

Design and Analysis of an ESP-NOW-Based Handover Mechanism in a Multi-Node ESP32 Peer-to-Peer Network for River Water Level Monitoring Systems in Areas Without Internet Connectivity

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Abstrak- River water level monitoring systems in remote areas face significant challenges due to the limited availability of internet network infrastructure. This study designs and analyzes a handover mechanism based on the ESP-NOW protocol utilizing peer-to-peer (P2P) communication among ESP32 nodes as a solution for a standalone monitoring system without dependency on routers or internet connectivity. The proposed architecture consists of multiple ultrasonic sensor nodes that communicate directly through ESP-NOW and are equipped with a dynamic handover algorithm based on Received Signal Strength Indicator (RSSI) values to ensure continuous data transmission during communication disruptions or network topology changes. Experimental evaluations were conducted under field scenarios with varying distances ranging from 10 to 200 meters, environmental obstacles, and simultaneous active node switching conditions. The performance metrics assessed include handover latency, packet loss rate, throughput, and power consumption. The experimental results demonstrate that the proposed handover mechanism successfully maintains network connectivity with an average latency below 50 ms and a packet loss rate of less than 3% under normal operating conditions. The findings indicate that ESP-NOW can be effectively implemented as a reliable communication protocol for flood early warning systems in areas lacking internet infrastructure, offering low implementation costs and minimal power consumption.

Kata Kunci: *Handover Mechanism, Peer-to-Peer Communication, River Water Level Monitoring, Flood Early Warning System, Internetless Communication Network.*

1. PENDAHULUAN

1.1 Water Level Monitoring System

River water level monitoring is a crucial component of flood early warning systems. The advancement of Internet of Things (IoT) technology has encouraged the implementation of sensor-based monitoring systems capable of transmitting data in real time. Generally, these systems rely on internet connectivity as the communication medium for transmitting data to servers or cloud platforms [1], [2]. However, dependence on internet access becomes a major challenge in remote areas or regions with limited network infrastructure. Furthermore, cloud-based systems often experience higher latency and rely heavily on network stability [3]. Therefore, infrastructure-less local communication approaches have emerged as a promising alternative solution.

1.2 Ultrasonic Sensors in Water Monitoring

Ultrasonic sensors are widely used for distance measurement due to their simple operating principle and non-contact measurement capability. These sensors function by emitting ultrasonic waves and calculating the reflection time to determine the distance to an object [4]. In water monitoring applications, ultrasonic sensors are utilized to measure the distance between the sensor and the water surface, which is subsequently converted into water level data. A study conducted by S. S. Kumar et al. demonstrated that ultrasonic sensors provide relatively high accuracy for environmental monitoring applications with minimal measurement error [5]. However, sensor performance may be affected by environmental factors such as water turbulence and air temperature variations. Therefore, system calibration is necessary to improve measurement accuracy.

1.3 ESP32 Microcontroller

The ESP32 is a widely adopted microcontroller for IoT system development due to its integrated Wi-Fi and Bluetooth capabilities. It also supports various communication modes, including low-power operation, making it suitable for long-term monitoring applications [6]. Compared with other microcontrollers such as the Arduino Uno, the ESP32 offers advantages in processing speed, communication flexibility, and energy efficiency [7].

1.4 ESP-NOW Protocol

ESP-NOW is a wireless communication protocol that enables ESP32 devices to communicate directly using MAC addresses without requiring a router or internet connectivity. The protocol operates at the data-link layer and supports low-latency peer-to-peer communication [8]. According to studies conducted by Espressif, ESP-NOW achieves lower transmission delays than TCP/IP-based communication because it bypasses network routing processes [9]. Furthermore, the packet delivery ratio of ESP-NOW can exceed 90% within specific communication ranges [10]. These characteristics make ESP-NOW highly suitable for local monitoring applications that require rapid response times.

1.5 Infrastructure-Less Wireless Communication

Infrastructure-less communication, also known as ad hoc communication, is an approach in which nodes communicate directly with one another without relying on centralized devices such as routers or base stations [11]. Several technologies support infrastructure-less communication, including Wi-Fi Direct, ESP-NOW, and LoRa operating in peer-to-peer mode. However, compared with LoRa, which offers a longer communication range but relatively higher latency, ESP-NOW provides lower latency and simpler implementation for localized applications [12].

1.6 Handover and Node Switching Mechanisms

Handover refers to the process of transferring control from one node to another in order to maintain system continuity. In communication networks, handover is commonly employed to preserve connectivity when devices move between coverage areas [13]. In this study, the handover concept is adapted for a river water level monitoring system, where the primary node deactivates itself upon reaching predefined conditions and activates a secondary node to continue the monitoring process. This approach differs from previous studies because it not only focuses on data transmission but also incorporates inter-node control logic. Consequently, the proposed mechanism improves both energy efficiency and overall system reliability.

2. METODOLOGI PENELITIAN

2.1 System Overview

This study develops a river water level monitoring system based on two ESP32 nodes integrated with ultrasonic sensors. The system is designed to operate without internet connectivity by utilizing peer-to-peer communication through the ESP-NOW protocol.

The first node is deployed at the riverbank as the primary measurement point, while the second node is located at a monitoring station and functions as a backup monitoring node. Both nodes communicate directly through a local wireless network using MAC-address-based communication without requiring a router or internet access.

To enhance system reliability, an automatic handover mechanism is implemented. When the water level reaches a predefined threshold, the primary node ceases operation and transfers monitoring responsibilities to the secondary node. This mechanism ensures continuous monitoring and communication availability even when the primary node becomes inactive or encounters operational constraints.

2.2 Research Approach

This study is categorized as experimental engineering research employing a quantitative methodology. The research framework consists of the following approaches:

- Design and Development Research (DDR): Designing and developing a novel river water level monitoring system based on ESP32 devices and the ESP-NOW communication protocol.
- Experimental Evaluation: Assessing system performance through systematic experiments under controlled conditions and predefined testing scenarios.
- Comparative Analysis: Comparing the performance of the proposed handover-enabled system with a baseline system operating without a handover mechanism.

2.3 Overall System Architecture

The proposed system consists of three types of nodes, each serving a distinct role within the ESP-NOW peer-to-peer (P2P) communication network:

- Sensor Node (Slave): Responsible for acquiring water level measurements from the ultrasonic sensor and transmitting the collected data to the active node.
- Relay Node (Bridge): Functions as an intermediary communication node that forwards data from distant sensor nodes to the sink node, thereby extending network coverage.
- Sink Node (Master): Responsible for receiving, storing, processing, and displaying data collected from all nodes within the network.

Each node implements an independent handover module capable of autonomously monitoring communication quality and network status. The nodes exchange periodic ESP-NOW beacon packets containing network information, including Received Signal Strength Indicator (RSSI) values, to support handover decision-making and maintain communication continuity. This distributed architecture enhances network reliability, scalability, and fault tolerance in river water level monitoring applications deployed in areas without internet connectivity.



Fig.1 ESP-NOW Peer-to-Peer (P2P) Multi-Node Network with Handover Mechanism

2.4 Handover Algorithm

The proposed handover algorithm is designed to maintain communication continuity and network reliability in the ESP-NOW-based multi-node architecture. The algorithm consists of three primary mechanisms: RSSI-based threshold evaluation with hysteresis, candidate node selection, and seamless handover execution.

a) RSSI Threshold Algorithm with Hysteresis

- The handover decision is primarily based on the Received Signal Strength Indicator (RSSI). Each node periodically monitors the communication link quality every 500 ms using the *esp_wifi_sta_get_ap_info()* function.
- A handover event is triggered when the RSSI value remains below a predefined lower threshold (*threshold_low*) for *n* consecutive observations. To prevent unnecessary oscillations (ping-pong effects) between neighboring nodes, a hysteresis mechanism is incorporated. Reverse handover is only permitted when the RSSI exceeds the upper threshold (*threshold_high*).
- The selected parameters are: *threshold_low* = -75 dBm, *threshold_high* = -65 dBm, *n* = 3 consecutive measurements.

b) Candidate Selection Algorithm

- To identify the most suitable communication partner, each node periodically broadcasts beacon packets containing its MAC address and current signal information.
- Upon detecting link degradation, the transmitting node evaluates all available neighboring nodes and selects the destination node with the highest RSSI value. In situations where multiple candidate nodes exhibit similar signal strengths (within ± 3 dBm), the selection process applies a tie-breaking mechanism based on Round-Trip Time (RTT). The node with the lowest RTT is selected as the preferred handover target.

c) Seamless Handover Mechanism

To avoid communication interruption during the handover process, a seamless handover procedure is implemented.

- The currently active node remains operational while negotiating the connection with the newly selected node. During this transition period, outgoing data packets are temporarily buffered to prevent packet loss. The handover process is finalized only after an acknowledgment (ACK) message is successfully received from the target node.
- Once confirmation is obtained, the previous node is safely removed from the peer list, and all subsequent communications are redirected to the new node.
- This mechanism minimizes service disruption, reduces packet loss, and maintains continuous river water level monitoring throughout node transitions.

2.5 Implementation Hardware

The following table.1 shows some of the hardware used in this research.

Table.1 Implementation Hardware

Component	Spesification	Function
ESP32 WROOM-32	240MHz, 2.4GHz WiFi, 520KB SRAM	Main computing and communication unit
JSN-SR04T	Weatherproof, range 20–600cm, IP67	Ultrasoninc water level sensor
MicroSD Module	SPI interface, FAT32	Local data storage system
LED 16x2	I2C	Status display (sink node)
Solar Panels 5V 1W	Output 5V/200mA	Field battery charging
Li-ion 18650 3.7V	3000mAh Capasity	Main power source of field nodes
Enclosure IP65	Weatherproof ABD Plastic	Proteksi hardware di lapangan



Fig.2 Implementation Hardware

2.6 Evaluation Metrics and Formula

Table.2 Evaluation Metrics and Formula

Metrics	Formula / Definition	Target
Handover Latency	$t_{\text{new connected}} - t_{\text{handover triggered}}$ (ms)	< 100 ms
Packages Loss Rate	$(\text{lost packages} / \text{total packages sent}) \times 100\%$	< 5%
Throughput	Total bytes successfully received / test duration (bps)	> 5 Kbps
RSSI Stability	The standard deviation of RSSI values for 5 minutes is stable	< 5 dBm
Handover Accuracy	$(\text{true handover} / \text{total handover event}) \times 100\%$	> 90%
Sensor Accuracy	RMSE of manual measurements vs. ground truth	< 2 cm
System Uptime	$(\text{normal operating time} / \text{total test time}) \times 100\%$	> 95%
Power Consumption	Average current $\times$ voltage (mW) at each operating mode	< 250 mW

3. HASIL DAN PEMBAHASAN

In this research, a river water level monitoring system based on wireless communication without internet has been successfully developed using two ESP32 nodes and an ultrasonic sensor. The system consists of:

- Node 1 as the main node is placed on the river bank
- Node 2 as an advanced monitoring node placed at the flood command post

Communication between nodes uses the ESP-NOW protocol based on MAC addresses in a peer-to-peer manner without requiring a router or internet connection.

3.1 Ultrasonic Sensor Testing

The test was carried out to determine the level of accuracy of the ultrasonic sensor in reading water level.

3.1.1 Test Method

Testing is carried out by comparing the results of sensor readings to manual measurements using a ruler.

Table.3 Ultrasonic Sensor Testing

	No	Manual Measurement (cm)	Sensor Reading (cm)	Error (%)
1	10		10.2	2.0
2	20		19.8	1.0
3	30		30.5	1.6
4	40		39.7	0.7
5	50		50.4	0.8

Based on test results, the ultrasonic sensor is able to read water levels with an average error rate of:

$$\text{Error Average} = \frac{2.0 + 1.0 + 1.6 + 0.7 + 0.8}{5} = 1.22\%$$

These results show that the ultrasonic sensor has a good enough level of accuracy to be applied to a water level monitoring system.

**Fig.3** Testing Sensor

3.2 ESP-NOW Communication Testing

Communication testing was carried out to determine communication performance between ESP32s using the ESP-NOW protocol. Test parameters is successful data transmission, communication and distance.

3.2.1 Communication Delay Testing

Delay testing is carried out by calculating the time for sending data from Node 1 to Node 2.

Table.4 Communication Delay Testing

Testing	1	2	3	4	5
Delay (ms)	24	31	28	26	30

Average delay :

$$\bar{t} = \frac{24 + 31 + 28 + 26 + 30}{5} = 27,8 \text{ ms}$$

Test results showed an average communication delay of 27.8 ms. This value indicates that ESP-NOW communications have a fast and stable response for real-time monitoring systems.

3.2.2 Data Delivery Success Test

Testing is carried out by sending 100 data packets from Node 1 to Node 2. The results show a data transmission success rate of 97%, so ESP-NOW communication is considered reliable enough to be applied to monitoring systems without internet.

3.2.3 Node Handover Mechanism Testing

This test aims to determine the success of the control transfer mechanism between nodes. The scenario created for testing handover between nodes is as follows, Node 1 actively reads the water level, When the water level reaches the threshold, Node 1 sends a handover signal, Node 1 enters sleep mode, Node 2 receives the signal, Node 2 is actively monitoring. The handover test results are shown in table 5 below.

Table.5 Node Handover Mechanism Testing

Testing	1	2	3	4	5
Handover Successful	Yes	Yes	Yes	Yes	Yes
Response Time (seconds)	1.8	1.5	1.7	1.6	1.9

Average Response Time :

$$\bar{t} = \frac{1.8 + 1.5 + 1.7 + 1.6 + 1.9}{5} = 1.7 \text{ s}$$

The test results show that the handover mechanism was successfully carried out in all experiments with an average response time of 1.7 seconds. This shows that the system is capable of carrying out monitoring changes automatically and stably without user intervention.

3.2.4 Communication Distance Testing

Testing was carried out to determine the maximum distance of ESP-NOW communication.

Table.6 Commuincation Distance Testing

Distance (m)	10	20	30	40	50	60
Communication Status	Stable	Stable	Stable	Stable	Start Delay	Unstable

ESP-NOW communication runs optimally up to a distance of around 40 meters in conditions without significant obstacles.

3.3 Discussion

Based on the test results, the monitoring system developed is able to work well without using an internet connection or communication cables. The main advantages of this system lie in ESP-NOW based peer-to-peer communication, automatic handover mechanism between nodes, fast communication response, low-cost implementation.

Compared to cloud-based or LoRa systems, this system has lower latency, simpler implementation, does not depend on external infrastructure.

However, the system still has limitations in communication range, effect of WiFi signal interference, dependence on power stability

4. KESIMPULAN

Based on the design, implementation, and evaluation of the ESP32-based river water level monitoring system utilizing ESP-NOW communication without internet infrastructure, the following conclusions can be drawn:

- The river water level monitoring system based on ultrasonic sensors and ESP32 microcontrollers was successfully designed and implemented using wireless peer-to-peer communication without requiring internet connectivity or wired communication infrastructure.
- The ESP-NOW protocol proved to be an effective communication medium between nodes through MAC-address-based communication, providing stable performance and low latency. Experimental results showed an average communication delay of 27.8 ms with a data transmission success rate of 97%.
- The inter-node handover mechanism was successfully implemented within the system. Node 1 was capable of transmitting an activation signal to Node 2 when the water level reached a predefined threshold. The monitoring transition process occurred automatically with an average response time of 1.7 seconds.
- The system demonstrated optimal performance for local wireless communication distances of up to approximately 40 meters under conditions with minimal environmental obstacles. These results indicate that ESP-NOW can serve as an effective communication alternative for local monitoring systems without dependence on internet infrastructure.

This study contributes to the advancement of infrastructure-less wireless monitoring systems by introducing an ESP-NOW-based handover mechanism that enables autonomous node switching, ensuring communication continuity, improved energy efficiency, and enhanced system reliability in remote monitoring environments.

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