Comparative Study of Packet Loss Models for Flooding Protocols in Dense Wireless Networks

Joseph Fares
TICKET Lab
Antonine University
Hadat-Baabda, Lebanon
Email: joseph.fares@ua.edu.lb

Eugen Dedu
Université Marie et Louis Pasteur,
CNRS, institut FEMTO-ST
F-25200 Montbéliard, France
Email: eugen.dedu@univ-fcomte.fr

Jad Nassar
TICKET Lab
Antonine University
Hadat-Baabda, Lebanon
Email: jad.nassar@ua.edu.lb

Abdallah Makhoul
Université Marie et Louis Pasteur,
CNRS, institut FEMTO-ST
F-25200 Montbéliard, France
Email: abdallah.makhoul@univ-fcomte.fr

***Abstract*—Dense wireless networks, such as electromagnetic nanonetworks, are characterized by high number of resource-constrained nanonodes close to each other. Testing communication protocols for these networks is an important challenge as real-world experimentation is complex and theoretical analysis is often too limited. Therefore, simulations are widely used as an alternative due to its cost-effectiveness, reproducibility, and efficiency. However, their accuracy depends on how they simulate the real conditions of the network. For instance, simulation accuracy depends widely on the packet loss model used. This paper addresses this challenge, by comparing the Unit Disc Graph (UDG) and shadowing packet loss models in the context of flooding protocols. The obtained results show that while both models can ensure similar outcomes in some cases, they diverge significantly in others, particularly when data delivery is not guaranteed across the entire network. Finally, this study shows the importance of selecting appropriate packet loss models in simulations to ensure reliable and generalizable protocol evaluation.**

***Index Terms*—Unit disc graph, shadowing, packet loss model, wireless communication, dense networks.**

I. Introduction

The evolution and ubiquity of wireless networks is leading to the emergence of dense network topologies, composed of a massive number of devices, and where nodes have a large number of neighbours (a large node density). As an example, Internet of Things network has continuously been growing to reach 16.6 billion devices in 2023, with forecast of 41.1 billions in 2030, according to the State of IoT report [1]. One recent incarnation of such networks is electromagnetic nanonetworks, composed of extremely small and resource-limited nanodevices, with various applications, such as software-defined metamaterials, wireless robotic materials, in-body communication, and on-chip communications [2]. Dense networks need novel communication protocols, which consider their unique peculiarities and challenges, and these protocols need to be tested before real deployment.

However, for protocol testing, mathematical analysis is too limited due to the interactive nature of data exchanges between devices, and real-world experiments are impractical because of the massive number of devices required (e.g., tens of thousands to build, deploy, and configure).Another option is to use simulations, using software on computers to simulate devices and network among them. However, simulations do not fully replicate real-world conditions due to their reliance on simplified models and underlying assumptions. Nevertheless, they have often produced realistic results, and are quite efficient from cost and time points of view. Contrary to experiments, they usually allow a controlled environment with a full reproducibility of results, increasing confidence in the results. Thus, it is not surprising that simulations are widely used in many studies, especially when the generated results can be clearly interpreted and validated against theoretical or experimental benchmarks. One aspect of the network to be simulated is is determining whether devices successfully receive a given packet or not. The commonly used packet loss model to simulate communication in wireless networks is UDG (unit disc graph, or all or nothing model), as it is simple and deterministic. However, it has some limitations: It assumes a perfect circular range with no interference, no shadowing and no fading, which are rarely true in real-world wireless environments. Other models, such as shadowing, are used to improve the realism of communications [3].

Unfortunately, the influence of the chosen loss model on the results remains unclear. It is a common practice to test protocols in one loss model only, without trying to confirm the results or the conclusions in another one. The absence of cross-model evaluations makes it difficult to generalize results, and may lead to protocol designs that perform well under specific assumptions to fail in other conditions. A comparison using several packet loss models is therefore essential.

This article aims to address this gap by comparing two commonly used loss models: UDG model and the shadowing model. The chosen use case is flooding protocols in wireless dense networks. Our findings show that the two models produce similar results in scenarios where the transmitted data is successfully received by the entire network. However, differences emerge in cases where parts of the network fail to receive the transmitted data.

The main contribution of this article is to deepen understanding of packet loss models used in simulation of network communication. It demonstrates that results produced by different loss models can differ, and explains the circumstances and reasons behind these differences. This understanding helps in selecting the most appropriate models when evaluating network protocols.

The article is organised as follows. Next section gives necessary background for flooding protocols and packet loss models to better understand this article. Then Section III presents the test scenario and gives interpretation of the results obtained. Section IV is dedicated to the related work. The article ends with conclusions and perspectives.

II. Flooding Protocols and Packet Loss Models

A. Flooding protocols

This article focuses on three flooding-based routing protocols widely used in wireless network simulations.

In *pure flooding* [4], nodes retransmit (forward) each packet they receive for the first time. This leads to a poor performance in dense networks and broadcast storms.

In *probabilistic flooding* [4], nodes retransmit packets with a predetermined probability p, thus reducing the number of retransmissions. The value of p is crucial to reduce broadcast storms and to guarantee message delivery, and various methods have been proposed to automatically tune it.

In *backoff flooding* [5], each node counts the received copies of each packet, and uses a random waiting time (backoff) before trying to forward it. Only nodes that have not received r (a redundancy factor) copies of a packet during the backoff period forward the packet. The backoff is automatically tuned based on the node density. This protocol offers a configurable balance between reliability and transmission efficiency, making it well-suited to a comparative evaluation within this work.

B. Packet loss models

Wireless network simulators often rely on simplified models to represent communication between nodes. These models include network links (packet loss or network topology, bandwidth, delay etc.) and flows (source, destination, number of packets, time to send them etc.), among others. This article focuses on packet loss model, usually specified as a graph giving the topology, and compares two such models: unit disc graphs and shadowing. For more topology models the reader is referred to [6].

Unit disc graphs (UDG), also known as all-or-nothing and free-space path loss models, are mathematically defined and initially studied in [7]. Formally, a unit disc is defined as the set of points whose Euclidian distance to a center point is smaller or equal to 1, and a UDG is an intersection graph where each set is a unit disc. Two nodes can communicate each other directly if there is an edge between them in the graph, i.e. if their two sets intersect each other. As shown in Fig. 1,

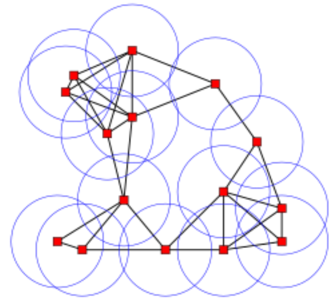

Fig. 1. Unit disc graph[1].

two nodes communicate if their sets, formed by unit discs, intersect, which in UDG is represented by an edge between them. In communication terms, a node can communicate with another iff the distance between them is less than or equal to the communication range (also called transmission radius). UDG model is very simple to formalise in mathematical analysis and to use in simulations, and as such it is commonly used to model the topology of ad hoc wireless communication networks. On the negative side, it does not consider obstacles, such as walls and buildings, weather conditions and various interferences which might obstruct signal propagation. From the point of view of a node, it does not matter where other nodes are located, neither their communications. UDG model is in 2D, and can be generalised to 3D to become USG (unit sphere graph).

Quasi-UDG is an extension of UDG aiming to increase its accuracy while keeping its simplicity. In the quasi-UDG model [8], nodes connect:

- always, if $d \leq r$
- never, if $d > R$
- yes or no (for ex. based on a probability), if $r < d \leq R$,

where r is the guaranteed connection range (minimum threshold), R the communication range (maximum possible transmission range), and the probability can depend on the distance between sender and receiver. This model does not consider interferences between nodes, neither obstacles, given that the probability applies to the whole ring, and not on the relative position of the two nodes. This model is called "shadowing" in NS-2[2].

The shadowing model [3] takes its name from a receiver being in the "shadow" of the sender, behind an obstacle. It tries to count the fact that the received signal power is strongly attenuated by obstacles on the propagation path between transmitter and receiver.

Simulators implement some form of these models.

For example, BitSimulator [9] blurs the border of the communication range, allowing random losses near the border, as shown in in Fig. 2. It uses the normal distribution, moved to the left 3*stddev (3 is chosen so that the probability

[1]Source: https://en.wikipedia.org/wiki/Unit_disk_graph.

[2]Shadowing model in the obsolete NS-2: https://www.isi.edu/websites/nsnam/ns/doc/node219.html (accessed June 27, 2025).

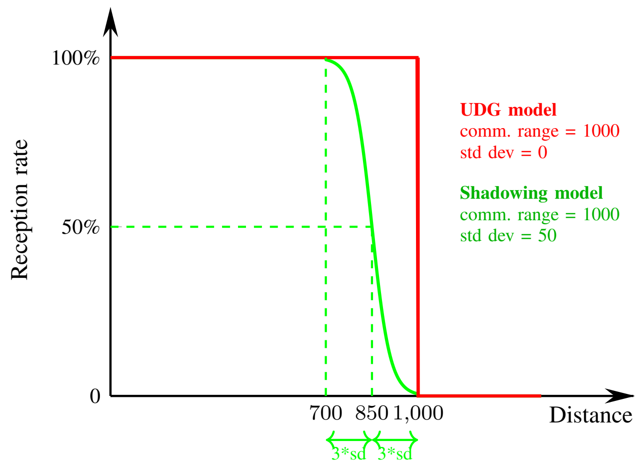

Fig. 2. Shadowing model in BitSimulator, where all packets are received up to some distance (700), no packet received beyond communication range (1000), and a decreasing probability of reception between the two thresholds (700..1000).

beyond the communication range be very small, 0.5%), and is cut (changes sharply) before commrange–6*stddev (i.e. all packets are received for a distance less than this value, which represents 0.5% of them) and beyond communication range (i.e. no packet is received by nodes at distance greater than or equal to the communication range, which represents 0.5% of them).

The well-known NS-3 simulator provides several propagation loss models. One of them considers obstacles and is found in the Building module[3]. It uses a log-normal distribution with a variable standard deviation, which depends on the relative position (indoor or outdoor) of the *MobilityModel* instances involved. A single random value is drawn for each pair of *MobilityModel* instances and remains constant for that pair throughout the entire simulation. Therefore, this model is suitable only for static nodes. It defines three cases for the standard deviation of shadowing loss, each following a normal distribution with zero mean and a specified variance:

- outdoor: $X_O \sim \mathcal{N}(\mu_O, \sigma_O^2)$, with $\mu_O = 0$ and $\sigma_O =$ `m_shadowingSigmaOutdoor` (default: 7 dB).
- indoor: $X_I \sim \mathcal{N}(\mu_I, \sigma_I^2)$, with $\mu_I = 0$ and $\sigma_I =$ `m_shadowingSigmaIndoor` (default: 10 dB).
- external wall penetration: $X_W \sim \mathcal{N}(\mu_W, \sigma_W^2)$, with $\mu_W = 0$ and v$\sigma_W =$ `m_shadowingSigmaExtWalls` (default: 5 dB).

NS-3 also provides specific loss models, such as models for vehicular environments (vehicular propagation loss model, and vehicular fast fading model etc.)

There are differences in the two aforementioned implementations. NS-3 models signal attenuation due to obstacles in the main path (i.e., vegetation, buildings, etc.), affecting the received signal strength (in dB), which can then specify whether a packet is successfully received or not. In contrast, BitSimulator uses a statistical model that applies a probability of packet loss near the edge of the communication range. Additionally, in NS-3, the received signal strength, or equivalently, the connectivity graph is static, since obstacles are assumed to be stationary. As a result, a node either always receives or never receives packets from the same source throughout the entire simulation. BitSimulator, on the other hand, introduces temporal and spatial variation in packet losses, ensuring that the same node does not consistently receive or miss packets. This adds realism by mimicking the dynamic nature of real wireless environments.[4].

III. Loss Models Comparison

This section compares two packet loss models: UDG and shadowing. As specified in the Introduction, protocol evaluation in dense networks can be done through simulations. Therefore, we first introduce the simulator used, afterwards we present the scenarios tested, the results, and provide explanations and findings.

A. Simulator used

BitSimulator [9] differs from other network simulators as it is dedicated to nanonetworks simulations. By targeting only one type of network, its design is simplified with very little overhead (as compared to general purpose NS-3 for example). Due to fine memory management and clever optimizations, simulations of tens of thousands of nodes are possible on a laptop, and it is the only scalable nanonetwork simulator [10]. BitSimulator targets routing and transport protocols, and pay attention to some low-level bit transmission peculiarities, such as transmission time and bit-dependent collision at the receiver. It uses TS-OOK (Time-Spread On-Off Keying) modulation [11]. It supports two types of topologies: UDG and quasi-UDG, the latter of which we will refer to as *shadowing* in the remainder of this article. It also provides a visualization tool, *VisualTracer*, which is particularly useful for observing communications in a visual manner. BitSimulator is a free software and has been used to validate the results presented in several research articles[5]. Therefore, it is used for the evaluation part in this section.

B. Scenarios tested

The network is a 2D rectangular strip, and nodes are placed randomly in it using a uniform distribution. Node antennas are omnidirectional.

To get a more accurate comparison between the two loss models, we test multiple scenarios. These scenarios change key parameters, specifically, the network area size, the number of nodes, and the communication range. To desynchronize node forwarding in dense networks and to reduce packet collisions, nodes choose a random backoff (waiting time) before forwarding a packet. We execute each scenario 50 times, each with a different seed of the random number generator (RNG) used to

[3] https://www.nsnam.org/docs/models/ns-3-model-library.pdf, section 8.1.5 (accessed June 27, 2025).

[4] User's and developer's manual of BitSimulator: https://dedu.fr/bitsimulator/manual.pdf (accessed June 27, 2025).

[5] BitSimulator's Web page: https://dedu.fr/bitsimulator.

TABLE I
SCENARIO PARAMETERS.

Parameter	**Value**
Network area	36 to 144 mm^2
Number of nodes	1000 to 2500
Communication range	0.1 to 1 mm
Probability p in probabilistic flooding	0.2 to 0.8
RNG seed	1 to 50

get the backoff. Tab. I shows the variation of the parameters used.

The number of scenarios tested can be computed as follows. We test 4 different values for the network area, 7 values for the number of nodes, 10 values for the communication range, 50 values for the RNG seed, and 3 routing protocols (with 7 values of the probability p in probabilistic flooding), which give a total of 4 * 7 * 10 * 50 * 9 = 126 000 simulations.

The simulation begins with a source node flooding the network with a single packet of 80 bytes. The standard deviation used in shadowing model is 5 µm, which, according to Fig. 2, means that the ring where packet loss can occur has width $2 * 3 * \text{sd} = 2 * 3 * 5 = 30\,\mu\text{m}$ (compared to a communication range between 100 to 1000 µm, cf. Tab. I). The metric considered is the number of nodes receiving at least one copy of the packet.

We provide a Web page[6] with the code allowing to reproduce all the results of this article.

C. Results

For each scenario, the results are averaged over 50 seeds and are expressed as percentages of nodes that successfully received the packet sent by the source, compared to the total number of nodes. The results are presented with a confidence interval of 95%.

In the following, we present results for each of the three flooding algorithms. To explain these results, we consider the following hypothetical scenario. Suppose eight nodes A, B, C, and D (group 1) and nodes E, F, G, and H (group 2) are receiving the same packet. These nodes are close each other and can communicate directly under both models. A ninth node R is in the communication range of all these nodes; however, in the shadowing model it will not receive packets from nodes in group 1.

For pure flooding, the percentage of nodes receiving the packet is the same for both models (UDG and shadowing), i.e. close to 100%, as shown in Fig. 3. To explain this result, we first recall that in pure flooding all nodes that receive a packet retransmit it. Thus, in the hypothetical example, all the nodes of groups 1 and 2 have received the packet and will retransmit it. Whereas in the UDG model R will receive the same packet from all the nodes of groups 1 and 2, in the shadowing model R will not receive any packet from group 1, but will successfully receive it from group 2. This is because each node that receives the packet independently

[6] https://dedu.fr/bitsimulator/wimob25

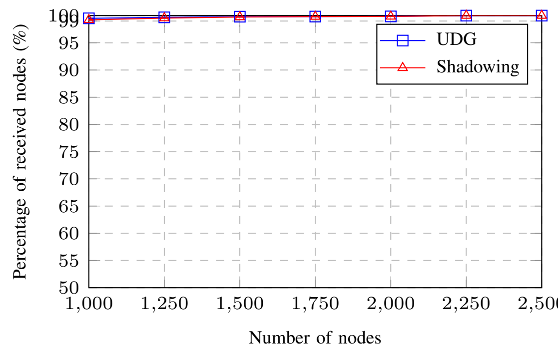

Fig. 3. UDG vs shadowing in pure flooding.

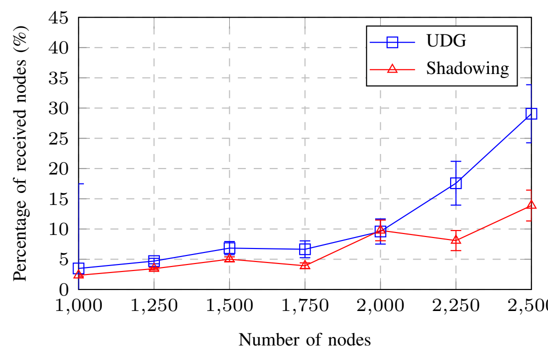

Fig. 4. UDG vs shadowing in probabilistic flooding with $p = 0.2$.

attempts to retransmit it. Hence, R eventually receives the packet. Generalising it, all the nodes in UDG and shadowing receive the packet.

In contrast, for probabilistic flooding and backoff flooding, the reception percentage varies between the two models.

For probabilistic flooding, Fig. 4, 5, 6, and 7 (for retransmission probabilities p equal to 0.2, 0.4, 0.6, and respectively 0.8) show that up to some threshold (e.g. 1250 nodes for Fig. 6), the percentage of received nodes is higher in UDG than in shadowing. However, as the number of nodes increases, the percentages become similar. To explain this result, we recall that each node retransmits the received packet with a given probability p. In the hypothetical example, if only a subset of group 1 nodes is selected to retransmit, while none from group 2 are, the packet is propagated only by group 1. Whereas in UDG R will receive the packet from the transmitting nodes of group 1, in shadowing R will not receive the packet. However, as the probability increases, the results get similar because it is less likely to have nodes from group 1 transmitting the packet and nodes from group 2 not transmitting the same packet.

For backoff flooding (UDG vs shadowing), Fig. 8 clearly shows that for less than 1250 nodes (like in probabilistic flooding), the percentage of nodes receiving the packet is higher in UDG than in shadowing. However, this difference diminishes as the number of nodes increases. To explain this result, we first recall that in backoff flooding, each node waits

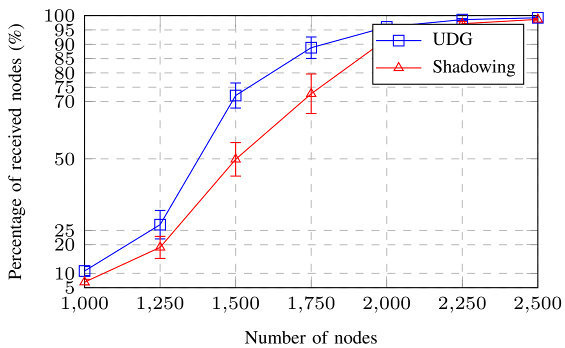

Fig. 5. UDG vs shadowing in probabilistic flooding $p = 0.4$.

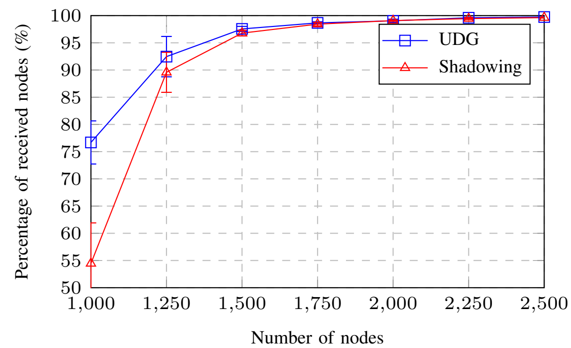

Fig. 8. UDG vs shadowing in backoff flooding.

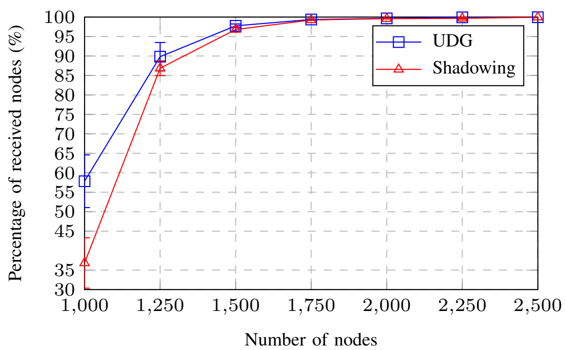

Fig. 6. UDG vs shadowing in probabilistic flooding $p = 0.6$.

for a random backoff period before retransmitting the received packet. In the hypothetical example, suppose a node from group 1 has the smallest backoff and therefore retransmits the packet first. All the other nodes, including those from group 2, receive it and cancel their own retransmissions. While in the UDG model R will receive the packet from the transmitting node of group 1, in the shadowing model R will not receive the packet (cf. the description of the hypothetical example).

We also found that the same pattern persists across other scenarios, when varying parameters such as the network area and communication range, as described at the beginning of this section.

In conclusion, pure flooding produces similar results under both packet loss models (UDG and shadowing), while probabilistic flooding and backoff flooding show significant differences in the number of receiving nodes.

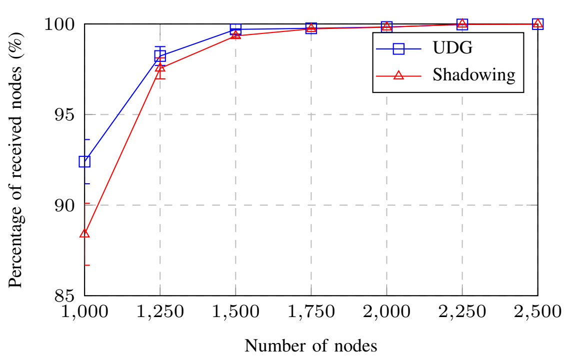

Fig. 7. UDG vs shadowing in probabilistic flooding $p = 0.8$.

IV. Related work

It is a common practice for simulation of network protocols to use the ideal UDG packet loss model, given its simplicity in implementation and analysis. However, some studies note the limits of UDG and turn to other models.

Among the numerous studies using quasi-UDG model we can cite [12], which considers quasi-UDG for node localisation using hop count because UDG is “unrealistic in a practical scenario”, and [13], for which ”quasi-UDG captures much better the characteristics of wireless networks” than UDG in the analysis of two of its properties, namely separability and the existence of power efficient spanners.

Some studies test their method in both UDG and quasi-UDG models, for instance [14] presents a boundary detection algorithm to recognise wireless sensor networks boundaries which works in both models, and [15] concludes that both models give the same quality of the solution to local algorithms, despite localisation errors occurring in quasi-UDG.

Instead of UDG-based model, some studies turn to shadowing models, such as [16], which considers that UDG is ideal and unrealistic, and uses a more realistic log-normal shadowing model to detect isolated nodes in a wireless network.

Some studies compare several models. For instance, [17] compares three line of sight probability models in shadowing for network performance and design. [18] studies the worst-case per node capacity of wireless sensor networks with n nodes: in an SINR-based physical model the sustainable rate is $O(\log^2 n)$, whereas in the so called protocol model (a variant of UDG) it is only $O(1/n)$; such an exponentially large gap clearly demonstrates the importance of the model in some cases. [6] compares theoretically graph-based models (“computer science” view) to SINR physical models (“electrical engineering” view) of wireless network topologies, and tries to find connections between them; in contrast, our work compares two forms of graph models: UDG and shadowing, and presents results of simulation of the two models compared.

In conclusion, all the aforementioned articles have different objectives from ours: they either focus on a single loss model or compare models that differ from the ones examined in this study.

V. Conclusions and perspectives

In this paper, we studied the impact of two packet loss models, UDG and shadowing, in the context of flooding protocols in dense wireless networks. The obtained results show that for a basic flooding protocol and due to the high redundancy in dense topologies, the UDG model ensures comparable results to the shadowing one. However, for other scenarios like probabilistic flooding and backoff-based flooding, the shadowing model provides more realistic results. Therefore, it is important to select appropriate propagation models in simulations. For instance, if we only use the UDG model, we might get results that are too positive. In future work, our aim is to study communication patterns that are more affected by lost messages, like request-response protocols. This will help the researchers to improve the accuracy and generalizability of simulations in dense wireless networks.

VI. Acknowledgements

This research is supported by the EIPHI Graduate School (contract ”ANR-17-EURE-0002”).

References

[1] Y. Myroshnyk *et al.*, “State of IoT summer 2024,” IoT Analytics, Germany, Tech. Rep., Aug. 2024.

[2] F. Lemic, S. Abadal, W. Tavernier, P. Stroobant *et al.*, “Survey on terahertz nanocommunication and networking: A top-down perspective,” *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 6, pp. 1506–1543, Apr. 2021.

[3] A. Goldsmith, *Wireless Communications*, 2nd ed. Draft, not yet published, 2020.

[4] D. G. Reina, S. Toral, P. Johnson, and F. Barrero, “A survey on probabilistic broadcast schemes for wireless ad hoc networks,” *Ad Hoc Networks*, vol. 25, pp. 263–292, Feb. 2015.

[5] T. Arrabal, D. Dhoutaut, and E. Dedu, “Efficient multi-hop broadcasting in dense nanonetworks,” in *17th IEEE International Symposium on Network Computing and Applications (NCA)*. Cambridge, MA, USA: IEEE, Nov. 2018, pp. 385–393.

[6] A. Faragó and S. Basagni, “Connecting two worlds: Physical models and graph models of wireless network topologies,” in *2011 IEEE International Conference on High Performance Computing and Communications (HPCC)*, Banff, Canada, Sep. 2011, pp. 739–744.

[7] B. N. Clark, C. J. Colbourn, and D. S. Johnson, “Unit disk graphs,” *Discrete Mathematics*, vol. 86, no. 1-3, pp. 165–177, Dec. 1990.

[8] F. Kuhn, R. Wattenhofer, and A. Zollinger, “Ad-hoc networks beyond unit disk graphs,” in *2003 Joint Workshop on Foundations of Mobile Computing*, San Diego, CA, USA, Sep. 2003, pp. 69–78.

[9] D. Dhoutaut, T. Arrabal, and E. Dedu, “BitSimulator, an electromagnetic nanonetworks simulator,” in *5th ACM/IEEE International Conference on Nanoscale Computing and Communication (NanoCom)*. Reykjavik, Iceland: ACM/IEEE, Sep. 2018, pp. 1–6.

[10] E. Sahin, O. Dagdeviren, and M. A. Akkas, “An evaluation of internet of nano-things simulators,” in *6th International Conference on Computer Science and Engineering (UBMK)*, Ankara, Turkey, Sep. 2021, pp. 670–675.

[11] J. M. Jornet and I. F. Akyildiz, “Femtosecond-long pulse-based modulation for terahertz band communication in nanonetworks,” *IEEE Transactions on Communications*, vol. 62, no. 5, pp. 1742–1753, May 2014.

[12] D. Gao, P. Chen, C. H. Foh, and Y. Niu, “Hop-distance relationship analysis with quasi-udg model for node localization in wireless sensor networks,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2011, pp. 1–11, 2011.

[13] J. Chen, A. Jiang, I. A. Kanj, G. Xia, and F. Zhang, “Separability and topology control of quasi unit disk graphs,” *Wireless Networks*, vol. 17, pp. 53–67, 2011.

[14] B. Huang, W. Wu, G. Gao, and T. Zhang, “Recognizing boundaries in wireless sensor networks based on local connectivity information,” *(SAGE) International Journal of Distributed Sensor Networks*, vol. 10, no. 7, p. 897039, 2014.

[15] M. Hassinen, J. Kaasinen, E. Kranakis, V. Polishchuk, J. Suomela, and A. Wiese, “Analysing local algorithms in location-aware quasi-unit-disk graphs,” *Discrete applied mathematics*, vol. 159, no. 15, pp. 1566–1580, 2011.

[16] L. Wang, P.-J. Wan, and W. Washington, “Connectivity of multihop wireless networks with log-normal shadowing,” *Wireless Networks*, vol. 21, no. 7, pp. 2279–2292, 2015.

[17] S. J. Seah, S. L. Jong, H. Y. Lam, and C. Y. Leow, “The study of shadowing effect for LTE and 5G networks in suburban environment,” *International Journal of Microwave and Wireless Technologies*, vol. 16, no. 2, pp. 339–347, 2024.

[18] T. Moscibroda, “The worst-case capacity of wireless sensor networks,” in *International Conference on Information Processing in Sensor Networks (IPSN)*, Cambridge, MA, USA, Apr. 2007, pp. 1–10.