A LoRa-Based Optimal Path Routing Algorithm for Smart Grid

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***Abstract*—For smart grids, suitable communication technologies and routing algorithms are very important in data transmission. Among various data transmission technologies, LoRa is an Internet of Things (IoT)-based wireless communication technology, characterized by its long communication distance up to a few kilometers and low power consumption. Therefore, LoRa is an appropriate candidate for data transmission in smart grids. In this study, the performance of a LoRa device is examined. Based on the experimental results, a routing algorithm that uses the AODV is developed for the LoRa device, and the algorithm enables a long-chain topology suitable for data transmission in a smart grid. A multi-hop mechanism is simulated to ensure a high final receiving rate of packets, by finding the optimal path with the least number of hops in the transmission topology for a power transmission line. The simulation results show a great performance of the proposed algorithm in long distance transmission.**

Keywords—*Smart Grid, LoRa, LPWAN, AODV, RSSI*

I. INTRODUCTION

In Taiwan, the distance between two power transmission towers usually exceeds 200m, or even reaches 1km [1], which is likely to cause packet losses during long distance transmission. Moreover, the power towers are usually deployed in a chain and the total length of a transmission line often reaches dozens of kilometers. For the smart grid in Taiwan, the disadvantages of the tower distribution and long distance transmission need to be overcome by using a suitable wireless communication technology and a routing algorithm. Therefore, in this study, the main concept of an Ad hoc On-Demand Distance Vector (AODV), a well-known dynamic protocol used by ZigBee, and the Received Signal Strength Indicator (RSSI) are adopted to develop an optimal path routing algorithm for smart grids. With the RSSI and AODV, an algorithm is proposed, which reduces the hops and makes the wireless communication more robust for the smart grid in Taiwan.

In a smart grid, the IoT technology can provide both power suppliers and users with critical power information, such as electric current, voltage, line temperature, surrounding temperature and humidity. With the information, power suppliers can adjust their plans on the dispatch of electricity to achieve the purposes of saving energy, reducing wire losses and enhancing grid reliability. It is also important to adopt an appropriate wireless communication device to meet the demand of smart grid operation. There are several well-developed IoT-based communication technologies, such as ZigBee, Wi-Fi and Bluetooth, but these technologies all have a limited communication range and consume relatively higher power, so they would not suit for performing data transmission in smart grids or other wide area applications [2].

To meet the demands of IoT-based devices in power saving and long distance data transmission, a low-power wide-area network (LPWAN), which is novel infrastructure for wireless communication, is emerging. An LPWAN reduces the trade-off between the transmission distance and energy efficiency. Developed by SemTech Corporation, LoRa is currently one of the most widely used LPWAN network technologies. In a LoRa module, several parameters can be customized, including the spreading factor (SF), bandwidth, transmission power, and code rate. With the increase in the SF, the signal-to-noise ratio and the communication range, the performance of LoRa modules can be improved. Some studies have paid attention to examine the relations between various parameters used by LoRa modules and the performances of the models. For example, [3, 4] discussed possible setting combinations and the performance of LoRa modules. , and they proposed an algorithm that was able to find suitable parameters for LoRa modules. In addition, [5, 6] developed a multi-hop mechanism for LoRa modules to improve their ability in data transmission.

This study uses the Packet Delivery Ratio (PDR) and RSSI to examine the performance of a LoRa device placed at different distances under the condition of no obstruction [7]. The RSSI measures the power of a radio signal received by a receiver, which shows the link quality between the receiver and the transmitter. Moreover, this study proposes a routing algorithm to ensure that the PDR of packets is above a level after long-distance multi-hop transmission. Finally, the routing algorithm is used to simulate an optimal path for Taiwan's power grid with a long chain topology.

The remainder of this study is organized as follows. Section II gives an overview of an RSSI and AODV routing protocol. Section III shows the operation of a modified AODV, based on the RSSI results, while Section IV describes the details of the system architecture and the experimental environment. Section V presents the experimental and the simulation results of the proposed algorithm. Finally, Section V concludes the study.

II. Overview Of RSSI And AODV

A. *RSSI*

In wireless communication, an RSSI is an important indicator of signal strength, and it is a negative value in dBm. It is also a relative index defined by manufacturers. Basically, a received signal is strong if its RSSI value is close to 0 dBm. Thus, the relative distance between different unknown nodes can be determined using the RSSI value. [8] described the derivation of RSSI-models from the basic radio free-space propagation model using the following equations (1) and (2).

$$RSSI\left(D\right)=-10n_p\log\left(D\right)+P0\left(D0\right)+10n_p\log\left(D0\right) \quad (1)$$

$$RSSI\left(D\right)=a\log\left(D\right)+b \quad (2)$$

where *RSSI*(*D*) is the RSSI value at distance *D*, and *P*0(*D*0) is the transmitter's signal strength at a reference distance *D*0, n_p is the path loss exponent. Therefore, the RSSI-range model can be rewritten as equation (2) [8], where $a=-10n_p$ and $b=P0\left(D0\right)+10n_p\log\left(D0\right)$.

B. *Ad Hoc On Demand Distance Vector routing protocol*

An Ad Hoc On-Demand Distance Vector (AODV) is a routing protocol for mobile ad hoc networks, and it is an on-demand algorithm operating only when the transmission is requested. The main purpose of the AODV is to find the shortest path between each node and the source node in the network. This protocol adopts the hop count between the source node and the destination node as the weight for choosing the optimal path. In addition, the AODV protocol establishes a routing table using two specific packets: a Route Request (RREQ) packet and a Route Reply (RREP) packet. First, the messages in the RREQ packet include source address, source sequence number, broadcast identification number, destination address and hop count. Second, RREP packet messages include source address, destination sequence number, destination address, hop count number and lifetime information. The detailed implementation of an AODV is described in [9]. The operating mechanisms in the AODV can be classified into two main approaches: route discovery and route maintenance.

1. *Route Discovery*

The route discovery process of an AODV is shown in Fig. 1.(a) where a link is established between the source node A and the destination node G. In the beginning, the source node starts a route discovery process through broadcasting a RREQ for searching the destination node. In this process, the RREQ propagates in the whole network to check each node whether the intermediate node is the destination node or not [10]. If not, the intermediate node re-broadcasts the RREQ until the destination node receives the RREQ from the source node for the first time. Then, the destination node replies a RREP back immediately to the source node according to a route reverse path. Eventually, the source node would receive multiple RREPs from the destination node with different paths, and it chooses the smallest hop count and records the chosen routing path for data packet delivering.

2. *Route Maintenance*

For route maintenance, the AODV uses Hello message packets to ensure the connection between nodes [11]. As shown in Fig. 1.(b), each node broadcasts a Hello message periodically to all of its neighbors and retains the link with other nodes. Also, nodes in the network receive Hello messages from their neighbors, and they would update the list of neighbors at the same time. Therefore, Hello messages can be used to detect or ensure all the connections with neighbor nodes.

III. Modified AODV Based on RSSI

In the real world, power towers are often located in mountain areas or at a higher ground where no obstacles exist in the surrounding areas, so the RSSI value can reflect the relative distance between wireless modules [12]. Therefore, in this study, a routing algorithm, called a "modified AODV" is proposed. The modified AODV is an AODV that is revised based on the RSSI results, for a chain topology. The algorithm essentially adopts specific message packet from an AODV. It consists of two major parts: route search and backup.

A. *Route Search*

The route search process of the proposed algorithm combines the processes of route discovery and route maintenance in an AODV. The route search is responsible for establishing route tables. Nodes play two major roles in the route search: the source and the receiver.

1. *Source node*

The flowchart and pseudo code of the source node are shown in Fig. 2 and Fig. 3. First, the source node broadcasts a RREQ and waits for the RREPs from the neighbor nodes who receive the RREQ. All the neighbor nodes who receive the RREQ from the source node would reply with an RREP that contains their node ID and the RSSI value. Then, the source node updates the list of all neighbors nodes and sorts them by using the RSSI value. According to the list of the neighbors,

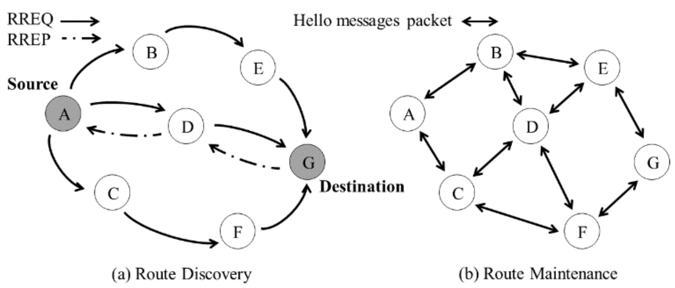

Fig. 1. The flow of AODV messages.

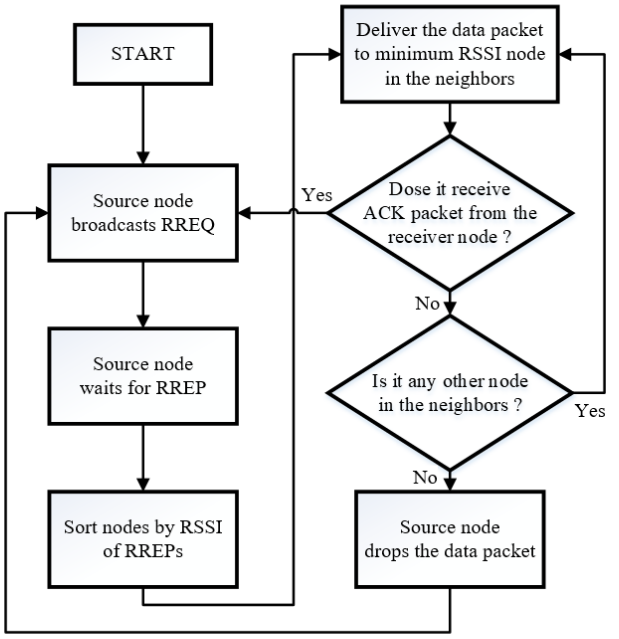

Fig. 2. The flowchart of the source node.

Pseudo code for the source node in the modified AODV

1: Broadcasts a RREQ and waits for the RREPs
2: **for** all RREPs **do**
3: Read the header for node ID and RSSI value
4: Add to the list of neighbors
5: **end for**
6: Sort the list of neighbors by RSSI
7: **for** each neighbor node in list
8: Deliver data packet
9: **if** receive ACK packet success with PDR
10: Switch to receiver node
11: **break**
12: **end function**

Fig. 3. The pseudo code for the source node in the modified AODV.

the source node chooses the best intermediate node to deliver data packets and waits for an ACK packet in a given time interval. If the time is up, the source node would choose an alternative node on the list to deliver the packet. Finally, when the delivery of data packets is complete, the source node changes its role to a receiver node and waits for the next round of data packet delivery. Receiver node

The flowchart and pseudo code of the receiver node are shown in Fig. 4 and Fig. 5. The receiver node would wait for the RREQ from the source node. When the receiver node receives a RREQ, it first checks whether the sequence number in the RREQ is smaller than its sequence number. If not, the RREQ be dropped and the receiver node waits for another RREQ. If so, the receiver node delivers an RREP with the RSSI value and waits for the data packet delivery during a specific time period. To avoid a data packet with the same sequence number is delivered from other source node, the receiver node only receives the data packet once by checking the sequence number. Finally, the receiver node switches its role to the source node to deliver the data packet.

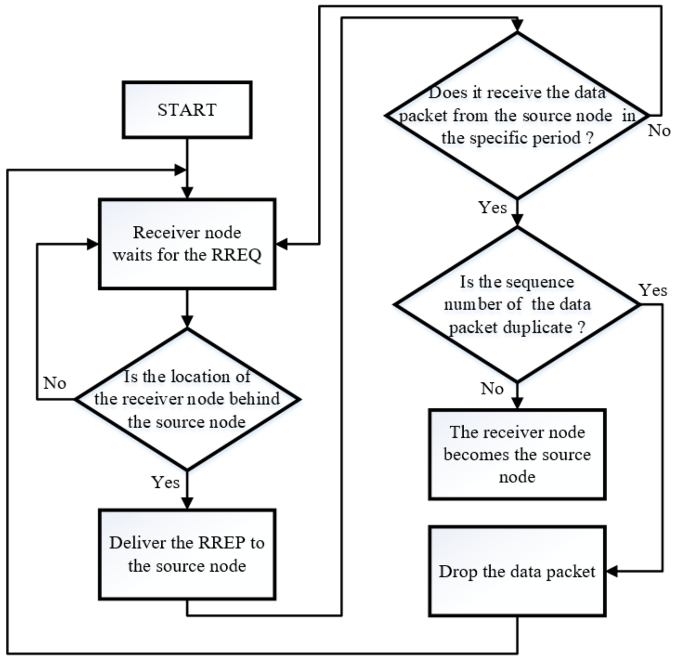

Fig. 4. The flowchart of the receiver node.

Pseudo code for the receiver node in the modified AODV

1: Wait for the RREQ and read the header
2: **if** the sequence number in RREQ < the sequence number of receiver
3: Deliver the RREP including the RSSI value
4: Wait for the data packet in specific period
5: **if** the sequence number in data packet haven't record before
6: Switch to source node
7: **else**
8: Drop the data packet
9: **end function**

Fig. 5. The Pseudo code for the receiver node in the modified AODV.

B. Backup Mechanism

In addition, the modified AODV includes a backup mechanism. According to the RSSI value, the source node can simply determine the distance between towers and select the optimal intermediate node to deliver the data packet. Also, each node holds a list of its neighbor nodes, and the nodes on the list are sorted by the RSSI value through periodically sending out an RREQ and waiting for the RREPs from neighbors. When a node discovers a new neighbor by receiving an RREP and it would add the neighbor to the list. By contrast, an existing neighbor would be dropped if no RREP is sent back to the node. There may be more than one neighbor in the that range. Therefore, a backup mechanism is developed to prevent the broken links using dynamic ACKs. Under a normal condition, the source node delivers a data packet to the optimal intermediate node and waits for an ACK to be sent back. If no ACK is sent back in time, the source node would select an alternative intermediate node from the list of neighbors. Such a backup mechanism can ensure the reliability of the communication link between the source node and the destination node.

IV. System Architecture And Experiment Setups

A. The Node

As shown in Fig. 6, the node, playing both roles of data transmitting and receiving, consists of two major components: a Raspberry Pi 3 Model B (RPI-3B) and LoRa module. The RPI-3B is used as the main data processing center. It is a popular embedded board, and its central processing unit is a quad-core 64-bit ARM-Cortex A53 clocked 1.2 GHz. The RPI-3B is equipped with four USBs and capable of connecting to a variety of modules. The LoRa module plays the most important role in the system. It is responsible for data transmission and establishing a communication link between two nodes. The specifications of a LoRa module are described as follows.

B. The specifications of a LoRa module and parameter settings

The LoRa module used by the node is an Ra-02 operating at 433 MHz. As shown in Fig. 6, the Ra-02 communicates with the PRI-3B via a serial peripheral interface (SPI) bus and adopts an advanced LoRa spread spectrum technology relying on a SEMTECH SX1278 wireless transceiver. The LoRa module supports a communication distance of 10,000 meters and has a high sensitivity of -148 dBm with a power output of +18 dBm. For LoRa modules, the SF parameter has a primary impact on the signal-to-noise ratio and the RSSI value. To increase the successful rate of packet receiving and allow a greater resilience, a bandwidth of 125 kHz, the highest spreading factor (SF12) and the transmit power of 14 dBm are used by both the transmitter and receiver of the Ra-02 chip. Also, the antenna of the node provides a 3.5 dBi gain over the band of 433 MHz and it is placed 2 m above the ground.

C. Experimental environment

The experiment was conducted on the shore of the Changbin industrial zone on May 2, 2018, where the transmission condition was expected be better, because the terrain was relatively flat and the line-of-sight was over 2.5 km, as shown in Fig. 7. The ambient temperature was in the range between 29 °C and 30 °C and the humidity was in the range

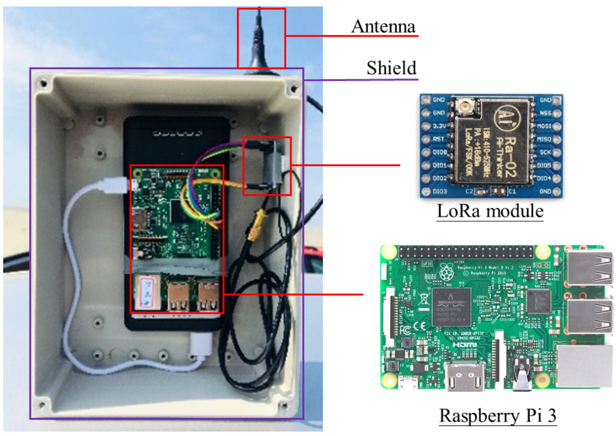

Fig. 6. The main components of the node.

Fig. 7. The google map of the Changbin industrial zone.

between 60% and 70%. In the experiment, all nodes were placed 2 m above the ground and stood upright to make sure that data collection would be successful. The total number of packets transmitted in the experiment was 1,000. Each packet included the packet sequence index, the RSSI value, and the receiver node information. The transmission process was repeated every 20 m until the distance reached 2.5 km. Such a distance might exceed the distance between any two adjacent power towers in Taiwan.

V. Results & Discussion

A. Experimental results

Fig. 8 show the experimental results on PDRs and distances in a case of good line-of-sight and communication. The Ra-02 module is capable of sending data at a distance of 2.5 km and achieves a PDR higher than 96%. Such a distance is sufficient if the proposed algorithm is used to perform actual packet transmission tasks between any two power towers in Taiwan. Moreover, it provides a corresponding PDR for each pair of power towers in Taiwan based on the distance between the pair of the towers.

Fig. 9 shows the relationship between the RSSI values and distances. Given that difference hardware components may have different performance, an ideal RSSI-range model in free-space propagation was considered, as discussed in Section II-(A). A logarithmic regression equation was used to explain the variations of the RSSI values brought by the distance, as shown in Eq. (3). This regression equation would also be used to calculate an RSSI value corresponding to a given distance between any two towers in Section IV.

$$RSSI = -8.937\ln(D) - 38.091 \qquad (3)$$

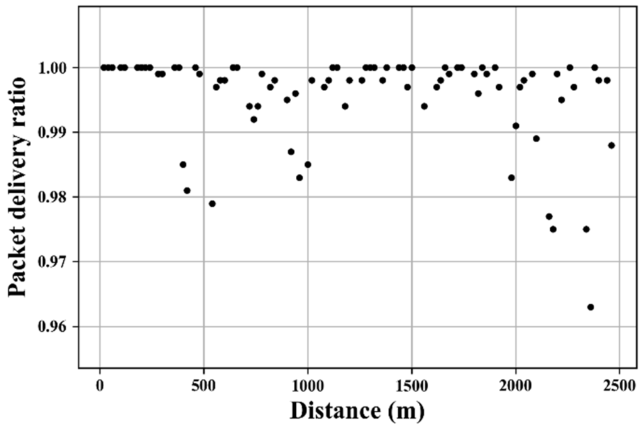

Fig. 8. Packet Delivery Ratio versus distance (m).

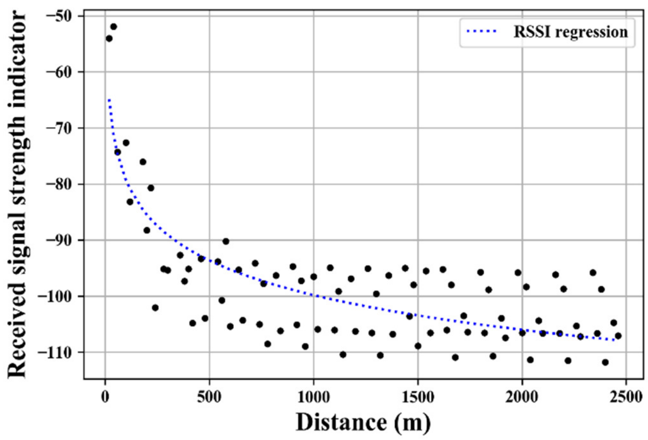

Fig. 9. RSSI values as a function of distances (m).

B. Pseudo code for the simulation

The pseudo code of the simulation is shown in Fig. 10. Since the location of a power tower is fixed, the distance between the towers can be determined in the network deployment. The corresponding RSSI value and the PDR can be calculated according to the distance between the towers using the formula shown in Section V-(A) and the PDR for the LoRa-based hardware. With the information, an RSSI threshold can be set in the proposed algorithm to ensure that each transmission should achieve a given PDR. The whole topology in this algorithm dynamically changes based on the demand, because each node selects the best neighbor node according to the RSSI weight between the nodes. When a hop in the packet delivery fails, the algorithm activates a backup mechanism to make a decision of using a different path. Finally, the data packet delivery dynamically follows the routing table created by each intermediate node, and the constant propagation process goes on until the destination node receives the data packet.

Pseudo code for the modified AODV

```
Require: the locations of the nodes; the threshold of RSSI; the start node
Calculate the distance between each node and return the corresponding RSSI;
for all nodes do
        Deliver RREQ
        Read RREPs for other nodes
        For (RSSI from RREPs of other nodes < the threshold of RSSI)
                Add to the list of neighbors
        end for
        Sort neighbor nodes by RSSI value
end for
while destination node hasn't received the data packet yet
        Read the header of packet;
        for each neighbor node in list
                Deliver data packet
                if receive ACK packet success with PDR
                        Intermediate node ← neighbor node
                        break
                end if
        end for
end function
```

Fig. 10. The pseudo code of the modified AODV.

D. Simulation results

In this study, a network simulator was conducted for LPWANs by Python 3.6.4. In order to validate the proposed modified AODV, the power towers in the selected transmission line served as the simulation nodes (hereinafter called the "tower") with sequential numbers. The goal of the proposed routing algorithm is to find the optimal path with the smallest hop count based on the RSSI value. As mentioned earlier, an RSSI threshold was set corresponding to the distance of 2 km between any two towers to guarantee that the PDR reached a given level in each transmission. Moreover, a tower selected a neighbor with the lowest RSSI value to optimize the hop count. The fewer hops, the higher the final PDR of the gateway and the lower the energy consumed by transmitting one packet.

In this study, the chain topology consisted of 34 transmission towers and the whole length of the chain topology was 13,680 m, the average distance between towers was 414.56 m, and the average number of neighbors of each tower was 4.33. In this simulation network, No.34 (the gateway) gathered all packets from other towers in the chain topology. In the simulation, the transmission range for each tower was set at 2,000 m. Table I shows the source tower ID (S), the number of neighbors (N), the average hops on the path (A), the average distance of a single hop (D), the average RSSI value of the single hop (R) and the final PDR of No.34 during 1,000 rounds of packet transmission from the 10 towers ahead. In average, these 10 towers (from No.1 to No.10) used more than 4 intermediate towers to relay the data packet, which meant that there were one optimal intermediate tower and three backup towers in average. Moreover, with the great performance of Lora module in Section V-(A) and the backup mechanism, the final PDR of No.34 was up to 99% and sometimes even reached 100%, after 1,000 packets were delivered.

Fig. 11 illustrates the deployment of power towers on the selected transmission line. Also, the hop count for tower No.1 to No.10, shown in different colors, is also compiled by the proposed algorithm in which an RSSI threshold was set for tower No.1 to No.10. Moreover, to avoid resource and energy wasting in the transmission, each tower was assigned a unique node id, and the id was in sequence in the topology to make

TABLE I. THE SIMULATION RESULTS FOR DELIVERING 1000 PACKETS.

Tower ID (S)	Neighbor number (N)	Average hops (A)	Average distance (D)	Average RSSI (R)	PDR (%)
1	3	8.03	1693	-104.49	100.0
2	5	8.00	1638	-103.68	99.7
3	5	8.00	1598	-103.46	99.9
4	6	7.04	1721	-104.64	100.0
5	7	7.00	1647	-103.64	99.6
6	7	7.00	1617	-103.50	99.6
7	6	7.00	1591	-103.36	99.8
8	6	7.00	1560	-103.19	99.9
9	5	7.00	1515	-102.96	99.9
10	5	6.02	1722	-104.65	100.0

Fig. 11. The deployment of power towers.

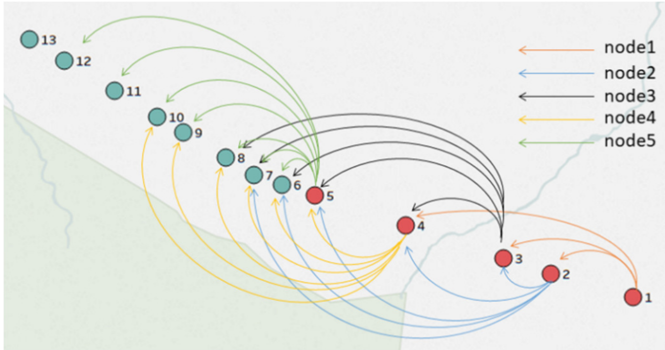

Fig. 12. The neighbor links of tower No.1 to No.5.

sure that the data packet was forwarded to No.34. If a receiver tower received an RREQ in which the tower id was larger than the id of the receiver, the packet would be dropped. By doing so, the case of a tower accepting an RREQ with an id larger than the id of the tower could be prevented. The total number of packets used in the experiment was 10,000 and they were transmitted from tower No.1 to No.10. The total number of packets received by No.34 was 9,984. These results indicate an excellent performance of the proposed algorithm on the accumulated PDR in the chain topology.

Fig. 12 show the neighbor links of tower No.1 to No.5 (the red points), and these links represent the backup mechanism of the proposed algorithm for each tower. Also, the number of neighbors reflects the robustness of the communication link for an intermediate node, and packet losses due to broken links can be prevented. Finally. it can be seen that the proposed algorithm successfully improves the communication robustness and guarantees great PDR performances of a chain topology.

VI. CONCLUSIONS AND FUTURE WORK

In this study, a routing algorithm is developed to find the optimal path for the data transmission in smart grids using a LoRa-based communication module. The simulation results prove that the proposed algorithm can improve the reliability of data transmission. The final PDR of the gateway is up to 99%, after a 13.6 km long-distance transmission on a power transmission line. The simulation results also show that with the consideration of RSSI values, the LoRa module can be effectively used in long-distance transmission with an average transmission distance of 1.6 km. Also, the route search process of the proposed algorithm reduces the number of hops and the possibility of sending additional packets. For future work, the proposed algorithm will be applied to LoRa-based devices deployed in real power towers.

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REFERENCES

[1] C.-Y. Liu *et al.*, "A novel embedded system-based backbone communication network for smart grid," in *Sensing Technology (ICST), 2015 9th International Conference on*, 2015, pp. 474-481: IEEE.

[2] V. C. Gungor *et al.*, "Smart grid technologies: Communication technologies and standards," *IEEE transactions on Industrial informatics,* vol. 7, no. 4, pp. 529-539, 2011.

[3] M. Bor and U. Roedig, "LoRa transmission parameter selection," 2017.

[4] F. Cuomo, M. Campo, A. Caponi, G. Bianchi, G. Rossini, and P. Pisani, "EXPLoRa: Extending the performance of LoRa by suitable spreading factor allocations," in *Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2017, pp. 1-8: IEEE.

[5] M. Bor, J. E. Vidler, and U. Roedig, "LoRa for the Internet of Things," 2016.

[6] K. Mikhaylov, J. Petäjäjärvi, J. Haapola, and A. Pouttu, "D2D communications in lorawan low power wide area network: From idea to empirical validation," in *Communications Workshops (ICC Workshops), 2017 IEEE International Conference on*, 2017, pp. 737-742: IEEE.

[7] M. Cattani, C. A. Boano, and K. Römer, "An experimental evaluation of the reliability of lora long-range low-power wireless communication," *Journal of Sensor and Actuator Networks,* vol. 6, no. 2, p. 7, 2017.

[8] J. Ramiro Martínez-de Dios, A. Ollero, F. J. Fernández, and C. Regoli, "On-line RSSI-range model learning for target localization and tracking," *Journal of Sensor and Actuator Networks,* vol. 6, no. 3, p. 15, 2017.

[9] E. M. Royer and C. E. Perkins, "An implementation study of the AODV routing protocol," in *Wireless Communications and Networking Confernce, 2000. WCNC. 2000 IEEE*, 2000, vol. 3, pp. 1003-1008: IEEE.

[10] I. D. Chakeres and E. M. Belding-Royer, "AODV routing protocol implementation design," in *Distributed Computing Systems Workshops, 2004. Proceedings. 24th International Conference on*, 2004, pp. 698-703: IEEE.

[11] I. D. Chakeres and E. M. Belding-Royer, "The utility of hello messages for determining link connectivity," in *Wireless Personal Multimedia Communications, 2002. The 5th International Symposium on*, 2002, vol. 2, pp. 504-508: IEEE.

[12] H. Sallouha, A. Chiumento, and S. Pollin, "Localization in long-range ultra narrow band IoT networks using RSSI," in *Communications (ICC), 2017 IEEE International Conference on*, 2017, pp. 1-6: IEEE.