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MODIFIED RPL ROUTING PROTOCOL FOR DENSE IOT NETWORKS

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***Abstract*- Dense IoT-WSNs are a subtype of IoT-WSNs in which a high density of deployed nodes and data exchange is considered. Due to the capacity constraints of nodes in the IoT-WSN, the routing process requires a unique design to accommodate a large amount of data while saving energy. The Internet Engineering Task Force (IETF) develops RPL, a routing protocol for low-power lossy networks based on IPv6 that can handle a large number of nodes. RPL nodes rely on an objective function mechanism for route selection. Each objective function utilizes different metrics. The primary objective of this paper is to modify the RPL protocol by proposing two objective functions to improve RPL performance over a dense network. The impact of the number of children is also investigated. The first proposed protocol is called ENCRPL. It used three metrics: energy level, number of neighbours, and a new metric depending on the number of children. The second protocol, called NCERPL, is based on combining node and link metrics by using the numbers of neighbor nodes and children's nodes as node metrics and the expected transmission count (ETX) as a link metric. The proposed protocols are implemented and evaluated using the Cooja simulator based on the Contiki OS. Regarding energy consumption, the results show that the proposed protocols outperform RPL and the previously proposed protocol, called the MET protocol. ENCRPL achieved a 93% improvement in energy savings over RPL with a density of 0.48 and 0.0075 nodes/m2. NCERPL provides about a 14% improvement in energy savings over METRPL with a 0.48 density and a 44% improvement with a 0.0075 density. Both ENCRPL and NCERPL achieved higher performance regarding the number of dead nodes than RPL and METRPL in all scenarios. Considering packet delivery ratio and throughput, ENCRPL and NCERPL perform better than RPL in high-density scenarios.**

keywords: **Dense IoT-WSN, RPL, Objective function, ETX, Cooja, Contiki-OS.**

I. INTRODUCTION

The Internet of Things (IoT) refers to a network of heterogeneous devices linked together and made accessible via the internet. Things given an IP address can gather and exchange data over the Internet without human intervention. IoT technology is used in various applications, for instance, wearable, healthcare, traffic monitoring, agriculture, etc. [1]. A wireless sensor network (WSN) is comprised of several individual sensor nodes distributed in specific areas to monitor the environmental and physical characteristics of a given system. Sensor nodes are the central part of the IoT, which is an inexpensive device with limited capacity for sensing, data processing, wireless communication, and energy [2]. Routing protocols for IoT-WSN are one of the domains where researchers are concentrating their efforts.

The Internet Engineering Task Force (IETF) in 2012 developed a routing protocol for low-power lossy networks (RPL) [3]. RPL is a proactive routing protocol. It is built on IPv6 to support a large number of sensor nodes. RPL used an objective function mechanism to select preferred parents in a network [3]. Many studies have aimed to reduce power usage while extending the node's lifetime. In [4], the hybrid proactive and reactive routing protocol ER-RPL is proposed. Without

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sacrificing dependability, the proposal enabled reliable peer-to-peer data transport. Unlike standard routing protocols, ER-RPL used a subset of nodes in particular locations in order to find a route. The ETX metric for link quality is also used. The NS3 simulator with 100 nodes is used, and the transmission range is 35 m. Nodes were randomly deployed in a 180 x 180 m2 network area. The performance results showed that ER-RPL achieved about a 150% improvement in PDR over RPL and more than a 60% improvement in energy consumption. In [5], a new objective function named Quality of Service (OFQS), which is a multi-objective metric, is proposed. OFQS considers three metrics, including average time delay, nodes' remaining energy, and ETX. 67 nodes are used, and the experiment was implemented through the Cooja simulator. The findings demonstrated that the OFQS is superior to RPL's OF by obtaining 91.8% improvement in PDR compared to 85.7% for the MRHOF and OF_0.

In [6], RPL performance in the high-density network was investigated using OF_0 and MRHOF. The experiment was performed by using the Cooja simulator with a number of nodes between 100 and 150. One node is deployed in each $10 \times 10m^2$ area. The results showed that the average PDR of OF0 achieved about 6% improvement over MHROF. In [7], two modified RPL protocols have been proposed: the first, called energy threshold RPL (ETRPL), focuses on reducing energy consumption. The second is called EERPL, which is based on combining energy consumption with ETX. The experiment was performed in Cooja simulators with up to 80 nodes over different areas of $100 \times 100m^2$, $150 \times 150m^2$, and $200 \times 200m^2$. The transmission range was 50 m. The results showed that EERPL and ETRPL performed better than RPL in small and large networks concerning energy consumption and PDR. In [8], four objective functions were proposed: the Maximum Number of Parent objective function (MNP), the Maximum Number of Parent objective function based on Remaining Energy (MRE), the Maximum Number of Parent objective function based on Energy Threshold (MET), and the Maximum Number of Parent objective function based on Expected Transmission Count (MEX). The experiment was carried out using Cooja simulators. The findings indicate that there is a loss of approximately 28% to 33% in the average remaining energy of MRE in small area networks when compared to RPL with 40 and 80 nodes. MRE acquired energy ranging from 29% to 100% in different network densities, and parent switching improved with the MET. In [9], a multipath version of RPL (MP-RPL) was proposed. It used the multiparent RPL features for the purpose of enhancing the delivery of video traffic via IoMT. The results were compared with traditional single-path RPL by using MRHOF and ETX objective functions. The experiment was performed in Cooja simulators with a total of 12 nodes. The simulation area was $150 \times 150m^2$. The findings demonstrated that employing the MP-RPL strategy in combination with an ETX-based goal function improved network performance by dispersing video traffic load over all existing routes rather than a single route. The average delay of MP-RPL is better compared with single-path RPL. In terms of energy consumption, the MP-RPL consumes nearly the same as the single-path RPL.

The number of nodes utilized in IoT applications is rapidly increasing, and one of the most significant challenges is keeping these nodes energized. Selecting efficient routing protocols is essential to minimize energy waste. RPL and its variant protocols are usually implemented and evaluated with a small number of nodes without considering the impact of dense networks. The main goal of this paper is to propose improved RPL-based protocols to improve RPL performance in dense networks while saving energy.

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The rest of the paper is organized as follows: Section II describes RPL and its challenges. Section III introduces the proposed RPL-modified protocols. Section IV evaluates the performance of the proposed routing protocols. Finally, Section V presents the concluding remarks of the work.

II. Low-Power and Lossy Networks Routing Protocols

Low-power lossy network routing protocol (RPL) is a routing protocol developed to work on wireless networks with limited energy and bandwidth [3]. It is a proactive protocol that operates on the IEEE 802.15.4 standard and uses distance vectors for communication. Multi-hop communication, many-to-one communication, and one-to-one communication are the three forms of communication that were developed to support RPL [10]. RPL arranges its topology using destination-oriented directed acyclic graphs (DODAGs). It is similar to the tree topology. It has a single destination known as the DODAG root, but it does not have cycles to prevent loops from forming. RPL utilizes distinct types of control messages to construct an RPL network. The DODAG Information Object (DIO) contains the information required to discover an RPL instance, establish its configuration settings, select a DODAG parent selection, and administer the DODAG. It is equivalent to IPv6 router advertising. DODAG Information Solicitation (DIS): This is employed to request DIO from other nodes. A DODAG Advertisement Object (DAO) is used by a child node to request a join acceptance from a parent node. Destination Advertisement Object Acknowledgement (DAO-ACK) is a reply to a DAO message sent by the preferred parent on behalf of the child node to confirm or deny the child node's request [7].

A. *RPL Operation*

RPL supports two routes to construct the RPL network: upward and downward routes. RPL builds multipoint-to-point (MP2P) routes from each node to the DODAG root. MP2P is a popular communication pattern in collection-based networks, where sensors feed their data to a DODAG root [8]. Using a DIO message, the node constructed its route to the root. In RPL, downward routes are constructed from the DODAG root to nodes to provide point-to-point (P2P) and point-to-multipoint (P2M) communication. The node used the DAO message to construct its path downward from the root node to others. RPL provides two modes for the downward route: storing and non-storing. In storing mode, the node is stateful. It sends data directly to the destination, bypassing the DODAG root. While in non-storing mode, nodes should communicate with each other through the root node.

B. *RPL Objective Function*

Two objective functions are generally supported by RPL. the Minimum-Rank with Hysteresis Objective Function and the Objective Function Zero (OF_0). Additionally, there are objective functions developed by different researchers to improve the performance of the RPL protocol. The following describes the limitations of the conventional RPL objective functions [3]:

1) Objective Function Zero: In this objective function, each node selects the preferred parents with the fewest hops to the root node, without regard to other metrics such as the node's energy level or the number of children nodes. This objective function works appropriately with a small number of nodes [3]. However, when this objective function is

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implemented in medium- or high-density networks, the nodes with the fewest hops to the root are selected by the large nodes. This will increase the traffic on the desired node and consume its energy quickly [2]. Moreover, this objective function ignores the energy level of the desired node compared to others. Fig. 1 describes the traffic load problem in OF_0. Assume nodes A and B are directly connected to the root node. Nodes D and E selected node A as the preferred parent, and node C chose node B as the preferred parent. Assume F wants to join the network. It can connect with either node A or node C. Because node A has the fewest hops to the root node, C will choose it as the preferred parent, according to the OFO. Even though node C has more energy than node A and has no children. This will increase the load on node A, thereby increasing its energy consumption.

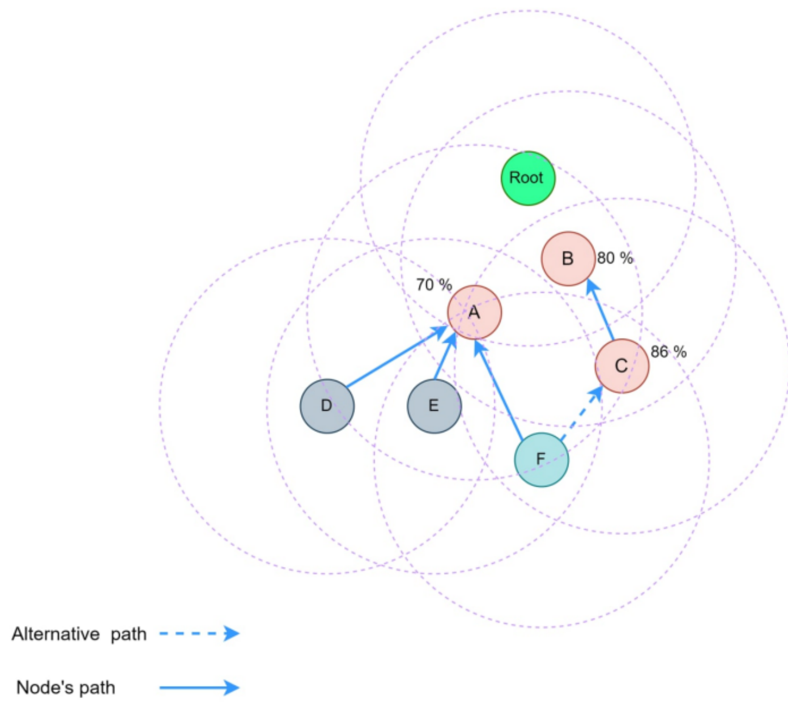

Figure 1: Example describing OF_0 preferred parent process.

2) Minimum-Rank with Hysteresis Objective Function:MRHOF uses EXT to select the optimal parent. ETX represents the number of times a node must send a message before obtaining a response. This objective function eliminates the effect of energy and other metrics. The limitations of the MRHOF are shown in Fig. 2. Assume nodes A, B, and C are directly connected to the root node. Node D is the child of node A. Nodes G and H are children of node B. Assume that node F wants to join the network. It compares the ETX of all routes that fall within its transmission range. According to the MRHOF, node F will choose node B as the preferred parent since it has the lowest ETX compared to other nodes. Ignored the effect of the energy level and the number of children on the preferred parent selection process.

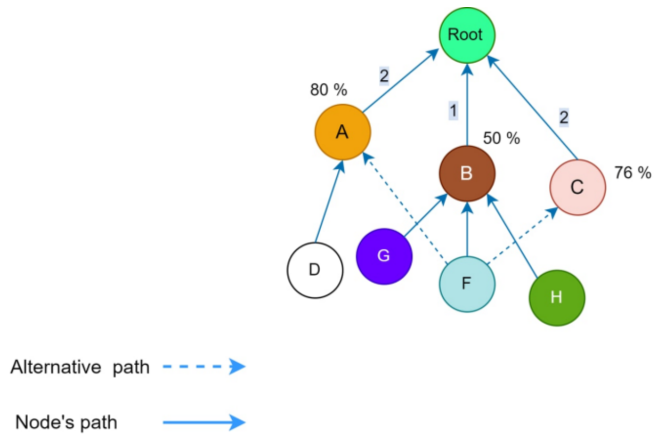

Figure 2: Example describing MRHOF process.

III. THE PROPOSED PROTOCOLS

A. ENCRPL Protocol

The ENCRPL protocol is based on combining three metrics: energy level, number of neighbours, and number of children. ENCRPL attempts to reduce the load on the desired node by evenly distributing nodes across the network. The ENCRPL protocol operates in the same manner as the RPL protocol. The root periodically transmits DIO messages to its neighboring nodes in a multicast fashion. When nodes receive a DIO message from the root, each node immediately selects it as the preferred parent and sends the DAO message back to the root node as a response. Root, on the other hand, replays with a Destination Advertisement Object Acknowledgement (DAO-ACK). Then, each node broadcasts DIO messages to all other nodes within its transmission range, forming a multicast network.There are two possible outcomes when a node receives a DIO message: first, if the node has the same rank as the sender, the node will have neglected the message. Second, a node with a higher rank than the sender receives a DIO message. There are also two possible outcomes. First: When a node receives a DIO message for the first time, it chooses the sender as the preferred parent, and the receiver adds the sender to the list of children. Second, if a node receives DIO messages, for the second time, the receiver will compute the ENC values of the current parent and the sender according to eq. (1) and compare them. If the ENC value of the sender is lower than the present parent, the sender will be removed from the preferred parent selection. Otherwise, the sender will be selected as the new parent. The receiver is then informed by sending a DOA message. After acquiring DOA, the sender will add the recipient to the child's list. Fig. 3 is the ENCRPL flowchart.

$$\text{ENC} = w_0 \frac{R}{I} + w_1 \frac{N}{c+1} \tag{1}$$

Where w_0 and w_1 represent weight parameters, we tried different values to provide the best results. R refers to the remaining energy. I is the initial energy. N refers to neighbour of a node, and C is the child's number. We added 1 to eq. (1) to compute the metric for the leaf node. This will make the numerator in fractions equal to zero.

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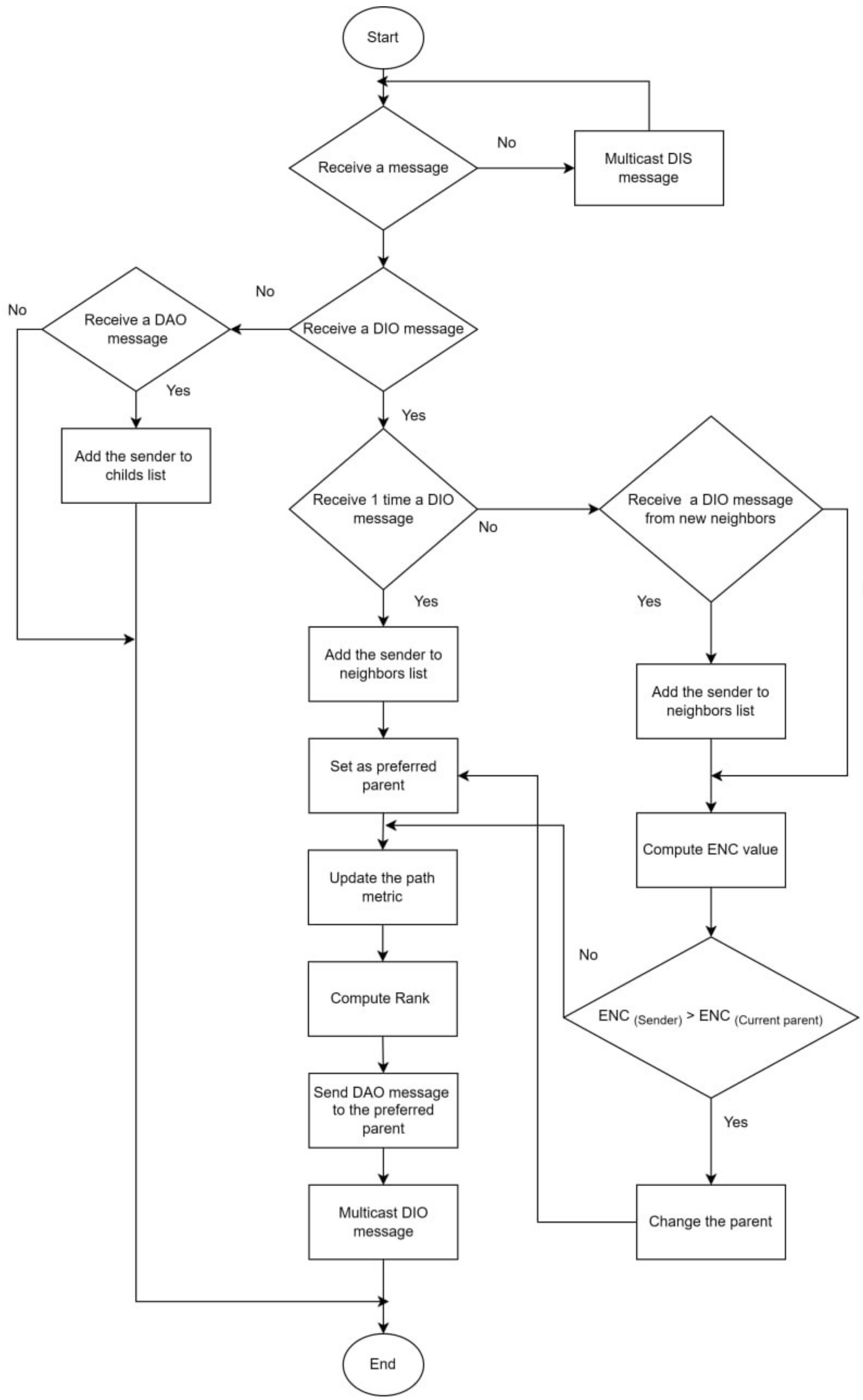

Figure 3: ENCRPL flowchart.

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- **ENCRPL Preferred Parent Selection Process** Nodes within the transmission range of the root send directly. It is not necessary to compute the preferred parent. For nodes in the middle of the network but not the leaf example Fig. 4 is used to explain the process of choosing a preferred parent. Presume that node D wants to join the network. It is within the range of the transmission of nodes A, B, and C. Assume node A has an energy level of 90%, the number of neighbors is ten, and there are seven children. Node B has an energy level of 80% and has fifteen neighbors and children. Node C has a total energy level of 90%, with ten parents and ten children. To select the preferred parent, node D must compute the ENC value of all the mentioned nodes using eq. (1) and choose the highest one. As a result, node D will select node A as its parent.

$$\text{ENC of A} = 20 \times \frac{90}{100} + 1 \times \frac{10}{7+1} = 19.25 \tag{2}$$

$$\text{ENC of B} = 20 \times \frac{80}{100} + 1 \times \frac{15}{10+1} = 17.3636 \tag{3}$$

$$\text{ENC of C} = 20 \times \frac{90}{100} + 1 \times \frac{10}{10+1} = 18.9090 \tag{4}$$

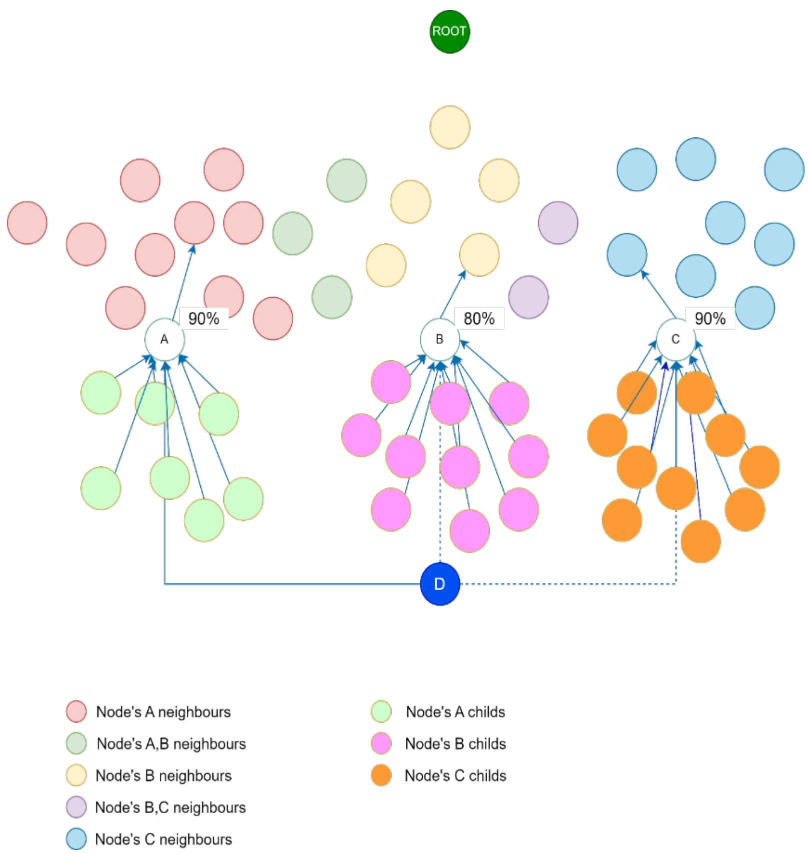

Figure 4: Example description of the NCERPL process.

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B. NCERPL Protocol

The NCERPL protocol is built using a combination of node and path metrics. In NCERPL, the number of neighbours and children is used as a node metric, while ETX is employed as a path metric. NCERPL operates similarly to ENCRPL. When a node joins the NCERPL network by receiving a DIO message, it will compute its node and path metrics according to eqs. (5) and (6), respectively. The compared NCE is then calculated using eq. (7) and is based on neighbours, children, and ETX value. The node with the lowest NCE will be chosen as the preferred parent. Fig. 5 shows the NCERPL flowchart. The following equations show the modified node and link metrics used in the proposed protocols:

$$\text{Node metric} = w_0 \times \frac{c+1}{N} \tag{5}$$

$$\text{Path metric} = w_1 \times \text{ETX} \tag{6}$$

$$\text{NCE} = \text{Node metric} + \text{Path metric} \tag{7}$$

where N refers to the number of neighbours of a node, and C is the number of children. Different weights are applied, and the desired result is achieved with w_0 equal to 1 and w_1 equal to 10.

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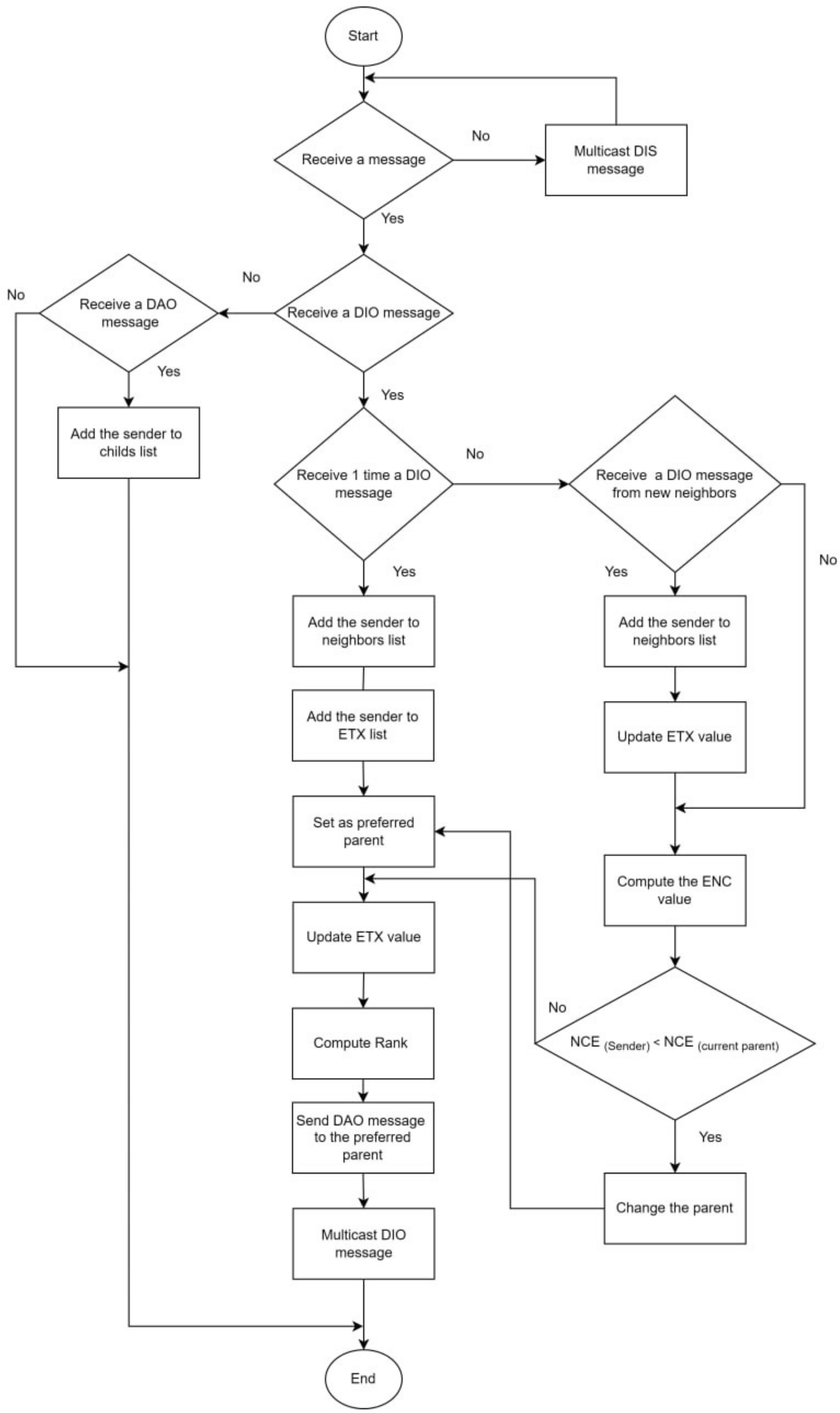

Figure 5: NCERPL flowchart.

– **NCERPL Preferred Parent Selection Process** Fig. 6 illustrates how the NCERPL works. Assume node A has four neighbors and five children, and the (ETX) is one. Node B has two neighbors, seven children, and four ETX, while Node C has three neighbors, two children, and three ETX. Assuming node D wants to choose the optimal parent, it should compute the NCE value foe all nodes in its transmission range according to Eq. (7). In the example, the NCE of node A is 11.5, the NCE of node B is 44, and the NCE of node C is 31. The selected parent will be node A since it has a minimal NCE.

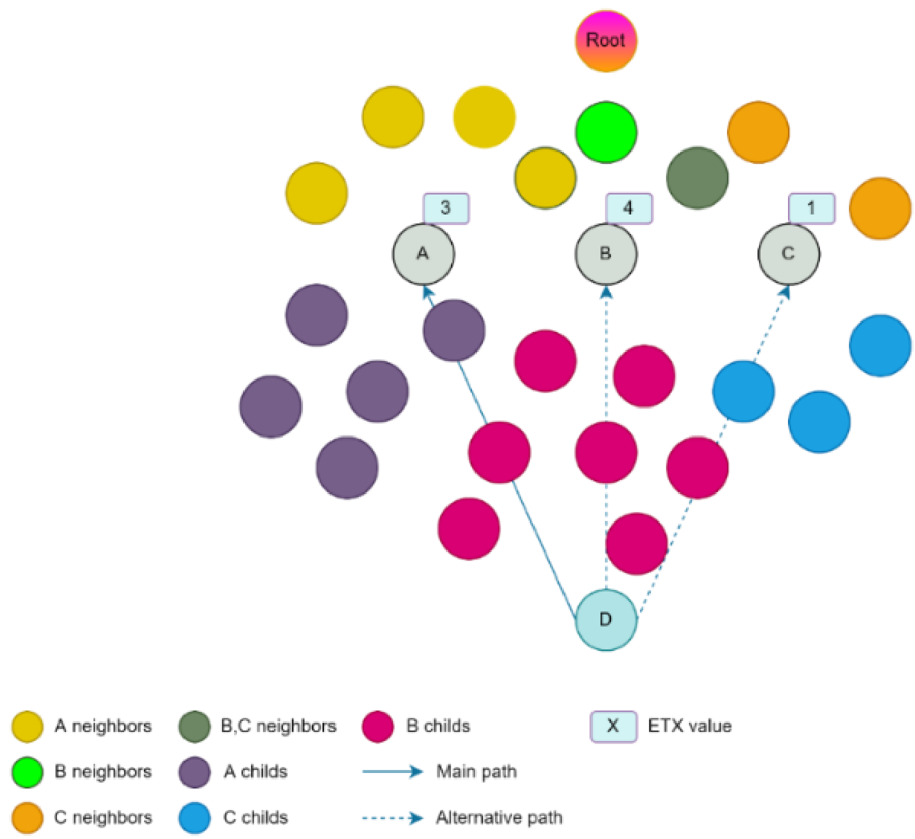

Figure 6: Example description of the NCERPL process.

IV. PERFORMANCE EVALUATION OF ROUTING PROTOCOLS

A different number of nodes is used in the experiment (up to 300 nodes). The nodes are randomly deployed. Four different areas are considered: $25 \times 25\ m^2$, $50 \times 50\ m^2$, $100 \times 100\ m^2$, and $200 \times 200\ m^2$. The communication range is given by $\sqrt{Area}/2$. The initial energy of each node is 6000 MJ. Each node is configured to operate as a (Tmote Sky) [11] with all its features. The work is accomplished through the Cooja simulator, which is based on the Contiki-OS. The Cooja simulator [12] is a component of the Contiki OS, which was created using the Java programming language. It provides simulation at various layers, from the physical to the application layer, and hardware simulation for a group of sensor nodes. RPL is completely supported by Cooja [33]. To build, perform, and

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evaluate WSN simulations, the Cooja simulator includes a powerful graphical user interface (GUI). Two machines are used to run and implement simulation scenarios. Table I presents the specifications of each machine. Table II presents all the parameters used. According to the number of dead nodes, average latency, packet delivery ratio, and residual energy, ENCRPL and NCERPL have been compared to RPL [3] and MET RPL [8].

TABLE I
THE SPECIFICATIONS OF THE USED MACHINE

Category	**Configuration 1**	**Configuration 2**
Operating System	Ubuntu 18.04 LTS	Ubuntu 18.04 LTS
Processor Type	10th Gen Intel® Core™i5	Intel® Xeon® CPU @ 2.20GHz $\times$ 8
Memory	32 GB	64 GB

TABLE II
SIMULATION PARAMETERS

Parameter	**Value**
Number of nodes	100, 200, 300
Node location	Random
Area	25x25 m^2, 50x50 m^2, 100x100 m^2, 200x200 m^2
Initial Energy	6000 m Joule
Simulation time	1800 sec
Node type	Tmote Sky [11]

A. The Average Remaining Energy

Fig. 7 illustrates the remaining energy of RPL, MET, NCERP, and ENCRPL. The performance of the proposed protocols (NCERPL and ENCRPL) is superior to that of RPL and MET for all utilized areas and densities. Using three metrics simultaneously to determine the preferred parent rather than relying on the number of neighbours as in MET or the minimum hop count or ETX as in RPL made the network more stable and distributed the load on nodes more evenly. It results in a reduction in the nodes' overall energy usage. Choosing a preferred parent based on a single metric reduces the number of desired nodes, which increases the distance between the preferred parent and the nodes, resulting in high energy consumption due to the transmission process. That is noticeable as the area and number of nodes increase. When the area is 25×25 m^2 as shown in Fig. 7 (a), the proposed protocols (NCRPL and ENCRPL) outperform RPL by 96.52% and MET by 13% and 14%, respectively. The difference is increased by expanding the area to 200×200 m^2, as in Fig. 7 (b). The ENCRL achieved 97% over RPL and 39% over MET, whereas the NCERPL gained 97% over RPL and 44.76% over MET. Choosing a more reliable route reduces the number of required retransmissions. It is leading to increased energy savings, especially within large areas, as shown by NCERPL, which relies on ETX alongside several neighbors and children. In comparison, NCERPL achieved better performance with an area of 100×100 m^2 and 200×200 m^2 than ENCRPL, as shown in Figs. 7 (c) and (d), respectively.

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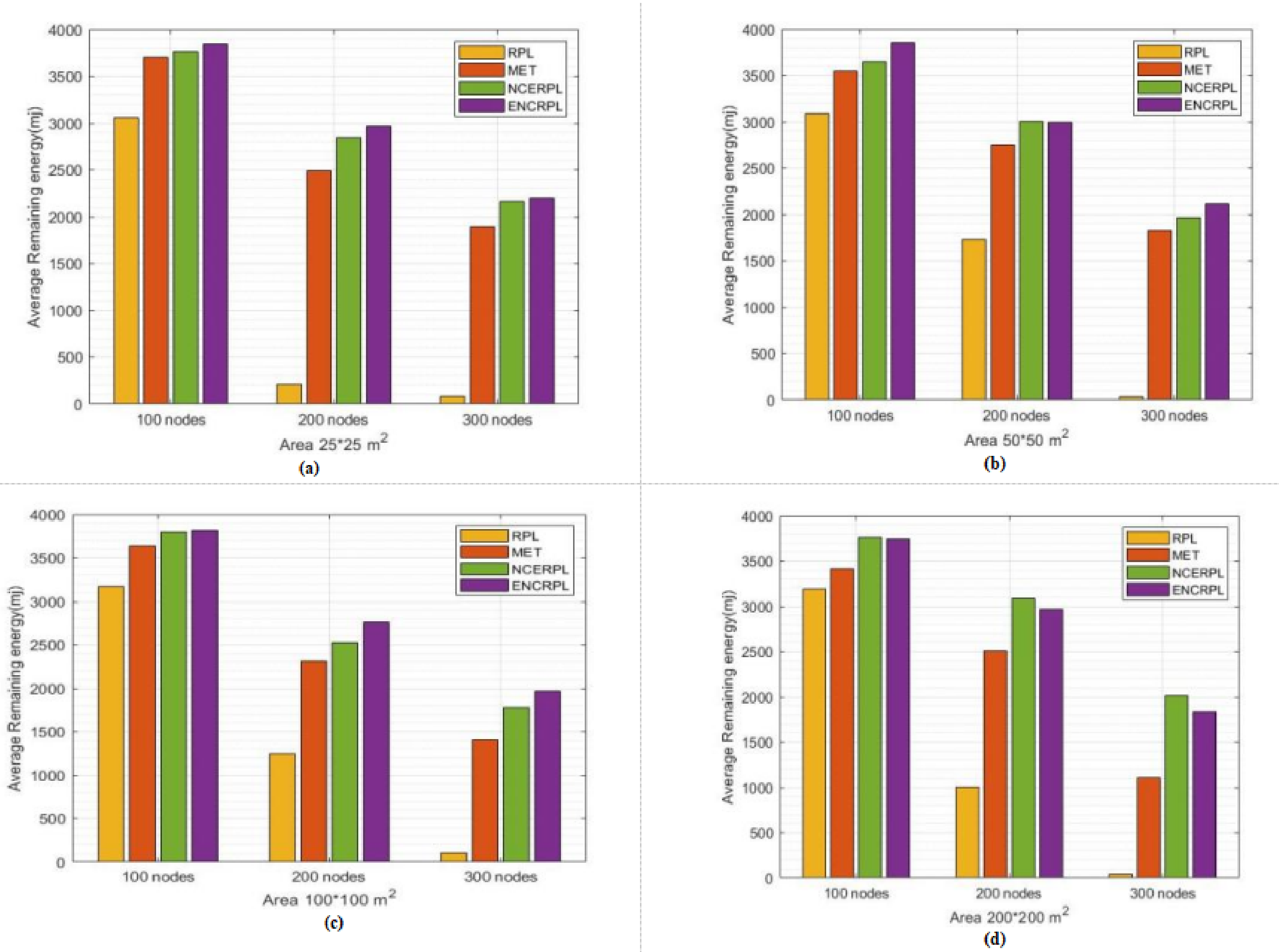

Figure 7: Remaining energy (mJ) results. (a). Remaining energy (mJ) of densities [0.16,0.32,0.48], (b). Remaining energy (mJ) of densities [0.04,0.08,0.12], (c). Remaining energy (mJ) of densities [0.01,0.02,0.03], (d). Remaining energy (mJ) of densities [0.0025,0.005,0.0075].

B. The Number of Dead Nodes

The overall number of dead nodes is shown in Fig. 8. The performance of ENCRPL and NCERPL is consistently better than that of MET and RPL in low- and high-density networks. A single node was lost in ENCRPL with a $25 \times 25\ m^2$ area and a density of 0.48. NCERPL also lost one node with a size of $25 \times 25\ m^2$ and a density of 0.32. Meanwhile, RPL achieves a significant number of dead nodes in all scenarios. RPL has 161 dead nodes at a density of 0.32 with an area of$25 \times 25\ m^2$, and the number rises to 269 when the density is increased to 0.48 with two dead nodes for MET. The RPL network had had 288 dead nodes for an area of $50 \times 50\ m^2$ and a density of 0.12. With an area of $100 \times 100\ m^2$ and a density of 0.03, RPL eliminated 244 nodes, while the dead nodes of MET were four. RPL and MET casualties' dead nodes increased compared to a 0.03 density. Considering that

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there are 286 dead nodes in the RPL network and that the MET is 63 with a density of 0.0075 and an area of $200 \times 200\ m^2$

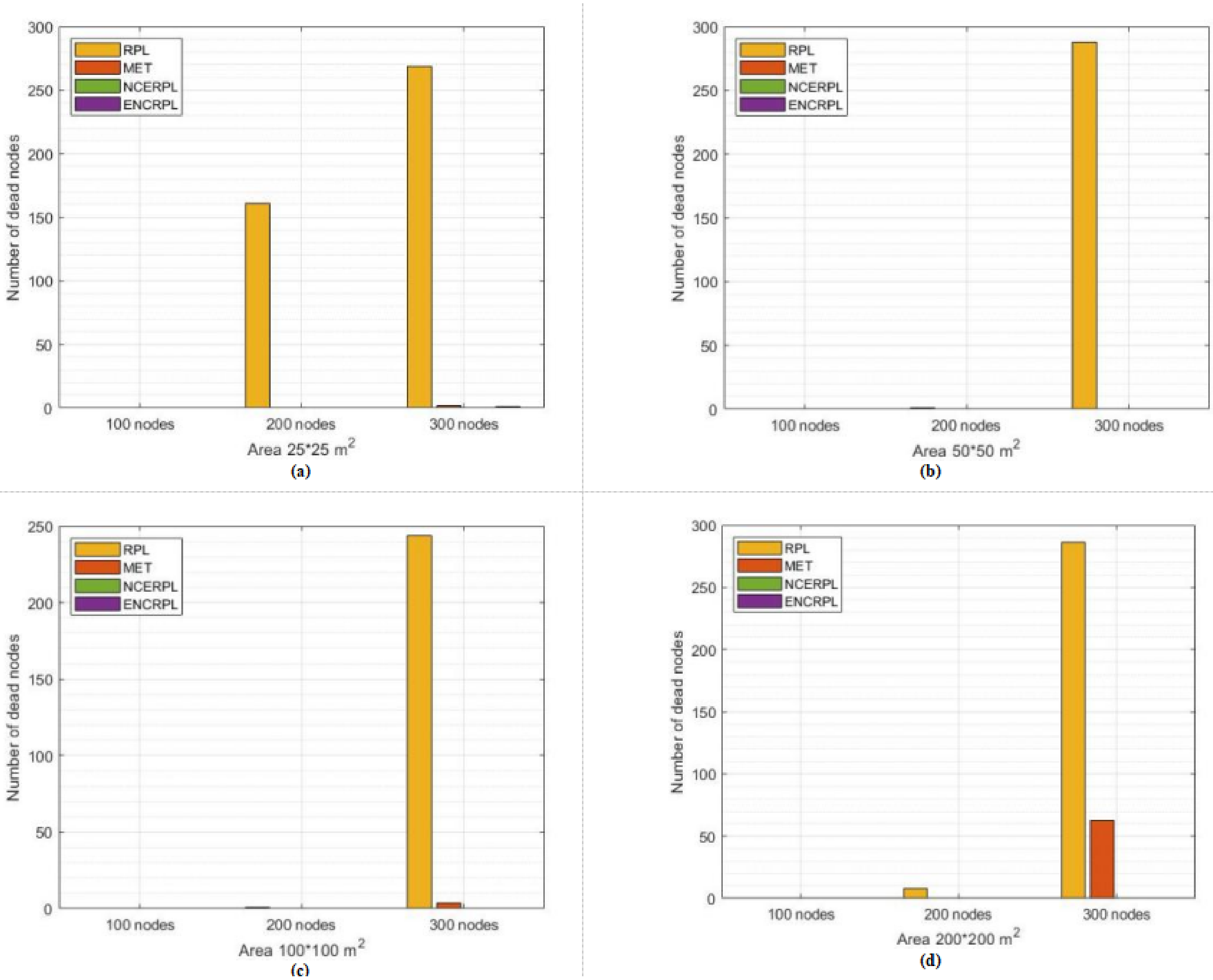

Figure 8: The number of dead nodes results.(a). Number of dead nodes in densities [0.16,0.32,0.48], (b). Number of dead nodes in densities [0.04,0.08,0.12], (c). Number of dead nodes in densities [0.01,0.02,0.03], (d). Number of dead nodes in densities [0.0025,0.005,0.0075].

C. Average time delay

Fig. 9 illustrates the average time delay of ENCRPL, NCERPL, METRPL, and RPL. The average time delay is substantially affected by dead nodes since the processing time rises as node number and density increase, in addition to the capacity constraints of nodes. As shown in Fig. 9 (a), ENCRPL consumes 0.1294 seconds with 100 nodes and an area of $25 \times 25\ m^2$, which increases to 0.22 seconds with 200 nodes and 3.88 seconds with 300 nodes. It is identical to all other protocols. Moreover, using three metrics increased the number of desired nodes and distributed

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load across the nodes on the network. This helped prevent a large number of messages from being sent to certain nodes, hence reducing waiting time.

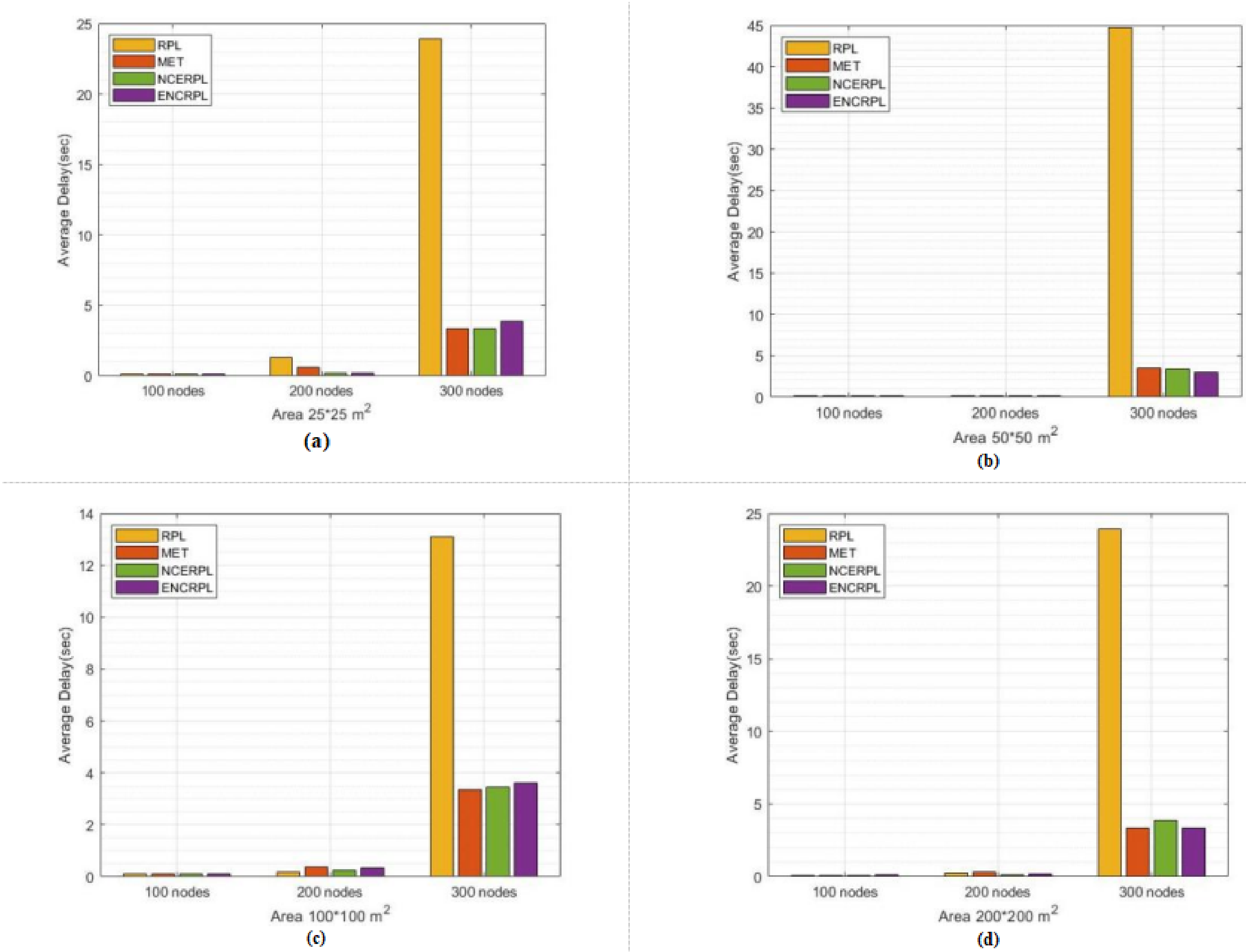

Figure 9: Average time delay results.(a) Average delay (sec) of densities [0.16,0.32,0.48],(b). Average delay (sec) in densities [0.04,0.08,0.12],(c). Average delay (sec) of densities [0.01,0.02,0.03], (d). Average delay (sec) in densities [0.0025,0.005,0.0075].

D. The Packet Delivery Ratio

Fig. 10 illustrates that for all scenarios, the PDR declines as the number of dead nodes increases. All protocols perform almost identically with 100 nodes and densities of 0.16, 0.04, and 0.05. In comparison, ENCRPL and NCERPL achieved a higher PDR than RPL and MET, with densities of 0.003 and 0.0075, due to the high number of nodes lost by RPL and MET.

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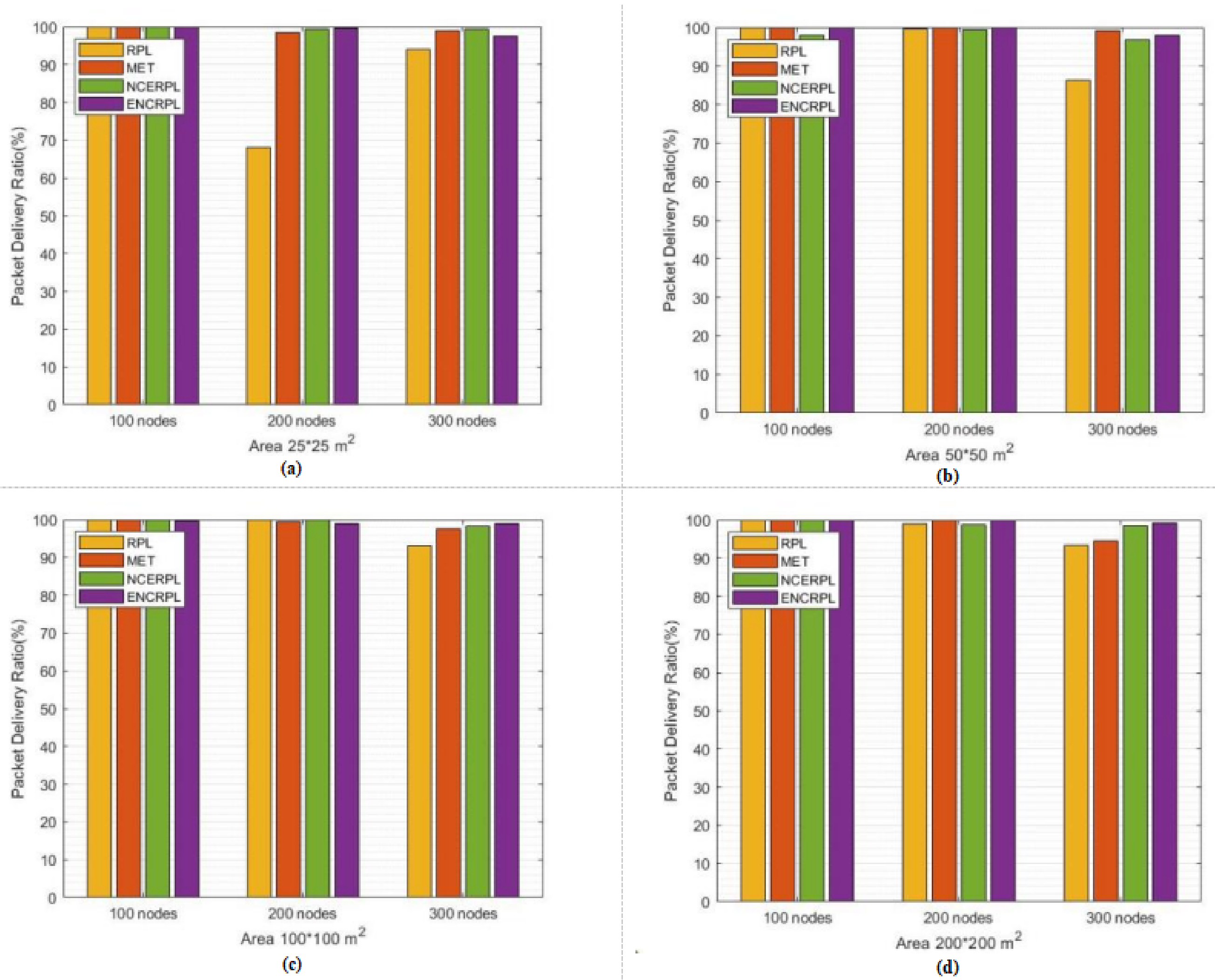

Figure 10: PDR results.(a). PDR (%) of densities [0.16,0.32,0.48], (b). PDR(%) of densities [0.04,0.08,0.12], (c). PDR (%)of densities [0.01,0.02,0.03], (d). PDR(%) of densities [0.0025,0.005,0.0075].

E. The Throughput

The throughput value increases as the number of nodes increases, and vice versa, as illustrated in Fig. 11. Due to the high number of dead nodes in RPL and MET, ENCRPL and NCERPL were capable of achieving high throughput with 200 and 300 nodes, respectively.

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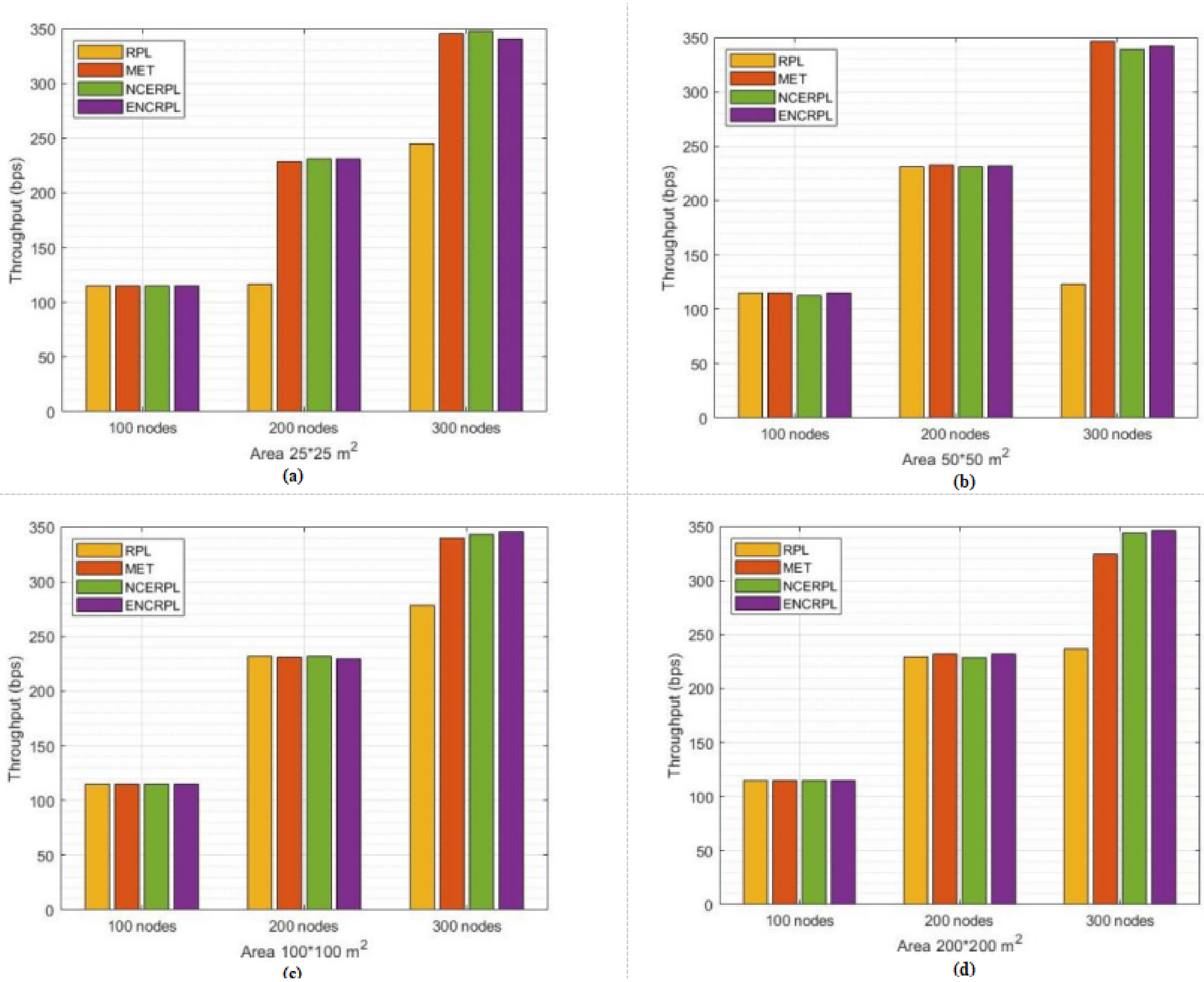

Figure 11: Throughput results.(a). Throughput (bps) of densities [0.16,0.32,0.48], (b). Throughput (bps) of densities [0.04,0.08,0.12], (c). Throughput (bps) of densities [0.01,0.02,0.03], (d). Throughput (bps) of densities [0.0025,0.005,0.0075].

V. CONCLUSION

Two modified RPL routing protocols are proposed in this work. ENCRPL is based on energy, neighbors, and child nodes, while NCERPL is based on energy, neighbors, child nodes, and ETX. The proposed protocols are implemented and evaluated through the Cooja simulator-based Contiki-OS. The proposed protocols achieved higher performance than RPL and its variant METRPL in all density ranges and areas considered in the work. In high and medium densities, ENCRPL consumes less energy than RPL and METRPL. NCERPL, in contrast, performed better with low density. ENCRPL outperformed RPL and METRPL with regard to energy consumption by 96.52% and 14%, respectively, in a 25×25 m^2 area with a density of 0.48 nodes/m^2.

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In comparison, NCERPL outperformed RPL and METRPL by 97% and 44.76% improvement, respectively, in $200 \times 200\ m^2$ area and density of 0.0075 nodes/m^2. Concerning dead nodes, ENCRPL is comparable to NCERPL and superior to MET and RPL. Considering throughput and PDR, all protocols perform approximately the same with 100 and 200 nodes, while with 300 nodes, the proposed protocols perform better than MET and RPL at all densities.

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CONFLICTS OF INTEREST

The author declares no conflict of interest

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