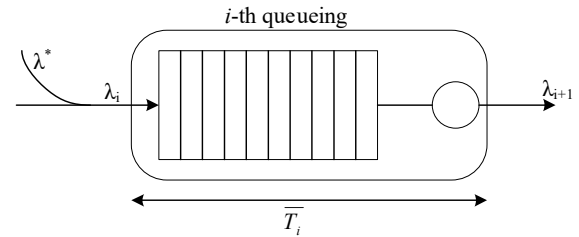


Fig. 2. A node is represented as a queueing system

When considering the M/M/1 model for each node, we will use the formula to calculate the time of the application in the system [15]:

$$T_i = \frac{t_i}{1 - \rho_i} \quad (5)$$

where T_i is the mean delivery time to the node i , and t_i is the mean duration of service request.

As described above, the transmission time of a LoRa data frame on-air depends on several parameters. This time on-air can be considered as the average time t_i . The calculation of the time on-air is described in [6].

The number of relay nodes is denoted by m . Hence, the total delivery latency of a data frame through m nodes to the target node is computed as:

$$T = \sum_{i=1}^{m+1} T_i = \sum_{i=1}^{m+1} \frac{t_i}{1 - \rho_i} \quad (6)$$

D. Propagation model

In the LoRa network, radio configuration parameters such as operating frequency, SF, BW, CR, and transmission power influence the communication range and reception accuracy. If the received signal power is greater than the receiver sensitivity, we can say that the transmission was successful. Transmission power decreases as it propagates over the air to the recipient. Thus, the received power depends on the transmission power and losses due to signal attenuation. As know well in wireless communication, a log-distance propagation model has been used in indoor and outdoor environments. Pathloss varies with logarithmic distance according to the following equation:

$$PL(d) = PL(d_0) + 10\gamma \log_{10}(d/d_0) + X_\sigma, \quad (7)$$

where $PL(d_0)$ is the average path-loss at a reference distance d_0 ; γ is the path-loss exponent; d is the distance between the receiver and the transmitter; X_σ is a random value in the Gaussian distribution with zero mean and standard deviation σ .

While considering the application of LoRa technology in the urban environment and dense urban development, which are the main obstacle to signal propagation. Based on research in [16], the parameters of path-loss propagation are set for the simulation model in the urban environment with $d_0 = 40$, $PL(d_0) = 127.51$, $\gamma = 2.08$, and $\sigma = 3.57$.

E. Simulation Model

The OMNET++ and inet frameworks are used to model the network [17], [18]. They are known well to be used in numerous domains for simulating wired and wireless networks. Based on these frameworks, we have developed a module of the LoRa node. Since the OMNET++ library and frameworks are designed based on modular and component-oriented principles, the LoRa node can be integrated with the build-in modules from the inet framework.

A LoRa node consists of modules modeling radio and upper-layer protocols. In the LoRa radio module, we can configure radio parameters corresponding to our hardware model. The other parameters, such as the spreading factor and coding rate, are configured for the LoRa node in addition to the usual configurations. In this case, the radio parameters taken from the datasheet of the SX127x LoRa chipset [5] are used for the simulation model.

Moreover, in the LoRa medium module, the path-loss propagation model is chosen in considering data transmission in the urban environment, as mentioned above. In this work, the propagation model parameters have been received from a series of measurements presented in [16]. The measurements in [16] correspond to the build-up urban environment, where devices are partially deployed indoors.

A sink node (gateway) is located at the center of the network. The locations of end nodes are randomly generated in the range of field simulation size.

The payload length is generated randomly from the end nodes in the interval from 20 bytes to 150 bytes.

According to the exponential distribution, the sent intervals between messages are random values with a mean equal to 120 seconds.

In each experiment, we analyze the delivery latency and packet delivery ratio to the sink node. The obtained results are presented in the next section.

The simulation parameters and values are shown presented in Table 1.

TABLE I
SIMULATION PARAMETER

Parameter	Value
Frequency, MHz	868
Bandwidth, kHz	{125, 250}
Spreading factor	{7, 8, 9, 10}
Coding rate	4/5
Transmission power, dBm	14
Antenna, dBi	5
Payload length, B	Random (20, 150)
Sent interval, s	Exponential(120s)
Number of nodes	{10, 20, 40, 100}
Field size, m ²	2000 x 2000
Simulation time, s	20000

IV. ANALYTICAL RESULTS

A. Delivery latency

Each device node is considered as a queueing system. Hence, the delivery latency in a communication link between two neighbor nodes is calculated according to the formula (5). Moreover, the delay time for transferring a payload size of 80 bytes is calculated when changing the load intensity. The calculation results are shown in Figure 3 with configuration parameters $SF = \{7, 8, 9, 10\}$ and $BW = \{125, 250\}$ kHz.

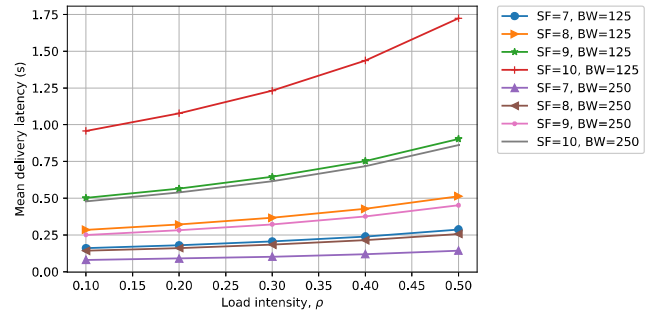


Fig. 3. Influence of load intensity on the delivery latency

As shown in Figure 3, the data transmission time increases when increasing the load intensity. It can be seen that a low spreading factor and a wide bandwidth provide low delivery latency. In the case of using $SF = 10$ and $BW = 125$ kHz, the delay time increases significantly up to 2 seconds. Hence the transmission latency via the relay nodes with such radio modules parameters will also be high and can increase up to tens of seconds as shown in Figure 4, where packets are transmitted via several relay nodes to the sink node.

In the mesh topology model, the node receives and relays the packets to the next destination. Therefore, the number of relay nodes that packet passes influences the delivery latency to the destination. With the load factor equal to 0.4 and the payload size of 80 bytes, as shown in Figure 4, the delivery latency increases linearly with the number of relay nodes.

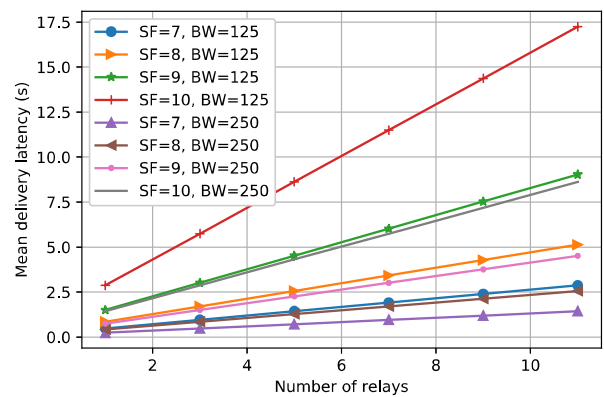


Fig. 4. Influence of the number of relay nodes on the delivery latency

According to Figure 4, when using a bandwidth of 125 kHz and spreading factors $SF = \{9, 10\}$, the transmission delay increases to tens of seconds while packets are relayed via 10 nodes. Depending on the requirements of IoT applications, the parameters SF and BW can be selected accordingly. On the other hand, using a wider bandwidth ($BW = 250$ kHz) provides a short delivery latency through several relay nodes.

Moreover, we can see the differences in latency distributions in the networks using the narrow and wider bandwidth in Figure 5.

When considering the impact of the spreading factor in the network of 100 nodes, different distributions of delivery latency are collected from device nodes to the target node. Figure 5 shows the latency distributions in various $SF = \{7, 8, 9, 10\}$ and $BW = \{125, 250\}$ kHz configured for LoRa nodes. Data delivery time is longer with a high spreading factor and a narrow bandwidth. The SF parameter represents the number of encoded chips, so a high SF value requires a longer transmission time.

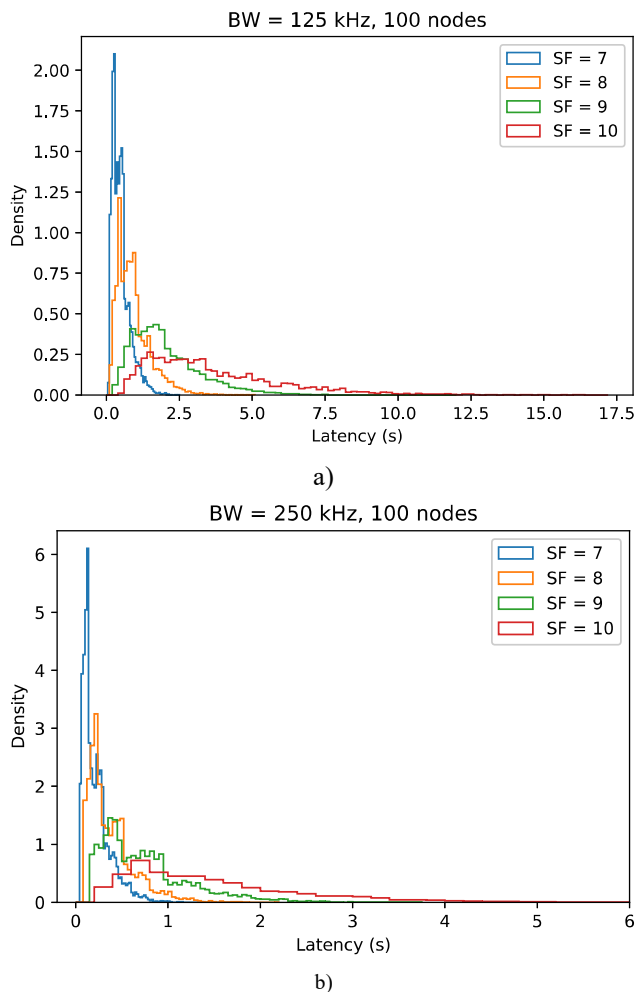


Fig. 5. Latency distribution in different SF and BW

Moreover, the latency is obtained in the networks having a different number of nodes. Figure 6 shows the latency distribution in the networks with 20 nodes and 100 nodes with the same configuration parameters. As more nodes in the network, there are more generated packets. In the relay nodes, received packets are waited in the queue to transmit to the next destination. Besides, the packets are relayed via several nodes to the sink node. The delay is high in the network of many nodes. Thus, we can use a Long-Range mesh network to connect other networks that cannot transmit data over a long distance. There may be 20 nodes in the mesh network. However, these nodes can communicate with each other and establish communication in a large area, where the short-range networks are used to collect data.

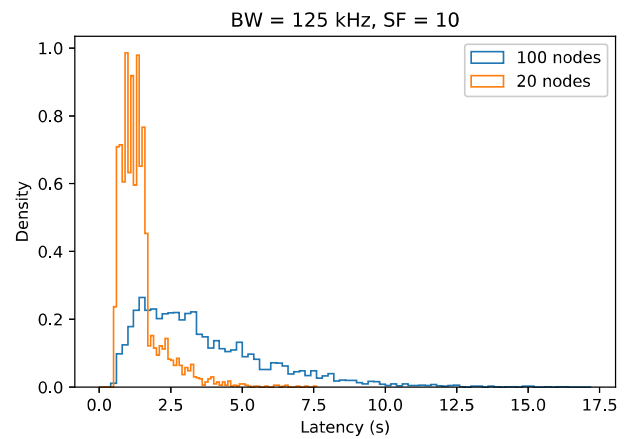


Fig. 6. Latency distribution in the network with different number of nodes

B. Packet delivery ratio

Considering the packet delivery ratio, the number of nodes in the network affects the packet delivery ratio. As shown in Figure 7, the results are received from experiments in the networks using $SF = 10$ and $BW = 250$ kHz. As the number of nodes increases in the network, the packets also are generated more. Hence, the latency of data transmission and packet loss may increase.

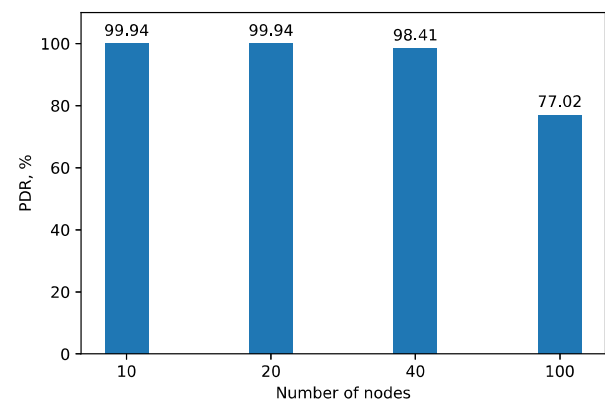


Fig. 7. Packet delivery ratio in the network with different number of nodes

V. CONCLUSION

Nowadays, LoRa technology is used in the communication part for many IoT applications. Taking the advantages of a LoRa mesh network, the network coverage area can be expanded without adding more base stations. The mesh network model based on LoRa technology was analyzed while considering the delivery latency and packet loss ratio with different configuration parameters.

Based on the analytical results, we can see the influence of configured parameters of the LoRa nodes on the latency distribution and the percentage of delivered packets to the destination node. Besides, the number of nodes in the network also affects the transmission latency and PDR. As using a high SF and a low BW, the transmission delay increases in the network, but it increases the reception sensitivity. Data transmission takes a long latency in the LoRa mesh network. However, it opens the ability to integrate with the other short-range networks in the mesh topology.

Thus, the mesh networks combined with LoRa technology

can bring more advantages in the application of the wireless sensor network in terms of increasing the coverage area and low power consumption.

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