Iran University of Science and Technology

Iranian Journal of Electrical and Electronic Engineering

Journal Homepage: ijeee.iust.ac.ir

Optimal Sink Node Placement and Routing Protocol Evaluation for 6LoWPAN Networks in IoT

Mahendra Shridhar Naik*, Chaitra S. N.** and Amit Kumar K.***(C.A.)

Abstract: 6LoWPAN is a significant innovation for low-power devices such as sensors and motes, enabling efficient communication in IoT networks. This paper examines the impact of topology and sink node placement on data delivery within these networks, focusing on the Routing Protocol for Low-Power and Lossy Networks (RPL). Various network performance metrics are evaluated to determine optimal routing paths, revealing that increased node density and network size lead to higher delays and congestion. The study highlights that the central placement of the sink node enhances performance. Comparatively, mesh topology outperforms random topology in terms of efficiency. Simulations were conducted to evaluate the effectiveness of Objective Functions (OFs), specifically OF0 and MRHOF. The results indicate that MRHOF surpasses OF0, with performance improvements scaling with network size.

Keywords: 6LoWPAN, IoT, Routing Protocol, QoS, Network Topology.

1 Introduction

NOWADAYS the field of wireless sensor networks is getting fly with the emergence of the Internet of Things (IoT). The IoT has a tremendous expansion in the Internet and its ability to gather, explore and circulate information that can be transformed into data or information. Certain conditions are suggested that are intelligent and self-deciding by direct correspondence between gadgets of different kinds that are essential for the IoT has arisen as the great situation of the relevance and effect of innovation in human existence. Internet of Things expands the idea of the Internet from a network of rather homogeneous gadgets, for example, PCs to an array of heterogeneous gadgets, for example, home machines, purchaser hardware, or WSN. As developed from traditional networks like the Internet, IoT is using the same technologies as Traditional internet networks rather than developing new techniques especially for IoT, for example, routing and logical layer concepts with few modifications in it.

As the Internet of Things networks comprises low power devices, to suit with new sort of network, methods utilized for the Internet are required change or even new strategies, conventions, or components are likewise recommended Routing Protocols for Wireless Sensor Network has been a rising exploration topic for a really long time and still. One of the network technologies in IoT is IPv6 over low-power personal area networks (6LoWPANs) is a prominent innovation for shrewd devices like sensors, automated homes, and smart offices. 6LoWPAN is used only for IPv6 addressing, for which a small adaptation layer has been characterized to optimize IPv6 over IEEE 802.15.4.

As there will be billions of devices joining the network the majority of which will occur through wireless technology henceforth it will be an especially new network that can be named a huge network than the present network. 6LowPan is a protocol that has helped overcome any issues between low-power sensor devices and networks.

Iranian Journal of Electrical & Electronic Engineering, 2025.
Paper first received 24 Aug. 2024 and accepted 26 Feb. 2025.

* The author is with the Department of ECE, New Horizon College of Engineering, Bengaluru, Karnataka, India.
E-mail: mahendrasnaik@gmail.com.
**The author is with the Department of ECE, GM University, Davangere, Karnataka, India.
E-mail: chaitrasn48@gmail.com.
*** The author is with the Department of ECE, Mangalore Institute of Technology and Engineering, Moodbidre, Karnataka, India.
E-mail: amit@mite.ac.in.
Corresponding Author: Amit Kumar K.

Especially routing is one of the bottleneck issues in the issue in WSNs, because of link failures, reduced data rates, and huge power consumption. To solve the above issues, modern strategies are expected. So, the optimization of routes, power wastage, and link failure can be avoided and resolved. Due to the uniqueness of WSNs, conventional IP routings protocols, like OSPF, IS-IS, AODV, and OLSR, can't fulfill the requirements of multipoint-to-point WSN applications consequently.

Paper briefs as the first section give about the introduction to 6LoWPAN, as we are interested in improving the QoS of the network the routing challenges have been discussed and the literature survey gives the related work in our domain. The next section gives the formation of DODAG and the RPL Protocol. The results and discussions and the future scope has been explained in the last part.

1.1 Research Challenges in IoT:

a) Deploying Nodes: Unlike traditional networks where the network was built after designing the topology for the deployment. The deployment of sensor nodes can be deterministic or random. In a deterministic way, the routing is also predetermined with the topology. Hence the path selection for sending data also remains the same means the routing path will be the same till the network lifetime. But in randomized node deployment, nodes are randomly scattered which in turn makes an unstable network which causes choose the dynamic path based on the type of data.

b) Energy consumption: Energy utilization is a major concern in WSNs because sensor nodes are passive in nature. Accordingly, routing protocols are expected to communicate, process, and calculations to expand the battery lifetime. Anyway, these sorts of interchange calculations actually give the required precision in routing protocols. Another thing in routing protocols is keeping precision in routing protocols by employing energy conservation methods in sensor networks. Any dis-functioning node in the network causes serious changes in the topology and processing. Hence the routing protocols should be more stable to handle any unexpected scenarios.

c) Network dynamic: Like traditional networks, the majority of WSNs contain static nodes and we have dynamic WSN networks too, for example, WSNs target recognition or following applications, and providing Routing for such kind of dynamic networks is quite challenging as the path keeps on varying frequently. Hence one can't have the routing topology and predetermined routing calculation strategies. one should provide the path on demand for the dynamic networks. Because of the unstable network pre-calculation of the path is of no use.

d) Fault resistance: WSN is very much susceptible to network failures due to power constraints of nodes, physical damage, and environmental conditions. Although the deployment of sensors is made in huge numbers the failures of certain nodes can greatly reduce the performance of the network. For instance, data should route through a long way, an entire network is partitioned into two sections. In this way, routing protocols should think about some adaptation to internal failure which occurs unexpectedly. to consider an example, by considering the residual energy of nodes the path can be selected, or more processing capability of the nodes can be selected to detect the fault detection in the path.

e) Scalability: WSNs are probably going to be extended at times. For instance, a network could be of 100 nodes during deployment later the network size can be increased to 1000 nodes and the designed routing protocol should be compatible with the increased network size.

1.2 Routing Protocol over Low power and Lossy network (RPL):

6LowPAN utilizes an adaptation layer called the 6LoWPAN layer between the network and data link layer for fragmentation and reassembling of IPv6 packets. The routing in 6LoWPAN is principally separated based on routing decisions taken by an adaptation layer. The RPL is a routing protocol of the 6lowpan adaptation layer, which mainly operates for IEEE 802.15.4 (Personal Area Networks). The name tells that the protocol is for low-power and lossy links and the nodes or the motes present in the networks are highly resource constraint. The IETF draft [17] gives complete knowledge about RPL.

Fig. 1 depicts the 6LoWPAN network architecture and describes a 6LoWPAN mesh network scenario. The Access Point (AP) known as the IPv6 router handles the uplink to the Internet. To AP, numerous electronic gadgets can be connected. A gateway node connects the 6LoWPAN network to the IPV6 network. Three tasks are handled by the edge router: 1) Information trade-offs between 6LoWPAN devices and the Internet (or another IPv6 organization); 2) local data trade between devices that are available internally in the 6LoWPAN network; and 3) the age and support of the radio subnet the maintenance of the 6LoWPAN network

The 6LoWPAN and IP networks connect to other networks by communicating using IP routers. Typically, the 6LoWPAN network operates on the periphery and serves as a stub network. This suggests that data entering the network is for a device inside the 6LoWPAN. Through at least one edge router that transfers IP datagrams between different media, one 6LoWPAN organization may be connected to other IP networks.

The IPv6 stack of 6Lowpan network is as shown in the Fig. 2. Different protocols in the IPv6 are as shown in the Fig. 3.

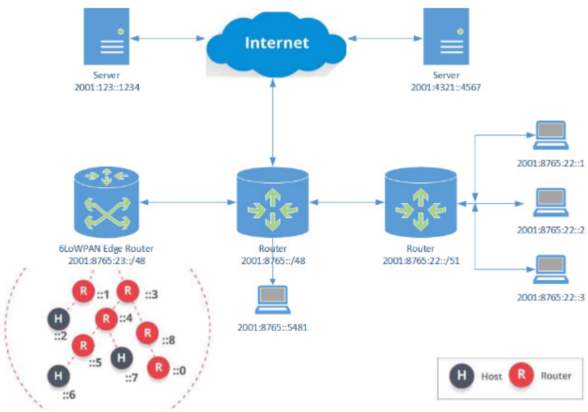


Fig 1. 6lowPAN Architecture

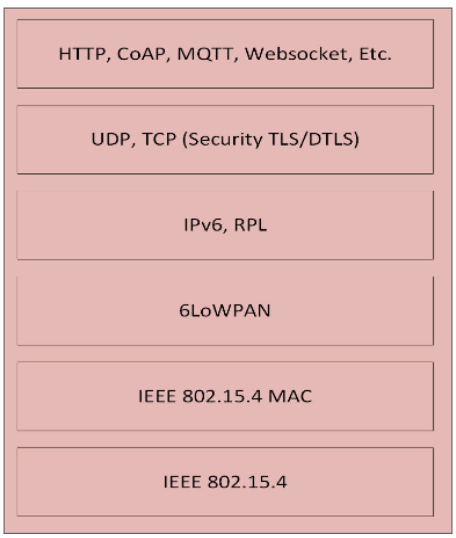


Fig 2. IPv6 Stack

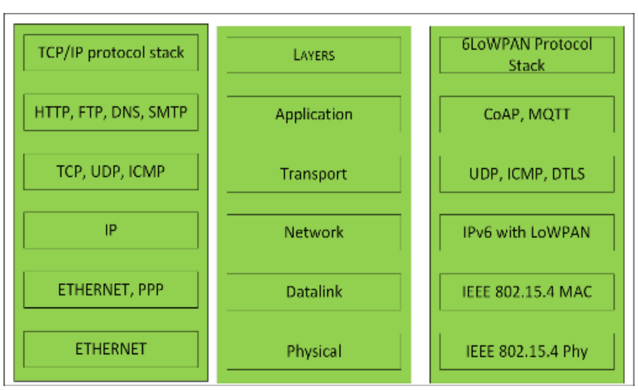


Fig 3. IPV6 Stack with protocols in each layer

1.3 Overview of RPL Protocol:

The Routing Protocol for Low power and lossy network (RPL) organizes the routers in a manner that generates a Destination Oriented Directed Acyclic Graph (DODAG). The proactive routing protocol periodically reconstructs the Destination Oriented Directed Acyclic Graph (DODAG). The RPL instances can be created multiple times with different topologies whenever new nodes are added to or removed from the 6LoWPAN network. The Low-power and Lossy Network (LLN) consists of sensor motes that are equipped with limited energy, memory, and processing capabilities. The establishment of topologies is a crucial objective of the Routing Protocol for Low-Power and Lossy Networks (RPL), given the absence of predetermined topologies in such networks. Root Path Length (RPL) involves the modification of at least one root to function as a sink, and thereafter directs the flow of courses either towards or away from these sinks. Each Directed Acyclic Graph of Destination Advertisement (DODAG) is characterized by the presence of a single sink node.

The utilization of four IDs is employed by RPL in order to characterize and maintain a topology. The RPL Instance ID refers to the identification of a specific RPL instance that is operational within a Wireless Sensor Network (WSN). The DODAG Version Number is incremented each time modifications are made to the DODAG. In this study, we want to rank and characterize certain mote positions in relation to the DODAG root. In the process of calculating the rank, the mote assumes exclusive responsibility for determining the Objective Functions (OF) of the RPL. It is expected that the rank will drop as the node progresses towards its intended destination.

The term "RPL" is an acronym consisting of three components that serve as a means to define a "DODAG." The DAG Information Option (DIO) encompasses many data elements such as information regarding the Objective Function (OF), the node's position (RANK), and unique identifiers (IDs). The DODAG is formed through intermittent communication by each mote. The Destination Advertisement Object (DAO) is employed for the purpose of transmitting information, namely to announce the presence of distance sensor nodes and the sink or gateway. The DIS (DODAG Informational Solicitation) nodes employ this mechanism to ascertain their necessity for involvement in a Directed Acyclic Graph (DAG). Each individual mote is equipped with a single sink. The DODAG's root node initiates the transmission of DIO messages, assigning them a rank value of 1. Upon receiving a signal from the Data Input/Output (DIO), the motes proceed to update their respective positions and calculate the associated cost for transmitting data to the sink. Each individual mote has the ability to make decisions based on the objective function (OF) that is applied. The objective function can be either a single metric or a combination of metrics, such as path cost, rank, and so on.

2 Literature Survey

The paper [1] presents an overview of the completer RPL protocol, including the process of DODAG creation, the characteristics of DODAG, the difficulties encountered in RPL, and the network management considerations during the operation of RPL. The authors assert that fault tolerance, namely DODAG repair, loop avoidance, and detection, are significant considerations. 2) Routing with Quality of Service (QoS) Considerations a) The Node State and Attribute (NSA) Object, b) The Node Energy Object, c) The Hop Count Object, d) The Link Throughput Object, e) The Link Latency Object, f) The Link Reliability Object, and g) The Link Color Object are some factors utilized for the management of a 6lowpan network. The authors additionally evaluate the convergence time, packet loss, and end-to-end packet delay as part of their performance analysis of a network utilizing the RPL protocol.

The performance examination of the 6lowpan network in the Contiki OS COOJA simulator was conducted by the authors [2]. The authors conducted a comparative analysis of two objective functions, namely OF0 and MRHOF, by evaluating certain Quality of Service (QoS) factors within each objective function. And last, by analyzing all results writers determined that MRHOF is the best objective functions to be taken.

The study conducted by the authors [3] involved the utilization of the NS2 simulator to execute simulations. They employed a machine learning technique to optimize the network lifetime and quality of service (QoS) by taking into account factors such as packet delivery ratio, energy consumption, and residual energy. The researchers have conducted a comparison between the optimized network lifespan and the default RPL network lifetime. After implementing machine learning methodologies, the outcomes achieved are highly favorable. The authors of paper [4] primarily concentrated on enhancing the specified objective functions. They conducted a survey to determine the metrics utilized and whether the network is static or dynamic. The study also identified the most commonly employed tool in this context. The enhancement of the objective function remains available for researchers as determined by the Internet Engineering Task Force (IETF). Therefore, the parent selection process takes into account the collective factors, and a new goal function may be illustrated. The authors of study [5] conducted a comparative analysis of two network topologies, namely grid and mesh. They evaluated many performance metrics including throughput, latency, ETX, and power consumption. The researchers have ultimately determined that the mesh topology is the superior choice. The authors in papers [6] and [7] have proposed a novel set of objective functions known as E-MRHOF. The authors conducted a comparison between the new objective function and the default MRHOF, and observed that the new objective function exhibits a superior PDR in comparison to the old one.

This research thoroughly examines the performance of 6LoWPAN networks, specifically emphasizing the influence of topology, sink node positioning, and objective functions on metrics such as Packet Delivery Ratio (PDR), packet loss, and Expected Transmission Count (ETX). The findings offer significant insights for optimizing these networks; nevertheless, a discussion of their practical applications in real-world wireless communication systems would augment the paper's significance and usefulness.

The discovery that MRHOF typically surpasses OF0 in bigger networks may be associated with particular applications, such as industrial IoT deployments, where scalability and dependability are paramount. Likewise, the insights regarding sink node placement could be utilized in contexts such as smart home networks, where central positioning may be advantageous for enhanced device connectivity.

Moreover, addressing the constraints of these findings in realistic applications, considering elements such as dynamic node mobility, fluctuating channel conditions, and external interference, will enhance the analysis's realism. This would also establish a framework for future research trajectories, perhaps resulting in more resilient and versatile 6LoWPAN implementations for various applications.

3 Performance Analysis of the 6lowpan Networks

The 6lowpan network is a resource-constrained network mainly for IoT-connected devices. The monitoring of QoS parameters in the network is very important. Since the application of the network is mainly on personal area networks like industrial IoT, home automation, water pollution monitoring, etc. The QoS parameters can be considered in two categories node parameters and link parameters, as shown in Fig. 4.

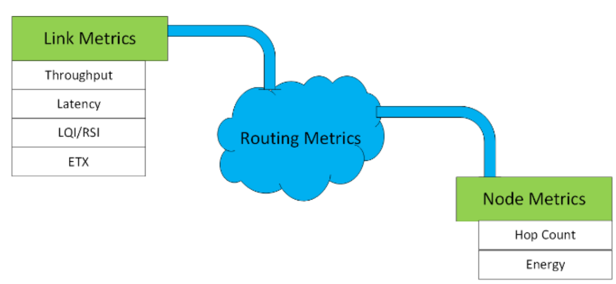


Fig 4. Metrices for performance analysis of 6lowpan network

The performance of the network is analyzed for different network sizes, the placement of the sink node, and two different topologies. The other analysis is done by considering more than one sink node in two different cases. They are when the sink nodes are within range of each other and when the sink nodes are not within range of each other. Here also, two different topologies are considered: the mesh topology and the random topology. All the simulations are conducted in Cooja Simulator under Contiki 2.7 OS. The two different cases are considered.

The Cooja simulator under Contiki software has been selected for performing simulations and Cooja parameter setup is given in the Table 1:

Table 1. Cooja simulator Parameter setup

Number of nodes	10-50
Objective Functions used	OF0, MRHOF
Parameters Measured	PDR, Hop Count, Total Power Consumption, ETX
Propagation Model	UGDM
Placement of sink node	Corner, centre
Topology used	Mesh, random

4 Results and Discussions

Different parameters, such as the average number of packets sent by nodes, average packet loss, average listen power, average transmitted power, average total packets consumed, average number of hops, and average expected transmission count (ETX), are computed for various topologies and node positions within the network.

The simulation is done using Cooja Simulator, and it is carried out for 30 minutes for different network sizes with different topologies. The simulation results are extracted as shown in Fig. 5.

The performance of the network hops for different nodes is shown in Fig. 6.

The experimental findings are analyzed for distinct scenarios

Initially the experimental findings are analyzed in four distinct scenarios, focusing on the objective function MRHOF.

1. A random topology with the sink node placed at the corner.
2. A random topology with the sink node placed at the Centre.
3. A mesh topology with the sink node placed at the corner.
4. A mesh topology with the sink node placed at the Centre.

Table 2 illustrates the performance of the network with a random topology, with the sink node strategically positioned at one of the corners of the node. Table 3 presents the performance results of the network when a random topology is employed, with the sink node positioned at the central location within the network. In Table 4, the performance outcomes of the network are displayed for a mesh topology, with the sink node situated in a corner position. Lastly, Table 5 provides the performance metrics for the network utilizing a mesh topology, with the sink node placed at the Centre.

An inference can be deduced from the values collected through experimentation.

The experimental study encompasses the examination of two distinct topologies, namely the mesh topology and the random topology.

Table 2. Case 1: Random topology and the sink node is placed in the corner (OF=MRHOF)

Parameters	Number of Nodes				
	10	20	30	40	50
Avg packets sent by nodes	24.7	23.85	26.75	27.30	23.95
Avg packet lost	1	2.4	1.5	0.875	1.347
Avg listen power	59.99	59.97	59.97	59.962	59.98
Avg transmitted power	0.005	0.024	0.009	0.010	0.019
Avg total power consumed	60.18	60.18	60.18	60.187	60.20
Avg number of hops	1.3	5.3	2.536	2.451	4.859
Avg etx of the network	18.57	61.40	34.04	43.504	50.43

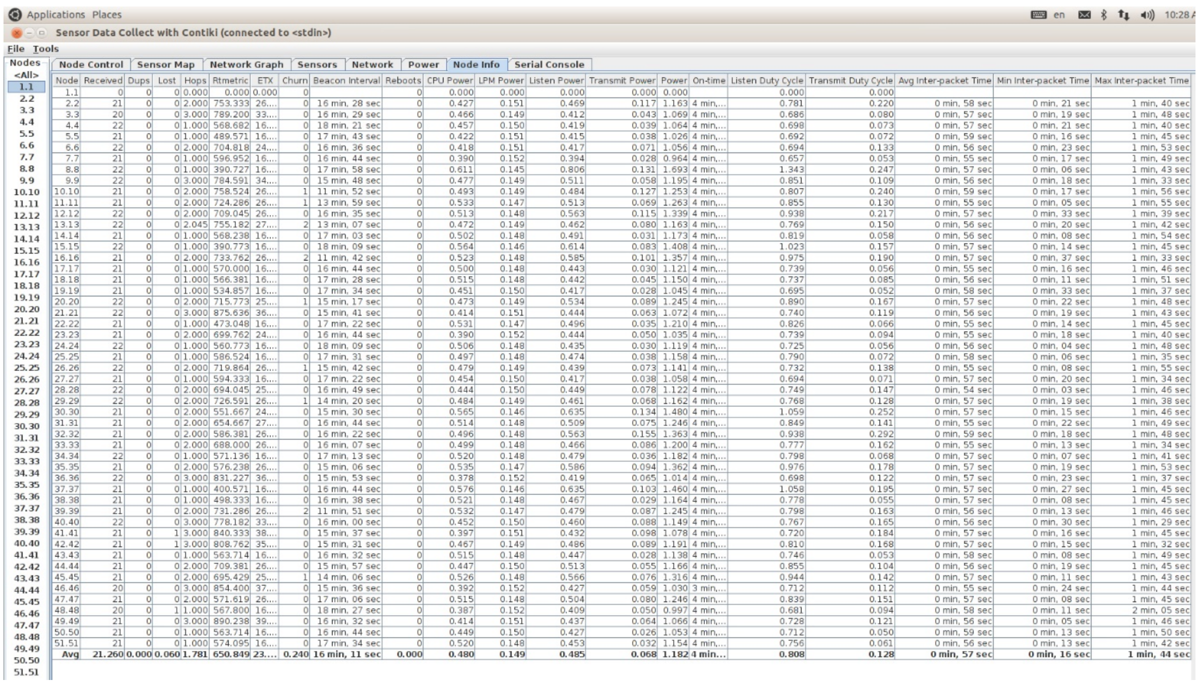
Another factor that is considered is the positioning of the sink node. The observed variation has been systematically tracked and duly recorded. The simulation is conducted using the Contiki 2.7 Cooja simulator. The experiment is conducted for both the objective functions OF0 and MRHOF. The case experiments are conducted with variable numbers of source nodes, ranging from 10 to 50.

The preliminary deduction can be drawn from the information presented in Tables 2 and 3.

Regarding cases 1 and 2, the topology used for this investigation is of a random nature. The objective function being considered is represented as MRHOF. There are two primary classifications for the placement of sink nodes: corner placement and center placement.

The average number of packets communicated by all nodes decreases when the sink node is located at a corner as opposed to being positioned in the middle. The central sink node demonstrates a reduced incidence of packet loss in comparison to the sink node situated in the corner. When a sink node is positioned at a corner, the number of hops needed to reach the destination grows in direct proportion to the quantity of source nodes. The sink node positioned in the corner demonstrates a higher expected transmission count in comparison to the sink node located in the center.

Next we consider the same scenario as described previously, with the only difference being the topology for examples 3 and 4, as presented in Tables 4 and 5.The topology employed in this context is the MESH topology. The objective function employed in this study is the MRHOF.



Node	Received	Dups	Lost	Hops	Rtmetric	ETX	Churn	Beacon Interval	Reboots	CPU Power	LPM Power	Listen Power	Transmit Power	Power	On-time	Listen Duty Cycle	Transmit Duty Cycle	Avg Inter-packet Time	Min Inter-packet Time	Max Inter-packet Time
1.1	0	0	0	0.000	0.000	0.000	0		0	0.000	0.000	0.000	0.000	0.000		0.000	0.000			
2.2	21	0	0	2.000	753.333	26....	0	16 min, 28 sec	0	0.427	0.151	0.469	0.117	1.163	4 min,...	0.781	0.220	0 min, 58 sec	0 min, 21 sec	1 min, 40 sec
3.3	20	0	0	3.000	789.200	33....	0	16 min, 29 sec	0	0.466	0.149	0.412	0.043	1.069	4 min,...	0.686	0.080	0 min, 57 sec	0 min, 19 sec	1 min, 48 sec
4.4	22	0	0	1.000	568.682	16....	0	18 min, 21 sec	0	0.457	0.150	0.419	0.039	1.064	4 min,...	0.698	0.073	0 min, 57 sec	0 min, 21 sec	1 min, 40 sec
5.5	21	0	0	1.000	489.571	16....	0	17 min, 43 sec	0	0.422	0.151	0.415	0.038	1.026	4 min,...	0.692	0.072	0 min, 59 sec	0 min, 16 sec	1 min, 45 sec
6.6	22	0	0	2.000	704.818	24....	0	16 min, 36 sec	0	0.418	0.151	0.417	0.071	1.056	4 min,...	0.694	0.133	0 min, 56 sec	0 min, 23 sec	1 min, 53 sec
7.7	21	0	0	1.000	596.952	16....	0	16 min, 44 sec	0	0.390	0.152	0.394	0.028	0.964	4 min,...	0.657	0.053	0 min, 55 sec	0 min, 17 sec	1 min, 49 sec
8.8	22	0	0	1.000	390.727	16....	0	17 min, 58 sec	0	0.611	0.145	0.806	0.131	1.693	4 min,...	1.343	0.247	0 min, 57 sec	0 min, 06 sec	1 min, 43 sec
9.9	22	0	0	3.000	784.591	34....	0	15 min, 48 sec	0	0.477	0.149	0.511	0.058	1.195	4 min,...	0.851	0.109	0 min, 56 sec	0 min, 18 sec	1 min, 33 sec
10.10	21	0	0	2.000	758.524	26....	1	11 min, 52 sec	0	0.493	0.149	0.484	0.127	1.253	4 min,...	0.807	0.240	0 min, 59 sec	0 min, 17 sec	1 min, 56 sec
11.11	21	0	0	2.000	724.286	26....	1	13 min, 59 sec	0	0.533	0.147	0.513	0.069	1.263	4 min,...	0.855	0.130	0 min, 55 sec	0 min, 05 sec	1 min, 55 sec
12.12	22	0	0	2.000	709.045	26....	0	16 min, 35 sec	0	0.513	0.148	0.563	0.115	1.339	4 min,...	0.938	0.217	0 min, 57 sec	0 min, 33 sec	1 min, 39 sec
13.13	22	0	0	2.045	755.182	27....	2	13 min, 07 sec	0	0.472	0.149	0.462	0.080	1.163	4 min,...	0.769	0.150	0 min, 56 sec	0 min, 20 sec	1 min, 42 sec
14.14	21	0	0	1.000	568.238	16....	0	17 min, 03 sec	0	0.502	0.148	0.491	0.031	1.173	4 min,...	0.819	0.058	0 min, 56 sec	0 min, 08 sec	1 min, 54 sec
15.15	22	0	0	1.000	390.773	16....	0	18 min, 09 sec	0	0.564	0.146	0.614	0.083	1.408	4 min,...	1.023	0.157	0 min, 57 sec	0 min, 14 sec	1 min, 45 sec
16.16	21	0	0	2.000	733.762	26....	2	11 min, 42 sec	0	0.523	0.148	0.585	0.101	1.357	4 min,...	0.975	0.190	0 min, 57 sec	0 min, 37 sec	1 min, 33 sec
17.17	21	0	0	1.000	570.000	16....	0	16 min, 44 sec	0	0.500	0.148	0.443	0.030	1.121	4 min,...	0.739	0.056	0 min, 55 sec	0 min, 16 sec	1 min, 46 sec
18.18	21	0	0	1.000	566.381	16....	0	17 min, 28 sec	0	0.515	0.148	0.442	0.045	1.150	4 min,...	0.737	0.085	0 min, 56 sec	0 min, 11 sec	1 min, 51 sec
19.19	21	0	0	1.000	534.857	16....	0	17 min, 34 sec	0	0.451	0.150	0.417	0.028	1.045	4 min,...	0.695	0.052	0 min, 58 sec	0 min, 33 sec	1 min, 37 sec
20.20	22	0	0	2.000	715.773	25....	1	15 min, 17 sec	0	0.473	0.149	0.534	0.089	1.245	4 min,...	0.890	0.167	0 min, 57 sec	0 min, 22 sec	1 min, 48 sec
21.21	22	0	0	3.000	875.636	36....	0	15 min, 41 sec	0	0.414	0.151	0.444	0.063	1.072	4 min,...	0.740	0.119	0 min, 56 sec	0 min, 19 sec	1 min, 43 sec
22.22	21	0	0	1.000	473.048	16....	0	17 min, 22 sec	0	0.531	0.147	0.496	0.035	1.210	4 min,...	0.826	0.066	0 min, 55 sec	0 min, 14 sec	1 min, 45 sec
23.23	21	0	0	2.000	699.762	24....	0	16 min, 44 sec	0	0.390	0.152	0.444	0.050	1.035	4 min,...	0.739	0.094	0 min, 55 sec	0 min, 18 sec	1 min, 40 sec
24.24	22	0	0	1.000	560.773	16....	0	18 min, 09 sec	0	0.506	0.148	0.435	0.030	1.119	4 min,...	0.725	0.056	0 min, 56 sec	0 min, 04 sec	1 min, 48 sec
25.25	21	0	0	1.000	586.524	16....	0	17 min, 31 sec	0	0.497	0.148	0.474	0.038	1.158	4 min,...	0.790	0.072	0 min, 58 sec	0 min, 06 sec	1 min, 35 sec
26.26	22	0	0	2.000	719.864	26....	1	15 min, 42 sec	0	0.479	0.149	0.439	0.073	1.141	4 min,...	0.732	0.138	0 min, 55 sec	0 min, 08 sec	1 min, 55 sec
27.27	21	0	0	1.000	594.333	16....	0	17 min, 22 sec	0	0.454	0.150	0.417	0.038	1.058	4 min,...	0.694	0.071	0 min, 57 sec	0 min, 20 sec	1 min, 34 sec
28.28	22	0	0	2.000	694.045	25....	0	16 min, 49 sec	0	0.444	0.150	0.449	0.078	1.122	4 min,...	0.749	0.147	0 min, 54 sec	0 min, 03 sec	1 min, 46 sec
29.29	22	0	0	2.000	726.591	26....	1	14 min, 20 sec	0	0.484	0.149	0.461	0.068	1.162	4 min,...	0.768	0.128	0 min, 57 sec	0 min, 19 sec	1 min, 38 sec
30.30	21	0	0	2.000	551.667	24....	0	15 min, 30 sec	0	0.565	0.146	0.635	0.134	1.480	4 min,...	1.059	0.252	0 min, 57 sec	0 min, 15 sec	1 min, 46 sec
31.31	21	0	0	2.000	654.667	27....	0	16 min, 44 sec	0	0.514	0.148	0.509	0.075	1.246	4 min,...	0.849	0.141	0 min, 55 sec	0 min, 22 sec	1 min, 49 sec
32.32	21	0	0	2.000	586.381	26....	0	16 min, 22 sec	0	0.496	0.148	0.563	0.155	1.363	4 min,...	0.938	0.292	0 min, 59 sec	0 min, 18 sec	1 min, 48 sec
33.33	21	0	0	2.000	688.000	26....	0	16 min, 07 sec	0	0.499	0.148	0.466	0.086	1.200	4 min,...	0.777	0.162	0 min, 55 sec	0 min, 13 sec	1 min, 34 sec
34.34	22	0	0	1.000	571.136	16....	0	17 min, 13 sec	0	0.520	0.148	0.479	0.036	1.182	4 min,...	0.798	0.068	0 min, 57 sec	0 min, 07 sec	1 min, 41 sec
35.35	21	0	0	2.000	576.238	26....	0	15 min, 06 sec	0	0.535	0.147	0.586	0.094	1.362	4 min,...	0.976	0.178	0 min, 57 sec	0 min, 19 sec	1 min, 53 sec
36.36	22	0	0	3.000	831.227	36....	0	15 min, 53 sec	0	0.378	0.152	0.419	0.065	1.014	4 min,...	0.698	0.122	0 min, 57 sec	0 min, 23 sec	1 min, 37 sec
37.37	21	0	0	1.000	400.571	16....	0	16 min, 44 sec	0	0.576	0.146	0.635	0.103	1.460	4 min,...	1.058	0.195	0 min, 57 sec	0 min, 27 sec	1 min, 45 sec
38.38	21	0	0	1.000	498.333	16....	0	16 min, 38 sec	0	0.521	0.148	0.467	0.029	1.164	4 min,...	0.778	0.055	0 min, 57 sec	0 min, 08 sec	1 min, 45 sec
39.39	21	0	0	2.000	731.286	26....	2	11 min, 51 sec	0	0.532	0.147	0.479	0.087	1.245	4 min,...	0.798	0.163	0 min, 56 sec	0 min, 13 sec	1 min, 46 sec
40.40	22	0	0	3.000	778.182	33....	0	16 min, 00 sec	0	0.452	0.150	0.460	0.088	1.149	4 min,...	0.767	0.165	0 min, 56 sec	0 min, 30 sec	1 min, 29 sec
41.41	21	0	1	3.000	840.333	38....	0	15 min, 37 sec	0	0.397	0.151	0.432	0.098	1.078	4 min,...	0.720	0.184	0 min, 57 sec	0 min, 16 sec	1 min, 45 sec
42.42	21	0	1	3.000	808.762	35....	0	15 min, 31 sec	0	0.467	0.149	0.486	0.089	1.191	4 min,...	0.810	0.168	0 min, 57 sec	0 min, 15 sec	1 min, 32 sec
43.43	21	0	0	1.000	563.714	16....	0	16 min, 32 sec	0	0.515	0.148	0.447	0.028	1.138	4 min,...	0.746	0.053	0 min, 58 sec	0 min, 08 sec	1 min, 49 sec
44.44	21	0	0	2.000	709.381	26....	0	15 min, 57 sec	0	0.447	0.150	0.513	0.055	1.166	4 min,...	0.855	0.104	0 min, 56 sec	0 min, 19 sec	1 min, 45 sec
45.45	21	0	0	2.000	695.429	25....	1	14 min, 06 sec	0	0.526	0.148	0.566	0.076	1.316	4 min,...	0.944	0.142	0 min, 57 sec	0 min, 11 sec	1 min, 43 sec
46.46	20	0	0	3.000	854.400	37....	0	15 min, 36 sec	0	0.392	0.152	0.427	0.059	1.030	3 min,...	0.712	0.112	0 min, 55 sec	0 min, 24 sec	1 min, 44 sec
47.47	21	0	0	2.000	571.619	26....	0	17 min, 06 sec	0	0.515	0.148	0.504	0.080	1.246	4 min,...	0.839	0.151	0 min, 57 sec	0 min, 08 sec	1 min, 45 sec
48.48	20	0	1	1.000	567.800	16....	0	18 min, 27 sec	0	0.387	0.152	0.409	0.050	0.997	4 min,...	0.681	0.094	0 min, 58 sec	0 min, 11 sec	2 min, 05 sec
49.49	21	0	0	3.000	890.238	39....	0	16 min, 32 sec	0	0.414	0.151	0.437	0.064	1.066	4 min,...	0.728	0.121	0 min, 56 sec	0 min, 05 sec	1 min, 46 sec
50.50	21	0	0	1.000	563.714	16....	0	16 min, 44 sec	0	0.449	0.150	0.427	0.026	1.053	4 min,...	0.712	0.050	0 min, 59 sec	0 min, 13 sec	1 min, 50 sec
51.51	21	0	0	1.000	574.095	16....	0	17 min, 34 sec	0	0.520	0.148	0.453	0.032	1.154	4 min,...	0.756	0.061	0 min, 56 sec	0 min, 13 sec	1 min, 42 sec
Avg	**21.260**	**0.000**	**0.060**	**1.781**	**650.849**	**23....**	**0.240**	**16 min, 11 sec**	**0.000**	**0.480**	**0.149**	**0.485**	**0.068**	**1.182**	**4 min...**	**0.808**	**0.128**	**0 min, 57 sec**	**0 min, 16 sec**	**1 min, 44 sec**

Fig 5. simulation results from Cooja Simulator

Fig 6. Network Hops per Nodes

Table 3. Case 2**:** Random topology and the sink node is place in the center (OF=MRHOF)

Parameters	Number of Nodes				
Number of nodes	10	20	30	40	50
Avg packets sent by nodes	29	25.80	28.786	27.154	26.77
Avg packet lost	0	0.950	0.071	0.744	0.683
Avg listen power	59.97	59.97	59.969	59.978	59.97
Avg total transmitted power	0.00	0.006	0.005	0.005	0.006
Avg total power consumed	60.159	60.17	60.166	60.179	60.18
Avg etx of the network	18.864	24.235	21.296	20.976	22.995
Avg number of hops	1.30	1.395	1.243	1.385	1.543

Table 4. Case 3: Mesh Topology with sink node place in corner (OF=MRHOF)

Parameters	Number of Nodes				
Number of nodes	10	20	30	40	50
Average packets sent by all nodes	29.220	27.55	27.821	24.45	25.958
Average packet lost	0.00	0.8	0.9641	1.725	0.625
Average listen power	59.971	59.972	59.977	59.97	59.995
Average transmitted power	0.006	0.006	0.007	0.006	0.005
Average total power consumed	60.162	60.165	60.175	60.171	60.166
Avg ETX	24.812	23.798	27.166	25.771	22.023
Avg number of hops	1.40	1.450	1.680	1.487	1.375

Table 5. Case 4: Mesh topology with sink node placed in the center (OF=MRHOF)

Parameters	Number of Nodes				
Number of nodes	10	20	30	40	50
Average packets sent by a node	25.875	21.329	27.379	27.775	21.958
Average packet lost	1.250	3.7222	1.034	1.850	2.524
Average listen power	59.968	59.964	59.968	59.939	59.987
Average transmitted power	0.011	0.013	0.010	0.013	0.013
Average total power consumed	60.163	60.165	60.182	60.166	60.228
Avg etx	32.392	58.076	31.265	33.790	30.290
Avg hop count	2.750	2.952	2.449	2.918	2.589

The node is positioned at both the corner and center locations. Upon comparing cases 3 and 4, it is evident that similar outcomes to those described in the aforementioned situation can be observed. Specifically, the location of the sink node in the middle proves to be superior in all assessed areas. In this scenario, it is observed that there is an increase in the average number of successfully delivered packets, a decrease in the number of lost packets, a decrease in the number of hops required to reach the sink node, and a decrease in the predicted transmission count.

So, with both the topologies and the objective function with MRHOF, the conclusion can be drawn that the placement of the node at the center is better.

By considering cases 1 and 3, the inference can be made with two different topologies, i.e., random and mesh, respectively. The placement of the sink node is in the corner in both cases, and the objective function is MRHOF for both. When these two cases are compared, the average packet loss is constant in random topology, but as the number of nodes increases, the number of packets lost increases in mesh topology. The expected transmission count (ETX) is constant with network size in mesh topology and significantly varies in random topology with respect to network size. In random topology, the average number of hops increases with respect to network size, but in mesh topology, the average number of hops remains constant over the network size. Cases 2 and 4 are chosen for comparison since they produce the same results as the earlier situation. The placement of the sink node and the objective function are the same as in cases 2 and 4, with the topology being the only difference.

The variation of the average packet delivery ratio, average packet loss, average expected transmission count (ETX), and average total power for the network size varies from 10 to 50, with a difference of 10, and the performance is analyzed for the same.

Fig. 7 gives the average packet delivery ratio of the above-mentioned four scenarios for each network size. From the graph, it is observed that the sink node situated at the center gives a better result irrespective of the topology and the network size.

Fig. 8 gives the values of the average packet loss in four cases. The packet loss is higher in corner-situated sink nodes compared to center-situated sink nodes, but as the network size increases, the packet loss can't be predicted irrespective of the placement of the sink node.

Fig. 9 illustrates the average total power usage of the network. The power usage exhibits a positive correlation with the expansion of the network size. Irrespective of the positioning of the sink node and the underlying network structure.

Fig. 10 presents the average amount of hops necessary to reach the sink node within the network. The number of hops increases when the sink node is positioned in the corner in both mesh and random topologies, and this trend remains rather consistent regardless of the network size.

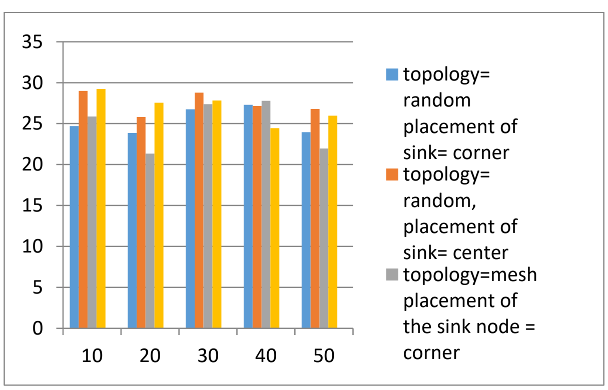


Fig 7. Variation of the average Packet Delivery with different number of sending nodes and the OF =MRHOF.

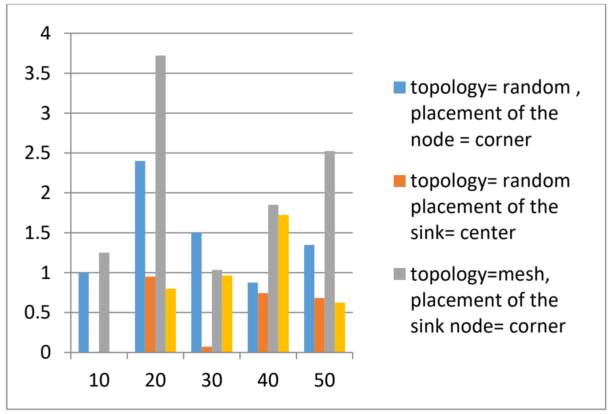


Fig 8. Variation of the average packet loss with different number of sending nodes and the OF =MRHOF

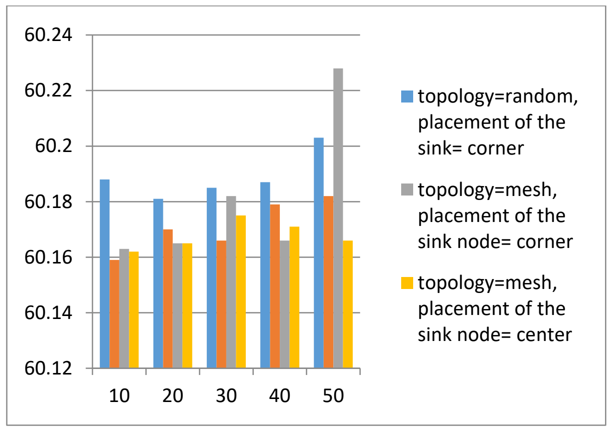


Fig 9. Variation of the average total power consumed with different number of sending nodes and the OF =MRHOF.

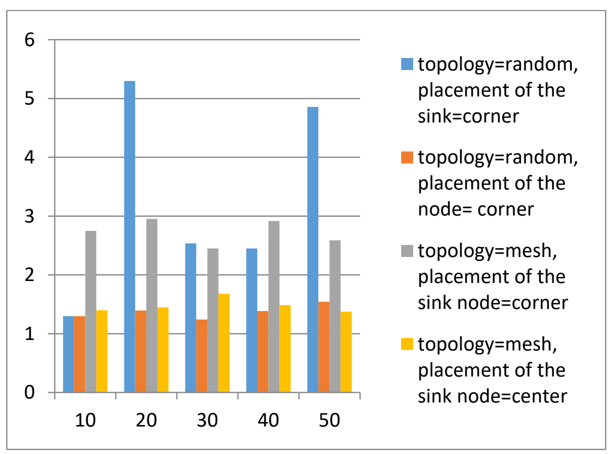


Fig 10. Variation of the average number of with different number of sending nodes and the OF =MRHOF

Next, we shall analyze the performance of the network for different scenarios with OF0 as an objective function.

The next four cases are the same as the previous four, but the objective function is different. Previously, we considered MRHOF an objective function, but now we are taking OF0 as an objective function. Here, four different cases are considered for the experimental observations with the objective function OF0.

1. A random topology with the sink node placed at the corner.
2. A random topology with the sink node placed at the centre.
3. A mesh topology with the sink node placed at the corner.
4. A mesh topology with the sink node placed at the centre.

Table 6 illustrates the performance of the network with a random topology, with the sink node strategically positioned at one of the corners of the node. Table 7 presents the performance results of the network when a random topology is employed, with the sink node positioned at the central location within the network. In Table 8, the performance outcomes of the network are displayed for a mesh topology, with the sink node situated in a corner position. Lastly, Table 9 provides the performance metrics for the network utilizing a mesh topology, with the sink node placed at the centre.

Table 6. Case 5 :Mesh topology sink node placed at center (OF= OF0)

Number of nodes	10	20	30	40	50
Average packets sent by nodes	29.1	27.7	28.5	22.895	26.304
Average packet lost	0.1	0.7	0.3	4.00	1.34
Average listen power	59.972	59.973	59.974	59.946	59.937
Average transmitted power	0.006	0.007	0.007	0.005	0.005
Average total power consumed	60.162	60.166	60.174	60.146	60.141
Avg ETX	20.80	25.60	26.14	24.00	22.08
Avg number of hops	1.3	1.600	1.633	1.5	1.380

Table 7. Case 6: Mesh topology sink node placed in corner (OF=OF0)

Number of nodes	10	20	30	40	50
Average packets sent by nodes	29	22.778	27.143	21.029	20.795
Average packet lost	0.0	2.443	1.107	2.771	3.045
Average listen power	59.965	59.815	59.971	59.931	59.813
Average transmitted power	0.012	0.007	0.009	0.01	0.009
Average total power consumed	60.16	60.016	60.181	60.133	60.029
Avg ETX	48	55.111	38.899	52.114	43.636
Avg number of hops	3	3.444	2.431	3.257	2.727

Table 8. Case7: Random topology sink node placed at center(OF= OF0)

Number of nodes	10	20	30	40	50
Average packets sent by nodes	28	26.50	25.357	23.947	24.72
Average packet lost	0	0.75	1.179	1.526	1.8
Average listen power	0	59.978	59.973	59.977	59.857
Average transmitted power	0.004	0.006	0.005	0.006	0.009
Average total power consumed	60.180	60.171	60.164	60.181	60.084
Avg ETX	17.6	21.6	21.714	22.91	24.396
Avg number of hops	1.1	1.350	1.357	1.43	1.529

Table 9. Case 8: Random topology sink node placed at corner (OF = OF0)

Number of nodes	10	20	30	40	50
Average packets sent by nodes	29	22.5	26.89	25.051	25.043
Average packet lost	0	1.00	2.241	1.128	2.653
Average listen power	59.967	59.978	59.963	59.949	59.938
Average transmitted power	0.01	0.01	0.008	0.01	0.008
Average total power consumed	60.164	60.179	60.168	60.166	60.143
Avg ETX	40	36.9	39.172	43.87	41.175
Avg number of hops	2.5	2.306	2.448	2.742	2.573

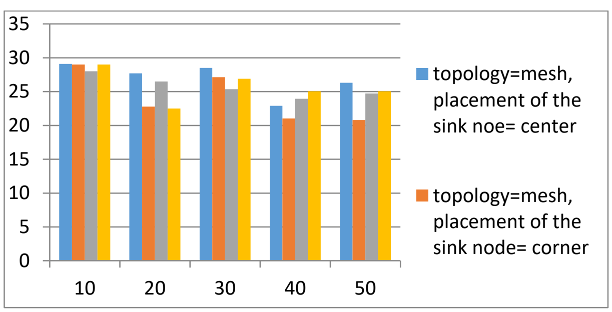


Fig 11. variation of the average packet delivery to sink with different number of sending nodes and the OF =OF0

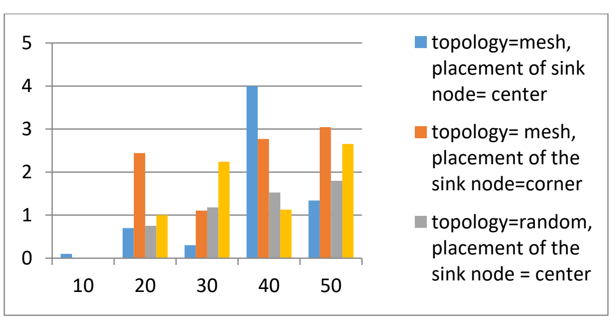


Fig 12. Variation of the average packet loss with different number of sending nodes and the OF =OF0

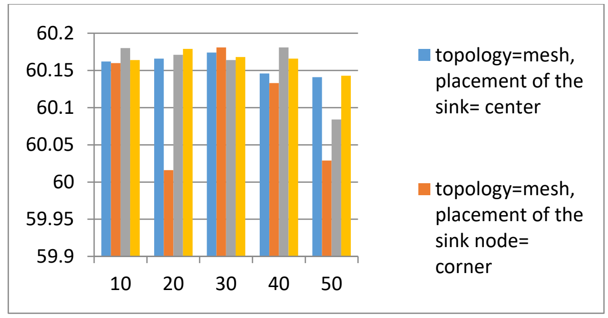


Fig 13. Variation of the average power consumption with different number of sending nodes and the OF =OF0

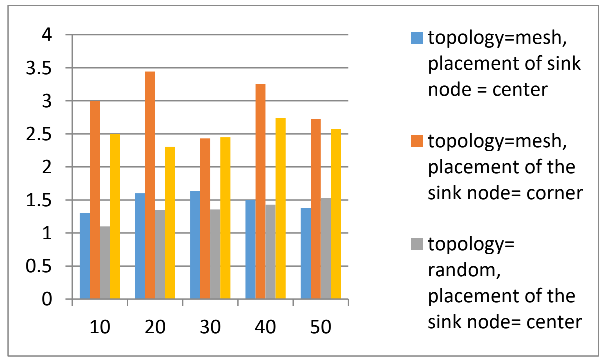


Fig 14. Variation of the average number of hops with different sending nodes and the OF =OF0

As the results for the PDR show, packet loss, total power consumption, and hop count have been taken for both the objective functions and for the different network sizes. The comparison can be made with two different objective functions.

By considering both objectives functions, the PDR decreases considerably with network size in OF0 when compared with MRHOF. The ETX is very high in all 4 cases, irrespective of the placement of the sink node, topology, or network size in OF0. The hop count and the total transmission power don't show much difference in both objective functions. But with the placement of the sink node, the hop count varies, which has already been given in Fig. 14.

In cases 5 and 7, the objective function is OF0, and the placement of the sink node is center. Here, comparisons can be made for two different topologies: random and mesh. PDR is comparatively better at mesh topology than random. In both cases, the hop count increases as the network size increases. The total power consumption remains approximately the same. The packet drop is less in mesh topology than in random topology. If we consider cases 5 and 6, the placement of the sink node is different in the corner and center, respectively, but the topology and the objective function are the same. According to the testing results, centering the sink node as opposed to placing it in a corner improves PDR performance. Additionally, packet loss is decreased when the sink node is central. ETX is substantially higher at the corner than at the sink node.

The second simulation was conducted to evaluate the objective function OF0, taking into account a total of 60 transmitting nodes and several sink nodes. In this analysis, we examine two scenarios: one where the sink nodes are in close proximity to each other, and another where the sink nodes are not within range of each other. In this particular scenario, similar to the previous case, the transmitting nodes do not establish communication with any of the receiving nodes, resulting in the absence of data transmission. Subsequently, the transmitting nodes underwent a division, thereby establishing communication with the sink nodes in closest proximity. However, there is minimal disparity in terms of the average measures. The comparison is shown in the Table 10.

When comparing the two objective functions OF0 and MRHOF in terms of energy consumption, packet loss, and the number of hops required to reach the gateway, the experimental analysis yielded the following values. The Fig. 15-18 presented indicate that the objective function MRHOF demonstrates improved performance as the number of nodes inside the network rises. The objective function OF0 exhibits a reduced level of energy use.

Table 10. Comparison of objective function and Node position for different metrics

Placement of the sink node	PDR	Packet Loss	Numbe r of Hops	ETX
Centre	GOOD	LESS	LESS	LESS
Corner	BAD	MORE	MORE	MORE
Objective Functions	PDR	Packet Loss	Number of Hops	ETX
OF0	BAD	MORE	MORE	MORE
MRHOF	GOOD	LESS	LESS	LESS

The Fig. 15-18 illustrates the distinction between the two objective functions employed by the RPL Protocol. Based on the obtained data, it can be shown that there is a positive correlation between network size and packet loss as shown in Fig. 15, indicating that larger networks experience higher levels of packet loss. Additionally, the Packet Delivery Ratio (PDR) remains relatively consistent across different network sizes as shown in Fig. 16. However, it is noteworthy that the Multi-Path Routing using the Hybrid Opportunistic Forwarding (MRHOF) protocol exhibits improved performance in larger network sizes as shown in Fig. 17. Nevertheless, it is important to acknowledge that the MRHOF protocol is associated with much higher energy consumption and Extended Transmission Time (ETX) compared to other protocols is as shown in the Fig. 18.

In very large networks, performance indicators including Packet Delivery Ratio (PDR), packet loss, average hops, and Expected Transmission Count (ETX) are considerably influenced.

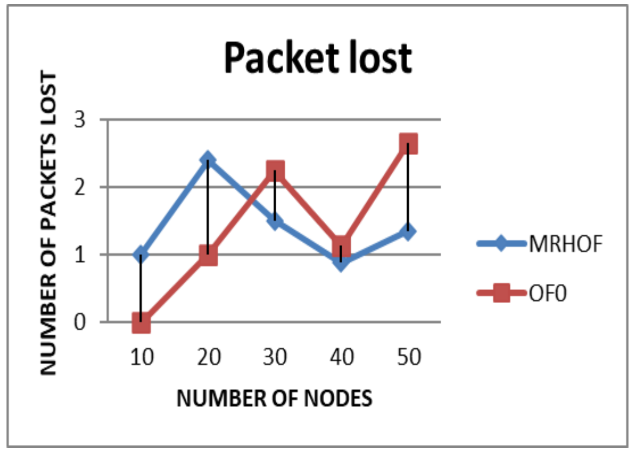


Fig 15. comparison of Packet Loss for two different objectives

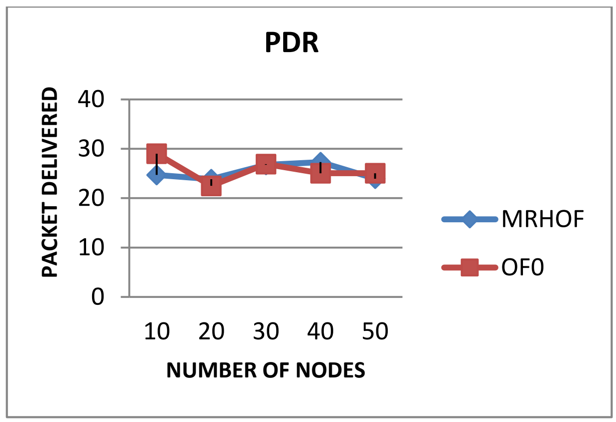


Fig 16. comparison of Packet delivered for two different objectives

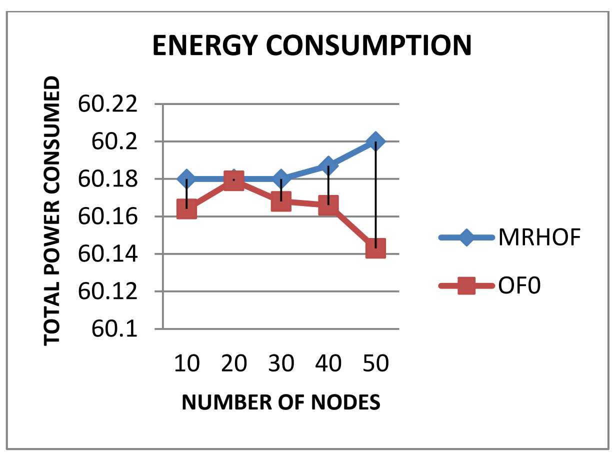


Fig 17. comparison of Packet delivered for two different objectives

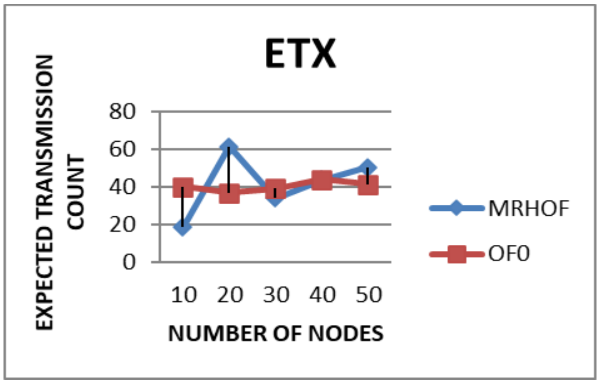


Fig 18. Comparison of Expected count for two different Objectives

In very large networks, performance indicators including Packet Delivery Ratio (PDR), packet loss, average hops, and Expected Transmission Count (ETX) are considerably influenced. The MRHOF protocol demonstrates superior Packet Delivery Ratio (PDR) in expansive networks relative to the OF0 protocol, which exhibits elevated energy usage and Expected Transmission Count (ETX). The selection of the goal function influences these measurements, with the MRHOF protocol typically exhibiting superior performance in bigger networks, but at the cost of increased energy consumption and elevated ETX. The network topology influences the variation of these measures with network size, as distinct topologies exhibit unique characteristics in managing congestion and routing packets. The number of nodes inside the network might influence these measures, since denser networks may encounter increased congestion and interference, resulting in elevated packet loss and diminished PDR. Further study is needed to investigate scalability, optimization, and real-world deployment of these measures in large-scale 6LoWPAN networks.

Although the study offers significant insights into 6LoWPAN network performance, it is essential to recognize the limitations of the presented approaches, particularly concerning bigger network sizes. As the network expands, elements such as increased node density, data traffic, and possible congestion might profoundly influence the efficacy of the assessed routing protocols and objective functions. For example, whereas MRHOF often exhibits superior performance in extensive networks, its elevated energy consumption and ETX may provide challenges with a substantial number of nodes. The work predominantly examines static topologies, but actual IoT implementations frequently entail dynamic node mobility and fluctuating channel conditions, which may further complicate the proposed optimization methodologies.

Moreover, the simulations are performed in a controlled environment, and aspects such as external interference, security vulnerabilities, and node failures are not thoroughly examined.

In extensive networks, these challenges may be exacerbated, thereby undermining the efficacy of the suggested techniques. Consequently, additional study is required to assess the resilience and flexibility of these approaches in more intricate and dynamic large-scale 6LoWPAN implementations. This may entail investigating alternate routing protocols, formulating more energy-efficient objective functions, and integrating techniques to address node mobility and external interference.

In real-world IoT systems, variations in packet loss, energy consumption, and hop count can significantly influence both network lifetime and application performance. For example, increased packet loss can lead to reduced data reliability and necessitate re-transmissions, consuming more energy and potentially hindering time-critical applications. This can be particularly problematic in applications like industrial automation or environmental monitoring, where timely and accurate data delivery is essential.

Higher energy consumption, especially in battery-powered IoT devices, directly impacts network lifetime. As nodes deplete their energy reserves faster, the overall network lifespan is shortened, leading to maintenance challenges and potential disruptions in service. Similarly, an increase in hop count can lead to longer delays in data transmission and higher energy consumption due to multi-hop routing.

This can affect the performance of delay-sensitive applications and reduce network lifetime. Therefore, optimizing these metrics is crucial for ensuring the longevity and effective operation of real-world IoT systems.

5 Conclusions

In every topology, the placement of the sink node is crucial. According to the findings, both the topology mesh and random have much fewer average hops than the sink node placed in the corner. If we consider two different objective functions, the average packet delivered to the sink node is good in MRHOF compared to OF0, irrespective of the number of nodes. But in the OF0, the average packet delivery ratio is very high with respect to the number of nodes. Again, if we consider the average packet loss, the OF MRHOF plays a better objective function when the number of nodes is less. The OF-MRHOF performs well when the sink node is placed in the center, irrespective of the number of nodes and topology. The objective function OF0 gives better results when the number of nodes is smaller. But considering the placement of the sink node in the center or corner, the packet lost is high in OF0. Considering the power consumption, the total average power consumption is nearly the same, with no significant difference with different topologies, placement of the nodes, or objective functions. In conclusion, it can be observed that the objective function has superior performance in networks of moderate size. The aforementioned scenarios are specifically examined within the context of random topologies. The mesh topology is associated with a decrease in energy consumption.

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Biographies

Mahendra Shridhar Naik is a Senior Assistant Professor in the Department of Electronics and Communication Engineering at New Horizon College of Engineering, Bengaluru, Karnataka, India. He holds an M.Tech in Digital Electronics and Communication Engineering and a Bachelor of Engineering in Electronics and Communication Engineering, both from Visvesvaraya Technological University, Belagavi, Karnataka, India. With over ten years of academic experience, his research interests encompass IoT, Wireless Sensor Networks, Communication, VLSI, Artificial Intelligence, Machine Learning, and Deep Learning. He has published extensively in reputable journals and holds multiple patents in the field of Intellectual Property Rights.

Ms. Chaitra S. N. is a Senior Assistant Professor in the Department of Electronics and Communication Engineering at GM Institute of Technology, Davangere, Karnataka, India. She earned her M.Tech in Digital Electronics and Communication Engineering and her Bachelor of Engineering in Telecommunication Engineering, both from Visvesvaraya Technological University, Belagavi, Karnataka, India, where she is currently pursuing her Ph.D. With over a decade of academic experience, her research interests lie in IoT, Wireless Sensor Networks, Communication, and VLSI. She has contributed to the field through publications in reputable journals and holds multiple patents in Intellectual Property Rights.

Dr. Amit Kumar K. is a Senior Assistant Professor in the Dept. of Electronics & Communication Engineering at Mangalore Institute of Technology & Engineering, Moodabidre, Mangalore, Karnataka, India. He holds a PhD degree Image Processing. He earned his M.Tech in VLSI Design and Embedded Systems and his Bachelor of Engineering in Electronics and Communication Engineering, both from Visvesvaraya Technological University, Belagavi, Karnataka, India. His research interests lie in IoT, Wireless Sensor Networks, Communication, and VLSI. He has contributed to the field through publications in reputable journals and holds multiple patents.