An Efficient Routing Protocol for Low-Power and Lossy Wireless Sensor Networks

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Abstract **—** A Wireless Sensor Network is formed of small devices with the capability of detecting nearby physical characteristics and sending them hop by hop to the destination nodes by means of low power and short range wireless transmissions. The lifetime of a Wireless Sensor Network primarily relies on the efficiency of the routing protocols. The nodes which lie on the perimeter of the parent node face the issue of packet loss due to the disturbance created by the surrounding devices operating on the same radio band, such as Wi-Fi, Bluetooth, and other 802.15.4 devices. The nodes present on the edge of a network have a packet delivery ratio much lower than the average packet delivery ratio of the whole network. As a result, much research has been carried out on improvement of the packet deliver ratio of the nodes on the edge of the network. In this paper, we propose an efficient routing protocol for low-power and lossy networks in Contiki based on evaluations of the packet delivery ratio and the throughput. Experimental results show that the proposed routing protocol performs better than the baseline models, with a very efficient packet delivery ratio (76.69%), and throughput (90.25%).

Index Terms**—**RPL; objective function; low-power and lossy network; wireless sensor network

I. Introduction

The utilization of low-power wireless devices is turning out to be important in our day to day lives. It has numerous application regions like modern mechanization, home automation, security, and the smart framework. Because of the limited amount of size, power, and cost, the devices in a Wireless Sensor Network (WSN) have very limited resources. Generally, sensor nodes run on batteries which can't be recharged easily [1]. It is key to make them run efficiently in terms of computation and communication. In wireless communication, radio transceiving takes most of the energy consumption [2], thus making the routing protocols more crucial than any other design issues in WSN designs. These networks are also termed as Low-Power and Lossy Networks (LLNs) [3], [4].

A lossy connection is a connection with high bit error rates. The packet drops on lossy connections are extremely frequent and the connections may get to be distinctly unusable for a long time because of the obstructions [1]. To make utilization of the rare resources in LLNs efficient, resource-consuming activities should be regularized.

A node in LLNs not only needs to advance its own packets, but also needs to pass packets from the adjacent nodes toward the destination (sink for instance) in an efficient way. The routing operations create a great concern in wasting the resources in these nodes as shown in Fig. 1.

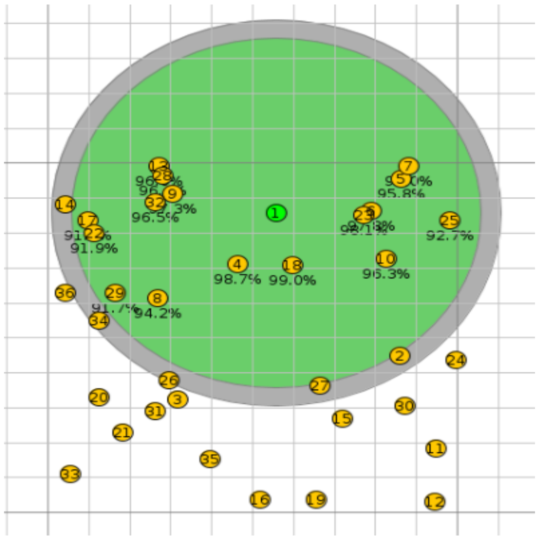

Fig. 1. A low power and lossy WSN

As mentioned above, the nodes used in a WSN are highly resource constrained. Therefore, improvement of the packet delivery ratio, the power consumption and the throughput plays an important role in routing protocol designs. In this paper, we propose an enhanced routing protocol, named RSSI-Rank Matrix (RRM), for Low-Power and Lossy WSNs. Simulation and evaluation of the proposed RRM routing protocol and the baseline protocol, Objective Function0 (OF0-IETF RFC6550) [5], are carried out based on two major design metrics, packet delivery ratio and throughput. Simulation results show an impressive improvement in both of performance metrics.

The organization of this paper is as follows. Section II provides a brief background about the communication in WSNs. Section III discusses the design of the existing protocols. Section IV presents implementation of the enhanced routing protocol, RRM. Section V shows the simulation results and justification. Finally, Section VI concludes the paper.

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II. Background

A. Wireless Sensor Network

A WSN consists of some small low power devices named sensor nodes which can act as a data creator, data forwarder, or data router. Sensor nodes can be deployed across various areas to monitor and/or control physical or environmental conditions. A WSN node may be equipped with all kind of sensors, such as temperature, humidity, pressure, power-line voltage, etc.

Each node performs few basic tasks:

- Record sensor reading or perform controlling
- Transmit/receive data to/from coordinator.

B. Overview of the Routing Protocol for Low-power and Lossy Network

A routing protocol is responsible for efficiently sending or directing the packets from the source nodes to the destination nodes. There are various routing metrics to select parent for routing. Basic routing metrics assigned by IETF include Hop Count, link Throughput, Link Latency, Link Quality Level, and Link ETX [5]. With the help of routing matrices, routing protocol can form the OFs, which will decide the parent and child relationship between two neighbor nodes [3].

By using the Routing Protocol for Low-power and Lossy (RPL) Networks, a WSN is equipped with the features of self-healing and dynamic network forming [7]. To maintain and update the link matrices for best parent selection, sensor nodes will broadcast Neighbor Advertisement (NA) packets. Each neighbor then responds with Network Solicitation (NS) messages. These two packets will be used by the RPL to calculate the link matrices [3].

The RPL shapes a tree like topology, called DAG. Every node in a RPL organization has a preferred parent which acts as a passage for that node. On the off chance that a node does not have an entry in its routing table for a packet, the node just advances it to its favored parent thus on until it either achieves the goal or a typical parent which advances it down the tree towards the goal. The nodes in a RPL network have routes for every one of the nodes down the tree, which implies the nodes closer to the root node have bigger routing tables [7].

C. Topology Formation

In LLN network, RPL must form the topology first. RPL forms a parent-child topology in which the latter node (child node) talks to the upper node (parent node) first before establishing the connection or link with the sink node. RPL also forms a smart tree-like topology in which the first or top node behaves as a root for the smart tree and the bottom nodes behave as edges [3], [5].

D. Objective Function

An Objective Function (OF) characterizes how a RPL node chooses, improves, and optimizes paths inside a RPL structure according to available objects data.

A physical network is made of few connections or links with various metrics, such as throughput, latency, packet delivery ratio, etc. In WSNs, based on different OFs, networks can carry out different types of traffic. These OFs help direct the traffic in the network to different paths as per requirements or conditions of the network. These requirements or conditions are encoded in a programming logic named OF and utilized by the RPL during routing operation [3, 5].

III. Related Work

Routing in LLNs is a difficult task not only because of its lossy nature of the radio medium and the limited resources of the sensor nodes, but also because of the various routing requirements and flexibility of the RPL configurations. Varieties of RPL metrics were used in the previous research to calculate its performance in various network scenarios and it has been discovered that a number of good developments can be added to a RPL network [2], [3].

One of the most important work of a routing protocol is to find the shortest and easiest route from the source node to the destination node. Then all the entries are saved in the routing table. Objective function basically decides the path entries because all the functions use different metrics and strategies to find the best and easiest path. Generally, the nodes on the edge perform very poorly [8].

Control Packet Overhead is an essential feature of a routing protocol and directly relates to Energy Consumption. To reduce (or control) generation of the redundant control packets and utilize the limited resources of a LLN more efficiently, RPL make use of a Trickle Timer [9] which periodically transmits control traffic.

The routing protocols in WSNs are divided into three categories:

- Data-Centric
- Hierarchical
- Location-Based [10]

In RPL network, throughput always fluctuates and depends on various aspects such as size of the network and location of the nodes. The throughput of a node depends upon its distance from the sink node. For example, if the node is closer to the sink node, its throughput will be more compared to other nodes. The nodes closer to the leaves receive more packets because the nodes in a RPL network not only forward its own data but also help the other nodes to send data to the sink [8].

In routing protocol, packet delivery ratio can be used as a parameter for choosing the best route. There are many methods for measuring or calculating the packet delivery ratio in WSN. In the first strategy, a number of hello messages are sent to the sink and the successfully received packets is counted at the sink. This first technique is very accurate but consumes more power. The second strategy considers the packet delivery ratio

(PDR) history, which helps in reducing the power consumption, but greatly lowers the accuracy.

IV. Implementation of the Proposed RRM Routing Protocol

As mentioned in the Introduction, OF0 (IETF RFC6550) works on Rank Matrix. There are some issues in the OF0 routing protocol. One of the major issues is with the edge nodes. In the network, the nodes which are present on the edge face issues in packet receiving. The nodes which lie on the perimeter of the parent node face the same issue, due to external noise generated by other device operators on the same frequency band.

To alleviate the problem, we propose a new routing algorithm which will focus on performance improvement of the nodes which are present on the edge of the network. These nodes generally have a much lower packet delivery ratio compared to the other nodes in the network.

The proposed RRM routing algorithm will use the RSSI and Rank Matrix instead of only the Rank Matrix in the OF0 protocol. This paper is mainly focus on parent selection process, where child node will select the best parent for further communication.

In this network, RSSI and LQI are the same when all the calculations are done at single hop. To take advantage of this fact, this protocol can select the best parent with zero control packet overhead. As per IEEE 802.15.4 draft, when packets are received at PHY layer, the node will get LQI(RSSI) of the transmitting node [1]. This protocol successfully retrieves value and store it for parent selection algorithm for each of the router candidates.

In the preferred parent determination method, when a DIO is received from a neighbor node, its RSSI is updated in the candidate parent table. This is done by using the weighted moving average of the RSSI(LQI) for the neighbor node.

Equation for updating Link matric which is used in RSSI matrix is as below:

$$\begin{aligned} &Parent \rightarrow Link\ Metric\ = \\ &\quad Base*(Parent \rightarrow Link\ Metric)+(1-base)*RSSI \end{aligned} \tag{1}$$

In the equation (1), base is the weighting factor for the historical Link Metric of that component. For example, if 90% weighting is given to the historical average of the Link Metric, then base is equal to 90%, and the above equation will be:

$$\begin{aligned} &Parent \rightarrow Link\ Metric = \\ &\quad 0.9*(Parent \rightarrow Link\ Metric)+(1-0.9)*RSSI \end{aligned} \tag{2}$$

To avoid OF0 issue, only those nodes selected as the parent candidates which are above the threshold of minimum Link Metric. It is selected to reduce the possibility that a weak signal in the total absence of noise may give a false low LQI. For preferred parent selection, nodes in the candidate parent table that have a Link Metric that is above the threshold are compared. Whichever node has the lower rank will be set as the preferred parent.

In other words, only the parent which satisfies both minimum rank and link matric above minimum threshold will be selected as parent of that node.

V. Simulation

A network with 35 client nodes has been created with 1 sink node in the Cooja simulator. The sink node acts as base of the DODAG. The network layout is shown in Fig. 2.

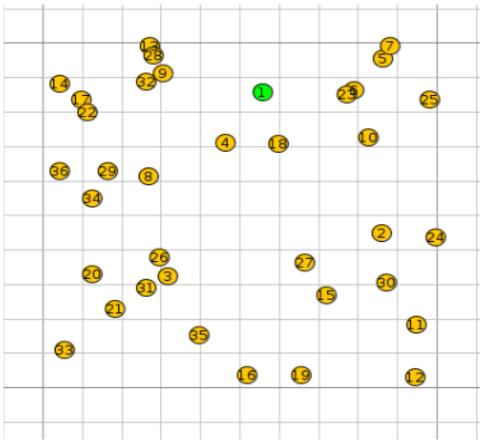

Fig. 2. Layout of the simulation network

The server node runs an example application udp-server.c while the other node run udp-client.c with minor modifications for maintaining packet sent and receive count. We utilize a Cooja [6] plugin called Contiki Test Editor to measure the simulation time and halt the simulation after the predefined time. This Cooja plugin makes a log record (COOJA.testlog) for every one of the outputs from the simulation which we will investigate at the end of test suits.

As shown in Fig.3, all source nodes send data and the sink node will receive and acknowledge it. Based on the received data, the script measures sent and received packets for each node.

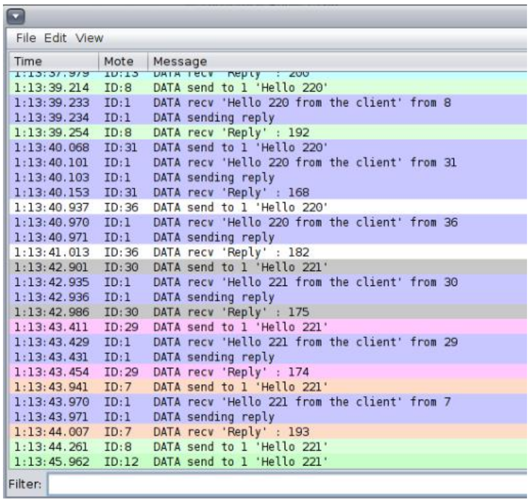

Fig. 3. Data receiving at the sink node

Considering the end goal is to present lossyness in the wireless medium, we employ the Cooja Unit Disk Graph Medium(UDGM) which introduces lossyness with respect to relative distance of nodes in the Radio Medium. The parameters for the simulation and its configurations are shown in Table I.

TABLE I. SIMULATION PARAMETER.

Parameters	Value
Start Delay	65 s
Packet Transmitted	57392 (OF0), 61974 (Proposed Network)
Packet Received	42070 (OF0), 47529 (Proposed Network)
Send Interval	20
RX Ratio	90%
TX Ratio	100%
TX Range	50m
Interference Range	55m
Client Nodes	35
Simulation time	9 Hrs.

As seen in Table I, the start delay is the initial delay for the application to start transmitting its messages to the sink node. The start time is the surmised time adequate for the initial network convergence. This guarantees the packets sent to the server won't get lost due to the absence of system network. In this way, a right assessment can be performed on the quantity of packet sent.

The send interval defines the interval between two progressive application level messages. Both the start delay and send interval have included time interval randomness. The number of total packets from a node transmits at a rate of 1 packet/(Send Interval± Randomness). So the minimum number of packet sent is 1 packet/(Send Interval) * Simulation Time; though the greatest number of packet sent is computed as 1 packet/(Send Interval+ Randomness) * Simulation Time. Since the packet transmission begins after the Start Delay (65s), the real simulation time will be less by Start Delay (Simulation Time – Start Delay). Every sink or sensor node will get distinctive randomness, and the right number of packets sent cannot be preconfigured. Instead, our metric measuring mechanism measures the number of packets sent. This empowers the reasonable calculation of the packet delivery ratio, and the Control Traffic overhead.

We set the RPL method of operation to No Downward routes since we are occupied with utilizing the multipoint-to-point activity for this assessment. DIO Min and DIO Doublings are set to ContikiRPL default values as shown in Table II. The reception ratio (RX) defines level of the lossness in the radio medium and is set in percentage during the progressive iteration of simulation. In the primary stage, we set it to various levels and along these lines we observe the execution or performance of the OF0 and the proposed RRM model for various values of lousiness. The transmission ratio (TX) is set to 100% (loss free) since we don't plan to add losses at the transmitter end, but we want to add losses at receiving end. The TX range is set to 50m and interference range to 55m.

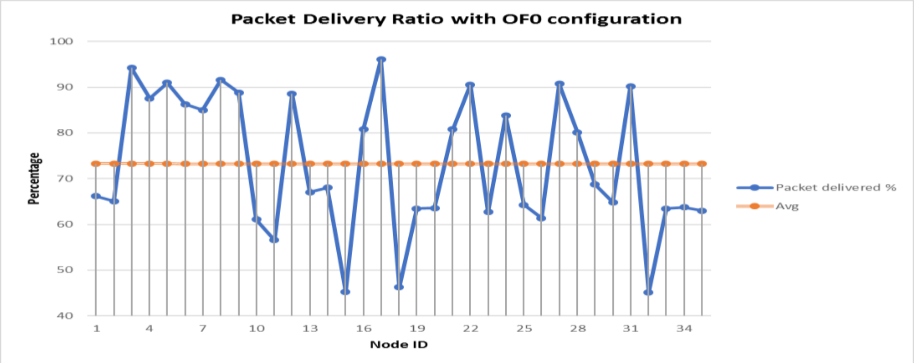

Fig. 4. PDR for OF0 routing protocol

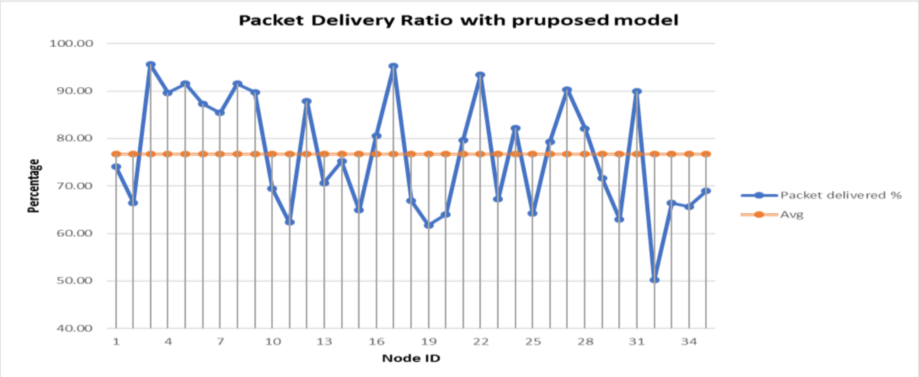

Fig. 5. PDR for proposed RRM routing protocol

TABLE II. ROUTING PARAMETERS.

Parameters	Value
OF	OF0, Proposed Network
DIO Min	12
DIO Doublings	8

VI. RESULTS AND JUSTIFICATION

In OF0 protocol (Rank Matrix), the child node selects parent using rank matrix. In our proposed RRM routing model (Rank + RSSI matrix), we mainly focus on edge nodes of the network where performance lags significantly. Within almost 9 hours' execution, the total number of transmitted and received packet across the network are around 57K and 42k respectively.

We compare the proposed RRM routing to the OF0 baseline model on the Packet Deliver Ratio (PDR) and the Throughput. By comparing output of the node #27, which lies on edge of node #1's communication range, it shows improvement in both PDR and Throughput. The PDR waveforms of the OF0 and the proposed RRM routing protocols are shown in Fig.4 and Fig.5. The average PDR and Throughput of the two routing protocols are shown in Table III.

TABLE III. AVERAGE RESULT OF BOTH THE PROTOCOLS.

Routing Protocol	Packet Delivery Ratio	Throughput
OF0	73.3%	89.74
Proposed	76.69%	90.88

The average PDR has been increased from 73.3% to 76.69%. At the same time, the network Throughput has been improved from 89.74 to 90.88 as shown in Fig. 6.

At the same time, deviation of the drop packets on edge nodes is reduced from 39% to 21% at the sampling node #27.

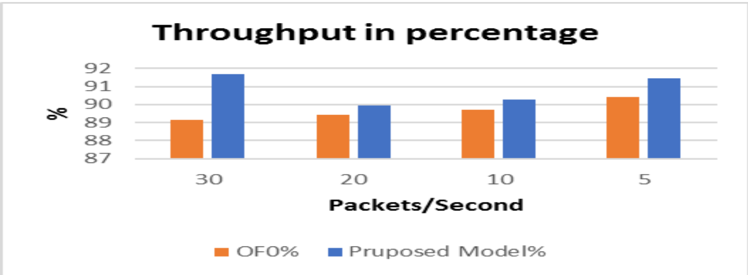

Fig. 6. Throughput comparison

VII. CONCLUSION

There are many problems in getting a good amount of success ratio (packet delivery ratio) in WSNs, especially when the nodes are non-stationary. It is hard to optimize the power consumption, packet delivery ratio, and connections with other devices. To overcome these problems, we propose to add more objective function to routing protocol to efficiently improve the success ratio. In this paper, we evaluate the packet delivery ratio and throughput of the network. By adding RSSI and Rank objective functions along with the rank matrix, the average network packet delivery ratio has been improved from 73.3% to 76.69% while the throughput is increased from 89.74 to 90.88. At the same time, deviation of the drop packets on edge nodes is reduced from 39% to 21% at the sampling node #27. This paper is an evaluation of parameter packet delivery ratio and it can be extended to real hardware or accurate analysis of the network.

Mainly, Packet delivery ratio and Power consumption are inversely proportional. It's really hard to find balance between both of them. In the near future, we plan to develop a method to improve the power consumption of the proposed routing algorithm for real-world applications.

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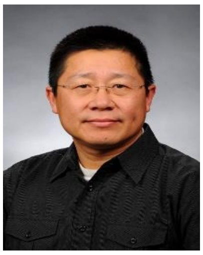

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