Additive Metric Composition-Based Load Aware Reliable Routing Protocol for Improving the Quality of Service in Industrial Internet of Things

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Abstract: *The Internet of Things (IoT) is the collection of low-power devices deployed in real-time applications like industries, health care and agriculture. The real-time applications must quickly sense, analyze and react to the data within a time frame. So the data's should be transmitted without any delay. The Routing Protocol for Low-power and Lossy Networks (RPL) is used to route the data by finding the optimal path. RPL forward the data packets from source to destination based on the objective functions. The objective functions can be designed using different routing metrics and most of the existing objective functions are not designed based on the characteristics of IoT applications. The Industrial Internet of Things (IIoT) environment with real-time data transfer characteristic is considered for this proposed work. Packet loss, power depletion and load balancing are the problems faced by real-time environment. Neighbor Indexed based RPL (NI-RPL) is implemented in two steps to improve efficiency of RPL. First, based on the Received Signal Strength Indicator (RSSI) and path-cost the preferred-parent set is formed from the set of neighboring nodes. Second, the rank of the nodes from the preferred-parent set is calculated based on the Neighbor Index (NI), Expected Transmission count (ETX) and Residual Energy (RE), and then the best route is selected based on the rank. The NI is used to avoid congestion, the ETX and RE helps in improving the Quality of Service (QoS) and lifetime of the network. The proposed objective function, NI-RPL is compared with other objective functions. NI-RPL guarantees the delivery of real –time data with better QoS, because it has improved the packet delivery ratio by 3% to 5% and decreases latency by 7 to 12 seconds.*

Keywords: *Neighbor index, objective function, reliability, residual energy, RSSI.*

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1. Introduction

In recent years, Internet of Things (IoT) plays a vital role in various applications like home automation, smart cities, healthcare and industries [2]. The IoT devices deployed in the application form a Low-power and Lossy Network (LLN), which is small in size with limited battery, storage and processing power [29]. The Figure 1 show that the IoT devices are connected to the Internet through gateways and they gather the information through the internet [29]. The number of IoT is nearly 26 billion in 2019, and forecasts predict that number will increase to about 75 billion by 2025 [2]. So the amount of data generated by the device will increase and the routing protocol is responsible for the communication process in LLN. Routing Protocol for Low-power and Lossy Networks (RPL) is the routing protocol proposed by Routing Over Low Power and Lossy Networks (ROLL) working group for IoT [34].

Routing helps to discover an optimal path based on node metrics like energy, processing power and link metrics like Expected Transmission Count (ETX), Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI) and latency [18]. The best path is selected based on the least path cost [27] by constructing a Destination Oriented Directed Acyclic Graph (DODAG). Each node communicates with the neighboring nodes, but has a single best parent for the formation of DODAG [29]. DODAG is constructed by using the following control messages:

- DIO: DODAG Information Object.
- DIS: DOGAG Information Solicitation.
- DAO: Destination Advertisement Object.
- DAO-ACK: DAO Acknowledgement.

RPL is a proactive protocol supports multipoint to point, point to multipoint and point to point communication [19] and chooses the best parent based on the objective functions. The objective functions make use of the link and node metric to calculate the rank of the node. The rank of the node should increase as we move down the graph, in order to avoid loops in Directed Acyclic Graph (DAG) [9]. The Internet Engineering Task Force (IETF) has presented two objective functions for RPL:

1) Objective Function zero (OF 0).
2) Minimum Rank with Hysteresis Objective Function (MRHOF) [14, 32].

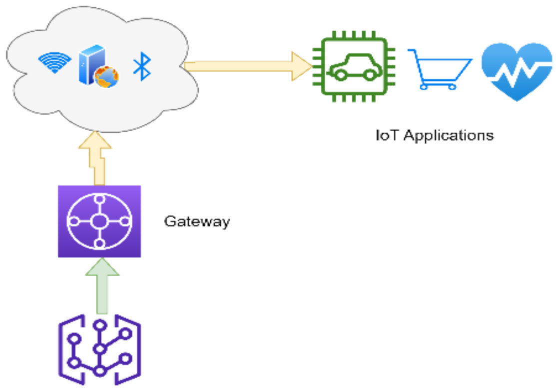

Figure 1. IoT communication architecture.

OF 0 uses the hop-count to calculate the rank of the node and it chooses the node nearest to root node as the preferred parent [30]. The OF 0 does not consider link metric and load balancing for parent selection process [32] and it selects the path with the lowest hop-count, even if there exist a longer path with better quality [30]. MRHOF uses metrics ETX for rank computation [10, 24]. A node selects a node with lowest rank as the preferred parent. MRHOF avoids instability by switching to the path with a minimum rank only if it is better than the current path [9].

1.1. RPL Challenges

The RPL designed for IoT has its own limitations which is not suitable for the real-time applications such as Industrial Internet of Things (IIoT). The limitations of RPL are listed below

1.1.1. Load Balancing

Load balancing helps in minimizing the traffic by distributing it among the nodes [20, 23]. In RPL the preferred parent is selected based on hop-count and ETX and it suffers from load balancing. Energy drains of the preferred parent may results in network partition [9]. So, the objective function should include a metric like queue utilization, number of child nodes to perform load balancing.

1.1.2. Reliable Routing

Achieving reliability in lossy environment is crucial. Unreliable routing paths results in data loss and frequent retransmissions [23]. So it is very much essential to discover a reliable routing path for data delivery. The reliable path depends on the reliability of the link and the metrics like ETX, RSSI and LQI are used to improve link reliability [6].

1.1.3. Energy-Efficiency

The nodes in LLN are battery operated and has limited power. The energy consumed by the nodes has to be reduced to prolong the network lifetime. Achieving good reliability with energy efficiency is an important issue in RPL [27]. Routing overhead should be minimized to conserve the energy [17].

1.1.4. Loop Management

RPL route the data by constructing a DODAG graph and it should be free from loop in order to avoid packet loss [16]. In order to construct a graph free from loop, a child node cannot choose a node with higher rank value as a preferred parent [29].

1.1.5. Scalability

LLN are large scale network, with the increase in the number of devices [20], so balancing all the devices and managing the network become complex. The routing protocol should support the large-scale network. Network scalability should be considered while designing a routing protocol for IoT [37].

1.1.6. Mobility

The mobility of nodes results in frequent path changes which increases the number of control packets [21]. The standard objective function OF 0 and MRHOF does not support mobility [8]. So the objective function should support dynamic changes in the network.

The routing quality can be improved by using a suitable objective function based on the application. The researches proposed different objective functions, but network scalability, link reliability and mobility can lead to packet loss, decreases network lifetime and increases the latency [18]. Therefore, to improve the routing process an enhanced objective function is proposed in this paper.

The Neighbor Index based RPL (NI-RPL) is used to enhance the performance of RPL by performing load balancing and by selecting the best parent based on the nodes rank. The NI-RPL works in two fold; first the node form a set of preferred-parent from the neighboring nodes based on the RSSI value and path-cost of the link. The RSSI and path-cost are the link metrics which helps to increase the reliability of the network [6, 15]. Second, the rank of the nodes is calculated based on Neighbor Index (NI), ETX and Residual Energy (RE). The NI depends on the number of one hop neighbors a node has and used in rank calculation which helps in a balanced selection of parent nodes [23]. The highlight of the proposed work is as follows:

- The set of preferred-parent is selected from the neighboring nodes based on the RSSI value and path-cost.
- The NI metric used in the selection of parent nodes helps to avoids network congestion.
- The selections of optimal route based on the rank of the node.
- The efficiency of the NI-RPL is compared with the other objective functions.

The experiment is conducted in Cooja simulator of Contiki Operating System (OS) for an IIoT application. The result of NI-RPL is compared with OF 0 [30], Minimum Rank with Hysteresis Objective Function-Expected Transmission count (MRHOF-ETX) [10] and Residual Energy and Expected Transmission count based RPL (RE-ETX) by varying the node density. The manuscript is structured as follows. Section 2 surveys the related works. Section 3 discusses the proposed work. Section 4 includes the simulation environment and results, and finally conclusion and future work in section 5 and 6.

2. Related Works Based on the Objective Functions

This section discusses the work related to the RPL under different objective functions.

The Energy and Load aware RPL (EL-RPL) protocol [26], is an enhanced version of RPL protocol. The rank of the node is calculated based on the combination of load of the path, Battery Depletion Index (BDI) and the ETX. The load of the path is calculated based on the cumulative traffic generated by the entire child node. The parent with a minimum rank value will be selected as the preferred parent. The performance of EL-RPL is compared with RER, BDI, RPL and fuzzy logic based RPL. The results show that EL-RPL has improved the network lifetime by 8-12 % and packet delivery ratio by 2-4 %. The authors Senkar and Srinivasan [26] have planned to introduce mobility to the nodes and to deploy it in real time environment.

In [16], the Routing Protocol power controlled RPL (PC-RPL) uses the RSSI value for the parent selection process. PC-RPL has used the children control, RSSI threshold to achieve load balancing. The algorithm has handled the hidden terminal and load imbalance problem by using the RSSI values. The PC-RPL is evaluated in real test bed and compared it with standard RPL and Queue Utilization based RPL (QU-RPL). PC-RPL has produced better results by reducing end-end packet loss by 7 fold and 17% improvement in aggregated bandwidth.

The Brad-OF [33], energy-aware objective function is implemented in two parts. In the first part, an energy-aware objective function is proposed to find the best path. In the second part, the congestion in parent queue is detected using the Node's Traffic Intensity and informed to the child node. The results indicate that the node RE level and the number of delivered packets were up by 65% and 81% when compared with CoLBA and HECRPL. The authors Vaziri and Haghighat [33] concluded that adding weight to the metrics based on the application will improve the equation for rank calculation.

The Child Count based Load Balancing in RPL (Ch-LBRPL) Sebastian [25], uses the child count to detect load imbalance. The Ch-LBRPL protocol implements load balancing in three levels: DAG load balancing, DODAG load balancing and Multi DODAG load balancing. The Ch-LBRPL algorithm has reduced the parent switching rate, reduces DIO messages and also improves the network lifetime. Sebastian [25] suggested that the algorithm should be implemented for large number of nodes with increased simulation time.

Hassani *et al*. [11], proposed a new objective function IRH-OF which is suitable for larger networks. The objective function has considered RSSI and hop-count to choose the optimal path and the metrics are combined together using additive metric composition method. The rank of the node is calculated based on the RSSI value and parents rank. The node with smaller rank is selected to route the packet. IRH-OF lowered the power consumption by 55% and the packets routed by the IRH-OF reached the destination faster than 25% when compared to ETX+Energy based objective function.

Using single routing metric results in the selection of non-optimized routes which in turn results in excessive energy consumption of nodes. To improve the networks performance Hassani *et al*. [12] proposed an objective function Forwarding Traffic Consciousness Objective Function (FTC-OF), which combines the metrics hop-count, RSSI, and Forwarded Traffic Metric (FTM). The rank of the node is calculated based on hop-count, RSSI, and FTM. The results show that the packet delivery ratio increases respectively with 2% and 11% in low and high traffics. FTC-OF has achieved a balanced traffic rate by using the metric FTM and considerably reduces the power consumption by 47%.

From the related work, it is inferred that the different objective functions are used to improve network performances but very few papers had paid attention for load balancing and had considered the important network metrics like RSSI to improve the reliability of the network. Most of the objective functions discussed in literature survey are not designed based on specific applications. This survey provides a solution to overcome the challenges faced by the RPL protocol and to design a new objective function based on the IoT application requirements. A new NI-RPL is proposed based on the characteristics of IIoT application to improve the network performance. The following are the contribution of the proposed works:

1) In NI-RPL, the NI is the metric used to achieve load balancing in the IIoT application.
2) Reliability of the network is assured by using the metrics RSSI and ETX.
3) Additive metric composition is used for the rank calculation of the nodes which improves the network parameters like packet delivery ratio, latency, throughput and RE.
4) The ranks of the node are calculated based on the metric order relationship to avoid loops in the DODAG graph.

3. Proposed Methods for Preferred Parent Selection and Load Balancing

Real-time data transfer is the important characteristic of Industrial Internet of Things (IIoT). The sensors deployed in the IIoT application should gather the real-time data and it should route the data without any delay. The RFC 5673 [22] defined the routing requirements for IIoT. In the proposed work, the nodes are deployed based on the characteristics of the IIoT application discussed in RFC 5673 and a new NI-RPL is proposed to achieve reliable data delivery in IIoT.

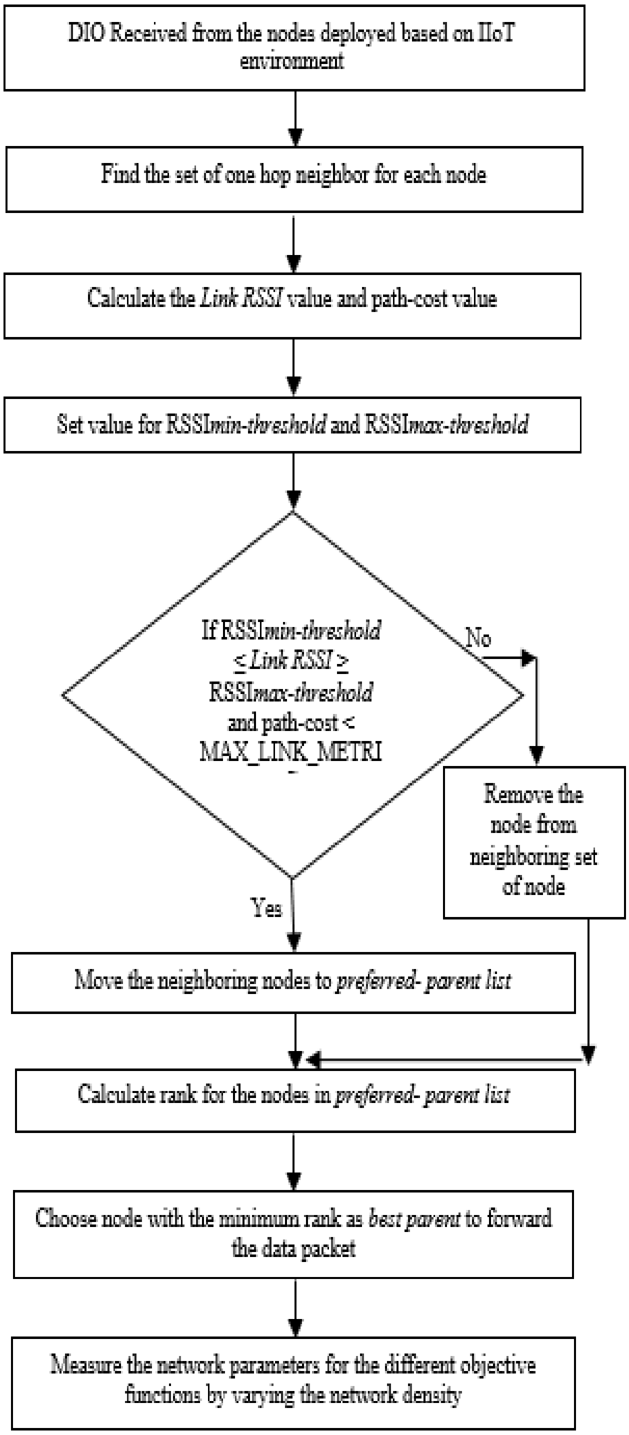

Figure 2. Work flow for NI-RPL.

The proposed objective function NI-RPL shown in Figure 2 works in two steps. First, the nodes on receiving the DIO message will calculate the Link RSSI and path-cost for the set of neighboring nodes. The preferred parents are selected from the set of neighboring nodes based on the Received Signal Strength Indicator (RSSI) and path-cost. If the link has a good Link RSSI and path-cost, then the node from the set of neighboring node is included in the preferred-parent list. Second, the best route is selected based on the NI, ETX and RE. The NI is used to prevent congestion and calculated based on the number of one hop neighbor nodes. The NI-RPL calculates the rank for all the nodes from the preferred-parent lists using the metrics NI, ETX and RE. The node with the minimum rank is selected as the best parent and it is used as an optimal path to the destination. The performance of the NI-RPL is compared with OF 0, MRHOF-ETX and RE-ETX in the IIoT environment by varying the node density. The network parameters like packet delivery ratio, latency, network convergence time, throughput, control packet overhead and energy consumption are measured for the different objective functions by varying the node density. The proposed work NI-RPL is simulated using the Cooja simulator Contiki OS.

3.1. Preferred Parent Selection Process

In a LLN network, RPL tries to find the best path by choosing the preferred parent from the neighboring set of nodes after calculating the path-cost for all the neighboring nodes [18]. If the calculated path-cost is greater than the MAX_LINK_METRIC then the neighboring node should not be included in the preferred-parent sets [10]. This parent selection process may result in frequent parent switching if more number of nodes are present in preferred-parent set. If more number of nodes shares the same minimum path-cost the algorithm has to consider one more selection criteria [10].

To rectify the above drawbacks, the node in NI-RPL, selects its set of preferred-parent from the set of neighboring nodes based on the RSSI value and the path-cost of the link. RSSI is the measure of signal power on a radio link [7]. The RSSI selects a network path that performs well in error–prone channel conditions [3]. A low link quality results in packet loss and retransmissions. RSSI value is calculated using the below Equation (1) [1],

$$RSSI = -10n\log(D) + C \quad (1)$$

Where D is the distance between nodes, n is the path loss exponent factor which depends on the environment for open environment the value is 2. C is a default received signal and it is 14 dbm for 802.11 [4]. The RSSI value and the path-cost help in the selection of more stable link.

3.2. Load Balancing

Load balancing is an important issue to be addressed in the RPL protocol. In RPL the best parent is selected based on the hop-count and ETX values, sometime the same node may act as a parent node for more number of child nodes [23]. These results in energy drain of the overloaded nodes and may results in network partition [9]. So the RPL protocol should include a metric to perform load balancing.

The traditional RPL makes use of MRHOF and OF 0 to route the data. The OF 0 makes use of the hop-count and MRHOF makes use of the link metric ETX [32]. The OF 0 and MRHOF does not address the load balancing issues. In order to address the load balancing issue number of neighboring nodes can be considered along with the other metrics like ETX, hop-count, energy, etc., while designing the objective function.

In the proposed work NI-RPL, load balancing is achieved by considering the metric, NI (number of neighboring nodes). NI, ETX and RE are used for the design of the new objective function. In the proposed work, the objective function calculates the rank of a node by considering routing metrics, ETX, RE and NI by using the Equation (2) [27, 35].

$$R_{node} = R_{parent} + R_{increase}$$
$$R_{increase} = (a1 * metric\ 1) + (a2 * metric\ 2) + (a3 * metric\ 3) \quad (2)$$

where *a1>=0, a2,a3 <=1 and a1+a2+a3 =1*.

In NI-RPL the *metric 1*, *metric 2*, *metric 3* are the ETX, RE and NI. NI helps to achieve load balancing; ETX maintains the link reliability and RE is used to improve the lifetime of the network.

3.2.1. Rank Calculation

RPL protocol calculates the rank of the nodes from the set of preferred-parent and the node with minimum rank is chosen to forward the packet. While designing the objective function for IIoT, link reliability and network life time are the important parameters to be considered, because the data should be transmitted to the destination without any delay [32]. The reliability of the link depends on the link metric ETX, RSSI and it helps to improve the packet delivery ratio and latency of the network [6]. NI is used to achieve load balancing and RE of the nodes is used to prolong the lifetime of the network. The metrics of interest while designing the objective function for NI-RPL are:

- Expected Transmission count (ETX)
- Residual Energy (RE)
- Neighbor Index (NI)

The ETX is defined as the number of transmissions needed for the successful delivery of the packets to the destination through a link [12]. The objective function MRHOF makes use of the link metric ETX for the rank calculation purpose. The network link is more reliable if the ETX value is low [10]. The ETX is calculated using Equation (3) [31].

$$ETX = 1 / (Df * Dr) \quad (3)$$

Where *Df* is the forward delivery ratio, that is the probability calculation of the successfully received packet at the neighboring node. *Dr* is the reverse delivery ratio, that is the probability calculation of the acknowledgement packet at the receiver node.

Energy is a node metric and energy consumed by the node depends on the transmission time, listen time, CPU time and Low Power Mode (LPM) time. The nodes energy consumption is calculated using Equation (4) [31].

$$Energy_{Consumed} = (Tcpu * Icpu + Ttx * Itx + Trx * Irx + Tlpm * Ilpm / \text{RTIMER\_ARCH\_SECOND}) * 3 \quad (4)$$

where I_{cpu}, I_{tx}, $I_{rx}$and I_{lpm} represent the energy consumed during the CPU run time, the radio transmit time, the radio listen time and the LPM run time. In Equation (4), RTIMER_ARCH_SECOND represents the number of ticks per second. The REcan be calculated as follows [31, 35]:

$$ResidualEnergy(RE) = \text{Initial}_{\text{Energy}} - Energy_{Consumed} \quad (5)$$

NI helps to enhance the network lifetime and also achieve load balancing. The NI is calculated based on the one hop neighboring node. The number of packets forwarded by the node depends on the number of neighboring nodes, which in turn results in energy depletion of the network. So NI plays a vital role in load balancing and network lifetime. In the proposed work the ETX and RE is calculated using the Equations (3), (4), and (5) and these metrics are used to calculate the rank of the nodes.

In RPL protocol the rank of the node is calculated based on metric order relation maximizable and minimizable are the two metric order relations used in the rank calculation of the nodes [36]. The metric order relation maximizable produce better result when the value is high, for example, if the objective function is designed based on energy then the node will select the node with maximum energy as the preferred parent. In rank calculation minimizable means lower the value produces better result, for example, if the objective function is designed based on hop-count and ETX then the node will select the node with minimum hop-count and ETX as the preferred parent [36].

In order to find the best parent for a node either lexical metric composition or additive metric composition can be used. In the lexical metric composition approach the algorithm uses two composite metric values [36]. In lexical metric composition the DODAG nodes select the best parent based on the first composite value, if the first composition values of the nodes are equal, then the nodes use the second composition values to choose the best parent. In additive metric composition, the composite function metrics calculate the weighted sum of all metric and advertise the weighted sum through DIO message [26]. The additive metric composition is calculated by using Equation (6) [36].

$$Additivemetric = (a1 * metric\ 1) + (a2 * metric\ 2) \quad (6)$$

Where *a1>=0, a2 <=1 and a1+a2 =1* and metric 1 and *metric 2* represents the metric like ETX, RSSI, energy or hop-count.

In this proposed work NI-RPL, the additive metric composition that is Equation (6) is used to calculate the rank of the node, because the additive approach is suitable to meet the requirements of various applications and composite metric does not guarantee network optimization [26]. The ETX, RE and NI are the metrics used in rank calculation of nodes in NI-RPL. While combining the metrics, the order relation of the metric should be followed [36]. The order relation of the metric is given below in Table 1.

Table 1. Metric order relationship in LLN.

Metric	Aggregate rule	Order relation
ETX	Additive	<
RE	Concave(min)	>
NI	Additive	<

NI-RPL calculates the rank of the node by using the Equation (7) which follows metric order relationship.

$$R_{node} = R_{parent} + R_{increase}$$
$$R_{increase} = (a1 * ETX) + (a2 * 1/RE) + (a3 * NI) \quad (7)$$

Where R_{parent} is the rank of the parent node, ETX and RE are calculated by using the Equations (3), (4), and (5). The value of *a1+a2+a3 =1* [36] and *a1*, *a2* and *a3* can be assigned weights based on the importance of the metric in rank calculation. In the proposed work in order to transmit the data without any delay ETX (metric 1) is given more importance than RE (metric 2) and NI (metric 3), so a1 is assigned with a weight of 0.4. NI and RE are used to increase the network lifetime, so equal weight is assigned to NI and RE. The value of *a1=0.4, a2=0.3* and *a3=0.3*. In the proposed work the rank of the nodes in the network is calculated using Algorithm 1.

Algorithm 1: Rank Calculation Process

Input: Set of preferred_ parent
Output: Best parent
for all nodes P in set of preferred_ parent do
Compute ETX, RE and NI
*ETX= (1/Df*Dr)*
RE=Initial $_{Energy}$ *- Energy* $_{consumed}$
NI = Count of one hop adjacent nodes
Compute rank (P)
rank (P)=rank$_{parent}$ *+ rank_increment*
rank_increment=a1 ETX +a2* (1/RE)+a3*NI*
where a1=0.4, a2=0.3, a3=0.3
if rank(P)>= rank of preferred_parent then
best_parent = preferred_parent
end if

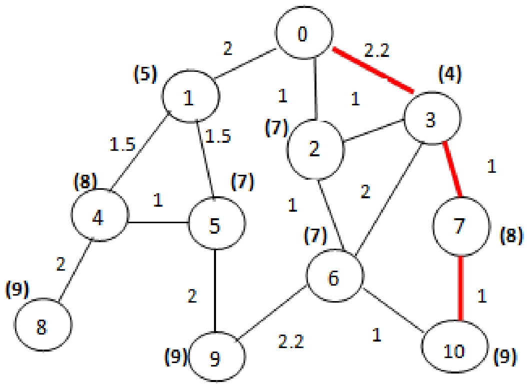

Figure 3. Route selection process in NI-RPL.

In the above DODAG graph in Figure 3 calculate the route from the sink node 10 to the destination node 0 using NI-RPL. Each node in the DODAG graph contains the ETX and RE values. The nodes calculate the rank by using Equation (7), based on the metrics like ETX, energy and NI. The optimal route from node 10 to sink 0 is selected based on the rank value. The node 10 has two parents 6 and 7 and it chooses node 7 to forward the packet because the rank of node 6 is 1.643 which is greater than the rank of node 7 (1.038).So in this example the optimal path from node 10 to node 0 is 10→7→3→0.

4. Simulation Environment and Performance Evaluation

In this proposed work, RPL is analyzed using Contiki OS, designed for resource-limited devices [4]. Contiki operates in low power systems and simulates the routing protocol RPL using Cooja simulator before using it in the hardware [4].

4.1. Simulation Environment

IIoT is the environment used to analyze of the RPL. The nodes are deployed based on the characteristics of IIoT discussed in RFC 5673 [22].The sensors deployed in Industries are used to monitor the emergency situation like rise in temperature, release of poisonous gas, fire, health of the equipment and so on. The information gathered by the sensor should be communicated with the server without any delay, because in case of emergency immediate action should be taken on the environment [14]. In order to communicate in an emergency situation the routing protocol RPL should perform well with a better packet delivery ratio and latency. In this proposed work, RPL is analyzed in the IIoT environment. The efficiency of RPL depends on the objective function. In this work, the objective function NI-RPL is designed to achieve a better QoS.

An IIoT application has four service categories based on traffic characteristics, namely periodic data, event data, Client/Server and bulk transfer [22]. Periodic data traffic generates data periodically at an average rate of

1/min and it is used for the implementation of proposed work.

The simulation parameters given in Table 2 are used for the simulation. In the proposed work the nodes are deployed randomly because most of the applications prefer random deployment [35].

Table 2. Simulation parameters.

Parameter	Value
Network Simulator	Cooja simulator under Contiki 2.7 OS
Network size	20,30, 40,50 and 60 nodes
Node type	Sky mote
Network topology	Multi-hop Mesh network
TX and RX values	TX=100 and RX= 80
Objective function	OF 0,MHROF-ETX,RE-ETX and NI-RPL
Traffic rate	1 packets/s
MAC layer protocol	CONTIKI MAC
Deployment area	100 m^2
Simulation time	90 minutes
Initial energy	3000 mA

The routing protocol RPL is analyzed for the different objective functions. The efficiency of RPL for IIoT application is measured based on the network parameters like packet delivery ratio, the average energy consumption, network convergence time, throughput, control traffic overhead and latency by varying the node density.

4.2. Performance Analysis

The nodes are deployed based on the IIoT application environment and the simulation is carried out for 90 minutes. The routing parameters like packet delivery ratio, the average energy consumption, network convergence time, throughput, control traffic overhead and latency are measured and NI-RPL is compared with OF 0, MRHOF-ETX, RE-ETX.

4.2.1. Packet Delivery Ratio

The packet delivery ratio is the ratio of number of packets received at the destination to the number of packets generated by the source [13, 28]. Packet delivery ratio helps to find the percentage of packets received successfully at the sink node. It is calculated using the Equation (8).

$$PacketDeliveryRatio = \left(\frac{TotalPacketsReceived}{TotalPacketsSent}\right) * 100 \quad (8)$$

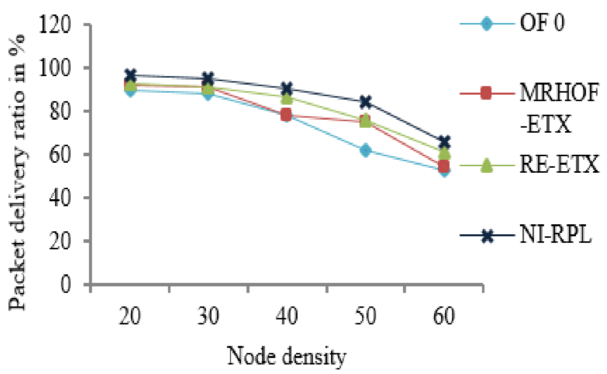

Figure 4. Packet delivery ratio versus node density.

Figure 4 shows that the packet delivery ratio decreases with the increase in node density, because the high density network generates more packets which in turn increase the collision rate. The packet delivery ratio of NI-RPL is increased by 3% to 5%, when compared with RE-ETX. The metric NI used in the rank calculation of NI-RPL avoids the congested path and helps in finding an alternate path to deliver the packets to the destination.

4.2.2. Latency

Latency measures the time the data packet takes to reach the destination and it is a measure of delay. Total latency is calculated by summing the latency for all the packets generated by the nodes.

$$Totallatency = \sum_{k=1}^{n} (Receivedtime(k) - senttime(k)) \quad (9)$$

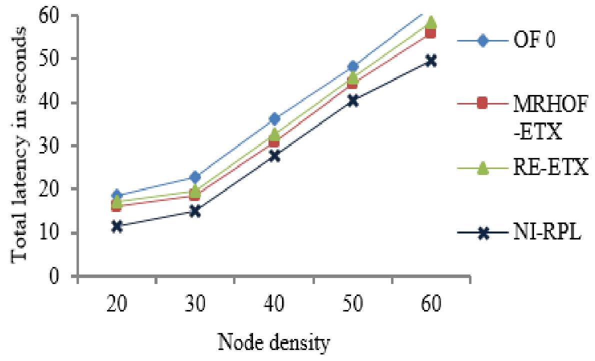

Figure 5. Latency versus node density.

Figure 5 shows that OF 0, MRHOF-ETX, RE-ETX has the highest latency when compared with NI-RPL, because NI-RPL makes use of the link metric RSSI and ETX for the parent selection process. RSSI helps in choosing the best path which reduces the latency by 7 to 12 seconds. Since NI-RPL has given a better latency this can be used as an objective function to improve QoS in a reliable environment.

4.2.3. Network Convergence Time

The RPL protocol uses the DAG network and the DIO message helps the nodes to join the network. Network convergence time is measured as the difference between last DIO joined and the first DIO that joins the DAG [28]. The lifetime of the network increases if the network convergence time is less. Network convergence time of the network is calculated using the Equation (10)

$$NetworkConvergencetime = LastDIOjoinedDAG - firstDIOjoinedDAG \quad (10)$$

Figure 6 shows that the network convergence time increases with the node density, because all the nodes in the network generate the DIO message to join the network. The network convergence time of NI-RPL ranges from 0.449 to 0.692. NI-RPL has produced better network convergence time, because the latency and number of control packets generated by NI-RPL is less when compared with other objective functions.

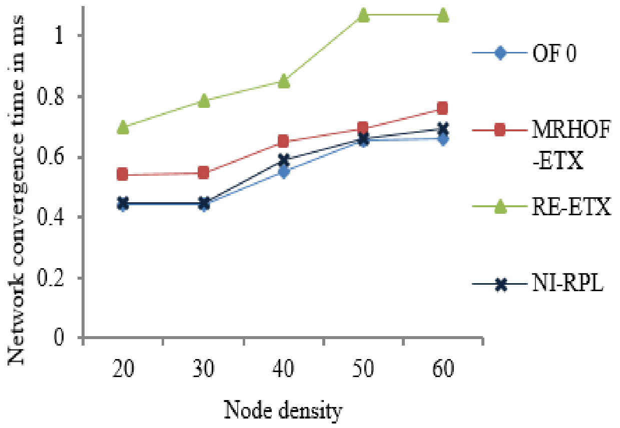

Figure 6. Network convergence time versus node density.

4.2.4. Average Energy Consumption

Energy consumed by the nodes depends on the transmission time, listen time, CPU time and LPM of a node. The average energy consumed by the network is calculated using the Equation (5). The energy depletion of the nodes results in network partition. The energy consumed by the sink node and the nodes which lie close to the sink node will be more, because the listen time and transmission time of these nodes will be high.

The Figure 7 shows that the average energy consumption increases with the increase in node density, because in larger networks the packet generation rate will be high and the retransmission will also increase due to collision. The results show that the average energy consumed by NI-RPL is 5% to 6% less than RE-ETX, but the energy consumption of NI-RPL is greater than MRHOF-ETX. So the energy consumption of NI-RPL has to be improved.

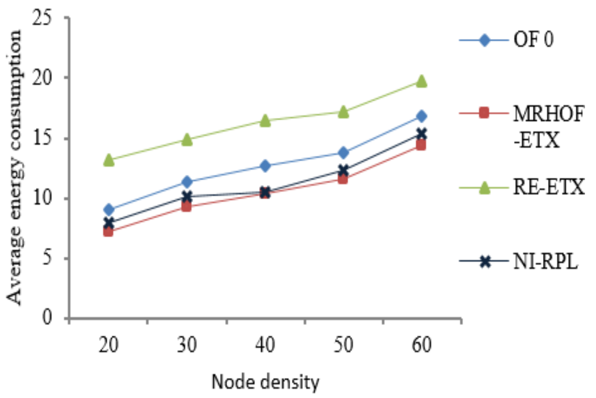

Figure 7. Average energy consumption versus node density.

4.2.5. Throughput

Throughput is defined as the amount of bytes received at the sink node to the duration of simulation [5] and gives a picture about how much amount of data was transferred from a node at a given time. Throughput is calculated using Equation (11).

$$Throughput\left(\frac{KB}{s}\right) = \frac{Number\ of\ delivered\ packet * Size\ of\ the\ received\ packet}{Total\ duration\ of\ simulation} \quad (11)$$

NI-RPL in Figure 8 has produced better throughput that ranges from 0.98 kbps to 0.69 kbps, because it makes use of the metric RSSI for the preferred-parent selection process and NI for rank calculation process. NI-RPL has produced better packet delivery ratio, latency and throughput, so this is the suitable objective function for the reliable environment with improved QoS.

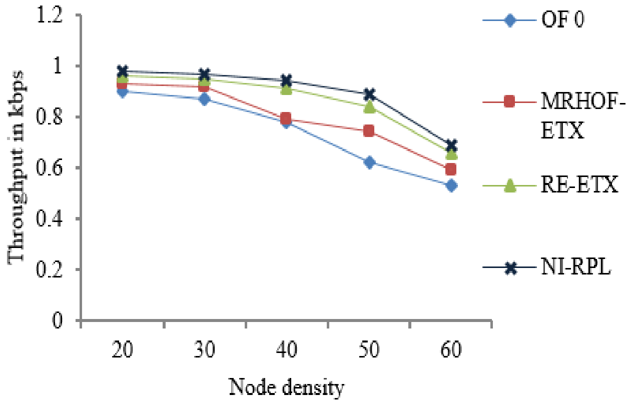

Figure 8. Throughput versus node density.

4.2.6. Number of Control Packets

In RPL, the DAG is constructed by using the control packets DIO, DIS and DAO. Control packets are used for repairing network routes [32]. Number of Control packets is the total number of DIO, DIS, DAO, DAO-ACK transmitted during the simulation process. Increase in control packets leads to network overhead and energy depletion [28]. The control packets can be reduced by using a proper objective function.

$$Number\ of\ Control\ packets = \sum_{k=0}^{n} DIO(K) + \sum_{k=0}^{n} DIS(K) + \sum_{k=0}^{n} DAO(K) \sum_{k=0}^{n} DAO - \sum_{k=0}^{n} ACK\ (K) \quad (12)$$

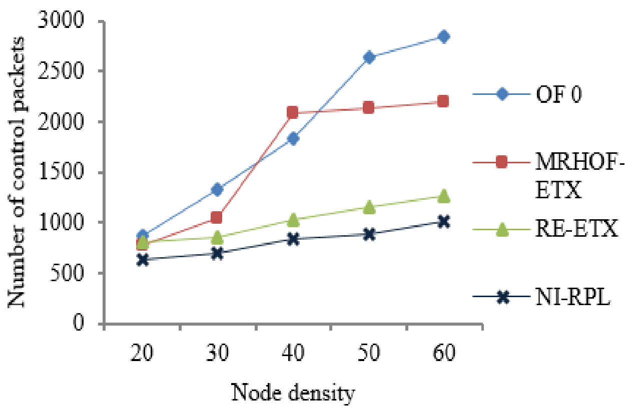

Figure 9. Number of control packets versus node density.

The number of control packet increases with increase in node density, because the number of control packets generated depends on the network density. From Figure 9 the number of control packets generated by NI-RPL is more or less 200 to 260 packets less than RE-ETX. The performance of NI-RPL is good because this makes use of good routing metrics like RSSI, ETX, RE and NI. The life time of the network will also increase due to the reduction in the number of control packets. So the network energy consumption of NI-RPL is being improved by 6 % when compared with RE-ETX.

Table 3. NI-RPL versus objective functions for a network with 60 nodes.

Objective function	Packet delivery ratio	Latency	Network convergence time	Average energy consumption	Throughput	Number of control packets
OF 0	52.8	61.83	0.658	16.8	0.53	2844
MRHOF-ETX	54.45	56.05	0.756	14.37	0.59	2190
RE-ETX	60.78	58.278	1.07	19.75	0.69	1267
NI-RPL	65.75	49.37	0.692	15.4	0.69	1006

The Table 3 shows that when the node density is increased NI-RPL has improved the packet delivery ratio by 4.975 when compared with RE-ETX. The proposed objective function NI-RPL has reduced the latency by 6.5s when compared MRHOF-ETX. NI-RPL also reduces the generation of control packets, the QoS depends on the packet delivery ratio, latency and throughput. So NI-RPL is the suitable objective function to improve the QoS in real time reliable environment.

5. Conclusions

In this paper, a load aware reliable objective function NI-RPL is proposed for the IIoT environment. The NI-RPL selects the best path based on the RSSI value and the path-cost of the link and it calculates the rank based on the metrics NI, ETX and RE. NI-RPL is compared with the other objective functions by varying the node density.

The results show that NI-RPL has improved the packet delivery ratio by 3% to 5% and latency by 7 to 12 seconds. The number of control packets generated by NI-RPL is around 260 packets less than RE-ETX. The average energy consumption of the NI-RPL is 1.03% greater than MRHOF-ETX, but it has produced better results when compared with OF 0 and RE-ETX. The results show that the network convergence time of NI-RPL is better than MRHOF-ETX and RE-ETX. NI-RPL has produced a better packet delivery ratio, latency and throughput which in turn help the application to achieve a better network reliability. So NI-RPL is considered as the suitable objective function to improve the QoS for the IIoT environment.

6. Future Scope

In future, the efficiency of NI-RPL can be verified through test beds. The Trickle timer and the MAC layer protocol can be optimized to improve the network lifetime because NI-RPL uses more network energy. Apply mobility to the nodes in LLN network and to develop a new objective function that supports the mobility of the nodes. Addition of more metrics will result in protocol overhead, so attention can be paid to develop a lightweight RPL protocol.

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