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An Analysis of Multicasting Optimisation Mechanisms for Intelligent Edge Computing with Low-Power and Lossy Networks

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***Abstract*—This work studies the built-in multicast model in Contiki OS to provide the basis of a comparative evaluation for a new optimisation model using Radio Duty Cycling (RDC) mechanism. A significant amount of energy is consumed at the edge node executing various multicast routing protocols in Low-Power and Lossy Networks (LLN). The optimisation of the routing protocol and selection of an efficient multicast transmission model has the potential to reduce energy consumption in Edge Computing (EC) enabled LLN. With the precise objective of reducing energy consumption, this paper utilises a well-known RDC technique in multicast communication scenarios. To this end, a series of experiments are conducted to evaluate the performance of the existing RDC mechanisms proposed in the literature. The evaluation results are then utilised to develop an efficient RDC-based multicast transmission model. The comparative performance analysis reveals a 23.7% reduction in the RDC rate compared to the traditional model, consequently improving the energy consumption of EC-enabled LLN.**

Keywords—Edge Computing, Multicasting, Energy Efficiency, RDC , RPL.

I. INTRODUCTION

The Internet of Things (IoT) information-sensing devices often referred to as low power and lossy networks (LLN) and equipped with non-replaceable, low-cost non-rechargeable batteries owing to either high replacement cost or strenuous human intervention when deployed in less approachable or inaccessible areas. The nodes in LLN, in addition, are characterised by limited resources including constrained computational capacity, restricted storage availability, and short communication range. Such limitations possess a great strain on designing efficient management of networking and sensing tasks including intelligent identification of nodes, mobility management, node positioning and tracking, environment monitoring and sensing, and preserving nodes' energy [1]. To cope with such limitations specifically to preserve nodes' energy thereby prolonging network lifetime and enabling sustained autonomous operations, Intelligent Edge Computing (IEC) enabled LLN utilises radio duty cycling (RDC) mechanism [2]. The RDC technique puts nodes into low-power sleep mode during an inactive period such as in the absence of any sensing, monitoring, or communication tasks, and subsequently activates them periodically to perform the necessary tasks.

Various unicast such as X-MAC and low power probing (LPP) and multicast such as ContikiniMAC RDC mechanisms are proposed in the literature as means to preserve energy consumption in IEC-enabled LLN. The multicast communication mode suits well in LLN as an optimal subset of network nodes is selected to participate in the communication that guarantees network connectivity and end-to-end sensory packet delivery. Multiple transmission nodes empower the network to selectively activate a further subset of nodes to forward the packet while putting the remaining nodes in a low-power state to conserve energy. This infers that energy preservation is primarily dependent on the sleep and awake cycle of the network nodes. A lower RDC value corresponds to higher energy preservation, and conversely, a higher RDC value indicates lower energy preservation. It is worth mentioning here that RDC frequency and the synchronisation of the sleep-awake cycle amongst nodes participating in transmission can not only greatly impact energy consumption based on network statistics or measurements but may also lead to packet loss.

However, the traditional RDC mechanisms in multicast mode are still not thoroughly examined and require further research efforts which serves as a motivation for our paper. The overarching objective of this research work is to conduct a thorough examination leading to the development of an appropriate multicast communication protocol for LLN (MPL) in IEC scenarios that ensure a further reduction in the RDC rate to conserve energy. To this end, at first, a series of simulation-based experiments are conducted in the Cooja simulator based on Contiki Operating System (Contiki OS) to perform the evaluations of the existing RDC mechanisms. The existing RDC approaches include NullRDC, XMAC, CXMAC and ContikiMAC RDC mechanisms in the RPL-UDP transmission model. The results obtained through experiments are then thoroughly analysed aiming to propose an optimised multicast transmission model ensuring the reduced RDC rate. In summary, the following are the core contribution of this paper.

- A basic background covering details on routing for IEC-enabled LLN, and multicast communication and a specific description of the working principles of multicast protocol and RDC are presented.

- A series of experiments are conducted in the Cooja simulator to evaluate the performance of various RDC mechanisms in multicast communication scenarios.
- The evaluation results are utilised to develop an optimised multicast transmission model with the objective of further decreasing the RDC rate to conserve overall network energy.
- Finally, a comparative performance analysis is carried out to demonstrate the effectiveness of the proposed model.

The rest of the paper is organized as follows. A basic background in the context of IEC-enabled EC and multicast communication is presented in Section II. Section III covers specific details on multicast protocols and the RDC mechanism. Section IV presents the design and implementation of the existing RDC mechanism describing the series of experiments designed in the Contiki OS-based Cooja simulator. Section V presents the analysis of the results obtained through experiments, describe the proposed optimised RDC-based multicast transmission model, and a comparative performance analysis that reveals the effectiveness of the proposed model. Finally, Section VI concludes our paper with brief details explaining the possible future research directions.

II. Background

This section briefly describes research works in relation with LLNs for IoT and IEC systems that mainly considers the routing protocols and application of multicast communication considering energy consumption. IPv6 over Low Power Wireless Personal Area Network (6LoWPAN) and RPL are the other areas that associates LLNs applications and communication protocols in IoT and Edge computing.

A. Routing for LLNs and IEC

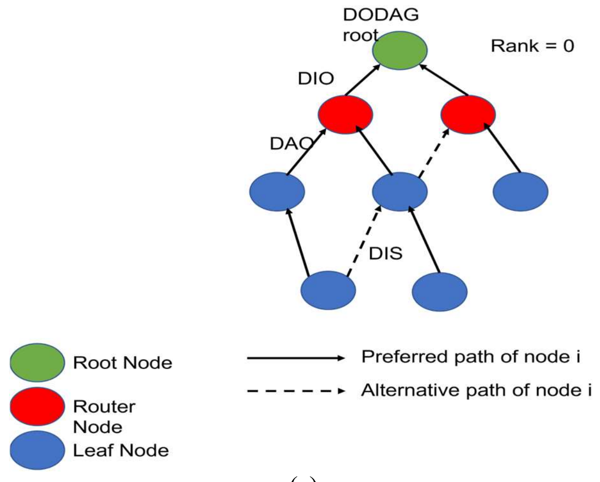
LLN consists of thousands of resource constrained nodes and when they are powered by batteries, they are limited with energy, memory, and processing power. These nodes are interconnected through the IEC border router are usually unstable and only support low data rates i.e., lossy links that supports various traffic modes. These are mainly not peer-to-peer (P2P), but multi-point to peer (MP2P) or point to multipoint (P2MP) in various scenarios [3]. Hence, the IEC border router can also provide application-level services by providing networking routing functions for low-power nodes. LLN characteristics is restricted in various arears for example, security, heterogeneous routing, traffic provision, path diversity, resource restriction, conversion time and node property awareness. Efficiency can be observed for data, filtering, and aggregation at a source to facilitate real time decisions at the edge border router by providing uniform and consistent routing capabilities for IoT applications in LLNs.

IETF ROLL working group defined RPL in RFC5548 as a distance vector tree based active routing protocol and an essential requirement for routing issue in resource constrained device network, in relation to application-oriented routing to benefit the application of LLNs. Destination-oriented directed acyclic graph (DODAG) in one or more LLN boarder router that serves IPv6 connection for various battery powered embedded wireless devices to support bi-directional communication in resource constrained device network. Building the network topology is the initial step to establish the communication in DODAG by using three types of control messages: DODAG Information Object (DIO), DODAG Information Solicitation (DIS), and Destination Advertisement Object (DAO) messages [4]. DIO messages publish routing metrics and constraints for each node in RPL and the node chooses the routing parent node according to its Objective Function (OF) and the routing information in the message after receiving the neighbour's DIO message. This is to construct the routing topology. A node can have more than one parent nodes in DODAG that may provide several routing paths. To establish the communication from the non-sink node which can be multiple nodes with the sink node of one point, the nodes finally converge to a root router with the root of the tree.

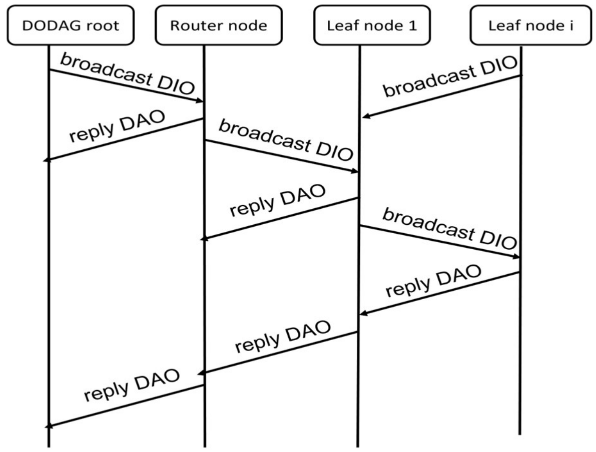
Figure 1 illustrates the message passing process in the relationship tree in the parent-child relationship tree diagram in DODAG. To form a RPL protocol infrastructure, multiple DODAGs converge in the same Internet as a component unit of RPL, and different DODAG units are connected by IPv6 communication. It is observed that a node is allowed to have parent nodes from different DODAGs that belongs to different DODAGs at the same time in multiple parent nodes.

B. IoT and Mulsticast Communication

The IoT of real-life scenarios is formed by the combination of various information sensing devices and the network by connecting all things over the Internet, which is basically a massive network. Hence, not only several specific sensor devices are needed to work together in an IoT system, but also these various information sensing nodes in the network cannot stop to wait for a broadcast transmission to complete transfer. Consequently, multicast transmission mode and IoT complements each other to develop many interesting applications in LLNs. However, energy consumption of resource constrained devices has become a significant consideration in the design of IoT application systems that consists of edge border router [5]. Point-to-point unicast is the key transmission mode of LLNs although LLNs are planned to meet the special requirements of IoT system in terms of deployment scope and sustainability. However, this is not because the performance of multicast is not as virtuous as unicast, but because the complex implementation of multicast compared to unicast transmission. Hence, a research gap is identified considering specific communication mode that suggested by the specification of LLNs standardisation. Avoid multicast when unicast is applied to reduce cost is not the right choice for researchers as this may miss other multicast profits like application enrichment.



(a)



(b)

Fig. 1. (a) DODAG parent-child structure diagram and (b) Message transmission diagram

III. MULTICAST PROTOCOLS

Multicast protocol for low power and lossy networks (MPL) has come into the attention of researchers in recent years to overcome the applicability of multicast mode in LLNs. MPL is intended for the transmission between the lossy links with low power consumption in an IPv6 multicast forwarding protocol-based network that is suitable for various topologies with different space and time scales. Considering the benefits on operation scheme and space utilisation of multicast in LLNs, various research has been conducted [6]. The multicast deployment in LLNs involves large elements and directed through MPL protocol specifications, maintaining the configuration parameters and message format that required for multicast forwarding leaving design space for specific message transmission process at the same time. M. Carlier et. al [7] considers the transmission of information from parent node to children node in the network and finds that the performance of broadcast is better than that of unicast when there is a tree topology with complex children node relationship.

Terminal sensors are the child nodes of a control centre in a simple IoT system where many sensors are often required to work together to achieve a goal considering real-life scenarios. The complex children node relationship is informed to all relevant network models by the Control centre to complete an operation. Hence, multicast will have more benefits than using consecutive unicast in real-life IoT systems. Optimisation of multicast transmission for suitable real-life application in IoT environment is the next research challenge after determining that multicast is more suitable for LLNs in IoT-based transmission mode.

Where the performance evaluation in [8] shows that the combination of unicast and multicast is a feasible way to balance delay, feasibility, and cost. Real-life IoT applications also considers the network security that related to the ability to resist interference and attack in addition to the delay and cost. Reliable Group Communication Protocol for Internet of Things (RECOUP) is a robust multicast transmission routing protocol that uses low-overhead cluster-based multicast routing to create a virtual cluster on DODAG topology to improve security for LLNs. In real-life scenarios, there are different topology and data transmission attacks on IoT systems that can be optimised through the inter-cluster routing to quickly distribute and maintain a high multicast packet transmission rate in the network. Hence this security feature helps to develop secure IoT systems to keep the stable operation in secluded circumstances.

A. RDC Mechanism

Wireless transceiver consumes most of the power among all the components of resource constrained devices and strictly maintain power consumptions to increase the device service life. Therefore, the transceiver needs to turn off while not in use to achieve the purpose of energy saving. However, a mechanism is required to turn on the transceiver periodically if the transceiver is totally turned off completely and the transceiver cannot receive any data when it is stopped [9]. Hence, the RDC mechanism is used for the periodic wake up for transceivers and divided into synchronous methods and asynchronous methods based on the sleep and wake-up schedule of various nodes. Asynchronous methods can be further categorised into Low Power Listing (LPL) and Low Power Provisioning (LPP) according to the technology used [10]. The LPL can be more classified into ContikiMAC, X-MAC, WiseMAC and BoX-MAC-2.

This work uses the Cooja simulator in Contiki OS [11] that is designed for resource-constrained embedded systems. It supports open source, Internet standards, power-aware, dynamic module loading, and many hardware platforms. Contiki OS uses an event-driven kernel and pre-emptive multithreading to achieve resource efficiency. It is designed to run on a low-power battery-powered Internet of things platform intended to run for years without human intervention. It supports a standard wireless communication stack. It also provides simulation software to run, debug, test and develop, and then write the program to the actual IoT device. Contiki Cooja simulator specially developed for IoT has built-in basic protocols commonly used in IoT application scenarios. Therefore, this work chooses to use Cooja simulator for simulation test, build communication models to test the performance of RDC mechanisms, and gradually forms a multicast communication model with RDC mechanism.

IV. EXPERIMENTAL DESIGN AND SETUP

This section presents an experimental design which can be broadly divided into two main phases. In the first phase, various unicast and multicast RDC protocols are evaluated whereas, in the second phase, the evaluation results are utilised to develop an optimised model. Fig. 2 illustrates the complete flow of the experimental phases in the Cooja simulator.

A. Experiment Setup

In terms of topology, the network comprises one edge node and various client nodes communicating with each other. Both edge and client nodes are of skype mote types, however running different RDC protocols. The key simulation configurational parameters are highlighted in Table I whereas Fig. 3 illustrates the communication model of the nodes during the evaluation of various RDC approaches. The table on the right side in Fig. 3 presents the real-time RDC rate for each node, as well as the average RDC rate for all nodes in the network after the initiation of the experiments. These values are crucial for the observation and analysis within the scope of our research. The experimentation includes the evaluation of NullRDC, XMAC, CXMAC, and Contiki MAC RDC mechanisms in the RPL-

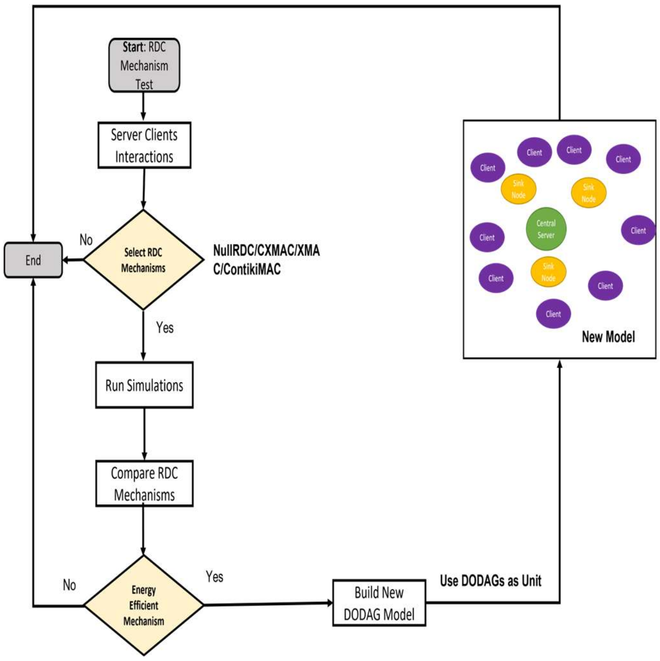


Fig. 2. Design flow of experiment in Cooja simulator.

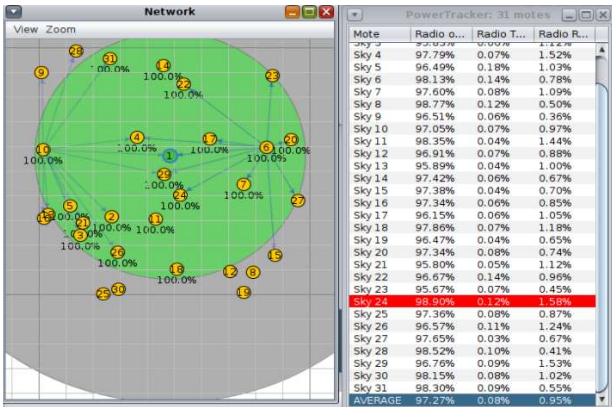


Fig. 3. Communication model for RDC mechanism performance test.

UDP transmission model, each running for a total of 5 minutes. Moreover, it is to note that the Contiki OS built-in RDC header file is employed for all sky motes in the network to configure RDC value. During the experimental evaluation, the RDC rate representing the sleep (inactive) and the awake (active) cycle of the nodes is observed dynamically. As mentioned earlier, the RDC rate reflects the proportion of the time a node is active during the total communication time. As the node consumes a negligible amount of energy during the inactive state, therefore, the lower the RDC rate the better the overall energy consumption in the network.

TABLE I. CONFIGURATION PARAMETERS: EXPERIMENT –RDC MECHANISM PERFORMANCE TEST

Parameters	***Value***
Edge Nodes	1
Client Nodes	30
Duration (Minutes)	5
Mote	Sky
Distribution	Random

To develop the multicast communication model, this work utilizes the establishment process of the DODAG in the RPL communication protocol. As discussed earlier, the DODAG is based on the parent-child relationship tree consisting of a root, router and leaf nodes to develop a multicast network, and that is incompatible with the sky mote type nodes. This limits the applicability of the RDC mechanism. Therefore, in this work, the parent-child relationship tree is constructed on sky mote type node to enable multicast communication.

V. EXPERIMENT RESULT ANALYSIS

In this section, we presented a performance evaluation of various RDC mechanisms and analyses the key factors considering energy preservation as a main objective. The evaluation results and analysis are then employed to develop a multicast communication model using an optimal RDC mechanism. Our analysis, in addition, also demonstrates the feasibility of introducing RDC in multicast transmission.

A. Performance Evaluation and Analysis of RDC Mechanisms

Fig. 4 shows the evaluation results of four RDC mechanisms namely NullRDC, CXMAX, XMAC, and ContikiMAC and are critically analysed below. TABLE II shows the simulation configuration in detail. In the NullRDC protocol, we observed that all nodes in the network remain active all the time, exchanging various messages amongst different nodes, thereby maintaining a constantly active network state. Although NullRDC contributes little or no energy preservation owing to the high RDC rate, the network operates smoothly, and the messages are exchanged without any network congestion. Compared to the NullRDC protocol, the RDC rate for the CXMAC protocol is an order of magnitude lower which is mainly attributed to the implementation of low-power sleep mode on different nodes in CXMAC to preserve energy. As shown in Fig. 4 the average RDC rate of all nodes in CXMAC is approximately 29% which as a result greatly reduces the load in the network. However, after a certain period of time, approximately two minutes, a significant amount of packet loss is observed in the network. This is because the CXMAX RDC is unable to effectively synchronise the sleep and awake cycles of multiple communication nodes in the network. As a result, the following situation arose multiple times where the sender forwards the packets towards the receiver, however, due to the receiver being in a sleep state or communicating with other nodes dropped the packets. Moreover, owing to inadequate synchronisation of the sleep-awake cycle amongst nodes, the sender may transition to a low-power sleep state or receive additional tasks when the receiver becomes available, that ultimately leads to inefficient network performance. These situations create excessive load in the network and a plethora of tasks piles up in the network which consequently leads to network congestion or network failures.

Similarly, compared to CXMAX, the RDC rate for the XMAC protocol is lower which is again fundamentally attributed to the implementation of low-power sleep mode on different nodes in XMAC to preserve energy. As shown in Fig. 4, the 17% RDC rate is observed in the case of XMAC. However, similar to the CXMAX, the nodes in XMAC also confronted sleep-wake cycles synchronisation issues amongst nodes that again eventually leads to poor network performance. Finally compared to the aforementioned RDC protocols, we observed that the ContikiMAC not only further reduced the RDC rate to 8% but also effectively synchronised the sleep-wake cycles of network nodes. Such characteristics of ContikiMAC suits well for multicast IEC-based LLN and hence we optimise the communication model based on the ContikiMAC protocol.

B. Model Optimisation using RDC Mechanism

This subsection shed light on the novel multicast communication model development by employing the ContikiMAC as the RDC protocol and by analysing the key features of ContikiOS [12]. At first, the feasibility of introducing a level-two sink node is analysed and verified by building a parent-child relationship tree in DODAG in which the sink node act as a parent and the IoT client node act as a child and associates itself with the parent (sink node). The rationale for introducing a sink node is to find a stable communication path between the remote client and the intelligent edge node. The introduction of the sink also aims at reducing the RDC rate but putting the child node into a low-power sleep state when the sink is itself inactive. Moreover, in traditional multicast communication models the nodes are incompatible to support RDC mechanism. The Fig. 5 shows the communication time of the traditional multicast model in which all nodes follow the same timestamp. As soon as the timestamp interval starts, all nodes immediately initiate the communication which results in excessive workload in the network and increases the chances of network congestion. In Fig. 5, the green node is the edge, the purple nodes are the clients, and the yellow are relay nodes which act merely as intermediate nodes between distant client nodes and the edge node. In our proposed scheme, we upgraded the relay nodes to sink nodes to improve the network performance. A detailed discussion is presented in the following.

At the network initiation stage, the IoT client nodes frequently forward the packet to determine the communication path and the sink nodes—the relay nodes now act as sink nodes. Gradually, packet forwarding lessens as soon as the parent sink is discovered. To adjust the nodes' sleep-awake cycles to preserve the energy, the network follows the ConitikMAC RDC mechanism. In the network diagram presented in Fig. 6, the green and purple nodes are edge and client nodes respectively, whereas the yellow nodes are now both the clients and sink nodes to maintain a parent-child relationship tree. It can be observed in Fig. 6 that the network is now no longer overloaded as it was traditional multicast as shown in Fig. 5. This is not only due to the RDC mechanism, but also because sink nodes share the working pressure of most client nodes. The sink node sacrifices its sleep time to deal with a large amount of information interaction with the edge node. An ordinary client node follows the RDC mechanism and only communicates with the sink node that governs the sleep-wake cycle. The sink node communicates on behalf of all client nodes within its jurisdiction with the edge node. In so doing, although the workload on the sink node increases, several client nodes under its control are free from the complex communication negotiation process. The lower workload on client nodes is validated by checking the RDC threshold rate of the nodes during the simulation in which the three sink nodes are although observed to have comparatively high load, the other client nodes are mostly sleeping. Fig.7 shows the optimisation model algorithm.

C. Results

Running the simulation for 5 minutes, our result reveals that when the nodes are busy searching for the parent node, the average RDC rate is the highest.

TABLE II. CONFIGURATION PARAMETERS: EXPERIMENT –RDC MECHANISM COMPARISON

Parameters	***Value***
Edge Nodes	1
Client Nodes	19
Duration (Minutes)	15
Mote	Sky
Distribution	Random
RDC Mechanisms	NullRDC, XMAC, CXMAC, ContikiMAC

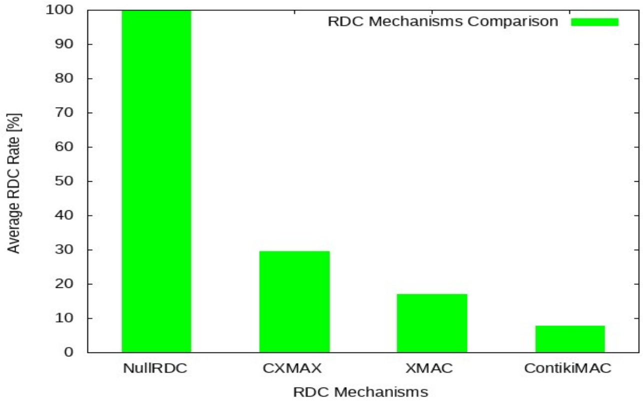


Fig. 4. RDC Mechanisms Comparison

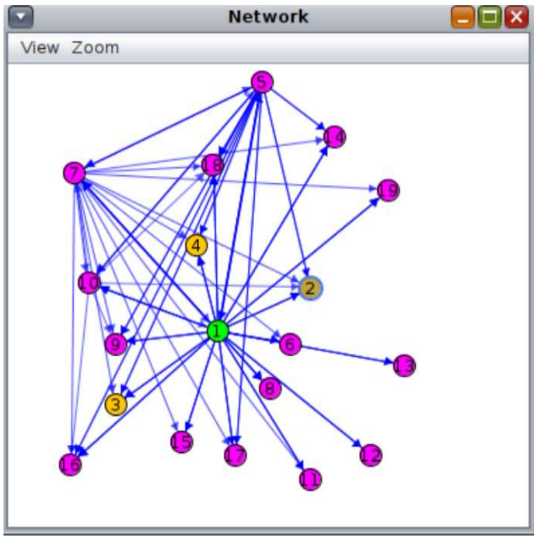


Fig. 5. Traditional Multicast Network Model

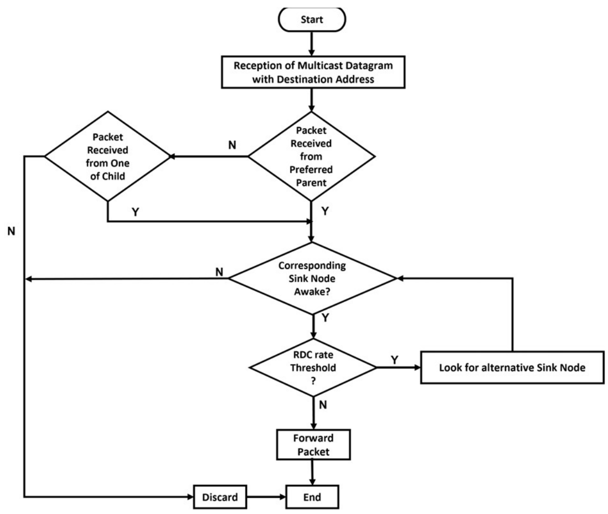


Fig. 6. Algorithm for the Proposed Model

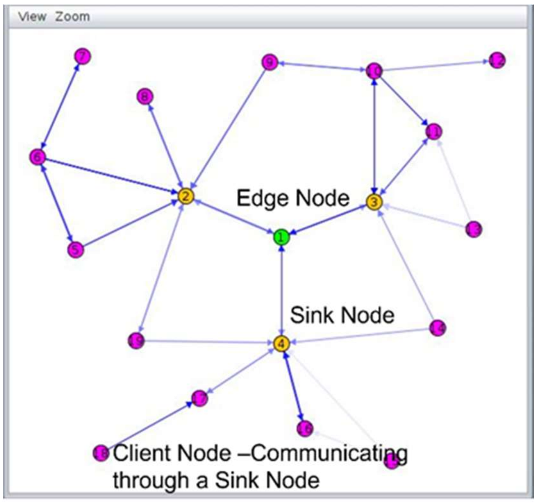


Fig. 7. RDC Optimised Model

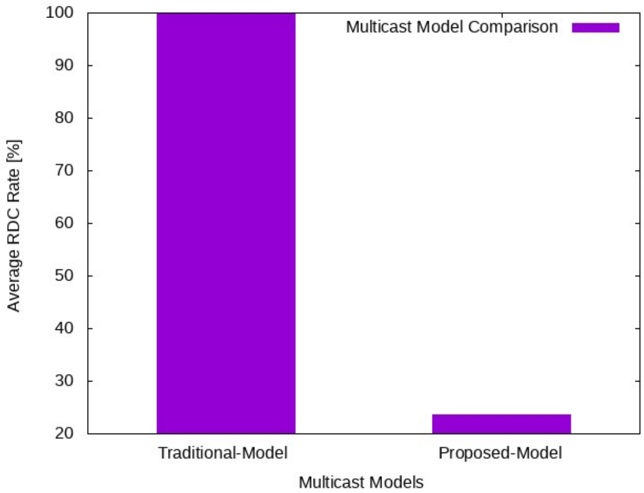


Fig. 8. Multicast Model Comparison

In the later stage, the average RDC rate drops, and average is approximately 23.7% less compared to the ContikiOS RDC protocol as shown in Fig. 8. Moreover, our finding reveals that the energy total energy preserved by most client nodes is an order of magnitude higher compared to the energy consumed by the sink nodes managing tasks on behalf of child client nodes.

VI. Conclusion and Future Work

This paper proposes a new multicast communication model by employing the RDC mechanism and introducing the level two sink nodes consequently further conserving the overall network energy consumption. The proposed RDC-based multicast communication model not only lessens the energy consumption to cope with the energy limitation of LLNs network but also meets the functional requirements of IoT and IEC for multicast transmission mode. The comparative performance analysis reveals a 23.7% lower RDC rate while maintaining a consistent and adequate communication flow in the network.

As future work, we further aim to optimise the multicast transmission model using the proposed sink-based communication approach. Specifically, our future objective is threefold: 1) proposing a novel RDC protocol rather than employing the existing ContikiMAC RDC protocol, 2) network performance analysis of in terms workload if the number of sink-nodes is increased to further reduce RDC rate, and 3) proposing an optimal sink-based RDC protocol that only preserves energy but also maintains consistent communication flow and low workload in the network.

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