

# State Aware Multi Hop Routing via Digital Twin for Iot Networks

Patel Nensi Rakeshbhai(student) , Dr. S.K. Hadia (Guide)

PG - IOT , Gujarat Technological University-School Of Engineering and Technology

[nensip2508@gmail.com](mailto:nensip2508@gmail.com)

Associate Professor - Gujarat Technological University-School Of Engineering and Technology

[asso\\_s\\_k\\_hadia@gtu.edu.in](mailto:asso_s_k_hadia@gtu.edu.in)

## Abstract

The Internet of Things (IoT) has seen rapid growth and is widely used across domains like healthcare, transportation, manufacturing, and smart cities. However, managing large-scale IoT networks, particularly in terms of efficient routing, presents significant challenges due to dynamic network conditions, energy constraints, and high demand. Traditional routing protocols, such as static and distance vector routing, are inadequate for these evolving networks. A promising solution emerges through integrating Digital Twin (DT) technology, which provides a near-real-time virtual replica of physical environments, allowing for better state-aware routing strategies. The synergy between state-aware multi-hop routing and Digital Twin frameworks to enhance performance and energy efficiency in IoT networks. Digital Twins simulate real-time network conditions, including device power, traffic status, and potential failures, enabling adaptive routing policies that respond to environmental changes. Multi-hop routing improves network resilience and connectivity but requires integration with real-time state information to reach its full potential. Metaheuristic optimization algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) are used to optimize routing paths dynamically, considering both static and dynamic network features, thereby improving throughput and reducing energy consumption. Security is a crucial consideration for IoT networks, as these systems are vulnerable to various threats due to their open deployment. By embedding security features within the Digital Twin framework, potential security issues can be predicted and mitigated before they impact the network. The paper also discusses the use of drones in IoT deployments, especially in challenging environments where traditional infrastructure is lacking, and highlights the role of Digital Twins in adapting routing strategies for such scenarios.

**Keywords:** *Digital Twin (DT), IoT Networks, State-Aware Multi-Hop Routing, Metaheuristic Optimization, Particle Swarm Optimization, Genetic Algorithm, Ant Colony Optimization, Hybrid Models, Deep Learning, Security, IoT Device Resource Management, Energy Efficiency.*

## Introduction

The Internet of Things (IoT) plays a crucial role in modern technology, with applications spanning healthcare, transportation, energy management, and industrial automation. IoT systems are complex networks of connected devices that interact dynamically, processing data from multiple sources to make real-time intelligent decisions. However, effectively managing these networks, particularly in terms of data routing among geographically

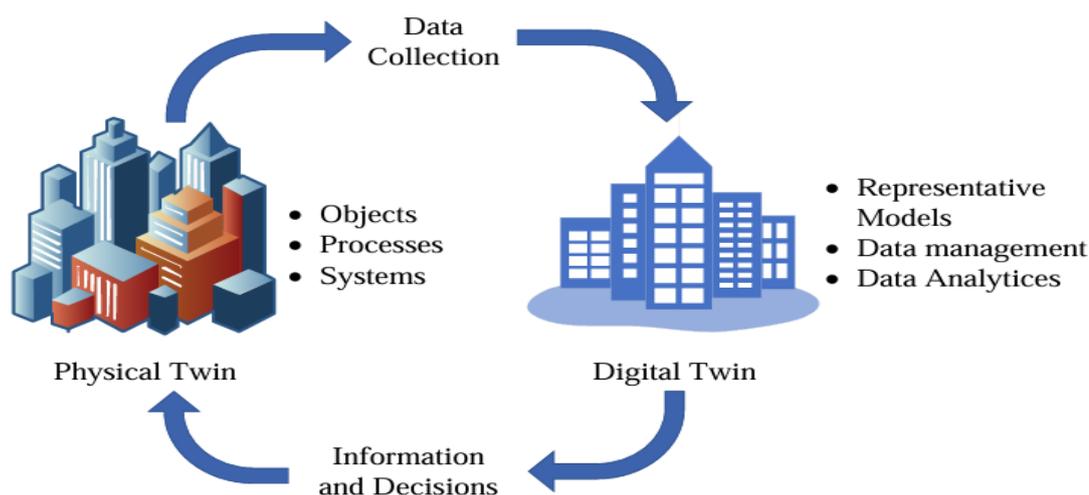
dispersed devices, presents a significant challenge. Multi-hop routing, where traffic is relayed through intermediate devices to reach its destination, is vital in large-scale IoT networks, especially when direct communication between devices is impractical due to physical constraints, network gaps, or interference.

Traditional routing algorithms, such as static routing and shortest-path methods, are inadequate for IoT networks due to their failure to adapt to dynamic network conditions like moving devices, fluctuating energy levels, and network congestion. As IoT networks continue to grow in size and complexity, there is an increasing need for adaptive, energy-efficient, and reliable routing solutions. State-aware multi-hop routing, which adjusts routing decisions based on real-time network conditions (such as energy consumption, link quality, and node mobility), offers a promising solution.

In large-scale, resource-constrained networks where nodes frequently change their operational states, ensuring optimal routing becomes challenging. Digital Twin (DT) technology, which creates a virtual representation of physical objects, can address this challenge. By modeling the network state (e.g., device energy levels, locations, and communication conditions), Digital Twin provides a real-time virtual representation of the physical IoT network. When combined with state-aware multi-hop routing, Digital Twin enables continuous monitoring, prediction, and optimization of routing decisions, enhancing the performance, energy efficiency, and security of IoT networks. This paper investigates the potential of integrating state-aware multi-hop routing with Digital Twin technology to improve IoT network performance in terms of effectiveness, energy consumption, and security.

### Digital Twin Technology in IoT Networks

Digital Twin Digital Twin technology has become available to the market place as a reality over the last few years after being spoken about by many for more than a decade, including representing a virtual model of real physical assets (structures) creating new process and service offering through applying predictive maintenance within Industry 4.0. From an IOT perspective, a digital twin is live simulation of the IOT network that faithfully replicates the attributes and status of what they represent. By emulating all the devices and nodes in your network, digital twins provide operators with visibility over how IoT systems are behaving at any moment – so you can see problems before they take your network down.



Roongpraiwan et al. [3] highlight the benefits of incorporating Digital Twin (DT) technology in IoT networks, allowing for the simulation and prediction of network behavior, such as node failures or energy depletion. This is particularly important for multi-hop routing protocols, where timely actions are needed to ensure effective data routing during time-sensitive events, like low energy in sensor nodes. With real-time feedback from the IoT environment, DT enables operators to model various routing scenarios and optimize data transport under current and future conditions. In DT-centric IoT applications, devices are represented as Virtual Twins, capturing device states like battery levels, connection status, and on/off status. These virtual models can be managed more efficiently, allowing operators to optimize routing without manually checking each device. Additionally, Roongpraiwan et al. [10] demonstrate how DT models can enhance routing strategies for Vehicle-to-Everything (V2X) communication, where nodes continuously change due to vehicle movement.

## Routing Protocol

### 1. Proactive Routing Protocols:

- **OLSR (Optimized Link State Routing):** A link-state protocol that keeps up-to-date routing tables and is suited for IoT networks with fixed topology. Digital Twin technology helps simulate the network, forecast optimal paths, and handle topology changes.
- **DSDV (Destination-Sequenced Distance Vector):** Maintains dynamic routing tables for immediate route access. With Digital Twin, it predicts node status and energy consumption to dynamically update routing tables.

### 2. Reactive Routing Protocols:

- **AODV (Ad-hoc On-Demand Distance Vector):** Routes are created on-demand when data needs to be sent. Digital Twin models predict congestion and energy depletion to optimize route selection ahead of time.
- **DSR (Dynamic Source Routing):** This protocol supports on-demand route discovery, where the full path is included in every packet. Digital Twin helps predict link failures and congestion, optimizing decision-making in real-time.

### 3. Hybrid Routing Protocols:

- **ZRP (Zone Routing Protocol):** Combines proactive and reactive methods by managing smaller zones with proactive routing and larger areas reactively. Digital Twin adjusts routing strategies based on real-time changes in energy levels and link quality.
- **TORA (Temporary Ordered Routing Algorithm):** A hybrid protocol designed for dynamic environments with low overhead. Digital Twin models predict mobility impacts and congestion, adapting routing strategies accordingly.

#### 4. QoS-Aware Routing Protocols:

- **Multipath Routing:** Uses multiple paths to forward data, enhancing redundancy and reliability. Digital Twin simulates multiple paths, evaluating energy, link quality, and congestion to determine the optimal path for QoS.
- **Real-Time Communication Routing:** Designed for low-latency applications, like video or voice. Digital Twin models real-time network behavior to dynamically adjust routes to meet strict latency and throughput requirements.

#### 5. Energy-Aware Routing Protocols:

- **LEACH (Low-Energy Adaptive Clustering Hierarchy):** Rotates cluster heads to save energy and communicate efficiently. Digital Twin simulates node energy consumption, adjusting cluster head assignments in real-time to extend network life.
- **EECS (Energy Efficient Clustering Scheme):** Saves energy by using node energy levels to form clusters. Digital Twin optimizes energy distribution across the network, adapting cluster formations and routes dynamically.

#### 6. Security-Aware Routing Protocols:

- **SEAD (Secure Efficient Ad hoc Distance Vector):** A secure routing protocol using cryptography to defend against attacks. Digital Twin simulates potential security threats and optimizes routes by excluding compromised nodes.
- **Trust-Based Routing:** Uses trust levels based on past node behavior for secure data forwarding. Digital Twin helps simulate security breaches, adjusting routing decisions to avoid insecure paths.

#### 7. Data-Centric Routing Protocols:

- **Directed Diffusion:** Focuses on data dissemination rather than routing paths, optimizing the flow of data across nodes. Digital Twin models simulate data flow and route paths to reduce energy consumption and unnecessary transmissions.
- **Data-Centric Storage Protocols:** Optimizes data storage and retrieval in the network, adjusting modes based on node status, link quality, and traffic load. Digital Twin technology helps dynamically manage data storage strategies.

### Literature Review

**Tran Cong Dao, et al. (2025)** - Multihop Routing for IoT-Based Digital Twin: Novel This paper addresses the MOUNTAIN problem, focusing on large-scale multihop routing optimization in IoT digital twin systems. The authors present two evolutionary algorithms, STEA and MTEA, to minimize energy

consumption while ensuring data transmission stability. Extensive experiments show that MTEA, with its knowledge-sharing mechanism, outperforms baseline approaches (AVOA, Greedy, Random) in terms of energy efficiency and network stability. However, the study uses synthetic datasets with uniform device distribution, and future work should extend the algorithms to dynamic and heterogeneous networks for further improvement.

**Shivani Dave, et al. (2025)** - Multi-Hop State-Aware Routing Strategy for IoT Networks Using This paper proposes a hybrid deep learning-based multi-hop routing strategy to enhance IoT network performance, addressing the challenges of dynamic topologies and energy constraints. The technique integrates deep learning (DL), deep reinforcement learning (DRL), WOA, and DBN to improve data transmission efficiency, reduce latency, and save energy. The authors aim to extend this approach for larger IoT networks, such as smart cities, to improve security and fault tolerance in real-time systems.

**Supat Roongpraiwan, et al. (2025)** - Digital Twin-Enabled Blockage-Aware Dynamic mmWave Multi-Hop V2X Communication: This paper presents a Digital Twin (DT)-enabled dynamic multi-hop routing scheme for mmWave Vehicle-to-Everything (V2X) communication. The routing decisions are based on real-time observations and trajectory forecasting, resulting in improved connectivity (99.62%-100%) in complex environments, particularly in high-traffic and obstacle conditions. The approach shows promise for Connected and Autonomous Vehicles (CAVs) and Intelligent Transportation Systems (ITS), and further research can explore scalability and real-world implementation.

**Cakir, L. V. et al. (2025)** - Intelligent Digital Twin Communication Framework for Addressing Accuracy and Timeliness Tradeoff in Resource-Constrained Networks: This paper introduces the Intelligent DT Communication (IDTC) framework to address the trade-off between accuracy and timeliness in Digital Twin synchronization across resource-constrained networks. The framework includes a Predictive Synchronization (PS) module that uses machine learning to predict updates, reducing errors and staleness. Experimental results show that IDTC achieves 80%-84% lower error and staleness, significantly improving communication performance in constrained environments, making it a promising approach for practical DT-enabled networks.

## Literature Analysis

Sr.no	Paper Title	Author, Year	Finding	Limitation
1	Multihop Routing for IoT-Based Digital Twin: Novel Metaheuristic Approaches	Tran Cong Dao, Nguyen Cong Luong Dusit Niyato, Ngoc Hung Nguyen, Xingwang Li, 2025	Improved energy efficiency and data transmission reliability using novel metaheuristic algorithms.  Strong performance in dynamic topologies, link failure, and node mobility.	High computational costs in large-scale IoT networks.  Limited scalability analysis in extremely large networks.

2	Multi-Hop State-Aware Routing Strategy for IoT Networks Using Hybrid Deep Learning Techniques	Shivani Dave, Dr. Sanjay Gour,2025	Dynamic routing based on real-time network state information, improving energy efficiency and resilience.  Deep learning-based predictions for network congestion and node failures	Heavy reliance on high-quality training data.  Additional computational overhead from deep learning models.
3	Digital Twin-Enabled Blockage-Aware Dynamic mmWave Multi-Hop V2X Communication	Supat Roongpraiwan, Zongdian Li, Tao Yu, and Kei Sakaguchi, 2025	Blockage-aware routing improves mmWave V2X communication reliability, even in high-density traffic and obstacle-prone scenarios.  Near-perfect connectivity (99.62% to 100%) is achieved with dynamic multi-hop routing.	Lacks outdoor validation in real-world environments.  Potential scalability issues in large-scale vehicular networks.
4	Intelligent Digital Twin Communication Framework for Addressing Accuracy and Timeliness Tradeoff in Resource-Constrained Networks,	Lal Verda Cakir*, Craig J. Thomson, Mehmet Özdem, Berk Canberk, Van Linh Nguyen, Trung Q. Duong, 2024	DT-based framework optimizes the accuracy and timeliness tradeoff, improving network performance.  Predictive synchronization (PS) enhances resource utilization and communication reliability.	Real-time implementation may incur computational overhead in large-scale networks.  Privacy and security concerns due to data sharing and network modeling in DT.

5	A UAV-Aided Digital Twin Framework for IoT Networks with High Accuracy and Synchronization	Ghofran Khalaf, May Itani, Sanaa Sharafeddine, 2025	UAV-aided DT framework improves accuracy and synchronization in IoT networks by leveraging UAVs for real-time data collection and system monitoring. The framework enhances network performance and efficiency, ensuring reliable communication in IoT Environments.	Dependency on UAVs can introduce operational complexities and costs. Limited scalability of the framework in large IoT networks due to UAV coverage and mobility constraints.
---	--	---	--	---

Table 1: Literature Analysis

#### Advantages of Digital Twin (DT) Technology in IoT Networks:

1. Provides continuous visibility into IoT devices and network conditions, enabling proactive management and optimization.
2. Anticipates potential failures or issues in IoT devices, allowing for timely interventions and reducing downtime.
3. Optimizes energy consumption by predicting usage patterns and adjusting routing decisions to minimize power usage.
4. Identifies potential security vulnerabilities in the network by simulating threats and optimizing routes to avoid insecure paths.
5. Easily adapts to growing IoT networks, adjusting routing and operational strategies based on real-time data.

#### Disadvantages of Digital Twin (DT) Technology in IoT Networks:

1. Maintaining and updating DT models in real-time requires significant processing power and resources.
2. Integrating Digital Twin with existing IoT systems can be complex and costly, requiring substantial changes to current infrastructure.
3. Handling sensitive data through Digital Twin systems may expose privacy risks, especially in industries like healthcare.
4. As IoT networks grow, scaling Digital Twin technology can become difficult and resource-intensive.
5. The accuracy of DT models may not always align with real-world conditions, limiting their effectiveness in live systems.

## Key Research Challenges:

- **Real-time Data Collection and Processing:** How can we handle data distributed in real-time from large scale IoT devices with minimal overhead?
- **Emulating complex IoT environments:** Reproducing dynamic and large-scale IoT applications using Digital Twin technology.
- **Scaling State-Aware Routing:** How to maintain the efficiency of state-aware multi-hop routing as the network size increases.
- **Security Integration:** By now to be able to best integrate security issues with the routing protocol in such a way that performance is not affected.
- **Energy Limitations:** How to develop performance-aware routing on energy limited, IoT networks.

## Conclusion

The rapid growth of the Internet of Things (IoT) has led to significant advancements in various sectors, including healthcare, transportation, manufacturing, and smart cities. However, the complexities of managing large-scale IoT networks, particularly with respect to efficient data routing, have become major challenges. Traditional routing protocols are inadequate for the dynamic, energy-constrained, and highly diverse nature of IoT networks. Multi-hop routing, although essential for large-scale networks, suffers from issues such as frequent topology changes, energy limitations, poor link quality, network congestion, and security vulnerabilities. The need for adaptive, energy-efficient, and reliable routing solutions has become increasingly critical as IoT networks grow in size and complexity.

State-aware multi-hop routing offers a promising solution by considering real-time network conditions, such as energy levels, link quality, congestion, and node mobility. This dynamic and flexible approach can significantly improve routing efficiency, but it requires continuous monitoring of network states, which is challenging for large-scale networks. This is where Digital Twin (DT) technology provides a breakthrough. By creating a real-time virtual representation of the IoT network, Digital Twin allows for continuous monitoring, prediction, and optimization of routing decisions, improving the overall performance, energy efficiency, and security of IoT networks.

Through the integration of Digital Twin technology and state-aware multi-hop routing, several key challenges can be addressed. Real-time simulation and monitoring, predictive analytics, energy-efficient routing, and better network resilience are some of the significant benefits that this integration brings. Digital Twin models also help enhance security by simulating potential threats and enabling proactive routing decisions to mitigate risks. Furthermore, the scalability and adaptability of this approach make it suitable for growing IoT networks, ensuring that routing protocols remain effective even as network complexity increases.

Despite these advancements, there are still several challenges to overcome. Handling real-time data collection and processing from large-scale IoT networks, ensuring the scalability of state-aware routing, integrating

security with minimal performance overhead, and managing energy constraints are critical areas that require further research. Nevertheless, the integration of Digital Twin technology with state-aware multi-hop routing holds great promise in addressing these issues and paving the way for more efficient, resilient, and secure IoT networks. Future research will be key to refining these models and extending their applicability to dynamic, heterogeneous, and resource-constrained IoT environments.

## Reference

1. Wang, Y., Su, Z., Guo, S., Dai, M., Luan, T. H., & Liu, Y. (2023). A Survey on Digital Twins: Architecture, Enabling Technologies, Security and Privacy, and Future Prospects. arXiv preprint. <https://arxiv.org/abs/2301.13350> arXiv
2. Javaid, M., et al. (2023). Digital Twin applications toward Industry 4.0: A Review. ScienceDirect. <https://www.sciencedirect.com/science/article/pii/S2667241323000137> ScienceDirect
3. Samaniego, M., & Díaz-Medina, E. (2023). Digital Twins and Blockchain for IoT Management. ACM Digital Library. <https://dl.acm.org/doi/10.1145/3594556.3594611> ACM Digital Library
4. Pracucci, A. (2024). Designing Digital Twin with IoT and AI in Warehouse to Support Optimization and Safety in Engineer-to-Order Manufacturing Process for Prefabricated Building Products. Applied Sciences, 14(15):6835. <https://doi.org/10.3390/app14156835>
5. Dangana, M., et al. (2024). A Digital Twin (DT) approach to Narrow-Band Internet of Things (NB-IoT). ScienceDirect. <https://www.sciencedirect.com/science/article/pii/S2542660524000556> ScienceDirect
6. Chen, X., Cao, J., Liang, Z., Sahni, Y., & Zhang, M. (2023). Digital Twin-assisted Reinforcement Learning for Resource-aware Microservice Offloading in Edge Computing. IEEE MASS. [https://ira.lib.polyu.edu.hk/bitstream/10397/107541/1/Chen\\_Digital\\_Twin-assisted\\_Reinforcement.pdf](https://ira.lib.polyu.edu.hk/bitstream/10397/107541/1/Chen_Digital_Twin-assisted_Reinforcement.pdf) PolyU Institutional Research Archive
7. “Mobility-Assisted Digital Twin Network Optimization over Industrial Internet of Things” (2024). Applied Sciences, 14(19), 9090. <https://doi.org/10.3390/app14199090>
8. Alsayed Kassem, J., Zhong, L., Taal, A., & Grosso, P. (2023). Adaptive Services Function Chain Orchestration for Digital Health Twin Use Cases: Heuristic-boosted Q-Learning Approach. arXiv preprint. <https://arxiv.org/abs/2304.12853> arXiv
9. “A Scalable and User-Friendly Framework Integrating IoT and Digital Twins” (2024). Applied Sciences, 14(24), 11834. <https://www.mdpi.com/2076-3417/14/24/11834> MDPI
10. “An adaptive mobile edge computing-based routing protocol for IoT” (2024). Cluster Computing (Springer). <https://link.springer.com/article/10.1007/s10586-024-04450-2> SpringerLink
11. Digital Twin-Empowered Routing Management for Reliable Multi-Hop Millimeter Wave V2X (Roongpraiwanet al., 2024) <https://arxiv.org/abs/2409.00040> Focuses on DT + multi-hop routing in a V2X context (mmWave) rather than general IoT.

12. Digital Twin-Enabled Blockage-Aware Dynamic mmWave Multi-Hop V2X Communication (Roongpraiwan et al., 2025) <https://arxiv.org/abs/2503.03590> arXiv+1
13. Digital Twin-Guided Energy Management over Real-Time Pub/Sub Protocol in 6G Smart Cities (Duran et al., 2025) <https://arxiv.org/abs/2508.18516>
14. Resource Efficient Asynchronous Federated Learning for Digital Twin Empowered IoT Network (Chu et al., 2024) <https://arxiv.org/abs/2408.14298>

