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Implementation of a wireless multi-hop network for supporting oyster farming

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***Abstract*—The labor shortage is a serious issue in oyster farming. To solve this problem, technologies like IoT are considered to automate the collection and management of real-time sensor information such as water quality. Furthermore, oyster farms are often deployed in small spaces, with multiple tanks and frequent movement from workers, so wired communication is difficult to install and maintain. These limitations make it an ideal environment to deploy a wireless multi-hop network. In this work, we created such network that integrates sensors and communication modules, operated by batteries. Our communication system considers a wireless multi-hop network using the popular IoT protocol ZigBee, which is efficient in short-distance communication and has a low energy print. Radio waves are significantly attenuated underwater, therefore, we considered this factor in our evaluations to estimate the communication range accurately. Our preliminary experiments, quantitatively measured underwater communication performance in a controlled environment.**

***Index Terms*—ZigBee, wireless multi-hop network, oyster farming, IEEE 802.15.4, IoT**

I. Introduction

Labor shortages at oyster farms pose a significant challenge, as most tasks are performed manually. To address this issue, many farms are gradually adopting Internet of Things (IoT) farming management systems. Generally, oyster farming occurs at sea; however, to maximize productivity, young oysters must first be cultivated on land for a certain period.

In this study, we focus on facilities that grow young oysters from seedlings. Typically, young oysters are raised in environments where multiple tanks are densely arranged in small spaces, requiring frequent movement of workers between these tanks. In such settings, implementing a wired communication system can be inconvenient.

To overcome this challenge, we propose a wireless communication system that integrates sensors and communication devices capable of exchanging information in a multi-hop fashion. This system is designed specifically for indoor oyster farming. We have taken into account some unique aspects of the deployment environment, such as signal attenuation caused by installing wireless communication modules underwater or near water tanks, as well as the typical limitations of indoor communication.

The remainder of this paper is organized as follows: Section II presents related research pertinent to this work, followed by Section III, which describes the experiments conducted in our simulated deployment environment. Finally, we present our conclusions.

II. Background

In recent years, there has been significant research involving the Internet of Things (IoT) in the agriculture, forestry, and fisheries industries. For instance, in oyster farming at sea, 5G technology has been utilized in underwater drones [1] to transmit high-quality images in real-time and operate the drones without lag. This advancement allows for a better visual understanding of underwater conditions, thereby improving productivity in these farms. However, a drawback of using this technology is that 5G remains expensive for most users and requires high power consumption, which can limit its applications.

In other studies [2, 3], Wi-Fi has been employed to gather data from water quality sensors and to monitor conditions in aquariums in real-time. In these cases, the communication modules are installed on land, with power supplied to the underwater sensors through cables. As a technology that is familiar to most users, Wi-Fi is easy to set up and operate. However, its multihop capabilities (Ad-hoc) are seldom utilized or supported, and its energy consumption can still be too high for battery-operated systems to function for extended periods.

To address the need for a wireless, multi-hop system with low energy requirements, other systems have implemented protocols such as ZigBee in smart irrigation systems [4]. These systems have reportedly succeeded in monitoring soil moisture in real-time while maintaining low energy consumption, which has led to increased productivity. ZigBee is a suitable communication standard due to its low power requirements; however, there have been few applications of it in underwater or near-water environments.

Other research [5] has evaluated the performance of underwater wireless communication using IEEE 802.11 (Wi-Fi). These evaluations considered factors such as temperature, communication distance, and data transfer rates. The results indicated that data transfer rates did not have a significant impact on communication distance, and that the stability of communication primarily depended on frequency and temperature. Since IEEE 802.11 operates on the same 2.4 GHz band as ZigBee (see IEEE 802.15.4), it is believed that the degree of signal attenuation is similar. However, ZigBee has a lower transmission power, resulting in a shorter actual communication distance.

The following section describes our own experiments using ZigBee in underwater and near-water environments.

III. Experiments

If the sensor and communication module are connected by wire, the cable must be positioned to avoid a physical cable, the cable will need to be replaced frequently due to deterioration over time, and its position will need to be corrected due to changes in water currents. This problem can be solved by integrating the sensor and communication module and immersing it in water. However, communication radio waves are attenuated underwater. Therefore, the experiments described in this section aim to quantitatively measure the communication range of a multi-hop capable node placed underwater. To achieve this, we prepared an environment with no obstacles other than the water tank where is placed.

A. Experiment setup

We used monostick [6] communication radio devices (MCU: NXP JN5169) for these experiments. These devices are widely available, inexpensive, and relatively easy to program compared to similar alternatives. The firmware flashed onto the MCU includes the IEEE 802.15.4 (PHY & MAC) standard along with ZigBee 3.0 and our custom control application.

In addition to the communication radio module, we combined Raspberry Pi (models 3B+ and 5) with batteries (Sugar Pi) to create our integrated nodes. Initially, we prepared two such nodes: one acts as an end device, and the other serves as a coordinator. The communication radio devices installed in these nodes were positioned to face each other.

We developed a program to generate dummy data that mimics the characteristics of actual sensor data on the Raspberry Pi connected to the end device. This data is transmitted to the communication radio (identified as NXP JN5169) via the Universal Asynchronous Receiver-Transmitter (UART) protocol. The contents of the sensor data transmitted via UART are (Figure 1):

- **Sensor number:** Represents the type of sensor used.
- **Packet handle:** Used to distinguish between packets.
- **Sensor data:** The actual sensor data transmitted.

Sensor Number	Packet Handle	Sensor Data
(1byte)	(1byte)	(2bytes)

Fig. 1. Data Structure for end device UART and wireless communication

Upon receiving the sensor data via UART, the communication radio retransmits the same data structure, as described in Figure 1, wirelessly to the coordinator. When the sensor data reaches the destination coordinator from the end device, the following information is added to the packet:

- **LQI:** The Link Quality Indicator (LQI) for the received packet.
- **Short Address:** The 16-bit address of the transmitting device.

The updated packet, now containing this additional information, is sent to the connected PC via UART communication (refer to Figure 2). The area surrounded by the dashed line in Figure 2 indicates the added information included upon reception. The LQI value reflects the quality of the radio communication and is expressed numerically from 0 (indicating low quality) to 255 (indicating high quality). A LQI value below 50 is considered to represent a low-quality link, while a value above 150 indicates a good quality link.

Sensor Number	Packet Handle	Short Address	LQI	Sensor Data
(1byte)	(1byte)	(2bytes)	(1byte)	(2bytes)

Fig. 2. Data Structure for coordinator UART communication

A program was created to display the contents of the received packet, and it was set up on the PC connected to the coordinator radio communication device.

B. Experimental Results

In our initial experiments, we measure the LQI values of receiving packets by variating the distance between the 2 communicating nodes and set our nodes in 1 of 3 possible situations:

1) We set our nodes in a line of sight (LoS) without water tanks or any other visible obstructions (Figure 3).

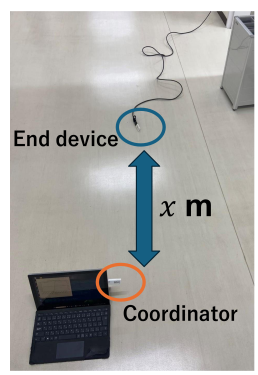

Fig. 3. First configuration: line of sight (LoS)

2) We submerged a single node in a water tank . The second communicating node remains outside a water tank (See Figure 4). When submerging the node, we removed as much air as possible from the sealed bag surrounding the node before conducting the experiment. The submerged node was placed at the center of the tank and it is surrounded by water in all directions. The node submerged into the tank was the end device (the node generating the dummy sensor data). Figures 5 and 6 show the placement of the node in the water tank.

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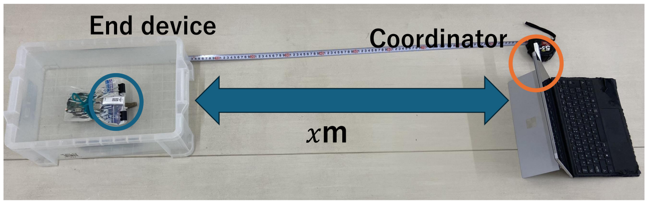

Fig. 4. Second Configuration: 1 node in water tank

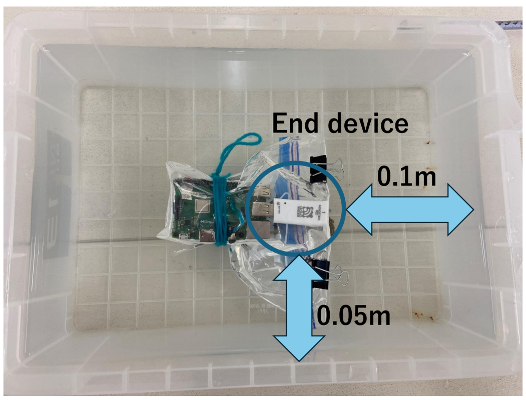

Fig. 5. Node in water tank (view from above)

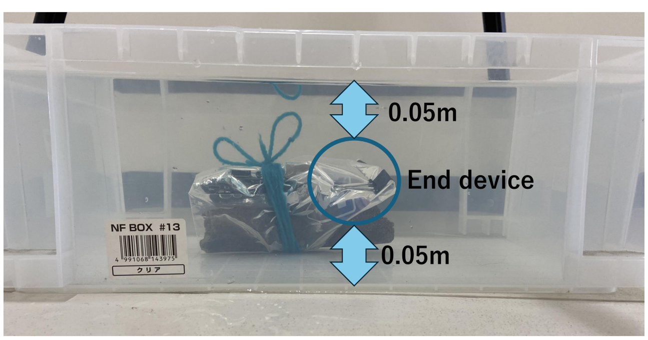

Fig. 6. Node in water tank (side view)

3) In our final configuration, we evaluated the communication quality when both nodes were submerged into water tanks. Figure 7 below shows the configuration of the experiment.

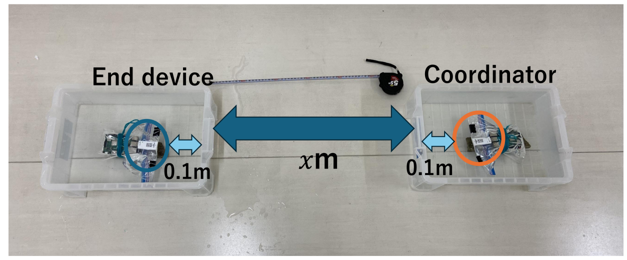

Fig. 7. Third Configuration: 2 nodes in water tanks

Figure 8 shows the results of our LQI evaluations using the described 3 configurations.

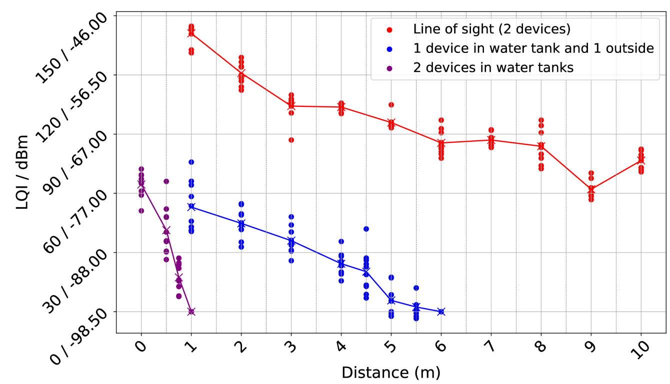

Fig. 8. Evaluation LQI over distance (2 nodes)

The vertical axis shows the LQI value in both LQI and dBm. For easy reading, LQI was also converted to a normalized unit dBm with the Equation (1) [6]. The horizontal axis shows the distance from the tank in meters.

$$P = \frac{7 \times LQI - 1970}{20} [dBm] \tag{1}$$

In the experiment, 10 packets were sent 10 times for each distance and the results were averaged. Experiments with the devices set within light o sight show the expected results of a linear decrease the LQI values as the distance increased. Unlike the LoS experiment, when a single end device was sumerged in a water tank, the maximum communication distance was registered at 6 meters with a less than optimal LQI values. Likewise it is possible to observe a sharp decrease of LQI values when both devices were sumerged in water tanks achieving only LQI optimal values when the distance between tanks remained within 1 meter.

Figure 9 shows the packet loss for the same experiment. The vertical axis represents the percentage of packet loss registered during the experiment. In our experiments, no packet loss was registed at any of the distances measured for the line of sight configuration, therefore, these are not shown in the Figure.

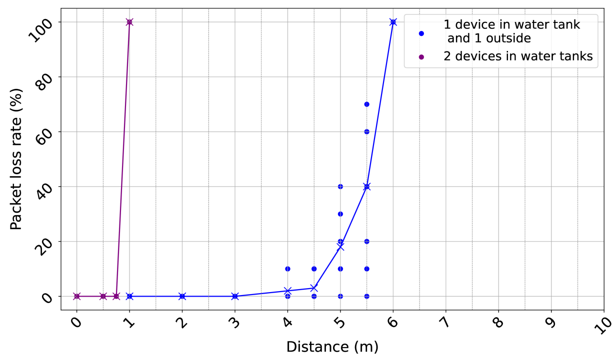

Fig. 9. Packet Loss Rate

The experiment demonstrated that packet loss ranged from 20% to 70% at distances between 4 and 5.5 meters when using a configuration with a single water tank. In contrast, when two water tanks were utilized, there was complete packet loss beyond 1 meter. This indicates that specific considerations must be addressed when establishing a communication system in an oyster farm, particularly when the communication nodes are located inside water tanks.

To address the issues identified in our previous experiments, we propose a network that facilitates communication between an end device and a coordinator, even when they are more than 5.5 meters apart and located inside water tanks. This is accomplished by installing a router device to bridge the distance between them. A simplified version of the proposed network is illustrated in Figure 10.

The I2C communication protocol allows multiple devices to connect on a single bus, making it easy to incorporate a variety of sensors. The data collected by the sensors is transmitted to a Raspberry Pi using I2C communication. Once the Raspberry Pi receives the sensor data, we use UART communication to relay this information between the Raspberry Pi and the NXP JN5169. In our experiments, we encountered no significant data loss when utilizing UART communications.

After the NXP JN5169 receives the sensor data, it wirelessly transmits this information using the ZigBee protocol integrated within the NXP JN5169. Finally, once the coordinator node collects the sensor data, it is sent to a PC via UART and displayed on a monitor for verification.

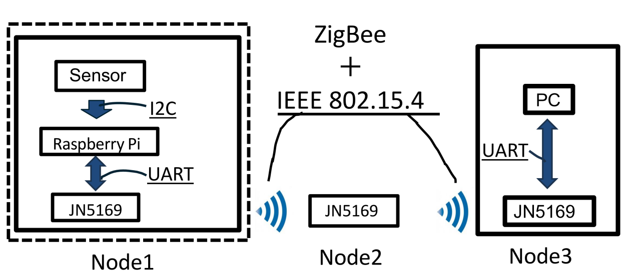

Fig. 10. Data Flow of Sensor Node

To evaluate the effectiveness of the proposed setup, we conducted an experiment where the router node was installed near a tank containing an end device submerged in water. The coordinator was kept out of the water, and communication was assessed by varying the distance (x) between the end device and the router. This distribution is illustrated in Figure 11. Communication was evaluated at intervals of one meter.

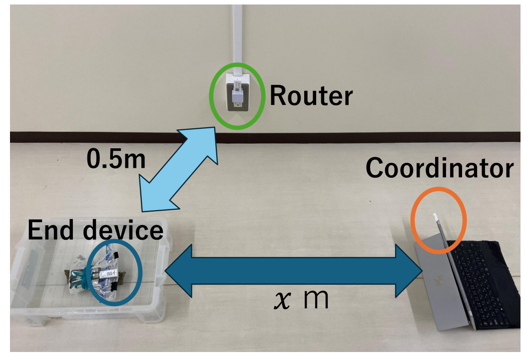

Fig. 11. Multi-Hop network: End device, router and coordinator

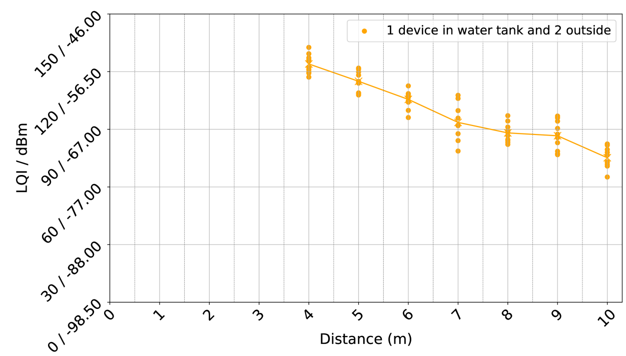

Fig. 12. Multi-hop network evaluation

Figure 12 presents the results of our multi-hop network evaluation. Similar to our previous tests, we conducted an average of 10 iterations at each distance. In earlier experiments, we observed that communication was only possible up to 5.5 meters when one device was submerged in a water tank. However, by installing a router, we were able to extend the effective communication area significantly. This finding demonstrates the effectiveness of the wireless multi-hop network, even in challenging conditions. Notably, in this experiment, we achieved communication without any packet loss.

IV. Conclusions

This study examined the setup and performance of a multi-hop network in challenging communication conditions similar to those found in an oyster farming environment. The results demonstrated that it is feasible to overcome significant signal attenuation, caused by environmental factors like water tanks, by using a multi-hop network instead of a single-hop network. The experiments indicated that this approach can serve as a cost-effective alternative to technologies like 5G and Wi-Fi, particularly in scenarios with unique constraints, as outlined in our findings.

Although the experiments were conducted in a controlled setting, future works plan to extend this research by incorporating real-time sensor data, expanding the size of the multi-hop network, and deploying it in an actual oyster farm environment.

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