Performance evaluation of low energy adaptive clustering hierarchy-based cluster routing protocols in wireless sensor networks using a new graphical user interface

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ABSTRACT

Wireless sensor network (WSN) is widely used for field data acquisition and monitoring in different domains. To make this type of network functional, efficient routing protocols must be implemented. Nevertheless, WSNs have an energy constraint due to limited batteries. Many clustered protocols are proposed to overcome it. However, the implementation of these protocols would be difficult to understand without a simulation tool, as some problems may arise during their development. Testing real-world applications requires a lot of effort and cost because they often use many nodes in large networks. Therefore, the simulation tool is the most relative way to evaluate these protocols. This paper presents graphical-based cluster protocols simulation interface for WSN (GCPS-WSN), a new interface to simulate some clustered protocols in WSNs. GCPS-WSN allows the user to evaluate the performance of certain low energy adaptive clustering hierarchy (LEACH) enhanced protocols to choose the most appropriate one for his system. The user can simulate protocols without any knowledge of software programming.

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1. INTRODUCTION

Nowadays, wireless sensor networks (WSNs) are extensively used to address the need for a reliable and secure networked system in diverse sectors, such as military, healthcare, environment, industrial applications, and even in the underwater sector [1]. The WSN is composed of many sensor nodes. Wireless communication and digital electronics enable the development of low-power, tiny sensor nodes [2], [3]. These sensor nodes are self-powered, self-organized devices with four units, including sensing (equipped with one or more sensors), processing, communication, and energy source (generally batteries). Sensor nodes in WSN must be functional for a long period of time in order to maintain data collection. However, the energy resources of the sensor nodes are constrained due to the limited power and the non-rechargeable and non-replaceable batteries [4].

Consequently, to extend the lifetime and optimize energy consumption of WSN, several routing protocols are developed and proposed in the literature [5]–[14] and, in particular, we have proposed three new cluster-based routing protocols [9], [12], [15]. The implementation of these routing protocols would be complicated to interpret without a simulation tool, as some problems may be encountered during their development.

Thus, validating and testing real-world applications implementing routing protocols requires a lot of effort, time, and cost because they often use a great number of nodes in such large networks [16]. Therefore, the simulation tool is the most relative way to evaluate and measure these routing protocols and the entire network. In addition, a graphical user interface (GUI) that presents the performance of the routing protocols and allows the user to interact effectively with the sensor network is becoming an essential element of the sensor network applications. In this context, there are many simulation tools available [17]–[20]. Nevertheless, these simulations are not very appealing to the non-expert users who are looking for a simple simulation tool or who do not have any knowledge of soft programming. Graphical interfaces facilitate the understanding of the routing workflow and allow us to learn how WSNs work and how their protocols work in reality [21], [22].

Therefore, this paper presents a new GUI, called graphical-based cluster protocols simulation interface for WSN (GCPS-WSN). The GCPS-WSN helps users and especially researchers to evaluate some clustered routing protocols based on many metrics. This GUI is based on the MATLAB tool. Furthermore, the proposed GCPS-WSN tool includes five clustered protocols, LEACH, LEACH-C, and our protocols balanced residual energy LEACH (BRE-LEACH), Improved-LEACH, and improved balanced residual energy LEACH (IBRE-LEACH). In addition, it provides a comparison between these protocols for every network configuration setting regarding stability, network lifetime, and energy consumption of the entire network. With this personalized interface and depending on the application where the routing protocol is to be implemented, the user can easily define the network configuration and choose the right routing protocol for his WSN application.

The remainder of this paper is structured as follows. Section 2 provides an overview of LEACH, LEACH-C, BRE-LEACH, improved-LEACH, and IBRE-LEACH. The proposed GCPS-WSN with its structure and areas included in this GUI are explained in section 3. Some examples of illustrative simulation using the GCPS-WSN tool are discussed in section 4. Section 5 describes the standalone application. Finally, section 6 concludes the paper.

2. OVERVIEW OF ROUTING PROTOCOLS IN WSN

Routing protocol is a technique for finding the right route for data to be sent from the source node to the base station (BS). They aim to achieve network scalability, enhance data transfer, and improve energy efficiency [23]. Clustering is an effective technique to balance energy in WSNs through data aggregation [24]. Clustering-based routing protocols are used in WSNs to realize energy efficiency as the clustering method reduces the number of packets routed in the network [25].

2.1. LEACH

LEACH [5] is a hierarchical routing protocol based on the clustering technique where nodes are grouped together to establish clusters. Hence, any cluster has a cluster-head (CH) to aggregate the data from the cluster members and send it to the BS. The objective of LEACH is to balance the energy in the network to improve the efficiency of WSNs by dividing the network into clusters, and by randomly rotating the CHs. The LEACH protocol consists of two phases in each round. In the first phase, each node decides independently of the other nodes to be a CH based on a randomly chosen value and a threshold function. Based on the received signal strength indicator (RSSI), each non-CH node joins its CH by selecting the closest one. When clusters are built, each CH assigns a time division multiple access (TDMA) schedule for its members. In the second phase, each non-CH node transmits its acquired data to its corresponding CH using a time slot in the TDMA schedule. After data fusion by the CHs, this data will be transmitted to the BS.

2.2. LEACH-C

LEACH-C was proposed by Heinzelman *et al.* in [13], it is one of the improved LEACH protocols. It is based on the clustering technique and consists of two phases as LEACH. However, LEACH-C is a centralized approach, where the BS selects CHs and forms clusters in the network depending on energy and node's location unlike the self-organization of nodes into clusters in LEACH. In the first step, each sensor node sends its location and remaining energy information to the BS. Thus, the BS chooses, based on this information, the nodes that will be the CHs in the network for each round. The second step is similar to the steady phase of LEACH.

2.3. BRE-LEACH

BRE-LEACH [9] is an improved LEACH approach. It enhances stability, network lifetime and optimizes energy consumption compared to LEACH. The BRE-LEACH approach consists of four phases. BRE-

LEACH enhances LEACH by selecting CHs based on residual energy to avoid quick depletion of CH energy, as CHs consume more energy than other nodes due to data aggregation and transmission to the BS. Subsequently, BRE-LEACH selects the CH with the most residual energy and the smallest distance to the BS as a root CH, which aggregates the data from other CHs and then sends it to the BS. Thus, the CHs use the multi-hop method to reach the root.

2.4. Improved-LEACH

McIntyre *et al.* [12] have proposed an improved LEACH-based clustering protocol, which aims to enhance the classical LEACH protocol by improving the network lifetime and optimizing energy consumption in the WSN. This protocol selects CHs in each round according to the residual energy. After clusters formation based on the RSSI, intra-cluster distance, and the maximum number of nodes in each cluster, certain nodes cannot join any cluster. This approach allows these nodes to send their data to the BS through a single hop. In addition, it suggests the multi-hop technique between CHs to opt for the optimal route to the BS or the single hop directly to the sink if that is the optimal route.

2.5. IBRE-LEACH

IBRE-LEACH [15] is a new and improved approach to LEACH and BRE-LEACH to select CHs, form clusters, and route data to the BS. It is designed to increase network stability, extend lifetime, minimize energy consumption, and enhance the number of packets arriving at the final receiver. After clusters formation based on residual energy, some nodes cannot be included in any cluster. These nodes are called abandoned nodes (ANs). When all nodes know their role, the IBRE-LEACH algorithm selects the CH or AN with the most energy and shortest distance to the BS as the root node. It aims to participate in routing. Thereafter, each CH/AN build its routing table based on the distance of all CHs, ANs, root, and BS. Each CH/AN use its routing table to determine the optimum route to the BS depending on conditions such as energy and distance factors.

3. GRAPHICAL-BASED CLUSTER PROTOCOLS SIMULATION INTERFACE FOR WSN

The GCPS-WSN tool could be precious for researchers working in the field of WSNs, and especially routing protocols, as it has many interesting properties. It facilitates understanding of the routing workflow and allows us to learn how WSNs work and how their protocols perform in reality. It is a user-machine interface that allows users to interact with a software program through different graphical objects (menus and buttons). Other objects (such as panels and tables) are used to format the graphical interface. It allows to control an application interactively from a menu, rather than launching commands and programs. It also allows presenting simulation results through graphic tools for a clear understanding.

The GCPS-WSN offers many features, such as i) providing a user-friendly interface that allows to define the desired network parameters according to the application and to choose the appropriate routing method; ii) allowing the user to evaluate the performance of several existing LEACH enhanced routing methods to choose the best one for its network; iii) presenting the architecture of each protocol and detailed graphical perception of what occurs in the network during the routing procedure; iv) comparing the performance of various protocols according to the configuration parameters; v) visualizing the distribution of nodes in the network, the number of alive, dead nodes and finally the total residual energy of the network.

Consequently, the proposed GCPS-WSN facilitates using clustered routing protocols in the WSN. It is characterized by rapid and easy access to parameters without touching programs. Even if the user has no knowledge of MATLAB, he/she can simulate these proposed clustered routing protocols and compare their performance according to different metrics. The user can easily define the network configuration and choose the right routing protocol for his WSN application. It can compare different clustered protocols based on several metrics, such as energy consumption, stability and network lifetime, and so forth. The GCPS-WSN interface supports five cluster routing protocols, including LEACH [5], LEACH-C [13], BRE-LEACH [9], Improved-LEACH [12], and IBRE-LEACH [15].

3.1. Proposed GCPS-WSN structure

Figure 1 displays the GCPS-WSN main screen interface. It consists of three principal fields: the routing method field, the comparison between LEACH and other methods, and the comparison of more protocols. The first area ‘routing protocol’ allows us to evaluate the performance of each clustered routing protocol separately according to the network configuration that will be entered later. The second area ‘Comparison to

LEACH' compares the performance of LEACH with another LEACH-based protocol among the four protocols (LEACH-C, BRE-LEACH, Improved-LEACH, and IBRE-LEACH). Finally, the third section 'Comparison of more protocols' concerns a comparison between several protocols, for example, a comparison between LEACH, BRE-LEACH, and IBRE-LEACH.

By clicking on the help button at the top right, a brief description of the GCPS-WSN application is displayed on the right. The "help documentation" button displays a pdf, with details of this application and its use. A click on the "close" button closes all open windows. Moreover, to know the interest of each button on our system, we pass the mouse over it and a comment is displayed. The GCPS-WSN interface allows the user to evaluate each routing protocol individually, then compare them to each other to find the best one for its application in the WSN, without going into the software details of each method.

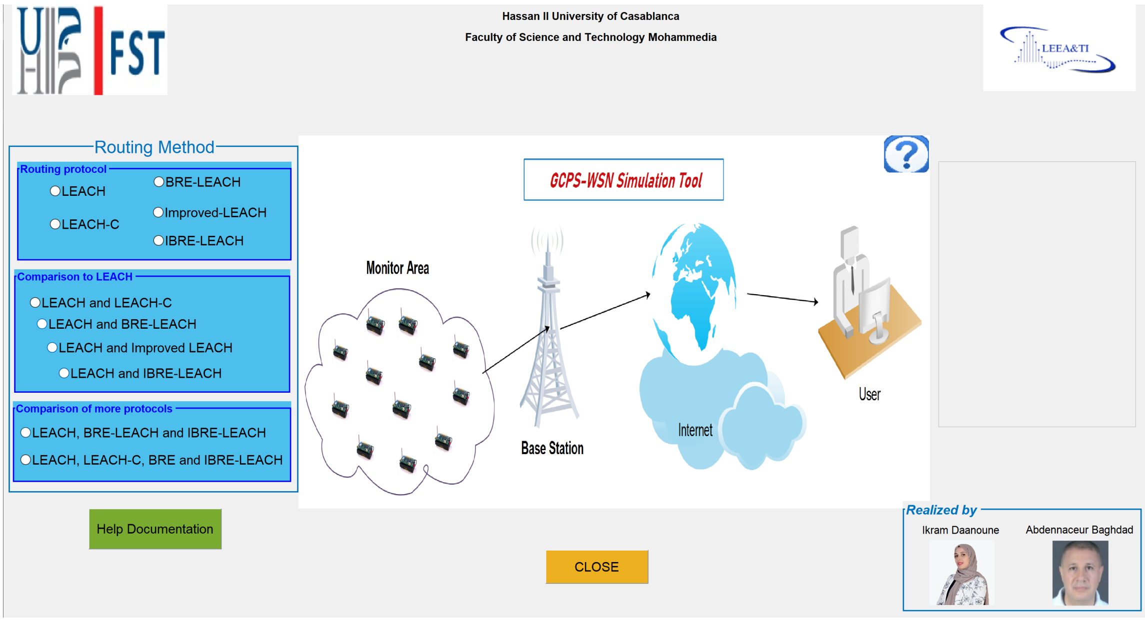

Figure 1. The main interface of GCPS-WSN

3.2. Network configuration

After selecting the desired protocol to be evaluated, a second interface is opened containing the protocol architecture in one field, the input parameters in a second field, which includes network configuration, the required energy for the devices, and clustering parameters. Then, the simulation buttons are presented in the third field. Let's take the example in Figure 2 if we select the BRE-LEACH protocol.

In the "input parameters" menu, new simulations can be carried out and the user can choose the desired parameters to run the simulations. In this menu, all input parameters are also chosen for the upcoming simulation. This menu consists of a network configuration area where all input data are entered, an energy area where the estimated energy consumption of each device and operation is specified, and a routing and clustering area that provides information on clustering and routing methods.

In this area, the user set information about his network, such as the number of nodes in the network, the monitoring area, the type of node deployment, and information about the BS, like its coordination and type. At this time, we only consider static BS and random deployment. In future work, we will consider other types. The initial energy, expressed in joule (J), shows the starting energy provided at the beginning of each node. Eelec indicates the energy dissipated in the electronic components for the transmitter and the receiver. Efs presents the energy dissipated in the amplifier for the free space (when the distance between the transmitter and the receiver is small). Emp indicates the energy dissipated in the amplifier for multi-path propagation. EDA exhibits the energy required for packet aggregation at the CH. The "routing and clustering" field includes information on the desired percentage of CH in the network, the length of each packet to be sent by each sensor node, and the simulation iterations.

In the “simulation” menu, the “clear” function is included to clean up the current simulation parameters and results. From here, the user can create a new configuration and update the existing one. The third option in this menu is “RETURN”, which allows returning to the main menu of the GCPS-WSN interface as shown in Figure 1. At any time, the user can stop the simulation execution and close all open windows by using the “close” option.

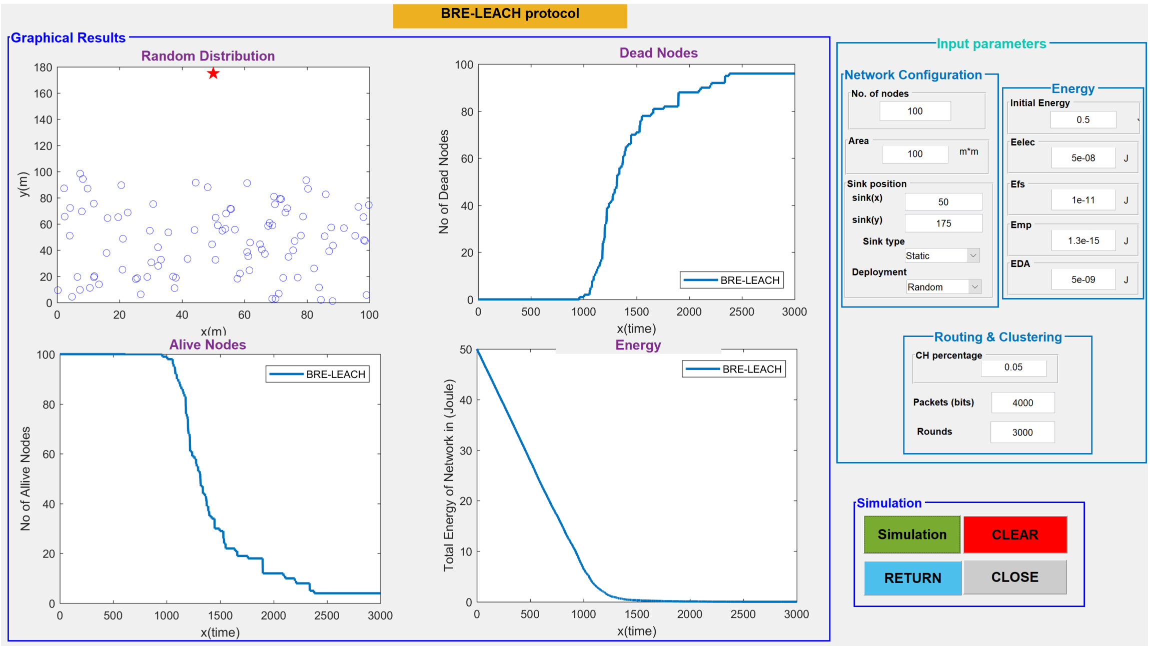

Figure 2. The BRE-LEACH protocol interface

By pushing the “simulation” button, described in Figure 2, the “graphical results” panel displays the simulation curves in terms of the distribution of nodes in the network, the curve of alive nodes, dead nodes, and the total residual energy in the entire network. As shown in Figure 2, the deployment of 100 random sensor nodes in the network in an area of $100 \times 100\ m^2$, with a static BS at coordinates (50,175) are presented in the upper left area of the graphical results field. The graph of dead nodes during the 3000 iterations is provided in the top right. Meanwhile, the curve of the alive nodes over 3000 rounds is given at the bottom left. Finally, the total residual energy of the entire network is shown in the lower right corner of the graphical results field. Considering that the percentage of CHs in the network is 5%, that the packet size to be transmitted is 4000 bits for each node, and that the initial energy of each node is considered to be 0.5 J. To illustrate more simulations using the GCPS-WSN interface, we do the same as BRE-LEACH to other routing protocols (LEACH, LEACH-C, Improved-LEACH, and IBRE-LEACH).

4. EXAMPLES OF ILLUSTRATIVE SIMULATIONS USING GCPS-WSN

From the GCPS-WSN interface, we can compare the performance of all the discussed cluster routing protocols with the original LEACH protocol. Figure 3 compares BRE-LEACH with LEACH according to setting parameters (see right side of the figure). The same applies to comparisons between the LEACH-C and LEACH, Improved-LEACH and LEACH, or between IBRE-LEACH and LEACH.

As the GCPS-WSN interface compares the performance of different protocols with the LEACH approach, it is also able to compare the performance of more protocols. Let’s take the example of the comparison between LEACH, LEACH-C, BRE-LEACH, and IBRE-LEACH. Figure 4 shows the distribution of nodes and a comparison between the mentioned protocols in terms of the number of dead nodes, the number of alive nodes in the network, and the total residual energy of the entire network.

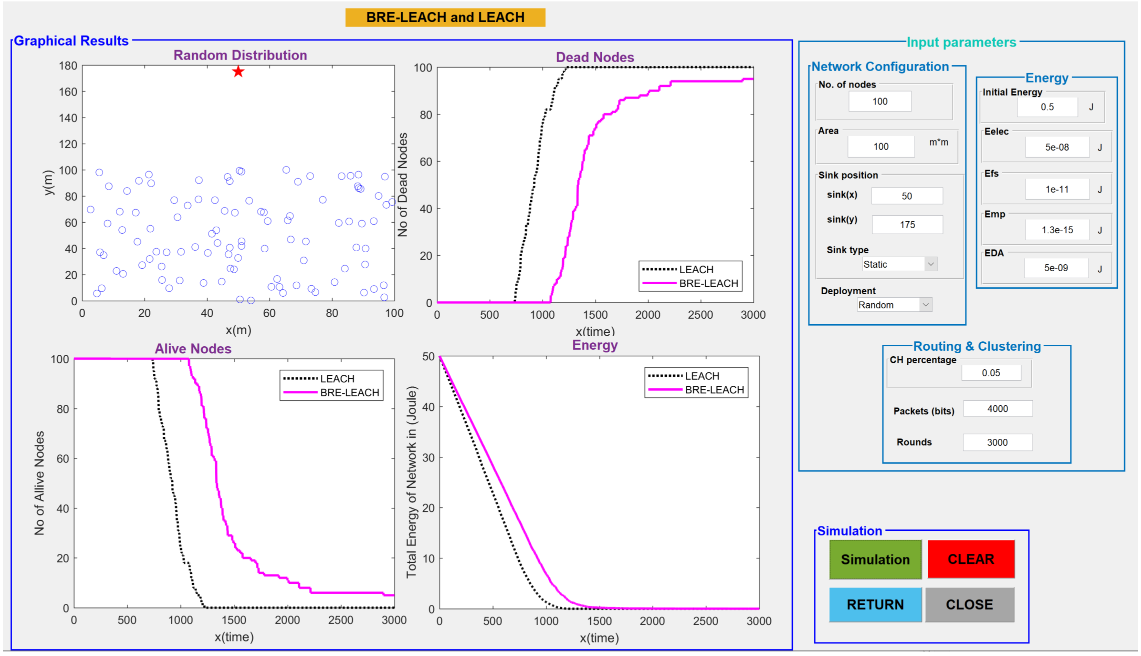

Figure 3. Comparison of BRE-LEACH with LEACH

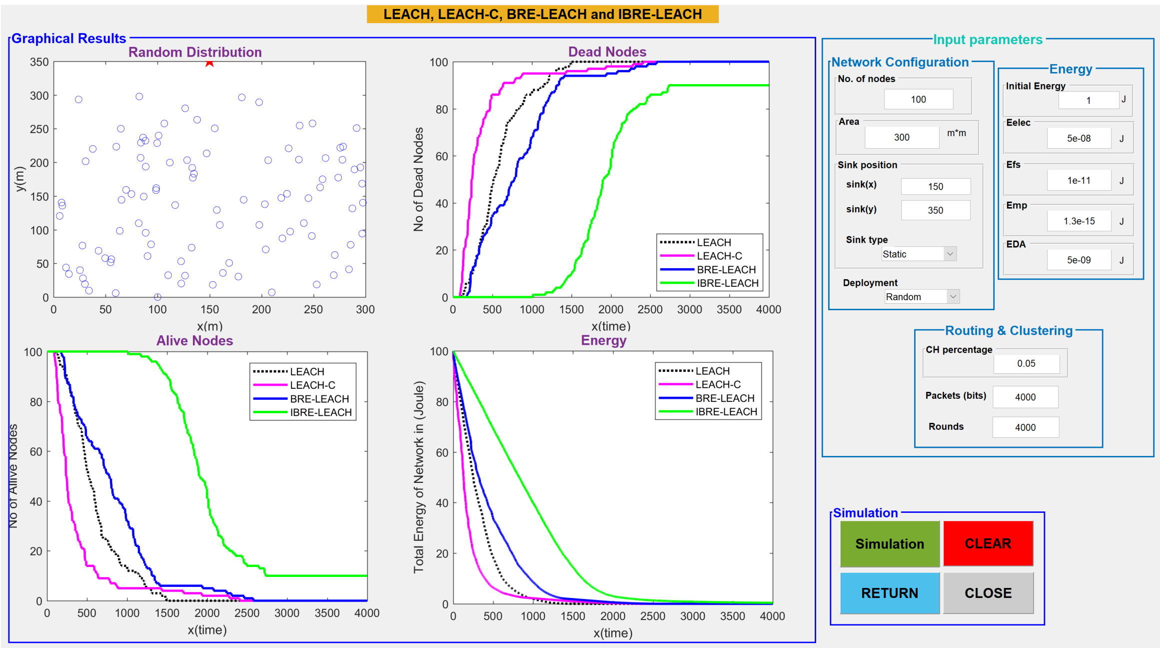

Figure 4. Performance comparison of LEACH, LEACH-C, BRE-LEACH, and IBRE-LEACH

5. STANDALONE APPLICATION

In order to render our GCPS-WSN GUI as an independent, executable application, we created a standalone application on MATLAB. In this context, GCPS-WSN was deployed and converted into an executable file (.exe). Our GCPS-WSN system can run successfully on computers with or without MATLAB software, thanks to the MATLAB compiler runtime (MCR). The MCR is a set of libraries for running MATLAB applications or components on computers where MATLAB is not installed. It is free to use and distribute and can be downloaded from the MathWorks website. After running the GCPS-WSN application (called GCPS

WSN.exe), our system's main interface is displayed as shown in Figure 1. All the other interfaces and options discussed in previous sections 3 and 4 remain at the same stage.

6. CONCLUSION

This paper provided GCPS-WSN, a new GUI tool to emulate and simulate some LEACH-based clustered routing protocols in static and homogeneous WSN. The GCPS-WSN provides many features, such as a simple interface to define the desired network parameters related to the application and to choose the appropriate routing method. Thus, it allows the user to evaluate the performance of some clustered routing protocols, including LEACH, LEACH-C, and our proposed protocols BRE-LEACH, Improved-LEACH, and IBRE-LEACH, and choose the one that best suits his system. GCPS-WSN describes the architecture of the mentioned protocols and gives a detailed graphical view of the network during the routing process. In addition, it is intended to compare the performance of these protocols based on the configuration parameters. The GCPS-WSN is used to visualize for each protocol the distribution of nodes in the network, the number of alive and dead nodes, and finally the total residual energy of the network. Furthermore, it compares the simulation results of different approaches for each network configuration considering different metrics. The proposed interface facilitates the use of our routing protocols in the WSN. It features quick and easy access to the parameters without touching the programs. Even if the user has no knowledge of MATLAB, he or she can simulate the proposed clustered routing protocols and compare their performance according to different metrics. In future work, we will include more flexibility in the support of protocols such as mobility and heterogeneity. In addition, we would like to extend the proposed GCPS-WSN to investigate other routing protocols and the possibility to integrate any protocol desired by the user. Moreover, other functionalities will be added to the GCPS-WSN, such as simulation registration, and color control of graphical results.

REFERENCES

[1] S. Souiki, S. M. H. Irid, and M. Hadjila, "An energy aware scheme for layered chain in underwater wireless sensor networks using genetic algorithm," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 5, pp. 4272–4280, 2021, doi: 10.11591/ijece.v11i5.pp4272-4280.

[2] M. A. Altaha, A. A. Alkadhmawee, and W. M. Lafta, "Uneven clustering and fuzzy logic based energy-efficient wireless sensor networks," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 25, no. 2, pp. 1011–1019, Feb. 2022, doi: 10.11591/ijeecs.v25.i2.pp1011-1019.

[3] B. Saoud, "Wireless sensor network lifetime improving based on whale optimization algorithm," *Ad-Hoc and Sensor Wireless Networks*, vol. 54, no. 1–2, pp. 95–111, 2022.

[4] S. S. Saleh, T. F. Mabrouk, and R. A. Tarabishi, "An improved energy-efficient head election protocol for clustering techniques of wireless sensor network (June 2020)," *Egyptian Informatics Journal*, vol. 22, no. 4, pp. 439–445, 2021, doi: 10.1016/j.eij.2021.01.003.

[5] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proceedings of the Annual Hawaii International Conference on System Sciences*, 2000.

[6] I. Daanoune, B. Abdennaceur, and A. Ballouk, "A comprehensive survey on LEACH-based clustering routing protocols in wireless sensor networks," *Ad Hoc Networks*, vol. 114, 2021, doi: 10.1016/j.adhoc.2020.102409.

[7] A. Iftikhar *et al.*, "Efficient energy and delay reduction model for wireless sensor networks," *Computer Systems Science and Engineering*, vol. 46, no. 1, pp. 1153–1168, 2023, doi: 10.32604/csse.2023.030802.

[8] N. E. H. Bourebia and C. Li, "A greedy energy efficient clustering scheme based reinforcement learning for WSNs," *Peer-to-Peer Networking and Applications*, vol. 15, no. 6, pp. 2572–2588, 2022, doi: 10.1007/s12083-022-01368-7.

[9] I. Daanoune, A. Baghdad, and A. Balllouk, "BRE-LEACH: a new approach to extend the lifetime of wireless sensor network," in *2019 Third International Conference on Intelligent Computing in Data Sciences (ICDS)*, Oct. 2019, pp. 1–6, doi: 10.1109/ICDS47004.2019.8942253.

[10] A. A. Abdulzahra, B. A. Q. Khudor, and I. S. Alshawi, "Energy-efficient routing protocol in wireless sensor networks based on bacterial foraging optimization," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 29, no. 2, pp. 911–920, 2023, doi: 10.11591/ijeecs.v29.i2.pp911-920.

[11] S. A. Alabady and S. S. Alhajji, "Enhance energy conservation based on residual energy and distance for WSNs," *Wireless Personal Communications*, vol. 121, no. 4, pp. 3343–3364, 2021, doi: 10.1007/s11277-021-08880-8.

[12] I. Daanoune, A. Baghdad, and A. Ballouk, "Improved LEACH protocol for increasing the lifetime of WSNs," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 4, pp. 3106–3113, 2021, doi: 10.11591/ijece.v11i4.pp3106-3113.

[13] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Transactions on Wireless Communications*, vol. 1, no. 4, pp. 660–670, Oct. 2002, doi: 10.1109/TWC.2002.804190.

[14] M. J. Al-Amery and M. H. Ghadban, "An energy consumption minimization approach in wireless sensor networks," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 22, no. 3, pp. 1485–1494, 2021, doi: 10.11591/ijeecs.v22.i3.pp1485-1494.

[15] I. Daanoune and A. Baghdad, "IBRE-LEACH: improving the performance of the BRE-LEACH for wireless sensor networks," *Wireless Personal Communications*, vol. 126, no. 4, pp. 3495–3513, 2022, doi: 10.1007/s11277-022-09876-8.

[16] D. Jabba and P. Acevedo, "ViTool-BC: visualization tool based on cooja simulator for WSN," Applied Sciences, vol. 11, no. 16, Aug. 2021, doi: 10.3390/app11167665.
[17] X. Chang, "Network simulations with OPNET," in *WSC'99. 1999 Winter Simulation Conference Proceedings. "Simulation - A Bridge to the Future" (Cat. No.99CH37038)*, 2003, vol. 1, pp. 307–314, doi: 10.1109/WSC.1999.823089.
[18] A. Varga and R. Hornig, "An overview of the OmNet++ simulation environment," in *Proceedings of the First International ICST Conference on Simulation Tools and Techniques for Communications Networks and Systems*, 2008, doi: 10.4108/ICST.SIMUTOOLS2008.3027.
[19] "The ns Manual (formerly ns Notes and Documentation)," Apr. 2022. [Online]. Available: https://www.isi.edu/nsnam/ns/doc/index.html
[20] A. Sobeih *et al.*, "J-Sim: a Simulation and emulation environment for wireless sensor networks," *IEEE Wireless Communications*, vol. 13, no. 4, pp. 104–119, Aug. 2006, doi: 10.1109/MWC.2006.1678171.
[21] N. Sabor, S. Sasaki, M. Abo-Zahhad, and S. M. Ahmed, "A graphical-based educational simulation tool for wireless sensor networks," *Simulation Modelling Practice and Theory*, vol. 69, pp. 55–79, Dec. 2016, doi: 10.1016/j.simpat.2016.09.004.
[22] K. Al-Zoubi and G. A. Wainer, "A grid-shaped cellular modeling approach for wireless sensor networks," *Simulation*, vol. 98, no. 10, pp. 875–895, Oct. 2022, doi: 10.1177/00375497221093379.
[23] R. Vinodhini and C. Gomathy, "MOMHR: a dynamic multi-hop routing protocol for WSN using heuristic based multi-objective function," *Wireless Personal Communications*, vol. 111, no. 2, pp. 883–907, 2020, doi: 10.1007/s11277-019-06891-0.
[24] I. Daanoune, A. Baghdad, and A. Ballouk, "A comparative study between ACO-based protocols and PSO-based protocols in WSN," in *7th Mediterranean Congress of Telecommunications*, 2019, doi: 10.1109/CMT.2019.8931320.
[25] B. M. Sahoo, T. Amgoth, and H. M. Pandey, "Particle swarm optimization based energy efficient clustering and sink mobility in heterogeneous wireless sensor network," *Ad Hoc Networks*, vol. 106, 2020, doi: 10.1016/j.adhoc.2020.102237.

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