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Optimisation of Node Placement Using Wireless Mesh for Machinery Monitoring: A Case Study in Industrial Facilities

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***Abstract*—This study investigates the effect of sensor node placement and optimises it within a wireless mesh network for Condition-Based Monitoring (CBM) of industrial machinery. It evaluates network performance across baseline, standalone, and optimised topologies with a particular focus on total latency. Results demonstrated significant improvements in network performance, especially reducing total latency for Node 4 from 13.5 minutes to as low as 7 minutes through strategic node placement. Detailed analysis using the wireless mesh evaluation (Ev) kit showed a correlation between the Received Signal Strength Indicator (RSSI) and latency results. These findings conclude that strategic node placement can effectively minimise latency and ensure stable connectivity. This is important in order to get reliable data transmission, especially in challenging environments for wireless networks.**

***Keywords*—Wireless mesh, Node placement, Condition-based monitoring.**

I. INTRODUCTION

Condition-based monitoring (CBM) is widely used in industry to monitor machine health. CBM involves continuous collection and analysis of vibration and temperature data to detect abnormalities in machine behaviour. It relies on real-time data to predict potential issues. This will allow maintenance teams to address them early before they lead to downtime or equipment damage [1, 2].

Beyond real-time monitoring, on-demand data collection is equally important for detailed troubleshooting of machinery. While continuous monitoring offers an overview of machine health, on-demand data, such as detailed vibration analysis, for instance, are usually requested only when initial anomalies are observed. This data is essential for identifying specific mechanical faults, such as bearing degradation or misalignment, thereby enabling precision [3].

Traditional CBM systems normally depend on wired sensor networks. The installation of this system, however often faces challenges such as high installation and maintenance costs and complicated rollouts [4]. On the other hand, Wireless Sensor Networks (WSNs) offer a flexible alternative within the Industrial Internet of Things (IIoT) framework. The WSNs allow remote data collection and transmission of sensor data to be done in real-time. Nevertheless, the performance of WSNs depends on node placement, which is influenced by factors such as latency, coverage, energy consumption, and network reliability [4]. Several factors need to be considered before the implementation of WSNs in complex industrial environments to ensure connectivity and reliable data flow. It includes physical obstructions and electromagnetic interference from machinery. Therefore, proper node placement becomes important [5, 6].

To address this issue, a wireless mesh network has been introduced. With their self-organising and multi-hop architecture, wireless mesh enables sensor nodes to relay data through intermediate nodes while at the same time maintaining reliable communication [7]. Wireless mesh networks also can improve connectivity by using multiple short-range hops to extend wireless coverage [8]. This capability makes wireless mesh networks

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suitable for condition-based monitoring of industrial machinery.

Available wireless mesh technologies such as Wirepas Mesh and Bluetooth Low Energy (BLE) Mesh further strengthen the case for implementing decentralised CBM systems. The protocols used in this technology support dynamic routing, redundancy, and self-healing properties. It will help to maintain stable communication even when individual nodes fail or network conditions change [9, 10].

This paper investigates the effect of sensor node placement and optimises it within a wireless mesh network for Condition-Based Monitoring (CBM) of industrial machinery. The network performance under various topological arrangements will be measured and analysed. The findings from this study provide practical insights for deploying wireless mesh-based CBM systems in real environments.

II. MATERIAL AND METHOD

The experimental work for designing an effective methodology for node placement in a wireless mesh network involves several steps. It includes node placement strategy, optimisation, and testing.

The node placement strategy was guided by referring to three key objectives. It comprises optimising signal strength (RSSI), minimising unnecessary hops, and balancing traffic load across the network [6]. The optimisation will be focused on reducing hop count, improving RSSI, and balancing traffic by introducing additional relay nodes. The testing part, on the other hand, will be emphasised on measurement and analysis of total latency, RSSI, and hop count. [3, 5-9].

A. Machinery Facility Environment

The experiment was conducted at the basement parking level where the machinery facility room is located. A centrifugal water pump system is installed for facility management in this room. This environment posed challenges for wireless communication, including physical obstructions, dense material structure, and electromagnetic interference generated by both operational equipment and nearby parked vehicles.

While the study was carried out in a specific location, the characteristics of this environment closely resemble those found in many typical industrial facilities such as factories, utility plants, and mechanical rooms where wireless communication is frequently hindered by similar issues. These shared conditions make the findings of this study relevant and applicable to a wide range of industrial scenarios involving wireless mesh network deployments.

The selection of this site for this study also reflects key attributes of complex industrial environments, including signal attenuation from metal enclosures, interference, and non-line-of-sight connectivity challenges. The methodology and optimisation strategies used, particularly those involving node placement, hop count management, and RSSI-aware routing, can be adapted and scaled for use in other industrial environments to enhance network robustness and ensure reliable data transmission.

B. Sensors

The industrial vibration sensor nodes were used to monitor the tri-axial vibration and temperature of the centrifugal water pump. These compact, energy-efficient nodes are well-suited for industrial environments and provide reliable data on machinery health. The sensor nodes transmit data wirelessly to a central gateway using Wirepas Mesh technology.

C. Gateways

The IoT gateway collects data from the sensor nodes and transmits it to the IoT platform. The gateway supports both wired and wireless connectivity and is enclosed in a protective casing designed for rugged industrial environments. It enables communication between hundreds of sensor nodes, ensuring comprehensive monitoring of the machinery. In this study, the gateway is connected primarily via cellular networks, with Wi-Fi as a backup. Figure 1 illustrates the sensor node and gateway.

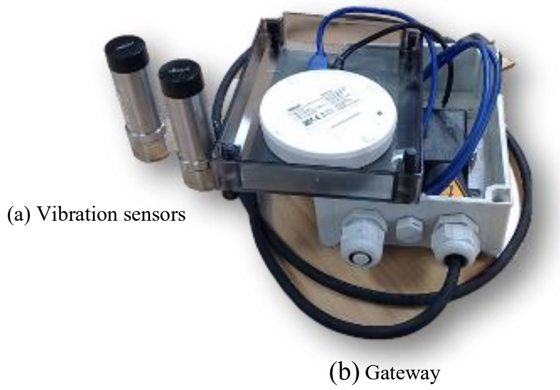

Fig. 1. Illustration of industrial (a) vibration sensor node and (b) gateway.

D. Node Placement & Test Setup

Table I. List of sensors and locations.

No.	Sensors Label	Distance from Gateway, m	Remarks
1	NODE 1	65	-
2	NODE 2	70	-
3	NODE 3	60	-
4	NODE 4	70	-
5	P1	5	Chilled water pump
6	P2	5	Chilled water pump

The primary objective of this study is to evaluate the impact of node placement on network performance in wireless mesh network topologies. Initially, sensor nodes, as shown in Table I, were placed at distances ranging from 5 to 70 metres from the gateway, as illustrated in Fig. 2. In this initial setup, some nodes showed an offline status, indicating no direct connection to the gateway due to physical obstacles. Sensors P1 and P2 were placed on the centrifugal pump of the chilled water system; however, only Nodes 1, 2, 3, and 4 are discussed in this paper.

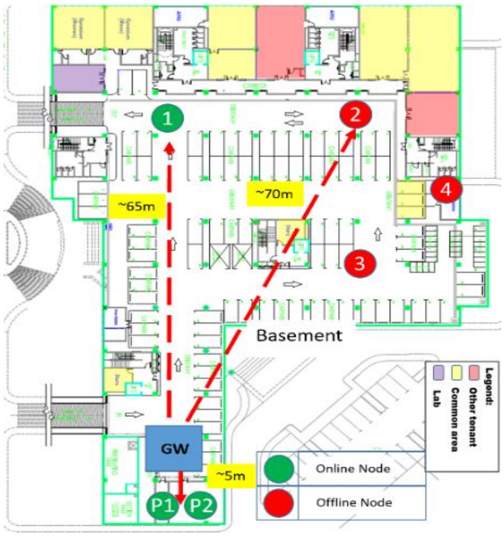

Fig. 2. Illustrate the node placement configurations used in this study.

Using the wireless mesh protocol, sensor nodes transmitted data related to machinery parameters, including vibration data (about 1 KB data size) and detailed on-demand vibration data (about 6 MB data size). The data was chunked and sent through multiple nodes using multi-hop communication, ensuring reliable connections even for nodes located farther from the gateway. Figure 3 illustrates the data flow in this study. The total latency was calculated based on the timestamps of the first and last data packets transmitted.

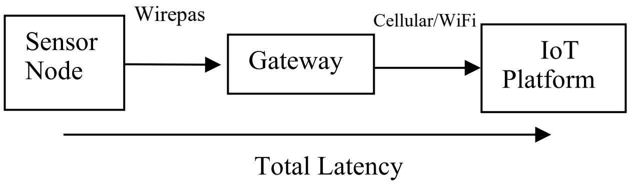

Fig. 3. Illustration of data flow.

E. Data Collection and Transmission

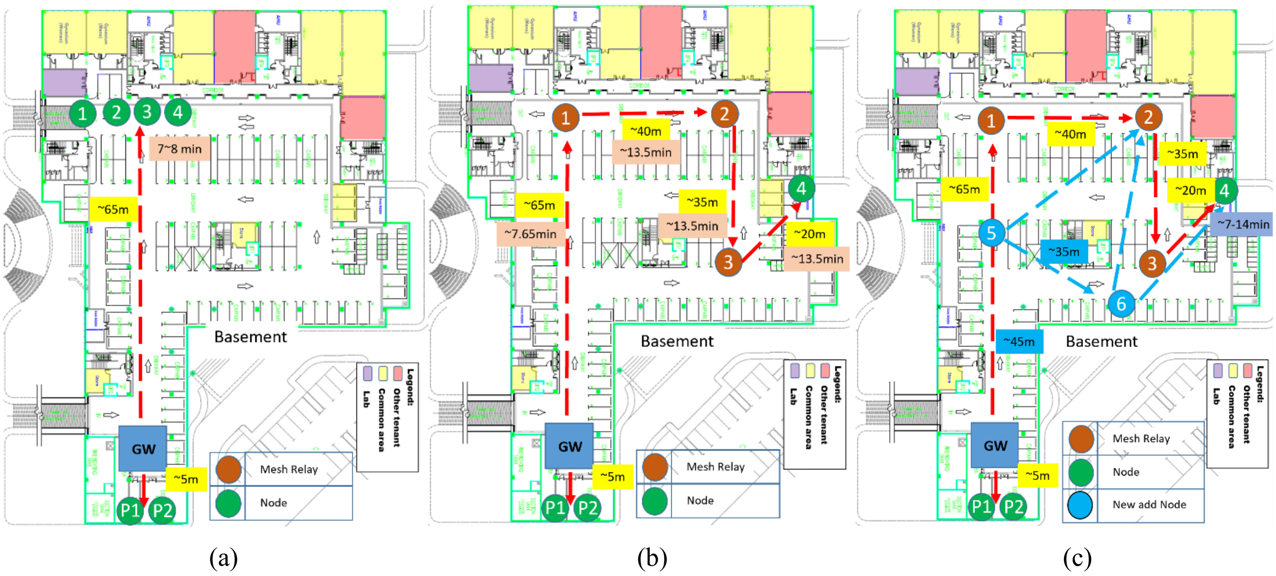

Fig. 4. The network topology and total latency results of (a) baseline, (b) standalone, and (c) optimised test of a node placement in a wireless mesh network.

F. Evaluation Kit (Ev)

To enhance the analysis of network performance, the experiment was repeated with the same topology and node placements using a wireless mesh evaluation kit (Ev kit). This allowed the capture of Received Signal Strength Indicator (RSSI) values at each hop, providing insights into the relationship between link quality and latency.

III. RESULTS & DISCUSSIONS

To evaluate the impact of node placement on the performance of the wireless mesh network for industrial IoT-based machinery monitoring, the tests were conducted under various conditions, focusing on latency, connectivity, and network stability [6]. The tests involved baseline, standalone, and optimised node transmissions to simulate real operational scenarios. Figures 4(a), 4(b) and 4(c) show the network topology and the total latency results of a baseline, standalone, and optimised test in a wireless mesh network, respectively.

Table II presents the results of the baseline test for node placement. Data was sent sequentially from each node located at a fixed position, as shown in Fig. 4(a). The shortest total latency was 3.65 seconds for vibration data and 7.62 minutes for detailed on-demand vibration data. Theoretically, a Wirepas sink node can transmit 120 packets per second (pps), with each mesh packet being up to 102 bytes [11]. The latency results of around 7 to 8 minutes in this work were found to align with this theory for approximately 6 MB of data. The small differences are likely due to environmental factors.

Figure 4(b) shows the total latency results of a standalone test of node placement. Node 1's latency was recorded at 7.65 minutes, while Nodes 2, 3, and 4 each had similar latencies of 13.50 minutes. The identical latency for Nodes 2, 3, and 4 suggests similar wireless transmission behaviour.

Table II. The latencies for a baseline test.

No.	Sensors Label	Latency	
		Vibration data, s	*On-demand data, min*
1	NODE 1	39.61	7.64
2	NODE 2	12.44	7.62
3	NODE 3	3.65	7.64
4	NODE 4	3.74	7.85

Table III. Network performance of a wireless mesh network of a standalone topology measured using Ev kit.

No.	Sensors	Total Latency, min	Latency, ms (Ev kit)	Next hop (Ev kit)	RSSI, dBm (Ev kit)	Number of hops (Ev kit)	Distance to next hop, m
1	NODE 1	7.65	63.50	GW	-75	0	65
2	NODE 2	13.50	1210.94	Node 3	-83	2	35
3	NODE 3	13.50	890.63	Node 1	-88	1	53
4	NODE 4	13.50	1078.13	Node 3	-67	2	20

Table IV. Network performance of a wireless mesh network of an optimised topology measured using Ev kit.

No.	Sensors	Total Latency, min	Latency, ms (Ev kit)	Next hop (Ev kit)	RSSI, dBm (Ev kit)	Number of hops (Ev kit)	Distance to next hop, m
1	NODE 1	-	929.69	GW	-82	0	65
2	NODE 2	-	968.69	Node 1	-82	1	40
3	NODE 3	-	250.00	Node 6	-86	3	25
4	NODE 4	7.00-14.00	1093.75	Node 3	-82	4	20
5	NODE 5	-	1140.63	Node 1	-85	1	30
6	NODE 6	-	1015.63	Node 5	-83	2	35

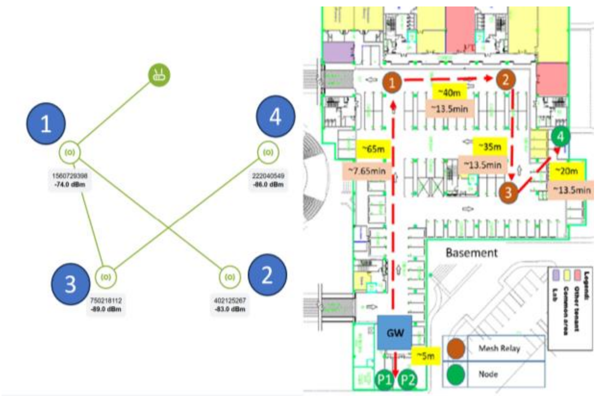

Fig. 5. Illustrate the hops involved in a standalone topology.

To understand the network behaviour of the wireless mesh vibration sensor nodes for this standalone topology, the evaluation kit (Ev kit) for wireless mesh was deployed at the same sensor node placements. This allowed for a detailed analysis of network performance, including RSSI, latency, and hop information. Table III compares the findings from the Ev kit test with the total latency of sensor nodes in the standalone wireless mesh network topology. The results show that the latency trend of the Ev kit is generally similar to the total latency of sensor nodes, except for Node 3, which exhibits a notable deviation. The results also suggest that latency is closely related to the hop count, as nodes with more hops tend to experience higher latency. Figure 5 illustrates the hop paths in the standalone network topology, while Fig. 6 depicts the relationship between RSSI and distance for the standalone topology. The graph indicates an irregular trend in RSSI with distance, which may be due to inconsistent signal patterns influenced by the standalone node placement.

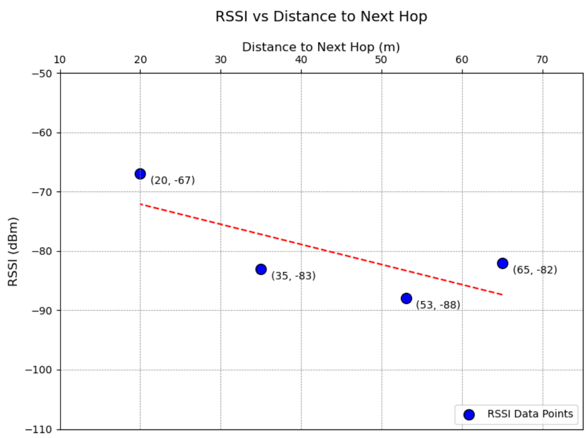

Fig. 6. Relation of RSSI and the distance in a standalone topology.

To further investigate the effect of node placement, two additional nodes were introduced to the wireless mesh network topology, as shown in Fig. 4(c), referred to as the optimised topology. It was observed that the total latency for Node 4 (the most isolated node) ranged between 7.00 and 14.00 minutes across several tests. Comparing this result with the earlier latency of 13.5 minutes for Node 4 in Table III, it was determined that optimised node placement can significantly improve total latency.

To explore this behaviour further, the Ev kit was also deployed at the same sensor node locations. The findings from the Ev kit tests are summarised in Table IV. The results show that the relationship between hops and latency observed in the standalone topology is no longer evident in the Ev kit tests. This is likely due to better node placement or shorter distances between nodes in the optimised topology. Figure 7 illustrates the hop paths in the optimised topology, while Fig. 8 shows the relationship between RSSI and distance for the same topology. RSSI values remain consistent across various distances, indicating a stable signal pattern. It may be affected by the optimised node placement.

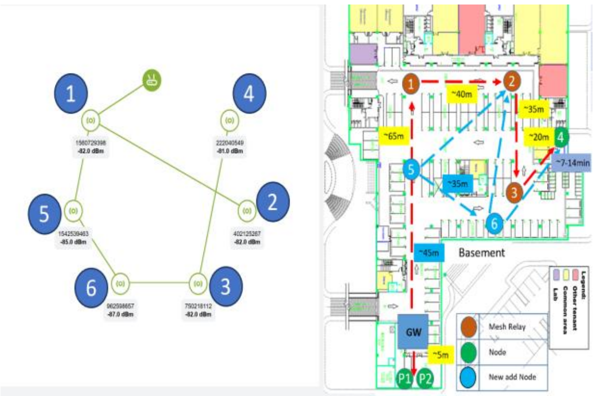

Fig. 7. Illustrate the hops involved in an optimised topology.

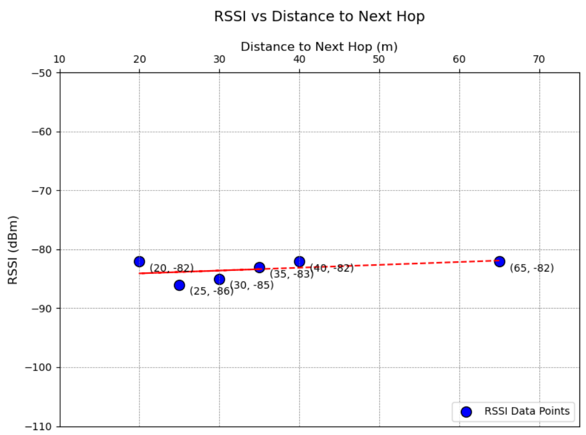

Fig. 8. Relation of RSSI and the distance in an optimised topology.

The results from tests reveal that the optimised topology demonstrates a more stable and predictable network performance compared to the standalone topology, as evidenced by reduced latency and improved RSSI values. Interestingly, the relationship between hop count and latency is less pronounced in the optimised topology. For example, while Node 4 has 4 hops, its total latency (7 – 14 minutes) is comparable to or even better than nodes with fewer hops in the standalone setup.

Theoretically, latency in wireless is given by

$$\text{Latency} = N\cdot(T_{tx}+T_{prop}+T_{queue}) \quad (1)$$

, where N is the number of hops, T_{tx} is the transmission delay, T_{prop} is the propagation delay, and T_{queue} is the queuing delay [12, 13].

In the standalone topology, this relationship holds, as nodes with more hops (e.g., Node 4) experienced higher latency. However, in the optimised topology, the findings of shorter inter-node distances and improved signal quality may reduce T_{prop} and T_{queue}. This will break the typical linear trend between hops and latency as shown in Eq. (1) above. From this finding, it can be suggested that better placement and shorter distances between nodes may reduce retransmission times, thus mitigating the typical latency penalties associated with multi-hop communication.

Overall, the node's placement with optimal RSSI values and efficient hop counts resulted in lower latency and improved transmission reliability. With the addition of relay nodes, the network congestion was reduced and latency was stabilised. These findings conclude that the node placement strategy with optimisation within a wireless mesh network can significantly improve the network performance.

IV. CONCLUSIONS

This study investigates the effect of sensor node placement and optimises it within a wireless mesh network for Condition-Based Monitoring (CBM) of industrial machinery. The network performance was analysed under various topological arrangements. The total latency of Node 4 (the most isolated node) was found to reduce to as low as 7 minutes from 13.5 minutes through strategic node placement. An improvement of the network performance results has been observed whereby the RSSI values remain consistent across various distances, indicating a stable signal pattern. Detailed analysis using the Ev kit shows the relationship between hop count and total latency is less pronounced in this optimised topology. It can be suggested that better placement and shorter distances between nodes may reduce retransmission times, thus mitigating the typical latency penalties associated with multi-hop communication. These findings provide a practical basis for deploying wireless mesh-based CBM systems, especially in challenging wireless environments. Further research will refine the node placement strategies and network modelling to enhance system reliability.

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AUTHOR CONTRIBUTIONS

Azmi Ibrahim: Project Administration, Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Validation, Visualization, Writing – Original Draft Preparation, Mardeni Roslee;

Supervision, Conceptualization, Technical Guidance, Writing – Review & Editing, Hizamel Mohd Hizan: Experimental Design, Methodology, Investigation, Resources, Mohd Fadzil Amiruddin: Testing, Data Analysis, Implementation, Validation and Zulkifli Ambak: Review & Editing, Manuscript Refinement, Technical Support.

CONFLICT OF INTERESTS

No conflict of interests was disclosed.

ETHICS STATEMENTS

Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

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