EVALUATION OF THE W-METRIC ROUTING USING RPL PROTOCOL IN LLNS

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ABSTRACT: The current de-facto routing protocol over Low Power and Lossy Networks (LLN) developed by the IETF Working Group (6LOWPAN), is named as Routing Protocol for Low Power and Lossy networks (RPL). RPL in the network layer faces throughput challenges due to the potential large networks, number of nodes, and that multiple coexisting applications will be running in the same physical layer. In this study, a node metric for RPL protocol based on the node's Queue Backlogs is introduced, which leads to a better throughput performance while maintaining the delay and the ability to use with different network applications. This metric depends on the length of Packet Queue of the nodes with the consideration of other link and node metrics, like ETX or energy usage, leading to better load balancing in the network. To implement and evaluate the proposed metric compared to other RPL metrics, ContikiOS and COOJA simulator are used. Extensive simulations have been carried out in a systematic way resulting in a detailed analysis of the introduced metric namely W-metric, expected transmission count (ETX) and objective function zero (OF0) that uses hop-count as a routing metric. The analysis and comparison are based on five performance parameters, which are throughput, packet delivery ratio (PDR), latency, average queue length, and power consumption. Simulation results show that the introduced W-metric has a good performance compared to other RPL metrics with regards to performance parameters mentioned above. At the same time, the results show that its latency performance is comparable with other RPL routing metrics. In a sample simulation of 500 seconds with 25 nodes and with nodes sending packets periodically to the network root at a rate of 1 packet per 4 seconds, W-metric showed a very efficient throughput of 5.16 kbps, an increase of 8.2% compared to ETX. Results showed that it has a packet delivery ratio of 93.3%, which is higher compared to 83.3% for ETX and 74.2% for OF0. Average queue length of 0.48 packet shows improvement of 15.8% better than ETX. In addition, it exhibits an energy consumption of 5.16 mW which is 2.1% less than ETX. Overall, W-metric appears to be a promising alternative to ETX and OF0 as it selects routes that are more efficient by working on load balancing of the network and by considering the link characteristics.

ABSTRAK: Protokol penghalaan de-facto semasa ke atas Rangkaian Kekuatan Rendah dan Lossy yang dibangunkan oleh Kumpulan Kerja IETF (6LOWPAN), dinamakan Protokol Penghalaan untuk Kekuatan Rendah dan Rugi (RPL). RPL dalam lapisan rangkaian menghadapi cabaran throughput berikutan jangkaan rangkaian besar, bilangan nod dan aplikasi berganda bersama akan diproses dalam lapisan fizikal yang sama. Dalam kajian ini, satu metrik nod untuk protokol RPL berdasarkan pada Backend Queue node diperkenalkan, yang membawa kepada prestasi yang lebih baik sambil mengekalkan kelewatan dan keupayaan untuk digunakan dengan aplikasi rangkaian yang berbeza.

Metrik ini bergantung pada panjang Packet Queue dari node dengan pertimbangan metrik lain dan nodus lain, seperti ETX atau penggunaan tenaga, yang mengarah kepada keseimbangan beban yang lebih baik dalam rangkaian. Untuk melaksanakan dan menilai metrik yang dicadangkan berbanding metrik RPL lain, ContikiOS dan COOJA simulator telah digunakan. Simulasi meluas telah dijalankan dengan cara yang sistematik yang menghasilkan analisis terperinci mengenai metrik yang diperkenalkan iaitu W-metrik, kiraan penghantaran dijangkakan (ETX) dan fungsi objektif sifar (OF0) yang menggunakan kiraan hop sebagai metrik penghalaan. Analisis dan perbandingan adalah berdasarkan lima parameter prestasi, iaitu throughput, nisbah penghantaran paket (PDR), latency, panjang panjang antrian, dan penggunaan kuasa. Hasil simulasi menunjukkan bahawa W-metrik yang diperkenalkan mempunyai prestasi yang lebih baik berbanding dengan metrik RPL lain berkaitan dengan parameter prestasi yang dinyatakan di atas. Pada masa yang sama, hasil menunjukkan bahawa prestasi latency W-metrik adalah setanding dengan metrik penghalaan RPL yang lain. Dalam simulasi sampel 500 saat dengan 25 nod dan dengan nod yang menghantar paket secara berkala ke akar rangkaian pada kadar 1 paket setiap 4 saat, W-metrik menunjukkan keluaran yang sangat efisien iaitu 5.16 kbps, peningkatan sebanyak 8.2% berbanding ETX. Keputusan menunjukkan bahawa ia mempunyai nisbah penghantaran paket 93.3%, yang lebih tinggi berbanding 83.3% untuk ETX dan 74.2% untuk OF0. Purata panjang giliran 0.48 packet menunjukkan peningkatan 15.8% lebih baik daripada ETX. Di samping itu, ia mempamerkan penggunaan tenaga sebanyak 5.16 mW iaitu 2.1% kurang daripada ETX. Secara keseluruhan, W-metrik nampaknya menjadi alternatif yang berpotensi menggantikan ETX dan OF0 kerana ia memilih laluan yang lebih cekap dengan bekerja pada keseimbangan beban rangkaian dan dengan mempertimbangkan ciri-ciri pautan.

KEYWORDS: *IOT; RPL; LLNs; queue backlog; objective function*

1. INTRODUCTION

The Internet is increasingly becoming an inevitable part of our lives and recently Internet of Things (IoT) appeared as an important future scenario of the Internet application. The number of computing and interconnected devices has grown exponentially within the last 2 decades, and it is expected to grow further. By the end of 2020, it is estimated that the world will have an approximate number of 50 Billion connected devices [1-3]. The Internet Engineering Task Force (IETF) used the term, Low Power and Lossy Networks (LLNs) to refer to networks of different types of smart devices and sensors. These networks challenges include highly varying link quality, limited device memory, power, and recurrent link outage. In many environments, LLNs are emerging as a new deployment communication, like smart buildings, industrial automation, and for the majority of the envisioned IoT [2].

Conventional routing protocols fail to meet the LLNs requirements due to the mentioned limitations. The IETF working group has identified Routing Over Low power and Lossy Networks (ROLL) as a solution for routing in this type of networks under particular deployment scripts. As a result, IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) is standardized in RFC 6550 to ensure IPv6 packets carried over IEEE 802.4 is achievable, as well as to empower the usage of IoT over WSN [4]. However, RPL in the network layer meets throughput challenges due to the potential huge network size, various coinciding applications in one physical network and the large amount of information and data created and imparted from the devices.

RPL existing implementations mostly use either Expected Transmission Count (ETX) or hop-count routing metrics. ETX measures the reliability of the link between two nodes. The ETX link value expects the number of times to transmit a packet until it is successfully delivered over that link. The weaker the link connecting two nodes, the higher the ETX value and the greater the number of required retransmissions [5].

On the other hand, the objective function that uses hop-count metric calculates the path cost based on the number of hops between the node and the destination. The hop-count metric does not take into consideration the LLNs characteristics; therefore, it may choose a route that leads to bad throughput performance. In the same way, the ETX metric is only concerned with the link loss [6].

Researchers introduced a variety of extensions for RPL to tailor to the specific requirements of network applications including three multipath routing mechanisms based on RPL such as Fast Local Repair (FLR), Energy Load Balancing (ELB), and ELB-FLR, which is a combination of the first two as reported in [1]. Results implied that this mechanism leads to better energy consumption and network lifetime. However, it didn't lead to the improvement of the throughput performance.

Another research work used a Backpressure routing protocol (BackIP) as a replacement for RPL Routing protocol for data collection applications [7]. This protocol resulted in a better throughput performance, however it led to an increase in the potential end-to-end delay, limited applicability only to many-to-one communication, and a more complicated design compared to RPL.

Most of the studies related to RPL did not lead to the enhancement of throughput performance in LLN networks. Another study reported enhanced throughput performance of RPL using a back pressure approach, but simultaneously affecting other performance aspects [8]. The study introduced a routing metric for RPL protocol based on the node's Queue Backlogs. The purpose of this metric was to enhance throughput performance of RPL protocol while maintaining the delay and preserving system resources such as the energy consumption. This metric depends on the length of the Packet Queue of the nodes with the consideration of other link and node metrics, like ETX or energy usage, leading to better load balancing in the network.

In [9], an investigation on the Objective Functions and related parameters which influence RPL performance is reported. A set of simulation runs using Contiki operating system and Cooja simulator is carried out. The RPL performance is evaluated in terms of Packet Delivery Ratio (PDR), latency, energy consumption, and others that showed ETX is a better routing metric compared to Hop-counts.

In this paper, investigation on the introduced routing metric, W-Metric, as reported in [8] is compared to other RPL routing metrics like ETX and OF0: Hop-count. This paper presents results of a simulation conducted using ContikiOS and Cooja simulator in terms of throughput, Packet Delivery Ratio (PDR), latency, and power consumption.

2. BACKGROUND

2.1 Determining Routing Protocol for Low Power and Lossy Network for IPV6

RPL builds and keeps up the network as a directed acyclic graph (DAG), which can be isolated into many Destination-Oriented DAGs (DODAGs) [5]. RPL uses DODAG Information Object (DIO) control messages for the configuration process, support nodes to join the DODAG, and then for parents' selection. Exchanging DODAG information between nodes begins as soon as the RPL network starts through DIO control messages. DAG Metric container defined in [5] used to carry needed routing constraints and metrics.

These metrics and constraints are used to determine the best path using the Objective Function (OF).

Once the neighboring node receives a DIO message, the rank is computed based on its parent's rank and the cost to reach that parent. For the parent selection process, it is essential to choose an arrangement of the routing metrics that will influence routing choice for different DODAGs that is called an Objective Function (OF). An OF characterizes an arrangement of functions to compute rank, which is the relative separation of one node towards the root, and in addition to contrast neighbors with respect to the rank [6].

After receiving the DIO message, the node joins the DAG before sending the needed information such as DAG-ID, rank, routing metric, and OF to its neighbors. Hence, the rest of the nodes will join the DAG after computing their ranks. This operation continues until the last node in the topology has computed its rank and joins the DAG.

Path cost is a scalar value calculated as a function of the node or link characteristics through the end-to-end route from node toward the root [5]. When ETX is used as a routing metric in RPL, then the path cost for node N towards DODAG root($Path\_Cost(i)$) can be calculated as in Eq. (1) and Eq. (2)

$$Path\_Cost(i) = Rank(j) + \; Rank\_increase \tag{1}$$

$$Rank\_increase = \mathrm{ETX}_{i\to j} * MinHopRankIncrease \tag{2}$$

with j as the preferred parent of i and $MinHopRankIncrease$ as a constant value. On the other hand, when the hop-count metric is used in the objective function, the path cost is equal to the number of hops from the node toward the root [6]. Then, the path cost for node N ($Path\_Cost(i)$) can be calculated as in Eq. (3) with $increment$ as a constant value.

$$Path\_Cost(i) = Rank(j) + \; increment \tag{3}$$

2.2 Queue Backlog W-metric for RPL

The motivation for this work is to define a routing metric that allows RPL to increase total network throughput and to achieve a better load balancing between nodes based on Queue-Backlogs. The Queue-Backlog $Q_{i\to j}$ is the queue length of the neighboring's queue in node i that holds packets to be forwarded to its neighbor, node j. The general equation for calculating the weight of each link from a node to other nodes is described in Eq. (4) [8].

$$W_{i,j} = x.\,Q_{i\to j} + \; \theta_{i\to j} \tag{4}$$

where $\theta_{i\to j}$ is the corresponding cost of using the link ($i \to j$), and x is a constant parameter for penalty minimization by trading system queue occupancy. The queue length, Q_i is computed at each node.

W-metric value will be recalculated as a moving average value as in Eq. (5) whenever the Queue length value or the used metric changes.

$$W_{i\to j} = p * \overset{\wedge}{W_{i\to j}} + \; (1-p) * W_{i\to j} \tag{5}$$

where p is a constant factor larger than zero and less than one and $\overset{\wedge}{W_{i\to j}}$ is the new value of $W_{i\to j}$, then update the metric container with the new value.

RPL is set to calculate node rank based on the W-metric. On a path between a node V and the root, W-metric is the summation of W-metric on each node along the path as in Eq. (6).

$$W_{V,T} = \sum\nolimits_{for\ all\ nodes\ through\ (V,T)Path} W_{i\to j} \tag{6}$$

As a result, to route the packets from a node to the DODAG root, a path with minimum W-metric value is selected.

The usage of ETX with W-metric leads to the calculation of the weight $W_{i,j}$ of the link $i \rightarrow j$ by a node i towards a neighbor j as follows in Eq. (7):

$$W_{i,j} = x\, Q_{i \rightarrow j} + ETX_{i \rightarrow j} \tag{7}$$

6. SIMULATION SETUP

In order to analyze and evaluate the performance of the introduced routing metric in comparison to other RPL routing metrics, a range of configuration settings have been considered. For this simulation, ContikiOS and Cooja simulators are used. A network topology consists of 25 Tmote-Sky nodes, which are the sensors sensing different aspects of the environment. Nodes are randomly positioned in an area defined in Fig. 1, with each grid square equal to 10 m^2. Node 1 works as a sink (the root of the DODAG) and the other 24 nodes as senders of upstream data packets periodically to the sink node. The total packet size of 120 bytes with transmitted power of zero dbm (or 31-contiki power level parameter) is identified.

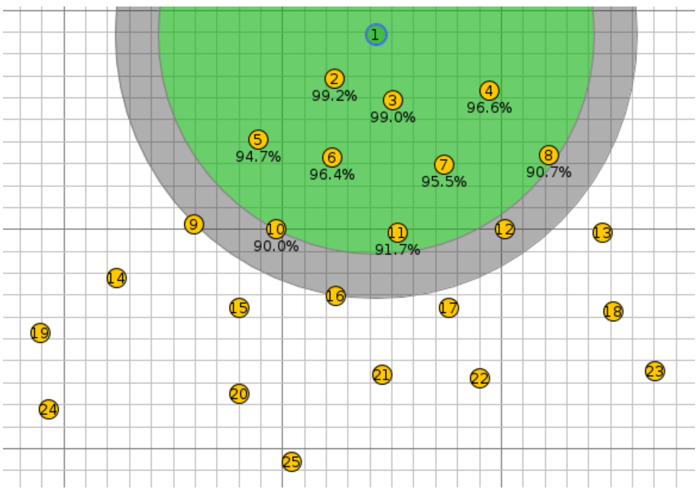

Fig. 1: Network topology used in simulation.

For measuring the simulation time and the simulation stop time (after a certain needed time), a Cooja plug-in feature, known as Contiki Test Editor, is utilized. This feature creates a log file containing the output of all simulations and can be used for data analysis. For the purpose of introducing attenuation (greater "lossiness") for the wireless medium with respect to the nodes relative distances, the Cooja Unit Disk Graph Medium (UDGM) is used. The UDGM uses two range parameters for transmission range as well as for interference range with other radios. In addition, it defines another two parameters, which are *Success-Ratio TX* to model the loss at the sender and *Receiver-Ratio RX* to model the loss at the receiver side. The value of Transmission Ratio TX and Reception Ratio RX was set to loss-free (equal to 1). On the other hand, the Transmission Ratio TX was set as loss free to 100% with the Reception Ratio RX set to 90% for another set of simulations in order to model packet loss at the receiver side in the network.

The operation mode of RPL is set to no-downward-traffic as the evaluation process of this study is only interested in using the multipoint-to-point communication. The interference range is set to 120 m and the transmission range is set to 100 m. For different iterations of the proposed simulation tests, different values for the send interval are used in order to study the network throughput at different traffic levels and densities. Table 1 presents the values of different network parameters used for this network topology and its set of simulations.

Table 1: Simulation parameters

Parameter	Value
Transmitting Power	0 dBm
TX Ratio	100%
RX Ratio	90%,100%
Transmission Range	100 m
Interference Range	120 m
X factor for W-metric	1
p factor for W-metric	0.8
Sending interval	4, 6 and 10 sec
MAX_NEIGHBOR_QUEUES	3
QUEUEBUF_CONF_NUM	8
Client Nodes	24 nodes
Simulation Time	500 c

4. SIMULATION RESULTS

4.1 Network Throughput

Throughput is the total data received at the root except duplicates and control packets to trace the throughput of all traffic flows. Figure 2 shows network throughput at the root for W-metric as compared to ETX and OF0 for a send rate λ equal to 1 packet per 4 seconds. Both transmission ratio TX and reception ratio RX are set to 100%. For simulation results presented in Fig. 3, TX=100% and RX= 90% with a send rate of 1 packet per 4 seconds is used. Figure 4 shows throughput for a simulation runs with TX=RX=100% and send rate of 1 packet per 10 seconds is considered. Table 2 shows the average throughput of the network at the sink. From the mentioned figures and table, it is noted that W-metric has a better throughput performance compared to both of ETX and OF0 for different sending rates. The advantage of W-Metrix over OF0 is higher than that over ETX. At lower sending rates throughput performance of the three metrics are very similar, however, as the sending rate increases, throughput difference also increases.

Table 2: Send Rate vs. Average Throughput per Second (measured in kbps)

Setting	W-metric (kbps)	ETX (kbps)	OF0 (kbps)
Send Rate: 1 packet per 10 sec	2.147	2.140	2.140
Send Rate: 1 packet per 6 sec	3.390	3.300	3.310
Send Rate: 1 packet per 4 sec	5.160	4.770	4.290
Send Rate: 1 packet per 4 sec (Lossy Network)	4.900	4.480	3.900

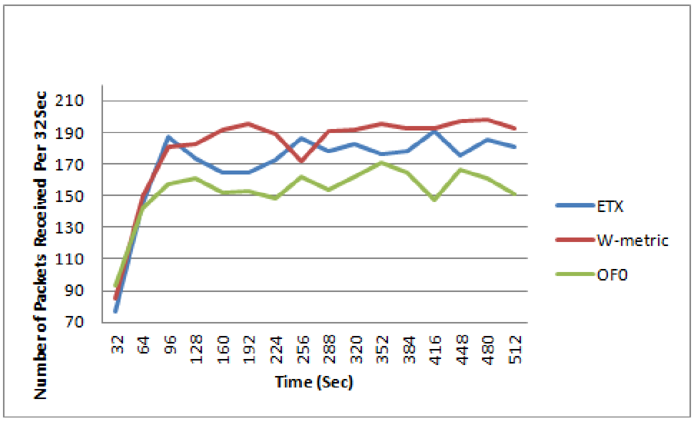

Fig. 2: Throughput of W-metric vs. ETX vs. OF0 at send rate of 1 packet per 4 sec.

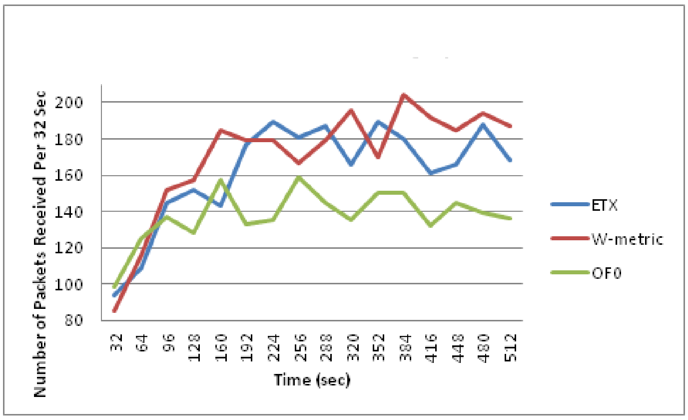

Fig. 3: Throughput of W-metric vs. ETX vs. OF0 at send rate of 1 packet per 4 sec (Lossy).

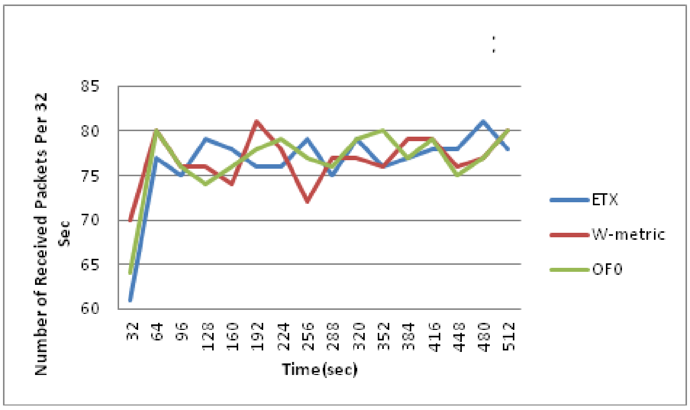

Fig. 4: Throughput of W-metric vs. ETX vs. OF0 at send rate of 1 packet per 10 sec.

4.2 Packet Delivery Ratio

The second performance evaluation metric is packet delivery ratio (PDR) which refers to the percentage of the number of packets successfully received at the root to the total number of packets sent from all the nodes. From Table 3, W-metric has a packet delivery ratio that is slightly better than ETX and OF0 ratio at low send rate. However, it shows more improvement for higher send rates. On the other hand, ETX also shows a better performance compared to OF0. This proves the efficiency of W-metric compared to other RPL metrics.

The better performance of W-metric regarding PDR also refers to better load balancing and better route options.

Table 3: Send Rate vs. Packet Delivery Ratio

Setting	W-metric	ETX	OF0
Send Rate: 1 packet per 10 sec	99.97%	99.96%	99.96%
Send Rate: 1 packet per 6 sec	98.80%	96.50%	97.10%
Send Rate: 1 packet per 4 sec	93.30%	88.50%	80.50%
Send Rate: 1 packet per 4 sec (Lossy Network)	88.60%	83.20%	72.00%

4.3 Power Consumption

Power consumption is considered to be one of the essential aspects of LLNs performance, as these devices need to work for years with limited power. For power consumption analysis, Powertrace system is used. Powertrace is a mechanism provided by Contiki software for calculating the power consumption of low power wireless networks. As shown in Table 4, W-metric has an advantage over both of ETX and OF0 for higher send rate. On the other hand, on lower and medium range rates, OF0 shows a slightly better performance compared to W-metric and ETX. However, OF0 has the worst power consumption at high send rates due to higher number of retransmissions and the highly congested routes. Because of the lossy nature of LLNs, the link quality changes frequently leading to frequent change in ETX for the path. W-metric and ETX can precisely reflect the link condition as both consider the path ETX. On the other hand, OF0 in path selection process does not consider the path ETX as it only concerns on selecting the shortest path. Consequently, the nodes will encounter more packet retransmissions, which results in more energy consumption.

Table 4: Send Rate vs. Average Power Consumption (measured in mW)

Setting	W-metric (mW)	ETX (mW)	OF0 (mW)
Send Rate: 1 packet per 10 sec	2.164	2.282	2.057
Send Rate: 1 packet per 6 sec	3.264	3.268	3.139
Send Rate: 1 packet per 4 sec	5.162	5.276	5.494
Send Rate: 1 packet per 4 sec (Lossy Network)	6.009	6.370	6.713

4.4 Delay Performance

The fourth performance metric evaluation is packet latency or end-to-end delay. The latency is defined as the total amount of time a packet needs to be transferred from the source node to the destination. Latency is calculated as the average of all the packet latencies in the network from all nodes.

Figure 5 represents the Cumulative Distribution Function (CDF) of the packets latency for the three metrics. It is noted that W-metric and ETX have a similar latency performance and that both have a much better performance compared to OF0. This is related to the fact that W-metric and ETX considers the details of the link level when compute the best routes, while OF0 only concerns about the hop-count separates the node and the root.

Table 5: Send Rate vs. Average of Maximum Inter Packet Time

Setting	W-metric	ETX	OF0
Average Latency	2.89 sec	3.37 sec	5.46 sec
Send Rate: 1 packet per 6 sec	3.264	3.268	3.139

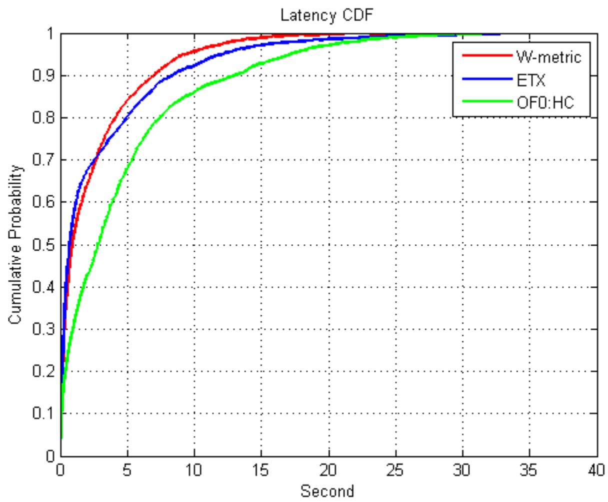

Fig. 5: CDF of the three routing metrics latencies.

5. CONCLUSION

In this paper, W-metric performance is evaluated using Cooja simulator with ContikiOS. The two objective functions in ContikiOS, which use ETX and OF0 (hop-count), have been used for benchmarking. Overall, W-metric shows a good performance compared to ETX and OF0. W-metric works on selecting more efficient routes by balancing the load of the network and taking into consideration the link characteristics, which leads to better throughput, PDR, and network latency. For power consumption, W-metric at high send rates had the best consumption resulting from selecting paths that lead to less radio collisions and re-transmissions through the network. On the other hand, OF0 showed the best performance regarding power consumption in low and medium range send rates. For more enhancements on the W-metric, the suggested aspects in the next session can be investigated.

There are many other aspects of W-metric design and performance need to be investigated as a future study. Firstly, the context of this paper was limited to fixed nodes, but with mobile nodes, issues such as latency, PDR, and energy consumption become harder to optimize, making many aspects of routing in LLNs more difficult to manage. Usual solutions for mobility depend on how frequently the routing information is updated; this is an important factor for LLNs that are limited in resources. Hence, evaluation of W-metric on mobile nodes may offer valuable suggestions for more enhancements on this metric. Secondly, memory utilization and routing table sizes are substantial parameters that need to be studied to be used with W-metric for further enhancements.

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