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# Building ZigBee Mesh Network using AODV Routing Protocol

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***Abstract***

*This research developed a Zigbee mesh network topology to assess the data transmission efficiency utilizing the Ad-Hoc On-Demand Distance Vector (AODV) routing protocol. AODV is Zigbee's low-power, low-data-rate wireless ad hoc network routing protocol. A physical mesh network was created using Zigbee components, namely the Zigbee Coordinator (ZC), Zigbee Router (ZR), and Zigbee End Device (ZED). Data transmission experiments were carried out among the Zigbee modules with the AODV routing protocol, and evaluated over four distinct versions. Modifications were made to key aspects of the AODV protocol, including mesh self-healing and link cost management. The experimental results revealed that during the self-healing phase, all modules in the network were engaged, resulting in a transmission time of 0.4 seconds. After the direction was established, data was sent in only 0.01 seconds, achieving a speed that was 40 times faster than the previous experiment.*

***Keywords:*** *ZigBee devices, routing table, self-healing, link cost*

## 1. Introduction

Several wireless technology standards for short-range data transmission, such as RF, Bluetooth, UWB, and Zigbee, have recently become quite popular. This technology facilitates data transfer by creating Star (1:1), Cluster Tree (1: n), or Mesh (1: n) network structures [1]. It can easily transmit data sizes of 50 kB at speeds reaching up to 250 kB/sec, enabling communication and data sharing among as many as 65,536 wireless modules [2]. As the protocols for data transmission in this technology continue to advance, the Zigbee versions from 2006, 2007, and PRO are currently in operation [3].

The Zigbee technology network comprises modules with three primary functions:

- ✓ ZC (ZigBee Coordinator): Acts as the overall network controller and is unique to the network.
- ✓ ZR (ZigBee Router): Extends the network and forwards incoming data to other modules.
- ✓ ZED (ZigBee End Device): Functions as a built-in sensor module. It receives data from all connected sensors and relays it to the data center through the ZR and ZC.

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Previous studies have explored the development of Zigbee networks utilizing a star topology [4, 5], while this study focuses on the development of a mesh topology.

### 1.1 Feature of Mesh Networks

A mesh network is distinct from a tree network because it can relay information without the constraints of branching structures. Within a mesh network, each module interacts with other modules in a specific order using its network router and coordinator module. The routers and coordinator modules serve as transmitters for the network and pre-establish the direction of the data transmission sequence. Figure 1 depicts the connections among the modules that make up the network in a mesh topology.

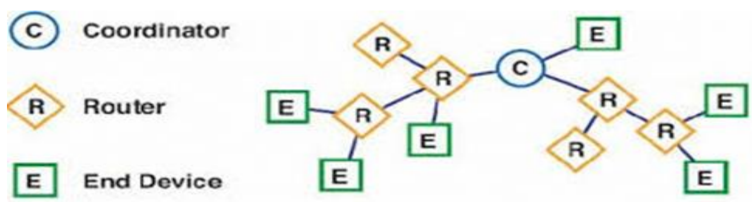


**Figure 1. ZigBee mesh network topology**

Each network module pair includes at least one channel for data transmission, from which we choose the most appropriate direction for communication. This strategy improves the reliability of data transfer in the mesh network. Should an error arise during data transmission in the chosen direction, the transmission module can detect an alternative route, providing self-healing capabilities. Various protocols, including MAC-I, MAC-II, Flooding, Gossip, and LEACH, are being developed to optimize the routing and transmission of data between modules [6, 7, 8]. Among these is the Ad-hoc On-demand Distance Vector (AODV) protocol, which offers privacy routing features [9 - 10]. AODV is a routing protocol that reduces the number of messages sent by creating a path between the source and destination nodes. It employs resource access and demand packets to aid communication among nodes within the network. When using a protocol for data transmission, several important parameters are assessed when choosing a path, such as connection quality, the quantity of transmitting devices, and energy consumption. Various methods are available to calculate these parameters. The maximum routing lifetime of the AODV protocol is estimated in [11]. Also, the energy-saving technology through energy monitoring using the ZigBee mesh network was investigated in [12].

The network developer will certainly carry out calculations tailored to the network's specific goals and the context in which it will be deployed. These calculations should rely on the Link Quality Indicator (LQI) or other signal quality metrics.

The simplest calculation method expresses the link cost as an integer value ranging from 0 to 7, as shown in equation (1).

The less reliable the data transmission between two devices, the higher the link cost.

$$C_{(l)} = min\left(7, abs\left(\frac{1}{p_l^4}\right)\right) \tag{1}$$

For example, if $P_l = 80\%$ $C_{(l)} = 2$.

$$C_{(l)} = min\left(7, abs\left(\frac{1}{0.8^4}\right)\right) = 2$$

Using the sum of each direction C{P}(2), the protocol compares multiple paths and selects the one with the lowest link cost for data transmission.

$$C\{P\} = \sum_{i-1}^{L-1} C\{[D_{i+1}]\} = \sum_{i-1}^{L-1} C\{l_i\} \quad (2)$$

### 1.2 Define the Direction of Data Transmission

In coordinator and router devices, devices that transmit within the same radio frequency range are called neighboring devices. These devices keep a neighbor table that holds information about their nearby peers. Each module updates the data in its neighbor table whenever it receives a transmission from a neighboring device.

When a transmitting device receives a request to send data to a specific address, the network layer operates in the following manner:

- ✓ If the address matches a module's address, that module will receive the request. Conversely, if it's an address for a peripheral device, the request will be sent straight to that device.
- ✓ If the address does not correspond to any known module, the router logs the transmission in its table and discovery route table, updates it with the intended device's address, and then sends the request to all neighboring devices.
- ✓ If an end device is available, the request is then passed on to its parent device.

As illustrated in Figure 2, the path is established, and the data transfer request is routed to the destination. The broadcast radius is set to the number of the first module to be passed through, decrementing by 1 for each subsequent module encountered. If the number of transfers exceeds the initial value, the route is considered invalid.

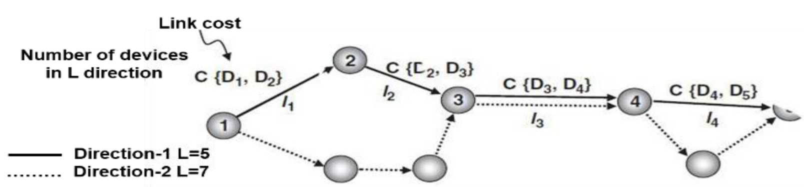


**Figure 2. Model of determining direction**

A data transfer request may arrive at the same transmitter multiple times, depending on the available paths. The transmitter selects the path with the lowest link cost. The specified device receives the request and sends a response, as shown in Figure 3.

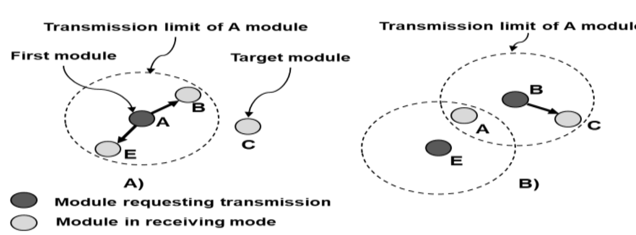


**Figure 3. Determine the direction or request to transfer data from module A to module C**

The routing process concludes when the first module receives the routed response. The forwarding module in that direction sets the address of the next device based on the specified path and transmits the information directly via unicast, as shown in Figure 4.

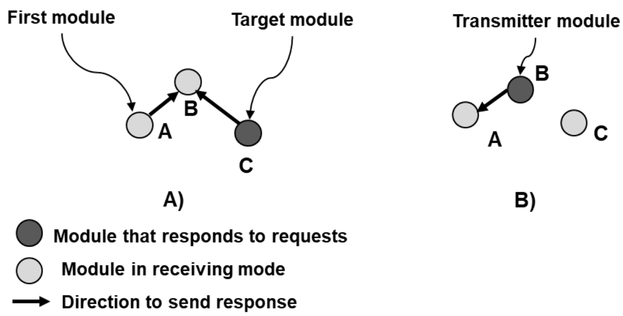


**Figure 4. Response to routing request from module C to module A**

Zigbee coordinator and router modules create routing tables at the network (NWK) level, which determine the next device to forward data to in a specified direction. When a new routing request arrives, it is stored in the routing table if there is available capacity.

## 2. System Design

A system using the AODV protocol was developed and evaluated with Texas Instruments' CC2530 SoC Zigbee chips. The primary diagram of the system is illustrated in Figure 5. During the experiment, a basic mesh network was established that included one ZC controller, three ZR routers, and one ZED end device. Data transmission was observed using a CC2531 packet sniffer module.

The network operates as follows:

- ✓ The button connected to P0_1 on the ZED module controls the LED connected to P1_0 on the Zigbee Coordinator (ZC) module.
- ✓ The ZR3 router serves as the parent to the ZED device and forwards routing requests on its behalf.
- ✓ The ZR-1 and ZR-2 router modules forward ZR3's request to the Zigbee Coordinator (ZC) module.
- ✓ The Zigbee Coordinator (ZC) receives commands and transmits a signal indicating the number of commands received, along with the state of the LEDs, to the computer via the serial port.
- ✓ The Zigbee packet sniffer module captures and analyzes data transmitted between Zigbee modules.

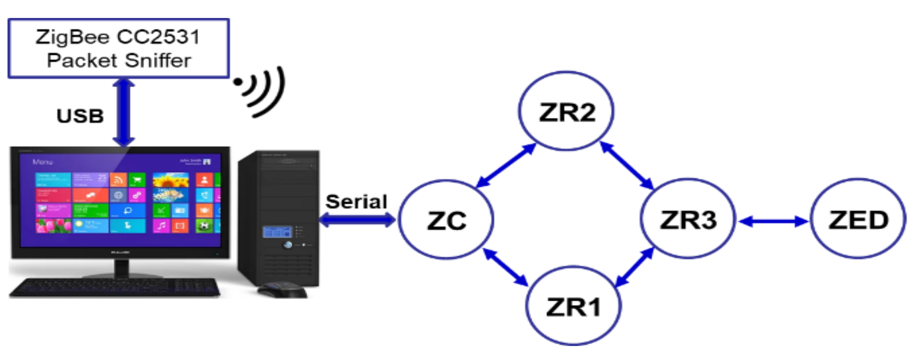


**Figure 5. System main diagram**

As shown in Figure 6, data can flow in the following two directions.

- ✓ ZED → ZR3 → ZR1 → ZC → PC
- ✓ ZED → ZR3 → ZR2 → ZC → PC
- ✓

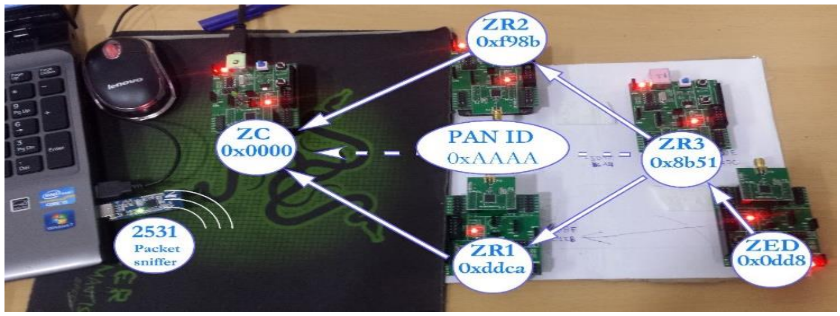


**Figure 6. Real experiment setup**

The module operates without an antenna to reduce the radio transmission and reception distances, facilitating easier testing. The network PAN ID is set to 0xAAAA, and the Zigbee Coordinator (ZC) assigns addresses to the router and end devices, as illustrated in Figure 7. The packet analyzer indicated that the coordinator and router devices broadcast information from the neighbor table every 15 seconds within the NWK link state data.

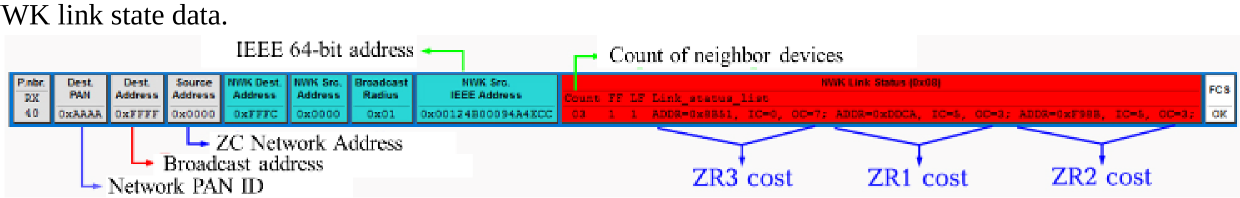


**Figure 7. Neighbor table of ZC**

During the initial transmission, the routing module creates a neighbor table and a route discovery table, with subsequent transmissions directed along the established path. If an error occurs during transmission in a previously defined direction, a new path is redefined to ensure self-healing capabilities. Therefore, the experiments were conducted in the following sequence.

## 3. Experiment and Results

### 3.1 Experiment Version-1

All ZigBee modules within the network are currently active. They possess self-healing capabilities and transmit information. Since the ZED module transmits data through its parent device, it first sets the destination address (0x8B51) for ZR3 and then sends the data to ZR3, as shown in Figure 8. The initial broadcast radius is set to 0x1E, with a transmission start time T1 of 35,026,308 µsec.

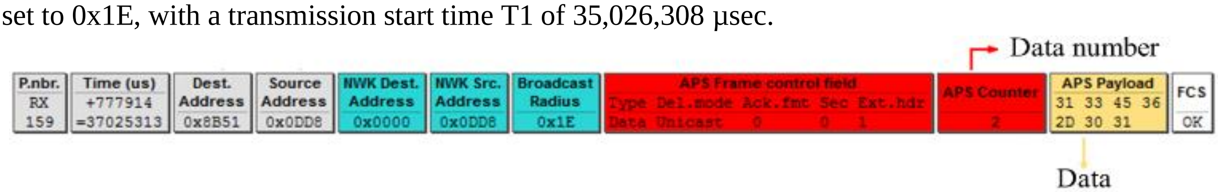


**Figure 8. ZED transfers directly to the parent module ZR3**

Upon receiving the request, ZR3 broadcasts a self-healing request to the destination address 0xFFFF, as depicted in Figure 9.

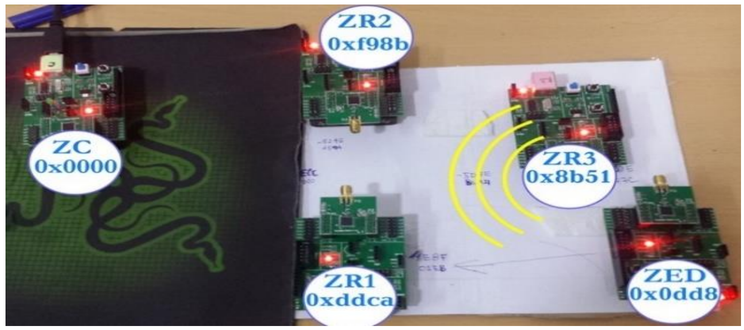


**Figure 9. A diagram of the ZR3 self-healing request to ZR1 and ZR2**

From the data received, ZR1 extracts the necessary information from its routing table and route discovery table, subsequently transmitting this information via broadcast. At this stage, ZR2 receives the self-healing request and remains on standby for an available waveband for transmission. The ZC coordinator receives the broadcast self-healing requests from both ZR1 (a) and ZR2 (b), as illustrated in Figure 10.

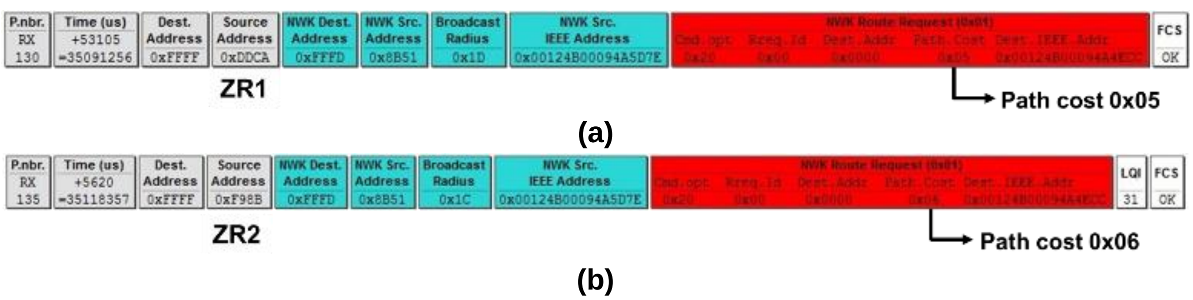


**Figure 10. Data formats of ZR1 (a) and ZR2 (b) self-healing to ZC**

The ZC coordinator subsequently sends a response to both ZR1 and ZR2. In turn, ZR1 and ZR2 relay their responses to ZR3. As illustrated in Figure 10, the path cost for ZR1 is lower at 0x05, compared to ZR2, which has a path cost of 0x06. Consequently, data transfer occurs along the path from ZED to ZR3, then to ZR1, and finally to the ZC, as represented in the corresponding diagram. This preference for ZR1 as the data transfer route is due to its lower path cost. Upon receiving the response to the routing request, ZR3 forwards the data along the path established through ZR1. Figure 11 shows the data transmission process of experiment version 1.

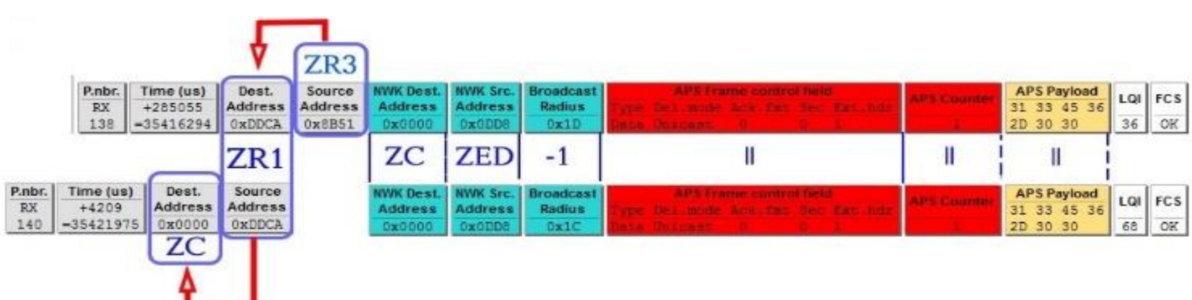


**Figure 11. The data transmission process of experiment version - 1**

When the ZC receives the data, the transmission concludes at T2 = 35,421,975μsec, marking the completion of the transmission. Consequently, the total transmission time is calculated as ΔT = T2 - T1 = 395,667 μsec, which is equivalent to 0.4 sec.

### 3.2 Experiment Version-2

Here, when transmitting data from the ZED module to ZC, a new direction is not determined, and the transmitting module reads the value of the neighbor table and immediately transmits it to the next module using experiment version 1. Table 1 presents an overview of the transmitter's neighbor table.

**Table 1. The routing table of ZigBee modules**

| No | Determined address | Determined the address of the next module |
|---|---|---|
| ZC | ZED (0x0DD8) | ZR1 (0xDDCA) |
| ZR1 | ZED (0x0DD8) | ZR3 (0x8B51) |
| ZR2 | - | - |
| ZR3 | ZC (0x000) | ZR1 (0xDDCA) |

The data transfer diagram of experiment version 2 is shown in Figure 12.

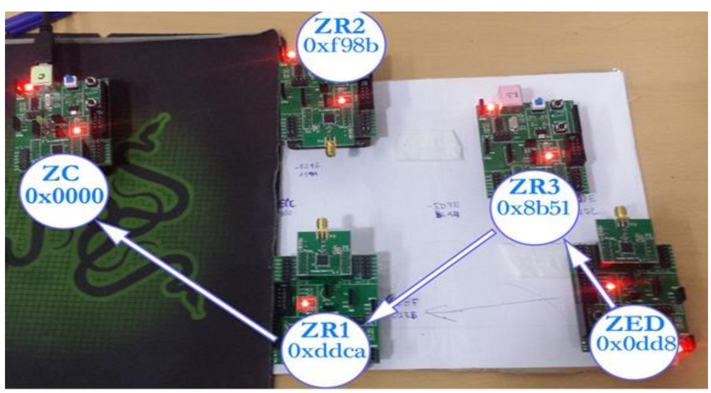


**Figure 12. Data transfer diagram of experiment version - 2**

As illustrated in Figure 13, the data is successfully received from the ZC, indicating the completion of the transmission.


**Figure 13. Direct transfer process from ZR1 module to ZC**

The transmission start time is recorded as T1 = 37,025,313 μsec. The transmission concludes at T2 =

37,037,947µsec, resulting in a total transmission time of ΔT = T2 - T1 = 12,634 µsec, which is equivalent to 0.01sec.

### 3.3 Experiment Version-3

This experiment was conducted using the model depicted in Figure 14, which involved deactivating the ZR1 module and subsequently implementing self-healing mechanisms for data transmission. In this manner, the transmitter executes self-healing procedures to facilitate data transmission. An error occurred during the forwarding process along the previously established route, specifically denoted as DAPSC_MAX_FRAME_RETRIES, resulting in three failed retry attempts. As ZC is present in the neighbor table of router ZR3, the data is forwarded directly to ZC.

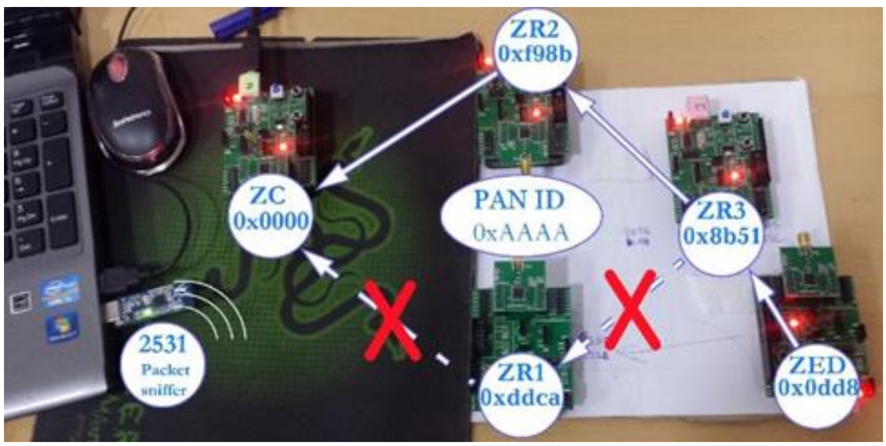


**Figure 14. Experiment model for version - 3**

When the data is received from the ZC and sent back, it is directed to ZR1, as ZR1 is the next device in the path specified by the neighboring table for transmission to the ZED module. In the event of an error, the system will attempt to retry the transmission three times. If all retries fail, a new direction will be determined, as illustrated in Figure 15.


**Figure 15. Structure when DAPSC_MAX_FRAME_RETRIES=3 errors**

When the ZED module transmits data, it will do so via its parent device. Therefore, the designated address must first be set to transmit the data to ZR3. The initial broadcast radius is set to 0x1E, and the transmission begins at T1 = 13,637,473µsec.

ZR3 receives the data and subsequently broadcasts a self-healing request. ZR2 stores the relevant data from the incoming information in both its routing table and route discovery table and then broadcasts it for further dissemination. At this point, the ZC receives the routing request and proceeds to send a response. The data received at ZR2 is subsequently forwarded back to ZR3. At ZR3, direction definition responses are received from both ZR2 and ZC. Given that ZR2's response has a lower path cost, ZR3 selects this path for transmitting information. Select the safest route for transmission. The data packet of the self-healing responses from the ZC and ZR2 are shown in Figure 16.

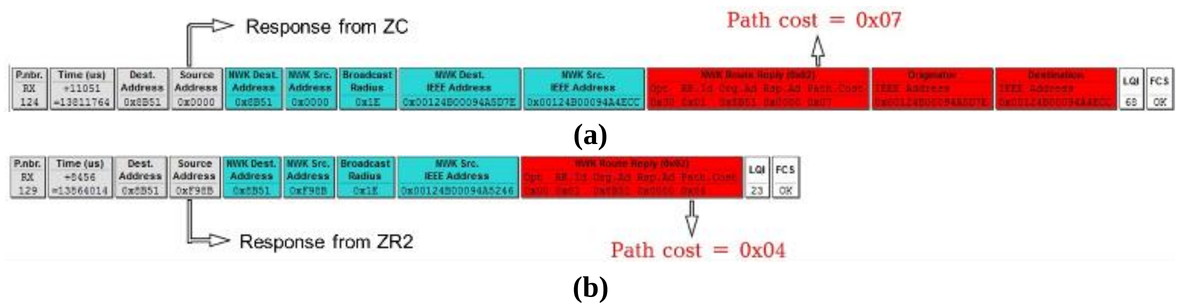


**Figure 16. Self-healing responses of ZC (a) and ZR2 (b)**

Upon completion of the self-healing process, the address of the next device is retrieved from the routing table, enabling direct transmission, as depicted in Figure 17.

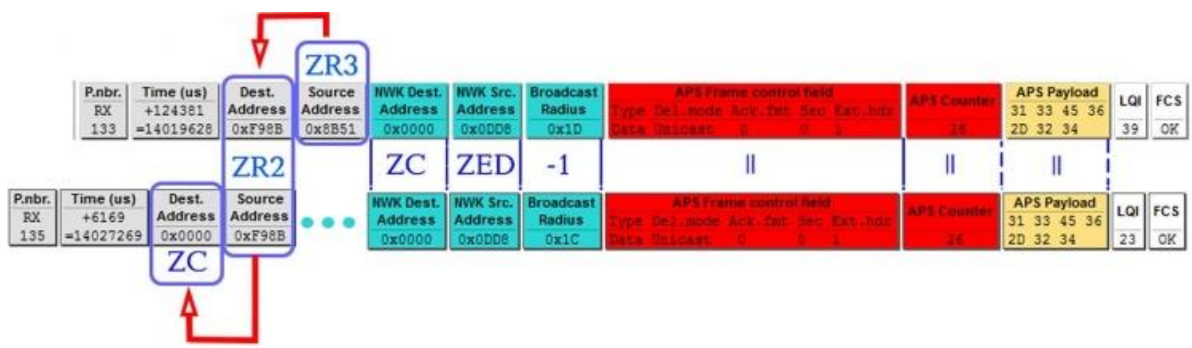


**Figure 17. The data transmission process of experiment version - 3**

The transmission concludes at T2 = 14,027,269 µsec, resulting in a total transmission time of ΔT = T2 - T1 = 389.796µsec, which is equivalent to 0.4 seconds.

### 3.4 Experiment Version-4

In this instance, when transmitting information from the ZED to the ZC, a new direction is not established. Instead, the transmitting device retrieves the relevant value from the routing table and directly transmits it to the next module using experiment version 3. Calculating the transmission time as illustrated in Figure 18, we find ΔT = T2 - T1 = 15,803,647 µsec - 15,790,304 µsec = 13.343 µsec, which is equivalent to 0.01 seconds. Figure 18 shows the data transmission process of experiment version 4.


**Figure 18. The data transmission process of experiment version - 4**

Table 2 summarizes the time spent under various transmission conditions for each test scenario.

**Table 2. Data transfer time of evaluation version**

| No | Experiment | Experiment conditions | Time (msec) |
|---|---|---|---|
| 1 | Version-1 | All modules will operate collaboratively, implementing self-healing mechanisms while transmitting data | 0.4 |
| 2 | Version-2 | Do not establish a new direction, transfer data along the path defined in version 1 | 0.01 |
| 3 | Version-3 | Deactivate ZR1 and transfer data through ZR2 | 0.4 |
| 4 | Version-4 | Transfer data along the direction established in version 3 | 0.01 |

## 4. Conclusion

A real mesh network was created using ZigBee modules, including the coordinator (ZC), routers (ZR), and end devices (ZED). Data transmission experiments between the ZigBee modules were carried out utilizing the Ad hoc On-Demand Distance Vector (AODV) routing protocol. The ZEDs transmit data to the ZC module via a shared ZR module, independent of their geographical locations. The experiment was conducted in four versions, employing the AODV routing protocol within a mesh network. Consequently, key functionalities of the AODV protocol, including mesh self-healing and link cost determination were modified. As demonstrated in experiment version 1 in Table 2, during the self-healing process, all modules within the network participate, resulting in a transmission time of 0.4 seconds. Once the transmission direction was established in experiment version 2, data was transmitted in 0.01 seconds, achieving a speed 40 times faster than that of experiment version 1.

In test version 3, ZR1 was deactivated to simulate potential issues with the ZigBee router modules, such as dead batteries or mechanical failures. At this point, the ZED redefines the data path through self-healing and successfully transmits the data via ZR2 in 0.4 seconds. Once the transmission direction was established in experiment version 4, data was transmitted in 0.01 seconds, achieving a speed 40 times faster than that of experiment version 3.

Thus, ZigBee mesh networks demonstrate suitability for monitoring and controlling systems in expansive areas that are challenging to manage manually, such as agricultural fields, vegetable gardens, oil refineries, and mining sites. In the future, it will be essential to deploy ZigBee modules in a real-world environment to establish a mesh network and conduct experiments on data transmission. Additionally, there are plans to develop a monitoring program that will oversee and analyze data collected from the ZigBee modules.

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