Hindawi
Journal of Computer Networks and Communications
Volume 2022, Article ID 3027202, 9 pages
https://doi.org/10.1155/2022/3027202

Research Article

Investigation of Error Probability for Grid and Random Uniform Topologies in a Variable Noise Environment

Mahmoud Zaki Iskandarani

Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan

Correspondence should be addressed to Mahmoud Zaki Iskandarani; m.iskandarani@ammanu.edu.jo

Received 14 December 2021; Revised 16 May 2022; Accepted 14 June 2022; Published 30 June 2022

Academic Editor: Juraj Machaj

Investigation of the effect of topology on the communication efficiency of WSN nodes is carried out through simulation of 9 nodes in a 12 by 12 meters area. The obtained data and plots indicate that the grid topology is a more efficient and stable topology to use in comparison to the random uniform topology. The deduction is supported by probability of error as a function of error distribution values. Five different noise levels are used in the simulation (0dBm, −20 dBm, −40 dBm, −60 dBm, −80 dBm, and −100 dBm) with an output power of −10 dBm. The work shows that at −60 dBm redistribution of probability of error as a function of error values started to occur with higher level error values associated with the random uniform topology compared with the grid topology occurring at −60 dBm noise. The work also shows the relationship between received signal strength indicator (RSSI) and probability of error which decreases as RSSI increase in a similar manner as signal to noise ratio (SNR). Both RSSI and SNR are related through the mathematical model presented in the paper which is based on the path loss model. Common features between the error probability model and Gaussian interpolation function are also presented. A simplified 1-D design model is also presented to enable initial topology considerations. Criteria are also established to enable relating SNR, RSSI, topology, and WSN incremental position.

1. Introduction

WSNs have the ability to monitor the physical environment as well as collect and report data for a specific application. WSNs can improve the capabilities of a wide range of applications in which the location information is critical. Search and rescue operations, tracking, medical, environmental, biological, monitoring of people and devices, and industrial control are some examples of WSN applications. Improved location and sensor communications can be seen as a key factor for overall WSN efficient operation [1, 2].

WSNs are usually placed in a specific area to collect data from the environment. The general plan is that once deployed, the sensor nodes will be able to monitor the area for a long time without needing to be replaced or recharged. WSN nodes have a limited communication range and they are subject to interference, bandwidth limitation, and topological layouts constraints. These are all areas in which more development is required.

Routing protocols, which are vital in enabling effective data transfer with efficient energy consumption, are also an important for the WSN nodes' communication system. WSNs feature self- and dynamic topological qualities in response interference and mobility, in addition to scalability and adaptability. Data aggregation can help a proposed WSN architecture to relate to bandwidth and data processing. Aggregation of data might be centralized or dispersed. The most effective arrangement is distributed, which can be organized, unstructured, or a combination of the two. In addition to overall efficiency and strength, the WSN distributed architecture is more robust. As a result, WSN nodes have information delivery functionality and are susceptible to data collection and reception failures, as well as require a high SNR in order to provide quality of service (QoS).

The selection of the communication channel and medium has an effect on data transmission and the required communication algorithms which are also affected by WSN size and used topology. Additionally, it is critical to sustain a high connectivity level with the right nodes density level to enable good coverage and quality. This is important in order to avoid high errors using selected communication channels [3–7].

Recent advancements in technology have enabled the construction of compact, low-cost WSN sensor nodes that can interact across short distances. Routing, topology, coverage, energy, and localization are some of the mainly studied topics in WSNs. The topology of a wireless sensor network is critical in determining network dependability, which is determined by sensor coverage and network connectivity [8–10].

WSN nodes are easy to deploy in huge numbers over a large geographic area, which make them very important in many applications. The location of the sensor node must be determined in order to practically and efficiently extract the data from sensors. Current localization methods rely on pairwise distance measurements between nodes, which can be obtained indirectly using the received signal strength RSSI. RSSI is also used in several applications to determine when the amount of radio energy is below a certain threshold as a function of position in order to give to node a clear to send [11–14].

Localization is a major issue in WSN applications, and location estimation is required in many of them. The RSSI is a measure of received power: the greater the RSSI, the stronger the radio signal, implying a closer position to the target. The radio component normally reports the current RSSI value when a valid packet is received. In real-world installations, relating RSSI to distance and acquiring it is difficult. Signal intensity is affected by three processes: path loss, fading, and shadowing [15–20].

Because spatial distribution is so crucial for WSN in the field, a particular study of all spatially associated elements that affect wireless channel communication is required to enable effective and efficient data exchange with low energy consumption. In addition to topological arrangement, other elements that affect WSN node transmission include distance between communicating nodes and their alignment, channel characteristics and signal attenuation and fading, and presence of noise and other interfering signals, such elements are approximated using path loss and shadowing models. WSN topologies are linked to path loss parameters, and better designs can be achieved when values resulting from node communication are obtained using an appropriate path loss model, which also includes routing protocols and WSN nodes life time [21–26].

Energy consideration with temporal considerations in conjunction with the channel error for WSN nodes is discussed in depth and modeled using various techniques with emphasis on ultralow power techniques aimed at minimizing energy consumption, which is related to enabling WSNs to become truly autonomous [27]. In addition, important consideration for energy harvesting and depletion with attention to channel error occurrence is also studied and discussed, where it is stated that in low-load wireless sensor networks, the power consumption of the node consists of data transmission and state switching parameters. Also, algorithms and techniques are developed to overcome sources of transmission errors, such as slot conflict [28]. Other models concerning energy conservation in WSN and fast convergence associated with data rate reduction, thus reducing energy and probability of error are also considered by researchers, where fast convergence of the signal processing algorithms are proposed, improving the effective bit rate with promising results [29]. Thus, lower power consumption, and lower bit error, together with higher bit rates will contribute to a better quality of service provided using WSNs.

Quality of service (QoS) with cost consideration related to resources in WSN nodes connected to cloud with channel quality is also studied together with WSN connection to cloud and cloud computing and resource allocation. QoS is further discussed in terms of soft and hard resource allocation and in particular in relation to the internet of things (IoT), in order to obtain optimum performance with target resources and preservation of channel and data quality with minimum error values [30].

2. Background

Positioning and localization based on the received signal strength indicator (RSSI) is found to be an effective way to determine the location. A path loss model, which can be implemented by path loss exponent (PLE) in association with data location, can provide more accurate position estimations using RSSI [31–33].

Localization and distance estimation using RSSI is frequently used in outdoor localization computation. However, using RSSI for ranging and distance estimation is also a function of surroundings, environment, and weather. Researchers used adaptive techniques for outdoor WSNs to enhance range quality [34]. The work investigated effects of PLE approximation on RSSI-based measuring ranging quality under variable outdoor conditions. The approach showed slight improvement in terms of error reduction.

Other studies proposed the use of RSSI both in its instantaneous capacity as an indicator of repetitive patterns and as a long term accumulative measurement to enable optimization of power networks by modifying the communication channel settings, which showed that RSSI can be effectively used to optimize network characterisitics in a WSN [33].

Some work [35] concluded that RSSI of RF signals can be used as a practical technique for cost-effective distance estimation. However, the problem of shadowing in many environments, which results in attenuation, is an obstacle. The authors proposed the use of outlier detection methods to eliminate errors in distance estimates using simulation algorithms. The researchers proposed three different approaches:

(i) Majority rule approach with spatial correlation

(ii) Centroid-based outlier detection with simple clustering

(iii) Localization using mean shift clustering

Other works proposed a multibarycenter localizing algorithm based on RSSI to improve the accuracy of nodes in wireless sensor networks (WSNs) [36]. The algorithm employs iterative filtering in order to optimize the obtained RSSI values of the WSN under consideration. The authors stated that such algorithm improves positioning accuracy, which would reduce network errors as a consequence.

Researchers also described traditional RSSI-based sensor nodes as having low accuracy and high sensitivity to noise [37]. The research found that the iterative centroid algorithm is more effective than the traditional ones. The work achieved success in removing the RSSI-distance based error and associated transmission errors using the iterative approach.

A RSSI localization approach is also discussed in [38]. Both range-based and range-free techniques are presented, with the range-based approach correlated with time of arrival of signal between communicating WSN nodes. Trilateration and multilateration techniques for RSSI and localization are also discussed, with evidence of better performance using multilateration.

As communication networks become more complex and with the increased use of WSNs, analytical modeling increasingly requires the use of simulation to understand a proposed model. This is critical in order to prove the functionality and establish performance criteria of the deigned WSN. Simulation can cover both continuous and discrete simulation. This will assist in checking the deigned system against all parameters before actual implementation.

Due to many constraints, designing a real model can prove to be impractical; thus, mathematical analysis and modeling through simulation can be a more effective approach for application-related WSN design. This approach enables optimization before actual implementation in real location and real time. Researchers worked on simulations using net simulator-2, net simulator-3, OMNet++, and MATLAB [39].

In addition, work is carried out using Cell-Discrete-Event Systems Specification (DEVS), where space is portioned into cells and topology-related parameters such as energy consumption, and signal strength are analyzed [40].

In this work, analytical and simulation approaches are used in relation to the wireless communication theory to correlate topology, noise floor, and output power to the occurring level of error using a noncoherent frequency shift keying (NCFSK). Symmetric communication channels are used to exchange data in a uniformly arranged wireless sensor network (WSN). To achieve the goals of this research work, RSSI is considered in relation to distance and travelled routes for both grid and random uniform topologies. The data are used to compute probability of error for the two topologies under different noise floor values to assess the effect of topology on susceptibility of WSN nodes and subsequent variation in RSSI values, which affects error occurrence [36, 37, 41].

The work also presents general characterization of the probability of error mathematical expression, which is very important in determining the shape function of the occurring error and ways to counter that with careful design and nodes placement. All of this is supported by the 1-D simplified model and mathematical expression that simplifies simulation and initial design analysis. The presented simulation covers limited number of nodes, however, it is valid for larger number of nodes as mathematical expressions developed are scalable through the general presented model.

3. Methodology

The objective of this work is to simulate and compute percentage of errors as a function of error probability and RSSI distribution as a function of RSSI values for both grid and random uniform WSN topologies in order to assess channel quality in both of the considered 9 nodes topologies in a 12 by 12 meters area. This will enable generalization for larger number of nodes covering wider areas. Table 1 contains list of variables and their description. In addition, an important focus of this work is to produce a general, scalable mathematical model that enables initial WSN design in order to minimize deployment costs and facilitate modifications and error prediction.

Path loss affects the received signal strength (RSS) as a result of factors impacting multipath propagation (multipath fading). When a signal is transmitted, it is subjected to diffraction, reflection, scattering, absorption, multipath fading, and attenuation due to the environment and infrastructure. These parameters have a random effect on signal strength over distance, as characterized by a logarithmic function of normal distribution spread around a distance dependent parameter.

The presented work establishes general mathematical model with optimization capability by utilizing a comparative model to the Gaussian interpolation function relating communication error probability to RSSI, noise, and transmission rate. This comparison allows design optimization. Also, the work aims at reaching a simplified 1-D model that indirectly relates RSSI to incremental WSN node positioning through SNR. This approach is new and it does allow faster and better optimization of WSN models in relation to topology before actual implementation.

The received signal strength power (P_{RSS}) can be described by the received signal strength indicator (P_{RSSI}) as in equation (1).

$$P_{\mathrm{RSSI}} = P_{\mathrm{Output}} - PL(d). \tag{1}$$

Using the path loss model with noise consideration leads to equation (2).

$$\mathrm{SNR} = P_{\mathrm{RSSI}} - P_{\mathrm{Noise}}. \tag{2}$$

RSSI is affected by different factors including path length, signal symmetry, and radiation power.

The transmitted and received signals between WSN nodes is carried out using NCFSK with probability of error computed as in equation (3).

$$P_{\mathrm{error}} = \left(\frac{1}{2}\right)\exp\left(-\frac{\mathrm{SNR}}{2}\right). \tag{3}$$

Table 1: Nomenclature.

Symbols/ acronyms	Meaning
P_{RSSI}	Received signal strength power
P_{Output}	Transmitter output power
$\text{PL}(d)$	Path loss, which is a function of transmitter-receiver separation distance (d) in meters.
P_{Noise}	Noise floor power
SNR	Signal-to-noise-ratio
NFCSK	Noncoherent frequency shift keying
P_{error}	Probability of error
RSS	Received signal strength
RSSI	Received signal strength indicator
E_b	Energy per bit
N_o	Noise spectral density
B_{Noise}	Noise bandwidth
D_{Rate}	Transmission data rate
β	Reference threshold
λ	Weighing parameter
γ	Spread control parameter

To take transmission rate and noise into consideration, equation (3) becomes equation (4)

$$P_{\text{error}} = \left(\frac{1}{2}\right)\exp\left(-\left(\frac{\text{SNR}}{2}\right)\left(\frac{B_{\text{Noise}}}{D_{\text{Rate}}}\right)\right). \tag{4}$$

With SNR given using equation (2). By substituting equation (2) into equations (4) and (5) is obtained.

$$P_{\text{error}} = \left(\frac{1}{2}\right)\exp\left(-\left(\frac{P_{\text{RSSI}} - P_{\text{Noise}}}{2}\right)\left(\frac{B_{\text{Noise}}}{D_{\text{Rate}}}\right)\right). \tag{5}$$

Equation (5) can be simplified to obtain equation (6).

$$P_{\text{error}} = \left(\frac{1}{2}\right)\exp\left(-\left(\frac{P_{\text{RSSI}} - P_{\text{Noise}}}{2\delta}\right)\right), \tag{6}$$

where δ is given by equation (7).

$$\delta = \left(\frac{D_{\text{Rate}}}{B_{\text{Noise}}}\right). \tag{7}$$

Equation (6) has some common properties with the Gaussian interpolation function that has the form shown in equation (8).

$$y = \lambda * \exp\left(-\left(\frac{(\alpha - \beta)^2}{2\gamma}\right)\right). \tag{8}$$

Comparing equations (6) and (8), it is realized that P_{Noise} is a reference threshold value as the P_{RSSI} values change as a function of nodes location, topology, noise bandwidth, data rate, and output power. Thus, P_{error} is affected by the difference between P_{RSSI} and P_{Noise}. Also, the factor 0.5 reflects λ, and the spread of error and its probability is definitely affected by the ratio in equation (7), which is equivalent to γ.

Thus, equation (6) is important as it shows the effect of both P_{Noise} and the ratio between B_{Noise} and D_{Rate}, which affect efficient communication in WSN nodes depending on topology.

Equation (6) can be further simplified as in equation (9).

$$P_{\text{error}} = \left(\frac{1}{2}\right)\exp\left(-\left(\frac{\phi}{\varphi}\right)\right). \tag{9}$$

Thus, the ratio in equation (9) controls the probability of error and its main affecting factors (P_{RSSI}, P_{Noise}, δ, topology). However, it is essential to account for energy per bit (E_b) and for noise spectral density (N_o) in the form of ratio related to SNR and δ as in equation (10).

$$\text{SNR} = \left(\frac{E_b}{N_o}\right)\left(\frac{D_{\text{Rate}}}{B_{\text{Noise}}}\right). \tag{10}$$

The ratio E_b to N_o is used as an indicator of the network power efficiency. From equations (6), (10) and (11) is obtained.

$$P_{\text{error}} = \left(\frac{1}{2}\right)\exp\left(-\left(\frac{10^{((P_{\text{RSSI}} - P_{\text{Noise}})/10)}}{2\delta}\right)\right). \tag{11}$$

From equation (11), it is evident that when $P_{\text{RSSI}} \gg P_{\text{Noise}} \longrightarrow P_{\text{error}}$ approaches 0, and when $P_{\text{RSSI}} \ll P_{\text{Noise}} \longrightarrow P_{\text{error}}$ approaches 0.5. When $P_{\text{RSSI}} = P_{\text{Noise}} \longrightarrow P_{\text{error}}$ approaches 0.25.

Considering equations (9) and (11) again, equation (12) is obtained.

$$P_{\text{error}} = \left(\frac{1}{2}\right)\exp\left(-\left(\frac{10^{(\phi/10)}}{\varphi}\right)\right). \tag{12}$$

Equation (12) can be modeled as in equation (13).

$$P_{\text{error}} = \left(\frac{1}{2}\right)\exp\left(-\left(\frac{\psi}{\varphi}\right)\right). \tag{13}$$

Thus, the new ratio in equation (13) determines the probability of error.

4. Results and Discussion

Figures 1–6 present percentage of errors as a function P_{error}. From the figures, the following observation is evident:

At high noise levels relative to output power level (0 dBm, −20 dBm, −40 dBm)

Both grid and random uniform topologies display high error values with 100% of the errors distributed in the interval [0.4-0.5]

As noise levels reaches −60 dBm, a redistribution of P_{error} values such that the grid topology occupies lower levels with the random uniform higher levels

Continue to reduce noise levels (P_{Noise}) to −80 dBm results in all P_{error} values for grid topology occupying the lower spectrum part with most of the random uniform occupying the higher part of the spectrum

When reaching −100 dBm, all P_{error} values for both grid and random uniform topologies occupy the lower part of the error spectrum

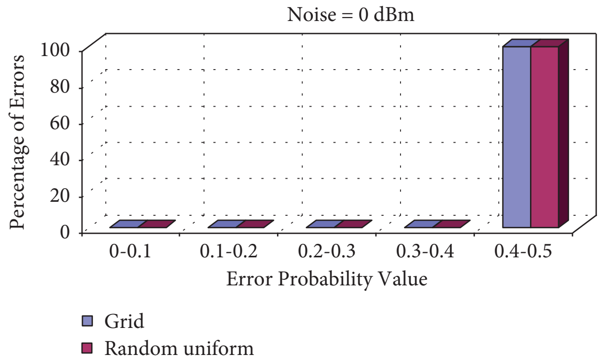

Figure 1: Percentage distribution of errors as a function of topology and noise level.

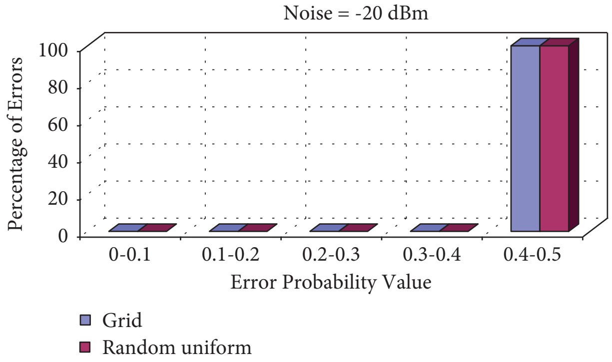

Figure 2: Percentage distribution of errors as a function of topology and noise level.

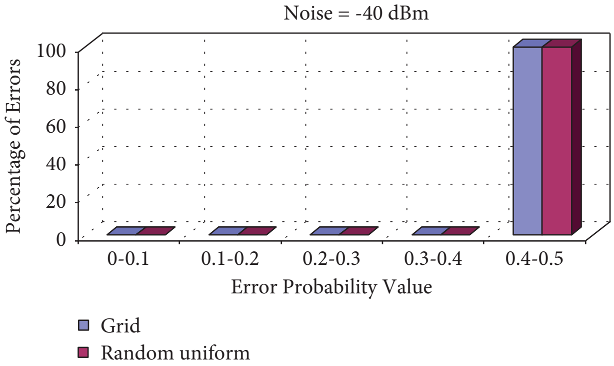

Figure 3: Percentage distribution of errors as a function of topology and noise level.

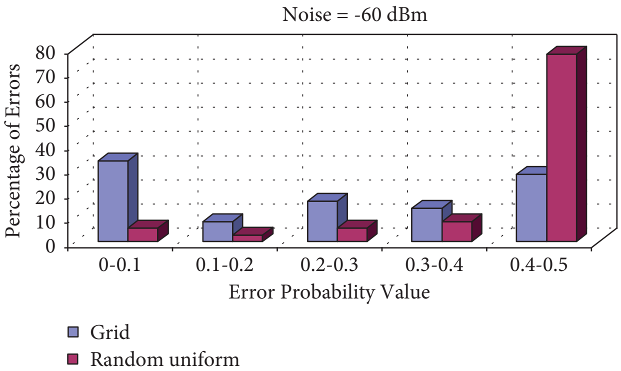

Figure 4: Percentage distribution of errors as a function of topology and noise level.

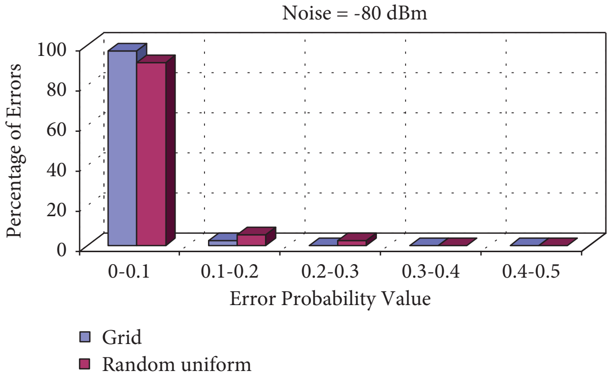

Figure 5: Percentage distribution of errors as a function of topology and noise level.

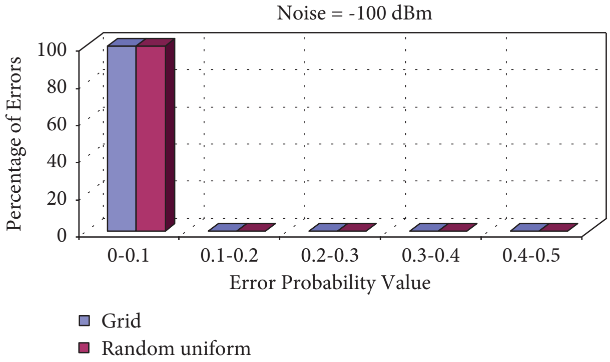

Figure 6: Percentage distribution of errors as a function of topology and noise level.

This is reflected in the RSSI behavior presented in Figures 7 to 12. From the Figures, it is evident that RSSI for grid topology is higher than those for random uniform, hence lower P_{error}, which indicates a more efficient channel communication and more stable WSN network.

As the process of error reduction and redistribution starts, it reaches a threshold value at which the RSSI improves dramatically. Figures 13–16 show both SNR and RSSI as a function of both topology and probability of error at a threshold value of $P_{\text{Noise}} = -60$ dBm, with Table 2 showing the simulated P_{error} as a function of SNR. From the plots, it is evident that as the RSSI increase, so does SNR and P_{error} starts to approach 0.

This is consistent with equations (6) and (11). Figures 17 and 18 show the WSN nodes and communication path followed for both grid and random uniform topologies as a function of RSSI plotted at −60 dBm noise and −10 dBm output power (P_{Output}). It is clear from the plots that the grid topology enables more efficient WSN communication and data transmission between nodes as it provides a regular

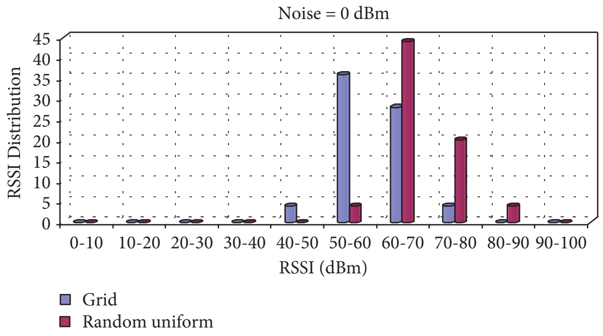

FIGURE 7: RSSI distribution as a function of topology and noise level.

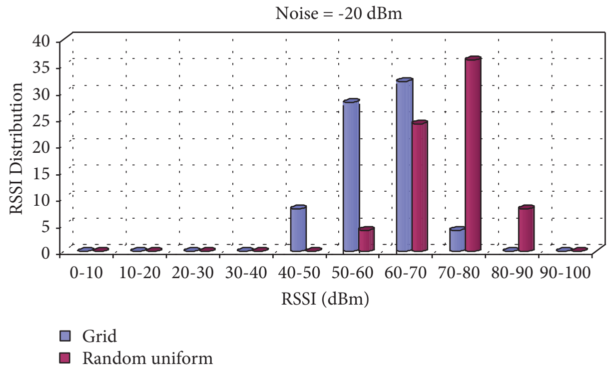

FIGURE 8: RSSI distribution as a function of topology and noise level.

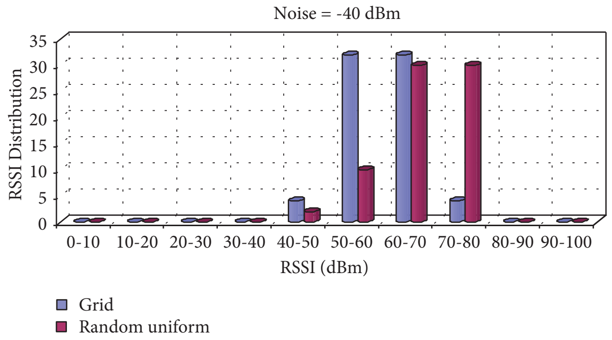

FIGURE 9: RSSI distribution as a function of topology and noise level.

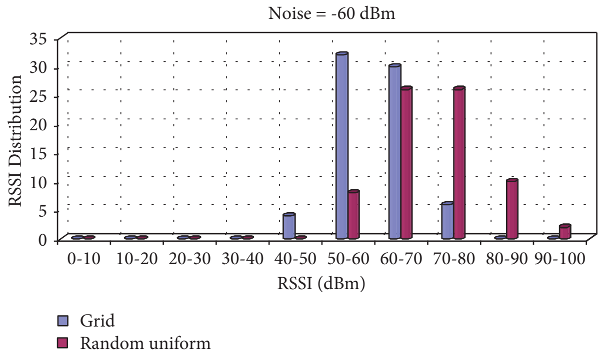

FIGURE 10: RSSI distribution as a function of topology and noise level.

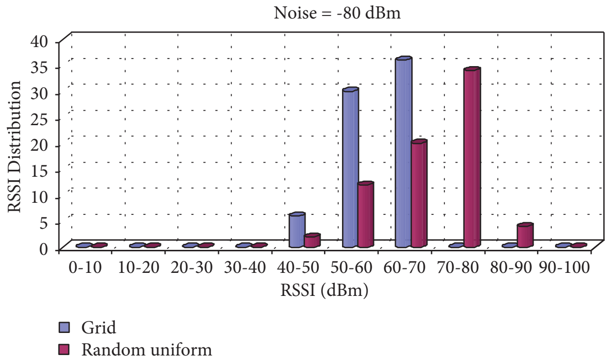

FIGURE 11: RSSI distribution as a function of topology and noise level.

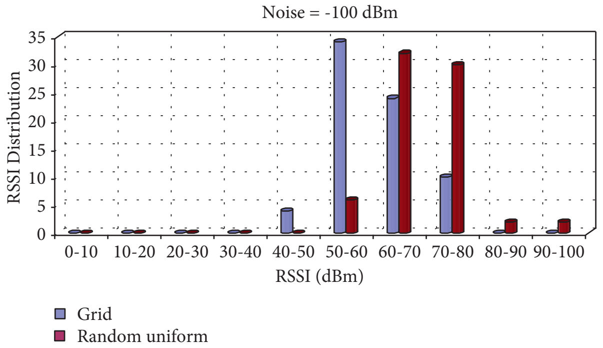

FIGURE 12: RSSI distribution as a function of topology and noise level.

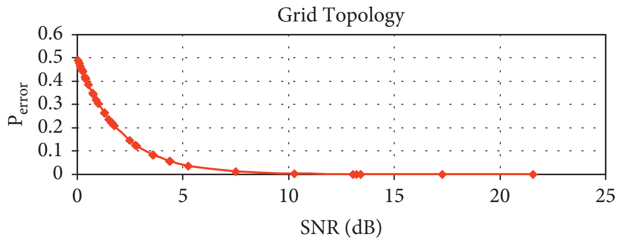

FIGURE 13: SNR as a function of topology and probability of error.

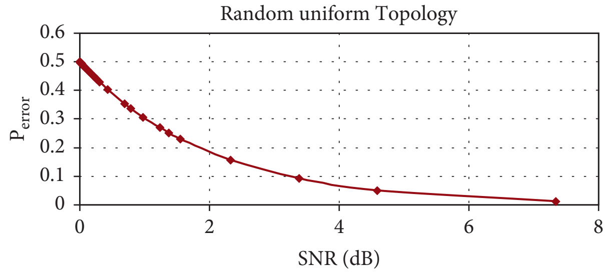

FIGURE 14: SNR as a function of topology and probability of error.

architecture where routing can take different paths but with stable nodes structure.

Figure 19 shows a plot representing nodes position in relation to SNR. From the plot, it is evident that the performance and characterisitics of the grid topology can be

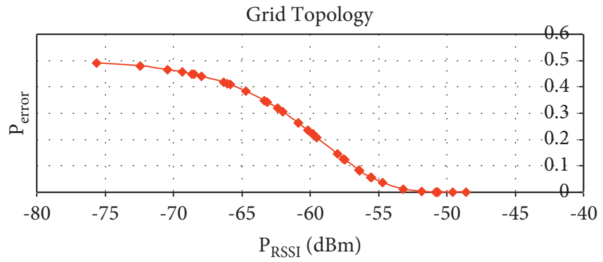

FIGURE 15: RSSI as a function of topology and probability of error.

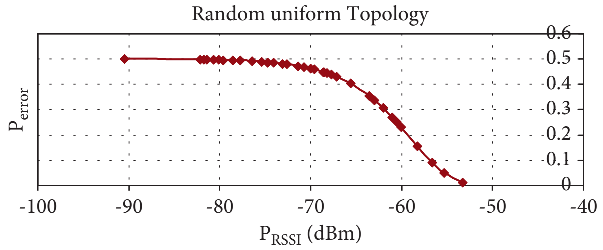

FIGURE 16: RSSI as a function of topology and probability of error.

TABLE 2: Comparison between topologies.

Grid		Random uniform	
SNR	P_{error}	SNR	P_{error}
21.58043	0.00001	7.33770	0.01275
17.27866	0.00009	4.58786	0.05043
13.41560	0.00061	3.38454	0.09205
13.20718	0.00068	2.32959	0.15599
13.02927	0.00074	1.55271	0.23004
10.26739	0.00295	1.36666	0.25247
7.50603	0.01172	1.23381	0.26981
5.26732	0.03591	0.97728	0.30673
4.38601	0.05579	0.78871	0.33706
4.35743	0.05659	0.68937	0.35422
3.61235	0.08214	0.42843	0.40359
3.55541	0.08451	0.30166	0.43000
2.81022	0.12267	0.26553	0.43783
2.74372	0.12682	0.23811	0.44388
2.47019	0.14540	0.21984	0.44795
1.75618	0.20779	0.21512	0.44901
1.63795	0.22044	0.17006	0.45924
1.63053	0.22126	0.15701	0.46225
1.49772	0.23645	0.13273	0.46789
1.28425	0.26309	0.11418	0.47225
1.27468	0.26435	0.08539	0.47910
0.98783	0.30512	0.07688	0.48114
0.89985	0.31884	0.06152	0.48485
0.75772	0.34232	0.05264	0.48701
0.72019	0.34880	0.05224	0.48711
0.53010	0.38358	0.04554	0.48874
0.40673	0.40799	0.03526	0.49126
0.38763	0.41190	0.02650	0.49342
0.36421	0.41676	0.02193	0.49455
0.25209	0.44079	0.01699	0.49577
0.22257	0.44734	0.01514	0.49623
0.21317	0.44945	0.01332	0.49668
0.18045	0.45686	0.01121	0.49720
0.14072	0.46603	0.01042	0.49740
0.08907	0.47822	0.00961	0.49760
0.04268	0.48944	0.00141	0.49965

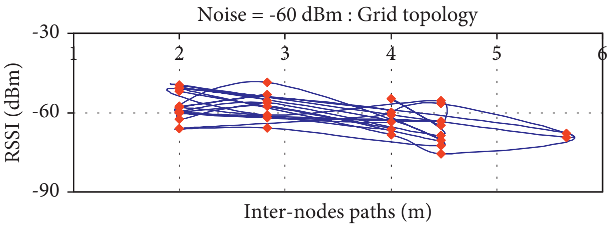

FIGURE 17: RSSI as a function of WSN nodes' communication.

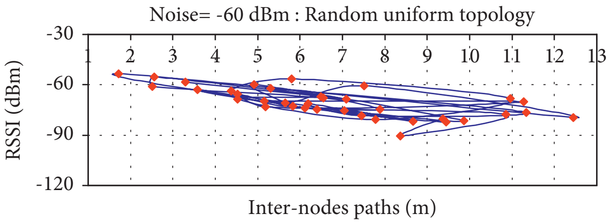

FIGURE 18: RSSI as a function of WSN nodes' communication.

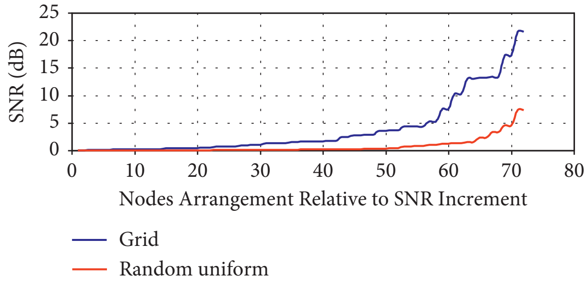

FIGURE 19: Grid versus random uniform as a function of node position.

distinguished from the ones of the random uniform topology. The plot also proves that grid topology is more efficient in WSN data transmission with lower error rates and better performance with lower P_{error}. This conforms with the previous plots and analysis that proved the grid to be a more efficient topology.

Further analysis of the plot in Figure 19 produces the approximation equation (14). The equation relates node position to SNR. The idea is to move from 2-D to 1-D in order to enable a more accurate and reliable comparison between two different topologies. This single dimension comparison (SDC) can be used as a metric for different topologies.

$$\mathrm{SNR}_{(\text{Topology})} = \omega \exp\left(\kappa \mathrm{Node}_{(\text{Incremental Position})}\right), \tag{14}$$

where ω and κ are topology specific coefficients with SNR dependency within the following criteria:

$$\begin{gathered} \frac{\kappa_{(\text{Random uniform})}}{\omega_{(\text{Random uniform})}} = 10, \\ \frac{\kappa_{(\text{Grid})}}{\omega_{(\text{Grid})}} = 1. \end{gathered} \tag{15}$$

We assume some obstacles that resulted in partial blocking and reflection, or refraction of signals in the WSN covered communication area. This will be equivalent to change in the incremental position of the placed nodes in the approximated mathematical model in equation (14), which is an indication of change in the RSS and RSSI pattern and affects error occurrence in data transmission over channel links. This will result in a modified 1-D expression, as in equation (16).

$$\mathrm{SNR}_{(\mathrm{Topology,Obstacles})} = \left((\varepsilon\omega)\exp\left(\kappa\Delta\left(\mathrm{Node}_{(\mathrm{Incremental\ position})}\right)\right)\right), \tag{16}$$

where ε is an obstruction coefficient that will result in lower SNR due to obstacles and signal reflection.

The expected result is for the grid topology parameters to become closer to the random uniform parameters as the affected signal will partially remove the difference in topology due to power loss and more marked effect for noise.

Thus, SNR comparison can be produced in the design and simulation stage, which enables better implementation in terms of topology selection, obstacles, signal reflection, and number and placement of nodes.

5. Conclusions

This work proved through simulation that the WSN nodes' structure actually affects WSN efficiency. The simulation over five different levels of noise, and resulting data showed that the grid topology is a more stable and efficient topology to use in comparison to random uniform topology. This is proved using the path loss model and localization through RSSI values coupled with probability of error and error distribution. The SNR values consolidated and supported such finding.

The research study also showed that there is a threshold value at which probability of error and error distribution starts to uniformly change in accordance to mathematical expressions presented in this work, which has similar distribution properties to the Gaussian interpolation function. The presented 1-D model allows for a simple approach to design optimization through correlation of RSSI, topology, SNR, and WSN nodes positioning and distance variation. This will greatly enhance localization and position estimation, which will affect WSN communication channel properties. Through better and more efficient node data transmission, better energy management for the WSN network can be achieved.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. The simulation part of this work was carried out using the MATLAB simulation program by the University of Southern California.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The author thanks the authors Marco Zuniga and Rahul Urgaonkar and Director Prof. Bhaskar Krishnamachari, Autonomous Networks Research Group, University of Southern California for their support.

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