Mobility Management with Digital Twin Networks for Bluetooth Mesh

Jorg Wieme
imec - IDLab
Ghent University
Ghent, Belgium
jorg.wieme@ugent.be

Jeroen Hoebeke
imec - IDLab
Ghent University
Ghent, Belgium
jeroen.hoebeke@ugent.be

NOMS 2026-2026 IEEE Network Operations and Management Symposium | 979-8-3315-9268-4/26/$31.00 ©2026 IEEE | DOI: 10.1109/NOMS69089.2026.11668139

***Abstract*—Digital Twin Networks have garnered increasing interest in both industry and academia for managing, monitoring, and controlling networks, irrespective of the underlying technology. However, managing mobility in dynamic networks like Bluetooth Mesh is particularly challenging due to the frequent movement of nodes and the need for seamless communication across multiple hops. This study explores mobility management in Bluetooth Mesh networks using Digital Twin Networks, addressing the limitations of the default flooding-based approach. We propose optimized solutions that apply Digital Twin Networks to efficiently manage nodes that join or move within the network by creating dedicated Mobility Applications. Theoretical evaluations using propagation models compare the proposed solutions with traditional flooding, while experimental results from a real-life testbed validate our findings, showing that Digital Twin Network based methods can reduce network strain and message overhead while maintaining high reliability for mobile nodes.**

***Index Terms*—Digital Twin Network, DTN, Bluetooth Mesh, Network Management, Network Reliability, Network Mobility, Propagation Models**

I. Introduction

In recent years, communication technologies have advanced rapidly to meet growing digital demands. Wi-Fi has evolved with Wi-Fi 6 and 7 [1]–[3], while Bluetooth has expanded with BLE, Mesh, and LE Audio [4]–[6]. As networks become more complex, software-driven management solutions integrating AI [7] and Digital Twin Network (DTN) [8], [9] have become increasingly important. With the rise of 5G, Wi-Fi 6, and future iterations, these approaches will be essential for ensuring seamless operation and scalability.

A Digital Twin Network [10] is a specialized form of a digital twin designed to represent and manage entire networks rather than individual entities like machines or processes. DTNs replicate the collective behavior, performance, and interactions of interconnected systems, enabling more efficient network optimization. In our previous work [11], we implemented a DTN for Bluetooth Mesh, focusing on enhancing performance and reliability through real-time monitoring and predictive what-if scenarios. This approach allows the network to anticipate and adapt to changing conditions, enabling proactive adjustments to improve overall efficiency.

Although our DTN has been statistically and experimentally validated, it does not yet account for mobility, where unknown or transient nodes briefly join or move through the network, something the DTN cannot handle.

This paper addresses the mobility challenge that occurs when a DTN is used to optimize Bluetooth Mesh networks. We first propose and describe a DTN-based mobility solution, then develop theoretical propagation models to characterize its behavior, followed by real-life testbed experiments. These models serve only as analytical tools and are not used to implement the proposed mobility mechanism. Finally, we analyze the results and compare the experimental observations with the theoretical predictions to evaluate the effectiveness and accuracy of the proposed approach.

The structure is as follows: Section II provides an overview of related work. This is followed by Section III, which offers a brief background on the two key components of this study, Bluetooth Mesh and the Digital Twin Network. Section IV presents our proposed solution, whereas Section V discusses its corresponding propagation model. Next, Section VI details the experimental evaluation conducted in a real-life testbed. Finally, Section VII concludes the paper with a reflection on the findings and potential directions for future research.

II. Related Work

Early studies, targeting Bluetooth Mesh, have primarily explored its advantages, disadvantages, challenges, efficiency, and power consumption [12]–[14]. Alongside these analytical studies, practical implementations and prototypes based on Bluetooth Mesh have been developed, as seen in [15], [16].

Beyond general evaluations, more in-depth investigations have examined specific aspects of Bluetooth Mesh. Security vulnerabilities were analyzed in [17], where the authors identified and evaluated potential attack vectors on physical devices. The flooding mechanism, crucial for message propagation, was studied in [18], where various selection procedures were tested and optimized. Speed performance and enhancements were explored in [19], while [20] investigated an advanced application of Bluetooth Mesh for indoor localization. However, there has been limited research on optimizing mobility for nodes in Bluetooth Mesh. While research on DTNs is still developing, several studies have made interesting contributions [8], [9]. These works have explored different aspects of DTNs, including their architecture, functionality, and applications

Authorized licensed use limited to: University of Gent. Downloaded on September 07,2026 at 09:57:39 UTC from IEEE Xplore. Restrictions apply.

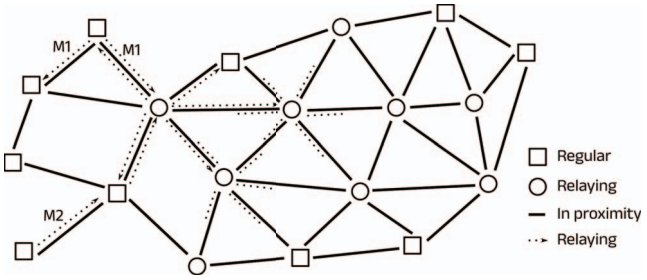


Fig. 1. Bluetooth Mesh network using flooding. Two scenarios: (M1) is being relayed, and (M2) due to network configuration, is not relayed.

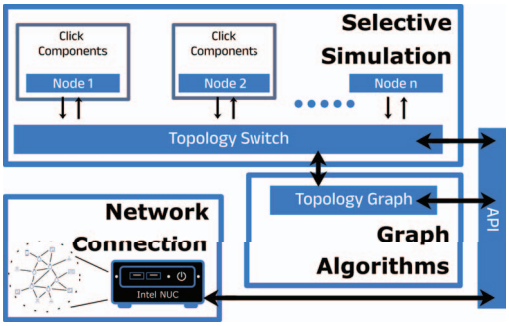


Fig. 2. Visual representation of a Digital Twin Network for Bluetooth Mesh.

across various domains. A key focus has been on improving network efficiency and predictive maintenance by enabling real-time analytics and intelligent network management

Propagation models have long been used to represent network behavior, with various models developed specifically for mesh networks and frequently integrated into simulators [21]. These models are also employed to evaluate network quality and predict performance [22], [23]. However, in the context of Bluetooth Mesh, aside from the work in [12], propagation models have seen limited use for performance assessment.

III. Background on Core Technologies

A. Bluetooth Mesh

Bluetooth Mesh, specifically Bluetooth Low Energy (BLE), operates on 40 channels of 2 MHz bandwidth within the 2400 to 2483.5 MHz frequency range. However, its advertisement mechanism utilizes only three primary channels: 37, 38, and 39. In BLE advertising, an advertiser transmits on one of these three channels and subsequently repeats the transmission on the other two. A receiving device continuously scans one of these channels and switches accordingly to capture the message.

Bluetooth Mesh is built upon this advertising mechanism and employs flooding-based communication. In this approach, a transmitting node sends a message while all other nodes in the network remain in scanning mode. Upon receiving the message, a node transitions into an advertiser role and retransmits it, as illustrated in Fig. 1. Additionally, message repetitions are added enhancing reliability, and a random backoff mechanism mitigates the risk of collisions from simultaneous transmissions by neighboring nodes.

B. Digital Twin Network

Digital Twin Network is a technique that integrates multiple advanced networking approaches into a complete system, enabling dynamic network management. A DTN continuously synchronizes a real-world network with its virtual counterpart through real-time, in-band monitoring. This synchronization allows the DTN to analyze network conditions, test various optimizations, and support performance enhancements based on specific needs and objectives. A visual representation of our DTN implementation in [11] is shown in Fig. 2, illustrating the interaction between the physical and virtualized network layers.

The DTN maintains a bidirectional link with the physical network, where real-time performance metrics continuously update its internal models. By using in-band traffic, the DTN actively influences the network itself; factors such as control-traffic frequency, data type, and routing strategies were thoroughly investigated in [24].

Because Bluetooth Mesh relies on global flooding, meeting the diverse performance needs of all applications is challenging. Therefore, our DTN optimizes each application independently to avoid cross-interference that occurs when only a single configuration per node is used. This per-application strategy enables latency-critical services, such as lighting control, to be tuned differently from delay-tolerant sensor traffic. To support these decisions, Quality-of-Service (QoS) tables are used, allowing nodes to apply DTN-controlled configurations such as repeat counts, relay permissions, and routing rules. However, the approach relies on known nodes, meaning QoS-based optimizations cannot be configured for devices that are not yet present in the network.

IV. DTN Improvement for Mobility

In a standard Bluetooth Mesh network, mobility is straightforward as long as a mobile node stays within range of any participating node and is already provisioned or can be provisioned remotely. In contrast, mobility poses a greater challenge for a DTN, which cannot model or optimize nodes that are not yet part of the system.

We therefore introduce a mobility support mechanism for Bluetooth Mesh networks managed by a DTN. The approach reuses the existing backbone of known nodes already tracked by the DTN, using data generated during its normal operation.

Mobility support is provided by a new application type, the Mobility Application. Each of the N nodes runs its own instance, creating $N-1$ mobility paths (excluding the gateway). These paths ensure that every node maintains an optimized route to the gateway, enabling newly arriving nodes to exchange data immediately. The DTN selects among multiple optimization strategies depending on network conditions. Mobile nodes do not need to identify themselves explicitly but just partake normally and the mesh nodes will automatically use the Mobility Application.

Authorized licensed use limited to: University of Gent. Downloaded on September 07,2026 at 09:57:39 UTC from IEEE Xplore. Restrictions apply.

This mechanism ensures that any newly arriving node can reach the gateway, and thus the DTN. Once initial communication has been established, two scenarios are possible. In the first scenario, a node indicates to the DTN that it will behave as a static or infrequently moving device. The DTN will then generate the required application configurations and updates the neighbors if needed. This mode supports remote provisioning as well and mitigates a known DTN limitation related to Friendship and Proxy nodes. In the second scenario, the node is continuously moving. In this case the configuration would quickly become outdated. Therefore, for such highly mobile nodes, the system simply re-executes the Mobility Application repeatedly rather than relying on custom configurations.

While this solution significantly improves mobility support, several challenges remain such as redundant message reception. Because multiple nodes may receive and forward messages from an external node, multiple parallel Mobility Applications could be triggered. Since each Mobility Application follows its own set of QoS rules, as these are based on the combination of source and destination address, thus they do not share cached messages between applications. This results in a less efficient Bluetooth Mesh network, as redundant transmissions increase network load without providing additional benefits. To address the limitations of the proposed Mobility Application solution, we will discuss two extensions. The first extension will use the caching system with global indicators instead of the source addresses for the QoS. This approach ensures that if a node has already received a message from a different Mobility Application, it will recognize it and avoid forwarding it again. The second extension focuses on eavesdropping at the beginning of the process. If a node hears one of its neighbors transmitting a message from the same mobile node it just received, it will not start its Mobility Application, thereby reducing redundancy and unnecessary transmissions.

V. Propagation Model

To analytically evaluate our proposed solutions with standard Bluetooth Mesh flooding, we define propagation models that approximate message propagation in terms of time. For simplicity, we do not consider factors such as packet collisions, switching delays between transmission and scanning, or the three channel advertisement mechanism of BLE.

We model the message propagation using an epidemic model based on the Susceptible-Infected (SI) model [25]. The SI model allows us to approximate the message propagation process as an exponential growth function, where nodes transition from a susceptible state to an infected state.

The following four subsections present these models, while the detailed derivations and intermediate steps are provided in the Appendix.

A. Bluetooth Mesh Model

Using the propagation model derived in Appendix A, the median time of a Bluetooth Mesh network is obtained from 4 as:

$$T_{med} = \frac{1}{\beta} ln\left(\frac{N-Z}{Z}\right). \tag{1}$$

B. DTN based Model

The second model corresponds to the default and thus baseline DTN solution introduced in Section IV, where each node forwards messages along predefined path groups toward the gateway. Using the propagation model derived in Appendix B, the delivery probability for the destination follows 5, and assuming uniform groups, the resulting median delivery time is

$$T_{med} = \frac{1}{\beta'} \ln\left(\frac{(N'-1)(1-\epsilon)}{\epsilon}\right), \qquad \epsilon = (1/2)^{1/Z}. \tag{2}$$

C. Global-DTN based Model

To reduce the message overhead generated in the basic DTN solution, we apply a small adaptation already supported by the DTN and its QoS system: enabling global caching across mobility applications. With global caching, propagation behaves like standard flooding, where Z represents the initial nodes or groups. The process therefore follows the flooding model in 4, and the median time T_{med} matches 1.

D. Backoff based Model

The global DTN-based solution reduces message overhead compared to the initial approach, but it is still inefficient. To further improve efficiency, we introduce an additional backoff mechanism. Nodes that hear a neighbor already transmitting the same mobility application refrain from sending their own. Using the modified propagation model 6 derived in Appendix C, the median time becomes

$$T_{med} = \mathbb{E}[B] + \frac{1}{\beta'} \ln\left(\frac{(N'-1)(1-\epsilon)}{\epsilon}\right),\ \epsilon = (1/2)^{1/Z_r}. \tag{3}$$

The key benefit of this approach lies in message reduction. Whereas the original DTN solution can require up to $\sum_{i=1}^{Z} N_i$ transmissions, the backoff mechanism suppresses redundant senders, lowering the total to approximately

$$N_{\text{tx}} \approx \sum_{i=1}^{Z_r} N_i, \qquad \text{with } Z_r \ll Z.$$

Because Z_r decreases with node density and reception range, the number of messages will fall below the overhead of standard flooding, while retaining DTN compatibility.

VI. Experimental Evaluation

Our testbed is the IDLab OfficeLab [26], an environment comprising 110 nodes across multiple floors designed to emulate an office setting. The experiments will focus on a single floor, using 16 nodes configured as regular Bluetooth mesh devices, and one as gateway.

The first scenario tests the default case where a mobile node is detected for a single message. The second emulates a node moving through the office space, aiming to replicate

Authorized licensed use limited to: University of Gent. Downloaded on September 07,2026 at 09:57:39 UTC from IEEE Xplore. Restrictions apply.

real mobility. Both scenarios are executed across the four previously discussed methods.

Each node within a group of an experiment receives and tries to forward 150 messages. To contain group sizes, an RSSI threshold is applied. For fairness, DTN decisions are restricted to minimal optimization in order to align with the standard Mesh baseline and to emphasize the introduction of the Mobility Application. All experiments were performed during regular business hours, with active Wi-Fi and Bluetooth activity and people moving around.

A. Testbed results

For our analysis, we evaluate results across multiple groups and individual forwarding nodes under different methods. Table I in Appendix D summarizes the metrics for the first scenario, focusing on how many messages were received by each forwarding node. A lower number of received messages directly indicates reduced spectrum usage and therefore less interference.

Reliability reflects the success rate of deliveries from Group 1 nodes to the gateway. Across all methods, the gateway received every message at least once, resulting in 100% group-level reliability. Individual nodes in the DTN-based methods show slightly lower per node reliability than standard Bluetooth Mesh, but this is acceptable since the gateway still receives at least one copy of every message.

The most notable differences appear in the total number of received messages and message duration. Both DTN-based methods drastically reduce overall traffic. Global DTN lowers message redundancy through cross sharing, and Backoff DTN further limits unnecessary transmissions through its randomized delays. When looking at the entire experiment, Global and Backoff DTN result in only a few thousand received messages, compared to tens of thousands in standard Bluetooth Mesh. In fact, Backoff DTN reduces the number of transmissions by nearly a factor of 30 compared to the theoretical maximum, representing the most substantial improvement. Message duration is slightly higher for Bluetooth Mesh, likely due to collisions, whereas the Backoff DTN approach introduce a small additional delay from the backoff mechanism. This tradeoff is favorable, where reduction of total message load is far more valuable than minimizing transmission duration, especially when new mobile nodes need to be processed and managed. The same observations carry over to the second scenario, where we again find that DTN-based approaches generate far fewer messages while maintaining full delivery success.

B. Comparison between propagation and testbed results

Fig. 3 compares the predictions of our propagation models with the behavior observed in the physical network. Across all DTN-based solutions, the models prove to be conservative, consistently predicting that the mean time has a longer message durations than those measured in practice. This indicates that, although simplified, the models provide a safe upper bound on expected performance. The impact of the additional backoff mechanism is also overestimated by the models. In the physical network, the backoff contributes only a minor delay, significantly smaller than suggested by the analytical expressions. This highlights that real-world temporal variation and asynchronous behavior naturally mitigate the delay that the model treats more pessimistically. In contrast, the Bluetooth Mesh model behaves overly optimistic when compared to real measurements. While the model captures the ideal forwarding behavior, it does not account for collisions, which are inherent in practical deployments. Thus, the optimistic predictions would only hold in scenarios devoid of interference, conditions rarely achievable in realistic environments. Overall, the comparison confirms that the DTN models provide reliable upper-bound estimates, while the Bluetooth Mesh model should be interpreted as a best-case scenario rather than a performance predictor.

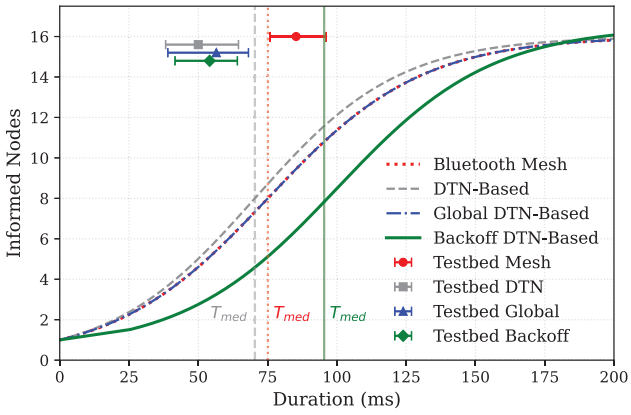


Fig. 3. Validation of propagation models against experimental results. The curves depict the theoretical number of informed nodes over time, where the markers at saturation represent the experimental completion time distributions extracted from real-world experiments. Vertical lines mark the theoretical median times (T_{med}). The parameters of the propagation models are selected to match observed values in the physical network.

VII. Conclusion

This work demonstrates that the inherent structure of a DTN is well-suited for handling mobile nodes in a Bluetooth Mesh network. Our findings indicate that with minor modifications, we can significantly reduce network strain while maintaining equivalent reliability across multiple methods. While the current Backoff solution introduces additional delay, future approaches could aim to eliminate this while preserving the same benefits. One potential solution could use the fact that most nodes in the network are static backbone nodes that remain active. By utilizing these nodes, the DTN could construct an RSSI-based network map, enabling a more efficient decision-making process similar to the Backoff model but without the delay.

Authorized licensed use limited to: University of Gent. Downloaded on September 07,2026 at 09:57:39 UTC from IEEE Xplore. Restrictions apply.

REFERENCES

[1] M. S. Afaqui, E. Garcia-Villegas, and E. Lopez-Aguilera, "Ieee 802.11ax: Challenges and requirements for future high efficiency wifi," *IEEE Wireless Communications*, vol. 24, no. 3, pp. 130–137, 2017.

[2] E. Mozaffariahrar, F. Theoleyre, and M. Menth, "A survey of wi-fi 6: Technologies, advances, and challenges," *Future Internet*, vol. 14, no. 10, 2022. [Online]. Available: https://www.mdpi.com/1999-5903/14/10/293

[3] Q. Qu, B. Li, M. Yang, Z. Yan, A. Yang, D.-J. Deng, and K.-C. Chen, "Survey and performance evaluation of the upcoming next generation wlans standard - ieee 802.11ax," *Mobile Networks and Applications*, vol. 24, no. 5, pp. 1461–1474, Oct 2019. [Online]. Available: https://doi.org/10.1007/s11036-019-01277-9

[4] Bluetooth SIG, "Bluetooth specification version 4.0," https://www.bluetooth.com/specifications/specs/core-specification-4-0/, 2010.

[5] ——, "Bluetooth specification version 5.0," https://www.bluetooth.com/specifications/specs/core-specification-5-0/, 2016.

[6] ——, "Mesh profile specification: 1.0.1," https://www.bluetooth.com/specifications/specs/mesh-profile-1-0-1/, 2019.

[7] H. Kim and N. Feamster, "Improving network management with software defined networking," *IEEE Communications Magazine*, vol. 51, no. 2, pp. 114–119, 2013.

[8] Y. Wu, K. Zhang, and Y. Zhang, "Digital twin networks: A survey," *IEEE Internet of Things Journal*, vol. 8, no. 18, pp. 13 789–13 804, 2021.

[9] P. Almasan, M. Ferriol-Galms, J. Paillisse, J. Surez-Varela, D. Perino, D. Lpez, A. A. P. Perales, P. Harvey, L. Ciavaglia, L. Wong, V. Ram, S. Xiao, X. Shi, X. Cheng, A. Cabellos-Aparicio, and P. Barlet-Ros, "Digital twin network: Opportunities and challenges," 2022.

[10] C. Zhou, H. Yang, X. Duan, D. Lopez, A. Pastor, Q. Wu, M. Boucadair, and C. Jacquenet, "Digital twin network: Concepts and reference architecture," https://datatracker.ietf.org/doc/draft-irtf-nmrg-network-digital-twin-arch/, 2024.

[11] J. Wieme, M. Baert, and J. Hoebeke, "Managing a qos-enabled bluetooth mesh network using a digital twin network: An experimental evaluation," *Internet of Things*, vol. 25, p. 101023, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2542660523003463

[12] R. Rondn, A. Mahmood, S. Grimaldi, and M. Gidlund, "Understanding the performance of bluetooth mesh: Reliability, delay, and scalability analysis," *IEEE Internet of Things Journal*, vol. 7, no. 3, pp. 2089–2101, 2020.

[13] Á. Hernández-Solana, D. Pérez-Díaz-De-Cerio, M. García-Lozano, A. V. Bardají, and J.-L. Valenzuela, "Bluetooth mesh analysis, issues, and challenges," *IEEE Access*, vol. 8, pp. 53 784–53 800, 2020.

[14] S. M. Darroudi, R. Caldera-Snchez, and C. Gomez, "Bluetooth mesh energy consumption: A model," *Sensors*, vol. 19, no. 5, 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/5/1238

[15] C. Martnez, L. Eras, and F. Domnguez, "The smart doorbell: A proof-of-concept implementation of a bluetooth mesh network," in *2018 IEEE Third Ecuador Technical Chapters Meeting (ETCM)*, 2018, pp. 1–5.

[16] L. Eras, F. Domínguez, and C. Martinez, "Viability characterization of a proof-of-concept bluetooth mesh smart building application," *International Journal of Distributed Sensor Networks*, vol. 18, no. 5, p. 15501329221097819, 2022. [Online]. Available: https://doi.org/10.1177/15501329221097819

[17] A. Adomnicai, J. J. A. Fournier, and L. Masson, "Hardware security threats against bluetooth mesh networks," in *2018 IEEE Conference on Communications and Network Security (CNS)*, 2018, pp. 1–9.

[18] E. A. J. Hansen, M. H. Nielsen, D. E. Serup, R. J. Williams, T. K. Madsen, and R. Abildgren, "On relay selection approaches in bluetooth mesh networks," in *2018 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, 2018, pp. 1–5.

[19] D. Pérez-Díaz-De-Cerio, Á. Hernández-Solana, M. García-Lozano, A. V. Bardají, and J.-L. Valenzuela, "Speeding up bluetooth mesh," *IEEE Access*, vol. 9, pp. 93 267–93 284, 2021.

[20] M. Jürgens, D. Meis, D. Mllers, F. Nolte, E. Stork, G. Vossen, C. Werner, and H. Winkelmann, "Bluetooth mesh networks for indoor localization," in *2019 20th IEEE International Conference on Mobile Data Management (MDM)*, 2019, pp. 397–402.

[21] V. Sridhara and S. Bohacek, "Realistic propagation simulation of urban mesh networks," *Computer Networks*, vol. 51, no. 12, pp. 3392–3412, 2007. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S138912860700059X

[22] V. Sridhara, J. Kim, and S. Bohacek, "Performance of urban mesh networks," in *Proceedings of the 8th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, ser. MSWiM '05. New York, NY, USA: Association for Computing Machinery, 2005, p. 269277. [Online]. Available: https://doi.org/10.1145/1089444.1089492

[23] M. L. Sanni, A. A. Hashim, F. Anwar, G. S. M. Ahmed, and S. Ali, "How to model wireless mesh networks topology," *IOP Conference Series: Materials Science and Engineering*, vol. 53, no. 1, p. 012037, dec 2013. [Online]. Available: https://dx.doi.org/10.1088/1757-899X/53/1/012037

[24] J. Wieme, M. Baert, and J. Hoebeke, "The role of monitoring frequency in optimizing digital twin networks," in *NOMS 2025-2025 IEEE Network Operations and Management Symposium*, 2025, pp. 1–7.

[25] W. O. Kermack and A. G. McKendrick, "Contributions to the mathematical theory of epidemics—i," *Bulletin of Mathematical Biology*, vol. 53, no. 1, pp. 33–55, Mar 1991. [Online]. Available: https://doi.org/10.1007/BF02464423

[26] imec IDLab UGent, "Testbed officelab," https://boss.wilab1.ilabt.iminds.be/inventory/?viewMode=inventory, 2024.

[27] L. Baldesi, L. Maccari, and R. L. Cigno, "On the properties of infective flooding in low-duty-cycle networks," in *2019 15th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, 2019, pp. 1–8.

APPENDIX A
PROPAGATION MODELS FOR BLUETOOTH MESH

To simplify the modeling process, we begin with a fully connected mesh and idealized propagation, ignoring repetition, caching, backoff behavior, and assuming homogeneous nodes without external interference. Under these assumptions, message spread follows the logistic equation from [27]:

$$\frac{dI}{dt} = \beta I(t)\left(1 - \frac{I(t)}{N}\right),$$

where $I(t)$ is the number of informed nodes, N the total number of nodes, and β the per-node transmission rate approximated as

$$\beta \approx \frac{p(d-1)}{\tau},$$

This yields the logistic solution:

$$I(t) = \frac{N}{1 + (N-1)e^{-\beta t}}.$$

Relaxing initial assumptions. Retransmissions modify the effective rate to

$$\beta \approx \frac{1 - \prod_{j=1}^{r} p_j (d-1)}{\tau},$$

and if a mobile node initially connects to Z neighbors, the solution becomes

$$I(t) = \frac{N}{1 + \frac{(N-Z)}{Z} e^{-\beta t}}.$$

To incorporate random backoff, we use

$$\beta \approx \frac{1 - \prod_{j=1}^{r} p_j (d-1)}{\tau + \mathbb{E}[B]}, \qquad \Delta t = \tau + \mathbb{E}[B].$$

Assuming $t \approx h\Delta t$ for h hops, we obtain the hop-based form:

$$I(h) = \frac{N}{1 + \frac{N-Z}{Z} e^{-\beta h \Delta t}}. \tag{4}$$

Authorized licensed use limited to: University of Gent. Downloaded on September 07,2026 at 09:57:39 UTC from IEEE Xplore. Restrictions apply.

To estimate when a message reaches the gateway, we define the median hop count through

$$I(h_{\text{med}}) = \frac{N}{2},$$

yielding

$$h_{\text{med}} = \frac{1}{\beta \Delta t} \ln\left(\frac{N-Z}{Z}\right),\ T_{\text{med}} = h_{\text{med}} \Delta t = \frac{1}{\beta} \ln\left(\frac{N-Z}{Z}\right)$$

APPENDIX B
PROPAGATION MODEL FOR DTN-BASED MESH

In the default DTN solution, each node belongs to one of $N-1$ path groups, where group i contains N_i nodes. Caching is applied only within each group, and the effective transmission rate is

$$\beta_i \approx \frac{1 - \prod_{j=1}^{r} p_j (d_i - 1)}{\tau + \mathbb{E}[B]},$$

This yields the logistic model

$$I_i(h) = \frac{N_i}{1 + (N_i - 1) e^{-\beta_i h \Delta t}}, \text{or equivalently,}$$
$$F_i(h) = \frac{I_i(h)}{N_i} = \frac{1}{1 + (N_i - 1) e^{-\beta_i h \Delta t}}.$$

A message reaches the gateway if at least one group succeeds:

$$F_{dest}(h) = 1 - \prod_{i=1}^{Z} \left[1 - \frac{1}{1 + (N_i - 1) e^{-\beta_i h \Delta t_i}}\right]. \quad (5)$$

Assuming identical groups size ($N_i = N'$ and $\beta_i = \beta'$), solving $F_{dest}(h_{med}) = 1/2$ gives

$$T_{med} = \frac{1}{\beta'} \ln\left(\frac{(N'-1)(1-\epsilon)}{\epsilon}\right), \qquad \epsilon = \left(\frac{1}{2}\right)^{1/Z}.$$

APPENDIX C
PROPAGATION MODEL FOR BACKOFF DTN-BASED MESH

The backoff-based solution extends the default DTN path-group model by adding an extra suppression layer: each of the initial Z nodes listens before transmitting, and suppresses its own mobility application if a neighbor already forwards the same message. Due to range, timing, and hidden terminals, only a subset of nodes transmit; we denote this reduced set by $Z_r \leq Z$.

Starting from the per-group model, the additional backoff is incorporated by shifting the hop index:

$$F_i(h) = \frac{1}{1 + (N_i - 1) e^{-\beta_i \left(h - \frac{\mathbb{E}[B]}{\Delta t}\right) \Delta t}}.$$

Assuming uniform groups ($N_i = N'$ and $\beta_i = \beta'$), the destination delivery probability becomes

$$F_{dest}(h) = 1 - \left[1 - \frac{1}{1 + (N' - 1) e^{-\beta'(\Delta t h - \mathbb{E}[B])}}\right]^{Z_r}. \quad (6)$$

Solving $F_{dest}(h_{med}) = 1/2$ and defining $\epsilon = (1/2)^{1/Z_r}$, we obtain

$$\frac{\epsilon}{1-\epsilon} = (N'-1) e^{-\beta'(\Delta t h_{med} - \mathbb{E}[B])},$$

$$T_{med} = h_{med} \Delta t = \mathbb{E}[B] + \frac{1}{\beta'} \ln\left(\frac{(N'-1)(1-\epsilon)}{\epsilon}\right).$$

Relative to the original DTN model, the backoff-based result adds (i) the delay $\mathbb{E}[B]$ and (ii) a smaller effective fan-out Z_r, which slightly increases delay but reduces message load. The total number of transmissions is upper bounded by

$$\sum_{i=1}^{Z_r} N_i,$$

showing a substantial reduction compared to the original DTN solution. To approximate Z_r, we model spatial suppression statistically. With node density $\rho = Z/A$ and communication radius R, the expected number of neighbors is

$$ne = \rho \pi R^2 = \frac{Z}{A} \pi R^2.$$

Assuming uniform placement, the expected number of active nodes becomes

$$Z_r = \frac{Z}{ne + 1} = \frac{Z}{\frac{Z}{A} \pi R^2 + 1}.$$

Thus $Z_r < Z$, and the total number of messages, $N' Z_r$, scales directly with the suppressed group size.

APPENDIX D
EXPERIMENTAL RESULTS

TABLE I
NETWORK PERFORMANCE METRICS FOR FOUR MOBILITY MANAGEMENT STRATEGIES EVALUATED IN A PHYSICAL TESTBED.

Methods		Reliability		Duration (ms)			# Traffic		
Mode	ID	%	$\sum$	M	μ	σ	M	μ	σ
BLE Mesh	1	62	150	99.6	81.9	21.9	89	87.5	16.9
	2	90	150	92.9	84.6	22.9	91	90.4	15.8
	3	72	150	93.8	69.8	15.2	94	93.1	13.6
	4	74	150	51.5	53.1	21.9	91	89.3	14.5
DTN based	1	54.7	150	76.0	57.2	21.2	14	13.7	5.2
	2	65.3	150	82.7	59.5	22.1	24	22.8	5.3
	3	62.7	150	75.9	60.6	19.6	23	23.0	5.5
	4	66	150	66.9	52.4	22.9	16	15.6	3.9
Global DTN	1	51.3	150	58.1	47.8	21.2	13	12.6	4.7
	2	63.3	150	74.7	59.5	22.5	13	12.8	4.2
	3	62	150	57.9	56.6	20.2	7	8.0	4.3
	4	69.3	150	48.3	57.6	22.8	8	8.6	4.8
Backoff DTN	1	62.2	53	80.6	61.6	25.0	20	19.4	7.5
	2	58.5	41	67.0	58.4	24.5	15	13.9	4.3
	3	69	42	78.1	71.5	27.9	18	16.4	8.7
	4	61.8	55	63.0	63.7	23.2	10	11.7	5.8

Authorized licensed use limited to: University of Gent. Downloaded on September 07,2026 at 09:57:39 UTC from IEEE Xplore. Restrictions apply.