Evaluation of the efficiency of delay tolerant network routing protocols for smart environment development in Makassar

Abdul Latief Arda[1], Syamsu Alam[1], Agussalim[2], Matalangi[3]
[1]Department of Computer System, Faculty of Computer Science, Handayani University Makassar, Makassar, Indonesia
[2]Department of Master Information Technology, UPN "Veteran" East Java, Gunung Anyar, Surabaya, Indonesia
[3]Department of Information Systems, Indonesian Christian University Paulus, Makassar, Indonesia

Article Info

Article history:

Received Mar 29, 2025
Revised Feb 26, 2026
Accepted Mar 29, 2026

Keywords:

Delay tolerant network
Epidemic routing
Makassar
PRoPHET
Routing protocol
Smart environment

ABSTRACT

Delay tolerant network (DTN) has become a promising communication paradigm for internet of things (IoT)-based smart environments, where intermittent connectivity and heterogeneous node mobility challenge reliable data delivery. However, selecting an appropriate DTN routing protocol remains difficult because existing protocols offer different trade-offs among delivery ratio, latency, communication overhead, hop count, and energy consumption. Although many studies have evaluated DTN routing protocols, few have examined their performance under heterogeneous urban mobility conditions representing emerging smart cities such as Makassar. This study compares four DTN routing protocols—Epidemic, probabilistic routing protocol using history of encounters and transitivity version 2 (PRoPHETv2), spray and wait, and MaxProp—using The ONE Simulator with a Makassar-inspired mobility scenario involving 50–125 nodes over a 12-hour simulation. Performance was evaluated using delivery ratio, average latency, overhead ratio, average hop count, and estimated energy consumption. The results show that MaxProp achieved the highest delivery ratio (0.69 at 125 nodes), whereas spray and wait consistently produced the lowest latency (≈118 s), overhead ratio (< 45,000), and average hop count (≈2). In contrast, epidemic generated excessive overhead and energy consumption because of uncontrolled message replication. These findings indicate that spray and wait is the most resource-efficient protocol, while MaxProp is preferable for applications prioritizing delivery reliability.

Corresponding Author:

Abdul Latief Arda
Department of Computer System, Faculty of Computer Science, Handayani University Makassar
Adyaksa Baru St., No.1, Pandang, Panakkukang, Makassar, South Sulawesi 90231, Indonesia
Email: abdullatief@handayani.ac.id

1. INTRODUCTION

The rapid advancement of information and communication technologies has accelerated the global transformation of conventional urban systems into smart cities. Smart city development integrates digital infrastructure, communication systems, cloud computing, internet of things (IoT), and intelligent data processing to improve urban sustainability, operational efficiency, public services, and quality of life [1]. Various sectors, including transportation, energy management, healthcare, environmental monitoring, disaster mitigation, and public security, increasingly rely on interconnected communication networks capable of supporting continuous and reliable data exchange. In developing urban areas such as Makassar, smart environment implementation has become an important strategic initiative to support sustainable urban growth and digital transformation. Furthermore, recent studies in cities such as Yogyakarta and Makassar emphasize the importance of interoperability and intelligent communication infrastructures to strengthen human security and sustainable smart city governance [2]. The Association of Southeast Asian Nations (ASEAN) smart cities network (ASCN) also recognizes Makassar as one of Indonesia's strategic cities for inclusive and technology-driven urban development [3].

Despite these developments, maintaining reliable network communication in smart city environments remains a major challenge, particularly in urban regions characterized by heterogeneous mobility, uneven infrastructure distribution, intermittent connectivity, and dynamic network conditions. In many real-world urban scenarios, communication disruptions frequently occur due to limited infrastructure coverage, mobility-induced disconnections, environmental obstacles, and varying traffic densities. These conditions become increasingly problematic for IoT-based smart environment applications that require continuous data transmission from mobile users, vehicles, sensors, and public infrastructure devices. Conventional communication architectures based on persistent end-to-end connectivity are often unable to maintain stable communication performance under such conditions. Consequently, communication reliability, latency control, energy efficiency, and resource utilization emerge as critical issues in large-scale smart urban deployments.

Delay tolerant networks (DTNs) have been proposed as a promising solution for communication environments with intermittent connectivity and highly dynamic topology changes. DTNs employ the store-carry-forward communication paradigm, where nodes temporarily store messages and forward them opportunistically when network connections become available. This mechanism enables communication continuity even in disconnected or partially connected environments. In smart environment deployment, DTNs can support various applications such as smart transportation systems, environmental monitoring, disaster response, energy management, and mobile urban sensing. However, DTN performance strongly depends on routing protocol behavior, node mobility characteristics, message replication strategies, and resource management mechanisms. Parameters such as delivery ratio, latency, overhead ratio, hop count, and energy consumption become critical indicators for evaluating DTN suitability in heterogeneous urban environments.

Previous studies have investigated various DTN routing protocols and their applications in different communication scenarios. Research on smart city communication has explored DTN implementation in urban planning environments such as the Surabaya smart city initiative [4]. Other studies have proposed optimization approaches for the binary spray and wait protocol to improve delivery probability and reduce replication overhead [3]. Hybrid mobility-aware routing mechanisms such as sink and delay aware bus protocols have also been developed to exploit human, vehicular, and public transportation mobility patterns [5]. In addition, several studies have examined DTN deployment in wireless fidelity (Wi-Fi) and Bluetooth-based opportunistic networks [6], as well as DTN applications in IoT systems, future internet architectures, underwater communication, satellite communication, and space networking environments. Recent advances further highlight the growing importance of energy-aware routing strategies, intelligent forwarding mechanisms, and machine learning-assisted DTN optimization to improve network sustainability and communication efficiency [1]–[4].

Although numerous studies have evaluated DTN routing protocols, several important limitations remain unresolved. Most existing evaluations are conducted using generic mobility models, homogeneous node behavior, campus-scale environments, or synthetic network scenarios that do not adequately represent the complexity of real urban mobility conditions. Limited studies investigate DTN performance under heterogeneous smart environment scenarios involving pedestrians, public vehicles, and IoT devices within a specific urban topology such as Makassar. Furthermore, many previous studies primarily focus on delivery performance metrics while providing limited discussion on resource efficiency, scalability, overhead control, and estimated energy consumption. In resource-constrained smart city environments, energy sustainability and communication efficiency are equally important alongside delivery reliability. Consequently, there remains a significant research gap in understanding how DTN routing protocols perform under heterogeneous mobility conditions and smart urban communication constraints specific to emerging Southeast Asian cities.

To address these limitations, this study evaluates the performance of four widely used DTN routing protocols epidemic, probabilistic routing protocol using history of encounters and transitivity (PRoPHETv2), spray and wait, and MaxProp within a Makassar-based smart environment scenario using the opportunistic networking environment (ONE) simulator. The evaluation considers heterogeneous mobility conditions involving pedestrians, vehicles, and IoT communication patterns across node populations ranging from 50 to 125 nodes over 12 hours of simulation time. Performance analysis is conducted using delivery ratio, average latency, overhead ratio, hop count, and estimated energy consumption metrics to provide a comprehensive assessment of routing efficiency and communication sustainability.

The main contributions of this study are as follows. First, this research develops a Makassar-specific smart environment simulation model representing heterogeneous urban mobility and intermittent communication conditions. Second, this study provides a comprehensive comparative evaluation of epidemic, PRoPHETv2, spray and wait, and MaxProp routing protocols under realistic multi-node mobility scenarios. Third, unlike many previous DTN studies, this work integrates estimated energy consumption analysis together with conventional delivery performance metrics to evaluate communication sustainability in IoT-based smart city deployment. Fourth, this study identifies protocol suitability based on different operational priorities, including delivery reliability, latency minimization, resource efficiency, and energy sustainability.

The significance of this study lies in both its scientific and practical implications. From a scientific perspective, this study contributes significant insights into DTN routing behavior under heterogeneous Smart Environment conditions representing emerging urban regions in Southeast Asia. The findings provide significant evidence regarding the trade-offs between delivery reliability, latency, replication overhead, and energy consumption in intermittently connected urban networks. This study also highlights the significance of integrating energy-efficiency evaluation into DTN performance analysis for sustainable smart city communication systems. From a practical perspective, the study provides significant recommendations for selecting and optimizing DTN routing protocols in real-world smart city applications such as environmental monitoring, intelligent transportation systems, disaster communication, and IoT-based urban sensing in Makassar and similar metropolitan environments. The results are expected to support the development of more resilient, sustainable, and resource-efficient communication infrastructures for future smart environment deployment.

2. RELATED EXISTING REVIEW

DTNs are communication architectures designed to operate in environments characterized by intermittent connectivity, long transmission delays, high mobility, and limited network infrastructure availability. Unlike conventional wireless networks that rely on continuous end-to-end connectivity, DTNs utilize opportunistic communication mechanisms that allow data transmission even when direct communication paths are unavailable. DTNs were originally developed to support communication in highly disrupted environments such as disaster recovery systems, remote rural areas, military communication, vehicular networks, underwater communication, and space networks [1], [7], [8]. In recent years, DTNs have also gained significant attention in smart city and IoT environments due to their capability to maintain communication continuity under heterogeneous and dynamically changing urban conditions.

In DTN environments, communication performance is highly dependent on node mobility patterns and encounter opportunities among devices. Figure 1, data exchange occurs opportunistically whenever nodes come into communication range. As a result, DTNs adopt the store-carry-forward paradigm, where nodes temporarily store messages, carry them while moving, and forward them to other nodes once communication opportunities become available. This mechanism eliminates the requirement for simultaneous end-to-end connections between source and destination nodes. Consequently, DTNs are highly suitable for smart environment scenarios involving mobile users, public transportation systems, wireless sensors, and intermittently connected IoT devices [1], [7], [8].

Figure 2 shows the fundamental architecture of DTNs, which introduces an additional communication layer known as the bundle layer, operating above the conventional transport and network layers. The bundle layer enables communication interoperability across heterogeneous network regions with different communication technologies and protocols. Unlike traditional Internet architectures that require stable connectivity throughout the communication session, DTNs use the bundle layer to support delayed message forwarding and temporary message storage [9]–[11].

Within the DTN architecture, transmitted data units are referred to as bundles or messages. The bundle layer is responsible for message encapsulation, storage management, forwarding decisions, and inter-region communication coordination. This layer allows heterogeneous communication infrastructures to exchange information seamlessly through DTN gateways connecting different network regions. The lower communication layers including transport, network, link, and physical layers may vary depending on the communication environment in each region. This architectural flexibility makes DTNs highly adaptable to smart city communication systems characterized by heterogeneous infrastructure and intermittent connectivity conditions.

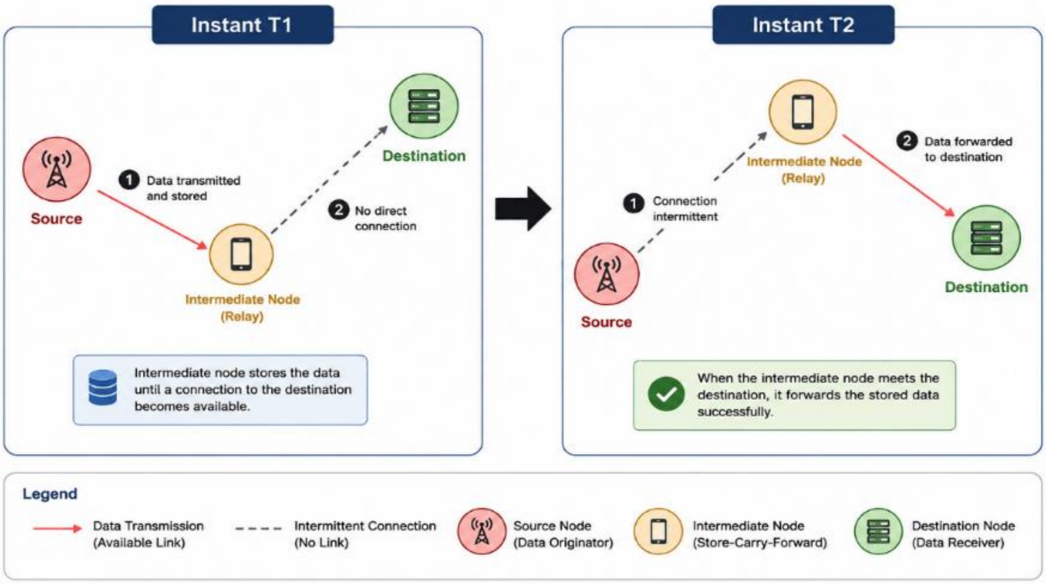

Figure 1. Example of DTN communication

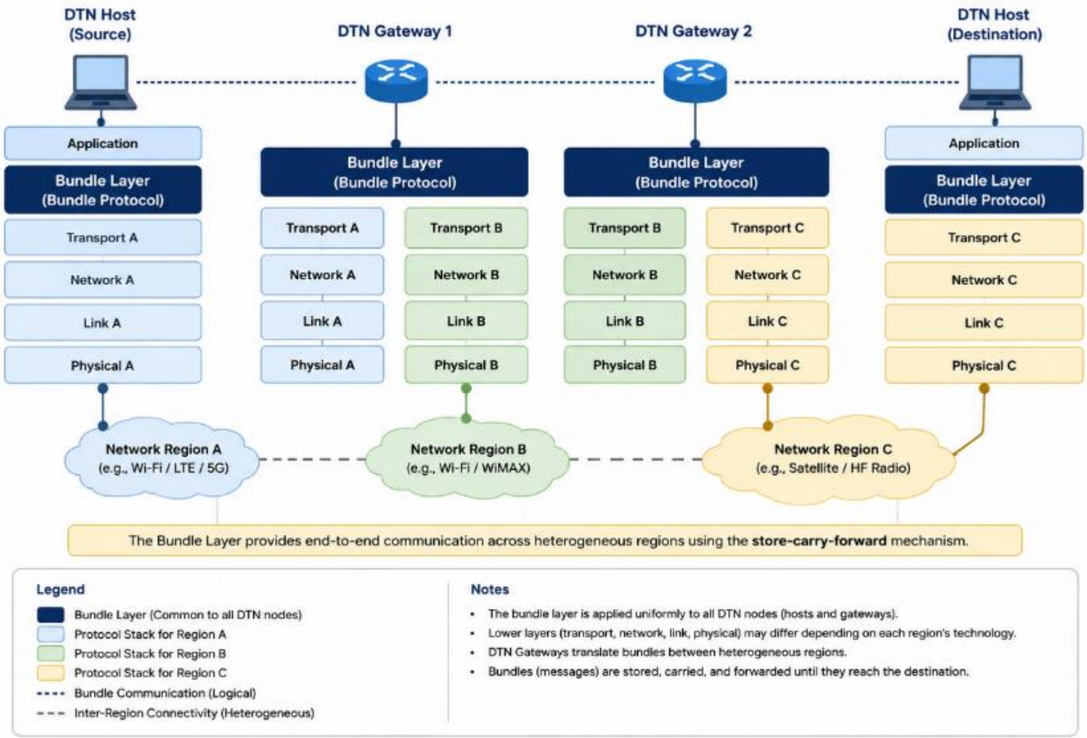

Figure 2. Bundle layer architecture in DTN

Figure 3 illustrates the store-carry-forward mechanism, which represents the core operational principle of DTNs. In this mechanism, data generated by a source node is temporarily stored until a communication opportunity with another node becomes available, then carried by intermediate nodes and progressively forwarded toward the destination node. This approach significantly improves communication survivability in disconnected or partially connected environments and reduces packet loss caused by unstable connectivity conditions.

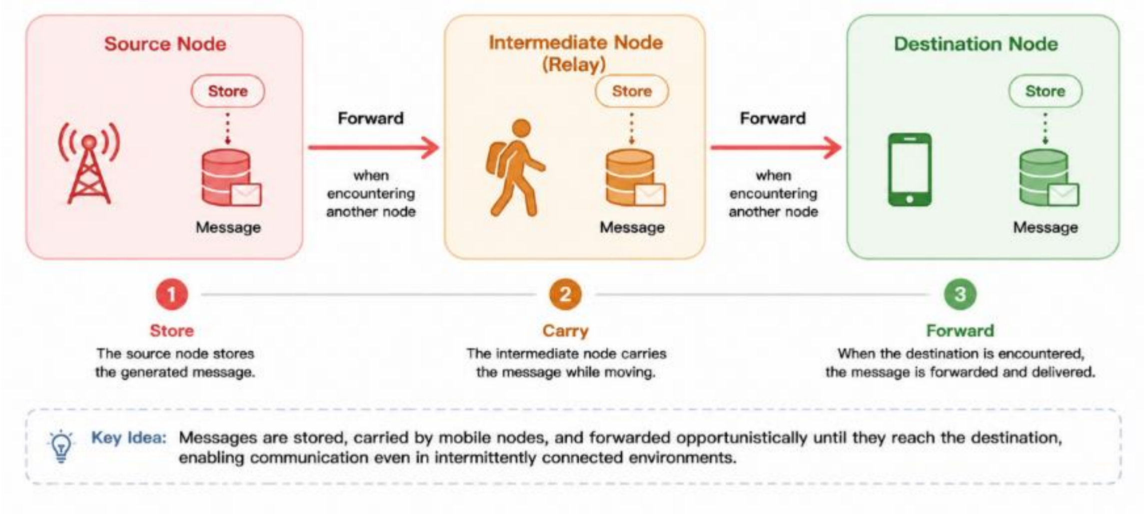

Figure 3. Store-carry-forward mechanism

The effectiveness of DTN communication strongly depends on the routing protocol used to determine forwarding decisions, message replication strategies, and buffer management policies. Consequently, numerous DTN routing protocols have been proposed to optimize delivery probability, latency, overhead ratio, and resource utilization under different network conditions. One of the earliest and most widely studied DTN routing protocols is epidemic routing, which aims to maximize delivery probability through uncontrolled message replication [12]–[14]. In epidemic routing, nodes exchange all non-duplicate messages whenever encounters occur, thereby increasing the likelihood of successful delivery in highly disconnected environments. Although this flooding-based strategy can improve delivery performance, it also generates excessive overhead, buffer consumption, bandwidth usage, and energy consumption, particularly in dense networks.

To overcome the excessive replication problem of epidemic routing, the spray and wait protocol introduces controlled message replication mechanisms [15]–[17]. Instead of forwarding unlimited copies of messages, spray and wait distributes only a predefined number of message copies into the network during the spray phase. Afterward, nodes carrying the message wait until they encounter the destination node directly. This approach significantly reduces overhead ratio and energy consumption while maintaining relatively low latency, making it suitable for resource-constrained DTN environments.

Another widely used DTN routing protocol is PRoPHETv2, which utilizes probabilistic forwarding based on historical encounter information [18], [19]. PRoPHETv2 estimates the probability that a node can successfully deliver a message to the destination based on previous contact patterns and transitive relationships among nodes. By exploiting historical mobility behavior, PRoPHETv2 improves routing efficiency and reduces unnecessary message forwarding compared to flooding-based approaches. This protocol is particularly effective in environments where node mobility exhibits repetitive or predictable movement patterns. Meanwhile, MaxProp is specifically designed for DTN environments characterized by highly limited and unpredictable connectivity [17], [20]. MaxProp prioritizes message forwarding and buffer management based on estimated delivery likelihood and path probability. The protocol also incorporates intelligent message deletion mechanisms to optimize buffer utilization when storage resources become constrained. Through prioritization-based forwarding strategies, MaxProp aims to maximize successful message delivery while minimizing packet drops in sparse and highly dynamic networks.

Recent studies further highlight the growing importance of DTN deployment in smart city and IoT-based communication systems. Researchers have investigated DTN integration in vehicular communication, public transportation systems, wireless sensor networks, environmental monitoring systems, and emergency communication infrastructures. Several studies also emphasize the increasing need for energy-aware routing, adaptive forwarding strategies, mobility-aware communication models, and machine learning-assisted DTN optimization to support sustainable smart environment implementation [1]–[4]. However, most previous evaluations are conducted using generic mobility scenarios or synthetic network topologies that may not adequately represent the heterogeneous urban mobility conditions of emerging metropolitan cities such as Makassar. Therefore, evaluating DTN routing protocols within realistic urban smart environment scenarios becomes essential to identify routing strategies capable of balancing delivery reliability, latency performance, overhead control, scalability, and energy efficiency under heterogeneous mobility conditions.

3. METHOD

3.1. Simulation environment and parameters

This study utilizes "the ONE simulator" to evaluate the performance of DTN routing protocols within a smart environment scenario representing Makassar city. the ONE simulator is one of the most widely used simulation platforms for DTN research because it supports heterogeneous mobility modeling, opportunistic communication analysis, realistic map-based simulations, and multiple DTN routing protocol implementations under dynamic connectivity conditions [21], [22]. The simulator is particularly suitable for evaluating communication behavior in environments characterized by intermittent connectivity, node mobility, and limited infrastructure availability.

The simulation scenario is designed to represent real-world smart environment deployment in Makassar. Mobile nodes represent public transportation vehicles, pedestrians, and urban mobility entities, while static nodes represent IoT-based environmental sensors installed at strategic locations such as intersections, parks, flood-prone areas, government facilities, and public service zones. This heterogeneous node configuration enables the simulation to capture realistic communication behavior under urban mobility conditions.

To improve geographical realism, the simulation environment integrates OpenStreetMap (OSM) data from Makassar city, allowing node mobility to follow actual road topologies and transportation routes. Vehicle nodes move along predefined urban road networks, while pedestrian nodes utilize random mobility patterns within designated urban areas. Static sensor nodes remain fixed throughout the simulation and continuously generate environmental monitoring data to be forwarded opportunistically through mobile nodes toward the monitoring server.

Performance evaluation focuses on four widely used DTN routing protocols: epidemic, PRoPHETv2, spray and wait, and MaxProp. These protocols were selected because they represent different routing paradigms, including flooding-based forwarding, probabilistic routing, controlled replication, and prioritization-based forwarding. The comparative analysis aims to identify protocol suitability under Makassar-specific smart environment conditions characterized by heterogeneous mobility and intermittent connectivity.

As illustrated in Figure 4, environmental sensor nodes are distributed across strategic locations within Makassar city. The collected data are opportunistically forwarded through mobile nodes, including vehicles and pedestrians, before reaching the monitoring server. Vehicle mobility follows the actual transportation routes derived from the Makassar city map.

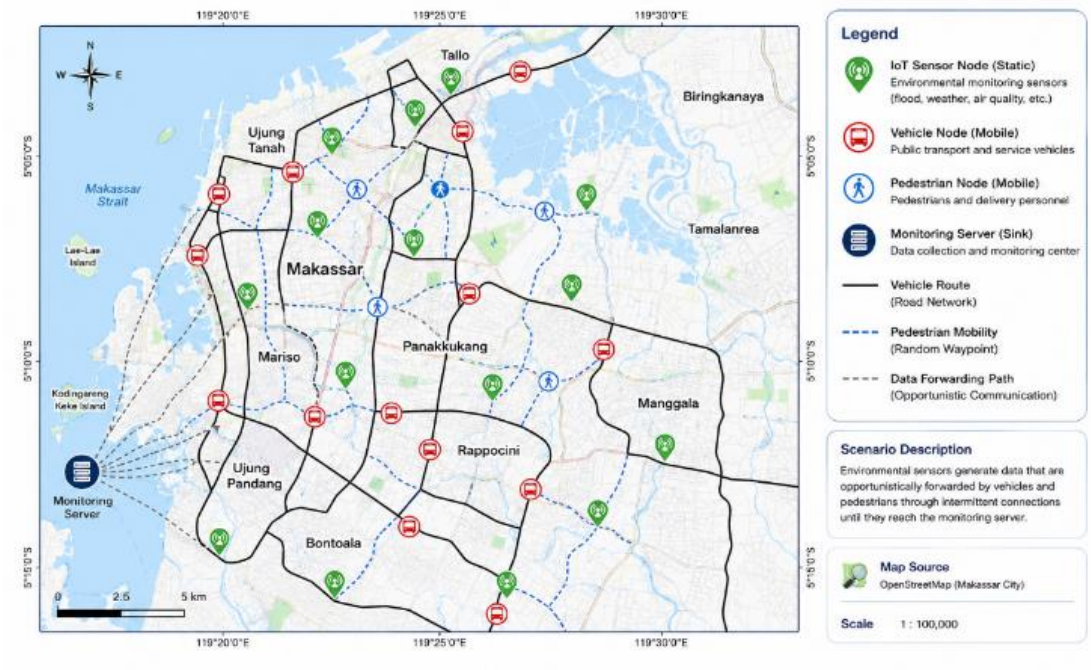

Figure 4. Smart environment scenario in Makassar city

Figure 5 illustrates the implementation of the smart environment scenario in the ONE simulator environment. The simulation evaluates routing protocol performance over a 12-hour communication period using heterogeneous node mobility and varying node densities. To investigate scalability and network density effects, the number of nodes is varied from 50, 75, 100, to 125 nodes. The simulation incorporates heterogeneous mobility speeds to represent realistic urban movement behavior. Pedestrian nodes move with speeds ranging from 0.5-1.5 m/s, while vehicle nodes move with speeds ranging from 2.7–13.9 m/s. Message generation intervals vary between 10-15 seconds, with message sizes ranging from 500 KB to 1 MB. The routing protocols are evaluated based on delivery ratio, average latency, overhead ratio, hop count, and estimated energy consumption. Table 1 summarizes the simulation parameters used throughout the study.

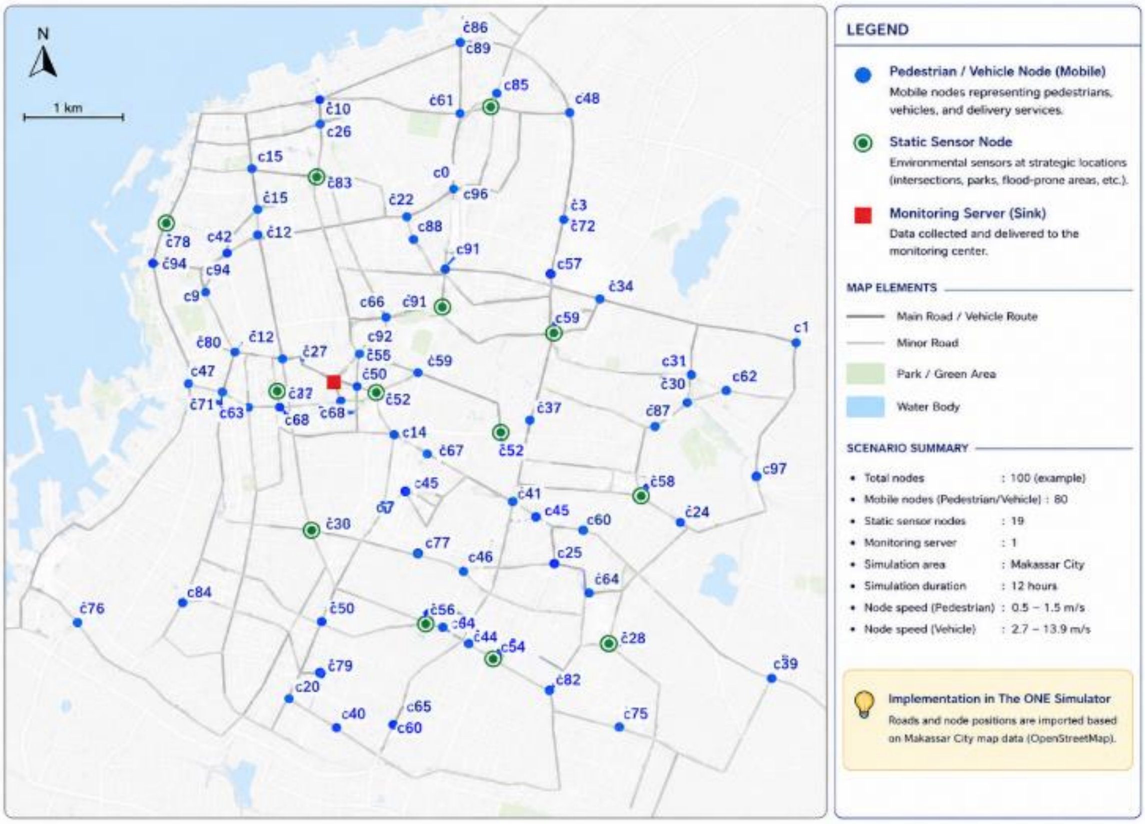

Figure 5. Scenario after implementation in the simulator

Table 1. Simulation parameters

Parameter	Value
Total simulation time	12 h
Simulation area	Makassar
DTN routing protocol	Epidemic, ProphetV2, MaxProp et spray and wait
Buffer size	5 M
Total no. of nodes	50, 75, 100, 125
Types of nodes	Pedestrians, cars
Pedestrians speed	Min=0.5 m/s Max=1.5 m/s
Cars speed	Min=2.7 m/s Max=13.9 m/s
Pedestrians wait time	0-120 s
Cars wait time	0-120 s
Seconds in time unit	30 s
No. of copies (L)	3
Transmit speed	5 M
Message TTL	300 minutes
Interface transmit range	10 metres
Message creation rate	10-15 S per 1 message
Message size	500 KB to 1 MB

The simulation configuration is designed to emulate realistic smart environment communication conditions in Makassar, particularly for intermittently connected IoT and mobile communication infrastructures. The selected parameters also allow comprehensive evaluation of protocol scalability, communication efficiency, replication behavior, and resource utilization under heterogeneous urban mobility conditions.

3.2. Energy consumption estimation model

In addition to conventional DTN performance metrics, this study evaluates the estimated energy consumption generated by each routing protocol. Energy efficiency is an important consideration in smart environment deployment because excessive message replication and transmission activities may significantly increase communication costs and reduce network sustainability, particularly for battery-powered mobile and IoT devices. Since the ONE simulator does not directly provide energy consumption measurements, an analytical estimation approach is adopted based on transmission and reception activities recorded during the simulation process. The energy model assumes that each message transmission consumes E_t joules, while each message reception consumes E_r joules. The total estimated energy consumption is calculated using (1):

$$E_{total} = (N_{tx} X_{Et}) + (N_{rx} X\, E_r) \quad (1)$$

where:
- N_{tx} represents the total number of message transmissions
- N_{rx} represents the total number of message receptions
- E_t denotes the transmission energy consumption per message
- E_r denotes the reception energy consumption per message

Protocols employing excessive replication strategies, such as epidemic routing, naturally generate significantly higher transmission and reception counts, leading to increased estimated energy consumption. In contrast, controlled replication protocols such as Spray and Wait and prioritized forwarding approaches such as MaxProp are expected to demonstrate better communication efficiency and lower energy utilization.

3.3. Statistical evaluation

To improve statistical reliability and minimize randomness bias, each simulation scenario was executed five times using different random seeds. The final results presented in this study represent the average values obtained from these repeated simulations. This repetition strategy ensures that the observed performance trends reflect consistent protocol behavior rather than stochastic simulation variations.

Performance evaluation and protocol comparison are conducted using descriptive statistical analysis, graphical visualization, and percentage difference analysis across multiple performance metrics, including: delivery ratio, average latency, overhead ratio, average hop count, and estimated energy consumption. The combination of repeated simulation runs and multi-metric evaluation provides a more comprehensive and statistically reliable assessment of DTN routing performance under heterogeneous Smart Environment conditions in Makassar city.

4. RESULTS AND DISCUSSION

This section presents the comparative evaluation of four DTN routing protocols epidemic, PRoPHETv2, spray and wait, and MaxProp under the Makassar smart environment scenario. The evaluation focuses on delivery ratio, average latency, overhead ratio, hop count, and estimated energy consumption. These metrics are essential for assessing routing efficiency, scalability, and communication sustainability in heterogeneous urban DTN environments.

4.1. Results

Delivery ratio represents the probability that a message generated by a source node is successfully delivered to the destination node within the simulation period. In DTN-based smart environments, delivery ratio becomes a critical indicator because intermittent connectivity and node mobility significantly influence communication reliability. Figure 6 illustrates the delivery ratio performance of epidemic, MaxProp, PRoPHETv2, and spray and wait under different node densities. Epidemic routing consistently demonstrates the lowest delivery ratio, beginning at approximately 0.10 for 50 nodes and increasing only slightly as node density grows. This indicates that uncontrolled flooding does not necessarily improve delivery reliability in heterogeneous mobility environments.

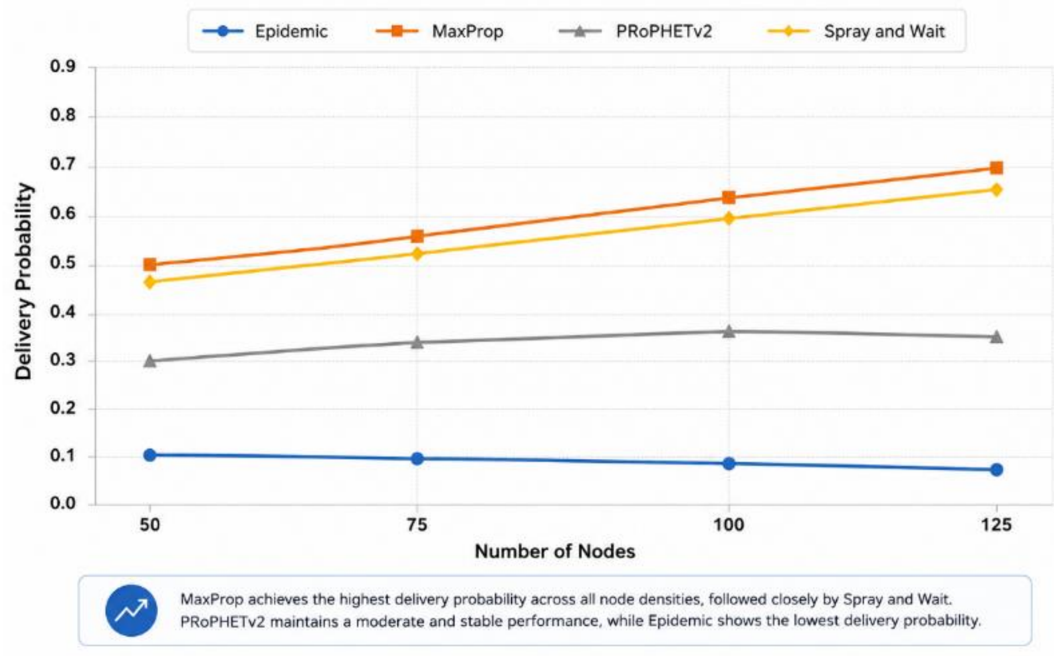

Figure 6. Delivery probability of protocols based on the number of nodes

MaxProp achieves the highest delivery ratio across all scenarios, increasing from approximately 0.50 at 50 nodes to nearly 0.69 at 125 nodes. The protocol benefits from its prioritized forwarding and buffer management mechanisms, enabling more effective message delivery in dense networks. Spray and wait also demonstrate strong performance, achieving delivery ratios close to MaxProp and reaching approximately 0.67 at 125 nodes. Its controlled replication strategy enables efficient dissemination without generating excessive traffic.

PRoPHETv2 maintains relatively stable performance, with delivery ratios ranging from 0.30 to 0.40 across node scenarios. This stability indicates that probabilistic encounter history can support moderate routing reliability, although its performance remains below MaxProp and spray and wait. Overall, the results indicate that controlled forwarding and replication mechanisms significantly improve delivery reliability in urban DTN environments.

Latency refers to the average time required for a message to travel from the source node to the destination node. In smart environment applications, low latency is essential for supporting responsive monitoring systems, transportation services, and environmental sensing infrastructures. Figure 7 compares the average latency values produced by the four routing protocols. MaxProp records the highest latency among all protocols, although its latency gradually decreases as node density increases. The higher latency is mainly caused by selective forwarding and prioritized scheduling mechanisms, which may delay message transmission while searching for optimal forwarding opportunities. Epidemic routing produces lower latency than MaxProp but exhibits higher fluctuation across node scenarios. The protocol aggressively floods messages throughout the network, enabling faster message propagation but simultaneously increasing congestion and transmission competition.

PRoPHETv2 demonstrates relatively stable latency values between epidemic and MaxProp, indicating balanced routing behavior based on encounter probability estimation. Spray and wait consistently achieves the lowest latency across all node scenarios, maintaining an average latency of approximately 118 seconds at 125 nodes. Its limited-copy dissemination mechanism minimizes network congestion while preserving efficient message forwarding. These findings indicate that controlled replication strategies are more suitable for low-latency smart environment communication.

Overhead ratio represents the additional communication cost generated by routing activities, particularly message replication and forwarding operations. High overhead indicates inefficient resource utilization and may significantly affect bandwidth availability and node energy sustainability. Figure 8 demonstrates that epidemic routing generates extremely high overhead as node density increases. At 125 nodes, epidemic reaches an overhead ratio of 512,430, which is approximately 11.4 times higher than spray and wait. This behavior is caused by uncontrolled message flooding, where messages are replicated to nearly all encountered nodes regardless of routing efficiency.

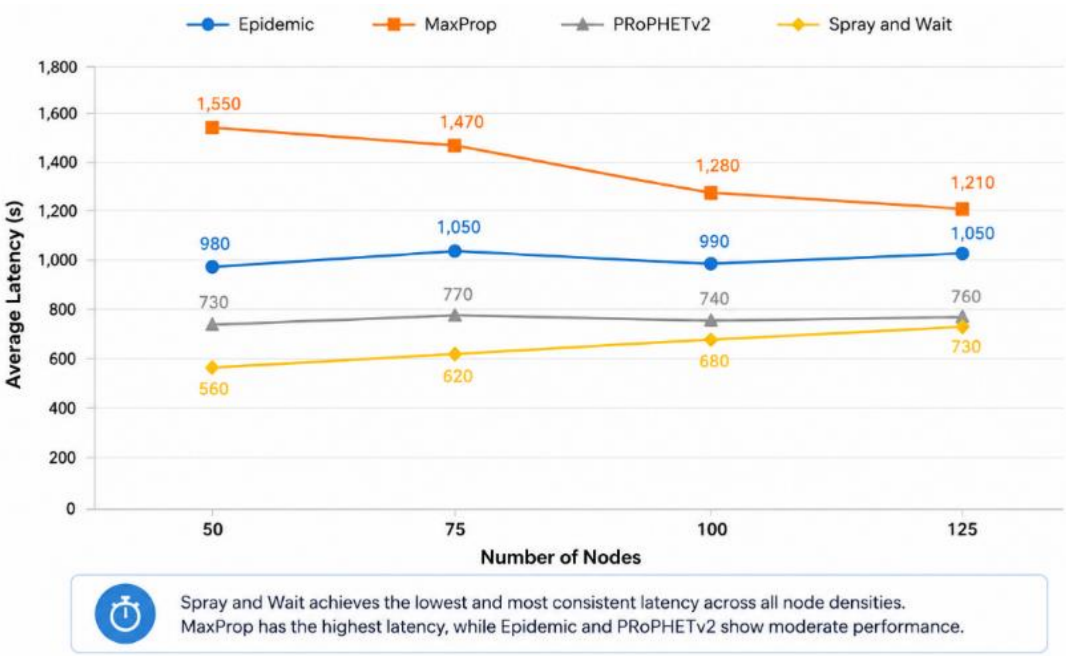

Figure 7. Average latency based on the number of nodes

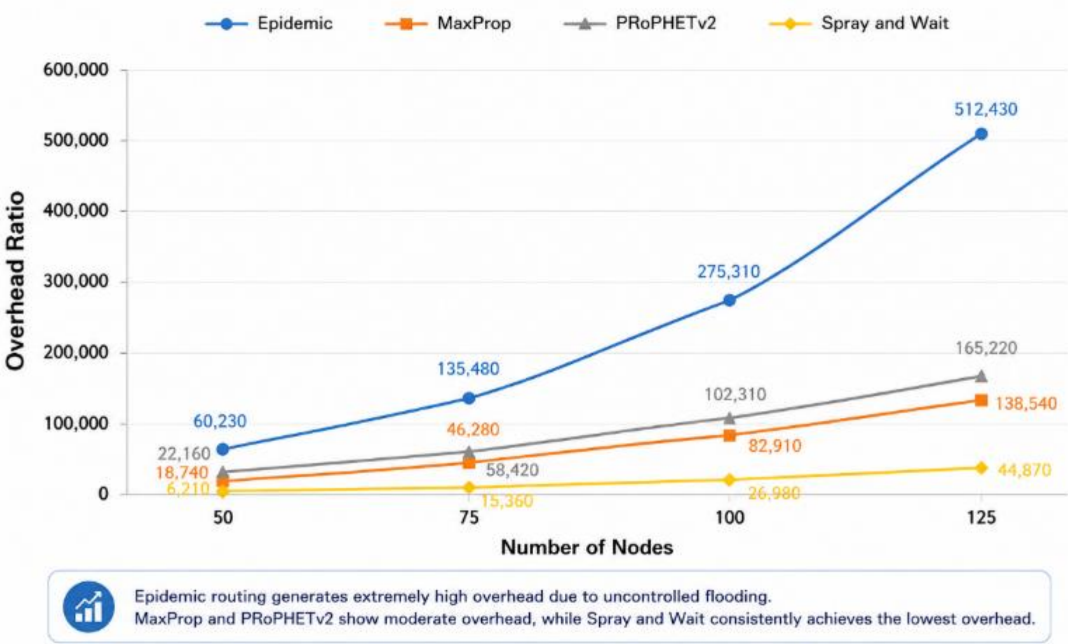

Figure 8. Overhead ratio based on the number of nodes

MaxProp and PRoPHETv2 produce moderate overhead values of 138,540 and 165,220 respectively, reducing overhead by approximately 73% and 68% compared with Epidemic routing. Their forwarding strategies are more selective and probabilistic, preventing excessive message duplication. Spray and Wait consistently records the lowest overhead ratio across all simulation scenarios, reaching only 44,870 at 125 nodes. The protocol restricts the number of message copies distributed in the network, thereby significantly reducing unnecessary transmissions. These findings confirm that replication control strongly influences communication scalability and resource efficiency in DTN-based smart environments.

Estimated energy consumption follows a similar trend to overhead behavior because message transmissions and receptions directly contribute to communication energy usage. In Table 2, epidemic routing exhibits the highest estimated energy consumption, reaching approximately 2.75 relative units at 125 nodes. This value is approximately 175% higher than spray and wait, which serves as the baseline protocol with the lowest energy consumption value of 1.00.

Table 2. DTN protocol efficiency evaluation results

DTN protocol	Delivery ratio	Avg latency (s)	Overhead ratio	Avg hop count	Estimated energy (relative unit)
Epidemic	0.15	320	512,430	6.8	2.75
PRoPHETv2	0.39	240	165,220	4.2	1.45
Spray and wait	0.67	118	44,870	2.1	1.00 (lowest)
MaxProp	0.69	355	138,540	3.9	1.62

PRoPHETv2 and MaxProp demonstrate moderate energy usage with relative values of 1.45 and 1.62 respectively. These results indicate that controlled forwarding mechanisms reduce unnecessary transmissions and improve communication sustainability. Spray and wait consistently achieves the lowest energy consumption because its limited-copy strategy minimizes transmission frequency and buffer activity. This result highlights the importance of energy-aware routing strategies for IoT-based smart environment deployment.

Hop count represents the average number of intermediate nodes traversed by a message before reaching its destination. Lower hop count generally indicates more efficient routing paths and reduced transmission overhead. Figure 9 shows that epidemic routing produces the highest average hop count, reaching approximately 6.8 hops at 125 nodes. This reflects inefficient message propagation caused by uncontrolled replication and redundant forwarding paths. MaxProp and PRoPHETv2 demonstrate more moderate hop count values, reaching approximately 3.9 and 4.2 respectively at 125 nodes. These protocols achieve better forwarding efficiency by considering encounter probability and message prioritization.

Spray and wait consistently records the lowest hop count, approximately 2.1 across all node scenarios. This result indicates that messages can reach their destinations through fewer intermediate nodes, improving routing efficiency while reducing transmission costs. Overall, spray and wait demonstrates the most efficient path utilization among all evaluated protocols.

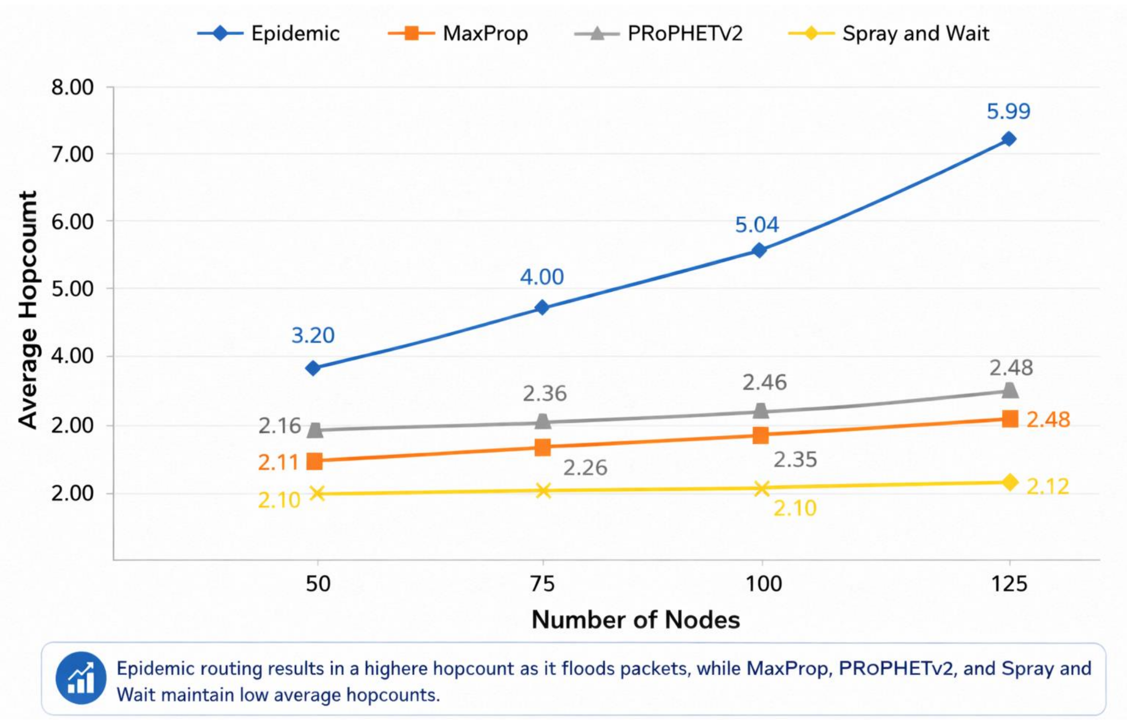

Figure 9. Average hop count based on the number of nodes

4.2. Discussion

The comparative evaluation reveals substantial differences in routing behavior among epidemic, PRoPHETv2, spray and wait, and MaxProp under Makassar's heterogeneous smart environment scenario, as shown in Table 3. Based on the comparative results, epidemic routing is unsuitable for dense urban smart environments because excessive replication produces extremely high overhead and energy consumption. Although flooding mechanisms may increase redundancy in severely disconnected environments, they become inefficient in heterogeneous urban mobility scenarios.

PRoPHETv2 demonstrates balanced performance and stable communication behavior. Its probabilistic forwarding mechanism performs reasonably well in environments with semi-regular mobility patterns, although its delivery ratio remains below MaxProp and spray and wait. Spray and wait emerges as the most resource-efficient routing protocol. The protocol achieves low latency, low overhead, low hop count, and minimum energy consumption while maintaining high delivery performance. These characteristics make spray and wait highly suitable for IoT-based smart environment deployment, where energy efficiency and scalability are essential. MaxProp achieves the highest delivery ratio due to its prioritized forwarding and buffer management strategy. However, this reliability comes at the cost of higher latency and moderate energy usage. Therefore, MaxProp is more appropriate for applications prioritizing delivery reliability over response speed.

Table 3. Comparison of several DTN protocols tested in this study

Metric	Epidemic	PRoPHET	Spray and wait	MaxProp
Delivery ratio	High (spreads messages to all nodes)	Medium-high (uses encounter probability)	Medium (controls message dissemination)	Medium (uses prioritized delivery strategy)
Latency	Medium - high (depends on the number of nodes)	Medium (faster than epidemic in regular mobility)	Low (messages are only sent to limited nodes)	High (selective in path selection)
Overhead ratio	Very high (due to excessive message duplication)	Medium (more efficient than epidemic)	Low (message count is controlled)	Medium (more stable than epidemic)
Energy consumption	Very high (due to frequent message transmissions)	Medium (still power-consuming but better than epidemic)	Low (fewer messages are sent)	Medium (minimizes unnecessary transmissions)
Advantages	Very suitable for emergency situations due to high delivery probability	Efficient in regular mobility conditions, more energy-efficient than epidemic	High efficiency in overhead and energy consumption, suitable for resource-limited networks	Uses a selective forwarding strategy, more stable in the long run
Disadvantages	Extremely resource-intensive and high overhead, unsuitable for large-scale networks	Less optimal if node mobility is irregular	Lower delivery ratio compared to epidemic and PRoPHET	

The results presented in Table 2 provide strong empirical evidence that controlled replication strategies significantly outperform flooding-based mechanisms in terms of scalability, communication efficiency, and energy sustainability. These findings are consistent with previous DTN studies [16], [22], which reported that controlled forwarding mechanisms are more suitable for resource-constrained environments. However, unlike previous studies conducted under generic or campus-scale DTN scenarios, this study evaluates routing performance within a Makassar-specific heterogeneous mobility environment combining pedestrians, vehicles, and smart environment communication nodes. Therefore, the findings provide stronger contextual relevance for DTN deployment in emerging smart cities and urban IoT infrastructures in Southeast Asia.

The significance of this study lies in its ability to bridge DTN protocol evaluation with realistic smart environment deployment scenarios. The proposed Makassar-based simulation model contributes a practical framework for evaluating DTN routing performance under heterogeneous urban mobility conditions. Furthermore, the inclusion of estimated energy consumption analysis provides additional insight into communication sustainability, which is increasingly important for large-scale IoT and smart city systems.

5. CONCLUSION

This study demonstrates that the selection of DTN routing protocols significantly influences communication performance, scalability, and resource efficiency in smart environment deployment within Makassar city. The comparative evaluation shows that spray and wait achieves the best overall efficiency by providing the lowest latency, overhead ratio, hop count, and estimated energy consumption while still maintaining a high delivery ratio. These characteristics make spray and wait highly suitable for IoT-based smart environment applications that require energy-efficient and scalable communication. Meanwhile, MaxProp achieves the highest delivery ratio, indicating superior reliability for message delivery in heterogeneous mobility environments, although this advantage is accompanied by higher latency. PRoPHETv2 provides relatively balanced and stable performance under semi-regular mobility conditions, whereas epidemic routing generates excessive overhead and energy consumption due to uncontrolled message replication, making it less suitable for dense urban deployments. The findings of this study provide significant practical implications for the development of smart transportation, environmental monitoring, disaster management, and urban IoT systems in Makassar and other emerging smart cities with intermittent connectivity challenges. In addition, this study contributes a Makassar-specific DTN simulation model that integrates heterogeneous mobility patterns and energy consumption estimation. Future research may extend this work through the development of hybrid DTN machine learning routing strategies, adaptive energy-aware protocols, and real-world deployment validation to improve routing intelligence and communication sustainability in smart city environments.

REFERENCES

[1] E. Spaho, K. Dhoska, H. Voci, R. Moezzi, and A. Annuk, "A novel energy-efficient routing protocol for delay-tolerant networks," *Proceedings of the Estonian Academy of Sciences*, vol. 73, no. 3, pp. 254–263, Aug. 2024, doi: 10.3176/proc.2024.3.09.

[2] Agussalim, M. Tsuru, W. Nur Cahyo, and P. Agung Brastama, "Performance of Delay Tolerant Network Protocol in Smart City Scenario," *Journal of Physics: Conference Series*, vol. 1569, no. 2, p. 022056, Jul. 2020, doi: 10.1088/1742-6596/1569/2/022056.

[3] G. Koukis, K. Safouri, and V. Tsaoussidis, "All about Delay-Tolerant Networking (DTN) Contributions to Future Internet," *Future Internet*, vol. 16, no. 4, p. 129, Apr. 2024, doi: 10.3390/fi16040129.

[4] Y. Chang, R. Zhang, J. Cui, H. Zhou, Q. Wan, and J. Wu, "A Probabilistic Spray-and-Wait Routing Algorithm Based on Node Interest Preference in Delay Tolerant Networks," *Wireless Communications and Mobile Computing*, vol. 2022, no. 1, Jan. 2022, doi: 10.1155/2022/7323978.

[5] A. Nurdiassa, A. Zulfikar, F. Rasyid, and A. T. Wulandari, "Implementasi Kebijakan Smart City dalam Mewujudkan Makassar Kota Dunia," *Journal of Public Administration and Government*, vol. 3, no. 1, pp. 37–46, 2021, [Online]. Available: https://jurnal.fisip.untad.ac.id/index.php/JPAG

[6] A. A. Wahyudi, Y. R. Widowati, and A. A. Nugroho, "Strategi Implementasi Smart City Kota Bandung," *Jurnal Good Governance*, Jun. 2022, doi: 10.32834/gg.v18i1.460.

[7] N. Alessi, C. Caini, T. de Cola, S. Martin, and J. P. Mayer, "DTN performance analysis of multi-asset Mars-Earth communications," *International Journal of Satellite Communications and Networking*, vol. 40, no. 1, pp. 11–26, Feb. 2022, doi: 10.1002/sat.1326.

[8] S. Dheenathayalan and B. Paramasivan, "Energy Based Random Repeat Trust Computation in Delay Tolerant Network," *Computer Systems Science and Engineering*, vol. 46, no. 3, pp. 2845–2859, 2023, doi: 10.32604/csse.2023.033326.

[9] G. Liu, X. Jiang, H. Li, S. Sun, Z. Zhang, and G. Liang, "An Improved DTN Scheme for Large-Scale LEO Satellite Networks," *Wireless Communications and Mobile Computing*, vol. 2023, pp. 1–19, Feb. 2023, doi: 10.1155/2023/4899124.

[10] A. Balaram, T. Sakthivel, and R. R. Chandan, "A context-aware improved POR protocol for Delay Tolerant networks," *Automatika*, vol. 64, no. 1, pp. 22–33, Jan. 2023, doi: 10.1080/00051144.2022.2095830.

[11] J. Visca and J. Baliosian, "rl4dtn: Q-Learning for Opportunistic Networks," *Future Internet*, vol. 14, no. 12, p. 348, Nov. 2022, doi: 10.3390/fi14120348.

[12] V. G. Menon and P. M. Joe Prathap, "Analysing the behaviour and performance of opportunistic routing protocols in highly mobile wireless ad hoc networks," *International Journal of Engineering and Technology*, vol. 8, no. 5, pp. 1916–1924, Oct. 2016, doi: 10.21817/ijet/2016/v8i5/160805409.

[13] A. Memon, M. N. Ali, and B. S. Kim, "A Sustainable Data Dissemination Approach by Utilizing the Internet of Moving Things," *IEEE Access*, vol. 12, pp. 26581–26590, 2024, doi: 10.1109/ACCESS.2024.3366227.

[14] B. S. Kumar, S. Vishnubhatla, C. M. Babu, and S. P. Shetty, "Performance Analysis of Prophet Routing Protocol in Delay Tolerant Network by using Machine Learning Models," *International Journal of Advanced Computer Science and Applications*, vol. 14, no. 5, pp. 213–219, 2023, doi: 10.14569/IJACSA.2023.0140522.

[15] S. C. Roy, M. S. Rahim, and M. A. Islam, "Performance assessment of routing protocols for campus area emergency delay-tolerant network," *International Journal of Advances in Applied Sciences*, vol. 13, no. 1, pp. 54–62, 2024, doi: 10.11591/ijaas.v13.i1.pp54-62.

[16] S. Hasan, M. Sharifi Sani, S. Iranmanesh, A. H. Al-Bayatti, S. Khan, and R. Raad, "Enhanced Message Replication Technique for DTN Routing Protocols," *Sensors*, vol. 23, no. 2, p. 922, Jan. 2023, doi: 10.3390/s23020922.

[17] R. Munjal, W. Liu, X. Li, J. Gutierrez, and P. H. J. Chong, "Multi-Attribute Decision Making for Energy-Efficient Public Transport Network Selection in Smart Cities," *Future Internet*, vol. 14, no. 2, p. 42, Jan. 2022, doi: 10.3390/fi14020042.

[18] A. Lindgren, A. Doria, and O. Schelén, "Probabilistic routing in intermittently connected networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 7, no. 3, pp. 19–20, Jul. 2003, doi: 10.1145/961268.961272.

[19] R. Lent, "Improving Bundle Routing in a Space DTN by Approximating the Transmission Time of the Reliable LTP," *Network*, vol. 3, no. 1, pp. 180–198, Feb. 2023, doi: 10.3390/network3010009.

[20] R. Kumar, M. Mathuria, and M. Sharma, "Study of Routing Algorithms in DTN Enabled Vehicular Ad-Hoc Network," *International Journal of Computer Applications*, vol. 159, no. 7, pp. 1–6, Feb. 2017, doi: 10.5120/ijca2017912971.

[21] Y. Zguira, H. Rivano, and A. Meddeb, "A comparative evaluation of the performance of the multi-hop IoB-DTN routing protocol," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2018, pp. 175–187. doi: 10.1007/978-3-030-00247-3_17.

[22] H. Chen and C. Wu, "Clustered DTN routing based on sensing node relationship strength," *IET Communications*, vol. 18, no. 12, pp. 726–743, Jul. 2024, doi: 10.1049/cmu2.12785.

BIOGRAPHIES OF AUTHORS

Abdul Latief Arda received a Bachelor in Computer Science at STMIK Handayani in 2000, a master's degree at the University Hasanuddin in 2008, a Master's degree in Computer System at Handayani University Makassar in 2015, and the doctoral degrees at Universitas Negeri Makassar in 2017. Since 2005, the academic status concerned is that a permanent lecturer at LLDIKTI WIL. IX, employed at Handayani University Makassar. He can be contacted at email: abdullatief@handayani.ac.id.

Symsu Alam received a Bachelor's degree in Computer Systems at STMIK Handayani in 2006 and a Master's degree in Computer Science at Universitas Hasanuddin Makassar. Currently, the author serves as a permanent foundation lecturer and holds the position of head at the Computer Systems Study Program at Handayani University Makassar. He can be contacted at email: syamsulalam@handayani.ac.id.

Agussalim completed a Bachelor's degree in Computer Science at Universitas Negeri Makassar, a Master's degree in Informatics Engineering at Universitas Hasanuddin, and a Doctoral degree in Computer Science at Kyushu Institute of Technology, Japan. Since 2019, he has been a permanent lecturer at Universitas Pejuang Nasional Veteran Surabaya. He can be contacted at email: agussalim.si@upnjatim.ac.id.

Matalangi received a Bachelor's degree from STMIK Handayani Makassar in 2013 and his Master's degree in Computer Science from STMIK Handayani Makassar in 2015. Since 2015, he has been a full-time lecturer under the PIKI Paulus Foundation and is currently serving at Universitas Kristen Indonesia Paulus. He can be contacted at email: matalangi18@gmail.com.