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Performance and Energy Evaluation of Multi-Hop Network Topologies for Water Distribution Monitoring

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Abstract - *Real-time monitoring of urban water distribution systems has become a critical requirement in modern smart urbanization, rendering traditional manual monitoring and data recording methods obsolete. To overcome these challenges, this paper presents a comprehensive study on the empirical evaluation of power consumption and communication performance in a low-cost Wireless Sensor Network (WSN) using the NRF24L01+ transceiver. Although natively restricted to basic point-to-point and single-level star topologies, a custom multi-hop routing protocol utilizing an advanced octal addressing scheme was developed to enable multi-tier network scalability. Three network topologies Star, Tree, and Series Tree were implemented and combined with two message scheduling mechanisms: By-Request polling and Round-Robin data aggregation. The system was subjected to rigorous testing under both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions across complex, obstacle-dense environments including concrete walls and heavy foliage. The experimental results reveal that the proposed multi-hop framework successfully achieves a 0% packet loss rate across seven obstacle zones where traditional Peer-to-Peer (P2P) connections fail entirely. Furthermore, the By-Request scheduling combined with a Series Tree topology demonstrated superior energy efficiency, requiring a minimal total power output of only 91.86 mWh over an operational period of one hour. Balancing data rates between 250 Kbps and 2 Mbps provides optimal real-time monitoring stability and low latency (6 ms per node). These findings provide a scalable, highly cost-effective blueprint for large-scale municipal water asset management.*

Keywords: *NRF24L01+, Topology, Communication, Multi-hop, Smart water monitoring*

I. Introduction

The rapid evolution of smart city paradigms relies The paradigm of the smart city relies heavily on the continuous collection, processing, and communication of operational data from core municipal utilities. Among these infrastructures, the urban water distribution network represents an essential public service whose efficient maintenance directly influences public health, resource preservation, and economic stability. In traditional municipal frameworks, water consumption profiling, pressure mapping, and leakage detection have historically relied on manual inspection routines, manual meter reading, and mechanical gauge logging. However, as contemporary metropolitan regions undergo exponential vertical and horizontal growth, manual workflows become entirely logistically impossible due to the sheer density of residential points, inaccessible physical pipes, and the required labor costs. Consequently, an automated, real-time mechanism is essential to support modernized water asset management. Wireless Sensor Networks (WSNs) have emerged as the primary technological framework to achieve this automation across wide urban environments [1, 2]. By retrofitting distribution pipelines with electronic flow meters, ultrasonic sensors, and acoustic loggers connected to localized radio transceivers, municipal operators can capture high resolution hydraulic data continuously [3]. Despite these clear advantages, deploying WSNs within dense urban centers presents severe technological trade off, primarily centered around operational range constraints, concrete wall penetration, and the long-term energy life of battery operated sensor nodes [4]. Because water distribution channels are routinely located below road surfaces, inside reinforced concrete basements, or buried under soil, radio waves suffer from extreme attenuation, multipath fading, and complex Non Line of Sight (NLOS) conditions [5]. o overcome these environmental barriers, industrial smart city initiatives frequently select high-power or multi-layered communication architectures based on protocols like ZigBee (IEEE 802.15.4 standard) [6],[7],[8]. ZigBee offers robust, native mesh routing and multi-node coordination designed for broad-area automation [9],[10],11]. Nevertheless, the commercial procurement cost of industrial-grade ZigBee transceivers poses a significant budget barrier for full-scale municipal installations, where tens of thousands of water meters

must be instrumented simultaneously. This financial challenge creates a critical demand for alternative low-cost wireless transceivers that maintain high reliability without driving up capital expenditure. The NRF24L01+ transceiver represents a highly cost effective, widely available commercial solution operating on the license-free 2.4 GHz Industrial, Scientific, and Medical (ISM) radio frequency band [12]. Featuring an integrated hardware link layer protocol termed Enhanced ShockBurst, the NRF24L01+ supports automated packet handling, address validation, and automatic retransmission handling natively, minimizing microcontroller computational burdens [13].

However, the module is fundamentally limited in its native baseline functionality, as it supports only point-to-point or single-level star topologies restricted to six simultaneous data pipes [14]. Out of the box, it lacks any native multi-hop routing layer or multi-tier network configuration capabilities. To bypass these limitations and adapt the NRF24L01+ for complex, wide-area municipal water networks, developer-defined software protocols must build a custom network layer capable of multi-tier routing. This comprehensive study profiles the architectural design, algorithmic implementation, and empirical validation of a custom multi-hop network protocol designed exclusively for NRF24L01+ modules in urban monitoring scenarios. We implement and evaluate three distinct network topologies Star, Tree, and Series Tree configurations under two contrasting message scheduling techniques. By-Request polling and Round-Robin aggregation. Furthermore, we evaluate these combinations through rigorous Non-Line-of-Sight (NLOS) indoor and outdoor environmental testing within areas blocked by dense concrete walls, brick structures, and heavy foliage. Our results demonstrate that structured multi-hop configurations completely eliminate packet drop issues, delivering a stable 0% packet loss rate while optimizing energy expenditure to a minimal 91.86 mWh under specific topology configurations.

II. Method

Researchers Junus et al. designed a wireless sensor network to aggregate energy data from a hybrid power plant using NRF24L01+ modules, microcontrollers, and a Raspberry Pi acting as a bridge to a cloud server. The study compared various network topologies to determine which performed better in terms of transmission speed. The precise timing of each packet transmitted across the network was recorded as research data. For multi-hop communication, the maximum latency was 11.3 seconds and the minimum was 5.3 seconds. In comparison, the maximum transmission time for a peer to peer connection was 2.7 seconds, with a minimum of 1.3 seconds. The study highlights a significant reduction in transmission speed associated with the use of the multi-hop network configuration in this scenario [15].

This study evaluates three network topologies: Tree, Series Tree, and Star. With a configuration comprising one master and six slaves, the performance of these three networks is tested under Line of Sight (LOS) and Non Line of Sight (NLOS) conditions, based on parameters such as transmission time, distance, and packet loss. A 1byte data payload is used to simulate flow rate data transmission, sent from the six slaves to the master. The design of the testbed is shown in Fig. 1.

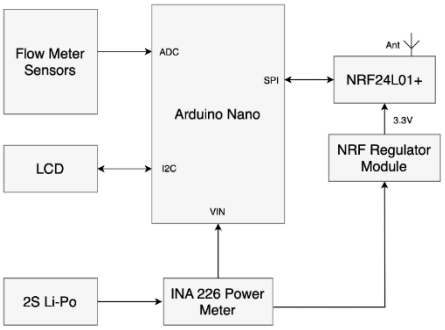


Fig 1. Experimental testbed diagram

The network layer is configured with up to five levels, ranging from Level 0 (master node) to Level 4 (leaf node). This protocol employs an octal addressing format to facilitate node identification, as illustrated in Fig. 3 (b). Due to the limitations of the NRF24L01+ module which supports a maximum of five simultaneous child node connections the maximum number of nodes configurable in this topology is 781, with the furthest address being 05555. The octal format was selected for its ability to represent the digits 0-7 using three bits, thereby enhancing the efficiency of bit-shifting operations and the identification process. With this structure, any transmitted message is automatically forwarded to the destination address through the network hierarchy, even if the sending and receiving nodes are not within direct communication range.

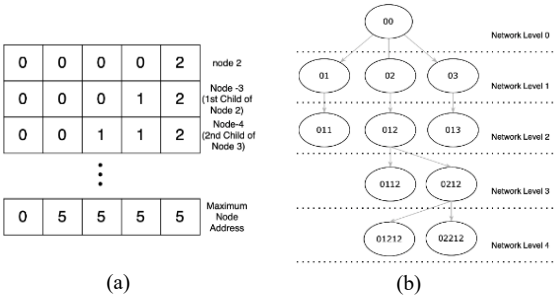


Fig 2. (a) network layer (b) Octal Address

This paper discusses three types of topologies that could be implemented in real-world municipal water distribution scenarios. Six slave nodes and one master node were used for the experiment; the topology was adjusted accordingly to monitor network performance. Tree, Series Tree, and Star network topologies, as illustrated in Fig. 3, were tested under both Line of Sight (LOS) and non-LOS configurations, with transmission time, distance, and packet loss being monitored. One byte of data was transmitted from the master or the final slave

(node 6) to simulate flow rate data. Transmission time is determined by Eq. (1), calculated as half of the total round-trip time for the transmitted data. Peak, minimum, and average transmission times are determined by Eqs. (2)-(4), respectively, where n represents the total number of data packets transmitted at one-second intervals.

$$T_{tx} = \frac{T_{roundtrip}}{2} \quad (1)$$

$$T_{tx(peak)} = \max\left(T_{tx}[n]\right) \quad (2)$$

$$T_{tx(low)} = \min\left(T_{tx}[n]\right) \quad (3)$$

$$T_{avg} = \frac{\sum_{i=1}^{i=n} T_{tx}[i]}{n} \quad (4)$$

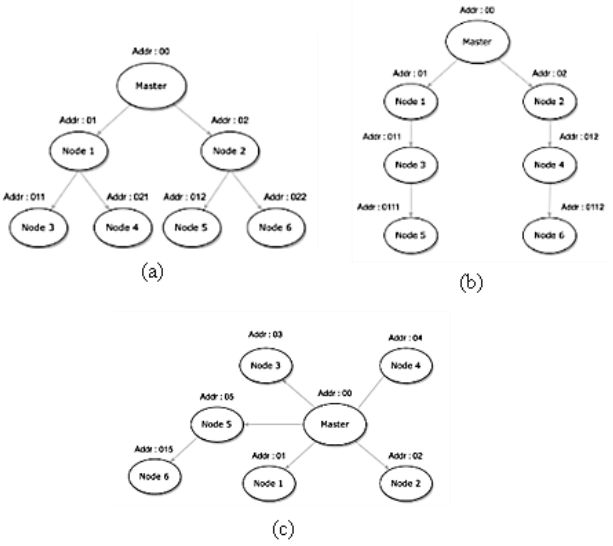


Fig 3. (a) Star topology (b) Tree topology (c) Series-Tree topology.

Round robin and on demand scheduling are used to determine the power consumption of the overall network node topology. The total network power consumption is calculated using Eq. 6, summing the power from the master to node 6. With on demand scheduling, the master requests packet data every n seconds. The overall data flow is depicted in Fig. 4 (a), where the master requests data by sending 1 byte of data, and the corresponding node responds with a data flow meter packet. Round robin scheduling, on the other hand, gives each slave node the opportunity to send data from the lowest node (node 6) to the master node (node 5), as depicted in Fig. 4 (b). Node 6 initiates the data transfer to node 5, and node 5 forwards the packet data from nodes 5 and 6, added to node 4, until it reaches the master node. The interval is controlled by node 6, which is set to 10 seconds. Each node after node 6 immediately sends and adds data after receiving data from the previous node.

$$PL(\%) = \frac{\sum_{i=1}^{i=n} PL[i]}{n} \quad (5)$$

$$P(mWh) = \sum_{i=1}^{i=node} P_{node}[i] \quad (6)$$

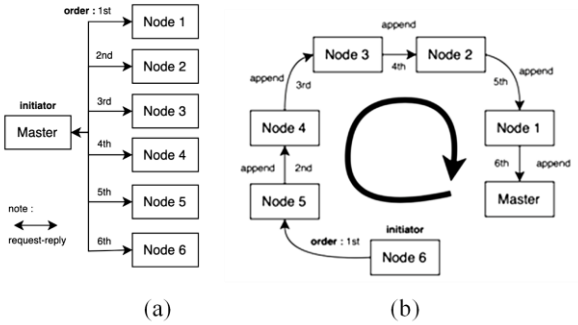


Fig 4. (a) By request (b) Round Robin

III. Results and Discussion

A. Power Consumption

Power consumption was measured for each topology and scheduling scheme; the power consumption of all nodes was summed using Equation 6. All nodes operated for one hour, with each node transmitting a 1 byte data packet. The total bytes column in Table I includes the master's data request bytes based on the request schedule. A Line of Sight (LOS) setup was used for this experiment conclusion.

TABLE I
POWER CONSUMPTION OF ALL NODES

No	Topology	Scheduling	Power Total (mWh)	Packet Success (%)
1	Tree	By Request	106.98	100
2	Tree	Round Robin	107.28	100
3	Star	By Request	92.88	100
4	Star	Round Robin	93.84	100
5	Series tree	By Request	91.86	100
6	Series tree	Round Robin	94.08	100

Although round robin scheduling passes less nodes in between rather than by request scheduling, total nodes power consumption of round robin is slightly higher than by request. Round robin scheduling appends data from the previous nodes and so on, makes the total bytes of data increasing nodes after nodes. Larger bytes meaning more operating time for the NRF24L01+ so the power consumption will be higher. By request scheduling has more advantages in terms of fully controlled communication, master can connect to the cloud and choose which nodes to be requested.

Star topology has advantages because hop lesser nodes rather others topology but also come with drawbacks in terms of distances. Series Tree is the most power efficient with more distances with only 1 mWh difference rather than star topology. Series Tree passes 2 nodes and extend the communication distances 3 times rather than peer to peer communication. Tree topology has advantages of

large area communication distribution, tree is fit with city center clean water distribution implementation which has more pipes in short distances. Drawbacks for tree topology is the power consumption much higher rather than others.

B. LOS Configuration

The results obtained using multi-hop were compared with those from direct transmission (P2P). The maximum testing distance was 1000 m, as illustrated in Fig. 5. As shown in Table II, the maximum transmission range for multi-hop was significantly greater than that of P2P, which was limited to 900 m before packet loss reached 100%. The P2P configuration held an advantage regarding transmission time, achieving a peak transmission time of 7.89 ms. In the Line of Sight (LOS) scenario, the tree and star topologies involved the same number of nodes for data traversal; consequently, there was little difference in the results. The tree topology exhibited the longest transmission time because the data had to pass through four nodes.



Fig 5. Layout LOS Scenario

TABLE II
DISTANCE COMPARISON

Topology	maximum distance	Peak Time (ms)	Average Time (ms)	Low Time (ms)
Tree	>1000	16.10	3.72	1.58
Star	>1000	16.02	3.7	1.60
Series Tree	>1000	15.17	4.92	2.35
P2p	>1000	8.21	6.6	1.40

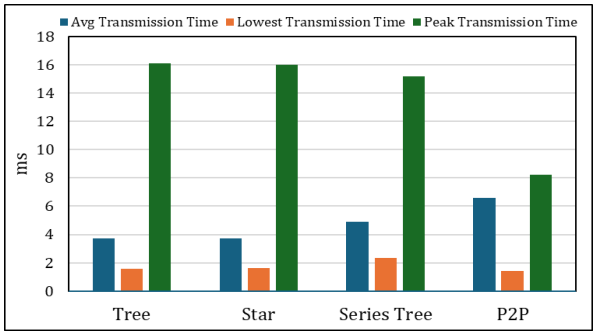
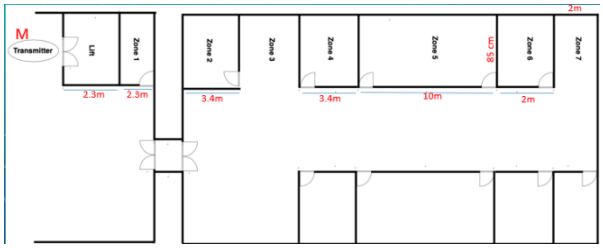


Fig 6. Distance Comparison

C. Non-LOS Configuration

All configurations, including P2P, were tested under a Non-LOS scenario simulating a real municipal water distribution network containing walls and other obstacles. The test area, illustrated in Fig. 7, comprised seven zones where receivers were positioned and tested. This test scenario facilitates a better understanding of multi-hop capabilities in overcoming complex obstacles. Packet loss, peak transmission time, and minimum transmission time were the recorded parameters.

Fig 7. Non-LOS Layout



Data from 20 transmission tests indicate that while Zones 1 through 5 demonstrated exceptional performance with zero packet loss and consistently low transmission times ranging from 1.46 ms to 1.93 ms Zone 6 experienced a significant decline in network quality, characterized by higher transmission times and a critical packet loss rate of 30%. These results are also presented in Table III. This table shows the transmission times for star and tree topologies in a Non-LOS scenario across seven zones, highlighting that packet loss remains at 0% in all zones while latency increases as the zone number rises, with Low Time increasing from 1.60 ms (Zone 1) to 6.20 ms (Zone 7), Peak Time climbing from 1.83 ms (Zone 2) to 10.20 ms (Zone 7), and Average Time rising from 2.46 ms (Zone 2) to a maximum of 17.17 ms (Zone 7).

TABLE III
P2P TRANSMISSION TIME IN THE NON-LOS SCENARIO

Zona	Lost (%)	Peak Time (ms)	Average Time (ms)	Low Time (ms)
1	0	1.59	2.12	1.40
2	0	1.59	2.31	1.40
3	0	1.46	2.65	1.42
4	0	1.71	2.92	1.34
5	0	1.93	3.21	1.60
6	30	2.29	3.33	2.20

TABLE IV
TRANSMISSION TIMES FOR STAR AND TREE TOPOLOGIES IN THE NON-LOS SCENARIO CONFIGURATION

Zona	Lost (%)	Peak Time (ms)	Average Time (ms)	Low Time (ms)
1	0	2.63	6.73	1.60
2	0	1.83	2.46	1.58
3	0	3.56	6.73	2.58
4	0	4.86	16.6	3.55
5	0	7.95	16.4	4.45
6	0	7.94	16.6	5.60
7	0	10.20	17.17	6.20

As shown in Tables IV, and V, the multi-hop network architecture experiences no packet loss up to Zone 7; in contrast, the P2P configuration completely loses connectivity at Zone 6, where seven walls must be traversed. Star and tree multi-hop topologies exhibit lower overall transmission times compared to the serial tree topology because they involve fewer node hops. While there is a linear increase in average transmission time relative to the number of walls traversed in multi-hop configurations, packet loss remains zero. Given that the

distance between nodes is uniform, Table VI indicates that the average transmission time between two nodes is nearly identical across all multi-hop topologies, demonstrating consistent average transmission performance for each node.

TABLE V
TRANSMISSION TIME FOR THE SERIES TREE TOPOLOGY CONFIGURATION IN THE NON-LOS SCENARIO

Zona	Lost (%)	Peak Time (ms)	Average Time (ms)	Low Time (ms)
1	0	16.2	19.3	2.36
2	0	16.9	23.7	3.7
3	0	16.3	19.1	5.58
4	0	14.5	19.3	6.36
5	0	15.4	20.36	6.36
6	0	18.3	22.75	12.7
7	0	26.2	36.99	12.28

TABLE VI
COMPARISON OF TRANSMISSION TIME PER NODE

Zona	Topology	Peak Time (ms)	Average Time (ms)	Low Time (ms)
7	Tree	10.2	17.17	6.1
7	Star	10.2	17.17	6.1
7	Series Tree	13.1	18.49	6.14

Tree and Star topologies are more highly recommended because their performance is far more stable and less prone to disruption compared to the Series Tree topology, even though both offer similar average speeds.

D. The Effect of Data Speed

To determine which data rate offers energy efficiency alongside adequate performance, the data rate was varied from 250 Kbps to 2 Mbps. As shown in Table VII, peak power increased linearly with the data rate, with 250 Kbps yielding the lowest power and 2 Mbps the highest. While increasing the data rate offers advantages regarding transmission time, in real world scenarios, this must be balanced against the specific application requirements.

TABLE VII
EFFECT OF DATA RATE ON TRANSMISSION TIME

Node	Data Speed	Peak Power (mW)	Peak Time (ms)	Average Time (ms)	Low Time (ms)
3	250 kbps	40.98	23.29	4.71	15.8
3	1 Mbps	44.24	18.16	1.77	5.22
3	2 Mbps	47.43	16.2	1.6	6.91
4	250 kbps	60.93	41.41	4.71	33.1
4	1 Mbps	63.94	18.16	1.77	9.61
4	2 Mbps	72.40	16.3	1.6	6.65

In municipal water distribution monitoring, data must be transmitted in real-time, passing through multiple nodes before reaching the master node. This approach results in faster transmission times and stable power usage, thereby ensuring energy efficiency in battery operated applications. This aligns with preliminary studies on power consumption across various topologies, which identified on-demand scheduling as the most energy-efficient method for multi-hop scenarios. Unlike methods that introduce extra messages which can prolong transmission time on demand scheduling transmits messages individually without increasing payload size. Consequently, the combination of a 250 Kbps data rate and on-demand scheduling proves to be the most energy efficient method for data transmission in multi-hop wireless sensor networks utilizing the NRF24L01+.

IV. Conclusion

The NRF24L01+ does not natively support multi-hop network architectures. Despite this limitation, its low cost and energy efficiency make it advantageous for large scale implementations such as urban air distribution monitoring that require numerous cooperating nodes. This study characterizes a multi-hop wireless sensor network using the NRF24L01+ advanced octal addressing across three different topologies and two message scheduling schemes. Performance was evaluated through Line of Sight (LOS) and Non Line of Sight (NLOS) configuration tests, power consumption analysis, and assessments of how data rates affect power consumption, transmission time, and packet loss. The study identifies the star and tree topologies utilizing 92 mWh of energy and on-demand scheduling as the most energy efficient configurations. The proposed multi-hop method offers more consistent timing than direct (P2P) routing, demonstrating a minimal gap between minimum and average transmission times. The multi-hop network approach excels in various communication scenarios, achieving 0% packet loss and an average transmission time of 6 ms per node. The authors recommend a data rate of 250 Kbps for real-time monitoring and 2 Mbps for scenarios involving delayed transmission. These findings contribute to the design of large-scale, real time, multi-hop urban water distribution monitoring systems by identifying the most efficient configurations to reduce costs, enhance performance, and conserve energy. Achieving efficient total power usage through a Series tree topology and a "Protocol by Request" method, resulting in a total power output of 91.86 mWh.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper

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