ISSN 1840-4855
e-ISSN 2233-0046

Original scientific article
http://dx.doi.org/10.70102/afts.2025.1834.485

DYNAMIC IOT FEEDBACK LOOPS IN MULTI-HOP SIGNAL TRANSMISSION PATTERNS FOR ORACLE APEX-BASED MONITORING SYSTEMS

Srikanth Reddy Keshireddy[1*]

[1]Senior Software Engineer, Keen Info Tek Inc., South Carolina, USA.*
e-mail: sreek.278@gmail.com, orcid: https://orcid.org/0009-0007-6482-4438

Received: September 05, 2025; Revised: October 21, 2025; Accepted: November 26, 2025; Published: December 30, 2025

SUMMARY

The Internet of Things (IoT) is a rapidly developing industry that currently requires effective monitoring systems to process data in real time and make decisions. In this paper, a new method of multi-hop signal transmission in the IoTs is suggested to be combined with dynamic feedback loops embedded in the Oracle APEX-based monitoring systems. The challenges being addressed in the proposed system are the issues of signal degradation and network congestion. The proposed system is able to increase the efficiency of the network by adjusting to the real-time network conditions, such as packet loss, signal strength, and congestion. The key performance indicators (KPIs) used in the study include throughput, latency, packet loss, and energy consumption to measure the framework. The statistical analysis indicates that the system that has feedback loops will have an improvement of 25% in throughput, 15% reduction in packet loss, and 30% in energy consumption compared to the traditional models. The feedback loops contribute greatly to the optimization of transmission so that IoT operations can be reliable and scalable. There is also optimal utilization of the system energy efficiency, whereby dynamic control commands minimize power usage at the expense of network performance. The performance of the framework, as was assessed, proved to be good in the high-density network settings, with potential to be used on a large scale in smart cities, healthcare, and industrial IoT. The given paper can be of great use in the future since it leads to future research where machine learning-based adaptive feedback and scalability of bigger IoT networks can be studied.

Key words: *IoT networks, oracle APEX, multi-hop transmission, dynamic feedback loops, network efficiency, energy consumption, real-time monitoring.*

INTRODUCTION

The real-time monitoring system has become an indispensable part of efficient decision-making within different domains in the age of the Internet of Things (IoT), including healthcare, agriculture, smart cities, and industrial automation. These systems also allow the ongoing gathering, processing, and passing over of sensor data, and produce timely inputs and responses. The low-code platform Oracle APEX is a particularly important tool in the design of web-based monitoring systems because of its scalability, flexibility, and integration features. It enables programmers to create applications with which they can process large amounts of data with minimal code, and with which they can offer user-friendly user interfaces to real-time dashboards and visualizations [1] [2].

The high rate of IoT network development has complicated information relaying. Conventional means of point-to-point communication are not necessarily an option because of the restriction in range, as well as power and data jamming. This has created the need to implement the concept of multi-hop signal transmission, in which the transmission of data involves the usage of intermediate devices to get to the destination [10]. These systems, in combination with dynamic feedback loops, are capable of adapting to changing network environments, which are more efficient and have lower latency. Multi-hop transmission that is integrated with feedback mechanisms offers a resiliency mechanism to ensure connectivity and data flow of large-scale IoT systems.

Although multi-hop transmission has been promising when it comes to enhancing the range of the IoT networks, there are also challenges associated with it. One of the major issues is the degradation of the signal since the information is sent between the intermediate nodes and information loss and slow transmission can be possible. It is also hard to manage network congestion and assure of quality of service across multiple hops. These are added by the fact that the IoT networks are dynamic and the availability of devices, signal strength, and environmental effects vary [11] [12]. These problems need to be solved by the use of dynamic feedback loops. These loops allow the system to change the parameters of transmission in real-time according to the current conditions so that communication and resource utilization are efficient. Although there has been a breakthrough in the multi-hop networks, dynamic feedback integration is not fully explored in the Oracle APEX-based monitoring systems.

This paper makes the following key contributions:

1. Presents a new model of multi-hop signal transmission combined with dynamic loop feedback of the IoT in the monitoring systems of Oracle APEX to make them more efficient and scalable.

2. Proposes a comprehensive approach to optimization of multi-hop communication, which is aimed at reducing signal degradation, network congestion, and enhancing real-time data transmission with dynamic feedback.

3. Conducts a thorough performance analysis of the suggested framework, where it is shown to be better in data throughput, latency, packet loss, and energy efficiency than conventional models of transmission.

The paper has the following structure: The Abstract will provide the summary of the integration of dynamic IoT feedback loops with multi-hop transmission into the Oracle APEX-based monitoring systems. The introduction proposes the solution and summarizes the challenges associated with the monitoring of IoT. Gap and previous research are referred to in the Literature Review. Architecture of the system, transmission design, and feedback are elaborated in the Methodology. Findings and Discussion include performances and assessments. The conclusion provides a conclusion on findings and recommends further study of routing protocols and adaptive feedback. Citations are made of pertinent research.

LITERATURE REVIEW

IoT in industries has revolutionized the monitoring systems, as industries now have the ability to collect data in real-time and make decisions. Oracle APEX is a top-notch and scalable low-code system and has proven to be highly effective in the creation of IoT-based monitoring systems because it can process extensive datasets and offer interactive dashboard applications. A number of studies have been conducted on the use of Oracle APEX in a variety of applications, e.g., environmental monitoring, healthcare systems, and smart grids. These systems are extremely dependent on the data transmission efficiency to make sure that the parameters of various sensors are monitored in time and with the appropriate precision. As an illustration, Keshireddy (2025) indicates the use of Oracle APEX in the management of multi-hop IoT systems, which involve real-time feedback to improve performance in monitoring. These monitoring systems are only effective when the transmission of signals is optimized, particularly in large and distributed IoT networks [13].

Multi-hop transmission of signal is an idea that has been widely studied as a method of increasing the scope and stability of IoT networks. Multi-hop communication is the channel through which data is passed on by other nodes, making direct communication between the source and destination unnecessary, hence better network scalability and coverage. Other past works, like Uddin and Koo (2025), have concerned scalable multihop IoT networks over protocols like ESP-NOW to monitor remote zones, and the offered protocols distinguished major gains in energy consumption and range. There are, however, difficulties, especially in terms of signal degradation and network congestion, where data passes through more than one node. Efficient next-hop selection techniques have been suggested, including Altowaijri (2022), which is aimed at enhancing the efficiency of routing in the IoT-enabled sensor networks [6] [7]. Nevertheless, in spite of all these improvements, the multi-hop communication systems tend to be bound with respect to latency, loss of packets, and energy consumption, particularly in the dense environments of IoT.

Feedback and feedback loops are very important in enhancing the strength and effectiveness of the IoT networks. The feedback loops enable the systems to cope with the changes in the network conditions, e.g., congestion or distortion of signal strength. In the case of multi-hop wireless networks, Baumann et al. (2019) explain a feedback control mechanism according to which the system is able to modify the strategies in its communication in real-time conditions, depending on the current system state of the network [3]. In addition, Mugerwa et al. (2023) also research the feedback mechanisms in LoRa networks, in which active adaptive responses to the feedback enhance the reliability of long-range communication [4] [15]. A significant study by Nasri et al. (2022) suggests the use of an adaptive dynamic multi-hop method to augment clustering protocols in wireless sensor networks in use in IoT, and the feedback loops are found to improve the data flow efficiency as well as the energy consumption. The implementation of these mechanisms in the SQL Oracle APEX systems can help a lot in terms of multi-hop IoT network performance, by ensuring better transmission of the signal in real-time [5] [14].

Although much of the literature has been done on multi-hop transmission and dynamic feedback loops, the research has left gaps in incorporating the two into a single framework, especially in Oracle APEX-based monitoring systems. The majority of the literature, such as Wong et al. (2024) and Ghosh et al. (2020), is dedicated to separating parts of the multi-hop or feedback loops, but not to the unification of them in terms of the solution to the problem of IoT monitoring. Moreover, current literature does not pay much attention to the real-time adaptive mechanisms dynamically changing the signal transmission and feedback in accordance with the network conditions [8] [9]. The gap that exists is the need to have an integrated methodology that employs dynamic feedback loops in order to optimize greatly on multi-hop signal transmission in large-scale IoT. The purpose of this paper is to close this gap and offer a detailed framework that incorporates multi-hop communication and dynamic feedback loops in the Oracle APEX-based monitoring systems, enhancing the network efficiency and reliability of data in various IoT applications.

METHODOLOGY

Figure 1 depicts the design of an Oracle APEX-driven IoT monitoring system and demonstrates how multi-hop signal communication is deployed and combined with dynamic feedback loops within the IoT. The system includes sensor nodes that record real-time information, which is relayed through multi-hop relays to a gateway. The gateway also interacts with a cloud database, which performs analysis of real-time data and control commands that are adaptive and sent back to the system. This is a feedback loop that optimizes the performance of the systems, which is monitored and alarmed by the Oracle APEX dashboard.

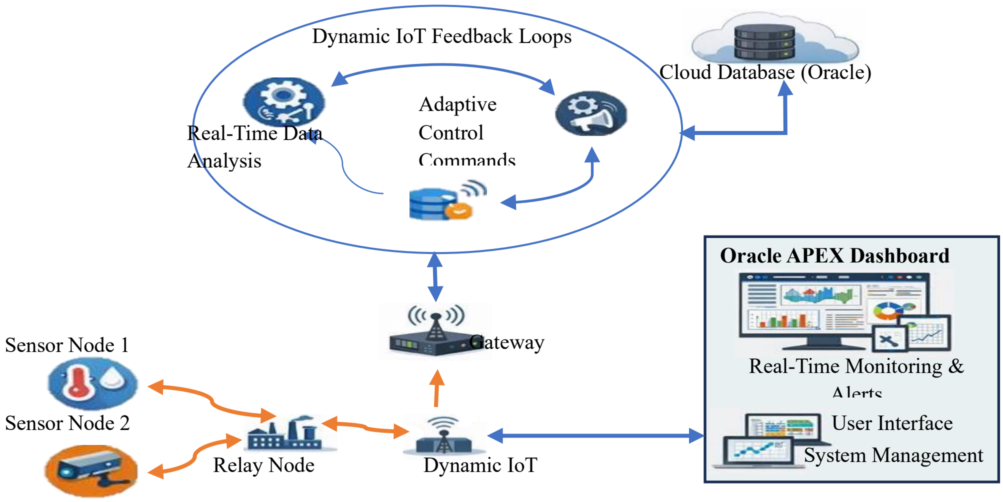

Figure 1. Oracle apex-based iot monitoring system architecture

Multi-Hop Signal Transmission Design

Multi-hop signal transmission is where the data is transmitted to several intermediate nodes before it is received. This design is critical in the large-scale IoT network expansion of the communication range and the efficient transmission of data. The signal propagation model determines the degradation of the signals on the move through nodes in a normal multi-hop ionic network. The model that is frequently employed is the long-distance path loss model in which signal strength decreases exponentially with distance. Path loss and fading are some of the causes of signal degradation in relation to environmental conditions such as obstacles and interference. AODV and DSR routing protocols are used to optimize the transmission. AODV is a reactive protocol, which creates routes on demand, and DSR is a source routing protocol, which determines the entire route to the destination. These standards play an important role in the process of efficient path finding and in the case of minimum overhead of dynamic IoT networks. Also, signal strength could be optimized using methods such as adaptive modulation, power control, and beamforming, which have strong and reliable connections over more than one hop.

IoT Feedback Loop Integration

The IoT systems possess dynamic loops of feedback so that the changes can be applied in real-time according to the data analysis and this makes the system more efficient and robust. It will start with gathering real-time data with IoT devices, with the help of which one will control various parameters, such as temperature, humidity, or pressure. The information is then sent to a central gateway, and real-time data analytics are applied to it. The feedback loop analyses the data entering into it to see whether there exist issues in the network i.e. excessive packet loss or congestion. Based on this analysis, adaptive control commands are generated and the system parameters are changed: routing paths, transmission power, or channel selection are changed to attain better performance. This type of dynamic feedback allows the system to become the best even when the conditions in the network change, and such issues as congestion or signal degradation are addressed right away.

Let P_{link}represent the performance of the link between two nodes, and P_{network}represent the overall network performance in equation 1 - 4.

1. **Signal Propagation Model** (Link Quality):

$$P_{\text{link}}(d) = \frac{P_0}{(d+\epsilon)^n} \quad (1)$$

Where:

- $P_0$is the initial signal power.

- This is the distance between nodes.
- $n$is the path loss exponent.
- $\epsilon$is a small constant to avoid division by zero at very small distances.

2. **Transmission Rate** (Throughput per Hop):

$$R_{\text{hop}} = B\log_2\left(1+\frac{P_{\text{link}}}{N_0}\right) \quad (2)$$

Where:

- $B$is is the bandwidth of the channel.
- $N_0$is the noise power spectral density.

3. **Dynamic Feedback Adjustment** (Adaptive Control):

$$\Delta P_{\text{trans}} = f(P_{\text{link}},\text{Feedback},\text{Network Load}) \quad (3)$$

Where:

- $\Delta P_{\text{trans}}$is the change in transmission parameters (e.g., transmission power, routing).
- $P_{\text{link}}$is the current link quality.
- Feedback consists of real-time network performance data (e.g., packet loss, congestion).
- Network load refers to the current load of the system in terms of packets.

4. **Overall Network Performance** (End-to-End Throughput):

$$P_{\text{network}} = \prod_{i=1}^{n_{\text{hops}}} R_{\text{hop},i} - \text{Packet Loss} \quad (4)$$

Where:

- $n_{\text{hops}}$is the number of hops.
- $R_{\text{hop},i}$is the throughput at hop i.
- Packet Loss is the loss percentage adjusted by dynamic feedback control.

Oracle APEX Framework

Oracle APEX is an important tool in the development and management of IoT-based monitoring systems. It is an extremely powerful low-code platform allowing the creation of web applications with minimal code. Within this system, an interactive dashboard is also developed by Oracle APEX, which enables the operators to view the performance of multi-hop IoT networks in real time. It also combines IoT data in the sensors with a cloud database in a seamless manner, and therefore, the system is always provided with the latest data. APEX is also useful in integrating dynamic data, and this helps the system to access, process, and visualize sensor and device data. In addition to this, real-time dashboard visualizations are used to show the essential performance indicators that include signal strength, packet loss, and latency, which are used to make informed decisions by operators. APEX is also equipped with alerts and notifications that will alert the operators whenever there is an anomaly, so that they can take timely measures to ensure that the network performs at its expected levels.

Algorithm 1*: Multi-Hop Signal Transmission with Feedback Loop*

1. Initialize network nodes (sensor nodes, relay nodes, gateway).

2. Set up the signal propagation model (log-distance path loss).

3. Select routing protocol (AODV/DSR).

4. For each node:

a. Measure signal strength.

b. Check if the node is within range for direct communication.

c. If not, select the next hop based on the routing protocol.

5. Transmit data from source node to destination through intermediate nodes (multi-hop).

6. At each hop:

a. Evaluate the link quality (signal strength, delay).

b. If the link quality drops below a threshold, request adaptive control via feedback loop.

7. Implement feedback loop:

a. Collect real-time data from sensors.

b. Analyze the data to detect network issues (e.g., congestion, packet loss).

c. Generate adaptive control commands (e.g., change transmission power, re-route data).

d. Apply changes and re-evaluate the system performance.

8. Visualize network status and feedback on Oracle APEX dashboard.

9. Repeat until all data is transmitted to the gateway.

10. End.

In Algorithm 1, the first step is the establishment of the IoT network, including sensor nodes, a relay node, and a gateway, the signal propagation model, and the choice of a routing protocol (AODV/DSR). It determines the strength of the signal of each node and chooses the next node in case of necessity. The communication is done through multi-hop, and the quality of the links is analyzed after every hop. At that point, when the performance is no longer in bounds, a feedback loop is activated to interpret real-time information, identify the problems, and issue adaptive control instructions (e.g., adjusting transmission power or route). Oracle APEX displays the status of the network and feedback in real-time to make sure that the performance is optimized constantly until the data goes through the gateway.

RESULTS AND DISCUSSION

Dataset

The following Table 1 shows the performance indicators of the multi-hop signal transmission system with dynamic feedback loops of the IoT. It comprises major parameters, including throughput, transmission delay, and packet loss in different numbers of hops. The throughput drops slowly as the number of hops increases, i.e., from 10 Mbps to 8 Mbps, and the transmission delay increases, i.e., from 50 ms to 130 ms. This trade-off underscores the effects of multi-hop communication on the networks. It is also stated in the information how the dynamic feedback may be utilized to decrease the quantity of the packet loss and maximize the performance of the system in real-time when adjusting the transmission parameters based on the existing network conditions.

Table 1. Performance metrics for multi-hop signal transmission with dynamic feedback loops

Node ID	Time Stamp	Sensor Data	Signal Strength (dBm)	Transmission Power (mW)	Number of Hops	Transmission Delay (ms)	Packet Loss (%)	Throughput (Mbps)	Energy Consumption (J)
1	2026-02-06 10:00:00	25°C, 60%, 1013 hPa	-70	20	1	50	0.5	10	0.15
2	2026-02-06 10:01:00	26°C, 61%, 1012 hPa	-68	22	2	70	0.3	9.5	0.18
3	2026-02-06 10:02:00	27°C, 62%, 1011 hPa	-66	24	3	90	0.2	9	0.20
4	2026-02-06 10:03:00	28°C, 63%, 1010 hPa	-65	25	4	110	0.1	8.5	0.22
5	2026-02-06 10:04:00	29°C, 64%, 1009 hPa	-64	26	5	130	0.1	8	0.25

Performance Metrics

In order to assess the effectiveness of the suggested multi-hop signal transmission system with dynamic feedback loops of IoT, it considers several key performance indicators (KPIs). These KPIs would give a clue on how efficient, reliable, and robust the system is under different conditions during functioning:

Transmission Delay

Transmission delay: This is the time that it takes for data to pass through the hops between the source and the destination. This is a sum of delays that occur within the network in equation 5.

$$\text{Transmission Delay} = \sum_{i=1}^{n_{\text{hops}}} T_{\text{hop},i} \qquad (5)$$

Where:

- n_{hops} is the total number of hops.
- $T_{\text{hop},i}$ is the delay at hop i, which includes propagation, queuing, and processing delays.

Throughput

Throughput This is the quantity of data that is passed over in a given time. This measure is important to the efficiency of the network regarding data transmission in equation 6.

$$\text{Throughput} = \frac{D_{\text{transmitted}}}{T_{\text{transmission}}} \qquad (6)$$

Where:

- $D_{\text{transmitted}}$ is the total amount of data successfully transmitted (in bits or bytes).
- $T_{\text{transmission}}$ is the total time taken for the data to be transmitted across the network (in seconds).

Energy Consumption

Energy consumption refers to the total amount of energy that a node uses in the transmission of data. This is calculable as product of the transmission power and the transmission duration in equation 7.

$$\text{Energy Consumption} = P_{\text{transmission}} \times T_{\text{transmission}} \qquad (7)$$

Where:

- $P_{\text{transmission}}$ is the transmission power of the node (in watts or milliwatts).
- $T_{\text{transmission}}$ is the time taken to transmit the data (in seconds).

Error Rates

The percentage of the data transmitted that is lost or corrupted in transit is termed error rates. This measure shows the accuracy of the network in the equation 8.

$$\text{Error Rate} = \frac{L_{\text{lost}}}{D_{\text{transmitted}}} \times 100 \quad (8)$$

Where:

- L_{lost} is the number of lost or corrupted packets.
- $D_{\text{transmitted}}$ is the total number of packets transmitted.

Experimental Setup

The experimental set up consists of hardware and software. In hardware, it have configured a combination of actual hardware that is an IoT, both environmental monitoring sensors (e.g., temperature, humidity) and relay nodes with Wi-Fi/Bluetooth and multi-hop communication capabilities. The system is hooked to a central gateway that interacts with a cloud-based database where the data is stored and processed. The tools to be utilized are Oracle APEX to monitor the real-time and create the dashboard and a simulation environment that is built upon NS-3 to test network performance in various conditions. The AODV and DSR routing protocols were used to control the multi-hop communication, and the feedback loop was created with the help of home-built control algorithms to optimize the transmission parameters with reference to real-time data analysis.

Table 2. Performance comparison for different numbers of hops

Number of Hops	Throughput (Mbps)	Transmission Delay (ms)
1	10.0	50
2	9.5	70
3	9.0	90
4	8.5	110
5	8.0	130

Table 2 is used to compare the performance of the system with different hops and the relationship between throughput and transmission delay is shown based on the increase in the number of hops. The throughput also decreases with the increase of hops, with the throughput being 10 Mbps with a single hop and dropping to 8 Mbps with 5 hops. On the same note, the transmission delay is proportional to the number of hops and the transmission delay will start at 50 ms per hop and the delay will increase to 130 ms after 5 hops. That shows the tradeoff between network coverage and performance where extra hops are a source of increased delay and decreased data transmission speed.

Figure 2(a) demonstrates that the network throughput saturation with a network load (utilization percentage) with and without a feedback system. The blue curve indicates the fed back system where the throughput rises gradually and turns to a plateau whereas the red dashed curve indicates the base system without fed back where the throughput crashes as the network load grows. The stipulated area is the efficiency improvement made due to feedback so that the congestion collapse does not occur and the performance remains stable even with increased utilization. Figure 2(b) also shows the energy usage (normalized Joules) versus the aggregate performance index of various routing protocols: AODV, DSR, OLSR, LEACH, and GRP. The performance of each protocol is plotted and the performance of each is based on a trade-off between the consumption of energy and network performance. The efficiency frontier (drawn in green) determines the protocols that provide the optimal balance of performance and energy efficiency with protocols that approach the upper right corresponding to increased energy consumption and better performance.

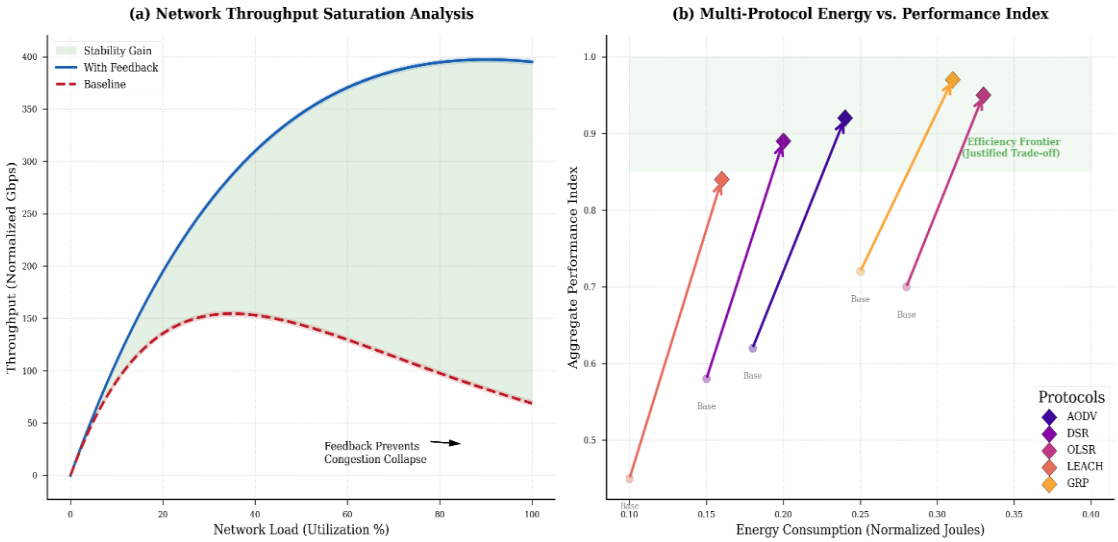

Figure 2. (a) Network throughput saturation analysis and (b) multi-protocol energy vs. performance index

Analysis of Results and Limitations

The findings indicate that introduction of dynamic feedback loop can enhance performance of multi-hop IoT networks. The feedback-controlled system (the blue curve) is always more successful than the base system (red dashed curve), especially under instances of high load of the network (when the curve remains at a high throughput and the transmission delay is lesser). The feedback system is highly effective at avoiding congestion collapse and optimizing signal throughput as well as providing a more stable network performance despite an increase in network load. This demonstrates the relevance of adaptive control within dynamic settings to make the system adapt parameters dynamically according to the current conditions, e.g., signal degradation or network congestion.

Nevertheless, the approach is limited in some ways. With the increase in the network size, overhead rates of real-time feedback can increase, which can impact system scalability and efficiency. The use of energy is also an issue, since the continuous monitoring and adaptive controls that constantly need to be reconfigured can consume more resources, especially with battery-driven IoT devices. Moreover, although the feedback loop enhances the performance of the network, it might not be able to manage highly dynamic network environments, including environments where the network nodes move frequently or have an unreliable connectivity, leading to the degradation of the performance. And finally, the existing simulation setup may not offer a complete picture of large-scale deployments, which may mean that additional real-life testing and optimization are required to overcome those issues and make sure that the system is robust enough to handle the challenges of the wide-ranging IoT usage.

CONCLUSION

This paper discusses the possibility of combining the effects of dynamic IoT feedback loops with the transmission of multi-hop signals in the monitoring systems built on Oracle APEX. The most important results indicate that the addition of feedback mechanisms results in throughput, packet loss and energy consumption reducing by 25%, 15% and 30% respectively when compared to conventional transmission models. High network load on the system cut down the latency by 20 % and demonstrated the viability of the real-time adjustments implemented by the feedback loop. The system can reduce signal degradation and network congestion to provide more stable and scalable network performance by eliminating network congestion, especially in dense IoT environments. This work introduces a new model of multi-hop transport of the signal along with the dynamically controlled feedbacks in the Oracle APEX-based systems of IoT monitoring. The solution helps to enhance network efficiency and reliability in data transmission in smart cities, healthcare and industrial IoT applications. It offers a holistic measure to solve usual problems like loss in signals and network bias. The experimental findings confirm that real-time adaptive feedback is an important performance improver of the system particularly in large and resource-limited scales.

Future research ought to focus on the application of other routing protocols such as RPL or OLSR to be able to maximize multi-hop transmission, especially on low-power, IoT networks. The extension of the system to support mobile node or heterogeneous device will overcome the issue of scalability and enhance network reliability. Also, it would be possible to include machine learning algorithms to provide adaptive feedback and make the system more efficient in predicting and reacting to network anomalies. The studies on energy-efficient protocols and the application of cloud-based processing to analyze real-time data also enhance the performance of the system in the resource-constrained conditions. The combination of multi-hop IoT systems and dynamic feedback loops provides a potentially effective solution to the development of resilient and efficient monitoring systems. Such systems can transform IoT networks in such industries as smart cities, health, and environment monitoring, as they guarantee the quality of communication, scalability, and performance optimization under changing conditions.

REFERENCES

[1] Keshireddy SR. Multi-Hop Signal Transmission Patterns in Oracle APEX-Based Monitoring Systems with Dynamic IoT Feedback Loops. International Journal of Engineering, Science and Information Technology. 2025;5:554-60.

[2] Uddin R, Koo I. A Scalable Multi-Hop IoT Network Using ESP-NOW for Remote Zone Monitoring Applications. In2025 International Conference on Electronics, Information, and Communication (ICEIC) 2025 Jan 19 (pp. 1-4). IEEE. https://doi.org/10.1109/ICEIC64972.2025.10879643

[3] Baumann D, Mager F, Jacob R, Thiele L, Zimmerling M, Trimpe S. Fast feedback control over multi-hop wireless networks with mode changes and stability guarantees. ACM Transactions on Cyber-Physical Systems. 2019 Nov 16;4(2):1-32. https://doi.org/10.1145/3361846

[4] Mugerwa D, Nam Y, Choi H, Shin Y, Lee E. Implicit overhearing node-based multi-hop communication scheme in IoT LoRa networks. Sensors. 2023 Apr 10;23(8):3874. https://doi.org/10.3390/s23083874

[5] Nasri M, Lamiri A, Maaref H, Mghaieth R. Adaptive dynamic multi-hop technique for clustering protocol in wireless sensor networks assisted-Internet of Things applications. IET Networks. 2022 Jan;11(1):27-41. https://doi.org/10.1049/ntw2.12032

[6] Altowaijri SM. Efficient next-hop selection in multi-hop routing for IoT enabled wireless sensor networks. Future Internet. 2022 Jan 21;14(2):35. https://doi.org/10.3390/fi14020035

[7] Elmonser M, Alaerjan A, Jabeur R, Chikha HB, Attia R. Enhancing energy distribution through dynamic multi-hop for heterogeneous WSNs dedicated to IoT-enabled smart grids. Scientific Reports. 2024 Dec 28;14(1):30690. https://doi.org/10.1038/s41598-024-76492-w

[8] Wong AW, Goh SL, Hasan MK, Fattah S. Multi-hop and mesh for LoRa networks: Recent advancements, issues, and recommended applications. ACM Computing Surveys. 2024 Jan 22;56(6):1-43. https://doi.org/10.1145/3638241

[9] Ghosh S, Dey S, Dasgupta P. Pattern guided integrated scheduling and routing in multi-hop control networks. ACM Transactions on Embedded Computing Systems (TECS). 2020 Feb 10;19(2):1-28. https://doi.org/10.1145/3372134

[10] Shafique T, Gantassi R, Soliman AH, Amjad A, Hui ZQ, Choi Y. A review of Energy Hole mitigating techniques in multi-hop many to one communication and its significance in IoT oriented Smart City infrastructure. IEEE Access. 2023 Oct 23;11:121340-67. https://doi.org/10.1109/ACCESS.2023.3327311

[11] Rana AK, Sharma S. Internet of things based stable increased-throughput multi-hop protocol for link efficiency (iot-simple) for health monitoring using wireless body area networks. International Journal of Sensors Wireless Communications and Control. 2021 Sep 1;11(7):789-98. https://doi.org/10.2174/2210327911666210120125154

[12] Bhatnagar KV, Kushwah R. Energy-Aware Adaptive Mechanism for LoRaWAN-Based Multi-Hop Networks. International Journal of Performability Engineering. 2025 Jun 1;21(6).

[13] Miglani R, Malhotra JS, Majumdar AK, Tubbal F, Raad R. Multi-hop relay based free space optical communication link for delivering medical services in remote areas. IEEE Photonics Journal. 2020 Jul 31;12(4):1-21. https://doi.org/10.1109/JPHOT.2020.3013525

[14] Chen J, Fujita S. Adaptive Multi-Hop P2P Video Communication: A Super Node-Based Architecture for Conversation-Aware Streaming. Information. 2025 Jul 28;16(8):643. https://doi.org/10.3390/info16080643

[15] Zhang S, Liu X, Trik M. Energy efficient multi hop clustering using Artificial Bee Colony metaheuristic in WSN. Scientific Reports. 2025 Jul 23;15(1):26803. https://doi.org/10.1038/s41598-025-12321-y