The Network Architecture of Reefer Container IoT System Based on ZigBee and LoRa Joint Technology

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Abstract

Reefer containers are the main transportation method for the import and export of food and medicine. It is necessary to monitor the condition of the reefer containers in order to avoid affecting goods quality due to environmental variations. Monitoring the reefer containers which are used to transport fruits, vegetables, and dairy products are one of the examples. In this context appears the necessity to develop this work expressed by designing a network architecture based on LoRa and ZigBee Joint technology and a routing algorithm that guarantees a well-balanced distribution of the energy load among WSN end nodes. The routing algorithm has been simulated and the effectiveness of the algorithm is verified by simulation results.

Keywords

ZigBee, LoRa, Wireless sensor networks (WSNs), Container IoT system.

1. Introduction

Since the 1990s, the global economy has changed and developed rapidly. Economic globalization and trade liberalization have become the trend of world economic development. This trend has effectively promoted the development of the international cargo transportation industry, which has led to a rapid increase in the volume of goods transported around the world. As one of the main modes for international cargo transportation, container transportation has also shown a good development trend. Nowadays almost 90% of the world trade is accomplished with the help of containers and they can be used in different means of transportation, including ships and trains [1].

One of the research hot topics in container monitoring is to study the reefer container monitoring system. With the progress of various technologies, people have higher and higher requirements for the quality of container transportation. Environmental factors such as temperature variations and humidity variations may affect the quality of transported goods during transportation. Sometimes the limit of the temperature and humidity can be quite strict, for example, as soon as the storage temperature is beyond 0 °C, the strawberry has a risk growth of microbial. Thus, the reefer container should be used to maintain the quality of the food and medicine. At the same time, it is necessary to monitor the condition of the reefer container to ensure that the reefer container is working properly. For example, monitor the reefer containers which are used to transport fruits, vegetables, dairy products to ensure the quality of the goods. Therefore, it is necessary to design and implement a temperature, humidity, and location monitoring system for reefer containers [2].

2. Organization of the Text

2.1 Containers states in the container terminal

The Containers in the container terminal generally have only two states: transportation state or storage state. After the reefer container arrives at the container terminal, it will be transported to the container yard and stored according to the container stacking rules. In order to facilitate the transport of containers into and out of the yard, the large yard is divided into small blocks by roads [3], as shown in Fig. 1.

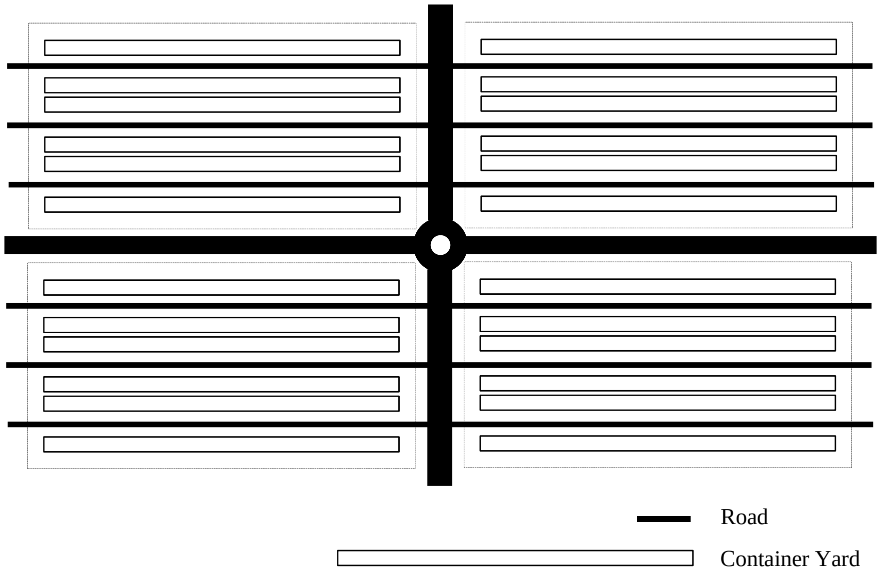


Fig. 1 The architecture of the container storage yard (top view)

In each storage block, the container is divided into multiple and orderly stacks. Generally, as shown in Fig. 2, each stack is composed of 30 containers, 6 containers are placed horizontally and 5 containers are placed vertically.

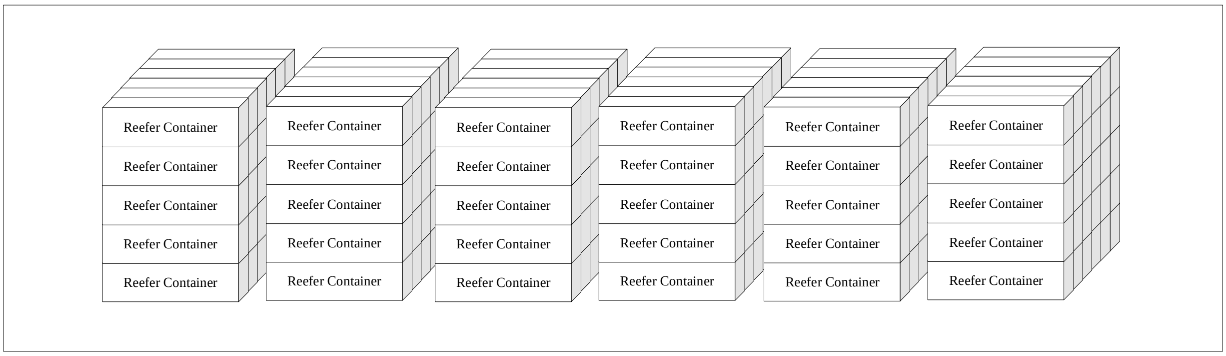


Fig. 2 The containers stored in the container yard

Data communication is mainly divided into two parts. In the first part, the end node acquires the data through the sensors and transmits them to the based station. Then, the based station transfers the data to the server and real-time displays it in on the web application.

2.2 The network Architecture

Because the reefer containers often store the items that are easily deteriorated by the temperature and humidity and have a high value. Thus, the first principle of designing the transmission architecture is to ensure that all of the reefer containers are under monitoring. Due to the high mobility of the reefer containers, it is very difficult to frequently replace batteries that support power to monitoring equipment. Therefore, the second design principle of the communication architecture is to minimize the energy consumption of the monitoring equipment under the condition that each reefer container can be monitored.

LoRa [4] and ZigBee [5] can meet the requirements of low power consumption. LoRa can transmit data within more than 5km in outdoors and is more suitable for large areas context, such as a container terminal. LoRa systems are also consuming less energy than ZigBee [6]. When the reefer containers are in the state of being transported in the container terminal, the most ideal transmission method is to directly transfer data to the LoRa gateway through LoRa. When the containers are in the storage yard, as shown in Fig. 3, the containers in the upper layer can transmit data to the LoRa gateway by using LoRa directly, but the containers in the lower layer will be blocked by other containers and cannot transmit data to the gateway through LoRa.

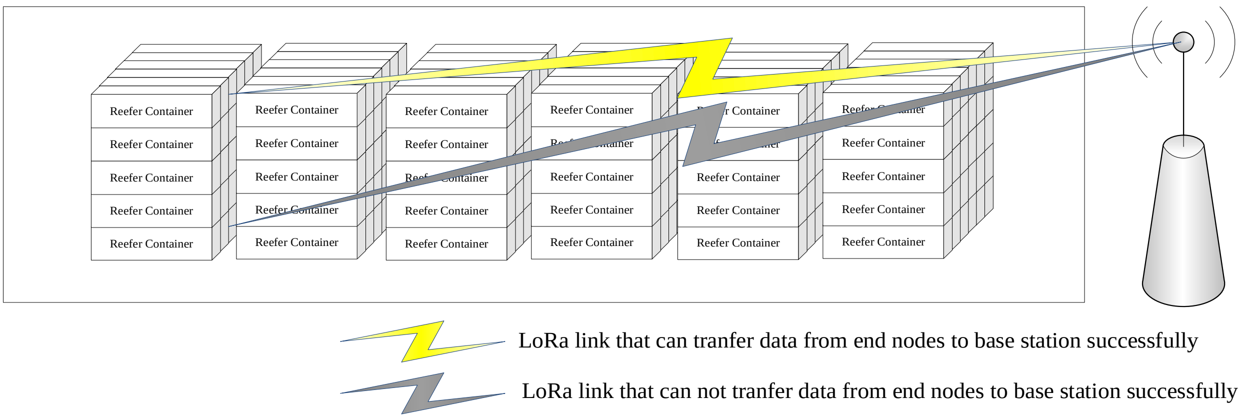


Fig. 3 The containers stored in the container yard

A Network architecture is proposed to solve the LoRa communication link which blocks by containers. Both LoRa and ZigBee communication modules are included in each monitoring terminal. When the WSN end node can use the LoRa module to transmit data to the LoRa gateway, the data is directly transmitted by using LoRa, and these devices are referred to as Advance Node (LoRa&ZigBee available). But some containers are in the lower layer of the storage yard and the WSN end node cannot directly use LoRa to transmit the data to the gateway, and these devices are referred to as Normal Node (only ZigBee available). As shown in Fig. 4, the Normal Node transfer the data to the Advance Node which is in the same ZigBee network (Some containers are undoubtedly on the upper layer, thus, in each ZigBee network there are undoubtedly have some nodes can communicate with the gateway). Those WSN end nodes that receive data from Normal Nodes and forward data to the gateway can be referred to as Cluster Head. After the Cluster Head receives the data packets from the Normal Node, it will aggregate the packets and forward it to the gateway.

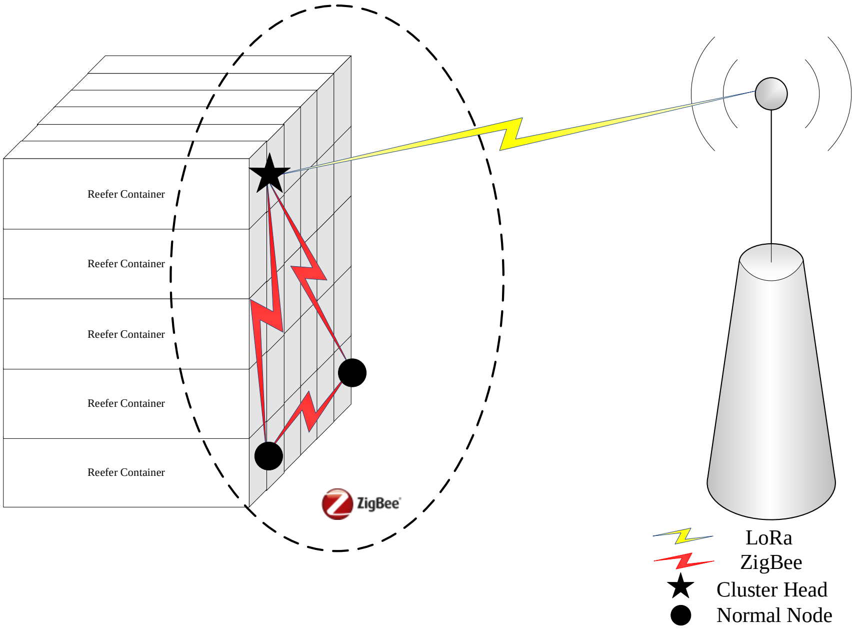


Fig. 4 The wireless communication architecture based on Lora and ZigBee protocols

3. Design of the routing algorithm

References According to the stacking principle of the port yard, we can know that each storage unit is composed of 30 containers, 6 containers are placed horizontally and 5 containers are placed vertically.

Therefore, a storage yard is composed of 30 containers, that is, a ZigBee network is also composed of 30 nodes. As shown in Fig. 5, according to the size of the reefer containers, 30 nodes are distributed in an area of 14628 mm in length and 12955 mm in width.

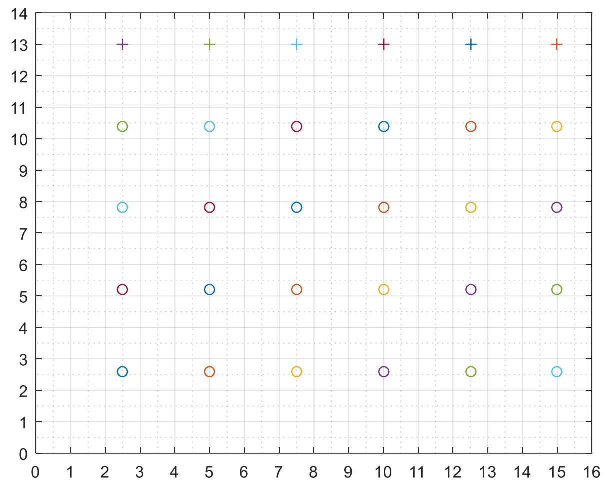


Fig. 5 The ZigBee network area for a storage unit

The 6 nodes in the upper of the area which can communicate with the LoRa gateway are Advance Nodes. The Advance Nodes has the possibility of becoming the Cluster Head, other nodes are Normal Nodes which can only transmit data to the Cluster Head.

Based on the proposed network architecture, an algorithm was designed which is suitable for this architecture. The algorithm is to calculate that in the ZigBee network, how many Advance Node (LoRa&ZigBee available) should become Cluster Head at the same time will extend the stability period (time interval before the death of the first sensor) of WSN. If the optimal number of Cluster Nodes is 2, in the ZigBee network there should be 2 Cluster Heads. Thus, the Normal Nodes should transfer data to the 2 Cluster Heads, and the Cluster Heads forward data from the Normal Nodes to LoRa gateway.

3.1 The optimal number of Cluster Nodes

In order to calculate the optimal number of Cluster Nodes, it is necessary to use the radio energy dissipation model.

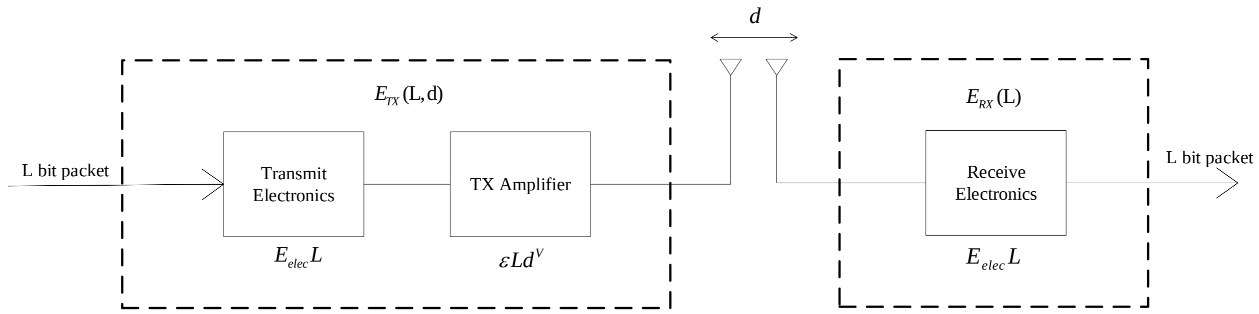


Fig. 6 Radio energy dissipation model

According to the radio energy dissipation model illustrated in Fig. 6 [7], in order to achieve an acceptable SNR (Signal-Noise Ratio) in transmitting L bit packet over a distance d , the energy consumed by the radio is given by:

$$E_{TX}(\mathrm{L},d)=\begin{cases} L\cdot E_{elec}+L\cdot\in_{fs}\cdot d^{2} & (\text{if } d<d_0) \\ L\cdot E_{elec}+L\cdot\in_{mp}\cdot d^{4} & (\text{if } d\geq d_0) \end{cases} \tag{1}$$

Where E_{elec} is the energy dissipated per bit to run the transmitter or the receiver circuit, $\in_{fs}$ and $\in_{mp}$ depend on the transmitter amplifier model, and d is the distance between the sender and the receiver.

Assume that the number of the WSN end node is n, the number of the Advance Nodes is m and the number of the Cluster Head is k .

Then the energy consumed by each Cluster Head in each round E_{CH} is:

$$E_{CH} = L \cdot E_{elec} \cdot \left(\frac{n-m}{k} - 1\right) + L \cdot E_{DA} \cdot \left(\frac{n-m}{k} - 1\right) + L \cdot E_{elec} \cdot \frac{n-m}{k} + L \cdot \in_{fs} \cdot d_{toGW}^2 \quad (2)$$

Where E_{DA} is the energy dissipated of data aggregation, d_{toGW} is the distance from Cluster Head to LoRa gateway. The energy consumed by each Advanced Node during each round E_{AN} is

$$E_{AN} = L \cdot E_{elec} + L \cdot \in_{fs} \cdot d_{toGW}^2 \quad (3)$$

The energy consumed by each Normal Node during each round E_{NN} is

$$E_{NN} = L \cdot E_{elec} + L \cdot \in_{fs} \cdot d_{toCH}^2 \quad (4)$$

Where d_{toCH} is the distance from Normal Node to the Cluster Head.

The sum of the distances of all Normal Node to the Cluster Head is

$$T\left[d_{toCH}\right]^2 = \iint \left(x^2 + y^2\right) \cdot \rho(x, y)\, dxdy \quad (5)$$

$$T\left[d_{toCH}\right]^2 = \int_0^{\frac{6 \cdot 24}{k}} \int_0^{6 \cdot 26} x^2 + y^2 dydx = \frac{(26 \cdot 6)^3}{3} + \frac{(6 \cdot 24)^3}{3 \cdot k^3} \quad (6)$$

Where $\rho(x,y)$ is the WSN end nodes distribution. Thus, the total energy consumed by each cluster in each transmission cycle $E_{cluster}$ is

$$E_{cluster} \approx E_{CH} + \left(\frac{n-m}{k} - 1\right) \cdot E_{NN} \quad (7)$$

The total energy dissipated of the ZigBee network E_{tot} is:

$$E_{tot} \approx k \cdot E_{cluster} + (m-k) \cdot E_{AN} \quad (8)$$

By differentiating E_{tot} with respect to k and equating to zero, the optimal number k_{opt} of constructed clusters can be found.

$$k_{opt} = \sqrt[4]{\frac{(n-m)(6 \cdot 2.4)^3}{d_{toBS}}} \quad (9)$$

4. Design of the routing algorithm

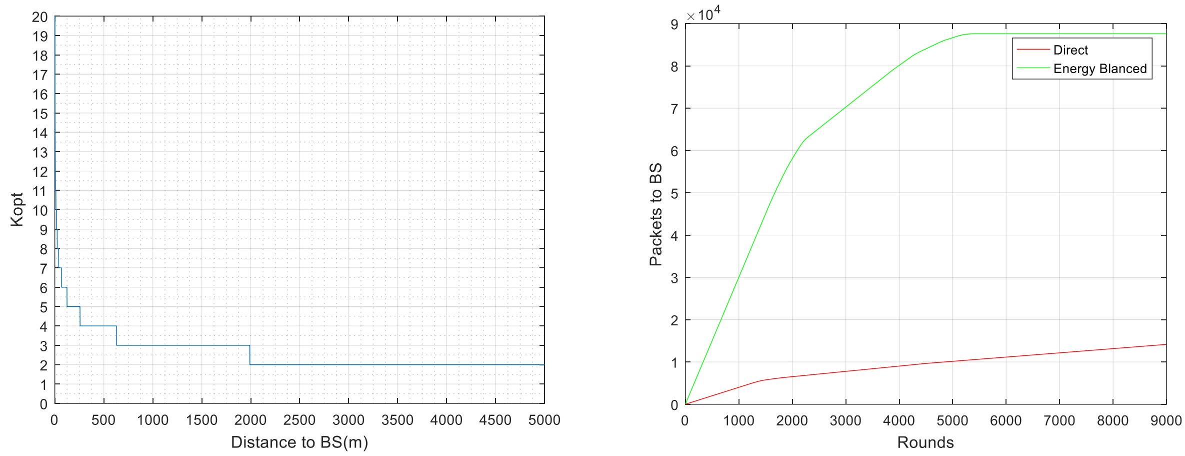
According to equation (9), k_{opt} is depend on the number of the Normal Nodes and the d_{toBS} . The MATLAB be used to calculate the k_{opt} in different d_{toBS}. The number of the containers in a storage unit is 30. So the number of the end node in a ZigBee network is 30 and the Advance node is 6. The $n-m$ in the equation (9) is 24. According to equation (9) the k_{opt} related with d_{toBS}. MATLAB was used to calculate the k_{opt} with different d_{toBS}. As shown in Fig. 6(a), the k_{opt} depends to the distance from Advance Node and LoRa gateway.

MATLAB is used to simulate this routing algorithm and compare with directly transfer the data. We simulate the WSN in an area with dimensions 15m × 13(m). The population of the nodes n is equal to 30 and the Advance Nodes m is equal to 6. The way nodes are distributed over the field is illustrated in Fig. 5. The distance from Cluster Head to LoRa gateway d_{toBS} is (instead of =)1(km). According to the results in Fig. 6(a), the optimal number of Cluster Node k_{opt} = 2. We assume the radio characteristics as shown in Table 1 [8].

Table 1 Radio characteristics

Transmitter Electronics	Receiver Electronics	Data Aggregation	Transmit Amplifier
$E_{elec} = 50nJ / bit$	$E_{elec} = 50nJ / bit$	$E_{DA} = 5nJ / bit / signal$	$\in_{fs} = 10 pJ / bit / m^2$

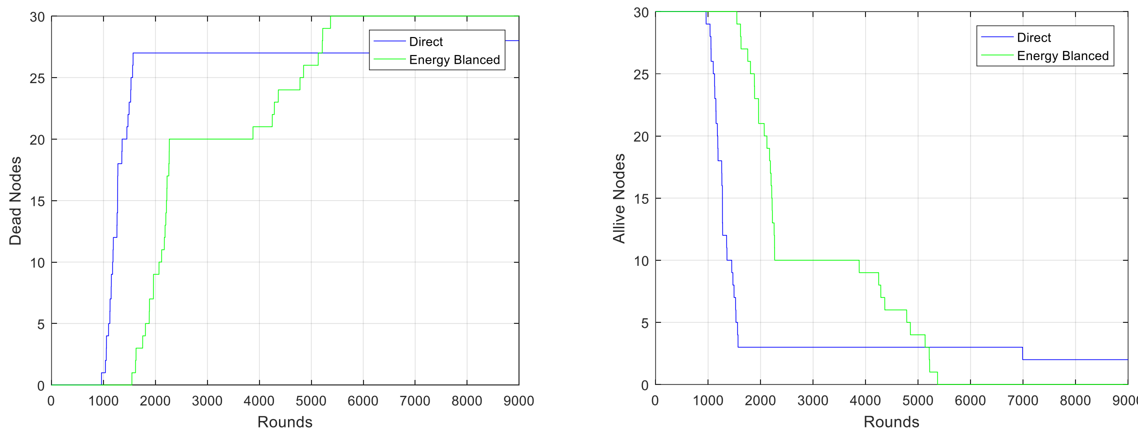
The round was set in 9000. Fig. 6 (b) shows the throughput from ZigBee network to the Base Station Per round. This algorithm has the ability to transfer more data to Base Station.



(a) (b)

Fig. 6 (a)The optimal number of cluster nodes (b) The throughput from cluster head to the LoRa gateway

As shown in Figure 5.5 (c), the blue line shows the number of the dead nodes when using direct transmission and the green line shows the number of the dead nodes when using energy is balanced. The death node will appear earlier when using direct transmission. When use the energy balanced algorithm, the stable period of the network is longer than the direct transmission.



(c) (d)

Fig. 7 (c) The number of dead nodes in the ZigBee network (d) The number of alive in the ZigBee network

5. Conclusion

Considering the container stacking rules, a network architecture that is suited for reefer containers IoT system and the system architecture was designed in this work. With the help of this WSN end node architecture, the WSN end node is possible to transmit the data by using ZigBee and LoRa joint technology. The WSN communication architecture provides the capability for the WSN end node to transfer the data to the LoRa gateway even if the LoRa communication link of the WSN end node is blocked by other containers. In this work, the energy dissipation model of the container WSN was used to calculate the optimal number of Cluster Nodes which is an important parameter of guarantee a well-balanced distribution of the energy load among nodes of the sensor network. MATLAB has been used to simulate the routing algorithm and the effectiveness of the algorithm is verified by simulation results.

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