

# Topology-Free Networking Using Implicit Coordination in Dense IoT Systems

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## ABSTRACT

The traditional networking topologies of Internet of Things (IoT) systems are based on explicit topology building, neighbor discovery, and routing state maintenance. Although they are effective in less dense and stable networks, these methods are inefficient in dense, dynamic, and unstructured IoT networks because they increase the control overhead, energy usage, and scalability. This study proposes a topology-free networking paradigm that does not require topology awareness, routing tables, node identifiers, or neighbor discovery. Rather, data propagation is realized via implicit coordination of nodes as decided by locally visible cues, such as signal strength, reception timing, and channel contention. An opportunistic forwarding based on a suppression strategy is presented, in which each node calculates a forwarding score based on these normalized parameters and applies opportunistic forwarding to the node. The proposed method was evaluated through simulations under varying node densities and traffic demands. The performance is evaluated by means of several metrics, such as packet reachability, end-to-end delay, transmission redundancy, scalability, control overhead, and energy consumption. The findings indicate that the proposed topology-free approach offers reliable data delivery, with a substantially reduced overhead and high efficiency in dense IoT contexts. These results suggest the promise of topology-free networking as a scalable and energy saving alternative to large-scale and resource-constrained IoT systems in the future.

## 1. INTRODUCTION

The accelerated development of Internet of Things (IoT) technologies has led to the implementation of larger-scale and denser wireless networks comprising resource-constrained devices [1]. These networks accommodate a large number of applications such as environmental monitoring, industrial automation, smart infrastructure, and large-scale sensing systems. With the density of the network, conventional assumptions of networking, including fixed network connectivity, explicit neighbor discovery, and persistent routing structure, become more and more challenging to maintain [2, 3].

Traditionally wireless networking applications are basically constructed on the notion of network topology. Nodes are expected to find their neighbors, preserve routing tables, exchange control messages, and make forwarding decisions based on an explicit or implicit model of the network graph. Though these techniques are effective in small to medium size and somewhat stable networks, they cause huge overhead in dense IoT networks. Control signaling, topology maintenance, and state synchronization

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all use valuable energy and prevent scalability due to frequent control signaling, channel contention due to topology, as well as scalability [4, 5].

The topology information is frequently costly to maintain, especially when the IoT system is very dense and there are numerous nodes distributed across a wide area. Failure of nodes, interference on wireless communication, environmental dynamics, and irregularities in deployment keep the topology learned invalid, and thus networks consume significant resources to maintain structural awareness. This can lead to the deterioration of network performance even in the case of sparse data traffic, which is one of the main flaws of topology-focused design. Recent studies have attempted to curb these problems using approaches like opportunistic routing, data-centric communication, gossip-based dissemination, and bio-inspired networking models [6]. Even though these methods ease some of the routing overheads, they implicitly make assumptions about topology such as node identifiers, neighbor information, probabilistic forwarding fences or partial routing data. As a result, the concept of topology is either present directly or indirectly in the network operation [7].

This paper introduces a networking architecture that dispenses with the traditional reliance on network topology, routing tables, and neighbor discovery. The suggested solution facilitates the propagation of data using implicit coordination, i.e., forwarding decisions are made independently based on the cues that can be seen locally i.e. signal properties, the time of reception, and contention dynamics. Nodes do not store the network state and do not have a global or local understanding of the network structure. Rather, communication comes out as a distributed phenomenon that is only propelled by instantaneous interactions with the wireless medium. The proposed framework should minimize control overhead to zero by eliminating topology as a design dependency, enhance scalability in a dense deployment, and resilience to varying network conditions. This paper conducts a topology-free networking study to examine their feasibility, performance, and constraints in dense IoT networks through a large-scale simulation study.

The key findings of this work are as follows:

- A different topology-free networking architecture is suggested to dense IoT systems that do not require explicit topology creation, routing tables, and neighbor discovery protocols.
- A complete forwarding protocol reliant on implicit coordination is proposed, in which autonomous forwarding choices are decided by the nodes based on the appearance of the locally viewable wireless indicators, e.g. signal strength, reception time and channel contention.
- The lightweight and efficient communication model is created, which is by far less resource-heavy in control overhead and does not require network-state maintenance, which is appropriate in the resource-constrained IoT environments.
- Simulation of the proposed scheme under different node densities has shown that the scheme is more scalable, the delay is lower and less transmission redundancy than the traditional forwarding schemes.

The rest of this paper is structured in the following way. Section 2 conducts a literature review and outlines weaknesses of topology-sensitive methods. Section 3 consists of the proposed topology-free networking framework and its principles of operation. Section 4 outlines the simulation environment and performance measures. The results obtained are discussed in Section 5, and the paper is concluded with the insights and the directions of future research in Section 6.

## **2. RELATED WORK**

Topology-aware networking has traditionally been the most prominent design trend in wireless sensor networks (WSNs) and Internet of Things (IoT) networks. The initial routing protocols were designed to build and maintain explicit topologies to support reliable multi-hop communications. For instance, Heinzelman et al. [7] proposed LEACH, a hierarchical clustering protocol that groups nodes into clusters to conserve energy and maximize network lifetime. Although efficient for small-scale networks, topology-dependent clustering protocols are highly inefficient in dense or large-scale networks. Distance-vector and on-demand routing protocols were later modified for wireless and ad-hoc networks. Perkins et al. [8] proposed AODV, a routing protocol that dynamically builds routes in response to demands, minimizing unnecessary routing overhead compared to proactive routing protocols. Likewise, Johnson et al. [9] proposed DSR, a routing protocol that uses source routing and route caching. Although more efficient than earlier protocols in terms of routing overhead for sparse networks, these protocols are still inefficient for dense and dynamic IoT networks since they require explicit route discovery and maintenance.

To address the scalability issue, data-centric routing and data collection based routing protocols have been suggested. Gnawali et al. [10] proposed the Collection Tree Protocol (CTP) that relies on the estimation of the quality of links to create a routing tree with the sink node as the root. On the same note. Opposite routing was suggested by Biswas and Morris [11], according to which packets may be forwarded by dynamically chosen nodes based on the availability of transmissions. In a similar case, gossip-based dissemination protocols, whose study was conducted by Haas et al. [12] avoided overhead through probabilistic forwarding packets. Nevertheless, the strategies still presuppose some awareness, node identifier, or probabilistic structure so some degree

of reliance on network topology remains. More recent studies have also suggested bio-inspired and swarm-based networking algorithms. As an example, self-organizing communication suggested by Dressler et al. [13] was based on conceptualization of biological systems. Such strategies enhance flexibility and yet, some degree of reliance on the network topology. Unlike the existing research, the suggested work does not resemble topology-aware and topology-relaxed approaches as it does not consider topology awareness.

The recent research work has also concentrated on scalable communication in dense IoT systems, such as low-power routing and opportunistic communication models. Nonetheless, those methods remain based on either explicit or implicit topology structures, which reduce their effectiveness and scalability in the highly dense and dynamic cases [14-16].

Unlike the current literature, the presented solution bases on the rejection of topology awareness as opposed to topology-aware and topology-relaxed solutions. Instead of keeping routes, neighbor data, or probabilistic forwarding graph, data propagation is done by implicit coordination by real-time wireless communication only. This intrinsic difference excludes the proposed approach to the traditional routing, opportunistic, and bio-inspired networking systems.

### 3. METHODOLOGY

In this section, the proposed topology-free networking framework is described, and its functioning principles, system components, and the mechanism of data propagation are discussed. The design of the methodology is to avoid explicit topology construction, routing tables, node identifiers and neighbor discovery processes. Rather, network behavior arises as a result of implicit coordination of nodes using only locally visible wireless interactions.

#### 3.1 Network Model and Assumptions

The network under consideration is composed of many densely spaced IoT nodes that are randomly distributed across a two-dimensional space. The nodes are modeled as being stationary at each point in time of the simulation and share a common wireless medium. The nodes are limited in both energy and processing as well as memory, which is characteristic of the IoT. The network does not employ:

- Node addressing or unique identifiers
- Neighbor discovery mechanisms
- Routing tables or path maintenance
- Periodic control or hello messages

Communication is a broadcast type and nodes utilize information that is only visible at the physical and medium access layers. The general working of the proposed topology-free networking approach is shown in Fig. 1. The present work is limited to the consideration of network scenarios that are not mobile whereas the mobility-based extensions are viewed as the work in the future.

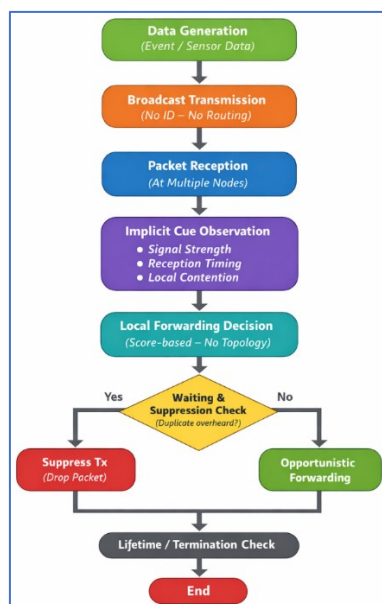


Fig. 1. Proposed topology-free networking method.

Figure 1 shows the working process of the offered topology-free networking approach. It starts with the data generation and then broadcasting without information address or routing. When received, the nodes glean implicit coordination information and make a local forwarding decision. Then a waiting and suppression scheme is implemented which prevents unnecessary retransmissions so efficient and scalable data propagation can be achieved without maintaining any network topology.

### 3.2 Implicit Coordination Principle

Implicit coordination is the capacity of nodes to base their forwarding choices on non-relationship communication and coordination schemes. Within the proposed framework, coordination is based on real-time observations of the wireless medium which include:

- Received signal strength variations
- Packet reception timing
- Local contention and channel access dynamics

The interpretation of these cues by each node is independent of any topology information on the globe or locally, and is done to decide whether it should forward a received packet.

### 3.3 Data Generation and Packet Structure

Application-level data is made available in sensor nodes or specific source nodes, which generate data packets. Every packet holds little information that is required in dissemination like:

- Event or data payload
- Transmission timestamp
- Limited hop or lifetime indicator (to prevent indefinite propagation)

No source routing information, destination addresses, or path identifiers are provided.

### 3.4 Implicit Forwarding Decision Mechanism

When a packet is received, a node reconstructs the suitability of forwarding packets with local decision function. This position is anchored on a synthesis of unspoken measures, such as:

- Relative signal strength compared to previous receptions
- Delay at reception compared to other neighboring nodes.
- Local channel occupancy or contention level

The nodes with less adverse circumstances (e.g. a larger signal to sink gradient or a better time of reception) are more apt than others to propagate the packet. The elimination of redundancy is not synchronized as the nodes that transmit more favorable conditions suppress transmission of other nodes that have worse conditions.

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#### Algorithm 1: Implicit Forwarding Decision

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Input: Received packet P

Output: Forward or Suppress

1: Observe RSSI, reception time, and channel contention

2: Normalize observed parameters

3: Compute forwarding score:

$$S = \alpha \cdot \text{RSSI} + \beta \cdot T + \gamma \cdot C$$

4: Generate waiting time  $T_w$  inversely proportional to S

5: If duplicate packet is overheard during  $T_w$ :

    Suppress transmission

6: Else:

Forward packet

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### 3.5 Opportunistic Propagation Process

The advancing process results in an opportunistic propagation exhibit:

1. A broadcast packet is sent to a node.
2. It computes a local forwarding score using implicit cues.
3. A local waiting time that is short is applied.
4. In the event that no duplicate packet is intercepted within this time the node forwards the packet.
5. When another transmission is received the node blocks the forwarding attempt.

This system facilitates smooth flow of data across the network without being subject to flooding and immoderate collisions.

### 3.6 Security Considerations

Even though the topology-free networking technique proposed eradicates the dependence of topology and control overhead, it can cause possible security vulnerabilities. Specifically, malicious nodes may use the implicit coordination mechanism to inject false signals, trigger unnecessary forwarding or discontinue data propagation. As the suggested strategy is not based on explicit routing or top-down control, the conventional security mechanisms might be inapplicable directly. Thus, security solutions which are light and distributed solutions are needed to guarantee the stability in work. Further research will involve incorporation of effective security solutions including anomaly detection, trust dependent forwarding and lightweight authentication to improve resilience to malicious behavior in decentralized IoT systems.

### 3.7 Loop Prevention and Redundancy Control

Since no topology or path history is maintained, loop prevention is handled through lightweight mechanisms:

- Packet lifetime or hop limit constraints
- Duplicate packet suppression using short-term local buffers
- Time-based forwarding inhibition

These measures ensure bounded propagation without requiring routing state.

## 4. SIMULATION SETUP AND PERFORMANCE METRICS

In this section, the simulation environment, baseline schemes, evaluation scenarios, and performance indicators that are to be used in evaluating the proposed topology-free networking method are described. The aim is to test the efficiency, scalability, and stability of the offered solution in the conditions of the dense deployment of the IoT.

### 4.1 Simulation Environment

The suggested approach is tested with a discrete-event network simulator which is used to model wireless communication among IoT nodes. The parameters of the simulation are chosen in such a way as to represent the dense IoT scenarios of a real-world setting whilst being reproducible and fair to all schemes being compared. The simulated network is a network of fixed sensor nodes randomly laid out across a two-dimensional space. The nodes share wireless medium in a broadcast sent. The proposed approach does not have any node addressing, routing tables, or neighbor discovery mechanisms. The main parameters of the simulation are summed up as follows:

- Simulation area: 100 m × 100 m
- Number of nodes: 50, 100, and 150
- Deployment model: Uniform random distribution
- Traffic model: Event-driven data generation
- Packet size: Fixed-length data packets
- MAC layer: Generic contention-based wireless MAC
- Radio propagation model: Log-distance path loss
- Simulation duration: 1000 seconds

Each of the simulation runs will be surrounded by various random seeds and their average outcomes will be reported to guarantee statistical reliability.

#### 4.2 Baseline Schemes for Comparison

In order to objectively test the proposed topology-free approach, the performance of the proposed approach is contrasted with well-known baseline forwarding schemes that do not use complicated routing protocols but still describe typical network behavior:

- Flooding: Every node rebroadcasts each received packet once.
- Gossip-based forwarding: Nodes forward packets with a predefined probability.
- Opportunistic forwarding: Nodes forward packets based on local link quality without maintaining full routing tables.
- RPL (Routing Protocol Low-Power and Lossy Network): One of the most common routing protocols in IoT systems is a conventional topology. It assembles a routing tree to a sink node by means of control messages, and is enclosed as a structured networking technique representative.

The inclusion of RPL is to give a comparison with a topology-based routing protocol of IoT which has been adopted widely and exhibit the difference between coordinated and uncoordinated communication methods. They are picked as the baseline schemes to emphasize on the effect of removing topology awareness with similar communication assumptions.

#### 4.3 Performance Metrics

The effectiveness of the suggested method is estimated on the basis of the following measures:

- **Packet Reachability (%):**  
The proportion of the packets that are successfully delivered to the number of the generated packets. Packet reachability is the measure of the reliability of data dissemination, and is defined as:

$$\text{Packet Reachability (\%)} = \frac{N_{\text{delivered}}}{N_{\text{generated}}} \times 100$$

where:

$N_{\text{generated}}$  is the total number of packets generated by source nodes

$N_{\text{delivered}}$  is the number of packets successfully received at the destination

- **End-to-End Delay:**  
The mean time in which a packet is transmitted between the source and its ultimate destination. The average end-to-end delay is evaluated as:

$$D_{\text{avg}} = \frac{1}{N_{\text{delivered}}} \sum_{i=1}^{N_{\text{delivered}}} (t_i^{\text{recv}} - t_i^{\text{send}})$$

where:

$t_i^{\text{send}}$  is the transmission time of packet  $i$

$t_i^{\text{recv}}$  is the reception time of packet  $i$

This measure is an indication of the temporal efficiency of the forwarding mechanism.

- **Redundancy Ratio:**  
The means of the packets transmissions to be made in order to deliver a packet successfully and is defined as:

$$R = \frac{N_{\text{tx}}}{N_{\text{delivered}}}$$

where:

$N_{\text{tx}}$  is the total number of packet transmissions in the network

$N_{\text{delivered}}$  is the number of successfully delivered packets

- **Control Overhead:**

The control transmission to data transmission ratio. As the suggested approach does not use routing tables or control signaling, control overhead is calculated as:

where:

$N_{control}$  is the number of control packets transmitted

In the case of the proposed topology-free approach:

$$N_{control} \approx 0 \Rightarrow O_{ctrl} \approx 0$$

**Scalability:**

The performance measures decrease as number of nodes grows.

A combination of these metrics represents reliability, efficiency, and scalability features of the network.

- **Energy Consumption**

$$E_{total} = N_{tx} \cdot E_{tx} + N_{rx} \cdot E_{rx}$$

**Throughput**

$$Throughput = \frac{N_{delivered} \times Packet\ Size}{Simulation\ Time}$$

These extra measures will give a more detailed analysis of the network effectiveness and efficiency.

#### 4.4 Evaluation Scenarios

Various evaluation situations are arranged to examine how the proposed method will behave in various conditions of network:

- **Node Density Variation:**

The increase in number of nodes in terms of dense to sparse deployment is evaluated as performance.

- **Traffic Intensity Variation:**

The rate at which events occur is varied in order to test network behavior when there is a light and moderate traffic load.

- **Wireless Interference Impact:**

The channel contention is enhanced to test the strength against interference.

- **Propagation Stability:**

The analysis of stability is done by analyzing the consistency of packet delivery with time.

### 5. RESULTS AND DISCUSSION

In this section, the results of the simulation of the proposed topology-free networking method will be described and discussed. The findings are evaluated with respect to the various node densities in order to measure the performance of the suggested method when compared to the other common protocols like flooding and gossip forwarding.

#### 5.1 Packet Reachability Analysis

We show the packet reachability analysis at various densities of nodes in Figure 2 below. In the case of a larger network size, that is, the number of nodes in the network, we find that the suggested topology-free scheme offers high packet reachability. The proposed method provides packet reachability higher than 88% even in high-density scenarios. In contrast, flooding protocol faces a sharp decline in packet reachability as we increase the number of nodes in the network. This is mainly due to the high number of collisions in the network due to redundant transmissions. Similarly, we observe that gossip-based forwarding protocol performs moderately in terms of packet reachability. This protocol faces packet losses in high-density scenarios. The results clearly indicate that the proposed method provides a good balance between propagating and suppressing packets to their destinations without using any routing or flooding mechanisms.

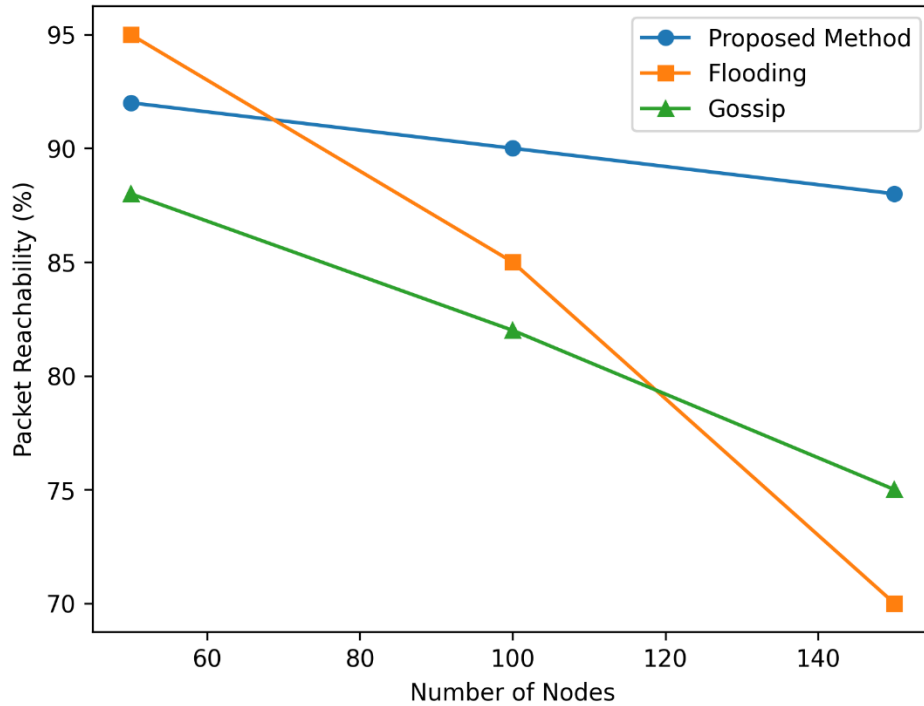


Fig. 2. Packet reachability versus node density.

### 5.2 End-to-End Delay Performance

The average end-to-end delay results are shown in Figure 3. The proposed approach always has the minimum delay for all considered network sizes. This is because of the opportunistic forwarding strategy, in which nodes with better implicit signals tend to forward packets earlier. Flooding has the highest delay due to high contention and retransmissions, and gossip-based forwarding has an intermediate delay value. As the node density increases, the difference in delay between the proposed approach and the other approaches becomes clearer. These results show that ignoring topology maintenance and control messages not only decreases overhead but also improves temporal efficiency.

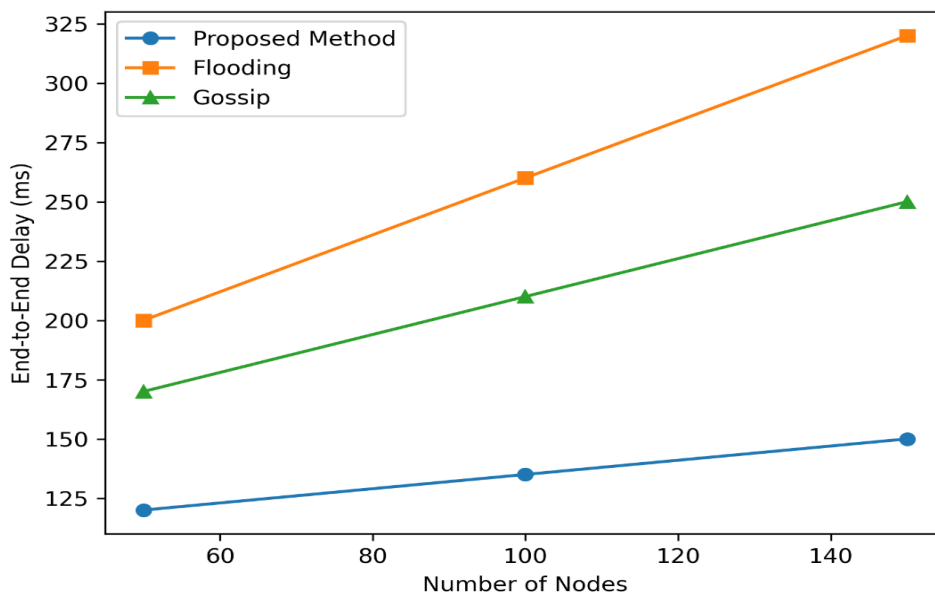


Fig. 3. End-to-end delay versus node density.

### 5.3 Transmission Redundancy and Overhead

Figure 4 shows the comparison of the transmission redundancy ratio for various methods. The topology-free approach has much lower redundancy than the flooding and gossip-based forwarding methods. The redundancy ratio of the proposed strategy is more or less one transmission per packet on average which represents optimum efficiency. Flooding method is most redundant due to indiscriminate rebroadcasting which grows exponentially with the density of the nodes. The gossip forwarding scheme is less redundant compared to the flooding scheme; however, it has a few redundant transmissions. The fact that the redundancy of the proposed approach is low justifies the efficiency of the waiting and suppression mechanism as a method of controlling redundant transmissions.

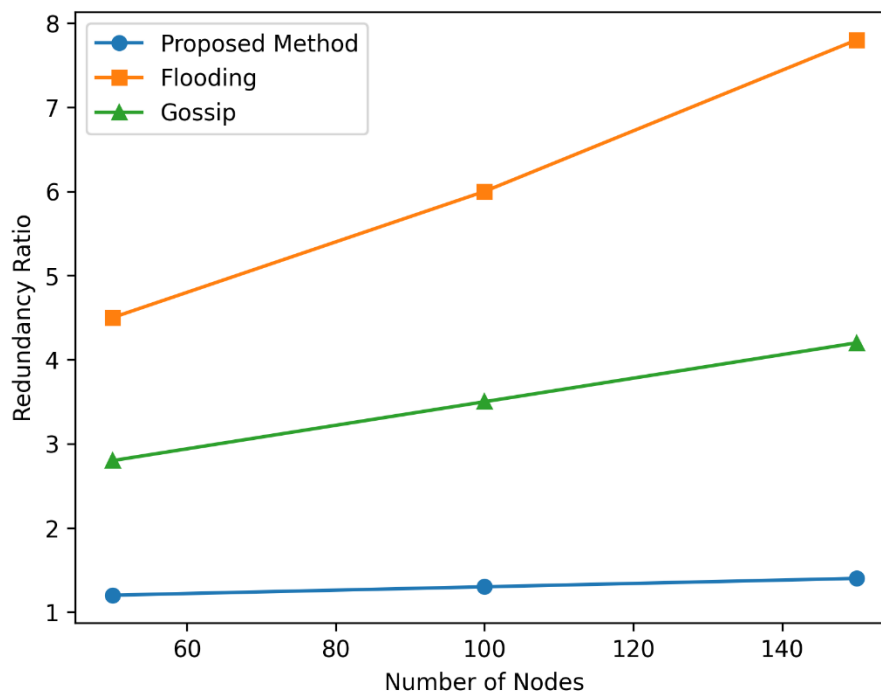


Fig. 4. Transmission redundancy versus node density.

### 5.4 Discussion and Insights

Overall, the findings highlight the advantages of topology-free networking in sparse IoT environments. As the proposed solution does not require the use of routing tables, neighbor discovery, and topology maintenance, it leads to the significant decrease of overhead levels and preservation of the data transportation. The proposed solution is known to scale with increase in network size unlike the traditional solutions since in the traditional solutions, a large portion of control and data traffic does not work effectively in a dense environment. The findings also reveal that implicit coordination suffices in driving data transport as opposed to the traditional opinion of explicit topology knowledge to enable efficient networking. Although the results show great performance up to 150 nodes, it is necessary to conduct additional evaluation in terms of ultra-large-scale deployments.

### 5.5 Limitations of the Proposed Method

Although the suggested topology-free networking solution is showing positive results, it must be admitted that there are some limitations to it. The given work presupposes a static network environment with identical nodes, which might not be fully applicable to the real-life cases of IoT implementation when mobility and heterogeneity are the usual characteristics. In addition, the simplified wireless channel conditions were considered in the simulation environment, and external interference or multi-channel communication was not explicitly considered. Moreover, the model of energy constraints is formulated in a generalized form without considering long-term node failures and battery depletion

processes. All these limitations point to the fact that some additional research is necessary to test the described approach in more realistic and dynamic settings.

## 6. CONCLUSION AND FUTURE WORK

The paper presented a topology-free networking architecture of dense IoT systems that do not require constructing topology, routing tables, or control messages. The strategy is instead an implicit coordination strategy which relies on local wireless signals to achieve efficient and fully distributed dissemination of data. The nature of simulation outcomes has shown that the proposed approach achieves high packet reachability, low end-to-end delay, and minimal transmission redundancy in dense IoT systems, thereby demonstrating the possibility of the provision of dependable communication in dense IoT systems without topology awareness. Further development of this method is to generalize it to include dynamic cases, such as moving nodes and changing traffic patterns, and interfering environments. Additional effort is required to incorporate security and experimental verification.

## REFERENCE

- [1] R. M. P. N. S. Bandara, A. B. Jayasignhe, and G. Retscher, "The Integration of IoT (Internet of Things) Sensors and Location-Based Services for Water Quality Monitoring: A Systematic Literature Review," *Sensors*, vol. 25, p. 1918, 2025.
- [2] Q. F. Hassan, *Internet of things A to Z: technologies and applications*: John Wiley & Sons, 2025.
- [3] A. K. Saini and A. K. Yadav, "A Comprehensive review on technological breakthroughs in precision agriculture: IoT and emerging data analytics," *European Journal of Agronomy*, vol. 163, p. 127440, 2025.
- [4] S. Kaur, S. Kour, and M. Singh, "Energy efficiency in wireless sensor networks: comparing traditional and advanced clustering protocols," *Engineering Research Express*, vol. 7, p. 015258, 2025.
- [5] S. Iyer, R. Khanai, D. Torse, R. J. Pandya, K. M. Rabie, K. Pai, et al., "A survey on semantic communications for intelligent wireless networks," *Wireless Personal Communications*, vol. 129, pp. 569-611, 2023.
- [6] J. Su, J. Fan, S. Wu, G. Li, S. Qin, and F. Gao, "Topology-driven quantum architecture search framework," *Science China Information Sciences*, vol. 68, p. 180507, 2025.
- [7] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, Maui, HI, USA, 2000, pp. 1-10.
- [8] C. E. Perkins, E. M. Royer, and S. Das, "Ad hoc on-demand distance vector (AODV) routing," RFC 3561, IETF, Jul. 2003.
- [9] D. B. Johnson, D. A. Maltz, and J. Broch, "DSR: The dynamic source routing protocol for multi-hop wireless ad hoc networks," *Ad hoc networking*, vol. 5, pp. 139-172, 2001.
- [10] O. Gnawali, R. Fonseca, K. Jamieson, D. Moss, and P. Levis, "Collection tree protocol," in *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems (SenSys)*, Berkeley, CA, USA, 2009, pp. 1-14.
- [11] S. Biswas and R. Morris, "Opportunistic routing in multi-hop wireless networks," in *Proceedings of the ACM SIGCOMM Conference*, Philadelphia, PA, USA, 2005, pp. 69-80.
- [12] Z. J. Haas, J. Y. Halpern, and L. Li, "Gossip-based ad hoc routing," *IEEE/ACM Transactions on Networking*, vol. 14, no. 3, pp. 479-491, Jun. 2006.
- [13] F. Dressler, "Bio-inspired networking: From theory to practice," *IEEE Communications Magazine*, vol. 45, no. 3, pp. 176-183, Mar. 2007.
- [14] I. Cheikh, S. Roy, E. Sabir, and R. Aouami, "Energy, scalability, data and security in massive IoT: Current landscape and future directions," *IEEE Internet of Things Journal*, 2026.
- [15] D. Yedilkhan, A. Turginbekov, B. Akhmetzhanov, Z. Talgatuly, and D. Marlambekov, "Comparative Analysis of IoT Wireless Technologies Communications through Experimental Simulations," *Procedia Computer Science*, vol. 257, pp. 382-387, 2025.
- [16] A. A. Qaffas, "AI-driven distributed IoT communication architecture for smart city traffic optimization," *The Journal of Supercomputing*, vol. 81, p. 916, 2025.