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Network Performance Enhancement of Multi-sink Enabled Low Power Lossy Networks in SDN Based Internet of Things

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Abstract
Software Defined Network (SDN) brought revolution in the network field with the partnership of Academia and Industry. SDN bridges the gap to overcome issues of IoT deployment, optimization and better utilization of network resources. The escalation in resource congestion in Wireless Sensor Networks (WSNs) can usually lead to scalability, data computation or storage, and energy efficiency problems with only a single sink node for data acquisition. Internet of Things (IoT) has resource and energy constraints for WSN devices. Low Power and Lossy Networks (LLNs) ought to be optimized for traffic with multiple sinks. RPL routing has constraints to support this approach. However, RPL inherits the ability to offer features like Auto-Configuration, Self-Healing, Loop avoidance, and detection. These features of RPL can be transformed into the improved performance of a WSN by increasing the number of sinks with a linear increase of data transmitting nodes in the network. Further, to mitigate the escalated computing needs, edge computing has emerged as a new paradigm to resolve SDN-enabled IoT and localized computing needs. This study proposes an SDN-based solution to the interconnectivity of resource constraint LLN devices with edge computing routers in mesh and cluster topological scenario using RPL as IoT routing protocol. Performance evaluation concerning different routing metrics and objective functions: Minimum Rank with Hysteresis Function (MRHOF) and Zero (OF0) are analyzed. COOJA simulator is used for emulation of random as well as linear grid topologies for the creation of WSN static nodes. Simulation results confirm that the gradual increase of a number of nodes from 16, 32, 48, 64 and a simultaneous increase in sinks nodes as 1, 2, 3, 4 respectively in LLN network reflects the desired advantages with the stable network.

Keywords Internet of thing · Multi-sink · Constrained devices · LLNs · RPLs · DODAG · Edge computing · CoAP · MQTT · SDN

Extended author information available on the last page of the article

1 Introduction

Information and Communication Technology (ICT) revolution and the Internet of things (IoT) mark the dawn of the future Internet. IoT is an idea to revolutionize the lifestyle with minimum or no human intervention, with a vision of embedded devices in everyday life objects [1, 2]. IoT witnessed the integration of a wide variety of sensors, actuators, systems, and environments taking advantage of IoT elemental process as shown in Fig. 1 [2]. IoT promises huge changes in almost every field from agriculture to health care providing information with a network of interconnected sensors. Different surveys advocate that IoT will immensely develop in the coming years. Huawei forecasts 100 billion IoT connected devices by 2025 [4]. McKinsey Global Institute [3] suggests that the financial impact of IoT on the global economy may be as much as $3.9 to $11.1 trillion by 2025.

IoT applications are non-negotiable and critically time-sensitive with very short response times (smart transportation [1], smart electricity grid [2, 3] smart city [4–6] and cannot be provisioned on conventional cloud computing-based facilities. Also, most of the IoT devices have limited power; it, therefore, necessitates to balance power consumption by scheduling computation to devices. In IoT, millions of sensors/devices are deployed in a wide area network such as IoT gateways, cloud/core network, etc. So, due to this rapid increase in the number of mobile devices, it is necessary to incorporate edge computing networks to address the challenge of QoS issues [7–9].

WSNs as a subset of LLNs has been deliberated as primeval part of the smart grid and smart environment such as smart homes, buildings, and cities [4, 5]. A typical LLN encompasses a resource-constrained node called sink that collects data from numerous data sources. The average number of hops between source nodes and the sink will rise with the increase in the size of the network. This will result in more consumption of energy, further packet loss and consequently, will reduce the lifetime of the sensor nodes. It is, therefore, necessary that hop distance between a sensor and the destination sink should be kept as small as possible. Authors in [6] provide a solution to this issue by increasing the number of sinks proportionate to the network scalability of LLN nodes where each device node has access to communicate with the nearest sink. It has resulted in the performance optimization of the WSN regarding lifetime, bandwidth, packet loss, etc. Installation of more sinks at different locations in the network will cause the average number of hops to reduce and accordingly will result in enhancement of performance as well as a decrease in energy consumption of LLN. The sensor node traffic load can also be spread over all sinks in a scalable network that will reduce traffic load on the nodes which was otherwise exaggerated earlier on

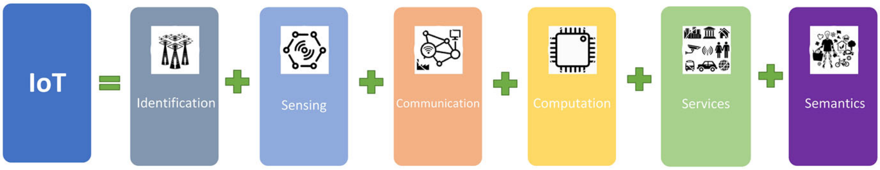

Fig. 1 IoT Elemental Process [3]

a single node environment. It results in the enhancement of network lifetime. In this paper, we highlight the significance of increasing the number of sinks as the LLN nodes increase randomly or in a symmetric grid fashion. SDN [7] in the background of the IoT deliver an indication of RPL with Tiny Software Defined Network protocols. SDN examines the routing characteristics, interoperability features, and support possibilities to legacy networks. RPL with TinySDN conclude in this study to SDN could enhance WSN and IoT implementations [8].

The remainder of this paper is structured as follows: In Sect. 2, we present the general overview of historical IoT including constrained devices family, IoT network protocol stack, and other basic concepts. It also includes the requirements and key challenges for routing protocols. In Sect. 3, Low-Power and Lossy Networks (LLNs) classifications are discussed. Sect. 4 is dedicated to (RPL) background, basic concepts, specification and other structural aspects. In Sect. 5 we introduce our proposed objective function and network framework and evaluate its performance against the contemporary literature while measuring parameters such as packet delivery ratio, power consumption, and churn. Finally, conclusion and future work are presented.

1.1 General Overview of Internet of Things

1.1.1 Devices Family of the Internet of Things

Devices in LLNs perform as data originators as well as data routers. Many routing protocols are proposed for LLNs in general and WSNs in particular [9]. These routing protocols only provide routing within the network, and the devices are not directly accessible through the Internet. Low power, ROM/RAM size and CPU specification categorize the constrained devices. LLNs is the best suitable network for these devices. LLNs networks are commonly resource controlled and restricted with limited bandwidth and highly dynamic topologies [9]. Constrained devices may be under control of processing information, sending, and receiving in any network. Now days, devices of different kinds are available with different functions, capabilities, and limitations. Some of these devices as described by [10] have the following properties:

- High-packet-loss
- Constrained on IP for multicast
- Larger packets usage consequences

On the base of features, Light Weight Implementation Guidance (LWIG) working group of Internet Engineering Task Force (IETF) segregated devices into diverse classes as illustrated in Table 1 [11, 12].

1.2 Internet of Things Network Stack

Internet of things presents a very promising wireless communication protocol stack to enable its framework applications on a broader scale for technically viable communication architecture capable of supporting the significant energy and connectivity needs of the emerging IoT [10]. It encounters the important criteria of power proficiency,

Table 1 Classes of constrained devices with control of processing information (1 KiB = 1024 bytes)

Group	Name	Data size (e.g., RAM)	Code size (e.g., Flash)	Remarks/examples
M	Class 0, C0	$\ll$ 10 KiB	$\ll$ 100 KiB	Too small to securely run on the internet depends on proxies for secure internet inclusion
M	Class 1, C1	~ 10 KiB	~ 100 KiB	~ 10 KiB data, ~ 100 KiB code "quite constrained" only low resource protocols
M	Class 2, C2	~ 50 KiB	~ 250 KiB	~ 50 KiB data, ~ 250 KiB code "not so constrained" can run most Internet protocols
J	Class 10, C10	4–8 MiB	(?)	OpenWRT routers
J		Fill in useful	J-group classes	–
J	Class 13, C13	0.5–1 GiB	(lots)	Raspberry PI
J	Class 15, C15	1–2 GiB	(lots)	Smartphones
J	Class 16, C16	4–32 GiB	(lots)	Laptops
	Class 19, C19	(lots)	(lots)	Servers

reliability, and Internet connectivity, and has become the de-facto standard, thereby bootstrapping early IoT developments with already deployed thousands of wireless nodes. Figure 2 exhibits its protocol stack in comparison with that of the traditional Internet.

In contrast to the traditional Internet, IoT has to be implemented in real time scenarios with constrained environments, i.e., using constraint devices in terms of power and energy. IoT merges wireless sensor networks with traditional networks resulting in a heterogeneous infrastructure. This heterogeneous network can have both constrained devices (w.r.t. resources) as well as resourceful devices. However, the majority of cases demand constrained devices. These constrained devices require more sophisticated IoT protocols, which can be used within any constrained environment [13]. To make devices energy efficient, they have been standardized by IEEE 802.15.4 standard, for the operation of low-rate wireless personal area networks.

Among these IoT protocols, IPv6 over Low power Wireless Personal Area Networks (6LOWPAN) and Routing Protocol for Low Energy Lossy Networks [14, 15]. (RPL) works at the Network layer, Constrained Application Protocol (CoAP) at the Application layer and IEEE 802.15.4 at the Link layer. CoAP is one of the proto-

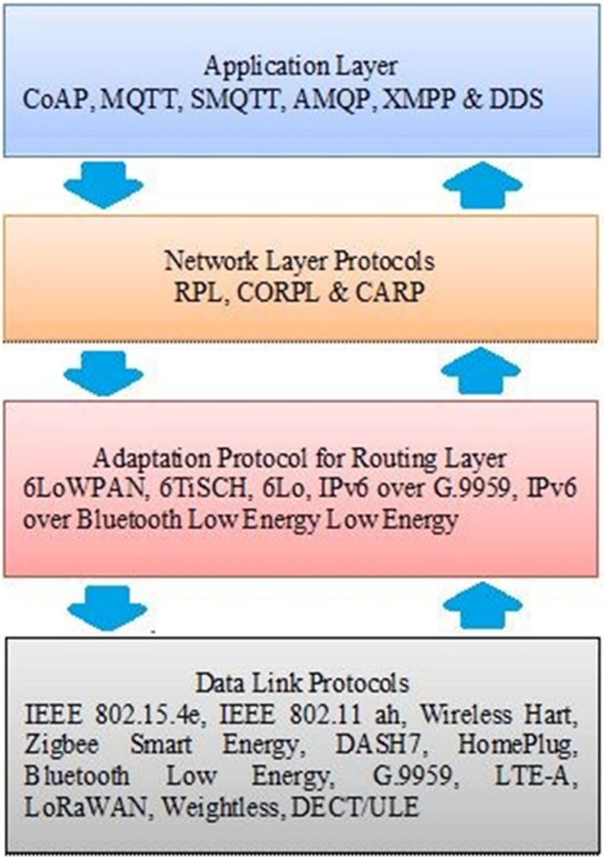

Fig. 2 Protocol Stack for IoT and traditional Internet

cols designed for LLN [6, 13] that makes communication possible between different devices at the Application layer. It has RESTful architecture having additional support for multicast and low overhead [16]. RPL is an IPv6 protocol for LLN which enables point to multipoint (P2MP) from devices to LLN central point and from central point to devices [multipoint to point (MP2P)]. 6LOWPAN uses adaptation for IPv6 Network layer which has the capability of auto-configuration of neighbors through neighbor discovery, and it has inbuilt support for IEEE 805.11.4 regarding fragmentation and addressing schemes [17, 18]. The traditional network differs from the IoT as shown in Fig. 2. Physical and Data Link Layers in IEEE 802.15.4 standards have been improved for energy-efficiency, and the capability to be deployed at Maximum Transmission Unit (MTU) up to 127 bytes on cheap devices.

1.3 Placement of Edge Computing in IoT

The IoT now embraces our daily lives by providing measurement and collection tools to appraise our decisions because millions of sensors, things and devices are produc-

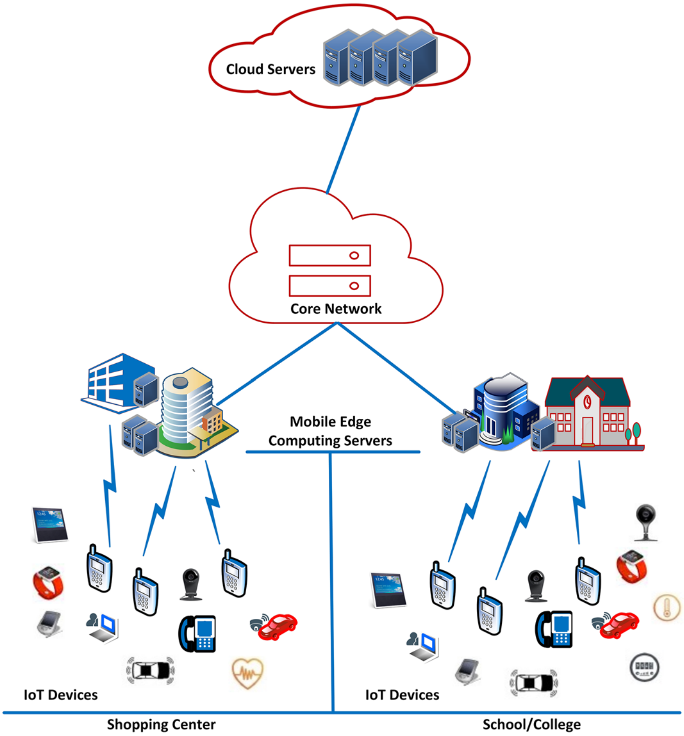

Fig. 3 Architecture to Enable Mobile Edge Computing

ing a constant amount of data and are exchanging messages via complex networks. These smart-world infrastructure networks are supported with machine-to-machine communication and monitored and controlled very critically. Strategically, to mitigate the escalation in resource congestion, a new paradigm known as edge computing has emerged to solve IoT and data computation requirements. Compared with cloud computing, edge computing will mitigate data computation or storage to the network "edge," near the end users [11, 12].

Edge Computing is the business-oriented model used as the enabling cloud computing platform for IoT environment. It lies within the range of radio access network and interfaces to the LLN network as depicted in Fig. 3. The network lies in the closed proximity of mobile users and subscribers for serving context-aware delay-sensitive applications (Table 2).

LLNs are met with different application scenarios of routing requirements such as urban low power networks, home automation or building automation [13, 18, 19].

In Table 2 IoT protocol applications requirements are generally characterized on the basis of network size, patterns and traffic flow and mobility. Despite these differences, the domains of their requirements can be categorized into four categories. First one is the traffic pattern of the IoT deployment area under consideration. Second is the energy efficiency of the deployed battery-driven LLN nodes for extended periods of time running autonomously. Next is the scalability of the protocol to increase a network size ranging from 100 to ranging 1,000,000 nodes. The last one is the measure of

Table 2 Characteristics of IoT, edge and cloud computing

Characteristics	Deployment	Components	Computations	Storage	Response time	Big data
Framework						
Internet of things	Distributed	Physical devices	Limited	Small	NA	Source
Edge computing	Distributed	Edge nodes	Limited	Limited	Fast	Process
Cloud computing	Centralized	Virtual resources	Unlimited	Unlimited	Slow	Process

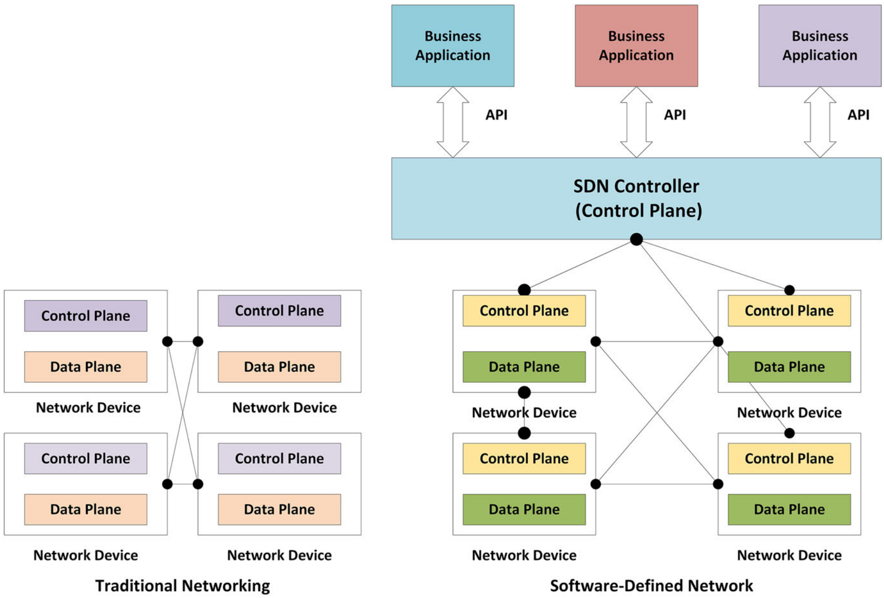

Fig. 4 Software Defined Networking vs Traditional Networking [20]

performance in terms of memory usage as well as mobility to cope with single node converge with location changes.

Open Networking foundation defines the SDN as the separation of the data and control planes as shown in Fig. 4. Moreover, the network state and intelligence are virtually centralized using the application abstraction for the infrastructure of the underlying network [21].

1.4 Low Power and Lossy Networks (LLNS)

Figure 5 illustrates LLN with constrained-resource routers and tiny devices. LLN working is characterized by devices memory, energy (battery power) and processing

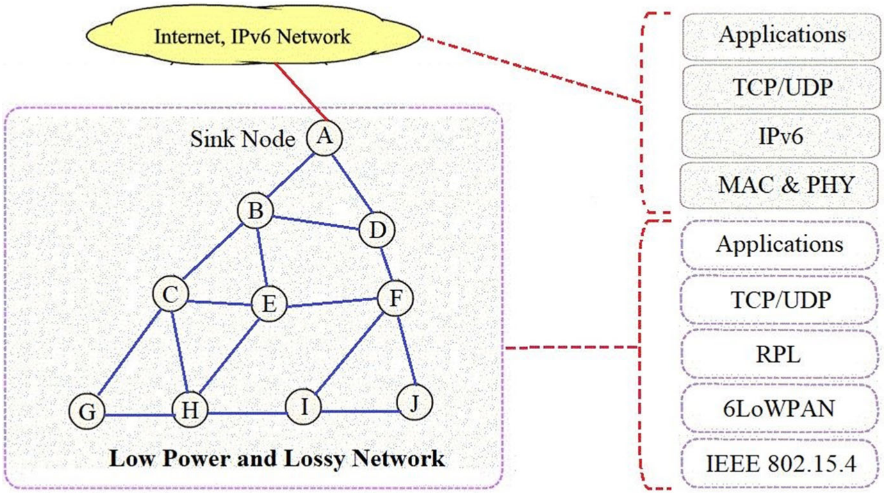

Fig. 5 LLN Architecture

power while their constituent components are distinguished by low data rates, high loss rates, and instability.

LLNs use IoT RPL protocol that makes use of distance vector routing mechanism for path calculations and creation of multi-hop WSN networks [22]. RPL is principally augmented to route the data traffic in three requirements: (1) point-to-point (between devices inside the LLN); (2) multipoint-to-point (from RPL nodes towards a single central node); and (3) point-to-multipoint (from the single control node to a subset of RPL nodes inside LLN). WSN-LLN routing approach determines the quality and network lifetime. Following main goals are determined by RPL:

- Minimization of memory requirements (i.e., storage space to maintain routing tables and routing information)
- Adaptation of less complicated routing schemes and information forwarding strategies to enable the deployed nodes as compatible with constraints
- Reduction of overheads of signaling to keep down the energy consumption and bandwidth usage
- Restricted frame sizes distribution containing routing data to link layer
- Efficient discovery of suitable multi-hop radio links which are not included in a predefined topology

Furthermore, the RPL is optimized based on a particular Objective Function (OF) and then other OFs are employed for the evaluation of RPL performance to encounter different requisite requirements such as building-, home-, urban-automation environment and industry control [23, 24].

1.4.1 Constrained Node

LLN nodes exhibit constraints with small power, low memory, and energy (battery driven). Also, some of the characteristics such as weight and size are not obtainable.

The upper bound limits on processing power and memory lead to the constraints in code space, processing cycles, bandwidth, and energy optimization in the network usage which are the dominant LLN design considerations. Moreover, few-layer-2 constraints such as full connectivity and broadcast/multicast may be missing [9]. A constrained node network exhibits the following constrained characteristics with link layers commonly used on the Internet:

- Less throughput/bitrate
- Highly variable packet loss and delivery rate
- Asymmetrically high link features
- Severe disadvantages by using large fragmentation packets resulting in high packet loss at link-layer
- Reachability limit with time where numerous devices may be off-powered any time, but they intermittently can wake up and communicate for short-lived periods of time.
- Constraints on advanced services, e.g., IP multicast.

2 Literature Review

RPL is link-independent IPv6 routing protocol for LLNs, standardized by the IETF Routing over LLNs named as ROLL working group [9, 25]. In open source Contiki operating system, RPL is being used as the defacto routing protocol. It is a Distance Vector protocol and works proactively, i.e., with initiating of the RPL network it starts making the node routes. It is an appropriate protocol for Low Power Wireless Networks (LPWN) having insufficient resources, i.e., energy bandwidth and memory. IEEE 802.15.4 is its underlying physical and link layer protocol with data rate less than 250 kbps consequent with high loss rates and ensuring low data throughput. The applications of LLN network nodes with battery powered constrained devices to mandate the specific routing requirements [26]. IPv6 is being responsible for designing routing protocol which is suitable for LLN networks with resource constrained devices in a large number of applications such as urban automation, building, industrial and home. ROLL explored the contemporary routing protocols, such as Optimized Link State Routing (OSLR), Intermediate System to Intermediate System (IS–IS) and Open Shortest Path First (OSPF). It is determined that no one standard among these can completely outfit routing requirements of LLN, consequently, ROLL intended to design RPL [27–29]. Cloud computing is another counterpart in edge computing that complements the service layer to ensure the provisioning of services by the servers' infrastructure and maintenance staff to their clients. Jabbar et al. [30] suggested a model in their work that helps the cloud service users to find out an efficient and trustworthy cloud services provider.

While taking into consideration mobile edge computing, mobile cloud computing (MCC) has been witnessed as another emerging contemporary domain to improve the mobile quality of service. In [31] an architecture of sharing hierarchical resources based mechanism has been proposed. It comprises the gateway server, local ISP server, and global cloud server. This unique effort anticipates a considerable latency in the network constructed on the base of deploying foglets for the clustering mechanism of each proposed algorithm.

Table 3 Types of Internet Control Message Protocol version 6 (ICMPv6)

Sr. No.	Control Message Type Code	RPL Code	Control Code Description
1	DIS	0 × 00	Information Solicitation of DODAG
2	DIO	0 × 01	Information Object of DODAG
3	DAO	0 × 02	Destination Advertisement Object
4	DAO-Ack	0 × 03	Destination Advertisement Object Acknowledgment
5	S-DIS	0 × 80	Secure DODAG Information Solicitation
6	S-DIO	0 × 81	Secure DODAG Information Object
7	S-DAO	0 × 82	Secure Destination Advertisement Object
8	S-DAO-Ack	0 × 83	Secure Destination Advertisement Object Acknowledgment
9	CC	0 × 8A	Consistency Check

An added endeavor of significant concern is to improve network lifetime and throughput in WSNs. Different energy efficient routing schemes have been exercised, and one out of many is apprehended [32]. This scheme proposes energy efficient multilayer cluster design for the selection of forwarding node in both intra-cluster and inters routing cluster heads rotation.

2.1 RPL Topology Concepts

RPL is a routing protocol with a proactive strategy; so, it builds the topology and maintains the topology to deliver always-on network devices for routing. The devices are interconnected through RPL using an explicit topology. This topology connects the mesh and tree topologies called Destination Oriented Directed Acyclic Graphs (DODAG). DODAG is a goal-oriented network topology in which all links between nodes have specified direction towards DODAG root as illustrated in Fig. 6 [33]. Each LLN RPL router recognizes some sustainable parents that all are the expected next hop for the path toward the "root" of the DODAG. The root node has no outgoing edges, and each DAG requires at least one root. Based on a predefined metric, one of the parents is selected as the "preferred parent" toward the root. A DAG root is a node within the DAG that has no outgoing edge.

In this network several DODAGs are identified by the following parameters:

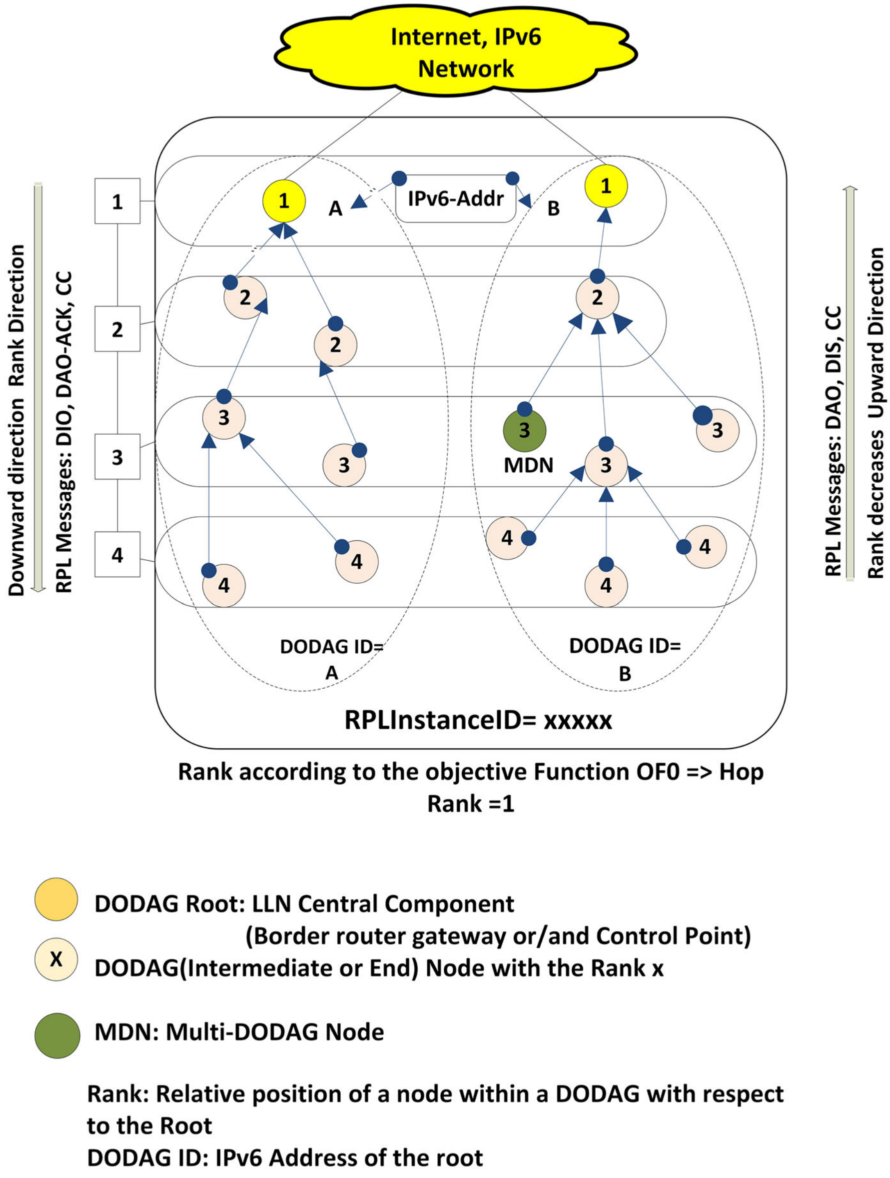

Fig. 6 Illustration of different operations of the RPL mechanism [27]

1. *RPLInstanceID* identifies an independent set of one or more DODAGs that are optimized and DODAG linked with RPL. Each RPL Instance functions independently of other RPL Instances.
2. *DODAGID* unique id in the scope of an RPLInstanceID in the LLNs and is an identifier of a DODAG root. The tuple (RPLInstanceID, DODAGID) uniquely identifies a DODAG.

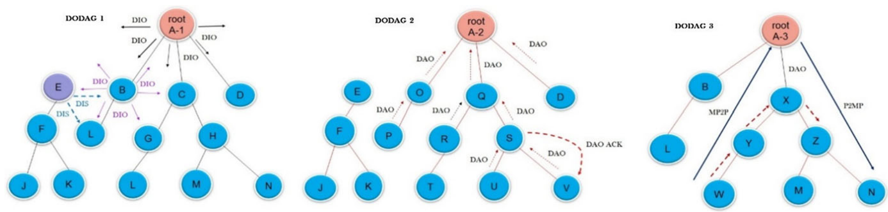

Fig. 7 A typical RPL Instance comprising three DODAGs with DODAG roots A-1, A-2, and A-3

3. *DODAG Version Number* named as a sequential counter which incremented by the root upon some specific events to form a new Version of a DODAG.

A node's Rank describes the location of a specific node concerning other nodes in its vicinity and concerning a DODAG root. Rank strictly increases downwards and strictly decreases upwards. A rank is an integer number, demonstrating nodes' location within a DODAG version. In the construction process of network topology, the exact way Rank is computed depends on the DAG's Objective Function (OF), whereby each outer associate with a preferred parent. The Rank can be linked to metric function, topological distance, and constraints. Accordingly, the objective function calculates a rank value based on the predefined metrics(s), such as delay, link quality, and connectivity [34, 35]. The default RPL implementation is founded on the Expected Number of Transmission (ETX) metric [36]. In Fig. 7, Nodes L and M have higher ranks (=3) than Nodes G and H (=2), and Node G and H have higher ranks than Node C (rank = 1). Upward traffic indicates the traffic from routers toward the root node, and downward traffic indicates the traffic direction from the root toward a router node. Therefore, the DODAG parent's Rank is lower than the nodes.

RFC 2463 [28] initially defined Internet Control Message Protocol version 6 (ICMPv6) Type 155 RPL control messages as shown in Table 3 and depicted in Fig. 7. The Code field identifies the type of RPL control message.

Four types of control messages defined in RPL are DIS, DIO, DAO-ACK, and DAO, already described in Table 3 are defined as follows:

(a) DIO (DODAG Information Object) message

DIO plays an important role by helping nodes in discovering different RPL Instances with their configuration parameters and in constructing a DODAG. The transmission of DIO message is issued by the root or sink node and then multicast by other nodes. DIO Message Format is shown in Fig. 8.

(b) DIS (DODAG Information Solicitation)

A node that requires a DIO message from neighbors requests it by multicasting DODAG Information Solicitation (DIS) message as shown in Fig. 9.

(c) DAO (Destination Advertisement Object)

Each node propagates a Destination Advertisement Object (DAO) message upward towards the root. Thus, this message enables the downward traffic from the root through the DODAG to this node as shown in Fig. 10.

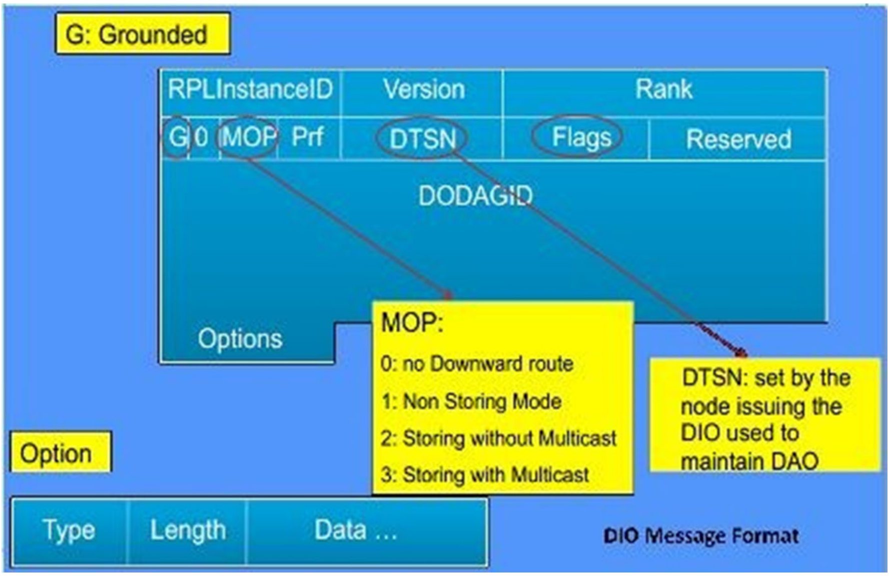

Fig. 8 DIO Message Format

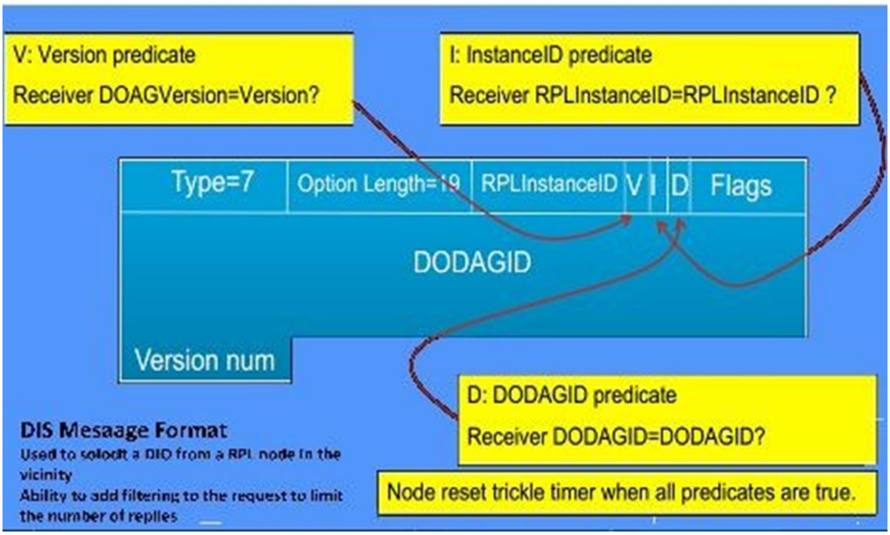

Fig. 9 DIO Message Format

(d) DAO-ACK (Destination Advertisement Object Acknowledgment)

The DAO-ACK unicast packet message is sent by a DAO recipient DAO parent or DODAG root) as a reply to a unicast DAO message.

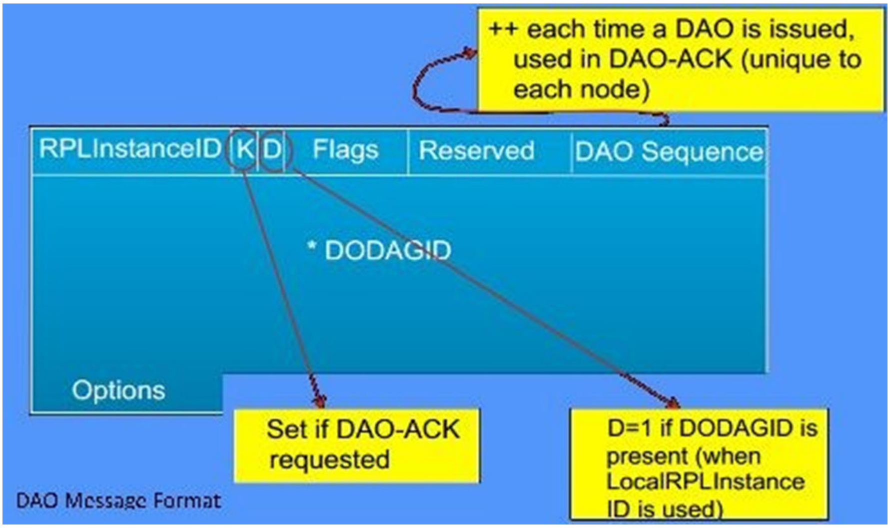

Fig. 10 DIO Message Format

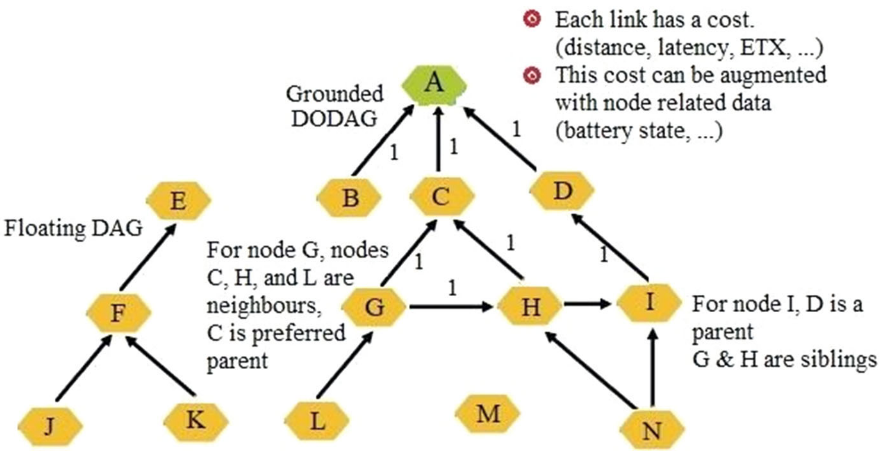

Fig. 11 DODAG building and maintenance topology

2.2 DODAG Building and Maintenance Model

In this section, the basic framework topology approach used in standard RPL is discussed. The work assumes that the network comprises multiple static nodes along with a sink. Network devices periodically issue the DIO and DAO messages to build the DODAG for network maintenance, as recommended by RPL protocol. Initially, the root starts broadcasting DIO message as illustrated in Fig. 11.

DIO message encompasses the RPL nodes' requisite information comprising of an RPL instance determination, configuration parameters and parent set selection, and DODAG graph construction. Upon receiving a DIO message, a node takes into account the objective function referred to in DIO message and accordingly adds the DIO sender to its parent's list and calculates its rank. The position of a node in the graph determines its rank of the DODAG nodes concerning the root which is all the time be higher than the rank of its parent's node. This shows that the DAG is always an acyclic graph. Then, this node multicast its updated DIO packets to its neighbors. When the DIO messages are received to the neighboring nodes, ranks are updated after accepting the DIO by these nodes which enable DODAG construction, and selection of the preferred parent depending on best rank. The nodes in the vicinity send DAO messages immediately to preferred parent nodes which so that they have joined the network.

Preferred parents in the constructed DODAG become the default gateways to the sink. The sink is now the preferred parent for all LLN devices at hop 1. Now, hop 1 devices broadcast DIOs while DAOs are sent back to their preferred parents. After the completion of this process of DODAG construction, the participating devices are included in upward default route to the DODAG sink. Similarly, all preferred parents compose the route.

2.3 Objective Function

An Objective Functions (OF) in RPL is an outcome of a process used by LLN nodes for the selection and optimization of routes in RPL instances. It tells that how to compute ranks by optimizing the routing metrics and how the parents are selected in DODAG construction in various topologies, i.e., random as well as a grid. Two kinds of objective functions are used in RPL, (1) Minimum Rank with Hysteresis Objective Function (MRHOF), which a little complex and computes ranks of the nodes based on additive metrics [37]. It is used for Expected Transmission Count (ETX). (2) Objective Function Zero (OFO), chosen as a default function which does not measure any metric. It uses the Hop Count (HC) in Rank calculation [38]. It is used as a path selection mechanism used during the formation of the networks.

ETX is the packet frame transmissions number delivered over the link by a node **x** to node **y** which can be calculated as in Eq. (1):

$$ETX = \frac{1}{(dxy \times dyx)} \tag{1}$$

where dxy and dyx represent the probabilities of neighbors' packet receiving to a node, and successful receipt acknowledged by that node respectively.

A precise packet is a multicast per second by every node to its neighbors, and after every duration of 0 s the received packets are counted by the receiver, which is given in Eq. (2):

$$dxy = \frac{(frames\ received\ \|y\|x)}{10} \tag{2}$$

Node **n** calculates its rank as given in Eq. (3):

$$Rn = Rp + ETX \tag{3}$$

where Rn and Rp are the ranks of the sending nodes and parent nodes respectively, and ETX belongs to the parent.

If Rn is different from the already calculated Rn of a node, it declares that packet receiving node as its parent with its rank Rp.

In hop count for every LLN device computes its rank after receiving the rank of its parent device. Rank of a device is equal to the sum of its parent rank and DEFAULT_MIN_HOP_RANK_INCREASE (defined as 256 in RFC 6550) [14]. Equation 4 is used to calculate the HP rank:

$$\mathrm{Rn} = \mathrm{Rp} + \mathrm{DEFAULT\_MIN\_HOP\_RANK\_INCREASE} \tag{4}$$

2.4 A trip to RPL Multi-sink Deployment Scenarios

RPL supports the deployment of more than on sink (root nodes) within the network if the network is scalable. As the network increases, the number of nodes will be increased accordingly. The network may be deployed randomly in a grid fashion. The proactive routing approach is used in RPL where each node always maintains an active path to the sink.

In WSN deployment paradigm, a lot of analytic and simulation research is currently witnessed, especially the multiple sink networks are popular understudy area regarding performance. It has been observed in [39, 40] that performance with regards to connectivity, energy consumption and latency can be improved by adding and using multi-sinks when the network increases. For large-scale dense network implementations such as home environment, agricultural monitoring, and smart grid metering, RPL furnishes multiple DODAGs with more than one sink (LBR). If the network is connected with single sink adequately covering the whole area of deployment, even then it is strongly recommended to use the multiple sinks to attain resilience and robustness when there are sudden outages or breakdowns commonly observed with the sink.

Several studies for RPL multiple sinks network divulges that RPL has the problem of load imbalance, both with single DODAG as well as with multiple DODAGs. In a DODAG mechanism. To improve this issue, Kulkarni et al. proposed tree balancing algorithm (TREEB) that disseminates the DODAG size through DIO messages and by using new routing metric with both Ranks and DODAG size, it balances traffic load amongst DODAGs [41, 42]. Tree balancing application considerably brings down the imbalance between the PDR achieved by the different concentrators in contrast to the application with no tree balance. Minkeun Ha et al. proposed a dynamic and dynamic and distributed load balancing scheme named MLEq (Multi-gateway Load Balancing Scheme for Equilibrium), a mechanism with cross-DODAG load balance [43] in which each sink observes its traffic, contributes its traffic load with other sinks, and computes its entire traffic load. The sink then fixes the priority of its DODAG by matching the perfect load and the current load and disseminates the same through DIO messages. This information is used to select the parent for each node to achieve load balancing. Here, to share the link status and configure the DOADs in RPL, the DIO and DAO messages are sent periodically. Preetha Thulasiraman implemented the RPL protocol in a multi-gateway architecture and suggested the routing metric RI3M as the link metric for uplink traffic [37]. RI3M uses cross-DODAG load balancing to determine traffic load and interference [44]. However, the authors employed COOJA and NS-2 simulations to calculate their schemes without the implementation and experiments on LLN nodes.

Kulkarni et al. in [45, 46] proposed RPL PHY layer multi-channel scanning solutions for redundant sink deployments and access RPL-6LBR to support multi-DODAG. A node access to join the DODAG at second best channel if it loses connectivity at the currently operational channel. The authors used COOJA simulations on large-scale and testbed to comprehensively evaluate the scheme.

Laurent Deru et al. proves that each LBR is required to be re-allocated with a global address but if a unique DODAG ID is assigned to each border router then instead of intra-DODAG parent change, inter-DODAG parent change becomes more complex. The authors proposed that multiple BRs compatible with RPL must be able to co-exist in the same infrastructure and LLNs connected with different BRs should be able to share the same global address [47]. The paper [40] by Kevin Andrea and Robert Simon describes the Hierarchical network of Observable devices with Itinerant Sinks Transporting data (HOIST) protocol in which the authors proposed an RPL-friendly three-tier hybrid cluster-tree multi-sink network architecture for a monitoring system of an agricultural geographically segregated area. HOIST encompasses many WSN-LNN nodes, a mobile sink, and multiple static sinks. The static sensor nodes provide data over RPL to each sink that saves this data. This information is then passed to a mobile sink which after using a modified mobility scenario, passes through the deployed area. Small-scale COOJA simulations with four nodes (only) were performed in HOIST monitoring application.

Pathfinding process is another issue of energy constraint for resource deployment in WSNs to gear up the network performance efficiency. It frequently makes the WSN scavenging process inappropriate. An approach by Jabbar et al. is Enhanced Pheromone Heuristic Control (EPHC) function composed of heuristic probability functions for releasing the route from the motionless path. EPHC improves the WNS in respect of end to end delay, queuing delay and energy consumption [48]. In [44], Kim et al. illustrated the scenario with two sinks in Fig. 12 of RPL's DAG architecture having multi-DODAGs and multiple RPL instances that have their own route construction objective functions. Multiple instances even with the same destination, allow RPL to offer different route flows having different QoS parameters. In the perspective of Internet management, bandwidth and path diversity, the use of multiple DODAG roots with single flow through multiple sinks can be provided at multiple exit points.

3 Materials and Methods for Setup and Simulations-MERIoT-SDN

The proposed solution is Multi-sink Enabled RPL Network Performance Enhancement for Scalable Low Power Lossy Networks in the Internet of Things and Software Defined Networks (MERIoT-SDN). This WSNs enabled IoT setup comprises devices capable of sensing/actuation, communication, and processing. Standardization is considered as a challenge while deploying such networks. We, here discuss and propose

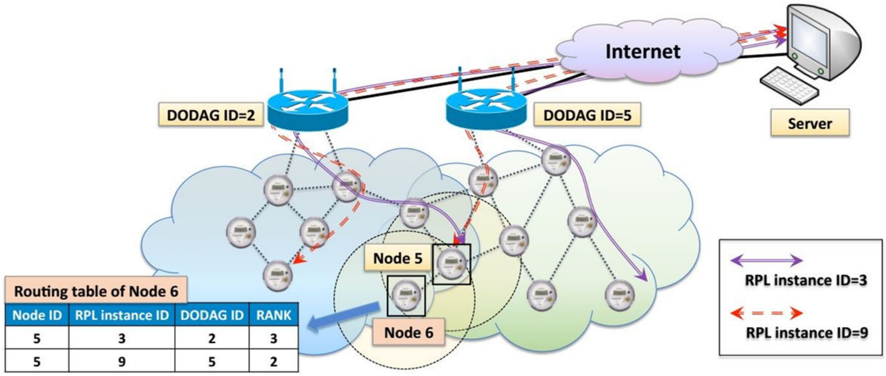

Fig. 12 RPL DAG architecture with multi-DODAG roots and multi-RPL instances [41]

an SDN enabled IoT which is virtually connected to a cloud. IoT can be regarded as a pervasive aid to the usual cloud which performs the monitoring and control through the collection, processing, and analysis of LLN devices' data. It, therefore, intends to employ interconnectivity of LLN device adapted with edge computing routers in mesh and cluster topological scenario using RPL as a routing protocol somewhat as the topology illustrated in Fig. 13 including the edge computing infrastructure shown in Table 4.

The proposed simulation-based IoT network environment is implemented in operating system Contiki (version 3.0) for result assessment and evaluation. This Contiki operating system is considered to run on constraint-based resource environment through restricted memory successfully. The COOJA simulator is embedded with Contiki is the best suited open source, lightweight and portable operating system dedicated to WSN and extensively used for IoT. It is a best-suited emulator for variations to the real systems before implementing it to real hardware as shown in Table 5. Very small as well as extensive networks of Contiki motes are easily simulated by Cooja simulator. Cooja is a highly expressive tool that helps researcher and developers to test their coding and on the hypothetical hardware, before running on the system. IoT protocols and tools are also supported by the Contiki like the 6LoWPAN adaptation layer, the IPv6 RPL protocol and the CoAP application layer. For our experiment, initially, we have designed a light density network of 16 Sky mote nodes with one sink.

We used two topologies simultaneously to distribute the nodes, i.e., random topology and grid topology for the same experiment. We set the UDGM transmitting model range to 50 meters and interference range to 100 meters. The Transmission Success Ratio (TX) was set to 100%, and we varied the Reception Success Ratio (RX) as 20%, 40%, 60%, 80% and 100%. Also, mote start-up delays were set to 1 ms and simulation results were collected after 1200 s with simulation speed of 100%. The above experiment was repeated as case 1, case 2, case 3, and case 4 by increasing the number of network nodes for 16 nodes with 1 sink, 32 nodes with 2 sinks, 48 nodes with 3 sinks and 64 nodes with 4 sinks respectively. Different positions of the sinks and senders were randomly chosen in the simulation.

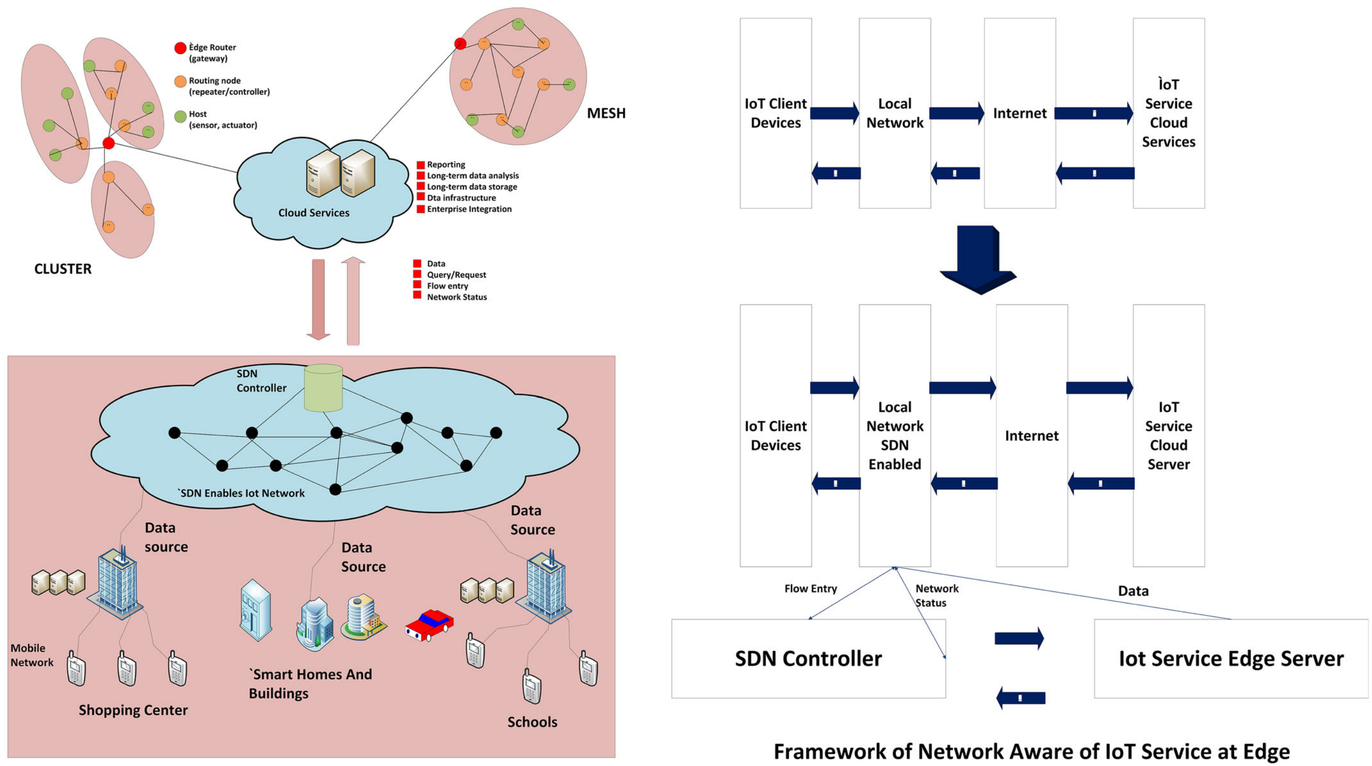

Fig. 13 MERIoT-SDN Framework for Edge Computing using RPL with Mesh, Cluster and other Topologies

Table 4 SDN-enabled IoT Network Framework for Edge Computing using RPL with Mesh and Cluster Topologies

Topology Applications	Cluster	Mesh
Type	Mesh to the gateway to cloud	ZigBee Pro
Usage	Client services to home	Home automation
Link type	Building control	Light link
Energy	LED lighting	Smart energy
Purpose	Safety, health	Routing/controllers
Host	–	Host for sensors

Table 5 Testbed for simulation used in Setup

Parameters	Table Value		
Network Simulator	Cooja under Contiki OS (3.0)		
Radio Environment	UDGM (Directed Graph Radio Medium) with Distance Interference		
Mote Type	Tmote Sky		
Number of Nodes	1	16 UDP sender nodes	1 sink node
	2	32 UDP sender nodes	2 sink nodes
	3	48 UDP sender nodes	3 sink nodes
	4	64 UDP sender nodes	4 sink nodes
Communication Range of nodes	Transmission range: 50 m interference range: 100 m		
Simulation Speed	100%		
Simulation Duration	20 min for each simulation		
Node Positions	Random as well as grid		
Objective Function	ETX, MRHOP		
MAC Protocol	CSMA/ContikiMAC		

The color scheme follows the step-wise creation of transmitting nodes following the distance as well as time optimization. The sink node is that root node where all the sender nodes and end devices transmit data for computing and try to join it. The deployed network has size scenario; nodes increase following random as well as grid topologies as illustrated in simulation network diagrams Figs. 14 and 15.

In actual scenarios, the random network topology is deployed in urban area where low latency communication is desired and where there is less chance of collision. To address such issues and to make our network energy efficient, we deploy grid topology in our testbed. Grid topology further enhances network reliability, safety and smooth integration with newly deployed potential network nodes [13].

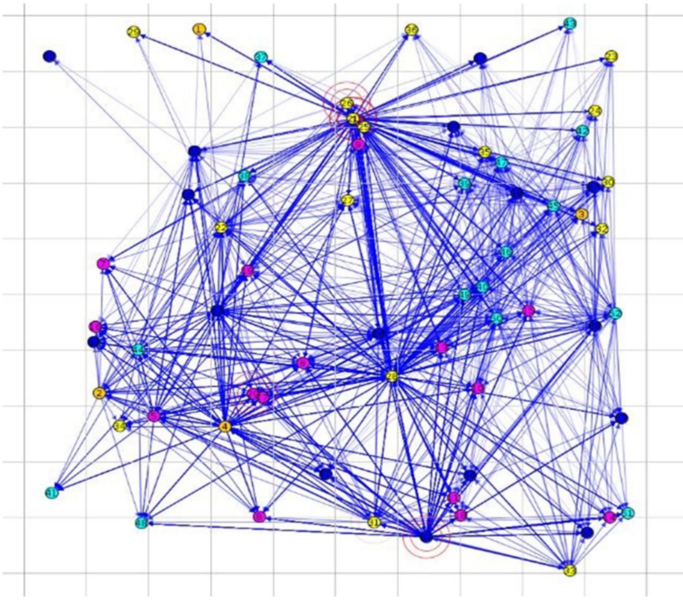

Fig. 14 Network deployment with 4 sinks and 64 random nodes topology

4 Results and Discussion

Software Defined Network controller performance in the proposed model is evaluated in different scenarios. First scenario, the number of packets required to be created in the DODAG is assessed. The number of packets required to construct in the DODAG in the traditional RPL and proposed RPL with and without SDN central controller evaluated. DODAG in each time reconstructed or created for both proposed-RPL and traditional RPL without the central controller. In different runs, a number of node and sinks are varying, which are compared and evaluated.

4.1 Performance Metrics

In the experiments we run, we have measured several metrics. We pinpoint the primary metrics for result evaluation of our research. Each metric will provide the essential properties which impacts result on the network layout topology and process. As described earlier in this paper, due to RPL specifications, which make it use more critical in its use concerning the network type, devices used and topology implemented. The proposed solution and scenario will discover the different variations in RPL performance conferring the following specific performance metrics.

- *PDR%* Packet Delivery Ratio is a measure of the ratio calculated by the formulae as given in the Eq. 5 in the MAC sublayer.

$$\text{Average PDR} = \frac{Total\ PacketReceived}{Total\ PocketSent} \times 100 \tag{5}$$

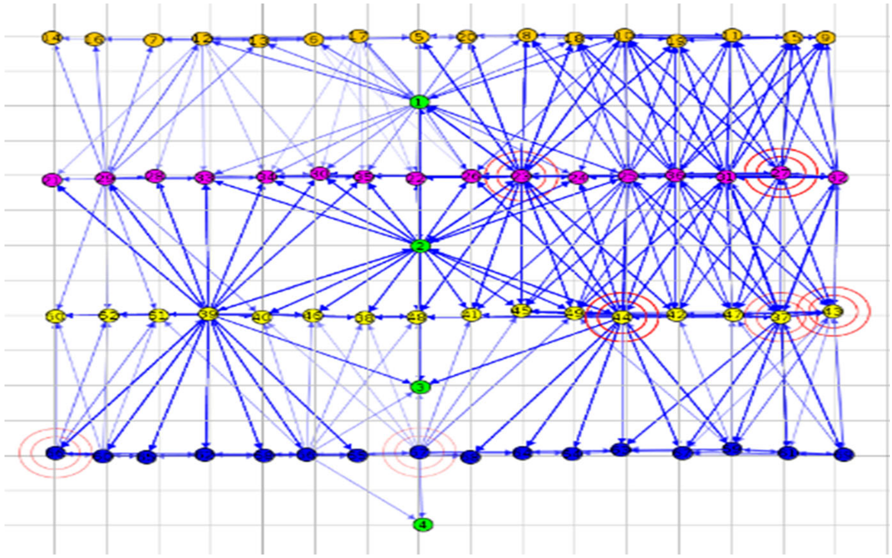

Fig. 15 Network deployment with 4 sinks and 64 grid nodes topology

- *Expected Transmission (ETX)* This is the max-number of the re-transmissions of an individual packet to be efficaciously delivered over a wireless network to the destination.
- *HC* The hop count metric signifies the number of hops between nodes like the root and candidate neighbor.
- *Energy Consumption* Measures the average energy consumed by the nodes to transport packets from nodes to sink node over the network in the lifetime.

By performing the comparative study of the above two scenarios, impact on the RPL routing behavior and network behavior has been observed by simultaneously considering all above performance metrics, i.e., the number of packets received and lost, ETX, number of Hops, Power Consumption and latency. The simulation results are computed with network deployment in Fibonacci sequence approach as well as in network deployment with random nodes. A reasonable network scalability optimization has been witnessed on our proposed simulation testbed, based on the analysis of RPL performance with better parameters' results.

$$Ws, d(x, r) = \frac{Pr}{r} x \tag{6}$$

whereas r is the rate of transmission of data, Pr is the power required to run circuit W s, d power need to transmission s to d x is the length of the packet in bits.

Equation 6 represents the energy required to transmit a packet within the network from source node s to destination node d [49]. This energy is consumed by the packet from source to destination in the receiving process.

Table 6 16 nodes network with 1 sink

	RX	PDR%	Average Power Consumption	Churn
Case 1	16 nodes network with 1 sink (random topology)			
	20	51	2.37	0
	40	57.4	2.518	0.375
	60	55.7	1.828	0.125
	80	45	2.205	0.188
	100	53	1.135	0
	16 nodes network with 1 sink (grid topology)			
	20	68	1.317	0
	40	68	1.35	0.375
	60	66	1.32	0.125
	80	65	1.209	0.188
	100	62	1.189	0

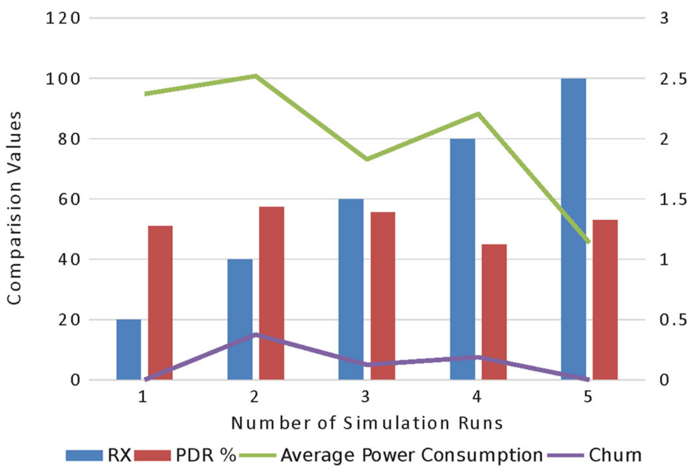

Fig. 16 Simulation with 16 nodes with 1 sink (Random Topology)

4.2 Performance Assessment in Network Scalability

In Table 6, we measure the PDR, average power consumption and churn for our 16-node network with 1 sink in random as well as grid topology respectively. By varying RX% with a gradual increase of 20%, 40%, 60%, 80% and 100%, we run the simulations. Figure 16 and Fig. 17 exhibit the obtained results. We observe that PDR in the random deployment was lower as compared to the PDR in grid topology network and this trend remain same when RX is increased from 20 to 100%. The packet reception in grid network is better.

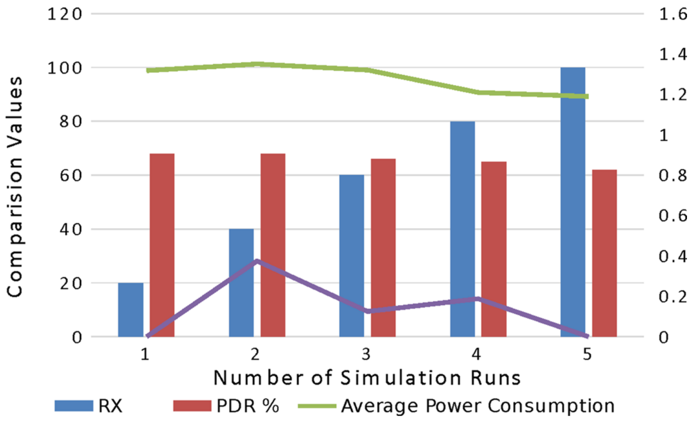

Fig. 17 Simulation with 16 nodes with 1 sink (Grid Topology)

Number of packets required to construct in the DODAG in the traditional RPL and proposed RPL with and without SDN central controller evaluated. DODAG in each time reconstructed or created for both proposed-RPL and traditional RPL without the central controller. In each node, the parameter used for the energy calculation is average energy dissipation. The average power consumption trend in the random network is higher while it remains lower in grid topology network which demonstrates the better performance of grid network. This parameter was witnessed with the same of simulation trend as the DODAG convergence observation trend.

Table 7 shows the network of 32 nodes network with 2 sinks. The corresponding Figs. 18 and 19 exhibit the PDR% comparison in both topologies. The PDR in grid network is the highest in grid network while the node energy consumption in grid network is very high in a random network with 32 nodes as it depicts the more average power consumption when RX increases from 20 to 40, 60, 80 and 100. Here one thing is worth to notes that churn in Table 7 of 32 nodes network with 2 sinks are more in the grid network. We observe that the churn increases as the RX% values increase and that churn in the random deployment was higher than the grid deployment. We notice that in most cases the proposed approach with more sinks in grid network is based on using MRHOF with ETX + Energy yielding better results compared to MRHOF with Energy metric and MRHOF with ETX metric.

In case 3 of Table 8 with 48 transmitting nodes and 3 sinks we observe the PDR% stability in both using random and grid topology networks even with the varying values of RX. This owes to the increase in some sinks. This behavior advocates the better performance results in grid topology with increase sinks regarding scalability and stability. Here again, we notice that MRHOF with ETX + Energy performed best with RX% set to 20–100% in the grid deployment. Here again, the churn increases with the increase in RX% values is witnessed in grid deployment and the churn in the random deployment at the lower side which show, the better performance of a grid network with increase sink nodes. Graphs in Figs. 20 and 21 depict this comparison.

Table 7 32 nodes network with 2 sinks

	RX	PDR%	Average Power Consumption	Churn
Case 2	32 nodes network with 2 sinks (random topology)			
	20	78	3.92	0.273
	40	71	1.236	0
	60	76	1.748	0.333
	80	74	1.412	0
	100	69	1.32	0.05
	32 nodes network with 2 sinks (grid topology)			
	20	99	60.7	0.267
	40	99	60.6	0.286
	60	99	60.7	0.077
	80	99	60.6	0
	100	99	60.7	0.073

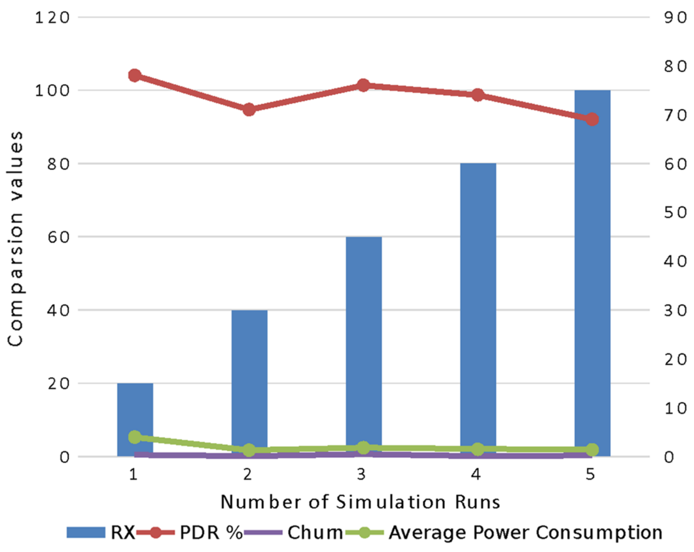

Fig. 18 Simulation with 32 nodes with 2 sinks (Random Topology)

The simulations in case 4 with results in Table 9, were repeated to recheck and confirm our observations even by further increasing the number of sinks in both topologies. Excellent results were found in the measure of PDR% with an increase in RX values. Average power consumption in both topologies is seemed astonishingly similar at random as well as grid deployments. Apparently, the churn stability trend is also very similar which tends to prove our concern of much better performance of the WSN

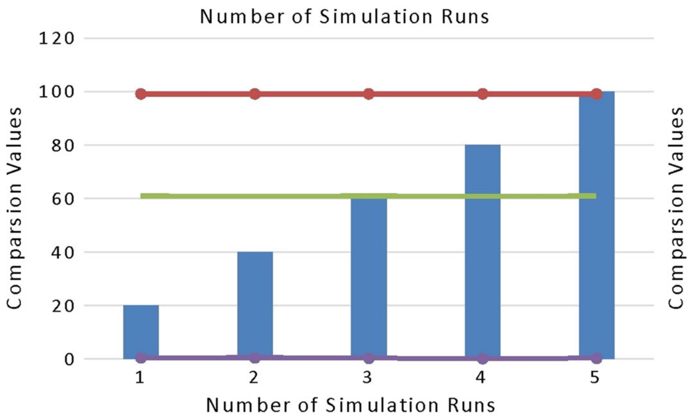

Fig. 19 Simulation with 32 nodes with 2 sinks (Grid Topology)

Table 8 48 nodes network with 3 sinks

	RX	PDR%	Average Power Consumption	Churn
Case 3	48 nodes network with 3 sinks (random topology)			
	20	98	60.67	0.83
	40	97	60.7	0.1
	60	98	60.7	0.118
	80	97	60.67	0
	100	96	60.67	0
	48 nodes network with 3 sinks (grid topology)			
	20	99	60.7	1.303
	40	99	60.8	0.714
	60	99	60.9	0.054
	80	99	60	0.094
	100	99	60.5	0.034

network by a gradual increase of sinks as the network grows. Figures 22 and 23 show this performance in both network topologies.

In general, we perceive that in the random as well as grid network deployment with low RX% the network performance is the poor concerning PDR, energy consumption, churn, and ETX and no improvement is observed by an increase in RX. Our proposed solution of increasing the number of sinks with scalable network deployed in both topologies improves the metrics and the MRHOF using ETX and energy in multiple sinks outperform default MRHOF using ETX and energy.

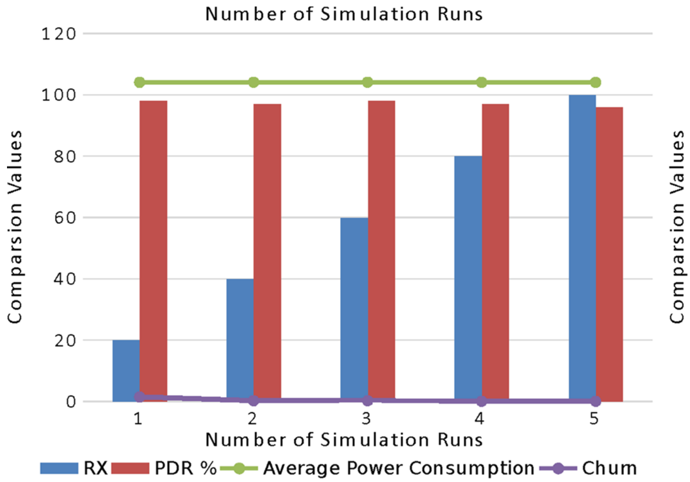

Fig. 20 Simulation with 48 nodes with 3 sinks (Grid Topology)

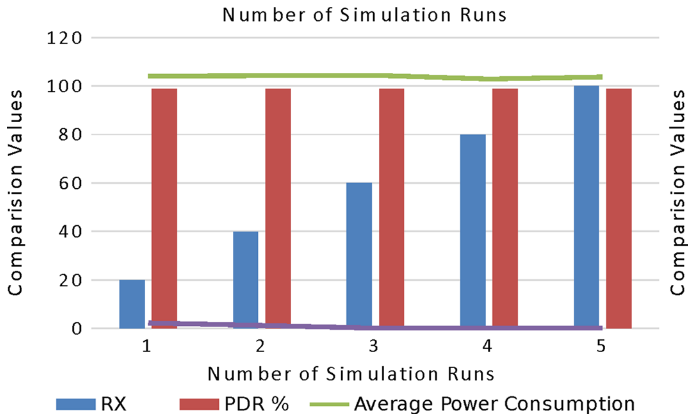

Fig. 21 Simulation with 48 nodes with 3 sinks (Grid Topology)

5 Conclusion

We intended to design a composite solution "MERIoT-SDN Framework" integrated with escalating edge for its nearby WSN-based end users. Here, edge computing is supposed to mitigate data computation and storage to the edge of the network, while using IoT routing protocol "RPL" in its local mesh, cluster and other IoT-edge integrated entities facilitate in the reduction of traffic flows of IoT devices to diminish their bandwidth requirements. SDN potentially provides centralized control, open interfaces and flexible links between nodes of the adaptive IoT network in an efficient way. We based on RPL default metric, Minimum Rank with Hysteresis Objective Function (MRHOF) to which we can modify to our desired specifications depending on the nature of WSN networks. We proved that as the networks escalate either randomly or following a grid, the impacts on data transmission and data acquisition pose

Table 9 64 nodes network with 4 sinks

	RX	PDR%	Average Power Consumption	Churn
Case 4	64 nodes network with 4 sinks (random topology)			
	20	99	60.7	0.13
	40	99	60.9	0
	60	99	60.8	0.071
	80	97	60.7	0.021
	100	96	65.7	0.001
	64 nodes network with 4 sinks (grid topology)			
	20	99	60.6	0.12
	40	99.8	60.7	0.002
	60	98	60.9	0.012
	80	97	60.5	0.017
	100	98	60.4	0.079

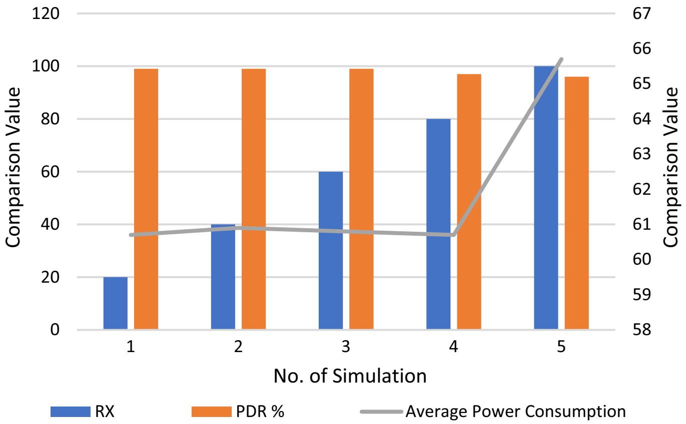

Fig. 22 Simulation with 64 nodes with 4 sinks (Random Topology)

constraints in default metrics conditions. In this paper, we perform modifications in MRHOF and ETX at the cost of PDR%, average power consumption and churn by gradually increasing the number of static sink nodes, proportionate to the network scale enhancement regardless of the network deployment topologies and patterns. We design this scalable medium to light density IoT network, and we implemented our work in Contiki3.0 COOJA simulator. We noticed that the performance of the network was enhanced regarding PDR, power consumption and churn in the network by using MRHOF with ETX and energy. This research discovers and demonstrates that the proposed technique can improve the performance of the network along with scalability in urban areas where population growth escalates exponentially either in random or grid

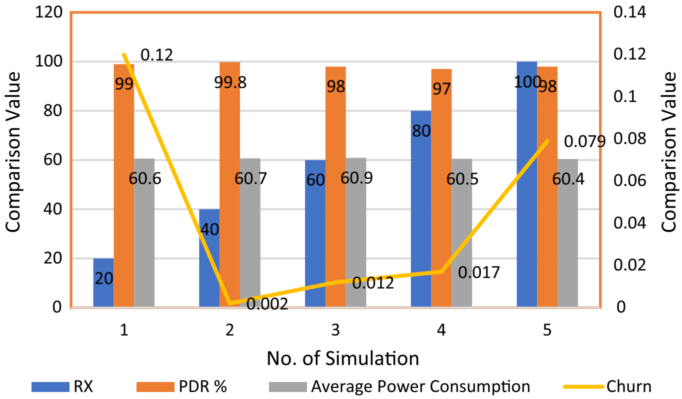

Fig. 23 Simulation with 64 nodes with 4 sinks (Grid Topology)

fashion. Moreover, the proposed technique is highly practical from an implementation perspective as a smart metering use-case in town planning. In the future, we intend to perform our proposed research to test the behavior of scalable WSN networks with multiple mobile sinks.

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